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Research article

Tectono-stratigraphic basin evolution in the Tehuacán-Mixteca highlands, south western México

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ABSTRACT

The morphological evolution of the basins in the Sierra Madre del Sur (SMS), southern México is poorly understood. This work explains for the first time the geomorphological development of the tectonic, fluvially-interconnected SMS basins named San Juan Raya (SJRb) and Zapotitlán (ZAPb). The evolution of the SJRb and ZAPb are analysed within the context of the transformations of the well-studied Tehuacán basin (TEHb). A new interpretation of a series of tectonic features of the TEHb valley area is also presented. Published geological data and extensive field work provided the basis for our geomorphological and evolutionary interpretation of basin evolution of this part of Mesoamerica during the late Cenozoic. Stratigraphic and sedimentary records suggest that after the late Cretaceous-early Cenozoic orogeny the TEHb and ZAPb were closed basins, and that the TEHb graben system was activated during the Paleogene as a response to the dominant regional NW-SE trending faults. We propose that the ZAPb and SJRb formed sequentially during the Neogene as a result of new E-W, N-S and NE-SW faults. The continuation of the TEHb extension during the Oligocene widened its lowland area and allowed the formation of an extensive lake. No alluvial or fluvial records of this interval are found in the ZAPb and SJRb. No sedimentation rather than formation and subsequent erosion of such sediments is supported by the basin morphology and by the absence of re-worked alluvial deposits at the outlet area where both connect to the TEHb. By middle to late Miocene the TEHb lost its endorheic configuration, ending the lake-type deposition while new faults initiated the opening of the ZAPb. Intensive tectonics, alluvial deposition and the confinement of the Tehuacán lake to the north sector of this basin characterised the Pliocene. During the late Pliocene to the early Pleistocene the formation of the SJRb was initiated. Quaternary faulting related to basin extension along the north watershed of the SJRb and ZAPb is supported by independent data on the biogeography of the cactus *Mammillaria pectinifera*. We introduce the idea that the departure from the regional NW-SE fault alignment that formed the major Miocene basins to a more local E-W trend that formed Neogene-Quaternary basins was probably a response to the latest post-orogenic relaxation of the crust in the Mixteca terrane.

1. Introduction

Most of southern México is formed by the Sierra Madre del Sur (SMS) geologic province (e.g. de Cserna, 1989; Figure 1), and yet the geomorphological evolution of its basins has been poorly investigated. The SMS is the southernmost expression of the late Cretaceous to Paleogene orogeny that created extensive cordilleras along the western margin of the North American plate, including the Rocky Mountains and the Basin and Range province (Bird, 1998; Nieto-Samaniego et al., 2006). North of the Trans-Méxican Volcanic belt the tectonic structures and sedimentary sequences of the later provinces have been studied intensively, providing good insights into the development of orogenic belts and the internal and surface processes involved in syn- and post-orogenic basin evolution (e.g. Stockli et al., 2003; DeCelles, 2004; Fosdick and Colgan, 2008; Wallace et al., 2008). Additionally, these studies have improved the understanding of the origins of the modern landscape of those highland settings. In contrast, because earlier studies on the SMS have focussed on the main pre- and syn-orogenic events, questions about the mechanisms that have

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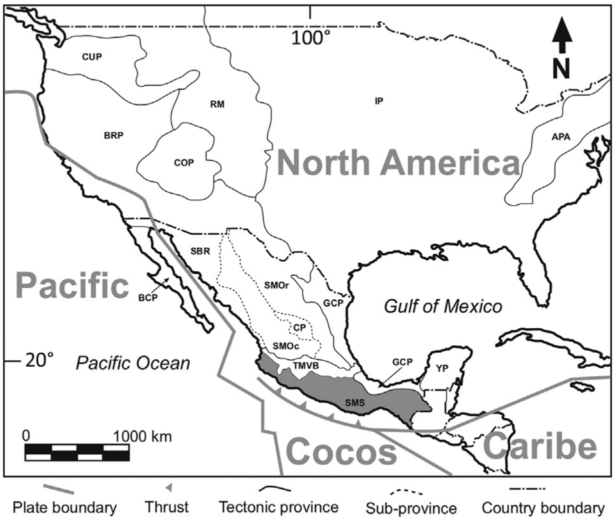

Figure 1. The Sierra Madre del Sur (*SMS*) province within the context of other Cenozoic orogenic belts formed along the southern edge of the North American plate, plus the older Appalachian range (*APA*) and the Neogene-Quaternary Trans-Mexican Volcanic Belt (*TMVB*). The Basin and Range Province (*BRP*), Colorado Plateau (*COP*), Columbia Plateau (*CUP*), Rocky Mountains (*RM*) and Interior Plains (*IP*) are drawn according to http://geomaps.wr.usgs.gov/parks/province/. The southern half of the BRP is sub-divided into Sonora Basin and Range (*SBR*), Sierra Madre Oriental (*SMOr*), Sierra Madre Occidental (*SMOc*) and the Central Plateau (*CP*), as indicated by dotted lines. The Gulf Coastal Plain (*GCP*) and the Yucatan Peninsula (*YP*) are also shown.

governed the morphology and environmental transformations of the Neogene intramontane basins of this province remain unresolved.

This work aims to provide a better understanding of the morphotectonic evolution of three interconnected Cenozoic Tehuacán–Mixteca basins, testing the applicability of the four-step evolutionary model of intramontane basin development proposed by De Vicente et al. (2011). The origin and evolution of the San Juan Raya and Zapotitán basins (SJRb and ZAPb respectively) had not been investigated before. The absence of Tertiary sedimentary rocks within the SJR and ZAP basins makes the evolutive reconstruction particularly challenging. The detailed geological mapping produced for over a century of research (Aguilera, 1896), their contrasting sizes, morphology and stratigraphy provided key information on geomorphic evolution-related processes that differ in scale and nature. Moreover, those three basins are the home of one of the most biodiverse arid ecosystems of the world (Dávila et al., 2002), and have been a diversity hot spot since the Palaeogene (Ramírez-Arriaga et al., 2017). The geomorphological context in which such biological richness developed has been poorly investigated; a problem that is being addressed in this work.

Because geophysical data for these basins are not available, studies on the shallow and surface geology and geomorphology are the only means to reconstruct their evolution. The only previous attempts to address how the geomorphology of modern basins has evolved in the SMS are found in works dealing with regional fault kinematics (Silva-Romo et al., 2000, 2018) and partially discussed in a study of the activity of the major Oaxaca fault (Dávalos-Álvarez et al., 2007). A study of the geometry, fault trends and stratigraphy of intramontane basins in the SMS can provide useful information on long-term regional tectonic processes that could potentially help to better understand the forces in operation in the deeper crust. The present and a recent study which describes the regional fault alignment pattern and the formation of basins in the SMS within the context of inter-plate interactions (Silva-Romo et al., 2018) add to the idea that a geomorphological approach can also be used to link surface features with tectonic trends (Pazzaglia et al., 2007).

The present work introduces a new model of the origin and evolution of the JSR and ZAP basins during the late Cenozoic and their relationship with the evolution of the TEH basin (Section 7). Such a model is based primarily on our geomorphological interpretation of the SJR and ZAP basins, extensive verification fieldwork and two radiocarbon dates. Published tectonic and geological structures were also utilised to frame the model. We interpreted, from a geomorphological perspective the main pre-Quaternary geological units and features reported in geological maps. The broad tectonic evolution of the TEH basin has been the subject of previous works (Dávalos-Álvarez et al., 2007; Silva-Romo et al., 2018) but its detailed geomorphological evolution has not been explained. Here we provide a new interpretation of the tectonic significance of the tufa outcrops distributed along the central valley of the THE basin, and in doing so we address the Quaternary geomorphological evolution of this major basin. One of the tufas was radiocarbon dated and the results discussed. Significantly, an earlier study on molecular biology provided an independent chronological reference for particular geomorphic processes (Cornejo-Romero et al., 2013), an approach not used before in the geological literature.

2. Geographical context

San Juan Raya and Zapotitlán are two medium-sized basins (128 and 270 km^2 respectively) of the Mixteca highlands, both draining to the prominent TEHb (7,165 km^2, Figure 2), making their combined areas the largest basin system in southern México. This region is characterised by steep mountains and valleys varying from poorly defined alluvial flats to kilometre-wide plains. The TEHb is bordered by the Mixteca and Mazateca mountains. All basins are contained within the main Papaloapan basin, which connects them with the Gulf of México. The west edge of the SJRb marks the continental divide and the boundary with the Balsas basin, which drains to the Pacific Ocean. The climate is semi-arid with summer rains, averaging 276 mm/yr and 24.7 °C mean annual temperature (Valiente, 1991).

3. Pre-cenozoic geological setting

The SMS highlands are made of tectonostratigraphic terranes, which are defined as joint, fault-bounded, deep Palaeozoic blocks of independent sedimentary and tectonic history (Figure 3A; Ortega-Gutiérrez, 1978; Sedlock et al., 1993; Keppie, 2004). Structurally the SJRb and ZAPb are part of the Mixteca terrane and located on the border with the Oaxaca terrane, which hosts most of the TEHb. The Caltepec and Oaxaca faults are the boundaries between the Mixteca and Oaxaca and Juarez terranes, respectively. Both originated during the Palaeozoic and have experienced activity until the Quaternary (Dávalos-Álvarez et al., 2007; Elías-Herrera et al., 2007). The oldest Palaeozoic rocks are grouped into the metamorphic Acatlán and Oaxaca complexes, basal groups of the Mixteca and Oaxaca terranes respectively (Ortega-Gutiérrez, 1978; Sedlock et al., 1993). These complexes resulted from the deformation of pre-existing marine rocks (Yañez et al., 1991; Ortega-Gutiérrez et al., 1999). Such deformation ended by the early Permian giving rise to the Matzitzi Formation (Sedlock et al., 1993; Centeno-García et al., 2009). The terrestrial plant fossils of the Matzitzi rocks are evidence of a phase of continentality and a rapid change that prevented deposition, leaving a hiatus in the area of the Acatlán and Oaxaca terranes. Part of the Triassic and Jurassic in the Oaxaca terrane is a hiatus (Figure 3). The Matzitzi rocks are covered unconformably by alluvial and fluvial conglomerates hosting metamorphic clasts of the older Acatlán complex (Calderón-García, 1956; Morán-Zenteno et al., 1993; Centeno-García et al., 2009). Middle-upper Jurassic shale, conglomerates and limestone account for a change to a coastal environment (Sedlock et al., 1993; Omaña and González-Arreola, 2008).

Most of the highlands around the TEHb are Cretaceous limestone (Figure 3B), whereas the valley area exposes a more complex variety of continental rocks formed since the Eocene (Figure 4). Dominant outcrops in the ZAPb and SJRb and immediate surrounding areas are early to late Cretaceous (Aguilera, 1896). Sandstone and lutite form the San

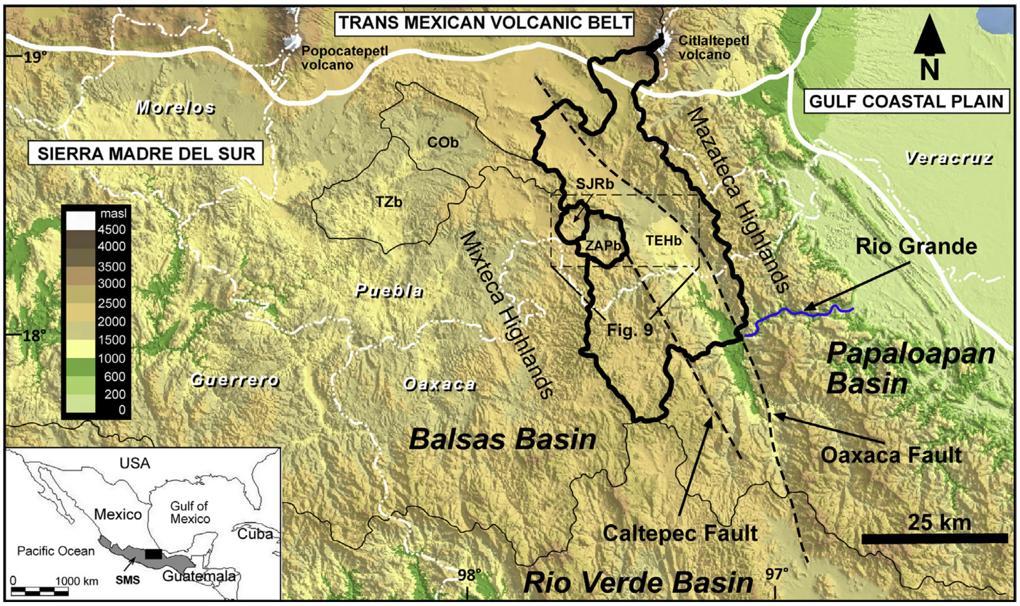

Figure 2. Geographical location of the Tehuacán (TEHb), Zapotitlán (ZAPb) and San Juan Raya (SJRb) within the SMS highlands, showing other Cenozoic basins also referred in the text: Coatzingo Basin (COb) and Tehuitzingo basin (TZb). White dotted line shows state boundaries. Background DEM and basin boundaries reproduced from "Simulador de Flujos de Agua de Cuencas Hidrológicas V 2.1-INEGI" (http://antares.inegi.org.mx/analisis/red_hidro/SIATL/).

