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New insights into the Upper Pleistocene directed blast eruption, Popocatépetl volcano, México

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Abstract

Volcanic eruptions of the directed blast type are characterized by powerful explosions with a significant lateral pyroclastic density current (PDC) component that can travel at speeds above 100 m s^{-1} and affect hundreds of square kilometers around a volcano. This study presents preliminary results of a detailed fieldwork and stratigraphic study of deposits associated with the Ocoxaltepec Blast deposit, which originated from the Popocatépetl volcano during a strong eruption associated with the southwestward sector collapse of the volcanic edifice around 23,500 ka BP. Within the study area, which contains 58,870 inhabitants, we found 42 new sites where the blast deposit outcrops, in locations up to 25 km from the volcano crater, with thicknesses up to over 20 m. We divide these blast deposits into two categories: confined channel-fill PDC deposits and unconfined interfluve and upland PDC deposits. With the new data we have estimated the dispersion area of the directed blast to be approximately 338 km^2. Twenty-nine of the new outcrops are located outside the hazard polygon associated with concentrated PDCs related to the lowest probability Plinian eruption currently considered from Popocatépetl.

Resumen

Las erupciones volcánicas de tipo explosión dirigida (blast) se caracterizan por ser potentes explosiones con una importante componente lateral que se desplazan a velocidades superiores a 100 m s^{-1}, que incluyen catastróficas corrientes de densidad piroclástica de alta energía y pueden afectar cientos de kilómetros cuadrados alrededor de un volcán. Este estudio presenta resultados preliminares de un detallado trabajo de campo y estudio estratigráfico de depósitos relacionados a una explosión dirigida "depósitos de Blast Ocoxaltepec", que se originó en el volcán Popocatépetl durante una fuerte erupción resultante del colapso sectorial del edificio volcánico alrededor de los 23,500 ka BP, que se extendió hacia el SO. Dentro del área de estudio, que tiene 58.870 habitantes, hemos encontrado 42 nuevos sitios donde aflora el depósito de blast, algunas localidades ubicadas hasta 25 km del cráter del volcán, con espesores de hasta más de 20 m. Dividimos estos depósitos de blast en dos categorías: depósitos de CDP confinados y depósitos de CDP no confinados de interfluvio y de zonas elevadas. Con los nuevos datos hemos estimado el área de dispersión de la explosión dirigida de aproximadamente 338 km^2. Veintinueve de los afloramientos se encuentran fuera del polígono de peligro asociado a las CDP concentradas relacionadas con una erupción pliniana de menor probabilidad del Popocatépetl.

Keywords: Popocatépetl; Directed blast; Debris avalanche; Pyroclastic density current; Volcanic hazard.

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1 Introduction

Directed blast eruptions are characterized by powerful explosions with a significant lateral component traveling at speeds above 100 m s^{-1}. These volcanic explosions are associated with or triggered by volcanic edifice collapse [Belousov et al. 2007; 2020]. Directed blasts occur when a partly degassed and crystallized magma body located near the surface immediately decompresses, causing sector collapse of a volcanic edifice, as occurred at Bezymianny (Kamchatka, Russia) and Mount St. Helens (USA) [Belousov et al. 2007]. These eruptions include catastrophic pyroclastic density currents of blast type or high-energy directed explosion type, which due to their genetic and emplacement characteristics can be devastating for the environment [Belousov et al. 2007]. Blasts and their accompanying high-energy pyroclastic density currents (PDCs) are among the most complex volcanic processes to model and predict, consisting of hot (>300 °C), high-velocity mixtures of gas, solids, and ambient air that are controlled by explosive radial expansion and gravitational forces [Komorowski et al. 2013; Cole et al. 2015]. Understanding the nature of directed eruptions is important for volcanic hazard assessment due to the extreme violence that characterizes these events: although their magma volumes are relatively small, usually fractions of km^3, the affected areas can reach hundreds of km^2 [Belousov and Belousova 1998; Belousov et al. 2007]. Assessing the nature, distribution, and magnitude of potential damage is particularly difficult since they are often part of a complex pulsatory eruptive sequence, and PDCs interact significantly with topography [Komorowski et al. 2013].

México is a volcanically active country, with more than 8000 volcanic structures [Macías and Arce 2019]. México ranks fourth in the world among countries with the largest number of inhabitants exposed to volcanic hazards (around 60 million) after Indonesia, the Philippines, and Japan [Brown et al. 2015].

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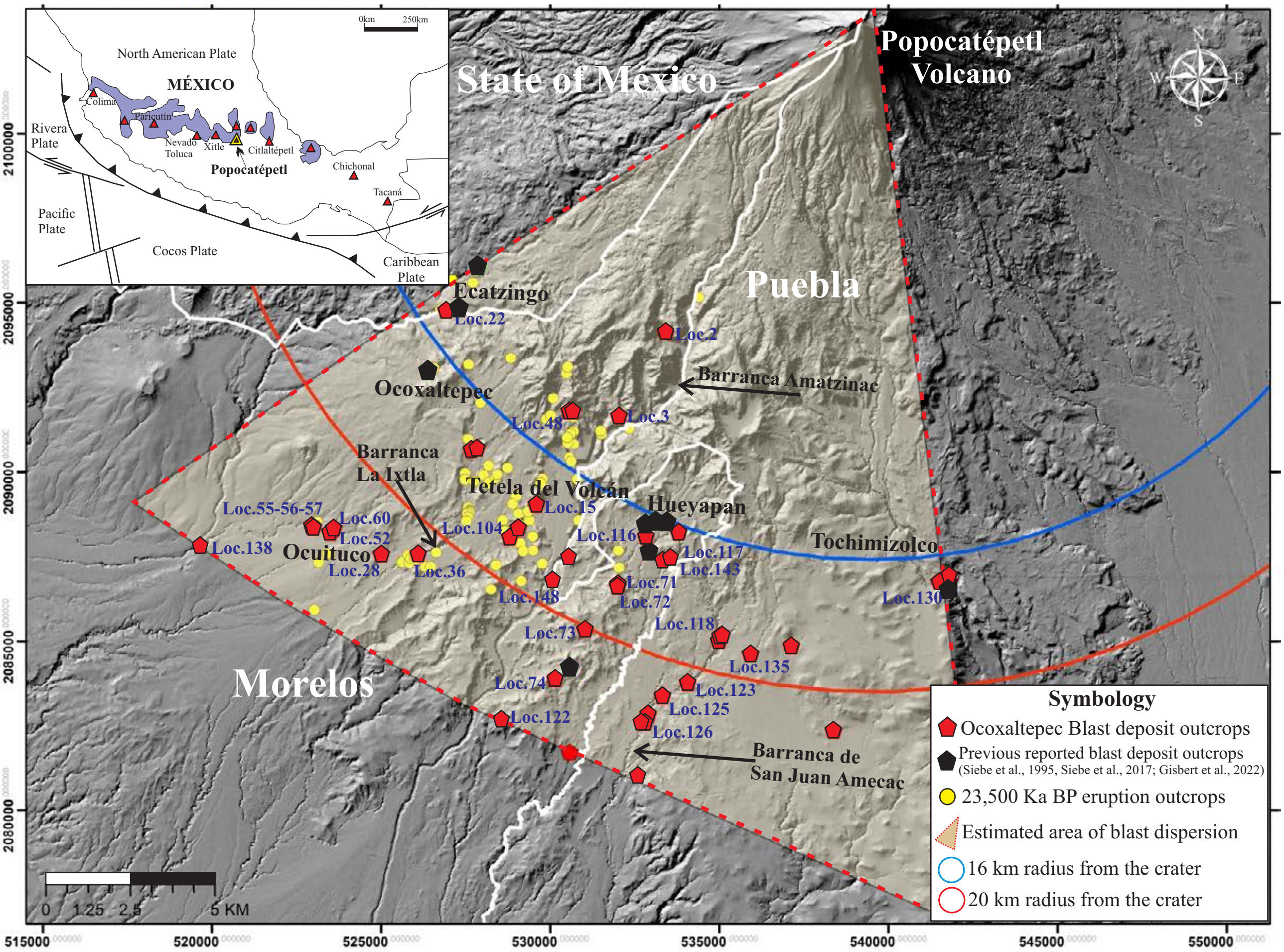

Figure 1: Map of the study area. The light brown triangle represents the preliminary dispersal area of the blast. The red pentagons correspond to the outcrops of the Ocoxaltepec Blast deposit reported in the present study.

Popocatépetl volcano is one of the most active volcanoes in Mexico and is considered the one with the highest potential risk because about 27 million people live within a 100 km radius of the crater [Siebe and Macías 2006; Espinasa-Pereña 2012; Martín-Del Pozzo et al. 2018; INEGI 2020; Espinasa-Pereña et al. 2021]. Popocatépetl volcano is a composite volcano of andesitic-dacitic composition located in the central part of the Trans-Mexican Volcanic Belt and has an elevation of 5454 m [De la Cruz-Reyna et al. 2017]. Due to its previous history of Plinian eruptions (VEI 4–5), Popocatépetl is considered a high risk for the numerous localities established on its slopes and surrounding areas [Siebe et al. 1996; Siebe and Macías 2006]. The volcano is located 65 km SE of México City and 45 km W of the city of Puebla. The modern volcanic edifice is built on the remnants of ancient cones that were partially destroyed by cataclysmic eruptions of the Bezymianny or Mount St. Helens type [Robin and Boudal 1987; Siebe et al. 2017]. Siebe et al. [1995] identified three different avalanche deposits in SW sector. The last major eruption related to a collapse of the volcanic edifice occurred about 23,500 ka BP, which extended SW of the current edifice and produced large debris avalanche deposits (DAD 1 or Upper Tlayecac), related deposits with a lateral eruption (blast deposit), fall deposits (White Pumice) and lava flows (Tochimilco lava) [Siebe et al. 1995; Espinasa-Pereña and Martín-Del Pozzo 2006; Siebe et al. 2017]. At Popocatépetl, we have found evidence of a large directed blast that dates back to 23,500 ka ^{14}C yr BP (27,800 cal yr BP) [Siebe et al. 2017] and affected a vast region located to the SW of the present volcanic edifice. This blast deposit is the object of the present study. We propose to name it the *Ocoxaltepec Blast deposit* after the locality where it was described by Siebe et al. [1995] and where we could observe an outcrop of more than 14 m thickness (locality 22 in this study, Type Section TS; Figure 1 and Figure 12). In this study we describe in detail the Ocoxaltepec Blast deposit based on extensive field observations in order to explain the events that took place during this eruption (Figure 1, red pentagons). The area studied is situated from the town of Ecatzingo in the State of México to the town of Tochimizolco in the State of Puebla (Figure 1). This study builds on the descriptions of this eruption from Siebe et al. [1995, 2017] to provide a full explanation of a large directed blast and what it means for future hazard at Popocatépetl volcano.

