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

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Abstract

Volcanic eruptions of the directed blast type can affect areas of hundreds of square kilometres and reach more than 25 km from the crater, as observed in the directed explosions of the Bezymianny (1956) and Mt. St. Helens (1980) volcanoes. These directed eruptions are characterized by powerful explosions with a significant lateral component that can travel at speeds above 100 m/s, which includes catastrophic high-energy pyroclastic density currents. We report new data and evidence on a blast originating from the Popocatépetl volcano related to a strong eruption resulting from the sector collapse of the volcanic edifice at about 23,500 ka BP, extending to the SW. The objective of this work is to study the blast-related deposits and to provide new data on their distribution in the S-SW sector of the volcano. The area studied is located between the municipalities of Ecatzingo and Atzitzihuacán, where 58,870 inhabitants live. We have visited 157 localities where we made descriptions of the eruptive sequence and stratigraphic sections. Within these localities, we found 42 new sites where the blast deposit outcrops. In the Barranca San Juan Amecac in the state of Puebla, the blast deposit is more than 20 m thick. We associate these blast deposits with three facies: confined channel-fill facies dominated by concentrated PDCs, confined channel-fill facies dominated by dilute PDCs, and unconfined interfluve and upland facies. With the new data we have estimated the dispersion area of the directed blast to be approximately 338 km^2. The most distal deposit we have located is 25 km from the volcano crater. Finally, twenty-nine of the new outcrops associated with PDCs of the directed blast are outside the danger polygon associated with concentrated PDCs of the Popocatepetl volcano related to a Plinian eruption linked with a low probability of occurrence.

Resumen

Las erupciones volcánicas de tipo explosión dirigida (blast) pueden afectar a áreas de cientos de kilómetros cuadrados y alcanzar más de 25 km de distancia del cráter, como se observó en las explosiones dirigidas de los volcanes Bezymianny (1956) y Mt. St. Helens (1980). Estas erupciones dirigidas se caracterizan por ser potentes explosiones con una importante componente lateral que se desplazan a velocidades superiores a 100 m/s, que incluyen catastróficas corrientes de densidad piroclástica de alta energía. Reportamos nuevos datos y evidencias sobre un blast originado en el volcán Popocatépetl, relacionada con una fuerte erupción resultante del colapso sectorial del edificio volcánico alrededor de los 23,500 ka BP, que se extendió hacia el SO. El objetivo de este trabajo es estudiar los depósitos relacionados con el blast y aportar nuevos datos sobre su distribución en el sector S-SO del volcán. El área estudiada se localiza entre los municipios de Ecatzingo y Atzitzihuacán, donde viven 58.870 habitantes. Hemos visitado 157 localidades donde realizamos descripciones de la secuencia eruptiva, secciones estratigráficas. Dentro de estas localidades, encontramos 42 nuevos sitios donde aflora el depósito de blast. En la barranca San Juan Amecac, en el estado de Puebla, el depósito tiene más de 20 m de espesor. Pudimos asociar los depósitos de blast con tres facies: facies confinada canalizada dominada por CDP concentrada, facies confinada canalizada dominada por CDP diluida y facies no confinada de interfluvio y de zonas elevadas. Con los nuevos datos hemos estimado que el área de dispersión del blast es de aproximadamente 338 km^2. El depósito más distal que hemos localizado se encuentra a 25 km del

cráter del volcán. Finalmente, veintinueve de los nuevos afloramientos asociados a CDP de explosión dirigida se encuentran fuera del polígono de peligro asociado a CDP concentrada de baja probabilidad del volcán Popocatépetl relacionado con una erupción Pliniana.

1. Introduction

Directed blast eruptions are characterized by powerful explosions with a significant lateral component traveling at speeds above 100 m/s. These eruptions include catastrophic pyroclastic density currents of blast type or high-energy directed explosion type, which due to their genetic 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 pulsed eruptive sequence, and PDCs interact significantly with topography [Komorowski et al., 2013].

Mexico is a volcanically active country, with more than 8,000 volcanic structures [Macías and Arce, 2019]. Mexico 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]. Popocatépetl volcano is the second most active volcano in Mexico and is considered the one with the highest potential risk because about 25 million people live within a 100 km radius of the crater [Siebe and Macías, 2006; Espinasa-Pereña, 2012; Delgado Granados et al., 2018; 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 5,454 m [De la Cruz-Reyna et al., 2017]. Due to its previous history of Plinian eruptions (VEI4-5), 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 Mexico 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 St. Helens type [Robin and Boudal, 1987; Siebe et al., 2017]. 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 Martin 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 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 (Fig. 1). 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 (Fig. 1, red pentagons). The area studied is located from the town of Ecatzingo in the State of Mexico to the town of Tochimizolco in the State of Puebla (Fig. 1). This study builds on the limited 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.

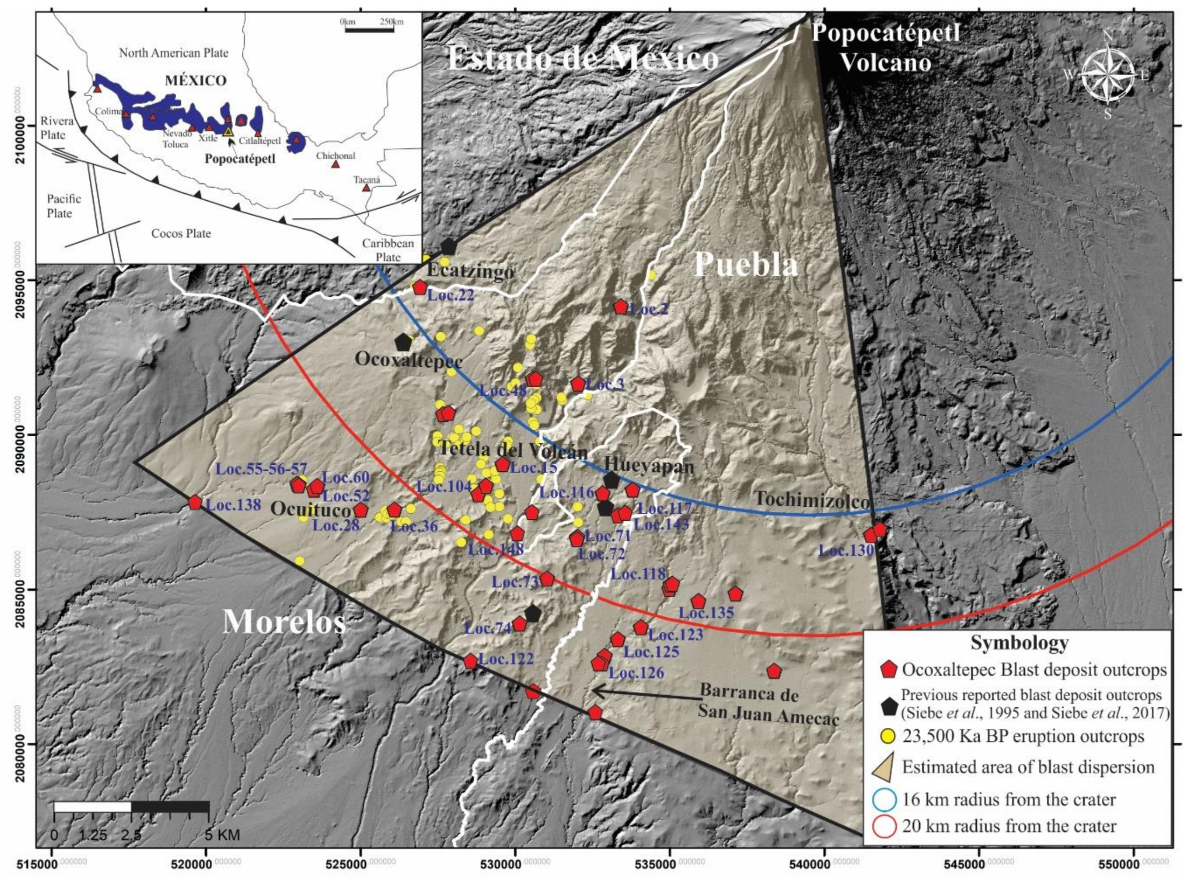

Figure 1. Map of the study area. The light brown triangle represents the preliminary dispersal area of the blast. The red pentagons correspond to the outcrops of the Ocoxaltepec Blast deposit reported in the present study.

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], Siebe et al. [1996], Siebe and Macías [2006], and Siebe et al. [2017]. 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 1,216 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; Siebe et al., 2017]. This strong explosion produced a stratified deposit with 4 m total thickness, consisting mainly of gray to pinkish angular to subangular dense lavas clasts [Siebe et al., 2017]. The layers that compose this deposit have thicknesses ranging from a few centimeters to decimeters, are composed of angular sands and gravels, 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 the 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-shaped area of 500 km^2 [Belousov, 1996]. A similar explosive event occurred in 1980 during the eruption of Mount St. Helens (MsH) volcano in the United States, where the directed explosion reached velocities of 100 to 235 m/s and covered an area of 600 km^2 [Hoblitt et al., 1981; Belousov et al., 2007]. Comparison of these two 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; Belousov et al., 2020].