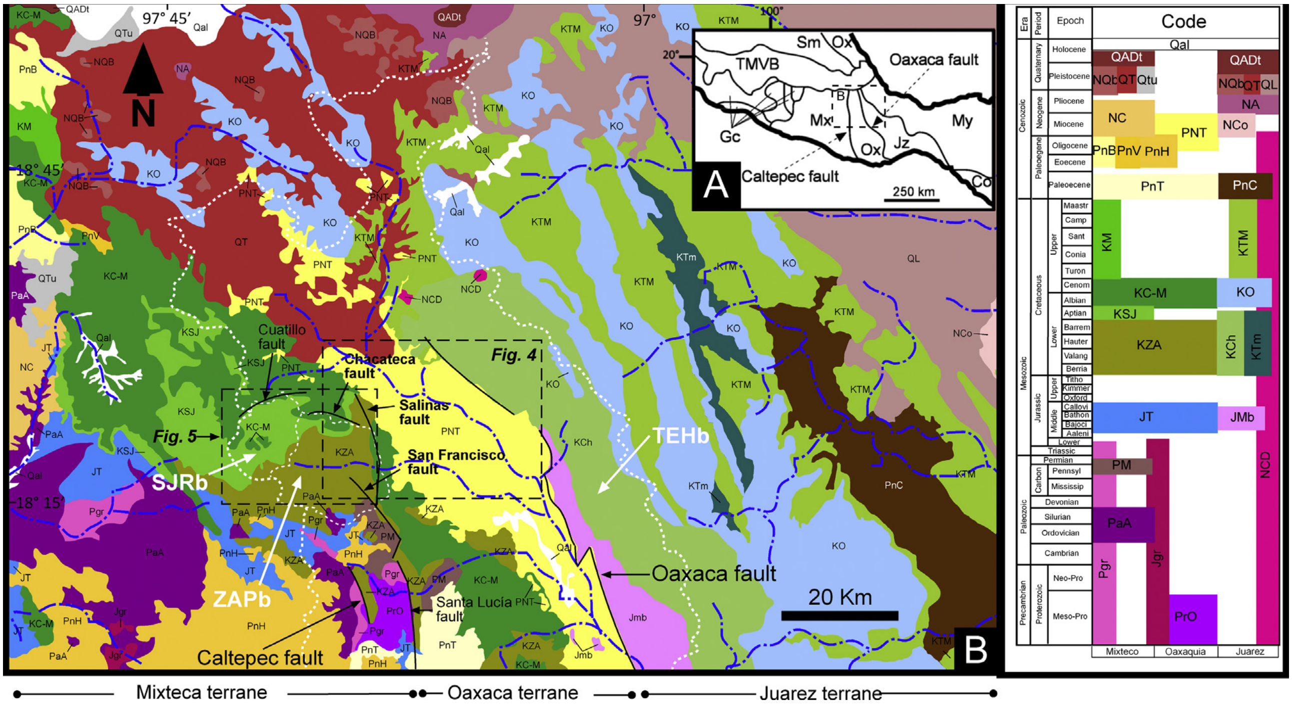

Figure 3. Simplified map of the regional geology of south-central México from Martínez-Amador et al. (2001). A: Structural terranes that form continental southern México according to Keppie (2004). The *SMS* is formed by the Guerrero Composite terrane (*Gc*), Mixteca (*Mx*), Oaxaca (*Ox*) and Juarez (*Jz*) terranes. The nearby Trans Mexican Volcanic Belt (*TMVB*), Sierra Madre (*Sm*), Maya (*My*) and Chortis (*Co*) terranes are also outlined. B: Summarised geology of the north sector of the SMS re-drawn from Martínez-Amador et al. (2001), and location of the *SJRb*, *ZAPb* and *TEHb*-white dotted line. *PrO*: multi-deformed basal Oaxaca complex; *PaA*: Acatlán basal metamorphic complex; *PM*: continental sedimentary Matzitzi Fm; *Pgr*: granite Caltepec and Totoltepec formations; *Jgr*: anatexis lower Jurassic granite; *JT*: sandstone and andesitic tuff, Tecomazuchil Fm; *JMb*: mylonitic belt; *KZA*; lutite-limestone, Zapotitlán Fm; *KCh*: sandstone, Chivillas Fm; *KTm*: lutite-limestone Tamaulipas Fm; *KSJ*; lutite-sandstone, San Juan Raya Fm; *KC-M*: limestone Cipiapa/Miahuatepec Fm; *KO*: limestone-dolimite, Orizaba Fm; *KM*: lutite-sandstone Mezcala Fm; *KTM*: tite-limestone, Maltrata, Mendez and Atoyac Fm; *PnT*: Tamazulapan Fm; *PnC*: lutite-sandstone Chicontepec Fm; *PnB*: conglomerates-sandstone Balsas Fm; *PnV*: limestone-conglomerates Pie de Vaca Fm; *PnH*: andesitic tuf-sandstone, Huajuapan Fm; *PNT*: conglomerates-travertine (tufa), Tehuacán Fm; *NCD*: monzonite-diorite; *NC*: conglomerate-andesitic tuff, Cuayuca Fm; *NCo*: sandstone-conglomerate; *NA*: andesite; *NQb*: basalt; *QT*: andesitic tuff-andesite; *Qtu*: travertine (tufa); *QL*: lahar; *QADt*: andesitic-dacitic tuff; *Qal*: alluvial. Dash-dot lines indicate main drainage.

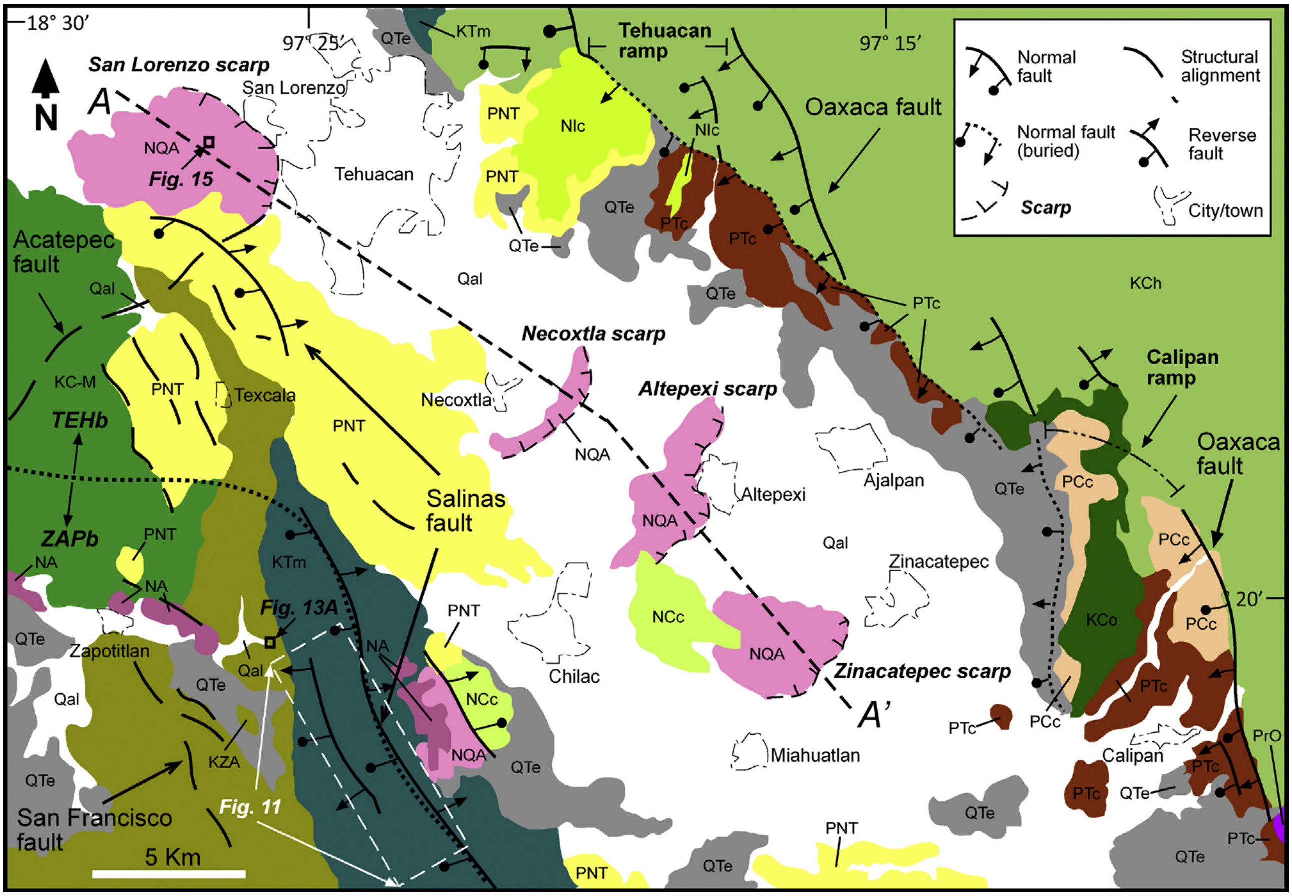

Figure 4. Geology of the central part of the Tehuacán basin modified from Dávalos-Álvarez et al. (2007). KZA: Zapotitlán Fm, (the stratigraphic position of the sub-members Agua del Burro [KZAb] and Agua del Cordero [KZAc] are shown in Figure 6 and their distribution in Figure 5); KSJ: San Juan Raya Fm; KCh: Chivillas Fm; KCo: Cerro Colorado conglomerates; KTm: Tamaulipas Fm; KC-M: Cipiapa (Miahuatepec) Fm; PTc: Tilapa red beds; PCc: Campanario conglomerates; PNT: Tehuacán Fm; NA: Atzingo Fm-andesite; NIc: San Isidro conglomerates; NQA: lacustrine Altepexi Fm; NQI: Neogene-Quaternary lacustrine; NCc: Coyoltepec conglomerates; QTe: Teotitlán conglomerate; Qal-QaIII: Late Quaternary unconsolidated alluvial deposits. Stratigraphic position of the post-Palaeozoic lithological units are presented in Figure 6. Names and codes of the pre-Mesozoic units as in Figure 3. The fault scarps along the valley zone are named after the closest locality. The A-A′ transect correspond to the cross section in Figure 16.

Juan Raya Fm, which occupies most of the area of the SJRb, whereas limestone of the Zapotitlán Fm covers most of the ZAPb (Figure 5). Both Formations are overlain by up to 600 m of limestone, formed during the last marine phase in pre-orogenic southern México (Figure 6). These last rocks were initially described and named Cipiapa Fm (Calderón-García, 1956; González-Arreola, 1974; Buitrón and Barceló-Duarte, 1980), but were later mapped as Miahuatepec (Figure 3) and more recently as undifferentiated Upper Cretaceous by Dávalos-Álvarez et al. (2007). The original name Cipiapa will be used hereafter to refer to this Formation.

4. Cenozoic geodynamics in south-central México

The orogeny in southern México started with the compression of the pre-Cenozoic rocks at the western margin of the North America plate and migrated eastwards to finish near the eastern limit of the SMS. Although the inter-plate interactions that caused this orogeny have been debated (Campa and Coney, 1983; Nieto-Samaniego et al., 2006; Cerca et al., 2007), there is consensus concerning the main intra-continental effects. Firstly an E-W contraction of the early Cretaceous marine rocks that commenced during the Coniacian (~88 Ma) to the west margin of the Mixteca-Oaxaca block and migrated eastwards, reaching the western part of Veracruz State during the earliest Paleogene (Nieto-Samaniego et al., 2006; Cerca et al., 2007). Secondly, a weaker shortening between the Palaeocene and earliest Eocene and gentle folding and clockwise rotation of the pre-deformed structures caused by transpressional left-lateral faults aligned in a general N-S trend (Cerca et al., 2007). Thirdly, an early Eocene to middle Oligocene shift of the shortening trend to the NE-SW and strike-slip fault activity (Nieto-Samaniego et al., 2006). Finally, a change from contraction to a NE-SW extension from the middle Eocene until middle Miocene (Nieto-Samaniego et al., 2006). Across the SMS the main faults formed during the contractional phases are perpendicular to the shortening, leaving roughly NW-SE structural alignments (Figure 7), most of which define the potential trend of the Cenozoic basin extension. An example is the half graben of the TEHb, formed by extension of the NW-SE Oaxaca fault. The post-orogenic dynamic is considerably less well understood.

