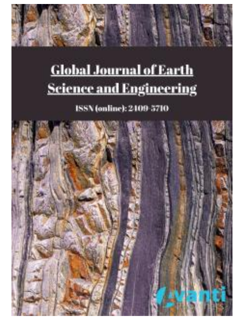
Published by Avanti Publishers

Global Journal of Earth Science and Engineering

ISSN (online): 2409-5710



Evidence of a Large Debris Avalanche Event (22.0 Ma) from the Comondú Group on the Baja California Sur Peninsula, Mexico

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ARTICLE INFO

Article Type: Research Article

Academic Editor: Chandra Prakash Dubey

Keywords:
Miocene
Comondú group
Debris avalanche
Baja California Sur Peninsula

Timeline:
Received: May 01, 2024
Accepted: July 13, 2024
Published: August 27, 2024

Citation: Alquiza MjP, Aviles RM, Kshirsagar PV, Zanor GA.. Evidence of a large debris avalanche event (22.0 Ma) from the Comondú group on the Baja California Sur Peninsula, Mexico. Glob J Earth Sci Eng. 2024; 11: 19-35.

DOI: https://doi.org/10.15377/2409-5710.2024.11.2

ABSTRACT

The morphological, sedimentological, and microtextural characteristics of Miocene debris avalanche deposits which extend from the Punta Coyote to the vicinity of the city of La Paz, were studied along the eastern of the Baja California Peninsula. The debris avalanche deposits studied include a mixture of angular mega blocks whose composition comes from the deposits that make up the Comondú Group: pre-Comondú (red sandstones and conglomerates with intercalated ignimbrites), the Upper Unit (brownish sandstones, shales, and conglomerate), and breccia, with a predominance of jigsaw cracks, injection structures, and fault structures. These deposits were studied and analyzed considering the stratigraphic relationships between the rock formations present in the mega-blocks. Six stratigraphic sections were measured to describe the composition and morphology of the clastic components present in the mega-blocks of the debris avalanche. Two different units (m_1 and m_2), were identified in the debris avalanche deposits. Unit m_1 is the oldest, with a thickness of 100m, and consists of a chaotic set of mega-blocks up to 100 m in diameter derived from the pre-Comondú Group, and Upper Unit. The deposits are highly heterolithic, with angular and highly fractured clasts at different scales. While the unit m_2 consists principally of 20-100 m thick volcaniclastic layers dominated by poorly sorted, breccias and minor epiclastic deposits. According to stratigraphic relationships, the collapse occurred at 22.0 Ma. The debris deposit covers an area of 150 km^2 and has an estimated volume of 1.3 km^3. The characteristic suggests a transport mechanism with a disintegration of the mega-blocks and a contact/collision interaction. Where mega-blocks moved within a dense flow in a buffered manner, remaining consistent over long distances. The observed structures and textures suggest that the mega-blocks were mainly produced by the alteration and ingestion of older substrates by the avalanche of moving debris. The avalanche flowed over pre-existing topography excavated in the Comondú Group sequence, and flow indicators reveal a west-southwest direction, exhibiting a typical mountainous avalanche topography. The study of ancient debris avalanche events not only provides a deeper understanding of these natural phenomena but also contributes to the development of tools to predict, mitigate, and manage risk areas.

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1. Introduction

In volcanic areas, stratovolcanoes can grow and collapse the central cone. The collapse of a volcano sector may be due to different factors such as magmatic intrusion, earthquakes, or increased interstitial pressure in hydrothermal zones [1-3]. These collapse events generate fast-moving landslides called volcanic rock slide avalanches [4-6] or volcanic debris avalanches [7-9]. Debris avalanches are described as breccia deposits in which clastic fragments of various sizes are trapped within a finer-grained matrix. According to [8], a debris avalanche is a rapidly moving, incoherent, and disorderly mass of rock and earth, mobilized by gravity. Similarly, several terminologies have been proposed for the description of debris avalanche deposits, some are based on the concept of facies, and others on the description of clastic components [10, 11]. Debris avalanche deposits present different morphologies, some associated with horseshoe-shaped or triangular shapes representing the collapsed volcano and a rough surface showing a mountainous surface. Internally, debris avalanche deposits show textures related to clasts with a jigsaw or jigsaw fissures, mega clast (clasts larger than 1 m in diameter) that preserve original primary structures, material injections with fluid contacts, internal faults, shear, and horst-and-graben structures associated with clast-rich, and matrix-rich facies [1, 3, 5, 9, 12, 13]. One of the problems in the study of avalanche debris deposits is understanding the mechanisms involving the mobility of their mega-blocks. Based on this, numerical models have been created that involve fluidization and lubrication processes [14], however, more detailed investigations are required, due to the complexity represented by the numerical modeling of the spatial and temporal variability of the flow. In recent studies, the concept of dynamic disintegration is introduced [15-22], where it is mentioned that the fragmentation of rock particles occurs during avalanche transport, reducing the size of the particles clasts by collisions between particles releasing energy [23, 24]. The occurrence of building collapses and the flows that derived from them occur along several of the best-known volcanoes of the Trans-Mexican Volcanic Belt (TMVB) in Mexico [25-34]. However, ignimbrite ignimbrite-rich areas of the Baja California Sur peninsula, no debris was documented in detail.

The debris avalanches mapped around La Paz, Baja California Sur Peninsula consist of a great variety of lithologies, including lavas, pyroclastic deposits, autoclastic deposits (non-explosive origin), and deposits derived from sedimentary processes (epiclastic). Epiclastic deposits, according to [35] are deposits that have been produced by normal surface fragmentation processes such as weathering, physical abrasion, and gravitational collapse, or deposited by normal surface processes such as traction, suspension, and mass flow. According to [36], epiclastic deposits are directly related to instability events on volcanic slopes and their erosion. Epiclastic deposits are classified according to several criteria, including composition, block size, distance from the source, block/matrix ratio, breccia structures, and content of clay [5, 7, 9, 13, 37, 38]. Likewise [39] has suggested that the occurrence of volcanic mega-slides is common in the evolution of Cal- alkaline volcanoes. One of the limitations in the study of old avalanche debris deposits is that they can be eroded or covered by vegetation, making identification and analysis difficult. On the other hand, human activities can alter or destroy geological evidence, making it difficult to reconstruct the historical record. Based on this, the objective of this research is to document the stratigraphic relationships, describe the morphological and sedimentological characteristics, and micro-textures of the debris avalanche deposit, discuss the origin of the debris avalanche, and propose a model for their transport and emplacement.

2. Description of the Study Area

The debris avalanche studied here is distributed in two areas, one of them the Punta Coyote area, which is located 98 kilometers in the direction Northeast of the Municipality of La Paz, on the Baja California Sur Peninsula, at 20 meters above sea level (Fig. **1**). These deposits are distributed along 10 km, covering the towns of Punta Tecolote, Playa Pulguero, El Pulguero, Playa Cachimbas, Punta Piedra de Bulle, Ensenada El Pulguero, Punta Coyote, Cañada Los Hornos, Cañada La Pedrera, Cañada Portezuelo, Pichilingue and Santa Victoria. The second area is located around the city of La Paz, southwest of the Punta Coyote area, at 20 meters above sea level. These deposits are distributed on the La Paz-Puerto Pichilingue highway section over 21 km (Fig. **1**).