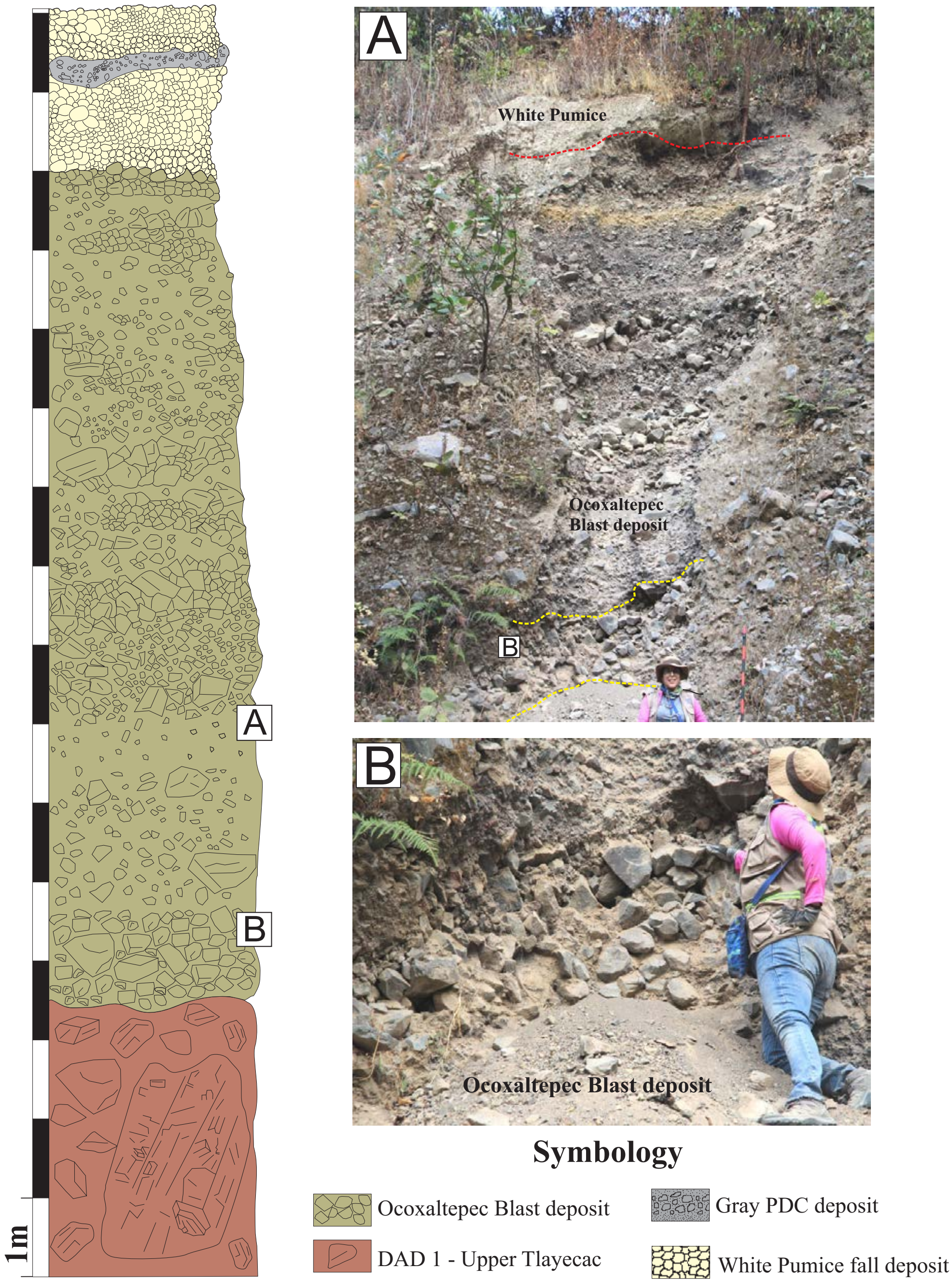

Figure 2: Stratigraphic section of locality 48 (RS1). [A] Ocoxaltepec Blast deposit enriched in angular blocks of gray lava. Vertical granulometric changes, as well as lenticular horizons enriched in angular blocks of gray andesitic lava, can be observed. [B] Zoom on the base of the deposit where the horizon is enriched in moderately sorted andesitic lava blocks It can be observed that the deposit is clast supported.

2 Background and conceptual framework

2.1 Popocatépetl volcano

Since the reactivation of the Popocatépetl volcano in 1994, a series of works have been carried out in the study area, the most relevant focused on the cataclysmic eruption of 23,500 ka BP done by Siebe et al. [1995, 1996, 2017] and Siebe and Macías [2006]. These authors describe the eruptive sequence resulting from the collapse of the SW sector of the volcano, emphasizing the deposits of the debris avalanche and the voluminous pumice deposit resulting from the Plinian fall, named as DAD 1 and White Pumice, respectively. The debris avalanche deposit covers an area of 1216 km^2 and reached a maximum distance of 72 km [Siebe et al. 2017]. The collapse that originated the debris avalanche caused a sudden and rapid decompression of the magmatic and hydrothermal systems of the volcano and gave rise to a directed explosion with lateral blast [Siebe et al. 1995; 2017]. This strong explosion produced a stratified deposit with 4 m total thickness, consisting mainly of gray to pinkish angular to subangular dense lava blocks [Siebe et al. 2017]. The layers that compose this deposit have thicknesses ranging from a few centimeters to decimeters, are composed of angular coarse ash and lapilli, and are significantly poor in fines. Robin and Boudal [1987] interpreted that all these features present in the deposit, together with its stratigraphic position located directly above the debris avalanche deposit, indicate it was originated by the successive emplacement of pyroclastic flows resulting from the depressurization of the magmatic system. It should be noted that Siebe et al. [2017] recognize that the characteristics of the blast deposits at Popocatépetl are different in several aspects to the blast deposits emplaced by the 1980 eruption of Mount St. Helens volcano. However, the use of the term blast deposit is correct due to the genetic interpretation of the deposits.

2.2 Directed blast eruptions

The term *directed blast* was introduced by Gorshkov [1959], who studied the eruption of Bezymianny volcano on the Kamchatka peninsula in 1956. The powerful eruption of Bezymianny was produced by a partial collapse of the volcanic edifice that gave rise to a rapid decompression of an intracrater dome and a cryptodome of andesitic composition, causing "blast-type pyroclastic density currents" that affected an elliptical area of 500 km^2 [Belousov 1996]. A similar explosive event occurred in 1980 during the eruption of Mount St. Helens volcano in the United States, where the directed explosion reached velocities of 100 to 235 m s^{-1} and covered an area of 600 km^2 [Hoblitt et al. 1981; Belousov et al. 2007]. The 1980 eruption of Mount St. Helens, associated with a large sector collapse and a directed explosion, caused a change in the understanding of volcanic eruption behavior. Prior to this eruption, hummocky topography was observed downslope of many volcanoes, but the interpretation of these large, randomly oriented mounds scattered across the landscape was not fully understood [Brand et al. 2023].

Comparison of the Bezymianny and Mount St. Helens eruptions with a much smaller explosion of the Soufrière Hills volcano in Montserrat in 1997 allowed Belousov et al. [2007] to summarize the main characteristics of this type of volcanic eruption. Directed/lateral explosions occur under certain conditions during shallow intrusions (cryptodomes) and/or extrusions (domes) of viscous andesitic-dacitic magma. A characteristic feature of a directed explosion is the inclined ejection of a mixture of gas and pyroclasts that is initially denser than air and, therefore, not buoyant. Consequently, the ejected mixture collapses gravitationally and generates a highly expansive, mobile and destructive pyroclastic density current [Belousov et al. 2007; 2020]. The 2010 eruption of Merapi Volcano (Indonesia) also produced high-energy PDCs, which spread over 22 km^2 and showed similarities to volcanic blast [Komorowski et al. 2013].

According to Belousov [1996], in the proximal zones the Mount St. Helens and Bezymianny the blast deposits consist of three main layers: (A) the lower layer consists of poorly sorted coarse material containing soil debris and abundant uncarbonized vegetation fragments; (B) the middle layer of the sequence consists of relatively well sorted fragments, poor in fines, with some partially carbonized vegetation fragments. This layer may show any type of gradation (reverse, normal, or complex combinations); (C) the upper layer of the blast deposit sequence is poorly sorted, massive and rich in fines. The upper part of the layer has sub-horizontal thin lamination. The stratigraphy of the distal zones of Bezymianny and Mount St. Helens is identical [Belousov et al. 2007]. In general, it is a unit composed predominantly of poorly sorted coarse ash with ripple laminations, sparse granules, and—in smaller proportion—uncharred wood. The high similarity of the Bezymianny and Mount St. Helens blast deposits suggests that the character of the transport system and the operative depositional processes were the same in both cases [Belousov 1996]. This succession of layers was named interfluvial facies consisting of three layers, A, B, C, numbered from bottom to top [Belousov et al. 2007]. This nomenclature was first applied to the deposits of the Bezymianny eruption [Belousov 1996], whereas for Mount St. Helens they would correspond respectively to the A0, A1, A2 layers described by Fisher [1990].

Belousov [1996] observed that in the valleys of the proximal zone the character of the deposits resulting from the directed explosion of Bezymianny differs from that observed in the elevated zones (interfluvial facies). This author proposed two types of valley-fill facies: (a) deposits in valleys that begin directly on the eastern slopes of the volcano, and (b) deposits in valleys located at the limits of the proximal zone but separated from the volcano by topographic barriers. In the first case, the deposit originating from the explosion lies above the debris avalanche deposit, the formation of which preceded the directed explosion. The blast deposit is represented by lapilli and very coarse blocks, which form a layer with a thickness of several meters. These valley deposits consist of lithic fragments with the same compositional characteristics as those found in the upper zones. Overlying the blast deposits are usually deposits of pyroclastic flows from the Plinian phase of the eruption. The contact between the debris avalanche and the blast deposits is sharp and very irregular, sometimes clastic dikes several tens of centimeters thick can be distinguished that penetrate several meters into the debris avalanche deposit [Belousov 1996; Belousov et al. 2007]. The character of the lower contact of the blast deposit, the grain size, and the high content of accidental material suggest that it was deposited close to the volcano above the moving debris avalanche, and both moved together for some distance [Belousov 1996; Belousov et al. 2007].

3 Methodology

In this study we use detailed fieldwork and stratigraphic analysis to provide preliminary interpretations of the Ocoxaltepec Blast deposit. Extensive fieldwork was carried out to identify new outcrops of the Ocoxaltepec Blast deposit, consisting of five field campaigns, in which 156 localities were visited (Figure 1). In the visited localities, we made detailed descriptions of the deposits related to the eruptive sequence of 23,500 ka BP. Initially, previous work by Siebe et al. [1995, 1996, 2017] was used as a guide to identify deposits related to the 23,500 ka BP eruption. Stratigraphic sections were made, and the stratigraphic relationships between the deposits were studied in detail in order to correlate them. The information

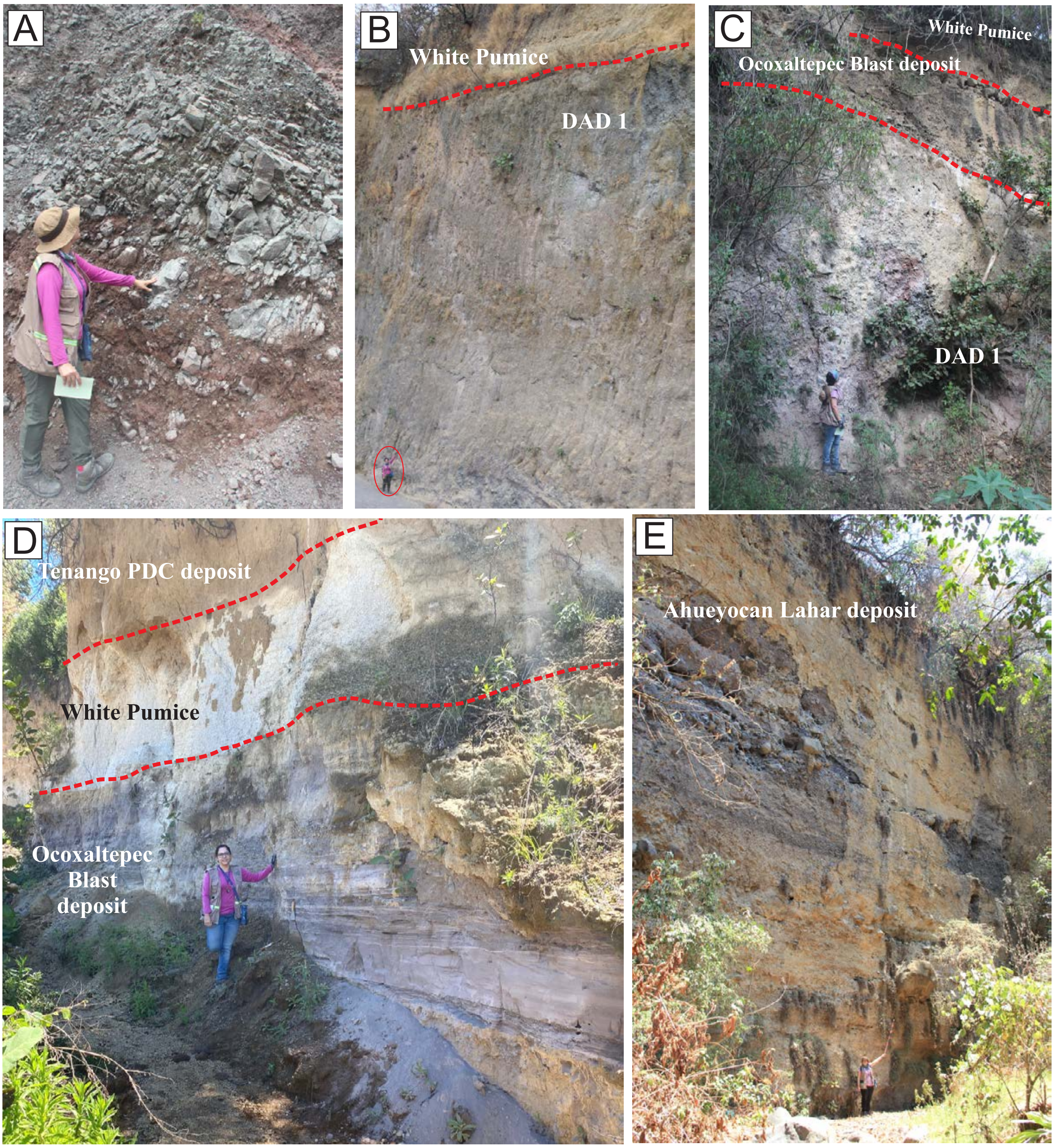

Figure 3: The 23,500 ka BP eruptive sequence. [A] DAD 1 or upper Tlayecac debris avalanche deposit, [B] Contact between the debris avalanche deposit and the White Pumice above, [C] Contact between the debris avalanche deposit and the deposit associated with the directed blast, [D] Contact between the Ocoxaltepec Blast deposit, White Pumice and Tenango PDC, [E] Ahueyocan Lahar deposit.

was used to estimate a polygon of the area of influence of the blast, based on the geographic distribution of the outcrops of the blast deposit in the study area, taking into consideration as limits the deposits that were located in the most distal zone (the .shp file of the polygon can be found in Supplementary Material 1). The descriptions of the types of deposits proposed in the present study are based on the topographic context where the directed blast deposits were located and categorized as either confined channel-fill PDC deposits or unconfined interfluve and upland PDC deposits, taking into account the previous works of Belousov [1996] and Belousov et al. [2007]. In the field the thickness of blast deposits was measured, where possible, with a measuring tape, accounting for the dip of the layers in order to get the most realistic thickness possible. Thicker deposits were measured with a Leica Disto D510 laser distance meter.