5. Post-orogenic basin formation in the north Tehuacán-Mixteca area

5.1. Palaeocene-oligocene post-orogenic basin formation: TEHb

The NW-SE-oriented faults created during the late Cretaceous-early Cenozoic compression (Section 4) favoured the opening of tectonic continental basins during the late Palaeogene, from west to east (Silva-Romo et al., 2018). The main formative period of these basins spanned from 36 to 16 Ma (Silva-Romo et al., 2018). In the Tehuacán area faults showing this trend, like the Oaxaca, Caltepec and Santa Lucía had normal activity during the late Palaeocene (Elías-Herrera et al., 2005; Dávalos-Álvarez et al., 2007). During the Eocene and Oligocene other

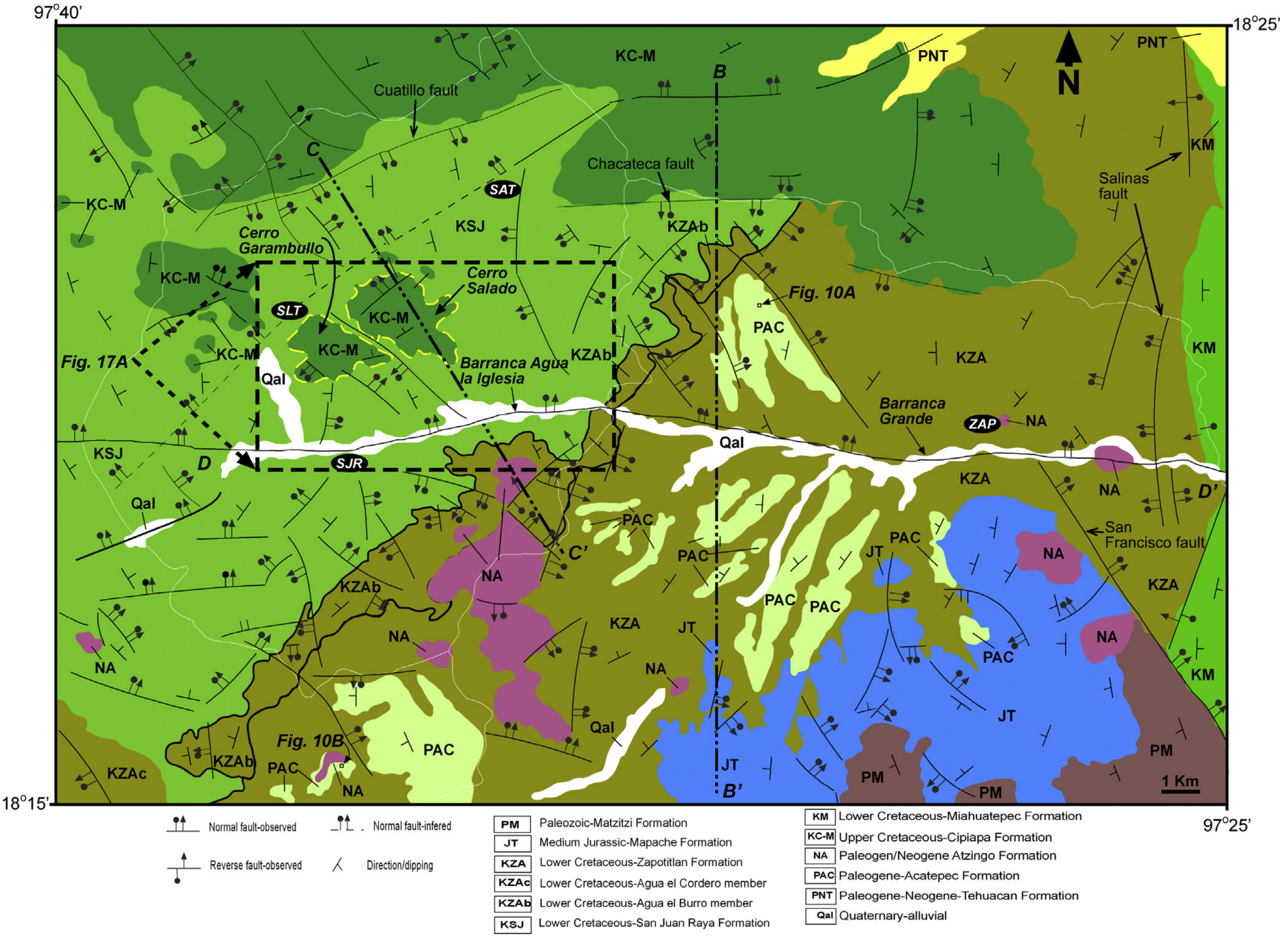

Figure 5. Geological map of the ZAPb and SJRb, modified from Buitrón and Barceló-Duarte (1980). The stratigraphic position of the lithological units for both basins are shown in Figure 6. The Zapotitlán de las Salinas (ZAP), San Juan Raya (SJR), Santa Ana Teloxtoc (SAT) and San Lucas Teteletitlán (SLT) towns are also indicated. The Cerro Salado and Cerro Garambullo tectonic klippes are outlined. Location of the B-B′ (Figure 12), C-C′ (Figure 14) and D-D′ (Figure 13) transects and the approximate area of Figure 17A (dashed rectangle) are also indicated.

basins (i.e. Coatzingo, and Tehuitzingo) were formed to the northwest of the TEHb (Figure 2) as pull-apart basins (Pantoja-Alor, 1990; Silva-Romo et al., 2000, 2018), suggesting a more widespread pattern of basin opening, guided by NNW-SSE trending faults.

The extension of the TEHb was the product of the Cenozoic inversion of the Oaxaca fault (Nieto-Samaniego et al., 2006). The activity of the Oaxaca fault produced the subsidence in the TEHb in three main phases (Dávalos-Álvarez et al., 2007). In the first synorogenic phase (late Palaeocene to early Eocene) the Tilapa red beds were formed as the earliest continental deposits (Figures 4 and 6). It is possible that these conglomerates were deposited in a relatively narrow fringe left during compression, before the TEHb graben was fully developed. At the same time, the west side of the SMS was still under a compressive and shearing regime (Nieto-Samaniego et al., 2006; Cerca et al., 2007). Later, northwards development of the Oaxaca fault probably caused a considerable widening of the TEHb as well as partial erosion of the Tilapa red beds in most of this sector. This could explain why the Eocene formations are constrained to smaller outcrops at the northeastern and southwestern margins (Figure 4 this work and Figure 2 in Dávalos-Álvarez et al., 2007). Fluvial Eocene (43 +/- 1.2 Ar/Ar Ma) rocks have been reported west of the Caltepec fault (Cerca et al., 2007), as well as lake deposits of the Chilapa Fm deposited in a fault-delimited closed basin, the age of which has been assigned to between 35.5 and 29 Ma (Santamaría-Díaz et al., 2008).

According to Dávalos-Álvarez et al. (2007) the second and third episodes of the TEHb opening were caused by the northward expansion of the Oaxaca fault (middle Eocene to early Oligocene). The development of the Tilapa and Calipan fault ramps (Figure 4), was followed by the establishment of shallow lake conditions. The expansion of that fault reached the current location of the Tehuacán City during the Miocene. A significant hiatus is apparent in the TEHb from the middle Eocene until the middle Oligocene, with the exception of an isolated outcrop of the El Campanario Fm conglomerates (Dávalos-Álvarez et al., 2007). Closed basin-lake conditions were re-established by the late Oligocene, with the deposition of the Tehuacán Fm, constrained by ages of 27.1 +/- 0.7 (K/Ar) Ma (Nieto-Samaniego et al., 2006) and 16.4 +/- 0.5 (K/Ar) Ma in the upper part of the Fm (Dávalos-Álvarez et al., 2007). Spatially, these evaporites are widely distributed in the TEHb, particularly along the northwest sector (Figure 4).

The role of the Caltepec fault on the formation of tectonic basins is less clear. The Cenozoic activity of this fault included the downward displacement of the blocks at its west (Elías-Herrera et al., 2007), lateral movement during the late Eocene to early Oligocene and an episode of NE-SW extension during the Oligocene, between 26 and 29 Ma ago (Santamaría-Díaz et al., 2008). Neogene activity of the Caltepec fault, including Holocene events, has also been identified in the southern part of the ZAPb, near Los Reyes Mezontla town (Elías-Herrera et al., 2007) and was probably related to the Quaternary extension of the ZAPb and SJRb.

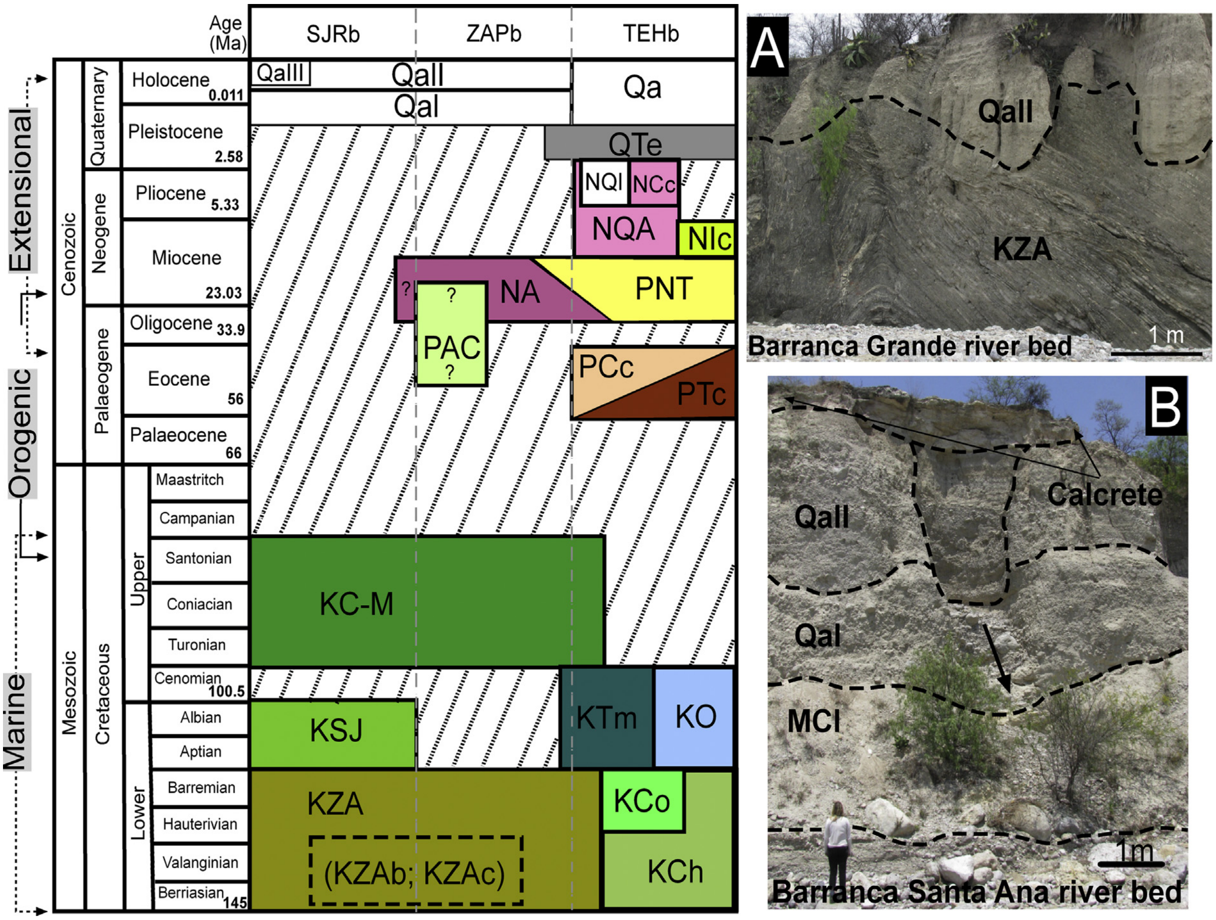

Figure 6. Post-Palaeozoic stratigraphy of the TEHb, ZAPb and SJRb and approximate chronologies for the different tectonic and environmental phases preserved in the sedimentary records. PAC: limestone-Acatepec Fm; see Figure 4 for other codes. A: Holocene QaII deposits resting directly on Cretaceous rocks which are faulted along the E-W Barranca Grande in the ZAPb. B: Pleistocene QaI surface exposed along the Barranca Santa Ana cuts in the SJRb; colluvial deposits (MCl) are forming at bottom part of the sedimentary section and at least two distinctive facies of alluvial deposition (QaII-QaIII) capped by a calcrete are shown. A karst-like form in the upper centre causes lateral erosion of the section. Absolute ages according to the International Stratigraphic Chart 2017 (http://www.stratigraphy.org).