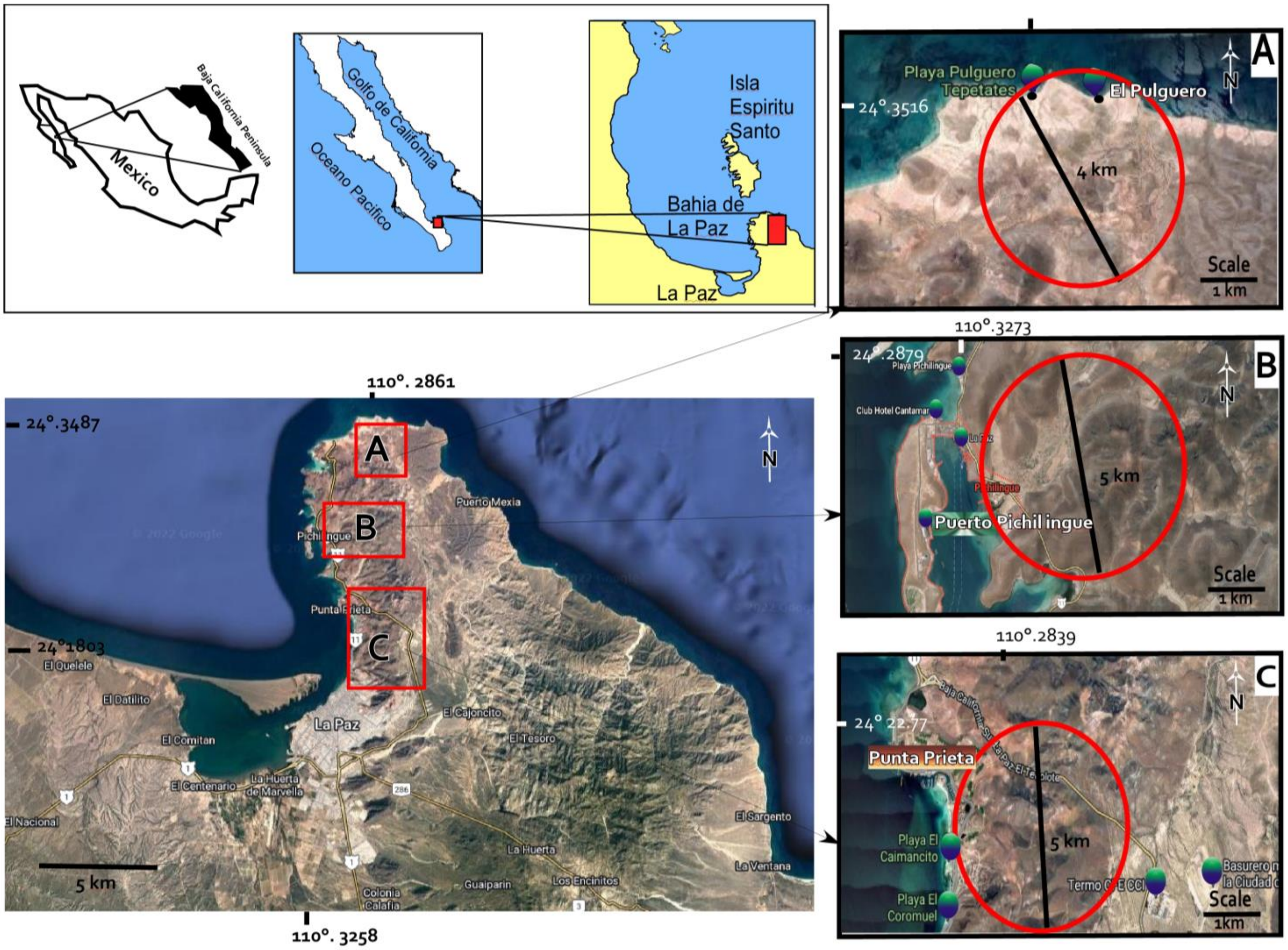

Figure 1: Study area. **A**) Punta Coyote area; **B, C**) La Paz area.

3. Tectonic and Geological Setting

3.1. Tectonic Setting

The Comondú Group is part of a volcanic arc and forearc basin that formed along the northwestern margin of Mexico, during the Oligocene [42, 47]. During this time the Pacific plate was subducting the western margin of the North American plate [37, 40, 41] originated two volcanic belts parallel to the continental margin. The oldest and easternmost belt of the Sierra Madre Occidental is composed of Oligocene (34-27 Ma) rhyolitic and ignimbrite rocks [42-45]. The youngest and westernmost belt, the Baja California Peninsula, is composed of Miocene (24-12 Ma) calc-alkaline rocks [45- 49]. The Comondú Group consists of alluvial fan facies, volcanic, and volcaniclastic deposits, and is part of the youngest volcanic belt [42, 44, 47, 50]. The Comondú Group crops out in the northeastern part of Baja California Sur (Fig. **1**). In the central portion of the Baja California Peninsula, the Comondú Group ranges in age from 30 Ma to 12 Ma [41, 42, 49, 50], whereas the southern part has ages of 25 Ma to 12 Ma [45-47, 50]. A thin belt of these rocks has been described along the coast of Sonora [51]. Around Bahia of La Paz, the oldest rocks of the Comondú Group are present [47, 50]. According to [47], these rocks are distributed around the Bay of La Paz and correspond to a sequence of volcanic-sedimentary rocks that mark the beginning of Comondú volcanism at about 24 Ma [52, 53]. Likewise, [47] mentions evidence of a syn-depositional deformation within the Comondú Group in the La Paz region, represented by a local, non-tectonic shearing and folding of tuffs and sandstones, displaced blocks within fault planes presenting a general west-southwest overlapping along the Gulf Coast. This deformation, according to [47] indicates a gravitational slide without depositional of large blocks in the lower part of the Comondú Group. On the other hand, [54], mention the existence of sedimentary deposits of red sandstone intercalated with volcanic material to the north of the Bay of La Paz, as well as the presence of allochthonous blocks of red sandstone within an andesitic breccia of the Comondú Group. These authors interpret that the blocks are olistoliths that were transported to the East or Southeast.

3.2. Regional Geology

The regional stratigraphy of arc-related rocks in Baja California Sur was presented by [47] in a map of three regional facies that was modified from the concepts of [55]. According to this facies scheme, the core facies extended along the eastern margin of Baja California before rifting, between Bahía Concepción and Loreto, the Pichilingue area, and north of La Paz. The core facies of lava flows, air fall ash, and colluvial deposits. The proximal facies consist of volcanic breccia, tuffs, sandstone, and conglomerate exposed in the east of the Gulf. Further west, the Comondú stratigraphy is best characterized as distal facies containing mainly sandstones with few ash-flow tuffs, breccias, or coarse-grained conglomerates. This gradation of facies occurs along areas of the Sierra de La Giganta and from Pichilingue to La Paz. These arc-related facies are the pre-rift foundation upon which the rift structures and basins related to the Gulf of California formed and thus these belts are locally extensively faulted and tilted [42].

3.3. Local Geological

In the area of Punta Coyote and La Paz, 30-20 Ma old ignimbrite, tuff, and debris avalanche deposits outcrop, corresponding to the Comondú Group [47, 56]. The Comondú Group comprises four main units in the study area (Fig. **2**). From oldest to youngest, these are the pre-Comondú deposits (red sandstone and conglomerate with interbedded ignimbrites), the Upper Unit (brownish sandstone, mudstone, and conglomerate), the Balandra breccia, and conglomerate. The 60m thick pre-Comondú deposits unconformably overlie Cretaceous granitic rocks and, are mainly composed of red sandstones and conglomerates. The red sandstone has distinct longitudinal cross-bedding layers. Most cross-bed sets range from about ~20-30cm to 20m in thickness and they include planar, parallel, and trough cross-bedding. The conglomerate is red-brown, moderate-to-poorly sorted, weakly stratified, and clasts and matrix-supported; it moreover includes minor to subequal amounts of interbedded sandstones. The conglomerate is, in most places, well indurated and resistant to weathering. The pre-Comondú deposits are dominated by sandstone and conglomerate with interbedded ignimbrites, 30.6 ± 0.4 Ma old [57], and covered in the section by rhyolitic tuff of age 21.8 ± 0.3 Ma [47, 57] suggesting that sedimentation of the Comondú Group began at the boundary of the late Oligocene and early Miocene.

The Upper Unit is ~200 m thick and is composed of brownish, sandstone, mudstone, and conglomerate covered by 21.8- ± 0.3-Ma-old rhyolitic tuff and debris avalanche deposit. The lenticular shape of the sandstone bodies and the small-scale cross-lamination in the massive sandstone suggest that deposition occurred in a fluvial system. Soft-sediment deformation structures, such as slumping folds, convolute, and desiccation cracks, disrupt the sequence. Moreover, brown mudstones contain desiccation cracks, indicating subaerial deposition. The oldest sandstone in the Punta Coyote was deposited around ~30 Ma when Baja California was still part of western Mexico.

