Chapter 6. Conclusions and outlook

The Tepoztlán Formation represents a remnant continental arc succession, displaying the initial phase of the Transmexican Volcanic Belt. The depositional patterns of the Tepoztlán Formation record volcaniclastic re-sedimentation in alluvial settings related to erosion and remobilization of huge volumes of ignimbrites and lava following explosive and effusive eruptions during the Lower Miocene. Vertical facies changes show that the fluvial system was superseded by progradational active fan lobes. Lateral facies distributions correspond to episodic influxes of volcanic material (pyroclastic, autoclastic, lava) from several point sources in the north and the south into a fluvio-lacustrine setting. The sources of the material, volcanic edifices and their aprons, are supposed to have been located north of Tepoztlán in the area that today belongs to the Sierra Chichinautzin and south of Malinalco. Direct evidence for a volcanic centre, however, could only be obtained for the latter, erupting mostly during the deposition of the Malinalco Member. In the Sierra Chichinautzin the presumable centres are buried under younger volcanic deposits. The source location within the Sierra Chichinautzin suggests an early activation of volcanism in this area during the Lower Miocene which was later reactivated during Pliocene-Quaternary times with similar LILE, REE and HFSE trends (Torres-Alvarado et al., in prep.). Furthermore, the three depositional models give evidence for an eastward shifting of volcanic activity within time from Malinalco to Tepoztlán.

The volcaniclastics of the Tepoztlán Formation accumulated mainly in proximal to medial distances to their source area in volcanic flank and apron settings, pointing to several small stratovolcanoes erupting into lowlands. Initially, pyroclastic material was mostly reworked by sheet floods and fluvial processes, indicating that volcanic centres were small and possibly more distant to the main depositional area. Increased production of volcanic material, related to volcanic edifice growth led to a progradation of the volcanic depositional system, which temporarily overloaded and buried the fluvial system with debris. Thick pyroclastic flows spread over the area which still had a smooth topography. Continuous build-up of the volcanic centres, however, accentuated the topography, and mass flows became more and more the dominant depositional process with intense mixing and reworking of primary volcanic products. The fact that the initial drainage system had a flow direction from west to east could indicate an outflow of the river system into the ancient Gulf of Mexico.

The here presented palaeomagnetic and geochronologic data are the basis for a first chronostratigraphy of the Lower Miocene volcaniclastic Tepoztlán Formation, establishing a reliable magnetostratigraphy which is correlated to the GPTS of CK95. The time of deposition of the Tepoztlán Formation ranges between 22.8 and 18.8 Ma (6Bn.1n-5Er), implying that the formation studied represents the deposits of the initial phase of the TMVB. Reliable palaeomagnetic and lithological correlations of nine individual sections enabled to establish a detailed overall stratigraphic framework. The results are consistent with the beginning evolution of the TMVB as stated by Ferrari et al. (2003) and Gómez-Tuena et al. (2007). Together with the San Nicolás Basaltic Andesite in Malinalco (García-Palomo et al., 2000), the Zitácuaro Volcanic Complex in Michoacán (Capra et al., 1997) and the volcanic rocks in the deepest part of the Mexico City Basin (Ferrari et al., 2003), the Tepoztlán Formation thus belongs to the few remnants of the ancestral TMVB.

In the frame of this study, a new subdivision of the Tepoztlán Formation into three units is proposed, according to the dominant type of deposition: (1) the fluvial dominated Malinalco Member (22.8 – 22.2 Ma), (2) the volcanic dominated San Andrés Member (22.2 – 21.3 Ma) and (3) the mass flow dominated Tepozteco Member (21.3 – 18.8 Ma).