According to Belousov [1996], in the proximal zones of the MsH and Bz volcanoes the blast deposits consist of three main layers: (A) Lower layer consists of poorly sorted coarse material containing soil debris and abundant uncarbonized vegetation fragments; (B) 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) 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 Bz and MsH is identical. In general, it is a unit composed predominantly of poorly sorted sand with ripple laminations, sparse granules and in smaller proportion uncharred wood. The high similarity of the Bz and MsH blast deposits suggests that the character of the transport system and the depositional process operating on it were the same in both cases [Belousov, 1996]. This succession of layers was named interfluvial facies consisting basically 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 Bz volcano eruption [Belousov 1996], whereas for MsH 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 the Bz 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 is superimposed on the debris avalanche deposit, the formation of which preceded the directed explosion. The explosion deposit is represented by gravels and very coarse clasts, 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 coarse composition 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

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 (Fig. 1). In the visited localities, we made detailed descriptions of the deposits related to the eruptive sequence of 23,500 ka BP. In addition, samples were taken from the deposits for laboratory analysis. Stratigraphic sections were made, and the stratigraphic relationships between the deposits were studied in detail in order to correlate them. The information was used to estimate a polygon of the area of influence of the blast, based on the distribution of the outcrops of the deposit in the study area. The thickness of blast deposits was measured, where possible, with a measuring tape. Thicker deposits were measured with a Leica Disto D510 model.

4. Results

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. This was clearly observed in locality 48 to the N of the town of Tetela del Volcán in the state of Morelos (Fig. 2).

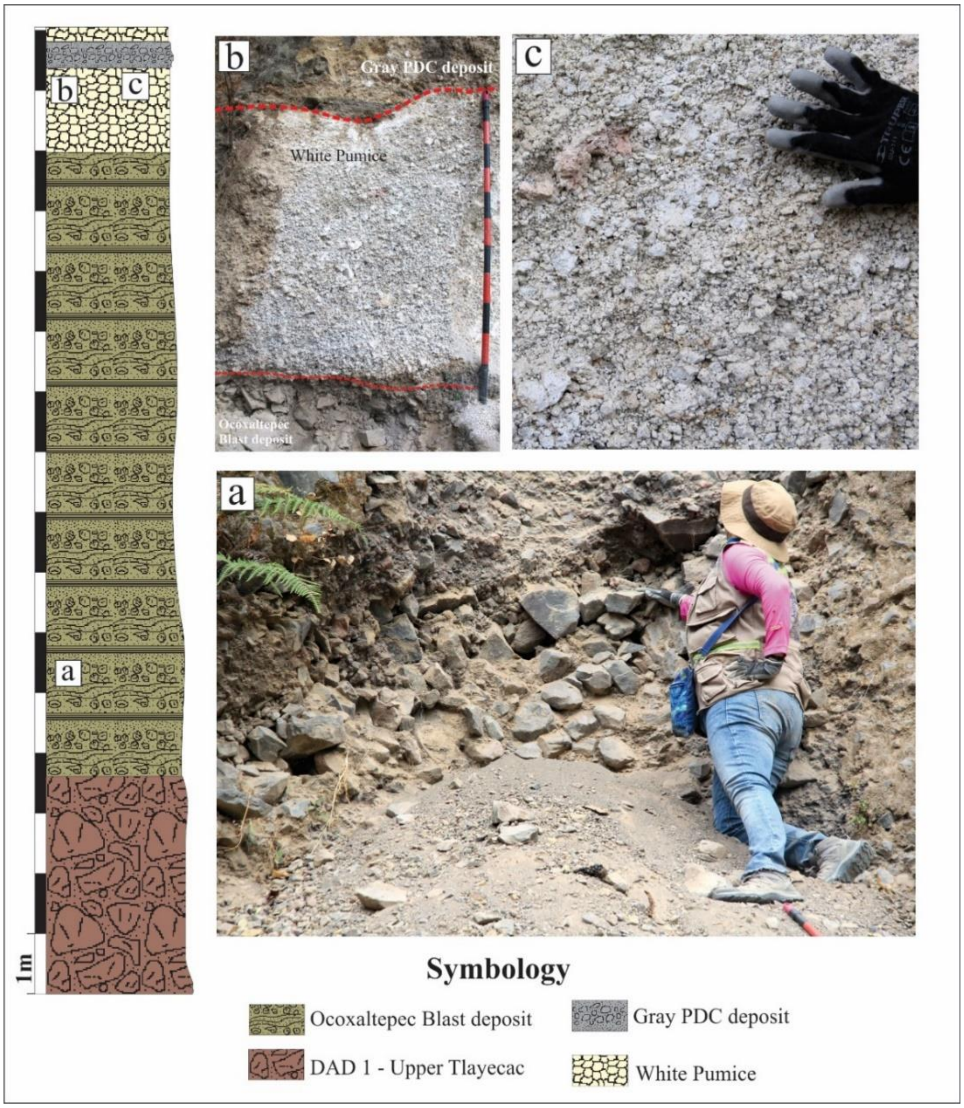

Figure 2. Stratigraphic section of locality 48. (a) Ocoxaltepec Blast deposit enriched in angular blocks of gray lava. It can be observed that the deposit is clast supported. (b) Contact between the Ocoxaltepec Blast deposit and the White Pumice deposit. (c) White Pumice massive deposit.

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

In the towns of Ocuituco and Tetela del Volcán in the state of Morelos we observed outcrops of the DAD 1 or Upper Tlayecac debris avalanche deposit with thicknesses greater than 20 m (Loc. 28, Fig. 1 and 3a, b and c). 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, Fig. 1 and 3c) we found the contact between the debris avalanche deposit and an overlying 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 (Ocoxaltepec Blast deposit), which will be described in more detail in the next section. At the contact between the debris avalanche deposit and the blast deposit, there is sometimes a light brown to beige colored deposit of fine material such as medium to coarse ash, with varying thickness (up to 2 m), resembling a lens, which we interpreted as dilute PDC. Overlying the blast deposit, we find a deposit of the White Pumice (Fig. 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 the state of 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 the state of Puebla. 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). This deposit has a transitional contact with the White Pumice (Fig. 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. 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 sandy to gravelly material with parallel and laminar stratification (Ahueyocan Lahars deposit). 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 gravels to blocks, which can reach a diameter of more than 2 m (Fig. 3e). The layers of fine-grained material range from sand to gravels, 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, Paraje Tenango, Barranca La Ixtla, Tlalmimilulpan and Barranca La Laja.