The breccia and conglomerate Balandra are constituted by breccias and epiclastic deposits. In the La Paz area, this unit is light gray, thick-bedded to massive, poorly sorted, matrix-supported, and contains clasts that range in size from centimeters to 2 m. Clasts include basalt and andesite. Clasts are generally subangular. The matrix of the breccia is a fine to coarse-grained mixture of ash and sand. Bedding in the breccia is thick to massive, typically 1- 5 m, and commonly unstratified.

In the Punta Coyote area, the pre-Comondú deposits are named by [47] as the Salinas Member and by [56] as pre-volcanic rocks. These deposits are assigned to the pre-Comondú Group by [42]. Stratigraphic and petrographic studies of this Group were presented by [42, 47, 56, 57]. Nevertheless, near the Punta Coyote, this unit is constituted by more epiclastic deposits than breccias. The epiclastic deposits are conformably overline by pre-Comondú, and Upper Unit deposits. This deposit has a brown to black color, is thick-bedded, and is moderately well-sorted. The conglomerate contains clasts that range in size from millimeters to 5 cm. Clasts include basalt minor rhyolite and rhyodacite. Epiclastic deposits overlie the breccia and this breccia was named Ocre breccia by

[56]. This unit is exposed widely in the Punta Coyotes area (Fig. **2**). The Ocre Breccia consists of andesite angular clast, poorly sorted, and chaotic. The clasts float in a groundmass of gray to brown, poorly sorted. Bedding in the breccia is thick to massive typically 20 to 100 m and commonly unstratified.

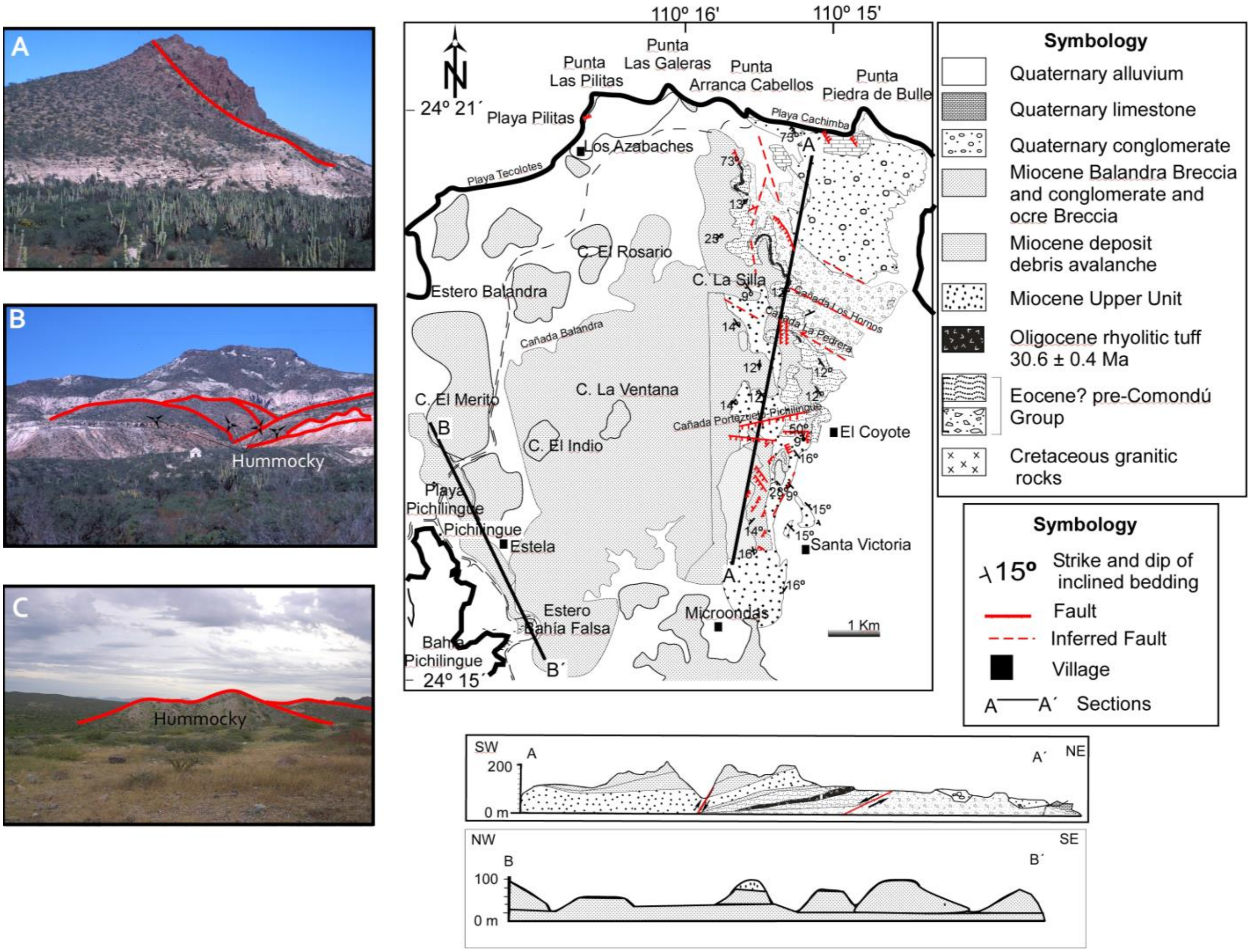

Figure 2: Local geology map. **A**) Rock avalanche; **B, C**) Low elevation hills (hummocks).

4. Methodology

To understand the stratigraphic relationships and describe the lithological characteristics of the debris-avalanche deposits in the Baja California Sur peninsula, two zones were chosen, the Punta Coyote area located to the northeast, and the La Paz area to the southwest. In the area of the Punta Coyote, two sections were measured (El Pulguero, and Cañada Portezuelo-Pichilingue) (Fig. **3**) while in the area of La Paz, four sections were surveyed (El Muellecito, El Tesoro, Enfermeria, and La Paz), (Fig. **3**). The description and interpretation of the volcanic facies were carried out by following the works of [5, 10, 13, 35, 58], the latter, of which was considered because according to his classification he considers that clasts (particles > 2 mm) and mega clasts (> 1 m) occur within a matrix (< 2 mm), the clasts can be non-fragmented, brecciated or stratified.

5. Results and Interpretations

5.1. Volcanic Facies of the Comondú Debris-avalanche Deposits

In this work, the volcanic facies of the Miocene debris-avalanche deposits were divided into two units (m_1 and m_2). The unit m_1 is observed around of La Paz City and the Punta Coyote area (Fig. **4** and **5**). Unit m_1 consists almost exclusively of pre-Comondú deposits (red sandstone and conglomerate with interbedded ignimbrites) and Upper Unit fragments (brownish sandstone, mudstone, and conglomerate). The unit m_2 is characterized by volcaniclastic layers (breccias and minor epiclastic deposits). In the Punta Coyote area, m_2 consists principally of 20-100 m thick volcaniclastic layers dominated by poorly sorted, breccias and minor epiclastic deposits. Near La Paz, the composition and texture of the m_2 are similar, but dominant in the epiclastic deposit. Overall, m_2 deposits are interpreted as the products of auto-brecciation of andesitic lava flow and epiclastic processes [56]. The dominant transport mechanism for these deposits is subject to debate and certainly varies among localities. For different sites, various authors [47, 56], favor an ash flow transport other than the result of hot volcanic debris flow associated with strato-volcanic eruptions. Debris avalanche deposits mobilized the upper part of the Comondú Group (mainly the pre-Comondú deposits and the Upper Unit). The precise age of the CDA deposit in the Punta Coyote and La Paz area is unknown. [47] suggested an age of 25.0 ± 0.6 m.y. based on K-Ar radiometric dates on various volcanic minerals (biotite) and 23.2 ± 1.6 m.y. (plagioclase) from rocks found in isolated exposures of the lowest stratigraphic unit in the La Paz area. According to [47], the bulk of Comondú volcanic in the La Paz area is from 25 to 17 m.y. old estimated the age of the Miocene. However, new geochronological data from a rhyolitic tuff deposit (30.6 ± 0.4 Ma) [57], found beneath the CDA deposit indicate that the avalanche occurred in the Early Miocene.