4 Results

4.1 Eruptive sequence of 23,500 ka BP in the study area

In the study area, it was possible to recognize the deposits related to the Plinian eruption of 23,500 ka BP and observe their stratigraphic relationships with the deposit associated with the directed blast. Generally, the eruptive sequence consists of the following deposits (from oldest to youngest): debris avalanche (DAD 1-Upper Tlayecac) [Siebe et al. 1995; Espinasa-Pereña and Martín-Del Pozzo 2006; Siebe et al. 2017], blast (Ocoxaltepec Blast deposit, this study), White Pumice fall [Siebe et al. 2017], Tenango PDC (this study), and Ahueyocan lahars (this study). The blast deposit is the object of the present study, although a brief description of each of the deposits is given below.

We found the contact between the DAD 1, White Pumice, and Ocoxaltepec Blast deposit at locality 48 (Reference Section RS1; Figure 1 and Figure 12) to the N of the town of Tetela del Volcán in Morelos (Table of localities can be found in Supplementary Material 2). Figure 2 shows a detailed stratigraphic section of the deposits found at locality 48, where lenticular horizons enriched in angular blocks of andesitic lava can be observed.

4.1.1 *DAD 1*

In the SW sector of the volcano, up to three avalanche deposits can be recognized, related to sector collapses of the volcano [Siebe et al. 1995]. During the field work carried out in this study it was possible to identify two different avalanche deposits (DAD 1 and DAD 2). The avalanche deposits present similar textural characteristics, so it is often difficult to distinguish them. The deposits can be found superimposed, and the criterion we use to differentiate them is the stratigraphic relationship with the blast deposit and the structures present in the contact between both deposits. The most recent one is related to the 23,500 ka eruption (DAD 1). In the towns of Ocuituco and Tetela del Volcán in Morelos we observed outcrops of the DAD 1 or Upper Tlayeca with thicknesses greater than 20 m (Loc. 28, Figure 1 and Figure 3A–3C). The deposit consists of blocks and megablocks of dense gray lavas which are intensely fractured, broken, and exhibit jigsaw cracks. The matrix is strongly altered, with a variety of colors, the most common being ranges of violet, yellow, and red. In outcrops located in canyons near the town of Ocuituco (Loc. 36, 55, and 56, Figure 1 and Figure 3C) we found the contact between the debris avalanche deposit and an overlying deposit (Ocoxaltepec Blast deposit) that can vary from clast-supported to matrix-supported with fragments of lapilli to block-size dense gray lavas and reddish altered lavas. We identify this as the blast deposit, which will be described in more detail in the next section.

4.1.2 *White Pumice*

Overlying the blast deposit, we find a deposit of the White Pumice (Figure 3D), consisting of vesiculated subangular to subrounded pumice with phenocrysts of plagioclase and amphibole. This deposit is massive and clast-supported at the base, while in some outcrops towards the top it is stratified. The best sites to observe this deposit are between the towns of Tetela del Volcán and Hueyapan in Morelos, where it can reach thicknesses up to 4 m, and in some outcrops near the Barranca Amatzinac and in the vicinity of the town of San Juan Amecac in Puebla (Figure 1).

4.1.3 *Tenango PDC deposit*

In contact with the White Pumice deposit around Tetela del Volcán, Hueyapan and San Juan Amecac, there is a deposit of fine material, with beige color and enriched in crystals. This unit is relatively well sorted with a thickness that can vary from 90 cm to 5 m (Tenango PDC deposit, named in this study). This deposit has a transitional contact with the White Pumice (Figure 3D). At the base of the deposit the material is compacted and is enriched in beige to light pink pumice that may have elongated shapes. The middle and upper section of the deposit is massive, without sedimentary structures, and enriched in plagioclase and amphibole crystals. The crystals are mostly tabular and euhedral, and there is also beige to whitish vesicular pumice and, in smaller proportion, lithics.

4.1.4 *Ahueyocan Lahars deposit*

At the top of the eruptive sequence there is a fairly consolidated deposit that can be observed as an alternating sequence of layers enriched in coarse, gravel- to block-size clast-supported material with layers of fine, matrix supported sand- to gravel-sized material with parallel and laminar stratification (Ahueyocan Lahars deposit, named in this study). The clast-supported layers may be discontinuous in thickness in the form of lenses or in continuous massive layers composed of poorly sorted material made up of subrounded to subangular fragments of gray and reddish lavas. The sizes range from gravel to block, which can reach a diameter of more than 2 m (Figure 3E). The layers of fine-grained material range from sand to gravel, with marked parallel and laminar stratification. The deposit can be more than 30 m thick. The sites where the deposit is thickest are in the surroundings of the towns of Metepec and Tetela del Volcán, Amatzinac river and tributary streams, and Barranca La Ixtla.

4.2 Ocoxaltepec Blast deposit

The Ocoxaltepec Blast deposits have been observed at 42 sites, in localities within the municipalities of Ecatzingo, Yecapixtla, Ocuituco, Tetela del Volcán, Hueyapan, Zacualpan de Amilpas, Cohuecan, Tochimilco, and Atzitizihacán, in the states of México, Morelos and Puebla (Figure 1, red pentagons). The maximum thickness of the deposit has been seen in localities 123, 125, 126, located in the Barranca San Juan Amecac, in Puebla (Figure 1 and 4), where it reaches up to 42.3 m, and around Ocoxaltepec (Loc. 22; Figure 4 and Figure 12 TS), within the limits of the states of México and Morelos, where it reaches a thickness of more than 14 m (Figure 4 and Figure 12 TS).

4.2.1 *General characteristics of the blast deposit*

Generally, the directed blast deposit can be observed in outcrops as alternate layers composed of coarse material (usually block- and lapilli-sized) with diffuse stratification and layers of finer diameter material (lapilli- and ash-sized) with marked low-angle cross stratification, which are described as

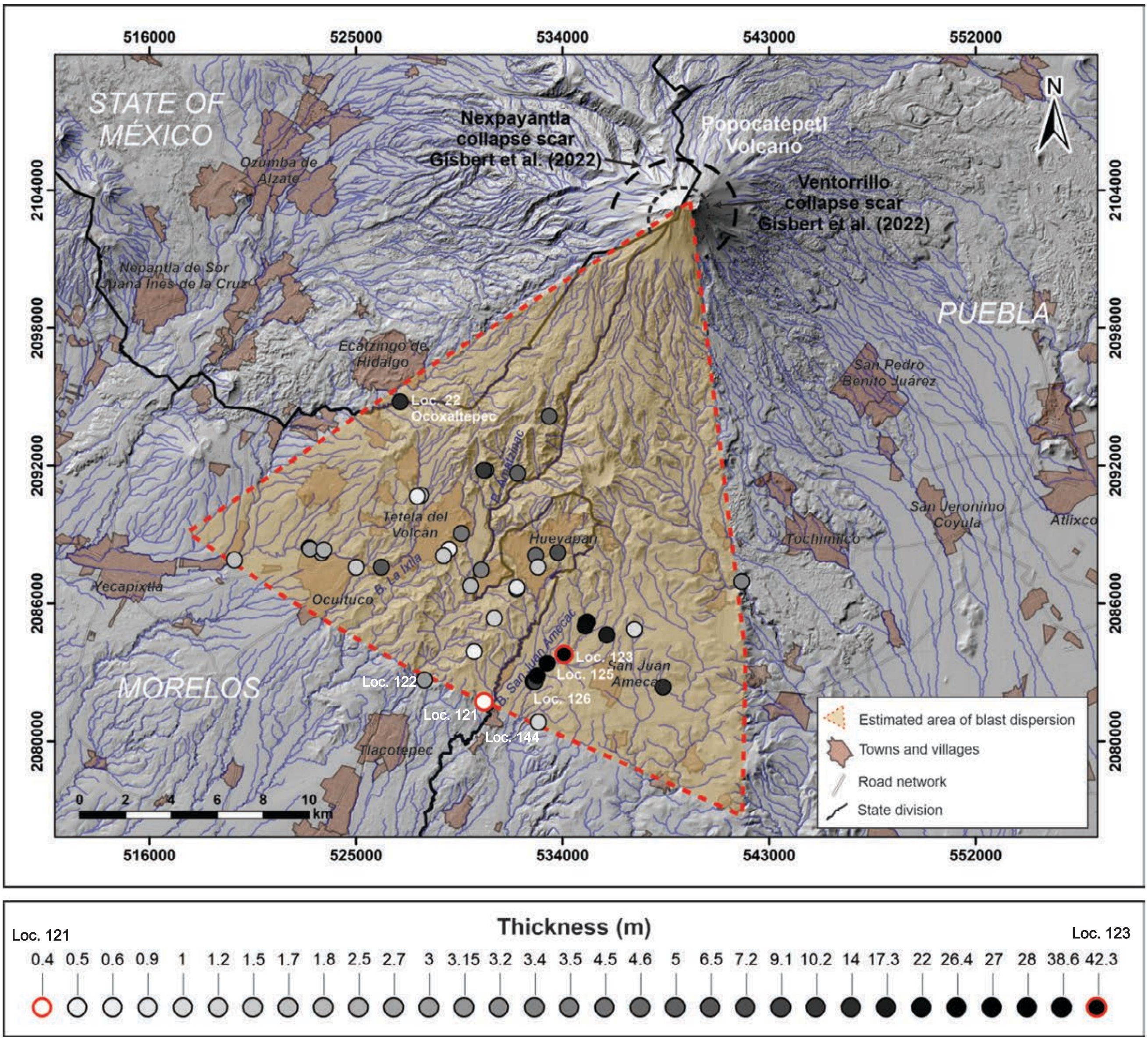

Figure 4: Blast deposit thickness distribution. The largest deposit thicknesses were located in the Barranca de San Juan Amecac. The light colors correspond to lower thicknesses (most of them related to unconfined interfluve and upland PDC deposits) and the dark colors to higher thicknesses (related to confined channel-fill PDC deposits). The map shows the collapse scar related to the 23,500 ka eruption (Ventorrillo) and the older ~98,000 ka collapse scar (Nexpayantla) proposed by Gisbert et al. [2022].

follows: (1) The coarse layers are composed of primarily clast-supported, dense, gray, moderate- to poorly-sorted, angular to subangular, lapilli- to block-size lava fragments. The textures of the lava blocks can vary from aphanitic to phaneritic with phenocrysts of plagioclase and, in minor proportion, pyroxenes. In hand sample, the dense lava fragments were identified as andesitic in composition. Fragments of reddish and light gray, subrounded to subangular altered lava can also be found and, in smaller proportion, fragments of dark gray vesiculated lava. Horizons enriched with coarse material are massive but may have diffuse parallel stratification and normal gradations and intercalated layers of fine material with well-marked laminar stratification. (2) Layers composed of finer material are characterized by medium lapilli-size lava fragments to dark to medium gray ash. The composition of the fragments is similar to that observed in the layers of coarser material, which can be found in most cases to be clast-supported but with rarely occurring poorly sorted matrix-supported layers. These layers show visible layering that may be parallel, laminated, and cross-laminated. The blast deposit is generally distinguished by being poorly to moderately consolidated.