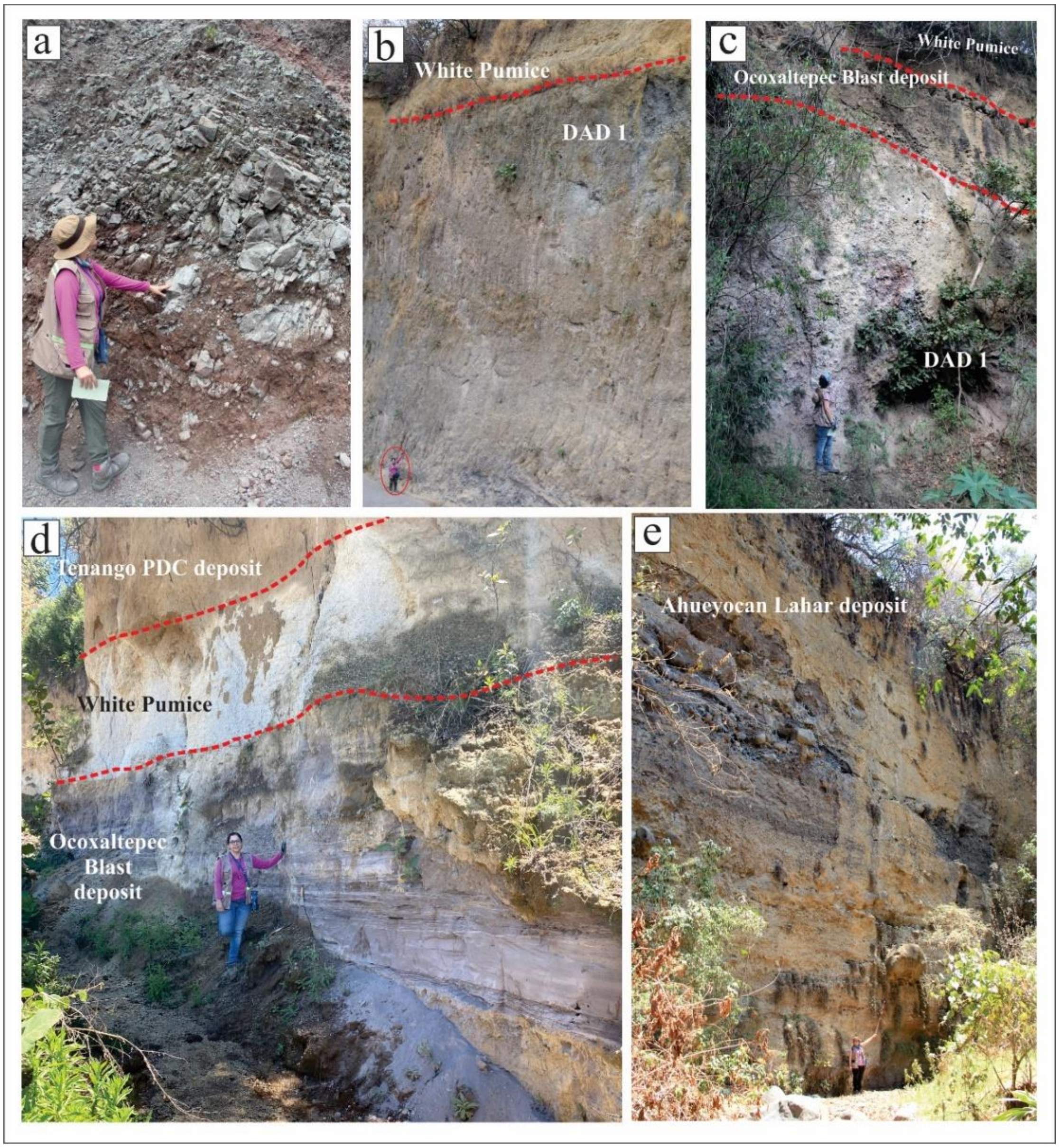

Figure 3. The 23,500 ka BP eruptive sequence. (a) DAD 1 or upper Tlayecac debris avalanche deposit, (b) Contact between the debris avalanche deposit and the White Pumice above, (c) Contact between the debris avalanche deposit and the deposit associated with the directed blast, (d) Contact between the Ocoxaltepec Blast deposit, White Pumice and Tenango PDC, (e) Ahueyocan Lahar deposit.

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 Mexico, Morelos and Puebla (Fig. 1, red pentagons). The maximum thicknesses of the deposit has been seen in localities 123, 125, 126, located in the Barranca San Juan Amecac, in the state of Puebla (Fig. 1), where it reaches up to 42.3 m, and around Ocoxaltepec (Loc. 22), within the limits of the states of Mexico and Morelos, where it reaches a thickness of more than 14 m (Fig. 1). 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 smaller diameter material (lapilli and ash sized) with marked stratification, which are described as follows:

(a) 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. Levels enriched with coarse material are massive but may have diffuse parallel stratification and normal gradations and intercalated layers of fine material with well-marked stratification.

(b) 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, markedly laminated, and cross laminated. The blast deposit is generally distinguished by being poorly to moderately consolidated.

In most cases, the deposit is characterized by significant granulometric and structural variations, which allowed us to recognize three main facies within the deposit. These facies can appear together in the same outcrop or individually. Each facies are described below:

A) **Confined channel-fill facies dominated by concentrated pyroclastic density current deposits.** This facies is characterized by the greater thicknesses and generally occurs in outcrops located on the flanks of canyons (barrancas) or fluvial streams and in places where the deposit has not been affected by erosion. 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 thin layers composed of ochre-colored laminated ash (Loc. 22, Fig. 4 a). These fine-grained layers are thin (a few centimeters thick), irregular and variable in thickness, and tend to wedge. This facies is depicted by the presence of layers with variable thickness and lenticular layers composed of dense gray lava blocks where block-to-block contact with absence of matrix dominates (Fig. 4 c). In the layers of coarse-grained material, the lava blocks have sizes ranging from 10 to 20 cm, but blocks between 40 to 80 cm can be identified. We found extraordinary lava megablocks with diameters from 1 to 1.6 m. These megablocks usually have subrounded shapes. This facies can reach thicknesses of more than 10 m (Loc. 22, 48, 118, 123, 135). 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 is massive or has diffuse parallel stratification. The best sites where outcrops associated with this facies are found are on the Ocoxaltepec-Ecatzingo road (Loc. 22, Fig. 4 a, b), to the north of the town of Tetela del Volcán (Loc. 15 and Loc. 48) and in the Barranca San Juan Amecac (Loc. 118).

B) **Confined channel-fill facies dominated by dilute pyroclastic density current deposits**. This facies is characterized by layers composed of medium gray ash and medium to dark gray dense lava fragments and reddish altered clasts. In general, the size of the components is fine to medium ash, but enriched levels of fine lapilli can be found. This facies is observed as an alternation of layers of ash and fine lapilli-sized lava fragments with marked parallel stratification and layers composed of medium to fine lapilli-sized lava fragments. Lapilli-rich levels are clast-supported. It is also possible to distinguish levels enriched in massive gray ash without stratification with scattered lapilli-sized lava fragments. The layers present sedimentary structures such as parallel, laminated, cross-laminated, lenticular, and channeled stratification. This facies can be seen very well in the Barranca La Ixtla in Metepec (Loc. 36) and San Juan Amecac in Puebla (Loc. 118), where it can have thicknesses above 6 m (Fig. 5).

C) **Unconfined interfluve and upland facies.** 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, Fig. 6 a). The blast deposit that we associate with this facies occurs in unconfined areas or areas topographically higher than the channel facies [interfluve facies; Belousov, 1996]. This facies is 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 facies. This layer is clast-supported and exhibits diffuse parallel stratification. The upper layer is enriched in ash, with the presence of lapilli sized subangular gray lava fragments (Fig. 6 b and c). This layer is massive with no apparent stratification. A characteristic of the upper layer is that disseminated charcoal can be found. This facies can present thicknesses in the order of 47 cm at 3.2 m in the towns of Tetela del Volcán, Alpanocan and Hueyapan (Loc. 71, 72, 116 and 148). Deposits associated with this facies can be found on the slopes of the hummocky geomorphology formed by the debris avalanche deposits (Fig. 6a).

The general textural and structural characteristics of the deposits related to the three facies show in figures 7 and 8. Deposits related to the confined channel-fill facies have been located throughout the study area (Fig. 7 a-d), for example in localities located in the state of Morelos such as Ocoxaltepec (Loc. 22), 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 the state of Puebla. The characteristics of the deposit are similar, with the greatest thicknesses found in the state of Puebla. Figure 7 e-f shows deposit characteristics associated with the confined channel-fill facies associated with dilute PDC observed at locality 138 (Xochitlan, Morelos) and 118 (Barranca de San Juan Amecac, Puebla). Finally, Figure 8 shows deposits associated with the unconfined interfluve and upland facies; this facies can be observed in outcrops located around the towns of Tetela del Volcán, Alpanocan (Fig. 8a) and to the south and east of Hueyapan (Fig. 8b).

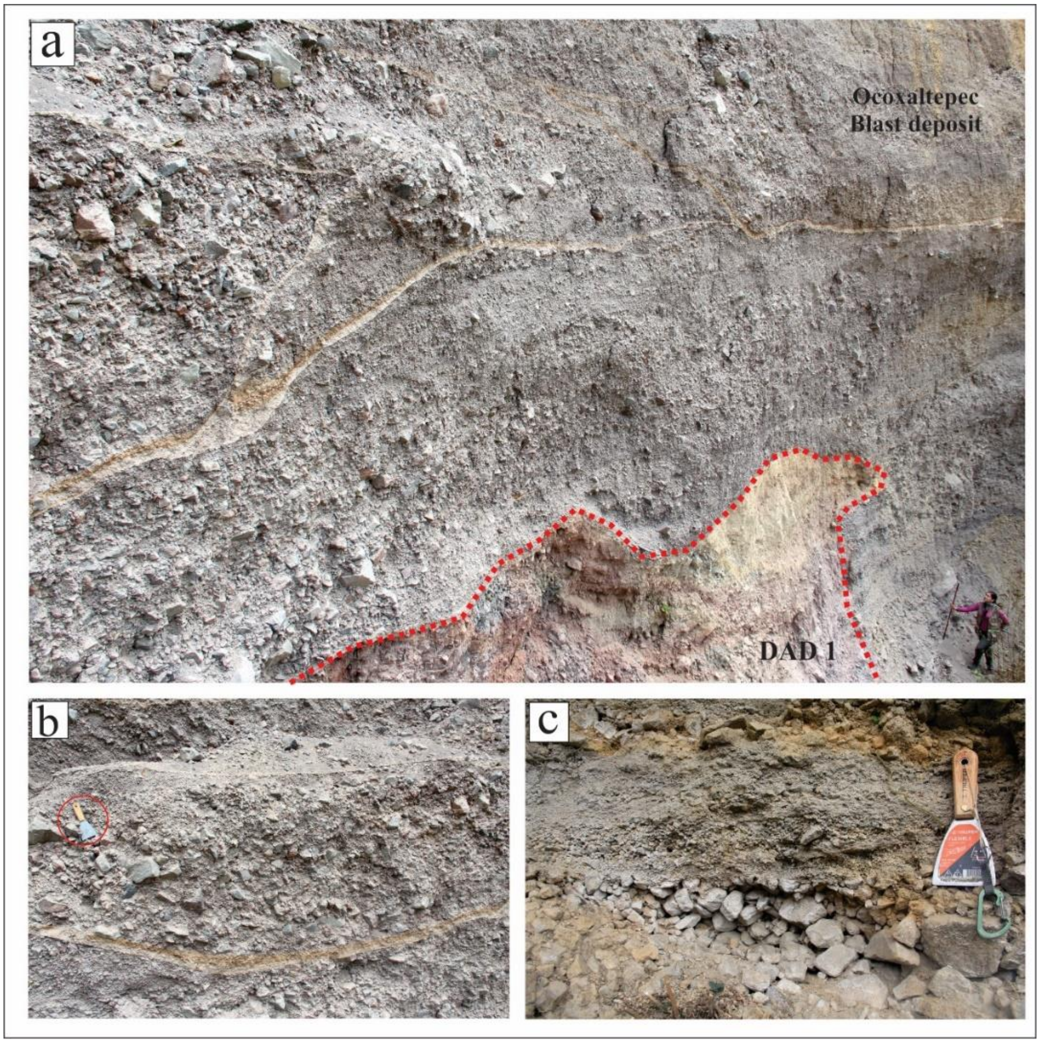

Figure 4. Confined channel facies dominated by concentrated PDC. (a) Blast deposit erosively overlying the DAD 1 debris avalanche deposit (Loc. 22). (b) Layer of irregular thickness composed of coarse material up to blocky lapilli size, bounded by thin ochre-coloured laminated layers (Loc. 22). (c) Lens composed of dense lava fragments; clast-supported with absence of matrix (Loc. 52).