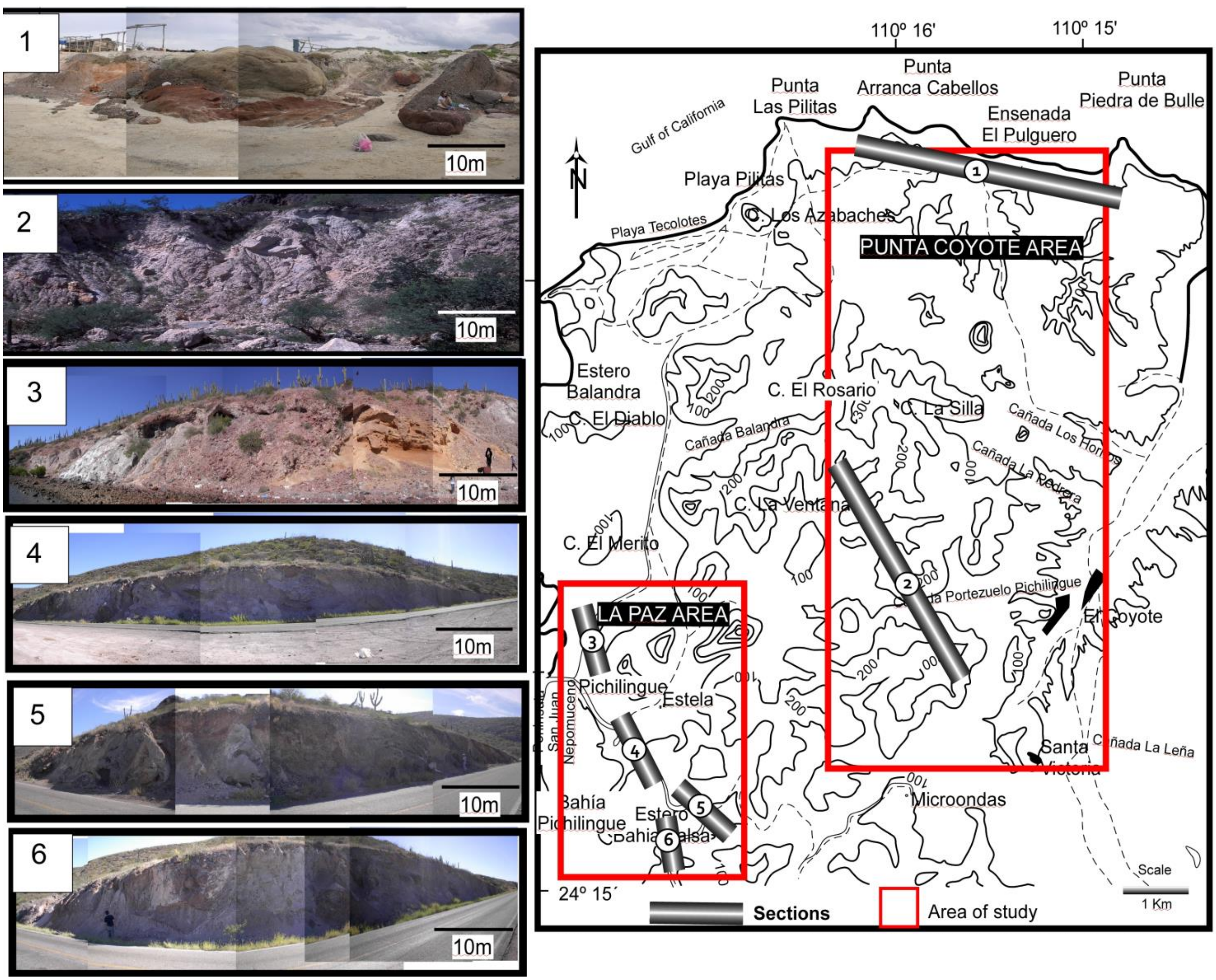

Figure 3: Sections of the study area. **1,2**) Punta Coyote area, **3,4,5,6**) La Paz area.

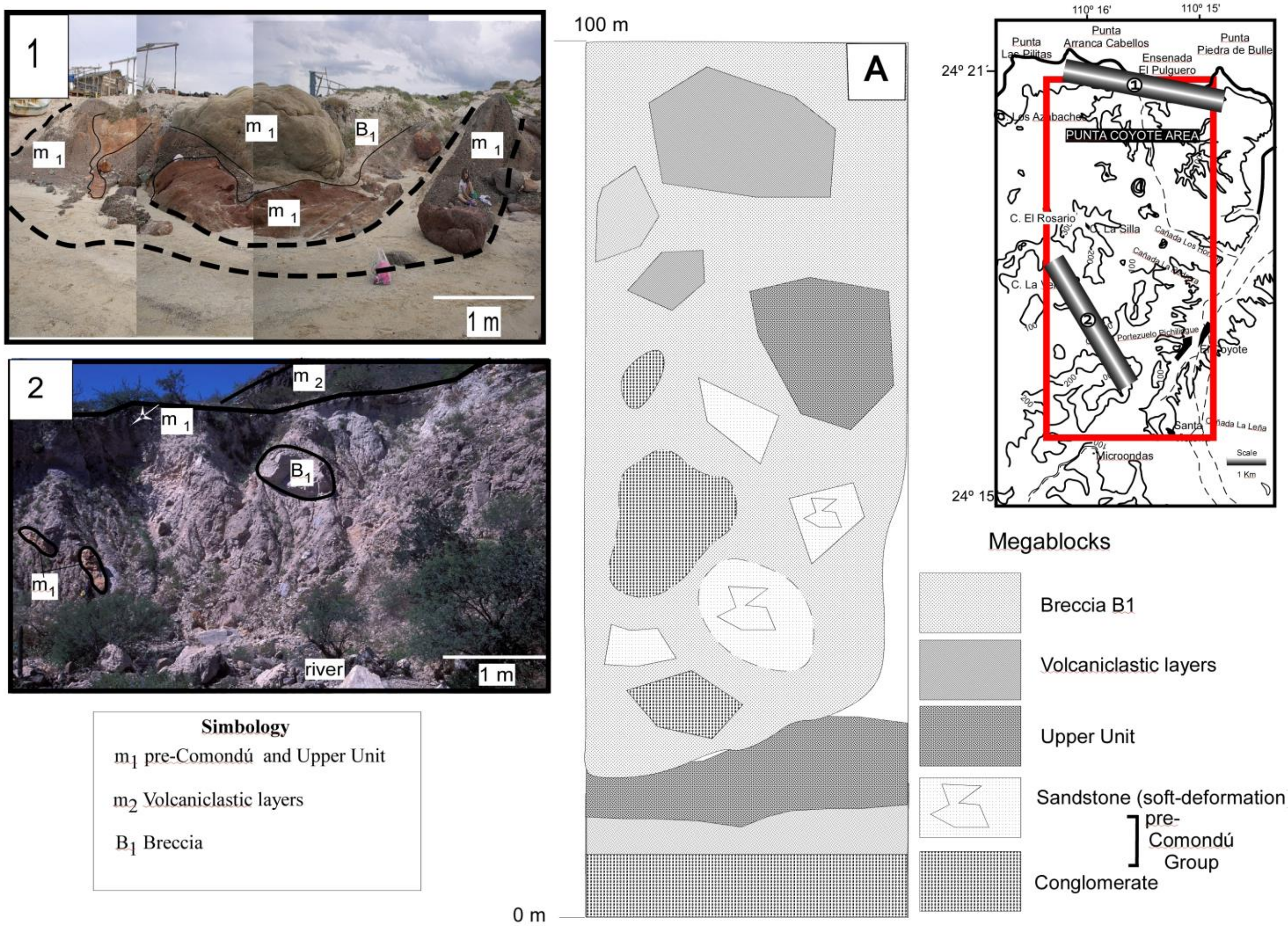

Figure 4: Stratigraphy section in the Punta Coyote area. **A**) composite stratigraphic column.