4.2.2 *Ocoxaltepec Blast deposit classification based on topographic context*

Field investigations of the deposits associated with the directed blast revealed significant differences between deposits found in confined and unconfined zones. In most cases, the deposit is characterized by significant granulometric and structural variations. The descriptions of the types of deposits are based on

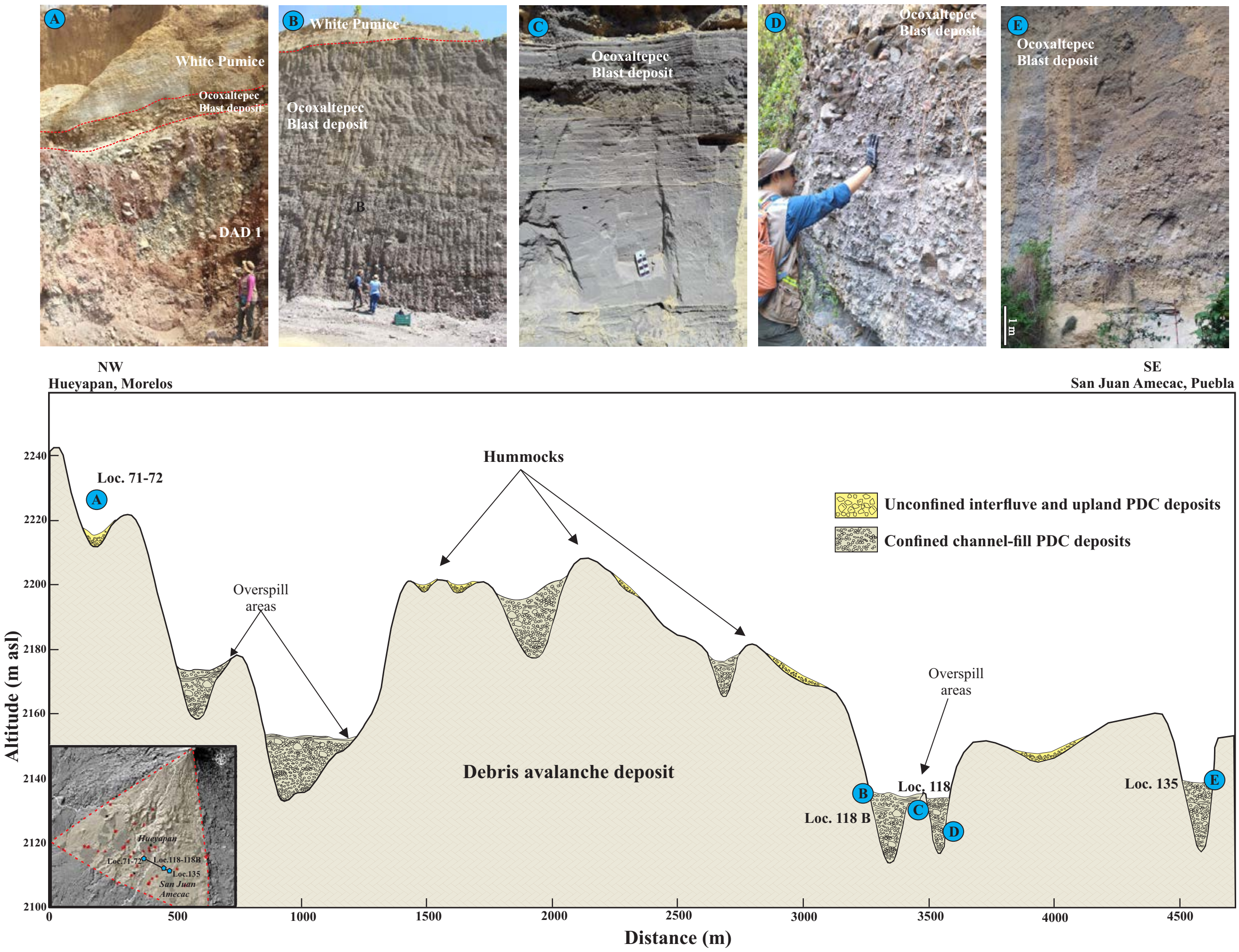

Figure 5: NW-SE profile (Hueyapan-San Juan Amecac), showing deposits associated with unconfined interfluve and upland PDC deposits and confined channel-fill PDC deposits.

the topographic context which allowed us to recognize two different types: (A) confined channel-fill deposits (composed of two sub-units) and (B) unconfined interfluve and upland PDC deposits. The description of the deposits in the present study is based on the topographic context and the associated genetic characteristics (Figure 5). We associated the genetic interpretation with the type of deposit from the beginning due to the position and stratigraphic relationship of the blast deposit with the lower deposit (debris avalanche deposit) and upper deposit (fall deposit), which was observed in several localities (this is described in detail in Section 4.3).

Each deposit type is described below:

A) **Confined channel-fill PDC deposits**. Based on textural characteristics, two sub-units can be differentiated within the confined channel-fill deposits. Each unit is described below:

- *Concentrated confined channel-fill PDC deposits*. This type of confined deposit exhibits greater thicknesses compared to unconfined deposits and generally occurs in outcrops located on the flanks of canyons (barrancas) or fluvial streams. It is distinguished by an alternation of massive layers of coarse material composed of dense gray angular to subangular lapilli- to block-size lava fragments and stratified layers with relatively smaller fine lapilli to medium gray ash-size lava fragments. Generally, the layers are delimited by discontinuous and anastomosing thin layers composed of fragments that can be ash- to lapilli-sized with an ochre color (similar to thin altered or oxidized horizons) (Loc. 22; Figure 6A). These layers are thin (a few centimeters in thickness), irregular and variable in thickness, and tend to wedge. Oxidation colors paint and fill fractures of the lava fragments. This deposit is distinguished by the presence of layers with variable thickness and lenticular layers composed of dense gray lava blocks where block-to-block contact or framework supported structure with absence of matrix dominates (Figure 6C). In the coarse layers, lava blocks are typically 10–20 cm but are sometimes up to 80 cm. Rarely, extremely large blocks up to 1.6 m have been identified. These blocks usually have subrounded shapes. These deposits can reach thicknesses of more than 10 m (Loc. 22, 48, 118B, 123, 135; Figure 4). In some outcrops located in the town of Hueyapan (Loc. 116 and 143) it is possible to observe in the upper part of the deposit a layer with lava blocks that are more subrounded, and the deposit

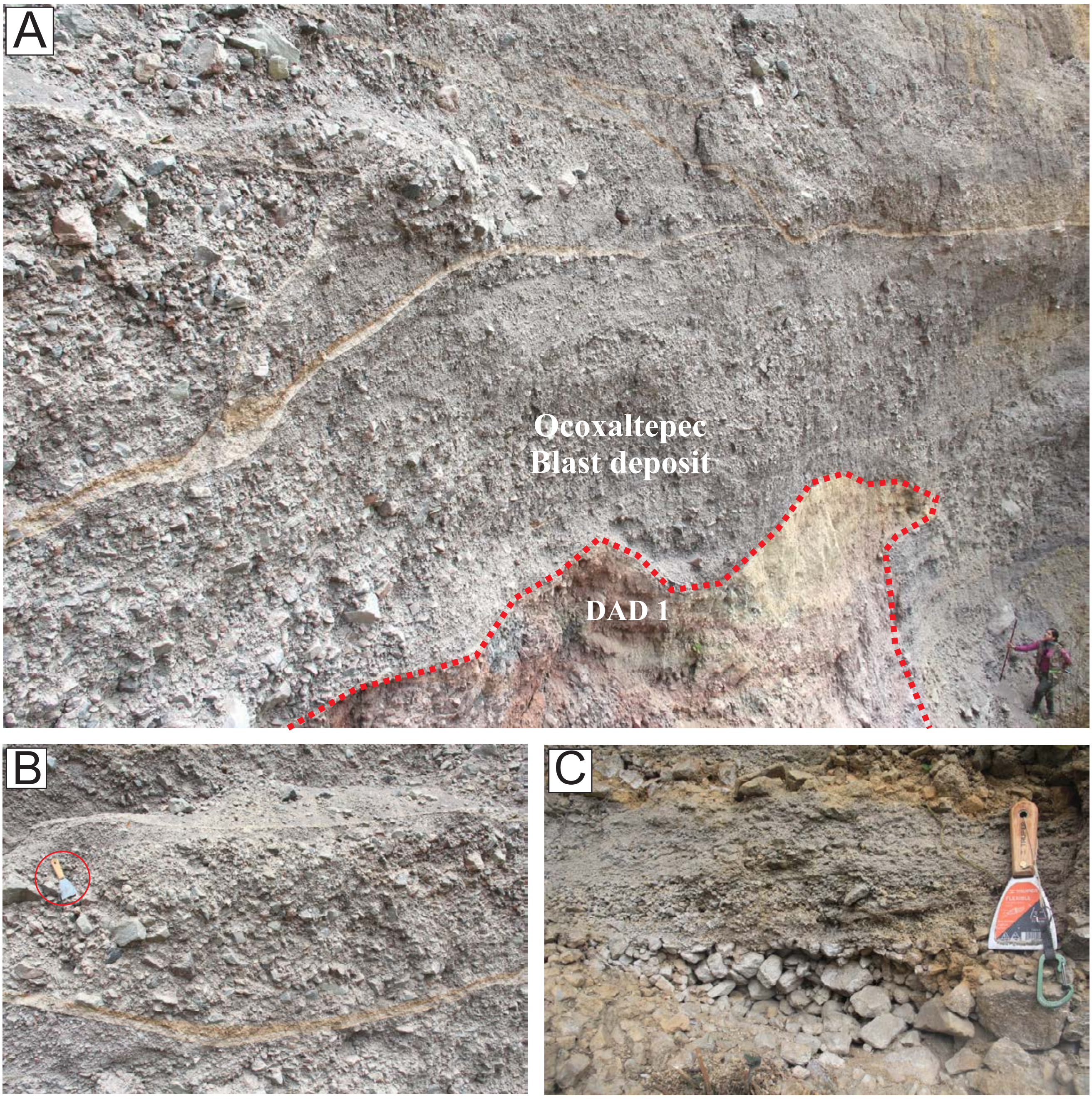

Figure 6: Concentrated confined channel-fill PDC deposits. [A] Blast deposit erosively overlying the DAD 1 debris avalanche deposit (Loc. 22). [B] (spatula is 15 cm) Layer of irregular thickness composed of coarse material up to lapilli to block size, bounded by thin ochre-colored layers (Loc. 22). [C] (spatula is 15 cm) Lens composed of dense lava fragments; clast-supported with absence of matrix (Loc. 52).

is massive or has diffuse parallel stratification. The best sites where outcrops associated with these deposits are found are on the Ocoxaltepec-Ecatzingo road (Loc. 22, Figure 6A, 6B), to the north of the town of Tetela del Volcán (Loc. 15 and Loc. 48 RS1) and in the Barranca San Juan Amecac (Loc. 118B; Figure 12 Reference Section RS2).

- *Dilute confined channel-fill PDC deposits.* In the upper-middle zone of channel-filling deposits, layers composed of medium gray ash and medium to dark gray dense lava fragments and reddish altered clasts can be identified. These deposits can be found on the upper margins of barrancas or in associated overspill areas (topographically higher areas overlying confined or channel-fill deposits) (Figure 7). These ash-enriched layers are usually bounded at the base and top by deposits of coarser material. In general, the size of the components is fine to medium ash, but enriched horizons of fine lapilli can be found. These deposits are observed as an alternation of layers of ash and fine lapilli-sized lava fragments with low angle cross stratification and layers composed of medium to fine lapilli-sized lava fragments. Lapilli-rich levels are clast-