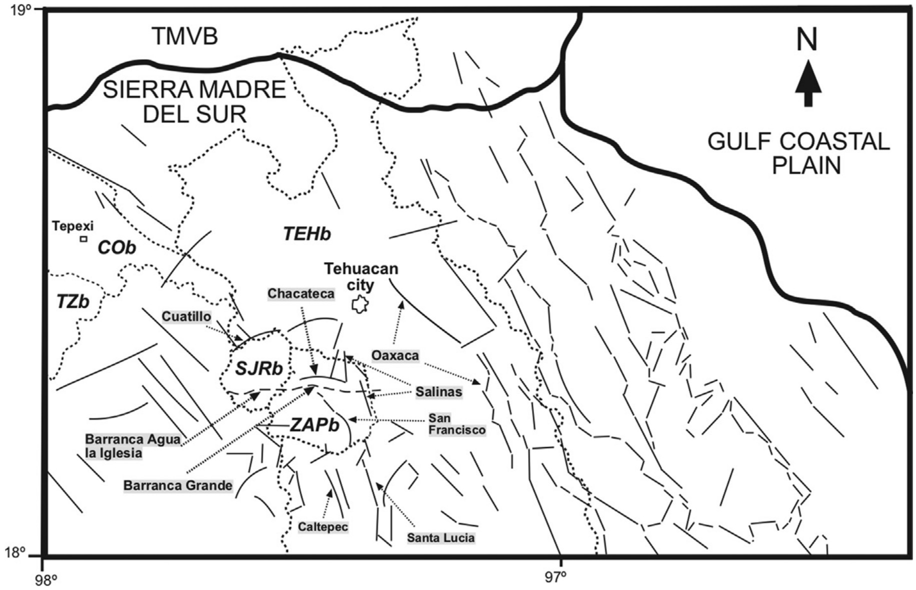

Figure 7. Simplified regional fault pattern of the north sector of the SMS, extracted from Martínez-Amador et al. (2001) and Dávalos-Álvarez et al. (2007) and supplemented with other local faults. Basin boundaries are indicated by dotted lines. Tehuacán and Tepexi cities are included for reference.

5.2. Oligocene-Miocene

By the early Miocene the TEHb was a developed endorheic tectonic basin and evaporites were forming. Barceló-Duarte (1978) indicated that the Acatepec Fm in the ZAPb area (PAC; Figures 5 and 6) was formed in a lake environment and that it correlates with the Tehuacán Fm because both had similar relations with older rocks (unconformably overlying the Zapotitlán Fm). Although stratigraphically the PAC Fm seems to date back to the Eocene, its lower age has not been accurately established. In the lithostratigraphic section described by Barceló-Duarte (1978) the upper limit of the Acatepec Fm is defined by andesitic rocks that have not been given an absolute age either. Other outcrops of andesite have been mapped in the ZAPb as part of the Atzingo Fm (NA, Figure 5). Dávalos-Álvarez et al. (2007) assigned a late Oligocene-middle Miocene age to the Atzingo rocks on the basis of similar Miocene andesite outcrops reported in nearby locations (Ferrusquilla-Villafranca, 1976; Morán-Zenteno et al., 1999), and on the fact that they also cover the Tehuacán Fm.

6. Materials and methods

To generate the new multi-basin evolution model introduced in Section 7, the modern geomorphology of the three basins was interpreted based on aerial photographs scale 1:20,000 (taken in 1997) and topographic maps scale 1:50,000 and 1:250,000 commercially produced by Instituto Nacional de Estadistica, Geografia e Informatica (INEGI). The geomorphological evolution was also interpreted from the spatial distribution and stratigraphic position of the main lithological units and structural features of the area, as identified in the geology maps Orizaba (Martínez-Amador et al., 2001) and Oaxaca González-Ramos et al., 2000, as well as from the maps in Dávalos-Álvarez et al. (2007), Mauvois (1977) and Buitrón and Barceló-Duarte (1980). All lithological units and pre-Quaternary stratigraphy in the model were taken from the above maps, except the QTe rocks and the Quaternary units in the SJRb and ZAPb which are identified here for the first time. The position and nature of the main landforms, lithological units and structural features were verified through several seasons of extensive fieldwork. To establish the stratigraphic position of key Quaternary features, a calcrete sample from the SJRb (18° 19′ 47″N, 97° 34′ 24″) and a tufa sample from the TEHb (18° 28′ 50″N, 97° 26′ 57″) were radiocarbon dated (Beta reports 302085 and 388912). The detailed Quaternary stratigraphy of the basins is part of a separate study and only the facies and basin areas that help explaining our model are presented here.

7. Results - model of basin evolution during the Cenozoic

7.1. Oligocene-Miocene post compression basin evolution (Figure 8A-B)

The sedimentary hiatus during the Miocene in the ZAPb may indicate a period of change in geomorphic setting and sedimentary conditions. According to the model presented in this work the ZAPb area could have had a different morphology because the graben had not yet been activated to create enough space to host sedimentary beds (Figure 8A). It is likely that after the termination of closed basin conditions (Acatepec limestone), the erosional processes in the relatively narrow basin channelised the sediments out of the ZAPb, preventing deposition. In the ZAPb the Acatepec rocks are part of the hanging wall, to the north of the normal fault that separates this outcrop from the San Sebastian Frontera-Acatepec basin. The formation (or re-activation) of this structure, as well as those cutting through the andesitic rocks, would have caused the dipping of the blocks and opening of the basin by extension. This interpretation favours a widening of the ZAPb by the extensional W-E faults during the Pliocene to Quaternary and the setting to a sedimentary basin morphology (Section 7.2).

Despite the uncertainties around its precise age (Section 5.2), the Acatepec Formation is of geomorphic significance because its calcareous nature means that the west part of the Zapotitlán area had a basin-type morphology during the Miocene, before a fully-developed TEHb graben. Such basin-type morphology could have been obtained during compression rather than for the activation of a graben because of the lack of evidence of faulting. The lack of connectivity between the Tehuacán and Acatepec Fms, and considering the minor thickness of the Acatepec rocks (~63 m) compared with the Tehuacán Fm (~225 m), support the hypothesis that the two basins hosted contemporaneous active lakes, separated by a highland bridge between the Cerro Grande and Cerro Chacateca (Figures 8A and 9). It can be noticed that the ZAPb lake was perhaps formed earlier (during shortening) and was short lived (Oligocene-Miocene boundary) compared to the TEHb lake. Dávalos-Álvarez et al. (2007) describe the lower and middle facies of the Tehuacán Fm as lake limestone with fine to medium-sized bedding, which coincide with the limestone nature of the Acatepec Fm (Figure 10). Upwards the Tehuacán Fm facies regress into evaporative deposits, reflecting a significant change to a drier environment, by which time the ZAPb lake had disappeared, ceasing sedimentation and preventing evaporite beds forming in this area.

It seems that during the Miocene the TEHb drainage extended to what is now part of the modern ZAPb. A discrete outcrop of the Tehuacán Fm is found near the border between the TEHb and ZAPb between 1,600 and 2,000 masl, and another one located 120 m above the modern valley floor of the ZAPb (Figure 4). This drainage connection between the TEHb and part of what is now the northeast part of the ZAPb during the early Miocene is consistent with the post-Oligocene quiescence of the Santa Lucía fault at its southern sector, as suggested by Elías-Herrera et al. (2007). Santamaría-Díaz et al. (2008) compared the stratigraphic relationships of the east and west sides of the Caltepec fault, south of the ZAPb area, and show a hiatus from the Miocene to the Pleistocene, which implies that tectonic extension in this area was not significant. The N-S faults bordering the ZAPb correspond to the north part of the Santa Lucía fault (Elías-Herrera et al., 2007); named Salinas and San Francisco faults in the ZAPb part respectively (Figure 3). Activity in these faults could have formed the ZAPb and connected it with the TEHb. However, there is no stratigraphic evidence of alluvial/fluvial activity during the Miocene in the ZAPb, indicating the absence of basin-type morphology. The TEHb Miocene lake extended westwards and the ZAPb was not formed as a separate tectonic basin until after the middle Miocene, when geomorphic conditions changed and the deposition of lake sediments in the TEHb under an endorheic regime ended (Figure 8A). The draining of most of the southern part of the Tehuacán lake was probably the result of the newly established fluvial connection with the system that directed the regional discharge to the Gulf Coastal Plain through the Santo Domingo river. Timing of fault activity in the proto-ZAPb area suggests that early activation of normal faults occurred during the Miocene, ending the endorheic geometry but not significant enough to give shape to a sedimentary basin and preventing the formation of recognisable sedimentary deposits.

During the early Miocene the sedimentary environment of the Acatepec Fm went through a final lacustrine phase because of the initiation of tectonics surrounding the ZAPb and the establishment of fluvial connectivity with the TEHb. By the late Miocene, as the activity of the Oaxaca fault continued to migrate northwards, the tectonic subsidence of the valley changed the endorheic setting in the TEHb, widening the catchment area and causing a major reduction of the lake size (Figure 8B). The Salinas fault separates the TEHb and ZAPb, perhaps participating in the opening of the former one (Figures 5, 9, and 11).

7.2. Pliocene shift of tectonic style: extension of the ZAPb (Figure 8C)

The faults that formed the ZAPb do not follow the NW-SE regional pattern of older basins in the Mixteca and Tehuacán regions (Section 5.1). On this basis we suggest that the ZAPb was formed by a new set of younger faults. The ZAPb was formed by N-S, NE-SW and E-W faults (Figure 12). The Cuatillo and Chacatea faults (Figure 5), part of the

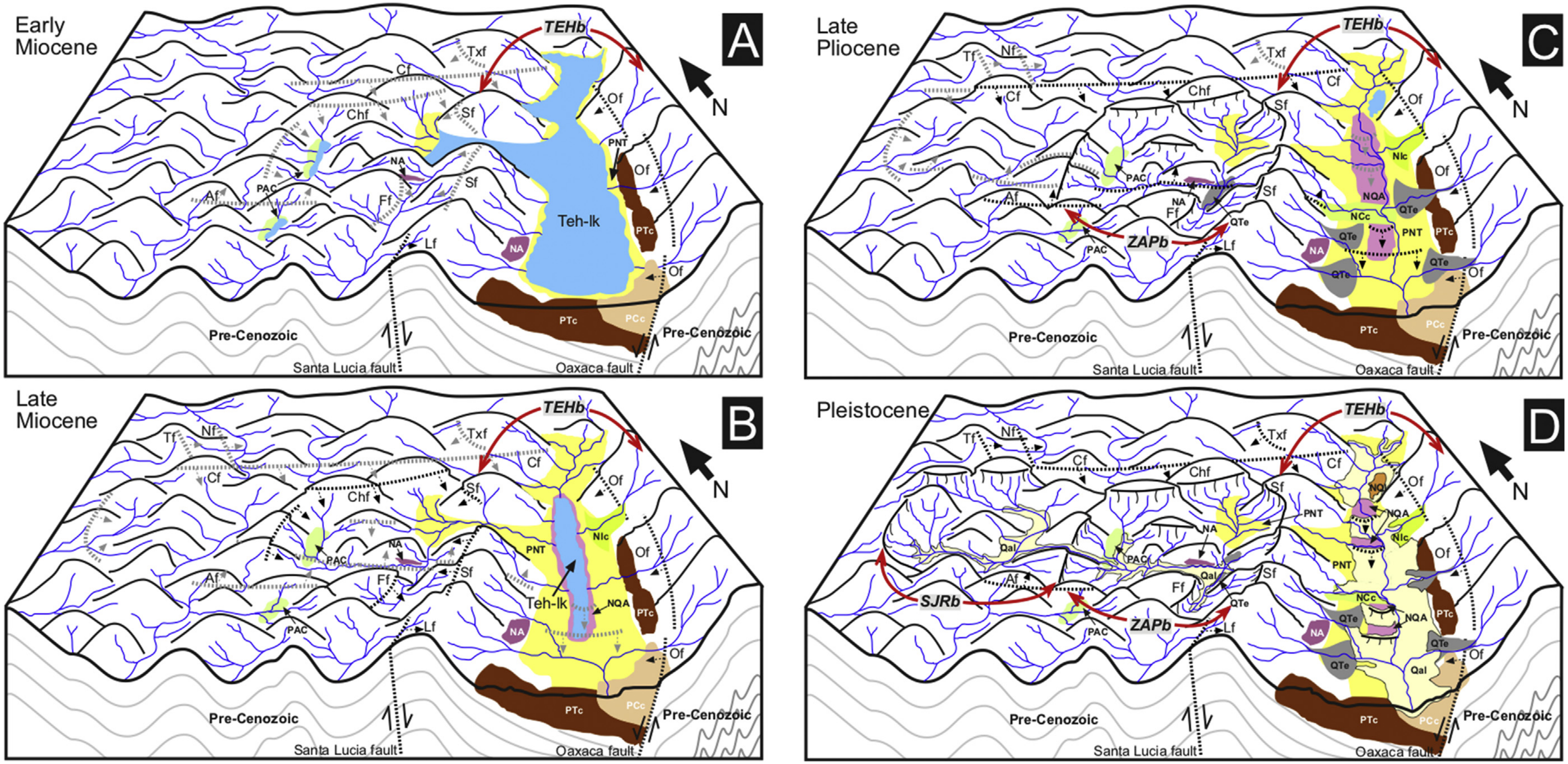

Figure 8. A–D. Suggested model of the geomorphic evolution of the TEHb-ZAPb-SJRb area since the Pliocene. Only the north half of the TEHb is depicted. Af = Acatepec fault; Cf = Cuatillo fault; Chf = Chacateca fault; Lf = Santa Lucia fault; Nf = Nopala fault; Of = Oaxaca fault; San Francisco fault; Sf = Salinas fault; Tf = Tepoxtitlan fault; Txf = Texcala fault. The extension of the Tehuacán lake (Teh-lk) is shown only with illustrative purposes because a chronology for the reduction phases of the water stand has not been established. Dotted lines indicate fault traces likely in development (grey) or fully active (black). Arrows point to the subsiding block. Lithology units as indicated in Figures 3 and 4.