5.2. Geometry and Composition of the Comondú Debris-avalanche Deposits in the Punta Coyote and La Paz area

5.2.1. Punta Coyote Area

In the Punta Coyote area, volcanism such as faulting is the geological event that prevailed during the Cenozoic. The CDA is best described as a chaotic set of breccias and mega blocks (Fig. **4**). Mega blocks are composed of mixed sedimentary and volcaniclastic lithofacies. The occurrences of mega blocks are unlike thick pyroclastic breccias in that their distribution is not uniform and an accumulation zone is observed in the north of the Punta Coyote. There, four lithological types of mega blocks can be distinguished (pre-Comondú deposits, Upper Unit, and volcaniclastic layers and breccias).

Dimensions of avalanche mega blocks are commonly 1–100 m but can be smaller or larger. The degree of fragmentation of the rocks is commonly high, producing a sandy matrix. Individual avalanche blocks have different colors (red, brown, and grey), which depend on their composition. Irregular blocks of different dimensions and contrasting colors form a peculiar patchwork pattern in outcrops that are easily recognizable in the field. The fabric inside the avalanche mega blocks is generally massive and matrix-supported, but some very poorly fragmented mega blocks have clast-supported fabric. Most clasts are angular and larger clasts are commonly broken by several intersecting cracks and multiple microcracks. Juvenile material was not found in the debris-avalanche deposits. In the Punta Coyotes area where CDA lies on pre-Comondú deposits, the contact

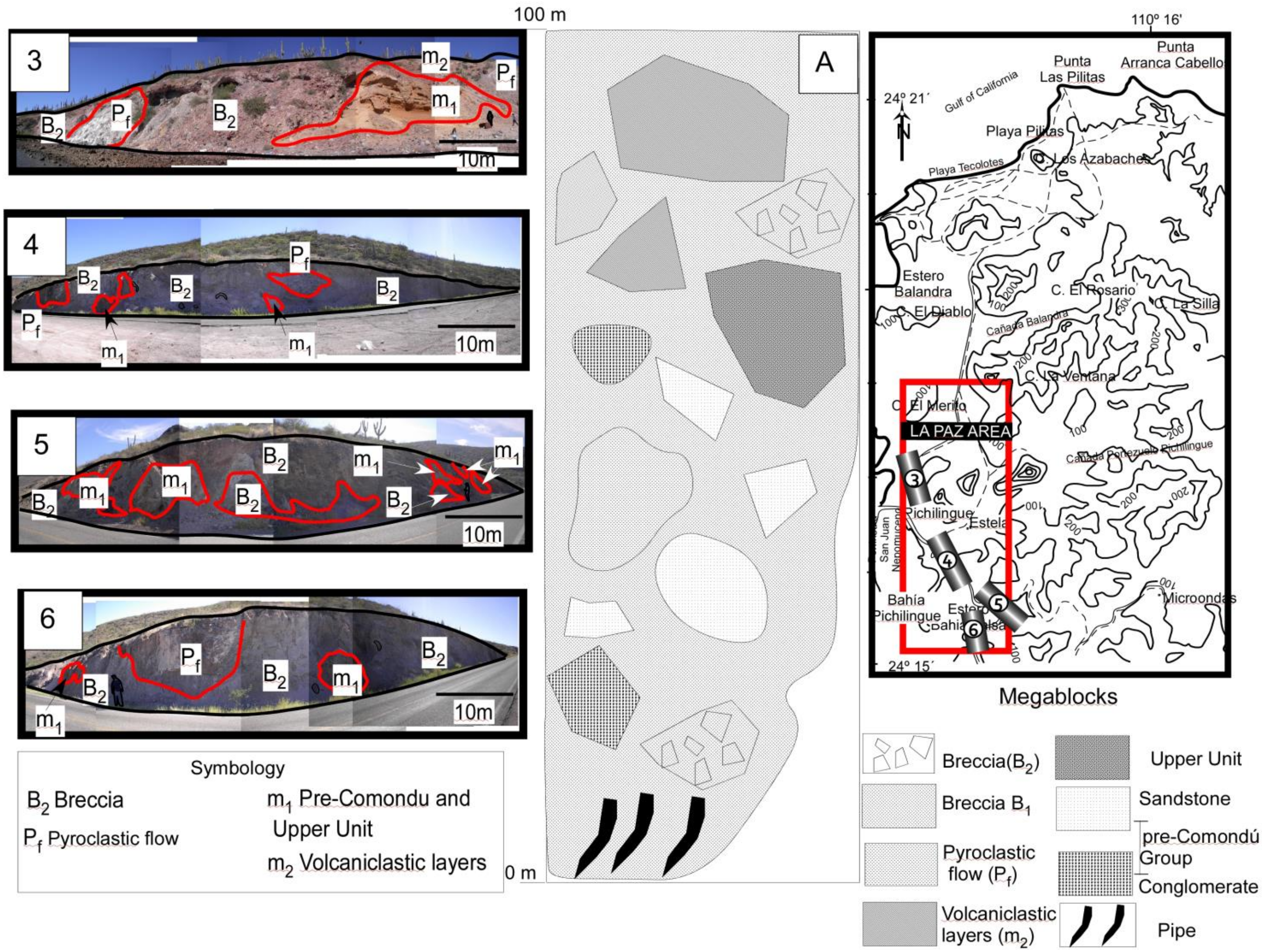

Figure 5: Stratigraphy sections in the La Paz area. **A**) composite stratigraphic column.

is sharp and erosive. The top of 1-3 m of the substrate is slightly fractured to brecciated and locally folded. The pre-Comondú beds have been folded, the folds have amplitudes between 50 cm to 2 m, and have northeast-trending planes with vergence perpendicular to the inferred transport direction of CDA (Fig. **6**). The deformation is principally in the form of fragmentation and block rotations. The pre-Comondú beds are rotated and folded within the brecciate B_1. The breccia B_1 is constituted by sedimentary rock fragments < 50 cm dispersed within a finer-grained matrix. The deformation in the contact with CDA indicates that the folds and fractures are related to the emplacement of the unit m_1 and result from compression and shear of the substrate by the moving mass of debris. In the m_1 case, the red sandstone mega blocks present complex shapes and form flame structures in the surrounding breccias, this suggests that they were poorly consolidated during transport and behaved in an almost fluidized manner.

The breccias with mega blocks constitute 85%-90% of the m_2 unit. In detail, the breccias show highly variable textures and compositions. Two principal types are distinguished according to their granulometry, contact geometries, and relationships; these are labeled B_1 and B_2. Breccia B_1 is observed in the Punta Coyote area. B_1 deposits are poorly sorted and ash fine-grained matrix composed of small particles similar to the composition of the mega blocks. Clasts of B_1 are usually angular, the clasts are dispersed within the matrix and sizes are centimeter to meter scale, these clasts are fractured and folded when the mega blocks are rotated. The existence of two superimposed breccias units implies at least two successive sector collapse events during the evolution of the volcanic complex.