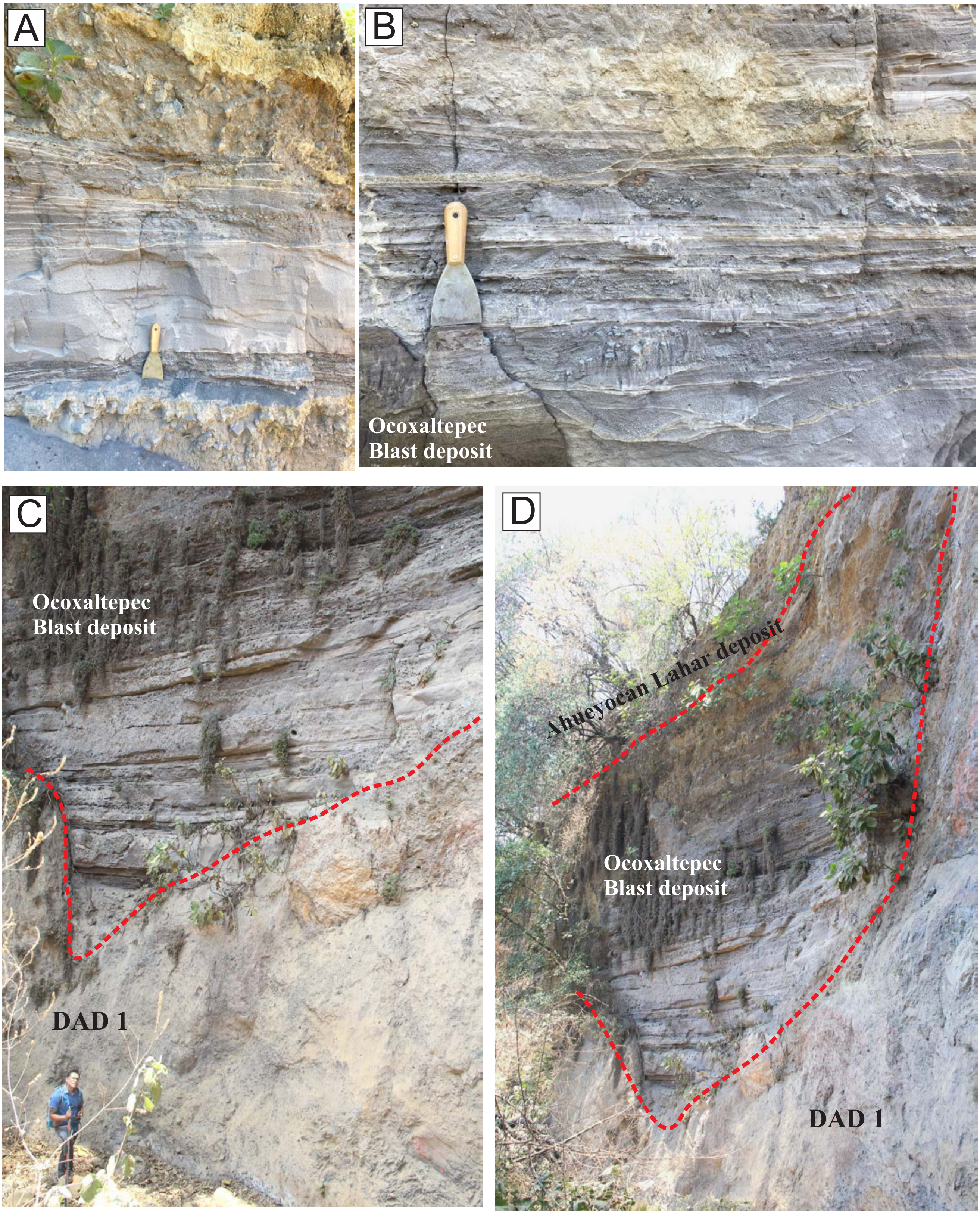

Figure 7: Dilute confined channel-fill PDC deposits. This deposit can be clearly observed at localities 118 ([A] and [B]b; spatula is 15 cm) in the Barranca of San Juan Amecac, Puebla and at locality 36 in the Barranca La Ixtla, Morelos ([C] and [D]).

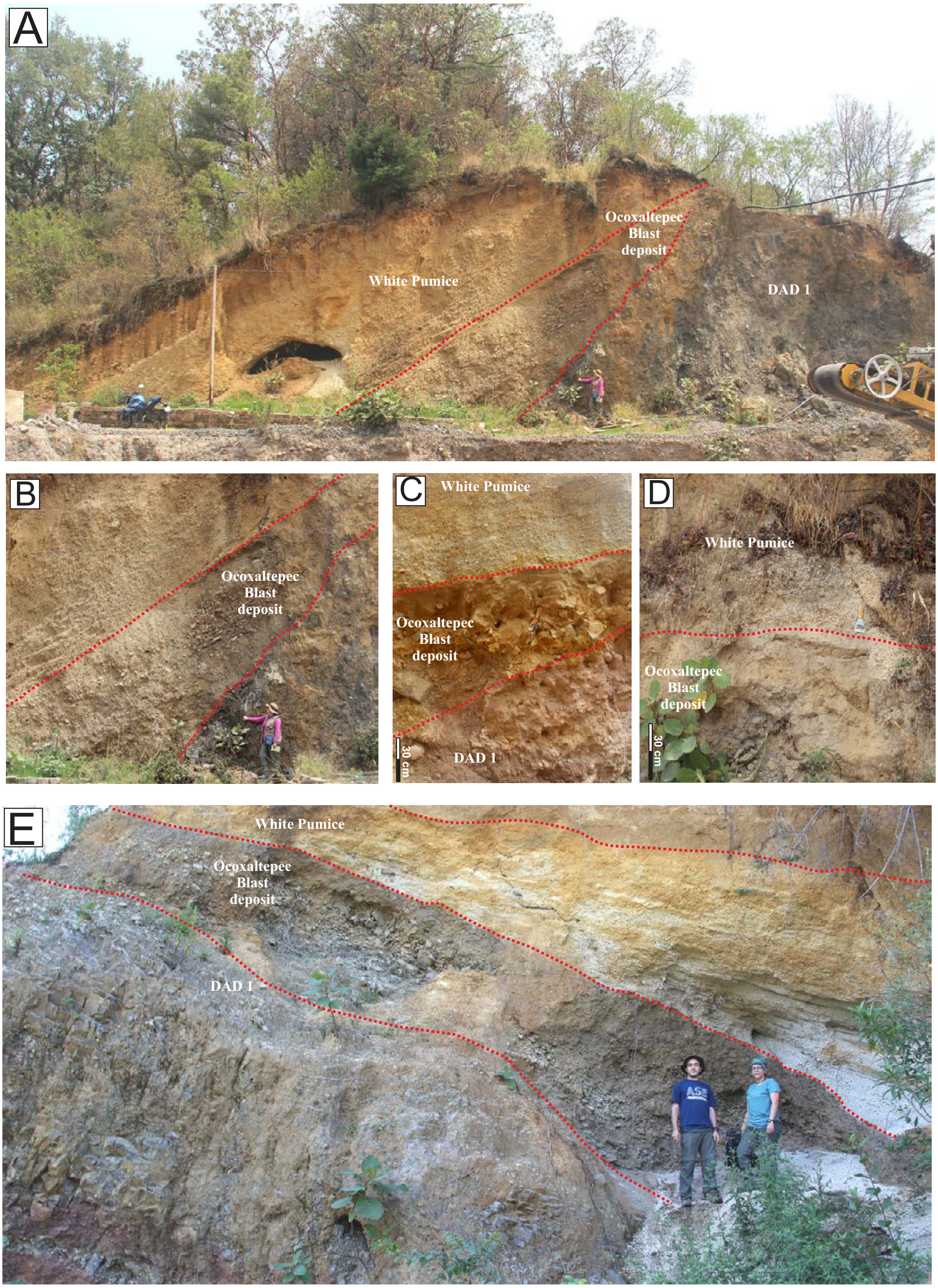

Figure 8: Unconfined interfluve and upland PDC deposits. [A]–[B] construction material extraction mine in Hueyapan (Loc. 71 SR3), at this point the deposit is 3.2 m thick. [C] At locality 72 the deposit is distinguished by two layers, one enriched in lava blocks and the other in ash with disseminated charcoal. [D] Outcrop at locality 104 in Tetela del Volcán, the contact of unconfined deposit and the white pumice deposit can be observed. [E] Loc. 148 contact between debris avalanche deposit DAD 1, Ocoxaltepec Blast deposit and White Pumice. The contact between DAD 1 and the blast deposit is very irregular. Photos [A] and [E] show the blast deposit rising above the debris avalanche deposit.

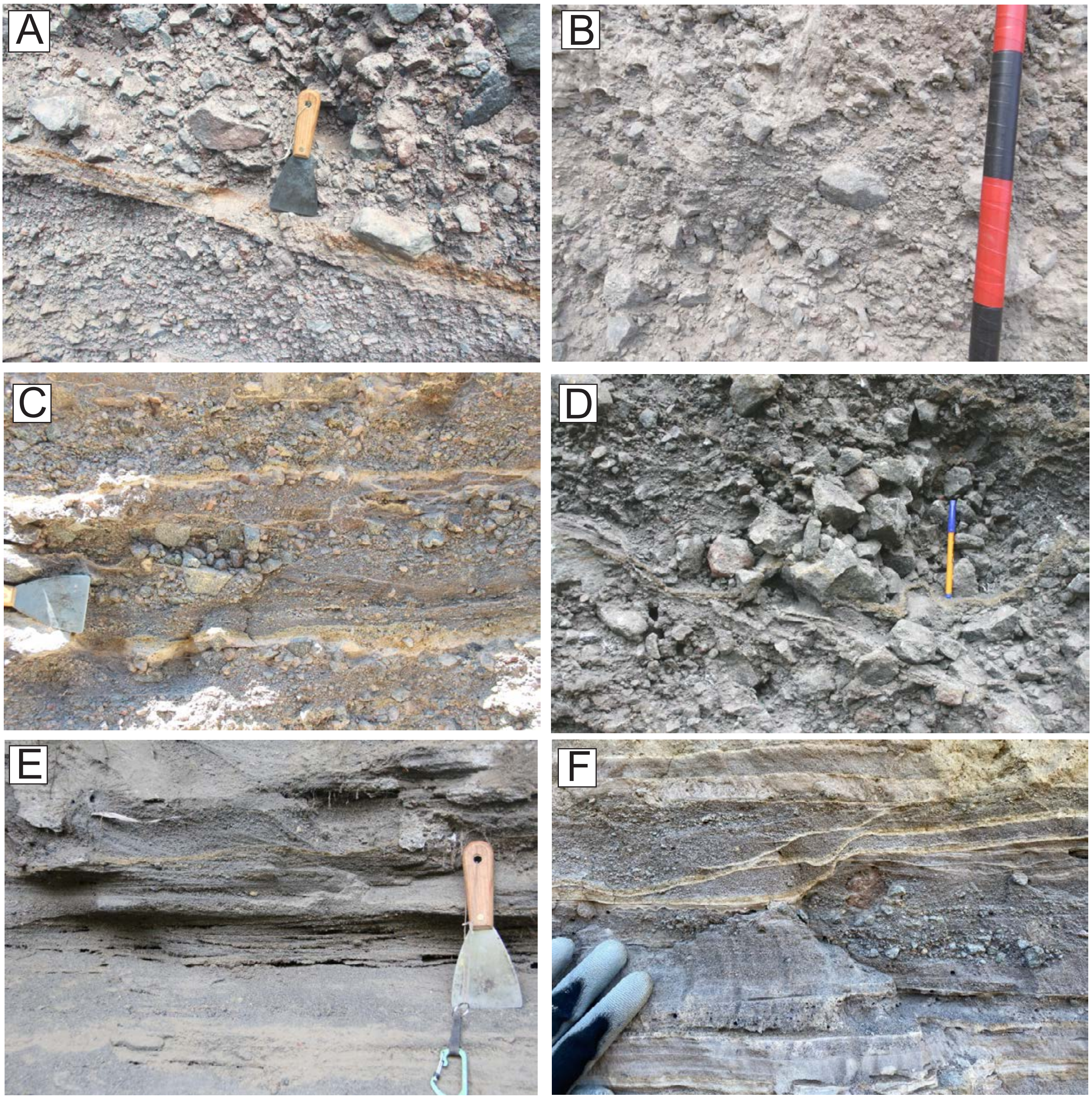

Figure 9: Textural and structural characteristics of confined channel-fill PDC deposits. [A]–[D] Concentrated confined channel-fill PDC deposits. [A] (spatula is 15 cm) on the borders of the State of México and Morelos (Loc. 22), [B] (each section of the scale is 10 cm) Tetela del Volcán (Loc. 15), [C] Hueyapan (Loc. 117) and [D] east of the town of San Juan Amecac (Loc. 131 at 20.8 km from the volcano crater) in Puebla. The characteristics of the deposit are similar, with the greatest thicknesses found in the state of Puebla. [E]–[F] (spatula is 15 cm) Dilute confined channel-fill PDC deposits observed at locality 138 (Xochitlan, Morelos) and 118 (Barranca de San Juan Amecac, Puebla).

supported. It is also possible to distinguish horizons enriched in massive gray ash without stratification with scattered lapilli-sized lava fragments. The layers present sedimentary structures such as parallel laminated, cross-laminated and lenticular stratification. The average thickness for these deposits is about 4 m (Loc. 2, 36, 118, and 138). This deposit can be seen very well in the Barranca La Ixtla in Metepec (Loc. 36) and San Juan Amecac in Puebla (Loc. 118; Figure 1), where it can have thicknesses above 6 m (Figure 7).