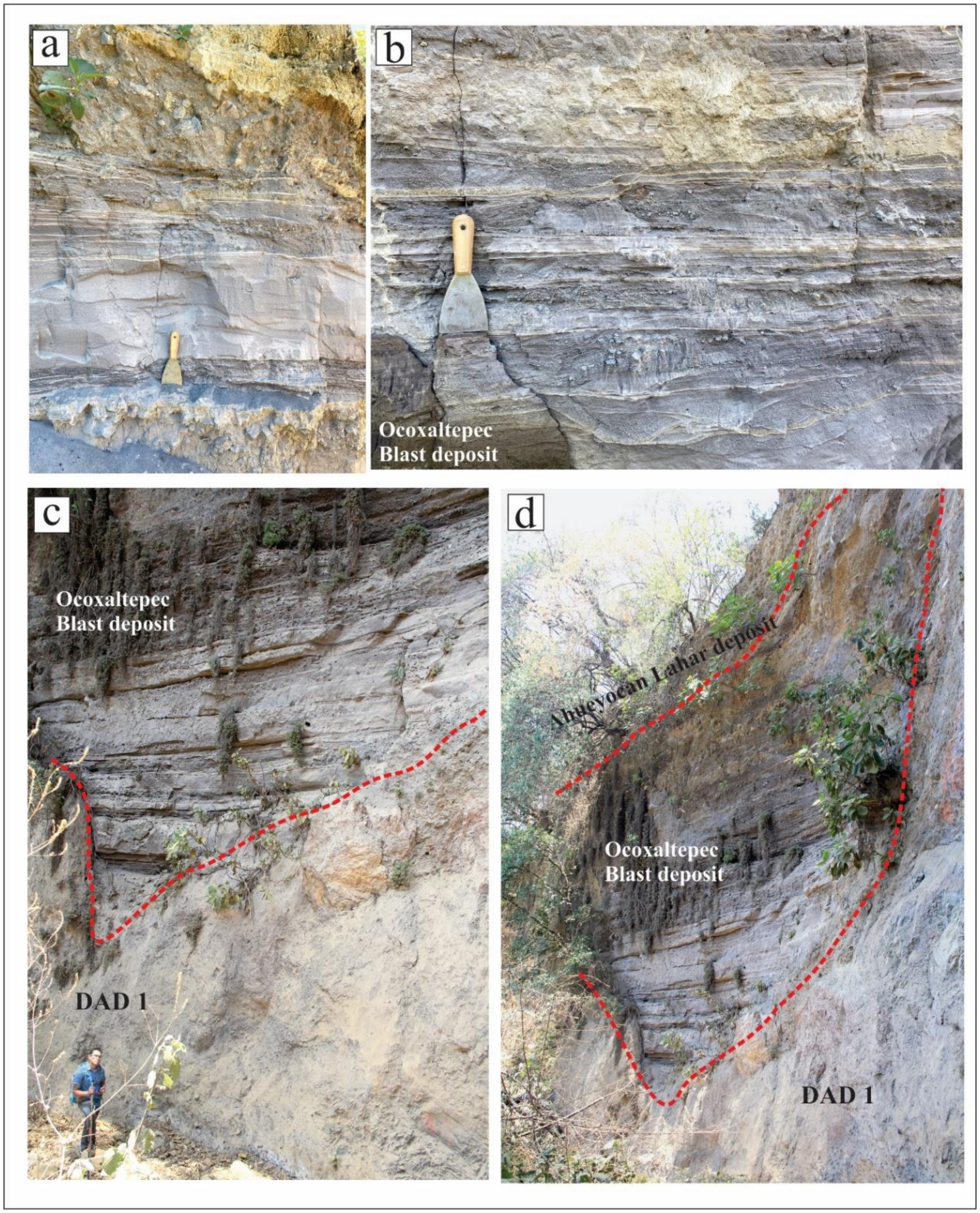

Figure 5. Confined channel facies dominated by dilute PDC. These facies can be clearly observed at localities 118 (a and b) in the Barranca of San Juan Amecac, state of Puebla and at locality 36 in the Barranca La Ixtla, state of Morelos (c and d).

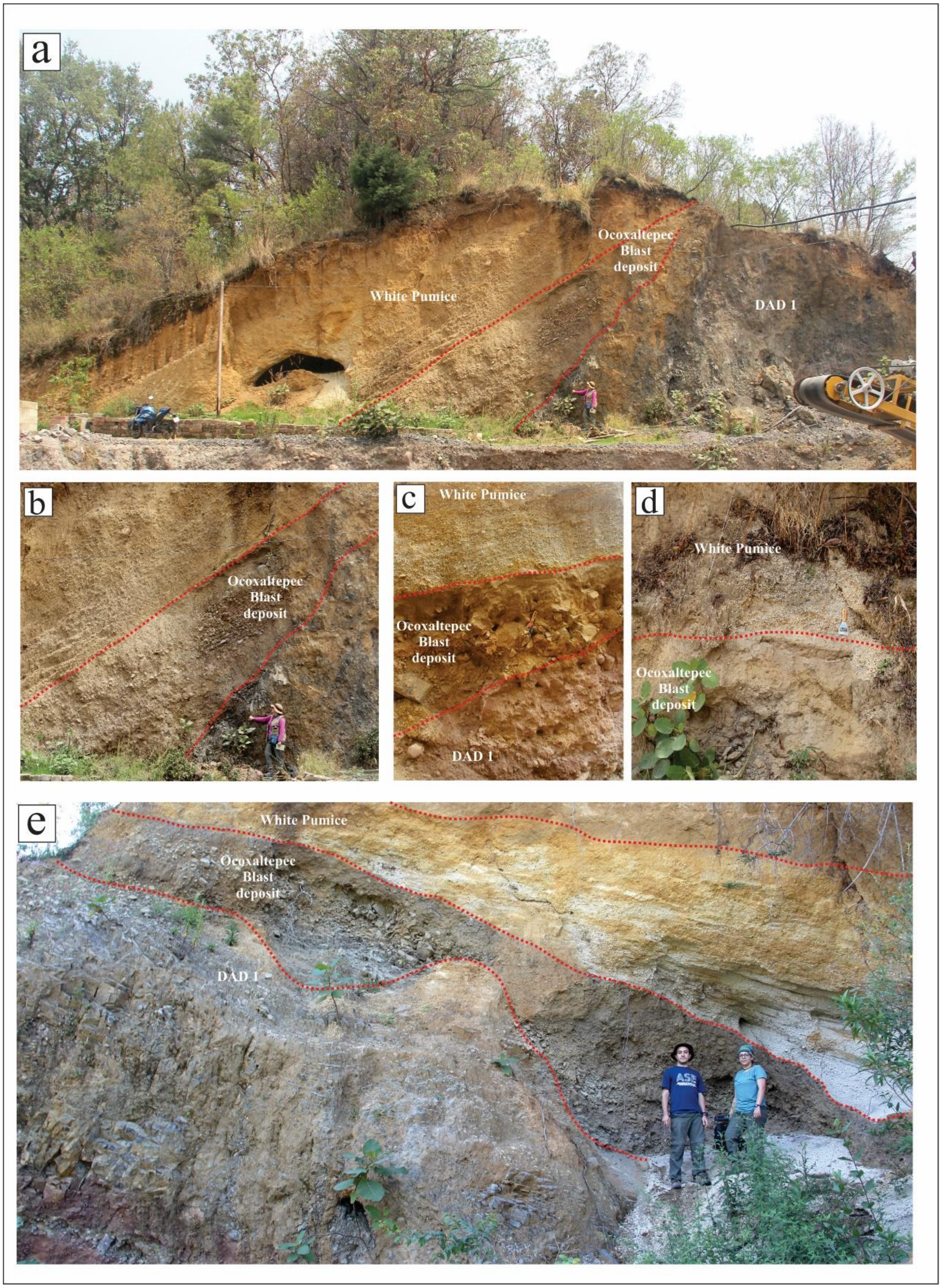

Figure 6. Unconfined interfluve and upland facies. (a-b) construction material extraction mine in Hueyapan (Loc. 71), at this point the deposit is 3.2 m thick. (c) At locality 72 the deposit is distinguished by two layers, one enriched in lava blocks and the other in ash with disseminated charcoal. (d) Outcrop at locality 104 in Tetela del Volcán, the contact of unconfined facies 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.