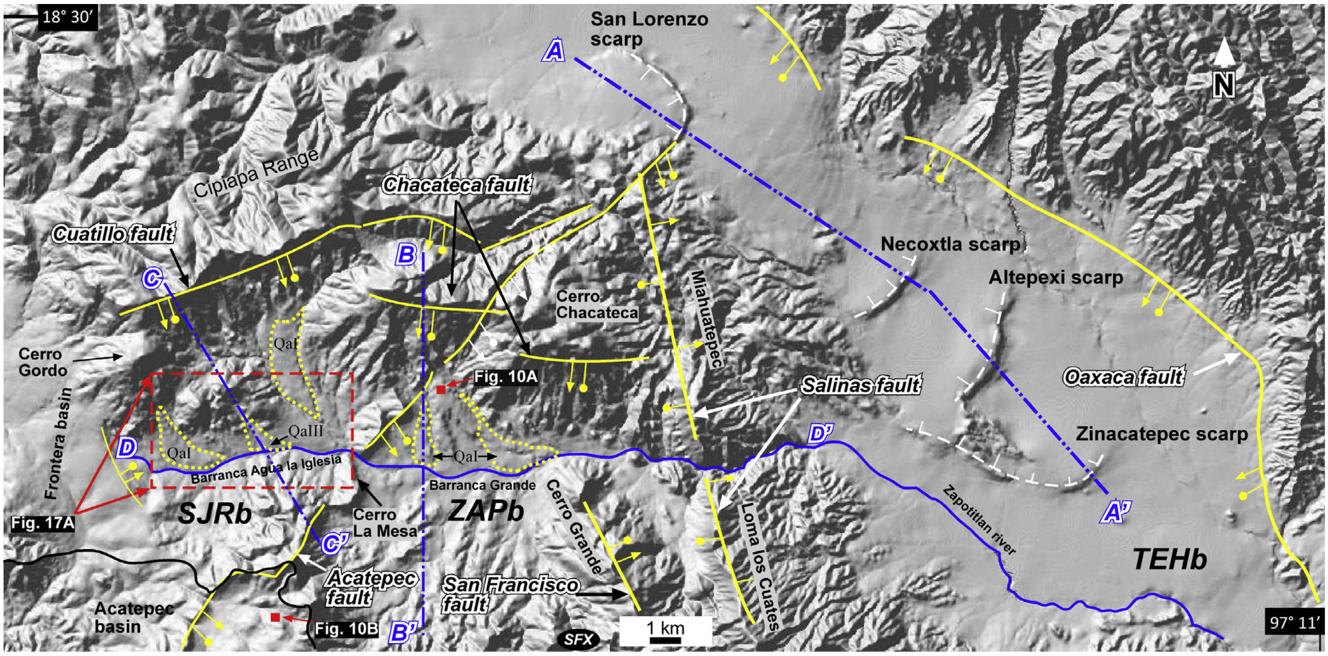

Figure 9. Digital elevation model of the study area, encompassing the central part of the TEHb and the ZAPb and SJRb. Fault symbols as in Figure 4. Background DEM obtained from Mapa Digital de México-INEGI: http://gaia.inegi.org.mx/mdm5/viewer.html. Location of the A-A′ (Figure 16), B-B′ (Figure 12), C-C′ (Figure 14) and D-D’ (Figure 13) transects are indicated.

graben system of the ZAPb, are perpendicular to the folding and regional alignment caused by the compression; which supports a post-orogenic extension of the ZAPb. The growth of the Oaxaca fault during the Cenozoic had its last phase affecting the TEHb to the east of the Altepexi-Tehuacán City sector around the late Miocene (Dávalos-Álvarez et al., 2007, Figure 4).

Figure 10. Field view of the Acatepec Fm as conglomerate in the ZAPb (A) and limestone in the Acatepec basin (B). See Figures 5 and 9 for the specific location of these outcrops.

The Cretaceous-late Neogene hiatus (obviating the Acatepec Fm for reasons discussed above) and the tectonic style of the ZAPb strongly suggest that its formation as a graben started after the Miocene. The tectonic activity to the west of the TEHb north half continued even after the final growth event of the Oaxaca fault, also supporting the hypothesis of post-Miocene formation of the ZAPb. The Caltepec and Santa Lucía systems and other parallel faults affected the Altepexi lake beds (Mio-Pliocene), the Coyoltepec (Pliocene) and Teotitlán (Pleistocene) conglomerates (Dávalos-Álvarez et al., 2007). Numerous triangular facets are exposed along the west slope of the Cerro Loma los Cuates range, marking the point cut by the Salinas fault (Figures 9 and 11).

The ample exposure of the “fresh” fault scarps in the Cerro Chacateca suggests more recent activity (Figures 9 and 12). Erosion of the north highlands as a cause of the abrupt scarps would be difficult to support because of the high erodability and low-resistance weathering properties of the calcareous limestone which makes up these rocks. Long-term exposure of this limestone would imply dissolution and weathering that would form less steep slopes, similar to the hills of the north-facing highlands in the ZAPb and SJRb.

The fault that cuts through the Miahuatepec and Loma los Cuates range forming the knick zone between the ZAPb and TEH basins probably appeared since the early phases of extension of the ZAPb (Figure 9). Subsidence of the ZAPb hanging wall and the TEHb-ZAPb knick zone during the extension of the basin can explain the formation of this deep cut between the N-S trending Miahuatepec-Loma los Cuates highlands, and the modern level of the Barranca Grande. Noticeably, no tectonic klippes of the Cipiapa Fm have been identified in the ZAPb, but are present in the SJRb (Section 7.3). It is likely that these tectonic remnants of tilted blocks were eroded during earlier stages of the ZAPb. The Salinas fault runs along the west side of the Miahuatepec highlands and the west slope of Loma los Cuates (Figures 9 and 11), explaining the subsidence of the blocks that form the ZAPb. It is likely that the drainage connection between the TEHb and the ZAPb is the result of the Neogene activity of the northern sector of the Salinas fault, which had not been previously investigated. It can be noticed that the knick zone between the TEHb and ZAPb coincides with the transverse crossing of the Salinas fault. A possible explanation is that the tectonics associated with the down-

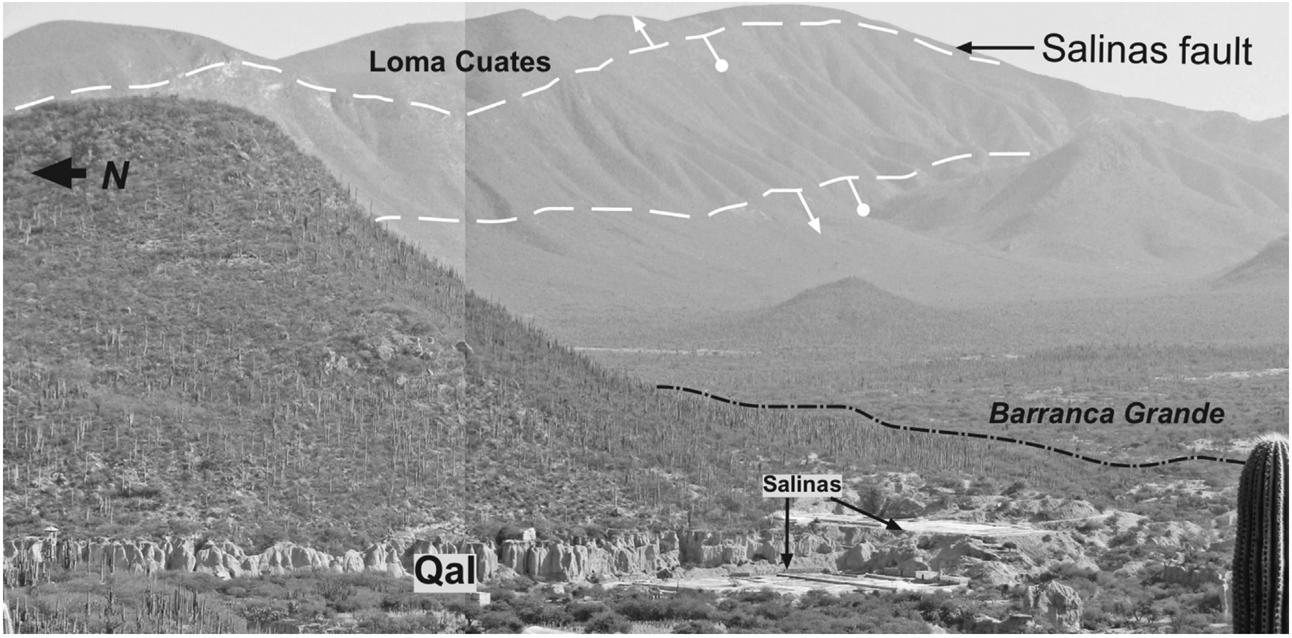

Figure 11. West facing slope of the Loma los Cuates mountains in the ZAPb. The Salinas fault caused the formation of the elongated triangular facets along the slope. These forms are cut by a smaller and younger fault, closer to the ZAPb valley zone. Highly eroded and dissected QaI deposits can be also observed in the valley area. The "Salinas" are pre-Columbian evaporative salt mining ponds still under use.

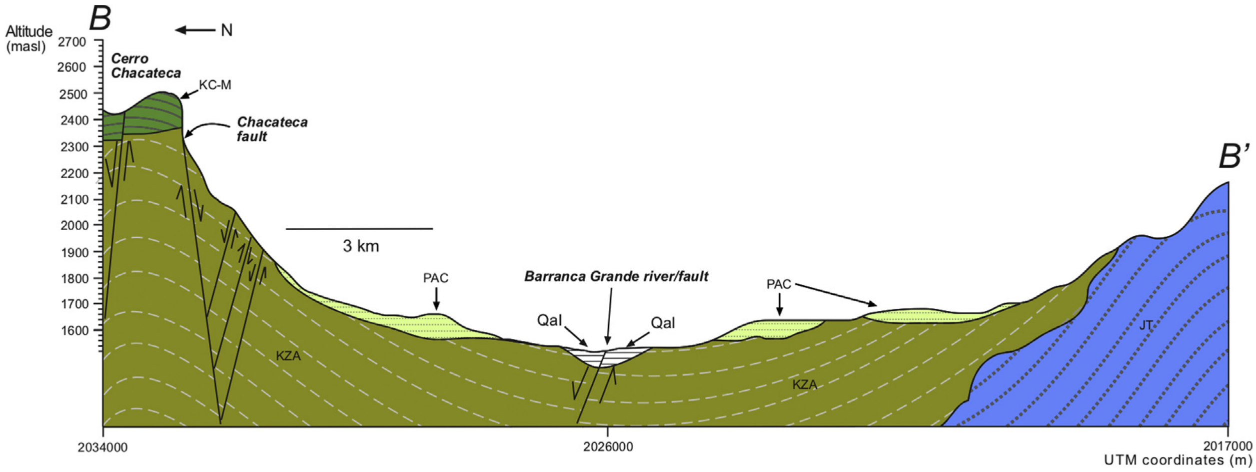

Figure 12. Schematic structural cross section of the ZAPb. See Figure 5 for lithological units and location of the B-B′ transect. The horizontal contour and coordinates were drawn from the topographic map (INEGI, 1998). UTM coordinates: zone14Q.

throwing of the Tehuacán block, after the middle Miocene to the east of the Caltepec fault (Dávalos-Álvarez et al., 2007), caused a lowering of the base level and downward migration of the TEHb-ZAPb outlet boundary, establishing a connection between the two basins.

If the subsidence of the ZAPb had taken place during the early to middle Miocene, implicit in the hypothesis of long-term fluvial connectivity with the TEHb, then detectable remnants of fluvial sediments would be expected to be preserved at different altitudes along the Miahuatepec and Loma los Cuates hills around the knick zone. If both basins' drainage had been connected through the Barranca Grande river for many millions of years, the knick zone between them would be expected to be considerably wider, perhaps turned into a narrow valley. Slow lowering of the Barranca Grande river base level to its modern location would have been accompanied by fluvial discharge from the ZAPb into the TEHb and the formation of fluvial deposits at different altitudes along the knick zone between the Miahuatepec and Loma los Cuates slopes. The absence of this sedimentary record and the considerably narrow passage also support the idea of a Pliocene subsidence of the ZAPb block.

The oldest unequivocal continental basin record in the ZAPb is a conglomerate outcrop found at the east end of the Barranca Grande, just before the knick zone between this basin and the TEHb (Figure 13A). This outcrop is cut by the modern Barranca Grande, indicating a late Quaternary change in base level that exhumed these rocks. Stratigraphically these lithified alluvial sediments are located between the Cretaceous limestone and the QaI Pleistocene surfaces. Sedimentologically they are clast-supported, poorly-sorted, ungraded and mixed in a small proportion of fine-grained material.