B) **Unconfined interfluve and upland PDC deposits**. In the area of Tetela del Volcán, Alpanocan, Hueyapan, Zacualpan de Amilpas, and Tochimilco, we found outcrops that we relate to the blast deposit due to the stratigraphic relationships at the base with the debris avalanche deposit and at the top with the fallout deposit (Loc. 71 Reference Section RS3; Figure 5, 8A, and 13). The blast deposit occurs in unconfined areas or areas topographically higher than the channel deposits (interfluve facies [Belousov 1996]). These deposits

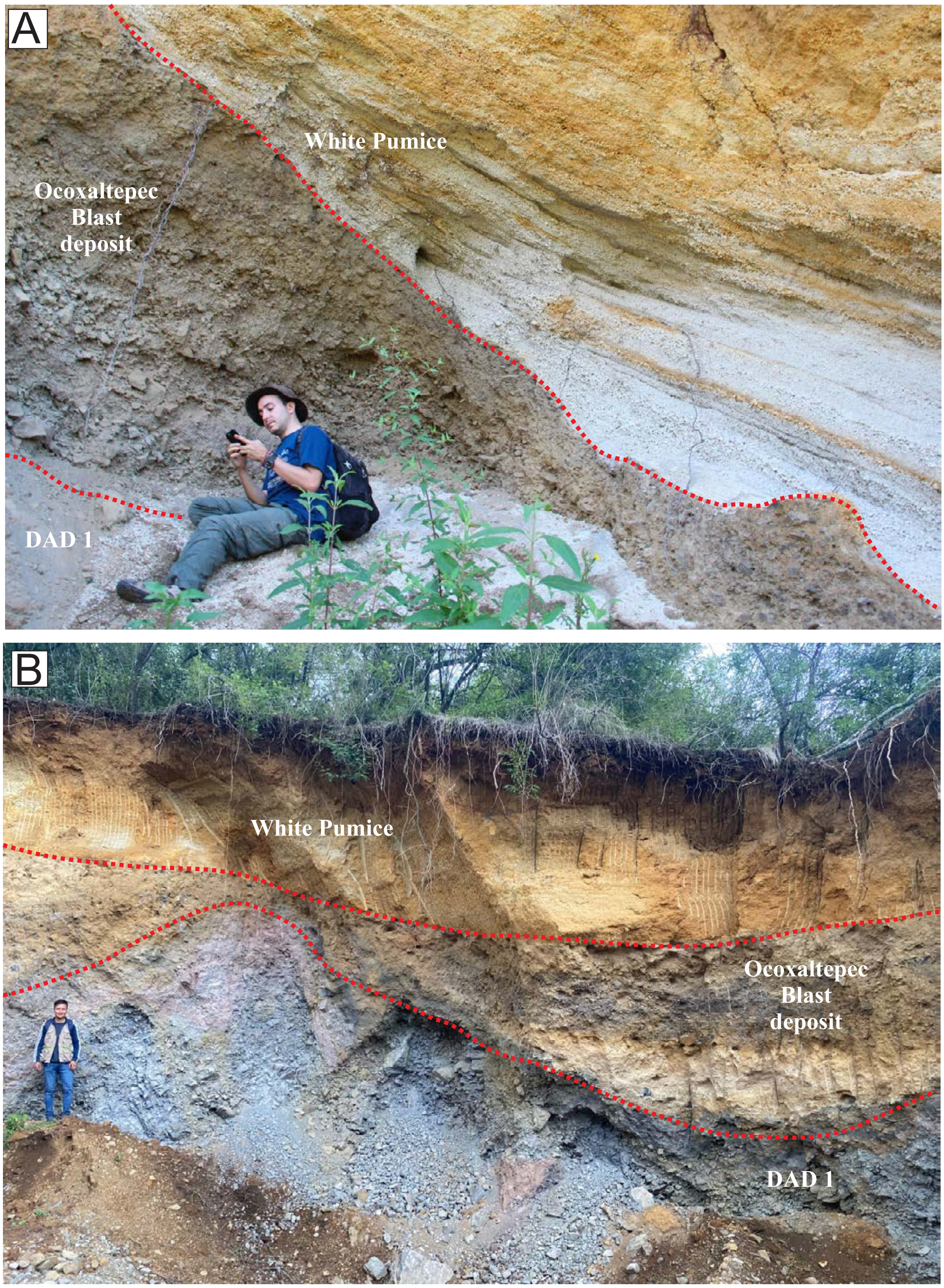

Figure 10: Textural and structural characteristics of unconfined interfluve and upland PDC deposits. [A] Outcrop located SW of the town of Tetela del Volcán, Loc. 148. [B] Outcrop located S of the town of Hueyapan, Loc. 122. Note the very irregular contact between the debris avalanche deposit and the blast deposit.

are composed of two layers, a lower layer is enriched in fine block-sized angular to subangular gray lava fragments in a brownish-ochre ash matrix. The lava fragments have phenocrysts of plagioclase and pyroxene, which are similar to the dense lava components of the confined channel-fill PDC deposit. This layer is clast-supported, and exhibits diffuse parallel stratification. The contact of this layer with the debris avalanche deposit can be erosive and very sharp. The upper layer is enriched in ash, with the presence of lapilli-sized subangular gray lava fragments (Figure 8A and 8C). This layer is massive with no apparent stratification. A characteristic of the upper layer is that disseminated charcoal can be found. These deposits can present thicknesses between 47 cm and 3.2 m in the towns of Tetela del Volcán, Alpanocan and Hueyapan (Loc. 71 (SR3), 72, 116, and 148). Deposits of this type can be found on the slopes of the hummocky geomorphology formed by the debris avalanche deposits (Figure 8A).

The general textural and structural characteristics of the deposits shown in Figure 9 and 10. confined channel-fill PDC deposits have been located throughout the study area (Figure 9A–9D), for example in localities located in Morelos such as Ocoxaltepec (Loc. 22, TS), Tetela del Volcán (Loc. 15), Hueyapan (Loc. 117) and east of the town of San Juan Amecac (Loc. 131 at 20.8 km from the volcano crater) in Puebla. The characteristics of the deposit are similar, with the greatest thicknesses found in Puebla. Figure 9E–9F shows deposit characteristics associated with the dilute confined channel-fill PDC deposits observed at locality 138 (Xochitlan, Morelos) and 118 (Barranca de San Juan Amecac, Puebla). Finally, Figure 10 shows unconfined interfluve and upland PDC deposits; these deposits can be observed in outcrops located around the towns of Tetela del Volcán, Alpanocan (Figure 10A), and to the south and east of Hueyapan (Figure 10B).

4.3 Stratigraphic relationships and correlation of the Ocoxaltepec Blast deposit

The stratigraphic relationships between the deposits such as the type and form of contact between the units, textural characteristics as well as the analysis of the components during field work helped us to differentiate the studied deposits from other volcanic and volcanoclastic deposits. At 34 of the visited sites, where the Ocoxaltepec Blast deposit was found in contact with some of the units of the 23,500 ka BP eruptive sequence, it was possible to identify stratigraphic relationships with the debris avalanche deposit and the fall deposit (White Pumice) (Figure 11). In general, the lower contact of the blast deposit with the debris avalanche and a dilute PDC deposit (found only at Loc. 117) is markedly erosional and very irregular (Figure 11A and 11B). In the field, it was possible to observe at Loc. 15 and 117 (Figure 1) injections of the blast deposit into the debris avalanche deposit, this can be identified as a type of large-scale deformation or injection structure (Figure 11A and 11B). These structures can be tens of centimeters to a few meters long (Figure 11A and 11B) and can be found between 17.8 km (Loc. 15) and 15 km (Loc. 22) distance from the crater. In contrast, the upper contact of the blast deposit with the fall deposit is straight, flat, and continuous (Figure 11C–11E). This can be clearly observed at localities 3 and 38 where the upper level of the blast deposit is composed of subangular gray lava blocks.

The new outcrops we have found together with their stratigraphic relationships allowed us to establish the stratigraphic correlation of the Ocoxaltepec Blast deposit in confined channel-fill deposits and unconfined interfluve and upland deposits (Figure 12 and 13). Figure 12 shows the stratigraphic sections and the correlation we determined between the confined channel-fill deposits along the study area, including three sections described previously by Siebe et al. [1995, 2017], two of them with dates obtained by the ^{14}C radiometric dating technique. We correlated deposits of blast from the locality of Ecatzingo in the State of México in the SW sector (Ecatzingo section [Siebe et al. 1995]) to the Barranca San Juan Amecac in Puebla (Loc. 118B) in the S sector. Figure 13 shows the stratigraphic sections and the correlation of unconfined interfluve and upland deposits. In each of the sections the distance in kilometers to the volcano crater is included.

5 Discussion and conclusions

Catastrophic eruptions related to directed blasts of stratovolcanoes with andesitic-dacitic compositions are considered one of the most dangerous volcanic phenomena for humankind [Bogoyavlenskaya et al. 1985]. These eruptions result from the emplacement of a viscous magmatic body at very shallow levels of the volcanic edifice [Belousov et al. 2007]. For this reason, direct observations and detailed studies in the geological record of past eruptions are of great importance for understanding the behavior of these very high energy phenomena. Our observations of the Ocoxaltepec Blast allow us to evaluate its deposits in the context of previously studied blast eruptions.

5.1 Blast deposit types and dynamics

We were able to recognize two types of PDC deposits (confined channel fill PDC deposits and unconfined interfluve and upland PDC deposits) within the Ocoxaltepec Blast deposits linked to the 23,500 ka BP eruption of Popocatépetl volcano, triggered by a sector collapse of the volcano [Siebe et al. 2017]. The distribution, stratigraphic relationships (especially with the debris avalanche deposit), sedimentary structures and textural and compositional (presence of juvenile lava fragments and altered lava fragments) characteristics of the Ocoxaltepec Blast deposit observed in the outcrops and in the study area allowed us to differentiate it from secondary deposits.

The confined channel-fill PDC deposits that we describe resemble the “valley facies” defined by Belousov [1996], where they note that the deposits can have thicknesses on the order of meters to tens of meters and are usually massive, but that layers can be differentiated and resemble concentrated lithic-rich PDC deposits. The maximum thickness found in this study reaches 42.3 m in the Barranca de San Juan Amecac in Puebla (Figure 4), associated with confined channel fill zones (as in the case of the Bezymianny blast deposit, which reaches 50 m in thickness [Belousov 1996]). In Bezymianny the large thicknesses of deposits found in confined areas of channel-fill are most likely related to backflow accumulation mechanisms of blast deposits directed from slopes of steep valleys [Belousov 1996]. This mechanism was probably present in some confined zones of our study area.

On the other hand, thickness fluctuations observed in deposits related to unconfined areas are most likely caused by very unstable deposition from PDC blast [Belousov 1996; Belousov et al. 2007]. Thinner deposits are related to topographically elevated zones such as hummocky areas. This is clearly observed in the sections containing low-thickness unconfined interfluve and upland deposits shown in Figure 13, which are located in a zone of hummocks with a NE–SW direction trend. Field investigations conducted on blast deposits from