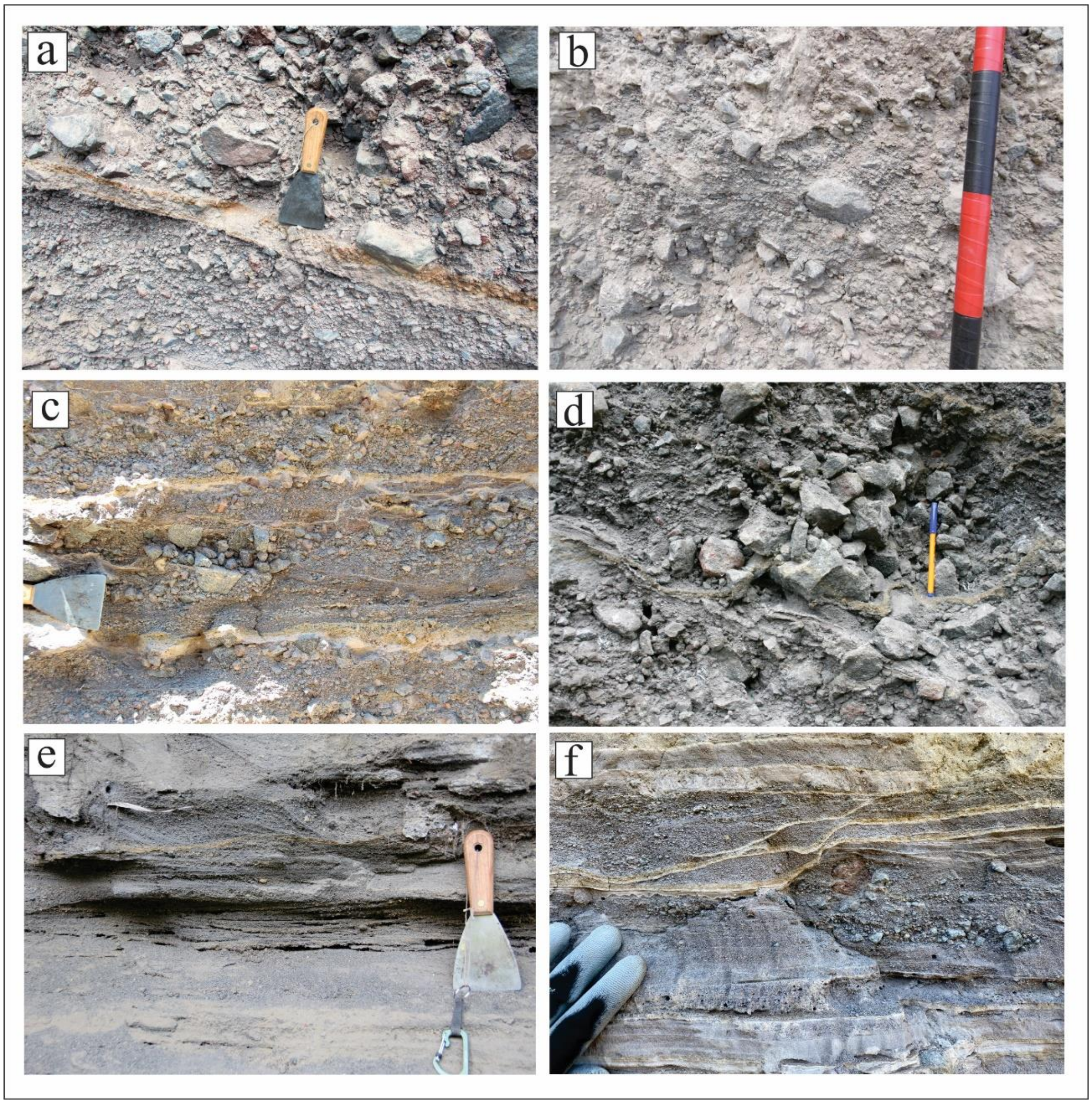

Figure 7. Textural and structural characteristics of deposits associated with channelized channel-fill facies. (a-d) Deposits associated with channel facies dominated by concentrated PDC, from locality 22 (a) on the borders of the State of Mexico and Morelos to locality 131 in the state of Puebla (d). (e-f) deposits associated with confined channel-fill facies dominated by dilute PDC.

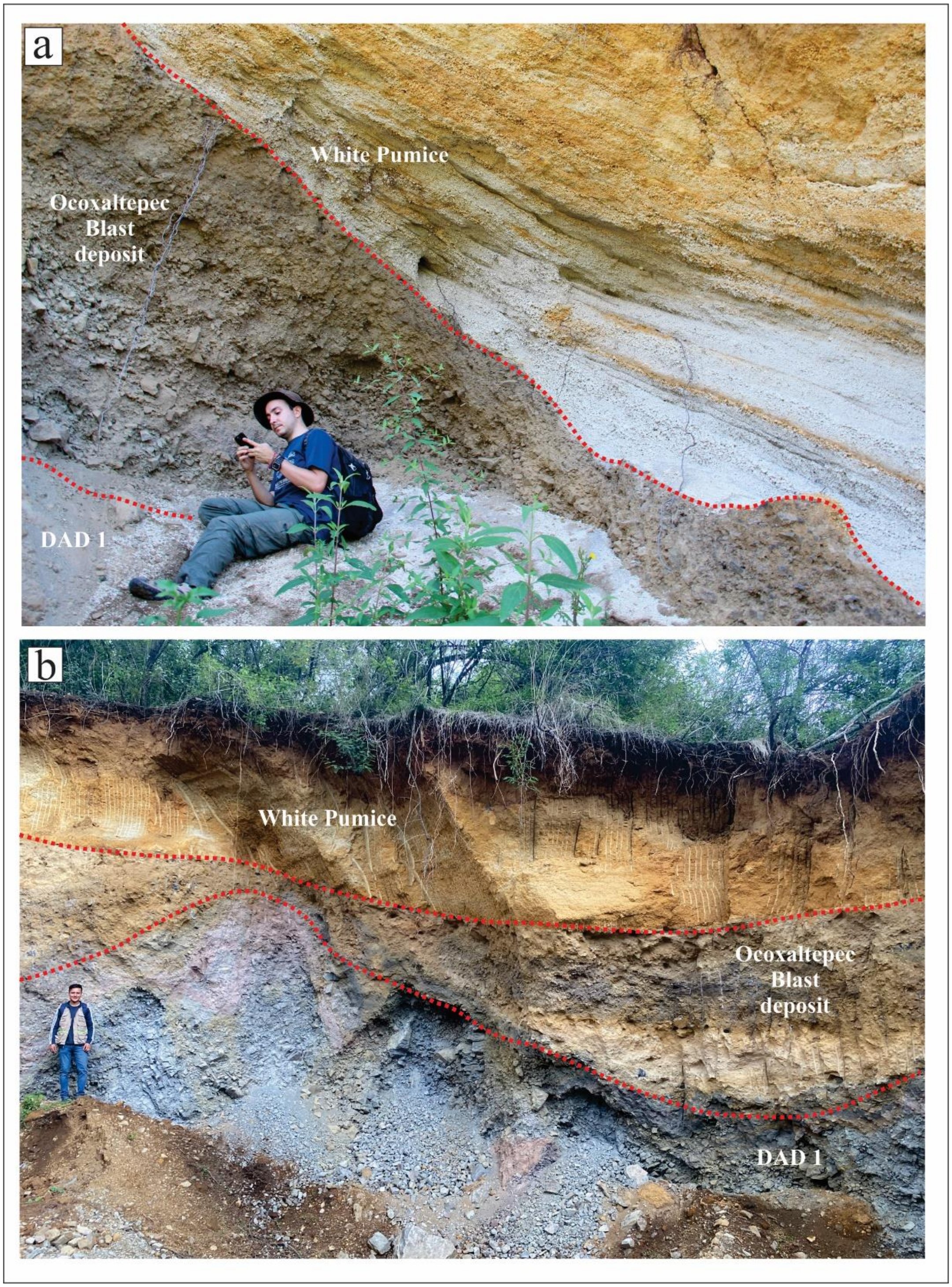

Figure 8. Textural and structural characteristics of the deposits associated with the unconfined interfluve and upland facies. (a) Outcrop located SW of the town of Tetela del Volcán, Loc. 148. (b) Outcrop located S of the town of Hueyapan, Loc. 122. Note the very irregular contact between the debris avalanche deposit and the blast deposit.