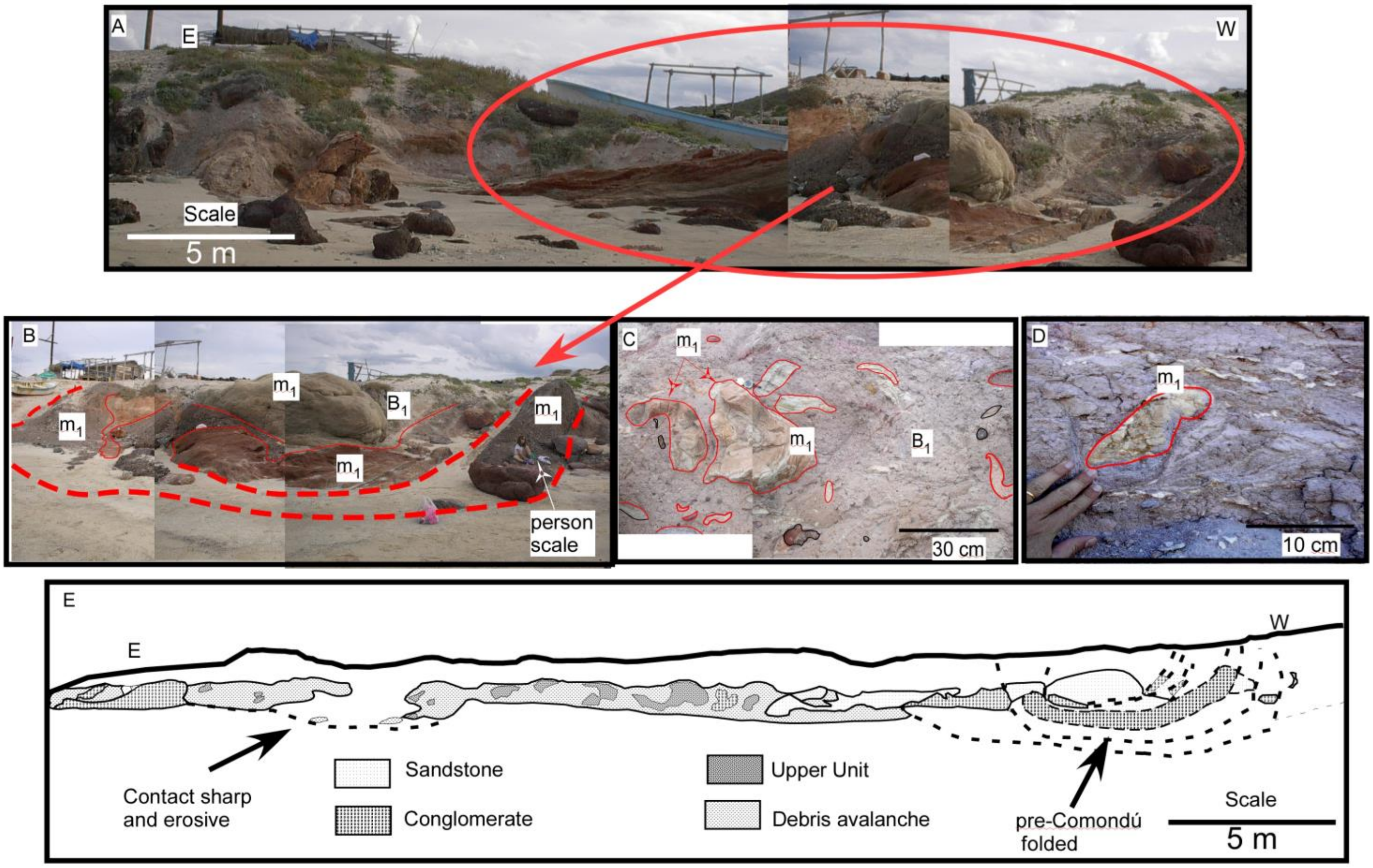

Figure 6: Punta Coyote area. **A,E**) Section, **B**) The CDA lies on pre- Comondú deposits, the contact is sharp and erosive. The top 1-3m of the substrate is slightly fractured to brecciated and locally folded. The pre-Comondu beds have been folded, **C, D**) Soft-sediment deformation structures slumping folds.

Between breccia (B_1) and breccia (B_2) in the Punta Coyote area, we document a pyroclastic flow and surge deposits. The pyroclastic flow deposit is composed of an ungraded layer of pink color 2 m thick and several tens meters long, it consists of larger pumice and lithic clasts. This ignimbrite presents ash matrix-supported. Underlying the ignimbrite are ground surge deposits, with individual layers of ten centimeters to various meters in length and 2 m thick. The unit lacks large pumice and lithic clasts. The geometry and extent are controlled by paleo topography. Present syn-depositional structures, and internal cross-stratification. Most cross-bed sets range from about 10-20 cm to 2 m thick. The dominant dip direction of the cross-stratification is to the SW 32º, dipping 6º-15º NW. [59] document the occurrence of syn-depositional structures and manifest that cross-stratification occurs closest to the vent. [56] the Cerro El Rosario can be one of the sources of the igneous material. The origin of the ground surge may be due to the ingestion of cold air in clefts at the flow front of the pyroclastic flow [60, 61]. Similarly, it is important to highlight the lithological contact between CDA and the sequence of rocks of the Comondú Group at ~200 m above sea level. Said contact extends along the 10 km^2, where it is observed that m_1 is covered by volcaniclastic layers that represent the unit m_2. The contact altitude of m_2 and the thickness of m_1 vary longitudinally on a kilometer scale, indicating a gently undulating upper surface for m_1.

5.2.2. La Paz Area

The geometry of the contact suggests that around the La Paz area was already a topographic depression at the time m_1 was deposited pre-Comondú deposits and Upper Unit crops out at ~40-100 m above sea level in the Punta Coyote area, 12 km northwest of La Paz city, implying that the depression was demonstrably at least 160 m deep. The maximum thickness observed for CDA is ~ 100m in the northeast of the La Paz area. The Breccia B_2 is generally much thicker than the B_1 and is observed around the La Paz (Fig. **5**), with a supported matrix and a poorly sorted fragment. Clast and mega block sizes are bigger than that B_1, these are fractured and rotated, and some clasts are folded. Breccias B_2 exhibits segregation pipes and mega blocks of rhyolitic composition (Fig. **7**).

Both breccias are hetero-lithic. The contacts between the breccias are generally not discrete. The transitions from one type to another are gradational and can occur over distances. The distribution of the breccia types is shown in Fig. (**7**). In Punta Coyotes and La Paz area, different styles of substrate deformation are observed. In the La Paz area, m_1 lies with pre-Comondú, Upper Unit. The sandstone bed not deformed is rotated within the brecciate B_2, conserving the primary structure. Locally, sandstone beds are brecciated and the fragments are tilted. The tilted fragments systematically dip toward the northeast with almost a matrix between them. The orientation of these rotated domains implies a transport direction toward the northwest by the structures observed in deposits in the La Paz area. The B_2 brecciate consists of sedimentary and rhyolite fragments > 50cm within a finer-grained matrix.