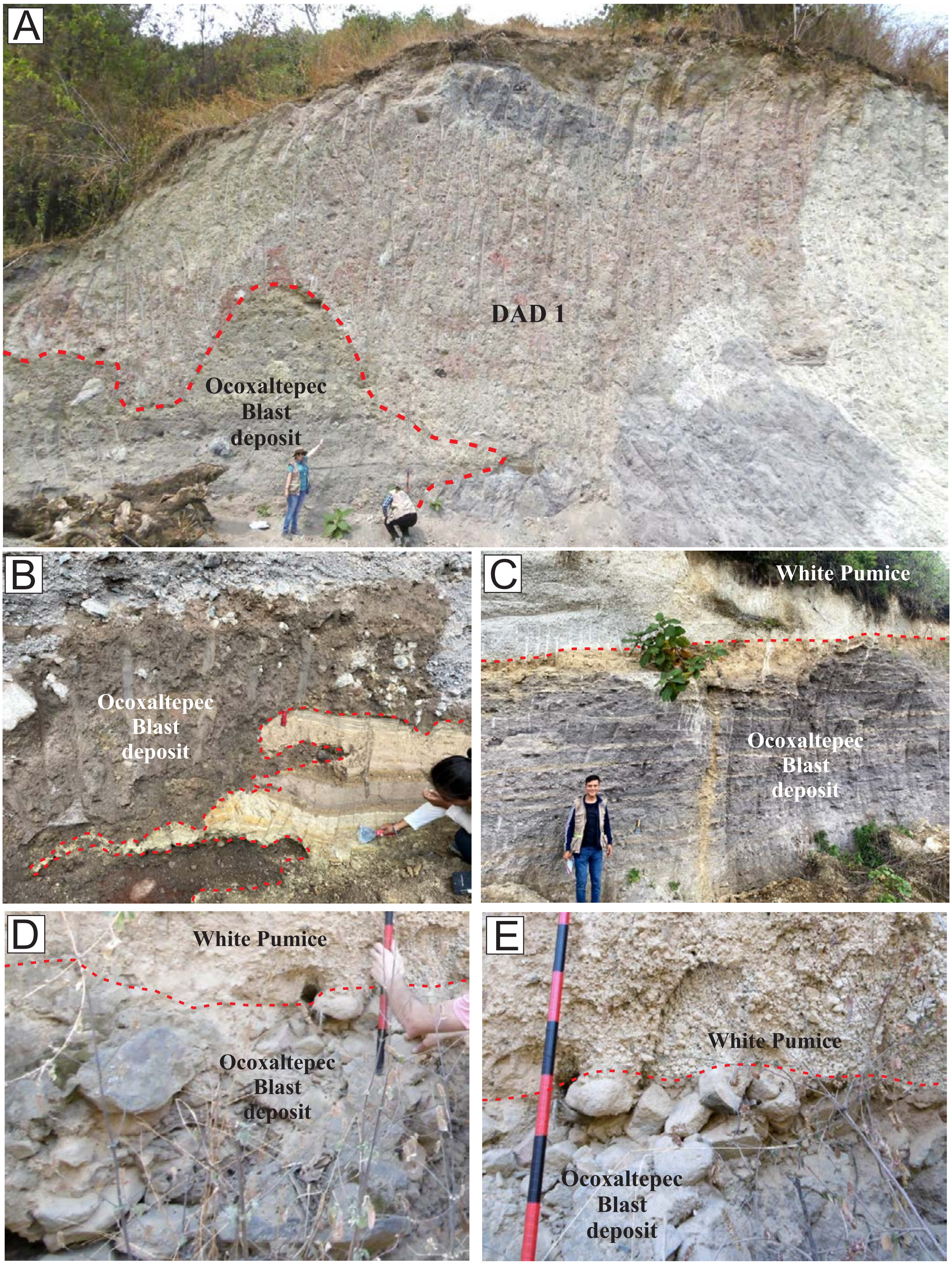

Figure 11: Contact of the Ocoxaltepec Blast deposit with the debris avalanche deposit and pumice fall deposit. [A]–[B] Erosional contact of the blast deposit on the debris avalanche deposit and on a PDC deposit, showing injection structures of blast deposit into other deposits. [C] Locality 117 in the town of Hueyapan, upper contact between the blast deposit and the White Pumice. [D]–[E] (each section of the scale is 10 cm) Locality 3, contact between the blast deposit (block-enriched) and the White Pumice deposit.

the Mount St. Helens eruption clearly show that topography influences the distribution of deposits and the distance of emplacement [Brand et al. 2023], as seems to be the case in this study. The Mount St. Helens blast PDC deposits are located more to the northwest, where valleys and ridges were predominantly parallel to the direction of blast flow [Fisher 1990; Brand et al. 2023].

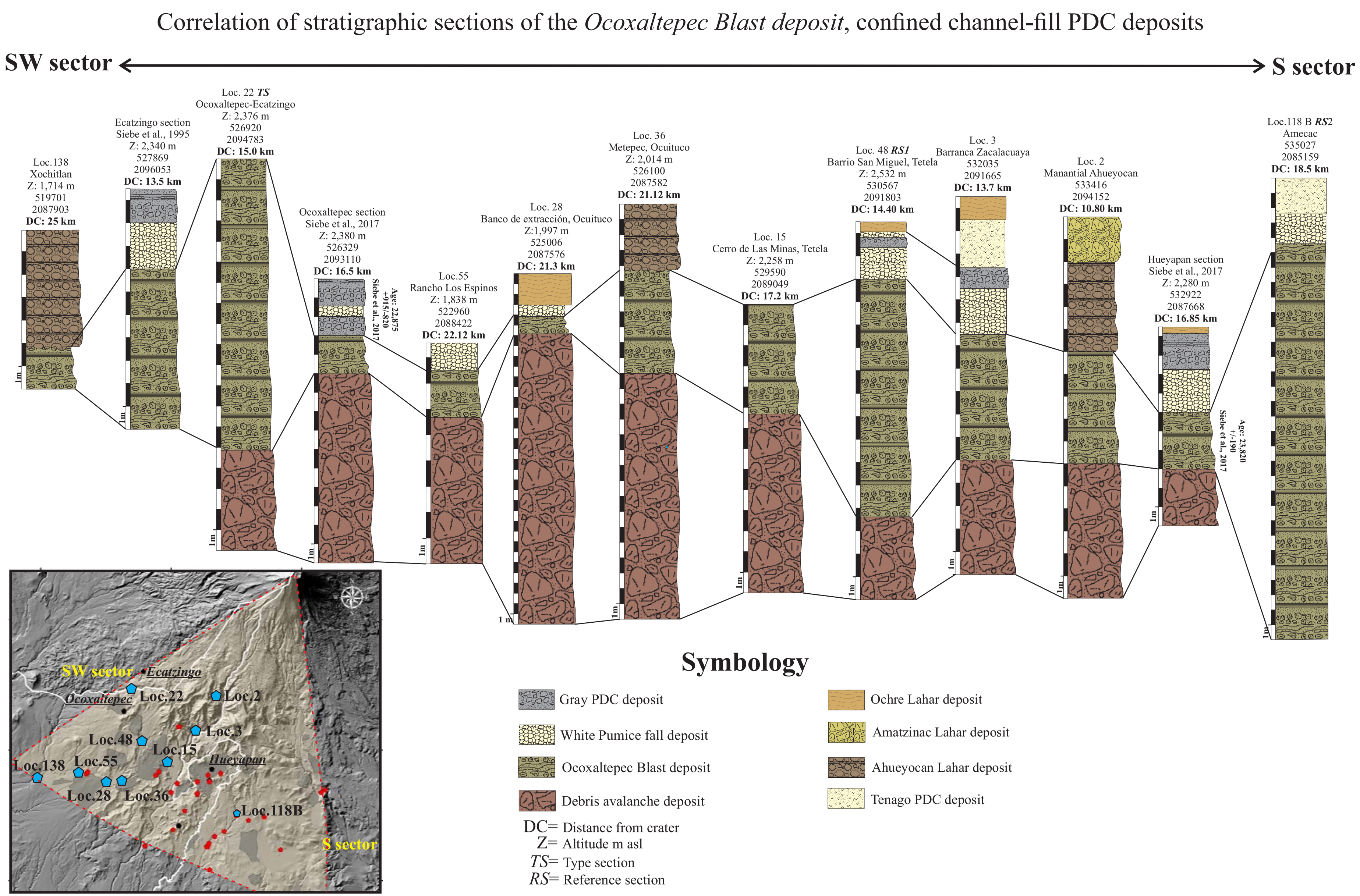

Figure 12: Stratigraphic sections and correlation of the confined channel-fill Ocoxaltepec Blast deposits. The blue pentagons on the map show the location of the sections.

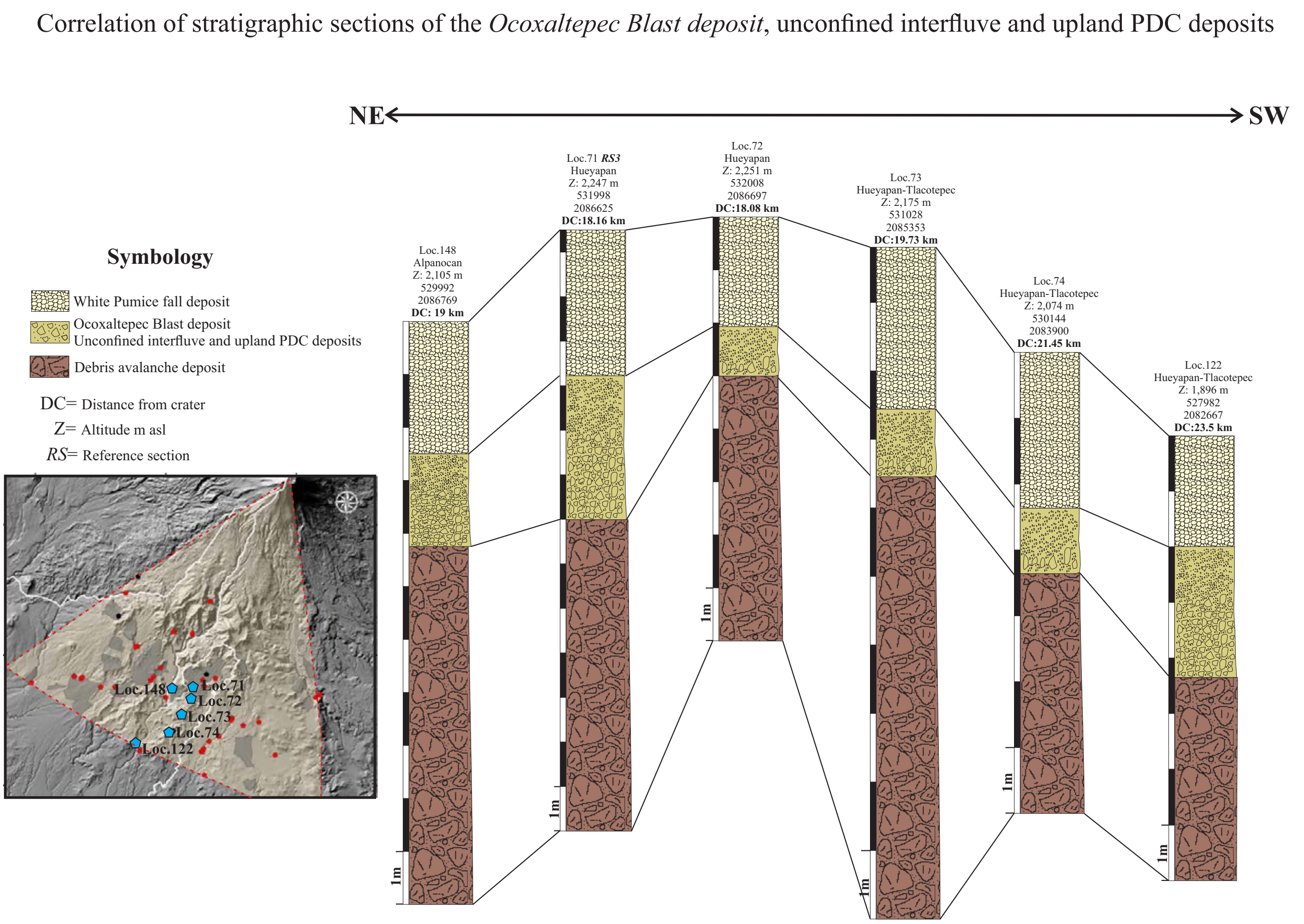

Figure 13: Stratigraphic sections and correlation of the unconfined interfluve and upland Ocoxaltepec Blast deposits. The blue pentagons on the map show the location of the sections.

The proximal deposits of the "valley facies" proposed by Belousov are characterized by being quite block-rich, composed of very coarse material with fines almost absent, and any matrix represented by coarse lapilli. This was clearly observed at locality 48 (Figure 2; RS1), north of the town of Tetela del Volcán, 14.5 km from the crater. In the outcrops located at localities 116 and 143 in the town of Hueyapan located 16.3 km and 16.9 km away from the crater, respectively, layers with subrounded blocks and a greater presence of matrix are seen; these notable subrounded blocks may indicate intense abrasion during transport [Belousov et al. 2007]. In outcrops associated with concentrated confined channel-fill PDC deposits we observed in the contact between the debris avalanche deposit and the blast deposit injections or deformation structures similar to those reported by Belousov [1996] and [Belousov et al. 2007] for Bezymianny. At these sites (Loc. 15, 22, and 117) the blast deposit is injected into the debris avalanche. In addition, very irregular contacts were observed (Loc. 36) (Figure 14). Deformation and load structures observed at the contact of the units can be diagnostic features in determining depositional conditions and may be evidence of probable coeval or temporally proximal deposition [Lira-Beltrán et al. 2022]. These observation indicate that deposition between the debris avalanche deposit and the blast deposit occurred almost simultaneously (as with Bezymianny [Belousov 1996; Belousov et al. 2007]).

5.2 Area and volume of the Ocoxaltepec Blast

In this work we report 42 new outcrops of the Ocoxaltepec Blast deposit that allowed us to preliminarily estimate a possible area affected by the directed blast, which has a minimum area of 338 km^2 (Figure 1 and 15). Since the deposits at the southern edge of our mapped area measured between 0.4 and 3.15 m in thickness (Loc. 122, 123, and 144, Figure 4), it is likely that the blast area is larger than our projected polygon, present in still unidentified (or not preserved) deposits. The greatest thicknesses of the blast deposit are in canyons or stream channels containing confined channel-fill PDC deposits (Figure 4), which may be characterized by layers with a high concentration of lava blocks, lacking matrix. The most distal outcrop of blast deposits related to the unconfined interfluve and upland PDC deposits is located 23.3 km from the present crater of the volcano, at locality 122, to the NE of the town of Tlacotepec in the municipality of Zacualpan de Amilpas in Morelos. In contrast, the farthest outcrop of the blast deposit containing Dilute confined channel-fill PDC deposits was located 25 km from the crater, at locality 138, located in Xochitlanin in Morelos.