Other post-Miocene alluvial rocks have been identified in the TEHb and ZAPb, providing a possible reference for correlation. A latest Pliocene to Pleistocene age estimate for the Teotitlán Fm conglomerates was presented by Dávalos-Álvarez et al. (2007) on the basis of stratigraphic relations. These conglomerates, which were first described as alluvial fans by Centeno-García (1988) and whose thickness was estimated by

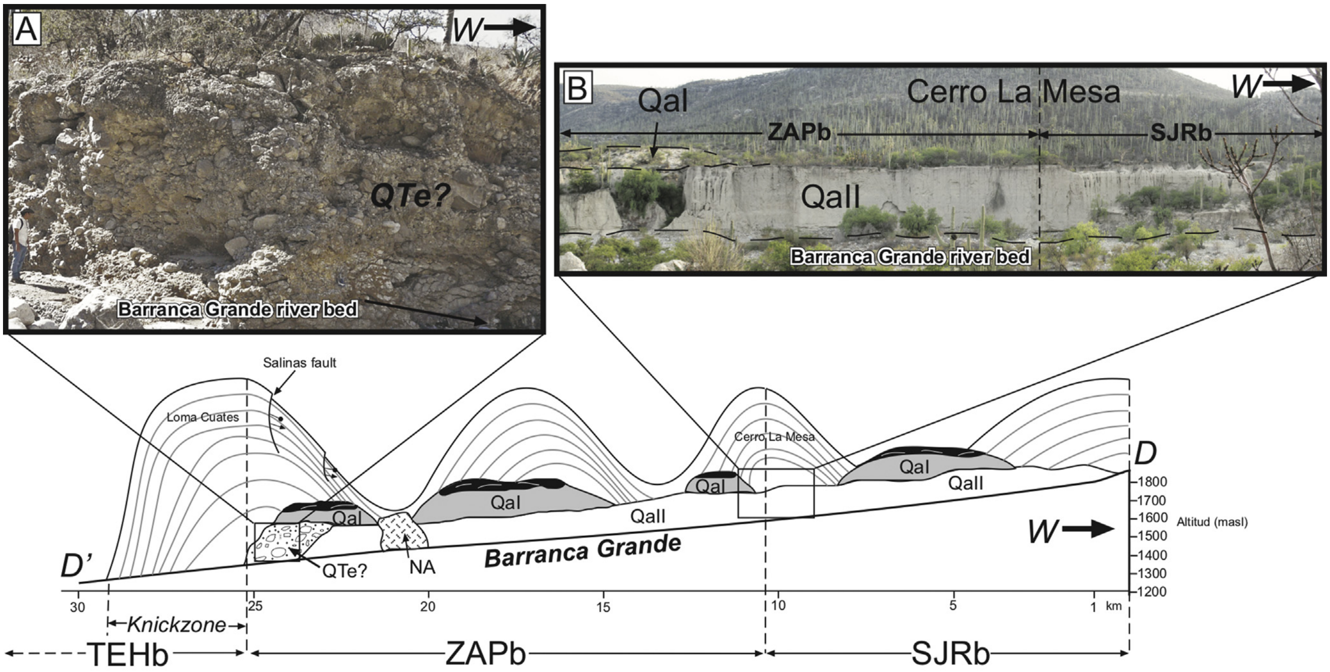

Figure 13. Cross section along the Barranca Grande ephemeral river. In the ZAPb the Plio-Pleistocene conglomerates rest between the Cretaceous limestone and the QaI units (A), whereas in the SJRb the unconsolidated alluvial cover overlies the bedrock directly showing the stratigraphical hiatus. Vertical and horizontal axes are not at the same scale. Vertical dotted lines indicate the basin limits.

Dávalos-Álvarez et al. (2007) to be at least 150 m, show that during this period the TEHb and ZAPb displayed intense alluvial activity. On the basis of those descriptions and the observation of the location where these deposits have been mapped we suggest that these fans were the product of tectonic activity along the N-S faults between the TEHb and ZAPb. The outcrop observed near the outlet of the ZAPb (Figure 13A) was not included in the map by Dávalos-Álvarez et al. (2007), but the alluvial nature of the beds and their stratigraphic position indicate that they are contemporaneous. In the context of the landscape evolution of the ZAPb these conglomerates represent the earliest preserved phases of basin-type sedimentation during the Plio-Pleistocene (Figure 8C).

Dating part of the extension of the ZAPb to the Pliocene, and perhaps extending until the Quaternary, also matches observations of the sedimentary records at the outlet of the ZAPb. Major fluvial activity in the ZAPb during most of the Paleogene-Neogene would have sent important amounts of sediment to the TEHb. However, no conglomerate rocks or landforms of this age/origin have been found around the outlet area of the ZAPb. This suggests that any fluvial contribution from the ZAPb to the TEHb did not occur until the late Paleogene-Neogene, or that sediment sourced from the ZAPb (plus the SJRb if also present) did not exceed the transport capacity of the fluvial system further down the Tehuacán valley.

An alternative idea of an earlier development of a sedimentary basin-type geometry in the ZAPb with the corresponding pre-Pliocene landforms is not supported by morphological (see Sections 8 and 9) or sedimentological evidence (see below). This scenario would require the instability of these landforms plus highly intense fluvial activity capable of selectively removing these sediments from the ZAPb, without affecting their contemporaries in the TEHb. Although localised tectonics could cause the required instability, a few km-scale changes in precipitation can be ruled out. The mobilisation of those sediments by intense fluvial activity would also require the reworked sediments from the ZAPb to be carried through Barranca Grande and to be deposited in the TEHb. However, the provenance and the nature of the sediments found in the area where the ZAPb drains into the TEHb do not support this hypothesis either (see below). Regular, non-catastrophic erosion and fluvial activity in the post-contraction ZAPb highlands, with a poorly developed sedimentary geometry, are more likely.

We consider that the Pliocene Coyoltepec conglomerates (western side of the TEHb valley, near the outlet of the ZAPb, NCc, Figure 4) are not part of sediment fluxes supplied from the ZAPb and SJRb. Near this point they were previously described as clast-supported, un-stratified, poorly sorted sediments varying in roundness and composed mainly of andesite and limestone (see Figure 40 in Dávalos-Álvarez, 2006). A higher portion of limestone clasts would be expected if these sediments had been sourced from the ZAPb because its lithology is mostly of this type of material. The proximity of the Coyoltepec conglomerates to the andesite outcrop and its position next to the piedmont suggest that the depositional environment corresponds to an alluvial fan, sourced from the eastern slope of the Cerro Miahuatepec-Loma los Cuates range. Further downstream from the ZAPb drainage outlet, the Coyoltepec Fm displays a calcareous matrix with clasts between 15 and 60 cm in diameter (Dávalos-Álvarez et al., 2007). This apparent coarsening away from the basin outlet indicates a channelised flow of coarse material and a more complex alluvial/fluvial system, which contrasts with the hypothetical fluvial valley that would be expected in this area if the sediment load from the ZAPb and SJRb had been emptied into the TEHb regularly during the Pliocene.

Dávalos-Álvarez et al. (2007) propose that the environment where the eastern outcrop of Coyoltepec rocks formed was a lake, although alluvial flows are also possible, especially if the significant reduction of the lake by the Pliocene is considered. A study of clast provenance could help to identify the source area of the clastic component and the relative contributions and interconnections of neighbouring basins (Adhikari and Wagreich, 2011). Future determination of the chronology of deposition, clast composition and primary source of the alluvial deposits preserved at the outlet point of the ZAPb could help to constrain the time when the ZAPb and SJRb contributed to the fluvial system, when connectivity was established and when these systems acted as sediment basins, rather than just sedimentary sources. It is very likely that the extension in the ZAPb continued during the Quaternary and that the E-W and SW-NE faults in the area around the SJRb were also more active.

7.3. Quaternary basin extension: opening of the SJRb (Figure 8D)

According to the present new interpretation of the surface geological mapping, the SJRb also corresponds to a graben system formed by faults that follow a different alignment to the regional ones formed before or shortly after the compressive phases (Figure 14). The northwest part of this basin is also affected by a group of smaller normal and reverse faults, crossing the basin in a NW-SE direction (Figures 5 and 9). Another group of faults runs along the eastern limit of the SJRb. In this basin the presence of two tectonic klippes of the Cipiapa rocks in its central part confirm the subsidence of the central blocks. Such tectonic klippes are named Cerro Salado and Cerro Garambullo (Figure 5). Mauvois (1977) identified their presence in the context of an apparent overriding of the Cipiapa Fm during the Neogene and Paleogene. We analyse their tectonic significance in the opening of the SJRb. The maximum thickness of the Cipiapa Fm is 600 m (Mauvois, 1977). Considering that the base of the northern outcrop is found at 1,100 masl and the base of the tectonic klippes located at 1,900 masl means that the klippes show a negative displacement of at least 200 m relative to the north highlands. Because of the lack of geophysical data the interpretation of the structural geology is based on the revision of surface features, the depth of these faults cannot be included in the model. Instead, and given that the length of the surface and sub-surface rupture of active faults are normally correlated (Wells and Coppersmith, 1994), we assumed that there is a relationship between the faults' horizontal exposure and depth.

Westward growth of the Barranca Grande fault into the SJRb during the Quaternary could account for the connectivity of the Barrancas of the ZAPb and SJRb and also for the formation and activity of the Barranca Agua la Iglesia fault (Figure 5). Later growth, possibly early Pleistocene of the E-W Barranca Grande fault towards the SJRb (becoming Barranca Agua la Iglesia fault) would cause the direct stratigraphic contact between the Cretaceous rocks with late Quaternary alluvial landforms (Figure 13). Significantly less time for erosion of Cerro la Mesa through Barranca Agua la Iglesia and/or younger subsidence at the west limit of the Barranca Grande fault can also explain the shallower knick zone between the ZAPb and SJRb, compared with the one formed between the TEHb and ZAPb (Figure 9).

As with the ZAPb, the depth and accurate timing of the activity of the E-W faults which opened the SJRb are unclear due to the lack of geophysical and isotopic data. A system of parallel faults of NE-SW orientation, outline and cross internally most of the SJRb, some of them extending into the ZAPb (Figure 9). One of the most important faults showing this trend is named here as Cuatillo and corresponds to the north limit of the SJRb.

The ZAPb and SJRb are separated from the TEHb by the Caltepec fault (Sedlock et al., 1993), although only the southern part of the ZAPb lies within the direct influence area of the Caltepec fault system (Figure 3). Ortega-Gutiérrez (1981) describes this fault as extending for at least 150 km from the west of Tehuacán city to Juchatengo in the state of Oaxaca. Elías-Herrera and Ortega-Gutiérrez (2002) estimate that its width reaches 2–6 km near the southern part of the ZAPb. The Caltepec fault outcrops around the Los Reyes Metzontla in a NW direction, as a series of normal faults just south of the ZAPb. Parallel and north of the Caltepec fault, there are at least two identifiable faults: Salinas and San Francisco, which can be related to the former major Palaeozoic structure.

Another line of evidence that the SJRb formed during the Neogene-early Quaternary is found at the southwest water divide of the SJRb. This divide is a small fault scarp (<10 m) that interrupts the continuity of the plateau that extends westwards into the neighboring basin. The tectonic cut through the Quaternary calcrete/plateau also caused the subsidence of the west border of the SJRb, resulting in drainage inversion, from the Pacific to the Gulf of México during the Quaternary. Establishing the stratigraphic position and age of the E-W faults in the SJRb is difficult due to their small length and because they cut through almost exclusively Cretaceous rocks. The Barranca Grande fault cuts the QTe (Figure 13) whereas the NE continuation of the Acatepec fault into the TEHb extends to the San Lorenzo scarp (Figure 9), cutting through the relatively recent tufa (NQA).

Extrapolation of the Acatepec fault towards the west margin of the valley of the TEHb, near the Tehuacán City coincides with the northernmost outcrop of the NQA tufa (Figures 4 and 9). The activation of this fault during the Quaternary could have played part in setting the spring outlet that formed these tufas and in the extension of the ZAPb and SJRb. These fractures acted as fissures where carbonate-rich underground water emerged to the surface and contributed to the tufa accretion. This and other tufas have been mapped in the TEHb as part of the Altepexi Fm (NQA tufa, Figure 4) and travertine in earlier geologic maps (see Dávalos-Álvarez, 2006 for a more detailed description). Dávalos-Álvarez (2006) considers this tufa as a later facies of the Altepexi Fm, formed in a lake environment during middle Miocene to the Pleistocene. However, we observed that in the TEHb these tufas are found associated with fault lines, forming a step-like sequence of scarps found along the basin bottom (Zinacatepec, Altepexi, Necoxtla and San Lorenzo scarps, Figure 4) and represent the bulk component of the landform. The exposed thickness of the San Lorenzo tufa is at least 50 m (Figure 15). We suggests that these tufas correspond to fracture lines developed across the TEHb valley during the Quaternary (Figures 9 and 16).