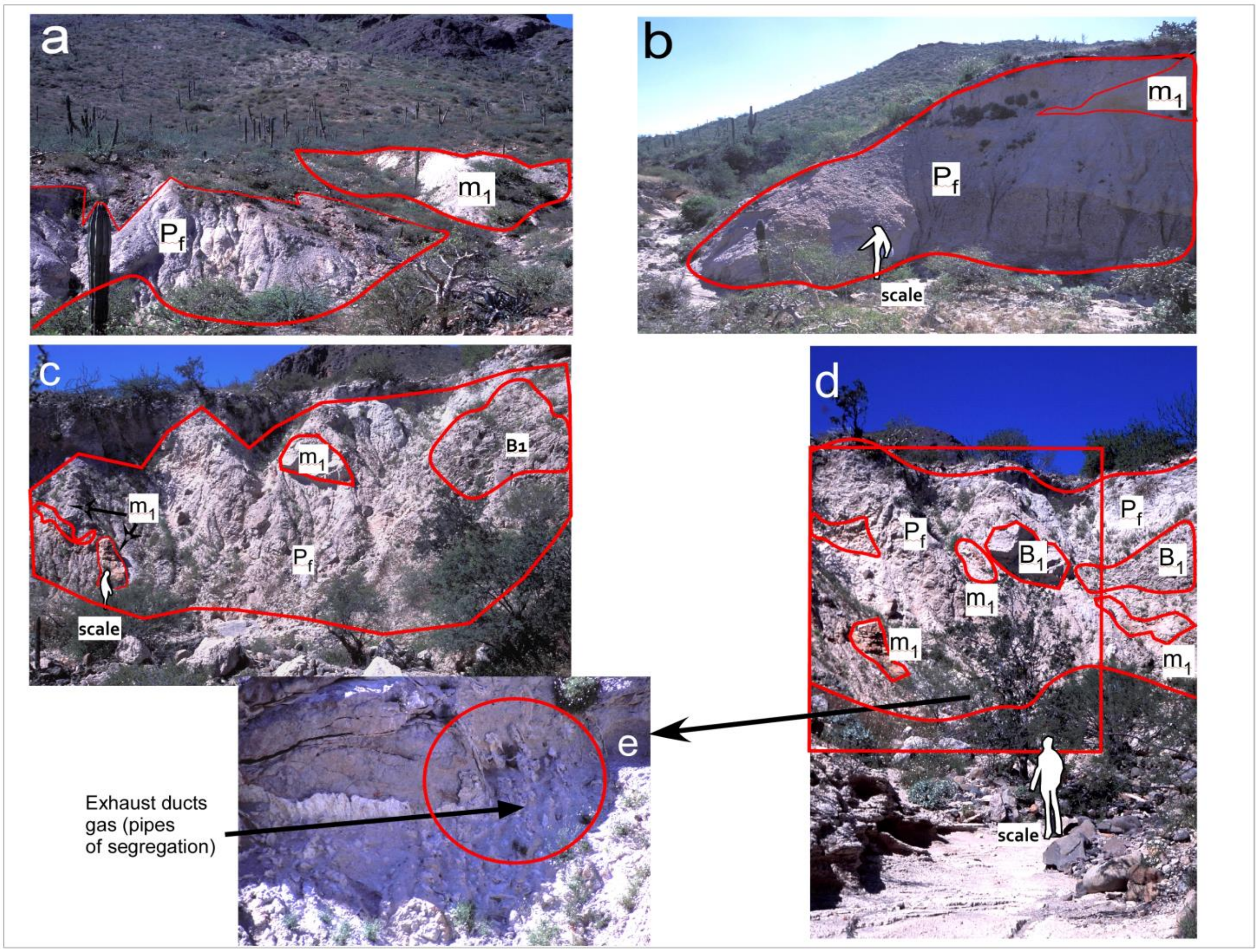

Figure 7: Comondú debris-avalanche deposits in the La Paz area. **a, b, c, d**) Broken and rotated mega-blocks of pre- Comondú and upper unit; **e**) pipes.

5.3. Morphology of CDA´S

The avalanche displays pronounced hummocky topography, in which hummocks volume and amplitude, as well as maximum block size within individual hummocks, tend to decrease with the transport distance [9, 13, 62]. In the Punta Coyote area, the hummocks represent a characteristic morphologic feature of volcanic avalanche deposits. The hummocks over 50 m wide protruded 50-300 m above the mean elevation of the debris surface and some were commonly bounded by post-Comondú tectonic faults. The hummocks are formed of large single blocks; present complex shapes commonly elongated and conical, and contain more than one lithology. Individual hummocks consist of coarse-grained, clasts-supported breccia of heterogenic material (sedimentary and rhyolitic rocks). The dip of the hummocks is usually 15°- 25° NW (Fig. **2**). We infer that elongated and conical hummocks represent small brecciated pieces of the former volcanic edifice that were not completely disintegrated during the emplacement of the debris avalanche. The origin of this depression is not clear. Perhaps they were formed during or immediately after the cessation of avalanche motion, as intact hummocks sunk into the loosened material of the mobile avalanche [63].

5.4. Transport Mechanism of Comondú Debris-avalanches

The geometry of the clasts and mega clasts, the abrasion of the substratum, the rotation of blocks, the and fragmentation of particles support the hypothesis that parts of the flowing debris avalanche had many of the characteristics of turbulent flows during transport. Although many debris-avalanche blocks retained their coherency, suggesting parallel paths and therefore laminar flow, many blocks were disaggregated and mixed. This mixing is one of the processes that created the matrix facies. According to [65, 72], the mobility of debris avalanches can be explained by the combined effect of the release of elastic energy during the dynamic disintegration of the larger clasts and frictional reduction within the matrix due to interactions between finer particles. The abundance of particles of pre-Comondú deposits and the Upper unit suggests more the reworking of soil material than a blast of avalanche material at its head. The transport mechanism of the debris avalanche was dominated by layer-parallel slip movements that favored the nonturbulent behavior of the granular material and the reduction of internal friction. Mechanical fluidization could play an important role in the dispersive processor of the particles moving.

5.5. Interpretation

5.5.1. Origin of Comondú Debris-avalanche Deposits

The characteristics of CDA at Punta Coyote and the La Paz area are similar. Both localities present the absence of bedding in a chaotic deposit up to 100 m thick, the presence of mega blocks up to 50 m in size, fragmentation, and rotation of mega blocks, the presence of distinct breccia, and dispersion of the fragments into the breccias. Such characteristic corresponds to debris-avalanche deposits. [47] proposed a syn-depositional deformation in the lower Comondú Group, generally westward gravitational sliding of immense slabs. [56] proposed an ash flow tuffs origin for the m_1 unit in the Punta Coyote area. The m_2 deposits consist exclusively of juvenile material; these deposits are thus probably the result of hot volcanic debris flows associated with strato-volcanic eruptions [47]. The similarity in lithology between the sedimentary fragments within B_1 and B_2 and mega blocks enclosed in these breccias suggest that B_1 and B_2 represent the final products of mega block disaggregation during transport within a debris avalanche. The lithology of the sedimentary mega blocks within CDA indicates that the initial slope failure released the pre-Comondú deposits and the overlying silicic tuff layers. The inferred transport direction for the debris avalanche toward the southeast would suggest a source situated roughly northwest of the deposits. We can only infer that the was east of what is now the Baja California Peninsula, and below the Gulf of California. The m_1 deposits consist of 35% pre-Comondú and Upper unit sedimentary material, which implies that the volume that collapsed was a volcanic edifice. The Comondú Group deposits have been deposited within basins formed by regional extension where the volcanism and faulting during the Miocene were activities simultaneous or the faulting began a short time after the initiation of volcanic activity [64]. In this context, it is evident that the Comondú Group was deposited in an active volcanic area, where the triggering cause of a debris avalanche could be magmatic phreatomagmatic or seismic over-steepening produced by normal faulting may be the most likely cause of slope instability if considered that structural failure in volcanic terrains inevitably involves the downslope, gravity-driven, mass transfer of material from the source to an area of deposition [32, 65].

5.5.2. Relationships between Pyroclastic Current and Debris-avalanche Deposit

In the study area, the sector collapse was immediately followed by a high-energy pyroclastic density current derived from pyroclastic flow eruptions. Witnesses of pyroclastic flow eruptions have recognized three allied phenomena: preceding blast and related surge, basal avalanche, and overriding cloud. Each of these phenomena may occur alone or in association with one or both of the others, in various degrees of development. The avalanche and cloud have been clearly distinguished in the earlier classic descriptions [66, 67]. Based on it, in the Punta Coyote area, the last unit emplaced during the eruption consisted of the pyroclastic flow deposits, which covered an area of 7 km^2 and overlie the debris-avalanche deposits. The thickness of the pumices pyroclastic flows depends on underlying relief and reaches a maximum of 3m (Fig. **8**). The ignimbrite deposits are typically poorly sorted, massive deposits containing variable amounts of ash, rounded pumice, and lithic fragments. Underlie the pumice deposits are found pyroclastic surge deposits, the type of ground-surge deposits characterized by their internal cross-stratification beds that contain ash, crystals, and occasional accessory lithics. Internally, deposits show unidirectional bedforms. This deposit is underlined by the ignimbrite's deposits, their origin may be due to the ingestion of cold air in clefts at the flow front [60, 61]. Within the hummocky area of the distal avalanche deposit, massive pyroclastic deposits with a repetitive two-layer stratigraphy occurred. These draped over eroded hummocks and were ponded between them.