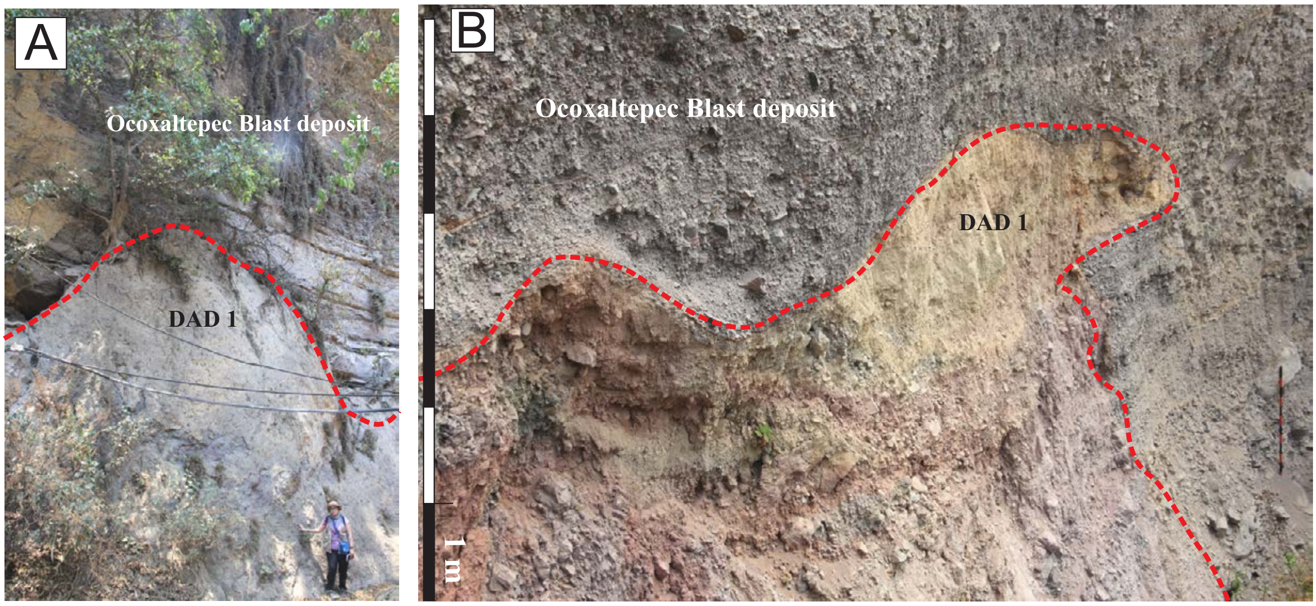

Figure 14: [A] Location 36, Barranca La Ixtla, abrupt and erosive contact between the debris avalanche deposit and the blast deposit. [B] Locality 22, highly erosive contact between the debris avalanche deposit and the blast deposit. Here the blast deposit is inside the debris avalanche deposit.

Table 1: Comparative directed blast data from Bezymianny, Soufrière Hills, and Mount St. Helens (modified from Belousov et al. [2020]). Blast data from the 23,500 ka BP Popocatépetl volcano are also presented.

Volcano	Composition	Volume (km^3)	Area (km^2)	Travel distance (km)	Maximum thickness (m)		Reference
					Unchanneled	Channeled	
Bezymianny (1956)	Andesite	0.2	500–365	30	2.5	50	Belousov [1996]
Mount St. Helens (1980)	Dacite	0.11	623	27	2–2.5	-	Belousov et al. [2007, 2020], Komorowski et al. [2013]
Soufrière Hills (1997)	Andesite	0.03	10	7	3	-	Belousov et al. [2007, 2020]
Popocatépetl (23,500 ka BP)	Andesite-Dacite	0.25	338	25	3.5	42.3	This study

With the new data, we were able to make a comparison of the Popocatépetl volcano blast (Table 1) with the eruptions of the Bezymianny (1956), Mount St. Helens (1980), and Soufrière Hills (1997), which have been studied in detail by Belousov et al. [2007, 2020]. However, in the case of the Popocatépetl volcano, we do not know the location characteristics of the superficial lava body or cryptodome. Therefore, we estimated the volume using average thicknesses for each of the deposit types and a maximum deposit coverage area, taking into account areas where no deposit was found (Table 1).

5.3 Hazard implications

It is now known that directed explosions can occur not only as isolated events, but as complex sequences of collapse and directed explosions (e.g. Merapi 5 Nov 2010 [Komorowski et al. 2013; Lerner et al. 2022]). Based on the sequence of deposits observed in the field, the Ocoxaltepec Blast likely represented one such event in a complex eruption of this type. Like other directed blasts, the Ocoxaltepec Blast covers a wide area from its source and appears to have been greatly affected by topography and channel confinement (e.g. Mount St. Helens, Bezymianny [Fisher 1990; Belousov et al. 2007; Brand et al. 2023]). Near the source, directed blast velocities can reach 150 m s^{-1} (Mount St. Helens 1980 [Esposti Ongaro et al. 2011]) and typically more than 90 m s^{-1} [Cole et al. 2015]. They typically have high dynamic pressure (more than 10 kPa) near the source and along the primary flow axis but lower dynamic pressures (less than 1 kPa) in more distal areas [Jenkins et al. 2013; Gueugneau et al. 2020] and in measured cases have shown temperatures above 300 °C [Cole et al. 2015]. While it is impossible to determine these parameters precisely from our observations, the Ocoxaltepec Blast would likely have had

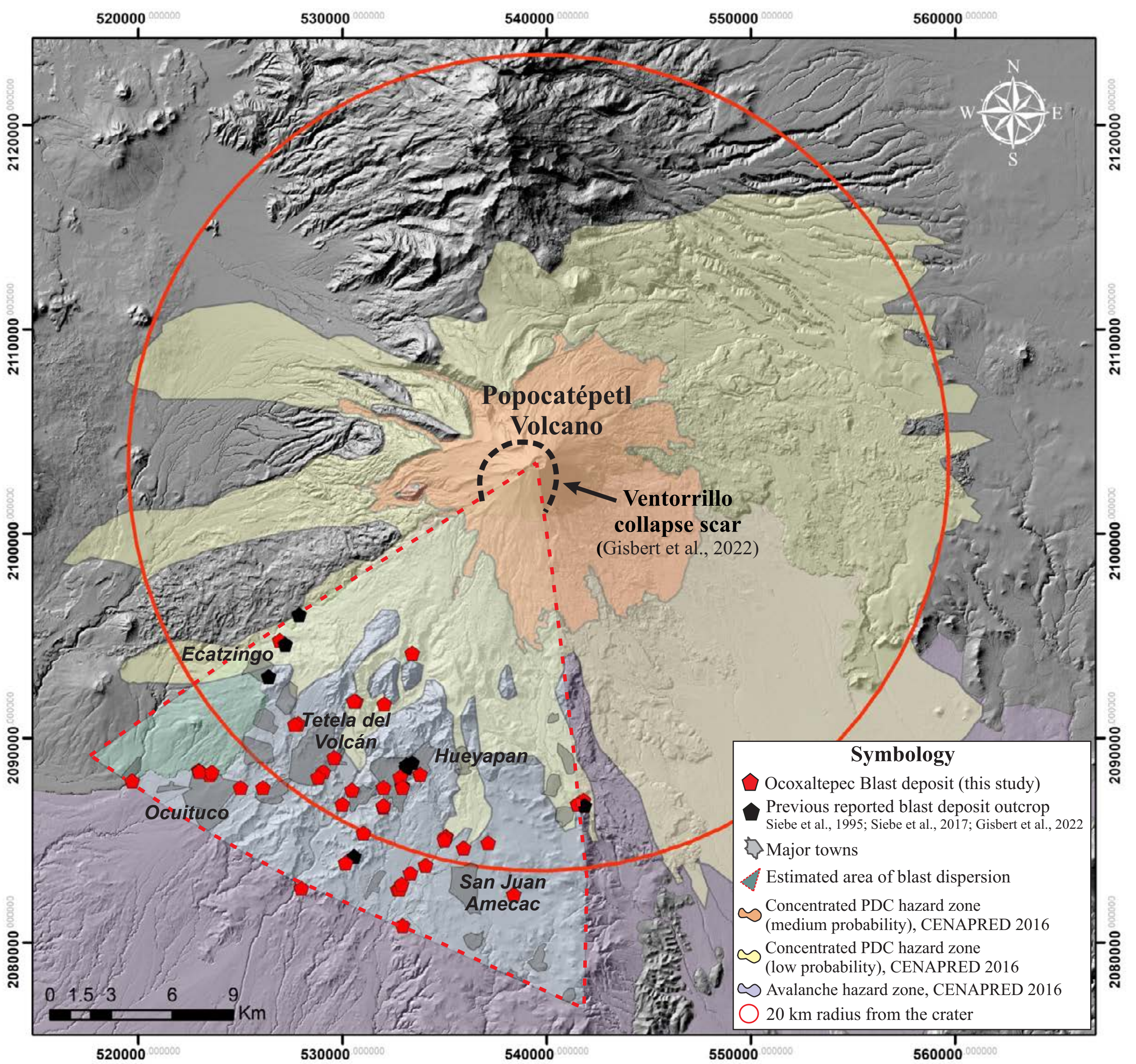

Figure 15: Polygons of the PDC hazard zone of Popocatepetl volcano [CENAPRED 2016] and the sites (red pentagons) where we have found outcrops associated with the 23,500 ka BP directed blast eruption. The map shows the collapse scar related to the 23,500 ka BP eruption (Ventorrillo) proposed by Gisbert et al. [2022].

similar characteristics. An eruption of this style in the present day would result in a wide range of effects on humans and the built and natural environment [Lerner et al. 2022].

Twenty-nine of the new outcrops associated with PDC of the directed blast are outside the hazard polygon associated with concentrated PDC of the Popocatépetl volcano related to a lower-probability (i.e. larger of the two anticipated scenarios) Plinian eruption (related to PDCs due to column collapse) [CENAPRED 2016] (Figure 15). A comparison between the areas that make up the low-probability polygon PDCs (those with the largest extent) and the area we have estimated for blast dispersion shows an area of 211.2 km^2 located outside the existing PDC hazard polygon. While much of this area overlaps with the potential area considered at hazard to debris avalanche [CENAPRED 2016], some of the projected area of the Ocoxaltepec Blast extends to zones not currently considered by any current hazard polygons (Figure 15). Additionally, while directed eruptions are frequently associated with sector collapse (as in the case of the Ocoxaltepec Blast), this is not always the case (e.g. Soufrière Hills 1997). Therefore, consideration of the hazard from a blast associated with a debris avalanche, but also individually, is warranted as a low-probability, high-impact future eruption scenario.

The preliminary area where we have found the Ocoxaltepec Blast deposit is located between the municipalities of Ecatzingo (State of México) and Atzitzihuacán (Puebla), where more than 58,987 people live [INEGI 2020]. The most important towns are Teleta del Volcán, Alpanocan, Barrio San Miguel (Hueyapan), Ocuituco, Metepec, Huejotengo, Tlalmimilulpan, and San Juan de Amecac. These towns are located at a distance of less than 25 km from the current crater of Popocatépetl and are located on deposits related to the eruption of 23,500 ka BP. While every potential directed blast scenario will depend on the individual characteristics of its complex eruption sequence, the fact that the two mapped debris avalanche deposits and one mapped blast deposit are located within this sector of the volcano [Siebe et al. 2017; Gisbert et al. 2022, this study] should not be discounted when considering hazard assessment of these areas.

Important characteristics of this eruption yet to be understood include the state of the superficial lava body or cryptodome prior to eruption. Valuable information that could aid in the better understanding of the blast include better dating of the eruption sequence, geochemistry and detailed textural analyses. Given the small number of blast deposits and eruptions have been studied in detail, the Ocoxaltepec Blast (as one of the oldest blasts studied in this level of detail) represents an important comparison for modern blast eruptions. More generally, these results demonstrate the importance of continued detailed geological and stratigraphic studies of active volcanoes. Even at well-studied volcanoes, these studies can still provide new evidence of their eruptive history, fundamental information for understanding their behavior and one of the bases for updating volcanic hazard maps.

Author Contributions

All authors declare no competing financial interests. MLB conceived the original idea of the work and was responsible for drafting the manuscript. MLB, DS, LC and GL performed the field work. DS was responsible for taking the field photographs. ML was in charge of the final editing of the photographs. GL was in charge of grammatical revisions of the English language during all stages of the work. LC and GRC were responsible for managing the resources used in this work. Finally, all authors reviewed the final manuscript.

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Data Availability

All data and results for the study are contained within the text and figures of the article, as well as the two supplementary documents.

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