4.3 Stratigraphic relationships and correlation of the Ocoxaltepec Blast deposit

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) (Fig. 9). 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 (Fig. 9 a and b). In the field, it was possible to observe at Loc. 15 and 117 (Fig. 1) injections of the blast deposit into the debris avalanche deposit, with a structure like a clastic dike (Fig. 9 a and b). These structures can be tens of centimeters to a few meters long (Fig. 9 a and b) 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 and continuous (Fig. 9 c-e). 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 deposits in confined channel-fill and unconfined interfluve and upland facies (Fig. 10 y 11). Figure 10 shows the stratigraphic sections and the correlation we determined between the deposits associated with the confined channel-fill facies along the study area, including three sections described previously by Siebe et al. [1995, 2017], two of them with dates obtained by the C14 radiometric dating technique. We perform the correlation of blast deposit from the locality of Ecatzingo in the state of Mexico in the SW sector [Ecatzingo section, Siebe et al., 1995] to the Barranca San Juan Amecac in the state of Puebla (Loc. 118) in the S sector. Figure 11 shows the stratigraphic sections and the correlation of the blast deposits associated with unconfined interfluve and upland facies. In each of the sections the distance in km to the volcano crater is included.

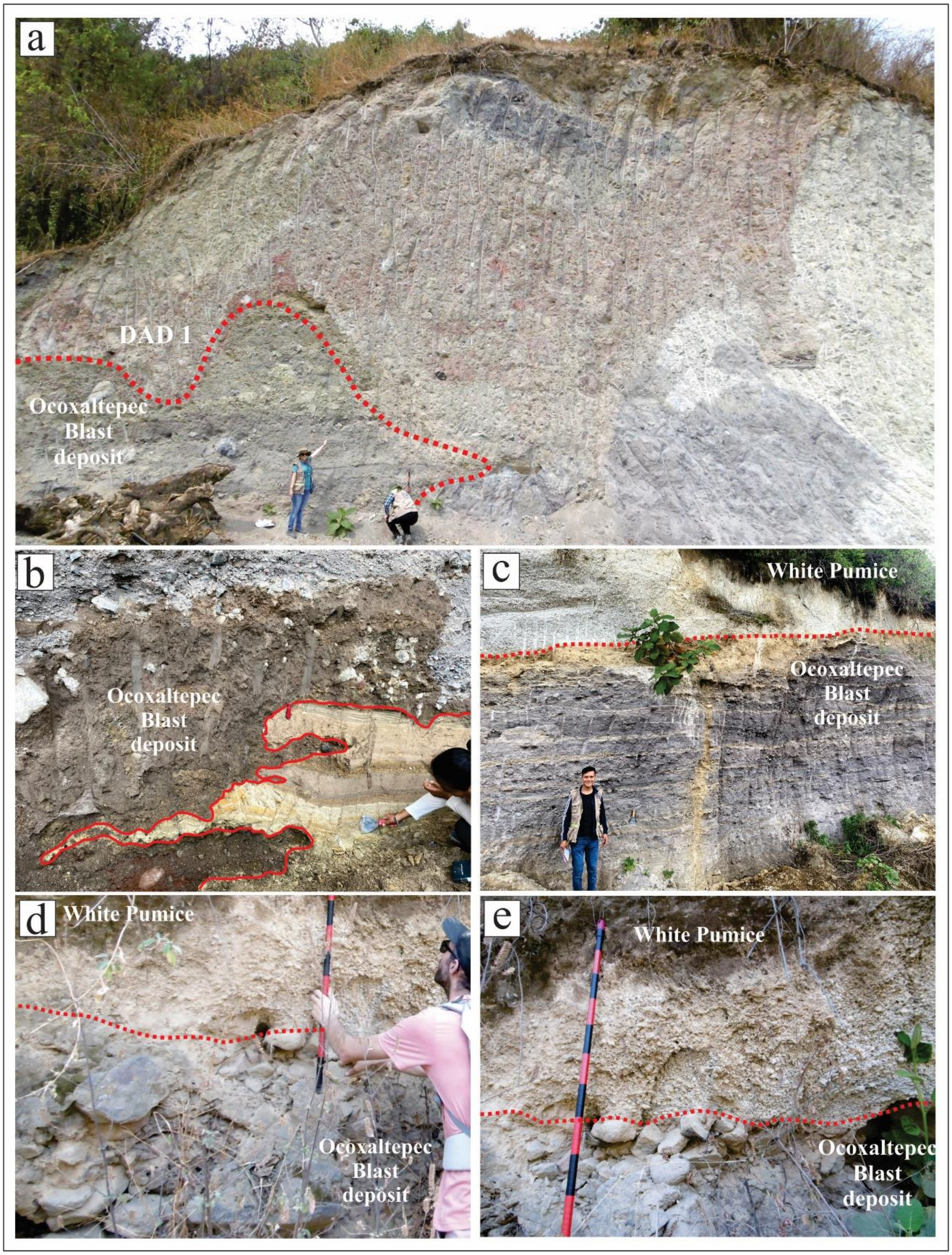

Figure 9. Contact of the Ocoxaltepec Blast deposit with the debris avalanche deposit and pumice fall deposit. (a-b), Erosional contact of the blast deposit on the debris avalanche deposit and on a PDC deposit, showing clastic dike intrusion of blast deposit into other deposits. (c) Locality 117 in the town of Hueyapan, upper contact between the blast deposit and the White Pumice. (d-e) Locality 3, contact between the blast deposit (block-enriched) and the White Pumice deposit.

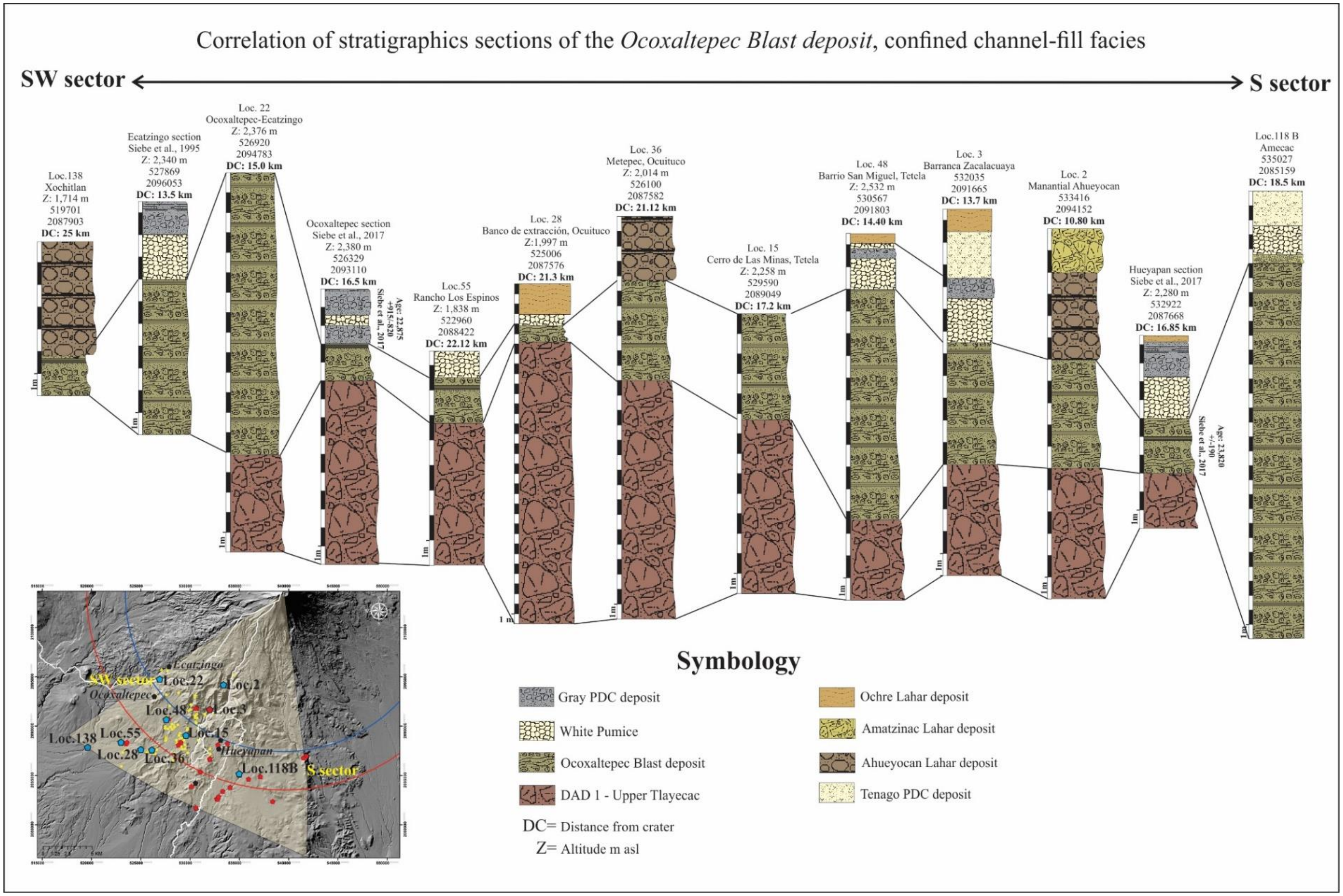

Figure 10. Stratigraphic sections and correlation of the Ocoxaltepec Blast deposit associated with the confined channel-fill facies. The blue pentagons on the map show the location of the sections.