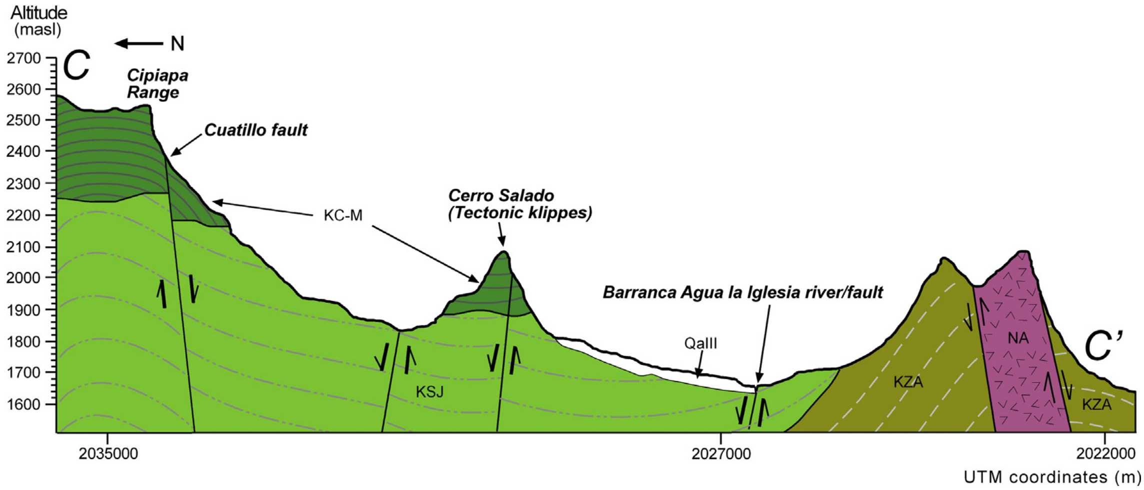

Figure 14. Schematic structural cross section of the SJRb. See Figure 5 for lithological units and location of the C-C′ transect. The horizontal contour and coordinates were drawn from the topographic map (INEGI, 1998). UTM coordinates: zone14Q.

Figure 15. Upper part of the tufa outcrop at the San Lorenzo scarp exposed in a cut of the 135 motorway. This tufa corresponds to the extrapolation of the Cuatillo fault.

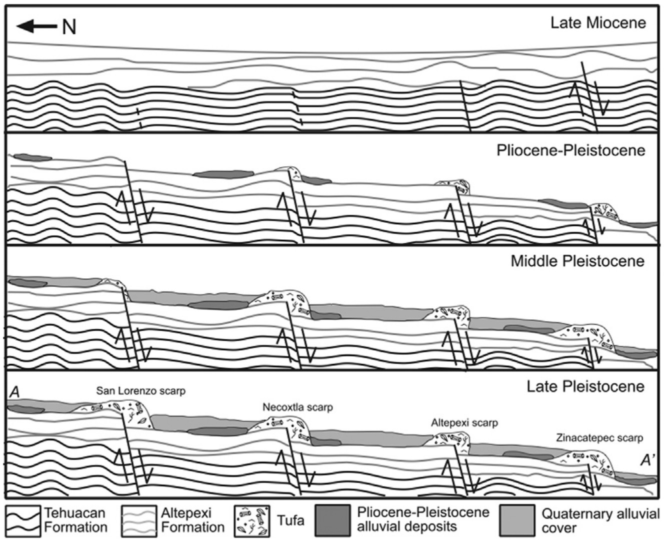

Figure 16. Schematic model (not to scale) of the geomorphic evolution of the valley area of the TEHb showing the site of tufa formation associated to the fault scarps (A-A′ transect in Figure 9).

None of the tufas found anywhere in the three basins are associated with lake or river systems. In addition, the arid nature and the geomorphological settings are not favourable for the formation of such chemical sediments. Tufas commonly form at points of fractures (Johnson et al., 2009). In the case of the TEHb they form scarps of tens of metres in the central part of the basin (Figure 9), exposing a rich diversity of plant fossils. Fracturing of bedrock beneath the TEHb valley area and the formation of these tufas during the Pleistocene is plausible under the tectonic setting that caused the subsidence of the TEHb valley area and diverted the drainage of the lake to the south, ending the closed basin conditions around the Pliocene-Pleistocene boundary. It is likely that fault scarps were formed in sequence from south to north as the base level of the TEHb subsided (Figure 16), following the tectonically-induced termination of lake conditions under which the Altepexi sediments were deposited. These four tufa landforms are aligned parallel to the north sector of the Oaxaca fault. This activity of the Oaxaca fault took place during the middle to late Miocene, which implies that these fault-related tufas formed during the last significant expansion of the Oaxaca fault. The tufa deposits have been assigned a Pliocene-Pleistocene age on the basis of correlation (see Dávalos-Álvarez et al., 2007), whereas a fissure-ridge "travertine" near to Texcala (Figure 4) has been U/Th dated at 52 +/- 5 kyr (Michalzik et al., 2001), suggesting that the north end of the Acatepec fault was active during the Quaternary.

A likely source of Quaternary water for the thick tufas developed in the TEHb lowlands was the meltwater from the Citlaltpetl volcano, which is known to have developed important glaciers during the late Quaternary. Climate change and intensive explosive activity during the late Pleistocene and the Holocene led to numerous occurrences of glacial melting, avalanches and geomorphic processes along the volcano slopes (Palacios and Vazquez-Selem, 1996). Important volumes of glacial melt water from the Citlaltepetl (5,600 masl), draining as underground water towards its south slope into the TEHb (Figure 2), could have fed the TEHb tufas. A sample from the base of the San Lorenzo scarp tufa was radiocarbon dated but produced a value beyond the ^{14}C range (>43,500 BP; Beta 388912) and, thus, cannot be used to locate the exact stratigraphic position of these tufas but can confidently be placed in the Pleistocene.

8. Tectonic geomorphology

During their evolution, basins can be exposed to alternate periods of compression and extension. In a dominant compressive regime, basin evolution can be affected by inverse faults, although normal faults can develop as secondary structures that accommodate part of the compression (Bonini and Sani, 2002). The dominance of normal faults (E-W and NE-SW) that opened the ZAPb and SJRb suggests that these are more recent than the inverse (NW-SE) ones formed during compression. The fact that the faults bounding the ZAPb and SJRb are neither covered nor deformed also indicates that these basins were opened after the contractional phases and that these faults are younger.

The geometry of the ZAPb and SJRb differs from that of the TEHb because they were formed by Neogene faults. The majority of faults that outline the ZAPb and SJRb are prominent scarps carved in the Cretaceous bedrock (Figure 9). Those scarps differ in exposure and extension between the ZAPb and SJRb, indicating differential processes of faulting. In the ZAPb the north faults form walls of more than 220 m (Figure 12), whereas in the SJRb these are prolonged for longer distances, forming vertical falls that can reach more than 500 m (Figure 14). It may be that such a contrast can be given by a non-contemporaneous activation of the faults and the concomitant differential time exposures of the bedrock and/or a differential subsidence rate between the blocks forming the two basins. Limestone is the same rock type cut by these scarps in both basins, and hence it has the same susceptibility to erosion and weathering. Less steep slopes in the north sector of the ZAPb may indicate a longer time of exposure to erosion and weathering, compared with those bordering the SJRb to the north. Alternatively, the two sectors of the fault may have experienced differential activity as a result of variations in gouge dimensions. Also, the west end of the SJRb shows a very gentle slope (<30 %), less prone to significant erosion. Long-lasting tectonic activity and erosion in the ZAPb and SJRb dividing scarps would have also produced wider basins than what is observable.

More pronounced slopes on the western side of the Cerro Miahuatepec and Loma los Cuates mountains (Figure 9), facing the ZAPb, and numerous triangular facets (Figure 11), indicate differential tectonic activity. A similar asymmetry between slopes is shown along the highlands dividing the ZAPb and SJRb north and south of the Barranca Agua la Iglesia. In both cases fault scarps of preferential N-S and NNE-SSW orientation cut the limestone ranges delimiting the basins (Figure 9). On one side most of the water divide of the SJRb is formed by scarps, whereas on the other side the slopes maintain a gentler angle, initially imprinted by the orogenic folding of the limestone and subsequent erosion. Also, the southwest boundary of the SJRb is another scarp formed along a fault, indicating more recent activity, compatible with a younger origin.

Significant extension dominated since the latest Pliocene to the Pleistocene in the three basins, leading to the lowering of the base level that allowed the merging of the fluvial systems of the ZAPb and SJRb and later deposition of the Quaternary beds and eventually to the modern-day geomorphology (Figure 8D).

9. Tectonic significance of Quaternary alluvial geomorphology

The distribution of the Quaternary alluvial landforms in the ZAPb and SJRb follows the asymmetry of the grabens. In both basins the northern halves of the valley areas host calcrete-capped alluvial fans (QaI) that extend for at least 3 km towards the basin floor (Figure 9), reaching 40 m in thickness in the middle fan (Figure 6). In contrast narrow terraces and channelized deposits constitute the alluvial landforms in the southern halves of the basins (Figures 9 and 17). Such arrangement suggests that the formation of voluminous alluvial fans sourced from the south-facing slope of both basins is linked to the tectonic activity of the north faults. The combination of high relief and tectonic activity of the Cipiapa foot wall provided a dynamic, vast and very steep hill slope that produced the QaI alluvial fans sourced from the south-facing slope (Figure 9). Contemporary alluvial fans from the north-facing slope are absent. This type of asymmetric alluvial fan development as a result of tectonic activity in arid lands basins is well known (e.g. McLaren et al., 2004; Ortega-Ramírez et al., 2004; Blair and McPherson, 2009). Late Quaternary tectonic activity in the SJRb has also been corroborated as minor faults that cut the last generation of Qa fans, but these results will be presented as part of a separate study on late Quaternary alluvial geomorphology. The QaI fans are considered to be of primarily tectonic origin because they are sourced directly from the faulted highlands in both basins and because no similar fans and/or correlating beds are found from the opposite slope. The most distal part of the QaI fans in the SJRb reaches the valley floor and the clast composition here is entirely limestone from the north highlands. A climatic control on QaI alluvial events would have caused widespread alluviation and noticeable contribution of igneous clasts from the south hills to the valley fillings, mixing material from both slopes. No igneous material forms these QaI deposits. The morphology, clast composition and the presence of a calcrete capping these QaI fans indicates their contemporaneous formation in the ZAPb and SJRb.

The small Quaternary alluvial landforms sourced from the southern highlands (QII) form continuous terraces along the valley floor and upper slope streams, lacking the well-developed thick calcrete common to QaI. The sedimentary sequences of QaII terraces show a series of intercalated alluvial beds and palaeosols, with no calcrete developed (Figures 6A and 13B). In contrast, QaI sequences were deposited very rapidly, preventing the development of palaeosol sequences (Figure 6B). A QaI surface calcrete in the SJRb yielded a conventional radiocarbon date of 19,460 (+/-150 ^{14}C BP, Beta 302085), suggesting that these alluvial fans were formed during the Pleistocene. Although the QaI fans in both basins share similar stratigraphy, size and a capping calcrete, the precise age of the ones in the ZAP has not been determined.

In the ZAPb the formation of the QTe conglomerates was followed by the deposition of the fine-grained QaI alluvial beds (Figure 13B). Finally, the lowering of base level caused by the fault along the Barranca Grande was accompanied by the deposition of the QaII terraces during the late Pleistocene-Holocene. Earlier phases of alluvial/fluvial activity in the ZAPb are possible, but such records have not been formed or preserved. Arguably the lack of alluvial/fluvial landforms along the knick zone could be explained by the rapid subsidence of the ZAPb. A shift from the initial closed basin conditions could have produced some fluvial transport out of the basin and into the TEHb via the knick zone, which at this time would be positioned at a higher altitude than the modern river. Empirical reasoning suggests that the sediment load from a younger basin is considerably less than that of a deformed and mature one. Subsidence of the hanging wall and erosion of the foot wall slopes increases the internal area and consequently the amount of potential material that could enter the fluvial/alluvial system. A rapid subsidence of the ZAPb blocks could have had a double effect; enhancing the erosion of the hill slopes in

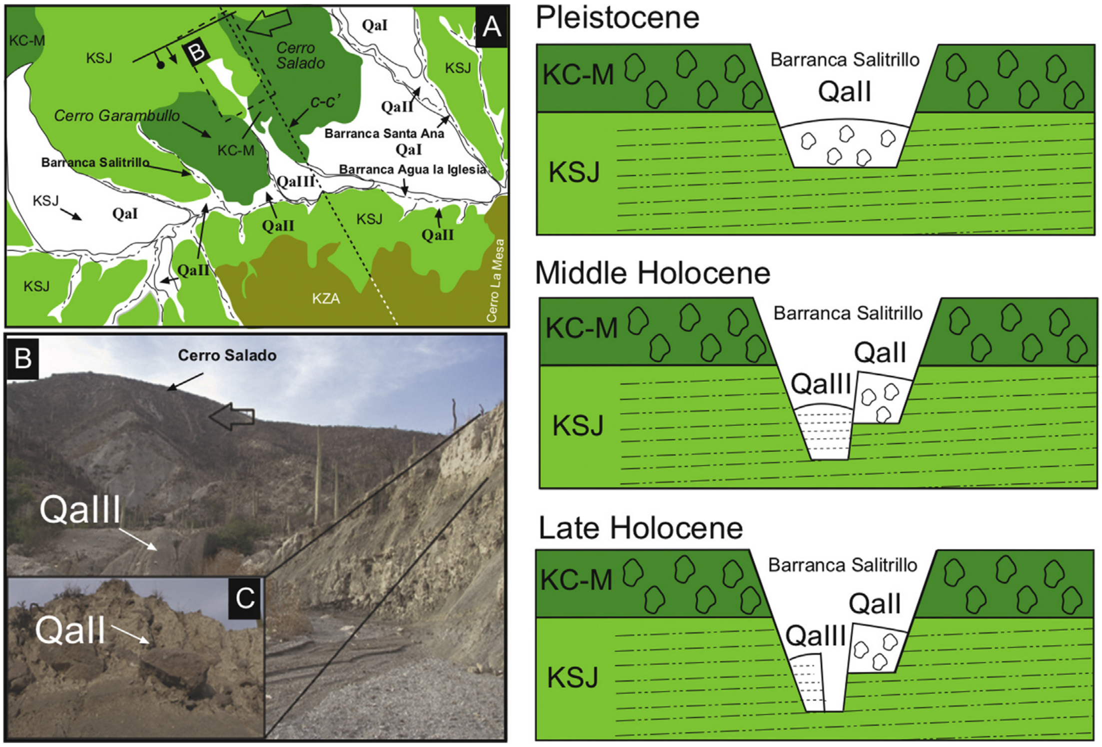

Figure 17. A: geomorphology of the central part of the SJRb and evolution model of the Quaternary alluvial landforms. The Cerro Garambullo and Cerro Salado highlands correspond to the central tectonic klippes of the KC-M rocks. B: Northwest view of the fault cutting the klippes and related alluvial terraces. C: Pleistocene alluvial terrace (QaII) showing clasts of the KC-M rocks. The QaIII Holocene fan is exclusively formed of lutite from the KSJ Fm.

the knick zone area and hence the destruction of Neogene fluvial terraces and a further increase of sediment load diverted through this path and the formation of the Plio-Pleistocene beds, followed by a relative quiescence and the re-establishment of tectonic lowering of the base level and the deposition of the Quaternary sediments.