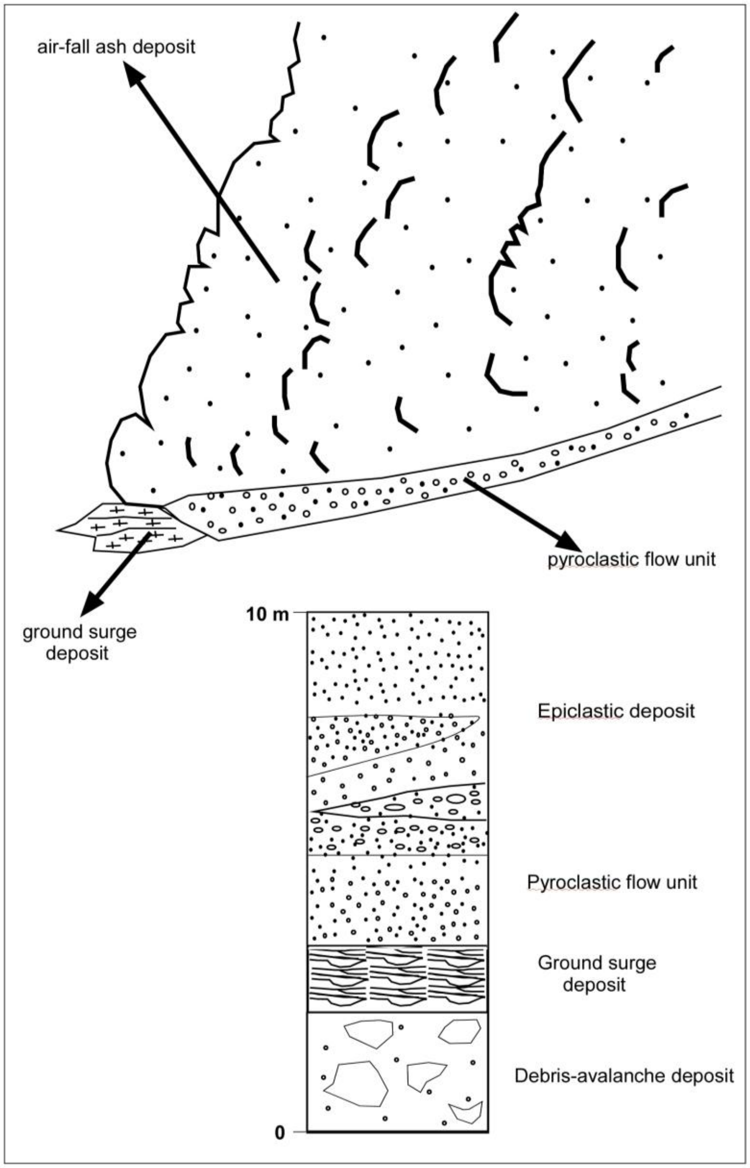

Figure 8: Relationships between pyroclastic and debris-avalanche deposit (CDA).

6. Discussion

Many of the largest landslides resulting from instability and structural failure are located on the margins of the island and coastal volcanoes. [68] highlighted several different ways in which volcanic edifices can become destabilized and experience failure. Two contrasting mechanisms involve (i) relatively deep gravitational spreading along basal thrusts, due to their increasing mass, of volcanic structures and (ii) shallow gravitational sliding of sectors of volcanoes due to overstepping, peripheral erosion, basement slope, or tilting, or a combination of these and other factors [69, 70]. Both mechanisms may contribute to greater edifice instability. Gravitational spreading and gravitational sliding are often used synonymously when applied to volcanic edifices [68]. At Punta Coyote and around La Paz city, the debris-avalanche deposit was produced by the sector collapse of a stratovolcano, the presence of mega blocks probably represents surficial sediments generated by the reworking of pyroclastic material. The fracture in mega blocks suggests that shear stress during the initial sliding is the principal cause of fracture. These data strongly indicate that debris-avalanche deposits are purely gravitational and argue for a model in which the initial sliding mass transforms into a flow due to differential in situ fragmentation caused by the shear stress.

6.1. Reconstruction of Eruptive Events

The growth of the dome was accompanied, throughout its history, by weak and medium-sized explosive eruptions with the deposition of ash pyroclastic flows. The slope failure was the first event, followed by a Plinian eruption accompanied by the collapse of the dome of the volcano, and the emplacement of surges and pumice flows (Fig. **9**). The slope failure is likely to occur along basal faults upon which the mass slide produces debris-avalanche deposits. Avalanche deposits demonstrate that the failure involved the pre-Comondú sediment basement.

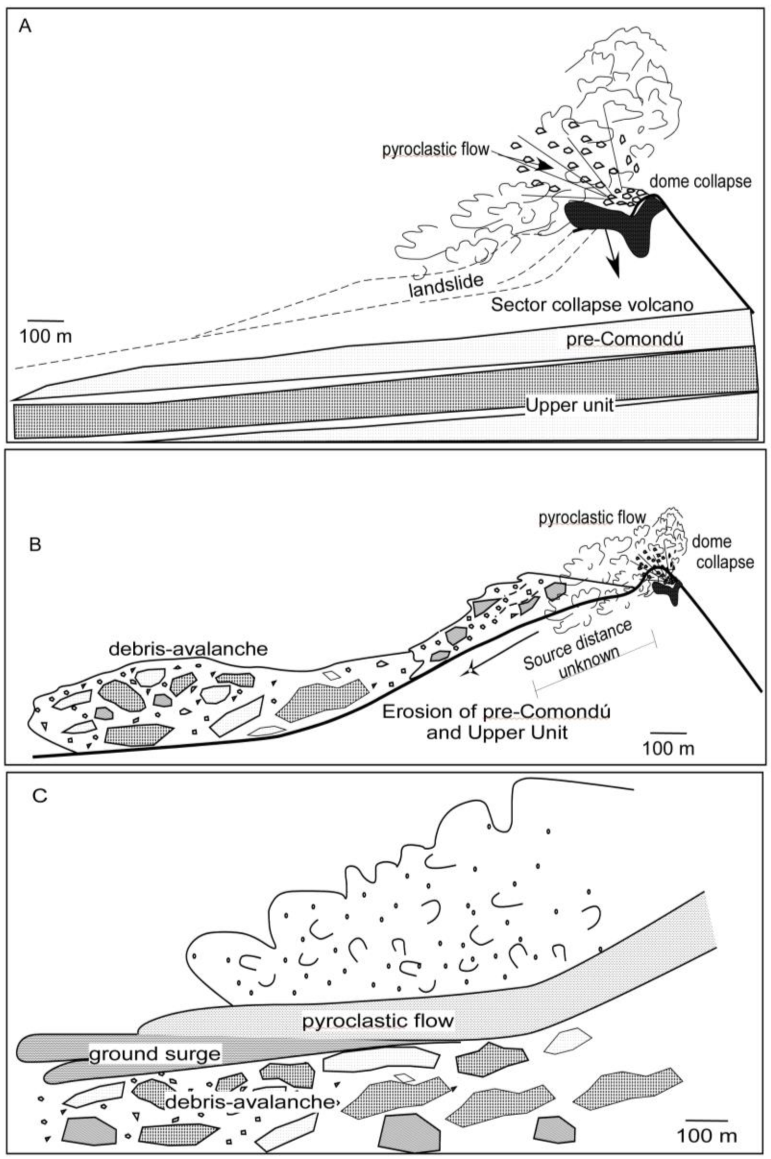

Figure 9: Schematic model showing the processes that caused the debris avalanche deposits **A**) initial explosion of the eruptive window, accumulation of volcanic deposits; **B**) instability of the deposits, sliding of volcanic material; **C**) avalanche debris deposits.

7. Conclusion

This paper presents the first description of a debris avalanche related to a large igneous province in the southern Baja California peninsula. The geological observations of the debris avalanche place some important constraints on the mechanisms of transport and emplacement of debris avalanches. The avalanche is attributed to the failure of a large volcanic edifice constructed over a sedimentary basin filled with fluvial and pyroclastic deposits. The resulting debris avalanche was sustained and consisted of several flow pulses that reflected the complexities of the source disruption, varying flow properties of the older rocks and dome talus, and channel topography. All evidence indicates that the CDA is dry volcanic debris–avalanches [11]. Most debris-avalanche deposits of the study area are similar in composition, structure, texture, grain size, and general appearance in outcrops. The breccias (B_1, and B_2) within the debris avalanche are heterolithic with components displaying a wide range of compositions. Such deposits indicate the collapse of a more differentiated edifice. Differences in clast size of the B_1 and B_2 could be related to fragmentation processes. The fracturing in the clast within breccias B1 could result from pre-avalanche mass failure (loss of cohesion) or brecciation [13, 71]. Perinotto *et al*. [72] proposed that clast and mega-clast brecciation could partly occur during the transport of the avalanche mass because of the interactions between clasts or with the substratum at the base of the avalanche. The debris-avalanche deposit in the Punta Coyote area is covered by a set of pyroclastic layers represented by fallout and/or flow deposit (locally with corresponding ground surge and/or as could surge layers). These pyroclastic deposits lie directly above the debris-avalanche deposits, with no evidence of a hiatus. The edifice failure and generation of a debris avalanche were the first events followed by pyroclastic flows resulting from the partial collapse of the source.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The study received no financial support.

Acknowledgments

Our thanks to the National Council of Science and Technology (CONACYT), for the support in the fieldwork.

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