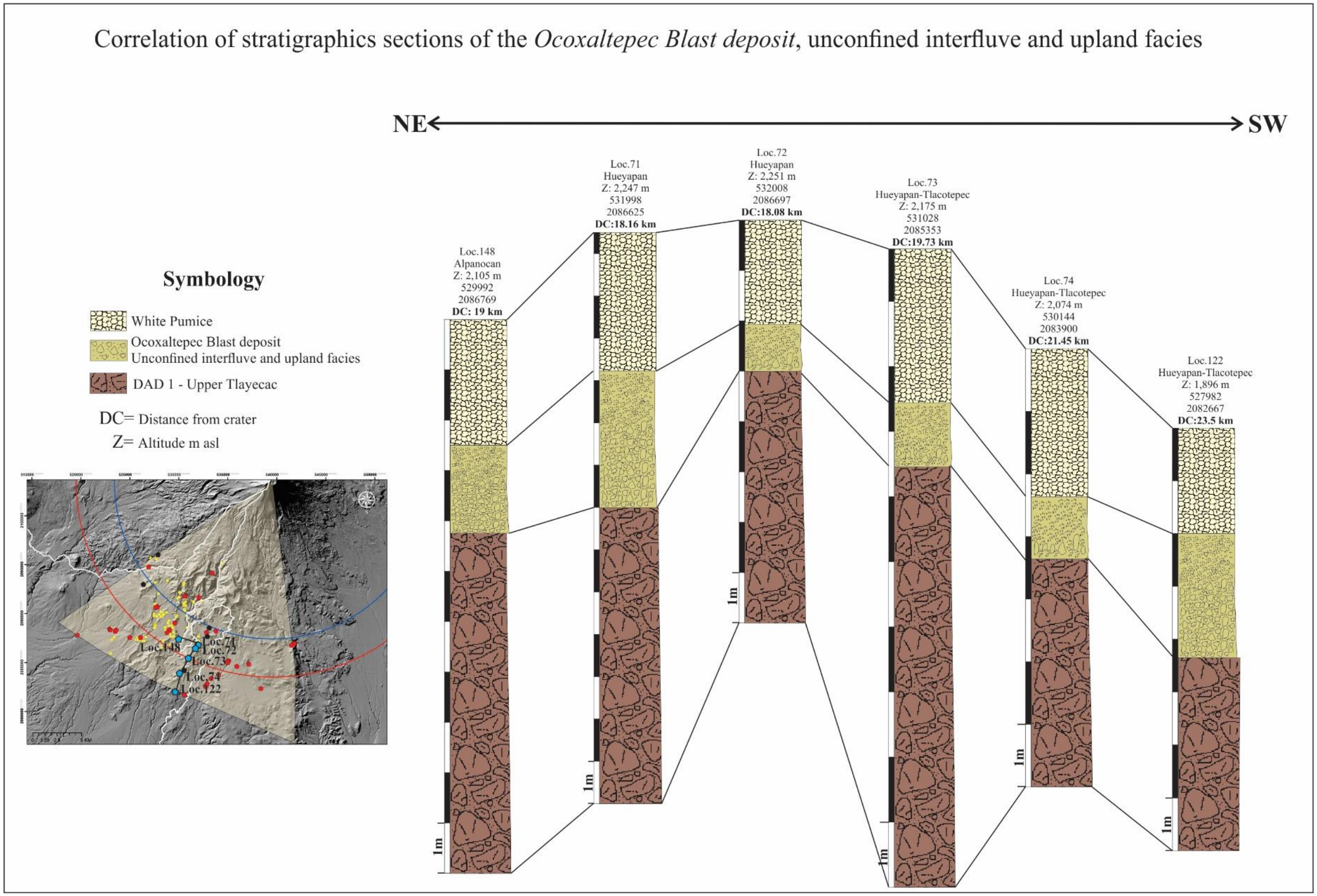

Figure 11. Stratigraphic sections and correlation of the Ocoxaltepec Blast deposit associated with unconfined interfluve and upland facies. The blue pentagons on the map show the location of the sections.

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. For this reason, direct observations, and detailed studies in the geological record of past eruptions are of great importance to understand the behavior of these very high energy phenomena. We were able to recognize three types of PDCs 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, sedimentary structures, textural, granulometric and compositional characteristics of the Ocoxaltepec Blast deposit observed in the outcrops and in the study area allowed us to differentiate it from secondary deposits. We preliminarily associate these PDCs with three facies: confined channel facies dominated by concentrated PDC, confined channel facies dominated by dilute PDC, and unconfined interfluve and upland facies.

The confined channel-fill facies that we describe resemble the valley facies described by Belousov [1996], where he describes that the deposits associated with this facies can have great thicknesses in 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 the state of Puebla, this thickness is associated with the confined channel-fill facies. In the study area, deposits related to the confined channel-fill facies can be tens of meters thick, as in the case of the blast deposit of the Bezymianny volcano, which is up to 50 m thick [Belousov, 1996]. 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 (Fig. 2), 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, layers with subrounded blocks with 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 confined channel-fill facies dominated by concentrated and dilute PDCs we observed in the contact between the debris avalanche deposit and the blast deposit clastic dike structures like those reported by Belousov [1996] and Belousov et al. [2007] for the Bezymianny volcano. 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) (Fig 12). This may indicate that in some sites this facies was deposited on the surface of the moving debris avalanche, and that both continued to move simultaneously for a short period of time before their final deposition [Belousov 1996; Belousov et al., 2007].

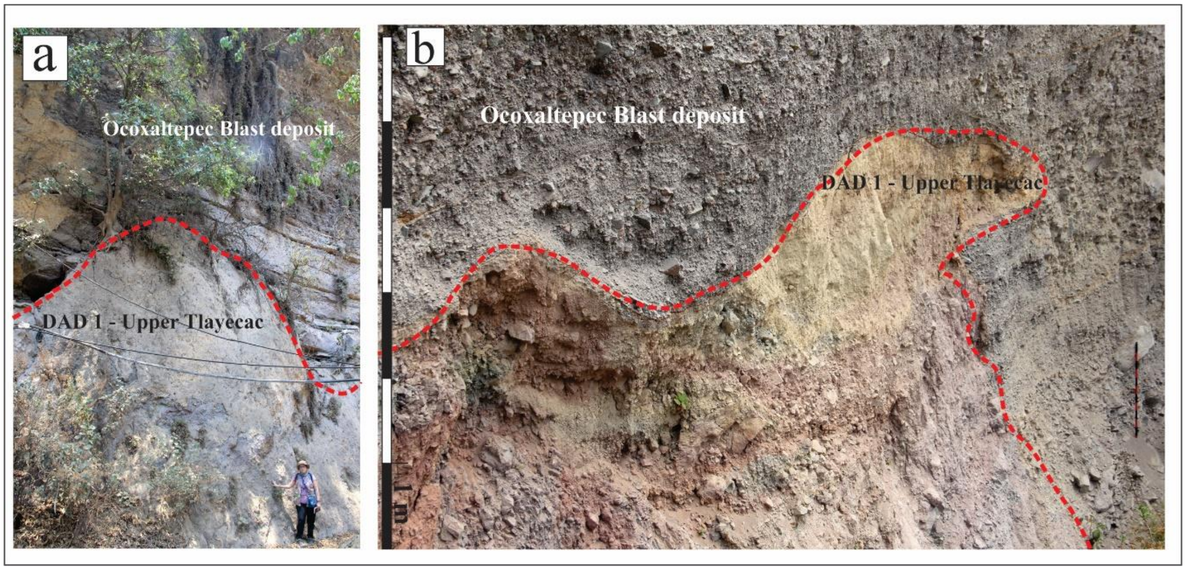

Figure 12. (a) Location 36, Barranca La Ixtla, abrupt and erosive contact between the debris avalanche deposit and the blast deposit. (b) Locality 22, contact between the debris avalanche deposit and the blast deposit which is very erosive. Here the blast deposit is inside the debris avalanche deposit.

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]. Directed blasts from their source tend to cover a very wide area and are largely unaffected by topography or channel confinement [Belousov et al., 2007]. Near the source, directed blast velocities can reach 150 m/s [Mt. St. Helens 1980; Esposti Ongaro et al., 2011] and typically more than 90 m/s [Cole et al., 2015]. Therefore, from a hazard point of view, these PDCs can have a large impact on the environment. 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]. This results in a wide range of effects on humans and the built and natural environment [Lerner et al., 2022].

In this work we report 41 new outcrops of the Ocoxaltepec Blast deposit that allowed us to preliminarily estimate a possible area affected by the directed blast, which has an area of 338 km^2 (Fig. 1). The greatest thicknesses of the blast deposit are in canyons or stream channels directly associated with the confined channel-fill facies, 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 facies 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 the state of Morelos. In contrast, the farthest outcrop of the blast deposit related to the confined channel-fill facies dominated by dilute PDC was located 25 km from the crater, at locality 138, located in Xochitlan, municipality of Yecapixtla in the state of Morelos. With the new data, we were able to make a comparison of the Popocatépetl volcano blast (Fig. 13) with the eruptions of the Bezymianny (1956), St. Helen (1980) and Soufrière Hills (1997) volcanoes, 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.