In the SJRb the stratigraphy shows a depositional hiatus from the Cretaceous to the late Quaternary (Figure 6). Two ways to explain this hiatus are either the removal of sedimentary rocks by erosion if the basin was formed as a graben during the Paleogene-Neogene, or the non-deposition if this area had not developed a depositional basin morphology. The absence of remnants of continental sedimentary rocks mixed with unconsolidated Quaternary deposits in the SJRb make the first scenario less likely. In the evolution model, prior to the Quaternary the area corresponding to the SJRb experienced erosion, but without a large enough valley area to accommodate alluvial landforms (Figure 8A–C).

10. Quaternary extension: evidence from molecular biology

An independent line of evidence supports the interpretation of a Quaternary tectonic opening of the SJRb. Cornejo-Romero et al. (2013) show that the modern geographic distribution of the genetic diversity of the cactus *Mammillaria pectinifera* is the product of tectonic-related geographical isolation. According to those authors, this species originated around 2 Ma ago on the flat summits that surround the TEHb, ZAPb and SJRb to the northwest. The environmental conditions of those landforms match the very specific requirements of the species. Because of this high habitat specificity and the type of seed dispersion it is thought that when the species originated, during the Pleistocene, the localities where the populations are distributed were part of an environmental and topographic unit. The populations of *M. pectinifera* commenced a process of genetic divergence since about 0.6 Ma ago, suggesting that the original geomorphic and environmental setting became fragmented. Notably, a topographic continuum is also a requisite for the expansion and genetic flow of these plants because seeds are dispersed exclusively by water moving at ground level. Because no biotic or aeolian vectors are involved in the dispersion of *M. pectinifera* seeds, the arrival of the cactus to Cerro Gordo in the SJRb must have occurred when this mountain and the Cipiapa highlands formed a single topographic unit (Figure 9). Subsidence of the Cerro Gordo, caused by the Cuatillo fault, and the subsequent erosion led to the formation of the v-shaped depression between this mountain and the Cipiapa highlands (Figure 9), preventing *M. pectinifera* seed dispersion. The genetic divergence of the population of *M. pectinifera* found in the Cerro Gordo is calculated to have started around 0.25 Ma, giving an estimated age for this tectonic event. The major subsidence of the internal block in the SJRb indicates an earlier beginning of extension, but still within the Quaternary.

11. Discussion

Intramontane basin evolution in the Sierra Madre del Sur Province, México, has occurred following known processes: lateral, reverse and/or normal faulting during and/or after the orogenic uplift (*i.e.* Crespi et al., 1996; Andersen, 1998; Boccaletti and Sani, 1998; Dezes et al., 1999; Bonini and Sani, 2002; Koukouvelas and Aydin, 2002; Bonev, 2006; Cruz-Orosa et al., 2012; Silva-Romo et al., 2018). Basin evolution during the transition from compression to relaxation of the upper crust has been shaping the SMS landscape since the Miocene. The four-step model of foreland basin evolution introduced by De Vicente et al. (2011) seems also to be valid for the SMS intra-orogen basins. According to this model alluvial sedimentation commonly occurs within the primordial tectonic basin and is followed by syn-tectonic filling, a shift to an exhoreic regime and finally intensive erosion. Similar phases are recorded in the intramontane TEHb, ZAPb and SJRb, but with apparent differences related to their relative sizes and ages, along with important phases of non-deposition.

The development of graben by extension where young basins host lakes due to an endorheic morphology is more clearly exposed in the bigger-sized TEHb. Closed basin conditions during the early extension in the ZAPb allowed the formation of a small lake. The interconnection and draining of formerly closed basins and lakes commonly follows the change to half graben morphology and is accompanied by a shift in deposition to alluvial/fluvial deposits. Notably, whereas the TEHb, ZAPb and SJRb host sedimentary beds that reflect these changes, basin size seems to control the alluvial/lake spatial ratio. Thick and extended alluvial fans relative to the basin size are common to the middle and small-sized ZAPb and SJRb, whereas lake-type beds dominate the internal basin floor area in the bigger-sized TEHb. Smaller basins will have a higher perimeter to area ratio, meaning that sediment mobilised from the footwall highlands by tectonics, would be more represented in the relatively smaller basin floor, whereas in big-sized basins a wider hanging wall area will accommodate tectonic alluvial landforms around the edges, leaving potentially more areas for flat plains and lakes. In the SMS, bigger basins have been the preferred study systems because their lake strata can provide longer and more detailed records of environmental change and also because major tectonic structures are linked to bigger basins. Observations of the ZAPb and SJRb show that smaller-sized basins could potentially be better systems for the study of tectonically-driven alluvial processes and can also contain additional information on local past environments. The stratigraphy and particularly the soil-colluvium sequences in small basins should be studied in order to understand the occurrence and periodicity of tectonic pulses and climate (Amit et al., 1995).

Comparison of tectonic style and stratigraphy between the SMS and the southern limit of the BRP suggest a similar tectonic evolution which overlies regional differences. The NW trend of the major faults of south central México around the Tehuacán Mixteca coincide with the main ones of the Basin and Range Province north of the TMVB (Nieto-Samaniego, 1990; Aranda-Gómez and McDowell, 1998). Bigger basins are normally formed by different tectonic stresses and faults than those responsible for smaller-sized basins. The recognition of this pattern in continental Europe raised the question of a generalised phenomenon of post-orogenic basin formation by orogen collapse (Alcicek, 2010; De Vicente et al., 2011). The fact that depositional basins formed by common processes often show similarities in stratigraphy and tectonic style (Purvis and Robertson, 2005; Ersoy et al., 2011), seems to be valid only if the basins are of similar size. A comparative analysis of sedimentary records in sequentially-formed continental basins like the TEHb-ZAPb-SJRb group also allows the reconstruction of tectonic and environmental changes coupled with the long-term evolution of these systems. A number of medium to large-sized Paleogene to Miocene basins in the SMS in central México share structural and stratigraphic similarities as a result of their analogue origin (Silva-Romo et al., 2018). These basins are the product of normal and reverse faulting of structures related to the alignment of N-S faults. Recently, the formation of these stratigraphically similar main basins in southern México has been linked to the migration process of the Chortis block (Silva-Romo et al., 2018). In contrast, extension of the Neogene ZAPb and SJRb basins responded to post-orogenic evolution of these highlands, in particular to a currently unknown behaviour of the deeper crust.

Based on an experimental simulation, Cerca et al. (2010) suggest that the different alignment of structures (N-S in the central and eastern part and NW-SE along the coastal margin) in the SMS is due to positive basin inversion during the contractional phase. One of the few examples of E-W trending faults is the Salado River fault, south of the study area (17° 45′-97° 55′). This fault was mainly active between the early Jurassic and the early Cenozoic, ending at around the Oligocene (Martiny et al., 2012), and therefore unlikely to be related to the Neogene tectonic trend of the north part of the SMS.

In terms of the intrinsic causes of basin formation, the SMS is perhaps one of the least-studied orogenes. Although several authors have associated the subsidence of the hanging wall of the TEHb to normal activity of the Oaxaca fault, the thick Tehuacán Fm could have played part in the Neogene evolution of the TEHb. Subsidence related to dissolution of evaporite beds has already been recognised (Gutierrez et al., 2002), and given the abundance of this type of lithology in the TEHb and the fact that this basin has captured drainage from a number of smaller basins for millions of years, it is possible that the rapid extension of this basin is the result of a combination of purely tectonic and solubility-related subsidence. This would partially explain why the TEHb has formed as a graben system even though some researchers have deduced episodes of lateral activity of the Oaxaca fault during the Cenozoic. Doglioni (1995) suggests that although extensional and compressional tectonics can occur simultaneously, they are not necessarily linked. In the case of the TEHb the lithological nature of the Paleogene formations can explain part of the subsidence while the SMS was still under compression.

Extension has been attributed to over-thickening of the crust and the resulting gravitational collapse (Darby and Ritts, 2009). Crust thickness in the central part of the Oaxaca-Mixteca block has been estimated to be approximately 45 km, thinning to 30 km to the east and to 28 km to the west (see references in Cerca et al., 2007). The relief around the ZAPb-SJRb-TEHb can reach 2,700 masl, with most of the northern border of the ZAPb and SJRb being above 2,500 masl, which make them some of the highest points of the northern part of the SMS; only comparable to the water divide of the Mazateca range (INEGI, 1998). If these elevations are the result of orogenic thickening, the tectonics forming the ZAPb and SJRb could be part of the post-orogenic collapse.

The almost complete absence of pre-Quaternary alluvial and fluvial deposits in the SJRb and ZAPb can be the result of two mutually exclusive scenarios: intensive erosion or no deposition. To accept the first one it has to be assumed that: 1) during the Neogene and Paleogene the SJRb and ZAPb were mature sedimentary systems as a result of earlier activation of the E-W faults and that the blocks have not significantly changed their relative positions since then; 2) that the small valley areas provided the geometry and area to accommodate and preserve significant amounts of sediment without leaving geomorphological and stratigraphic evidence; 3) that several millions of years of erosion caused the removal of alluvial and fluvial beds without contributing to increase the size of the basins themselves and their valley areas or decreasing the angle of the limestone scarps; and 4) that the alluvial and fluvial beds were the subject of intensive or very lengthy erosional removal which did not affect the TEHb in a comparative way. However, the dimensions of the SJRb and ZAPb, and their narrow valley areas provide little support to back-up such a hypothesis. Also, the prominent scarps formed by the Cuatillo and Chacateca faults are not features that evidence long-term stability. The alternative idea that the pre-Quaternary alluvial/fluvial beds were eroded abruptly by great inputs of rainfall, rather than long periods of erosion, is also implausible because the region has been under a semi-arid environment since at least the middle Miocene (Ramírez-Arriaga et al., 2014).

12. Conclusion

Thrusting and normal faulting compatible with orogenic and post-orogenic Cenozoic processes of south-central México were characterised by tectonic processes that gave rise to a series of internal basins that constitute the modern landscape. The geomorphic and stratigraphic Cenozoic evolution of three basins in the SMS has been modelled. The ZAPb and SJRb were formed through extensional tectonics initiated during the latest Paleogene-Neogene and the late Pliocene-earliest Pleistocene respectively. The sequential opening of these two basins followed the northern development of the Oaxaca fault and the associated evolution of the TEHb. The activity of the faults that formed the ZAPb and SJRb post-dated and deviate spatially from the main regional processes responsible for the formation of other major basins of the SMS. Their stratigraphy shows no evidence of contemporaneous development with the surrounding main basins. We propose that the SJRb was formed during the Pleistocene and its connection with the ZAPb established during the Holocene. The SJRb is one of the youngest geomorphic systems in the region and represents a potential location where early stages in the evolution of a continental sedimentary basin in arid environments can be studied. The high biological diversity in the Tehuacán and Alta Mixteca regions and the close relationship of some species with particular landforms can hold valuable genetic tools to provide time constraints for geomorphic evolution. Studies of more regional basins are important in order to gain a better understanding of the tectonic regimes, timing and causes of crustal extension as well as to provide a clearer picture of environmental changes on a regional scale.

Declarations

Author contribution statement

Javier Medina-Sánchez: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sue McLaren: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alfonso Valiente-Banuet: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

José Ortega-Ramírez: Performed the experiments; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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