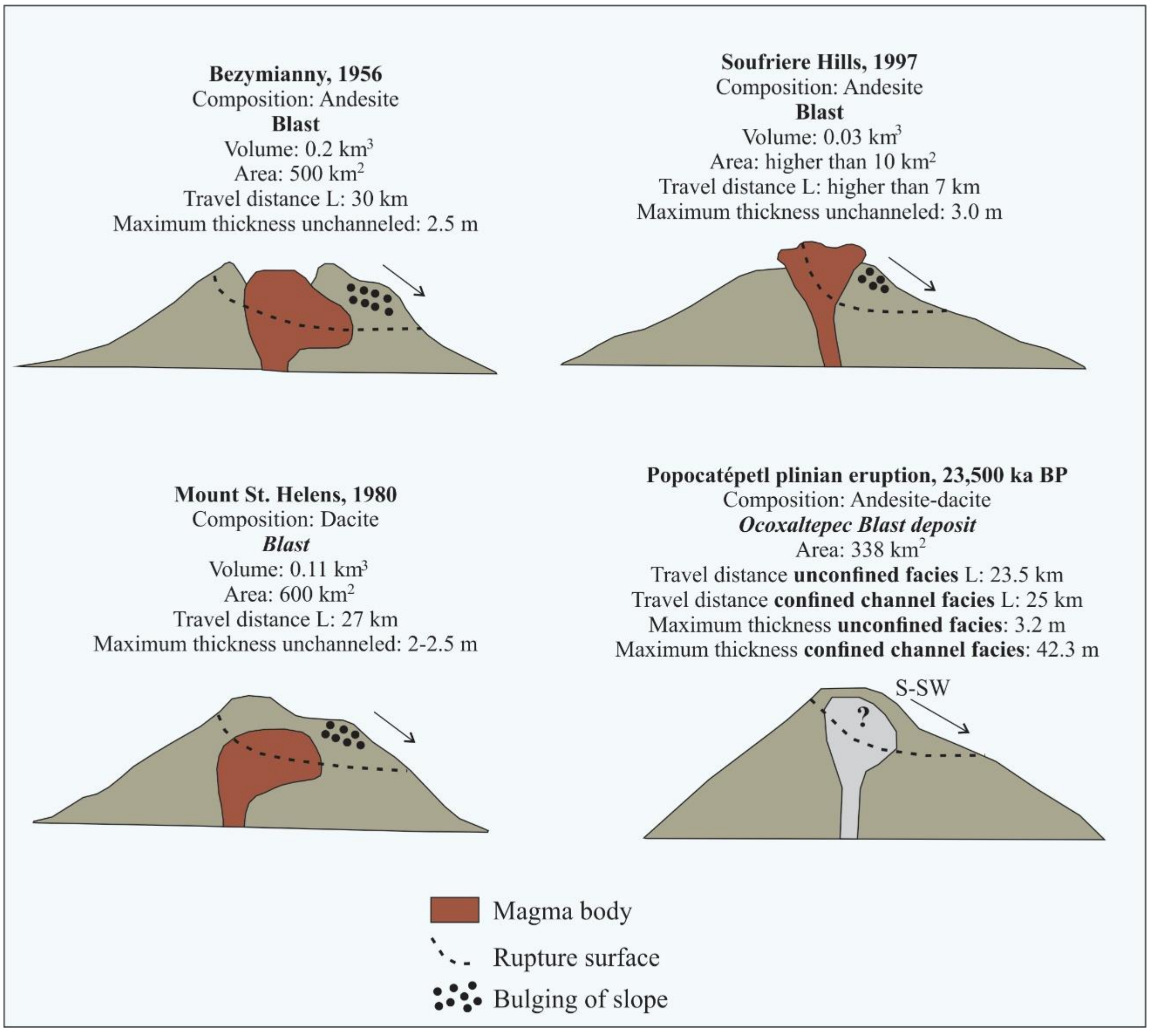

Figure 13. Comparative sketches with directed blast data from Bezymianny, Soufrière Hills, and St. Helens volcanoes [modified from Belousov et al., 2020]. Blast data from the 23,500 ka BP Popocatépetl volcano are also presented. The position of the magmatic body or cryptodome of the Popocatépetl volcano is uncertain.

As can be seen in Figure 14, twenty-nine of the new outcrops associated with PDC of directed blast are outside the danger polygon associated with concentrated PDC of the Popocatepetl volcano related to a Plinian eruption associated with the lowest probability of occurrence [CENAPRED, 2016]. A comparison between the areas that make up the polygon of lowest probability for PDCs and the area we have estimated for blast dispersion would correspond to an area of 211.2 km^2 located outside the polygon of lowest probability for PDCs in a Plinian eruption. The preliminary area where we have found the Ocoxaltepec Blast deposits is located between the municipalities of Ecatzingo (State of Mexico) and Atzitzihuacán (state of Puebla), where more than 58,987 people live [INEGI, 2020]. These population inhabits an area of 32.11 km^2 within the impact zone of the directed blast eruption. 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 the Popocatépetl volcano and are located on deposits related to the eruption of 23,500 ka BP. Finally, it is important to continue carrying out detailed geological and stratigraphic studies of active volcanoes because this will provide new evidence of their eruptive history, fundamental information for understanding their behavior and one of the bases for updating volcanic hazard maps.

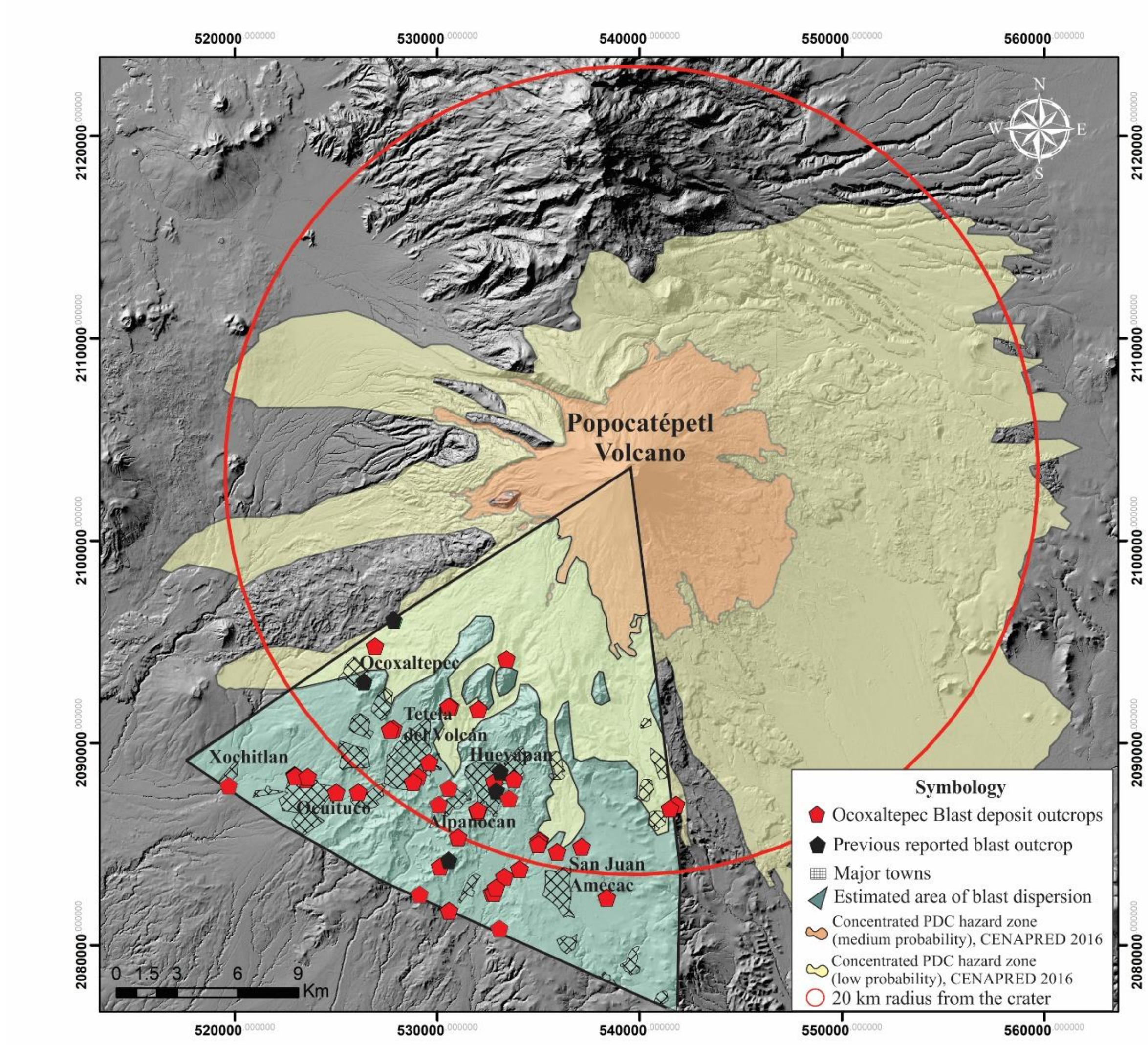

Figure 14. Polygons of the PDC hazard zone of Popocatepetl volcano (CENAPRED, 2016) and the sites (red pentagons) where we have found outcrops associated with the 23,500 ka BP directed blast eruption.

Author contributions

All authors declare no competing financial interests. MLB conceived the original idea of the work and was in 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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