The diverse Lower Miocene microflora from Tepoztlán allows to reconstruct the vegetation and climate during the initial phase of the evolution of the Transmexican Volcanic Belt. It is interpreted as recovery vegetation following disruption by several episodes of volcanic activity. The vegetation units are characterised by riparian and deciduous forest elements, represented by 38 angiosperm, seven gymnosperm and eight pteridophyte/bryophyte taxa. Applying the coexistence approach, the first quantitative climatic reconstruction of the Lower Miocene in Central Mexico is established. The Lower Miocene (Upper Aquitanian – Lower Burdigalian) was a period of cool temperate and humid climate in this area pointing to an already highly elevated area with volcanic edifices clearly exceeding 3000 m in altitude. The data reveal only small fluctuations in the palaeoclimatic parameters. Over the entire period the temperatures tend to decrease about 2° C which is interpreted to indicate an increase in elevation during the growth of a volcanic induced alluvial fan within the study area. The seasons during the time of deposition of the Tepoztlán Formation were strongly affected by the monsoon. Furthermore, the data show that the seasonality was stronger compared to the modern climate as documented by colder winters and warmer summers which was due to the open Central American Seaway and thus a different distribution of land and sea masses during the Lower Miocene.

Implications for the evolution of the TMVB

Despite the huge number of publications on its tectonic framework, stratigraphy, petrology, geochemistry, and geophysics the evolution of the TMVB is still not fully understood. Especially its initial phase from Early to Middle Miocene time is still lacking detailed information, due to the fact that wide areas of the volcanic arc are covered by several hundred meters thick Late Miocene to Quaternary lava flows. Especially the southern limit of the central portion of the TMVB, to which the study area belongs, is covered by volcanic deposits from Nevado de Toluca and Popocatépetl volcanoes and from the volcanic field of the Sierra de Chichinautzin (Alaniz-Álvarez and Nieto-Samaniego, 2007).

Besides the Tepoztlán Formation, the calc-alkaline andesites of the Sierra de Mil Cumbres and Sierra de Angangueo volcanic complexes in the State of Michoacán (Pasquaré et al., 1991; Capra et al., 1997), basaltic lavas in the Tenancingo area (Ferrari et al., 2003) and basaltic and andesitic lavas in the deepest part of the Mexico City basin (Ferrari et al., 2003) are considered to be the oldest remnants of the initial phase of the TMVB, which could be studied so far, ranging in age from 22.7 to 16 Ma. In later time, volcanism migrated further away from the trench, forming stratovolcanoes and lava cones, ranging in age from 15 to 10 Ma (Gómez-Tuena et al., 2007). These volcanic rocks can be found along the border of the states of Querétaro and Guanajuato (Carrasco-Núnez et al., 1989; Pérez-Venzor et al., 1996; Valdéz-Moreno et al., 1998; Verma and Carrasco-Núnez, 2003) and in the state of Puebla (Carrasco-Núnez et al., 1997; Gómez-Tuena and Carrasco-Núnez, 2000). The emplacement of dykes within the Tepoztlán Formation (15.83 ± 1.31 Ma) falls into this time frame and is related to a period of plutonic to subvolcanic body emplacement and large fissure eruptions with widespread lava plateaus between the states of Nayarit and Veracruz (Ferrari and Rosas-Elguera, 2000; Ferrari, 2004; Ferrari et al., 2005). Fig. 47 shows the location of the early arc (Early to Late Miocene), which extended between the cities of Morelia and Querétaro and the Gulf of México, already showing an E-W orientation. So far, there is no evidence for any Early to Mid-Miocene volcanic activity to the west of Morelia and Querétaro cities (Gómez-Tuena et al., 2007). However, so far, no model can explain this volcanic gap.

Another open question is the transition of volcanism from the N-S oriented Sierra Madre Occidental (SMO) to the E-W oriented TMVB before and during its initial phase. The SMO, a volcano-plutonic belt, dominated by rhyolitic and granitic rocks, is the largest silicic igneous province of the Cenozoic area (Ferrari et al., 2007). It stretches out along the western coast of Mexico (Fig. 1) and ranges in age from Cretaceous to Oligocene (Ferrari et al., 2007). After a period of reduced volcanic activity at the end of the Oligocene, a change in the dominant composition of volcanic rocks, from silicic to intermediate and mafic composition, took place (Ferrari et al., 2000b). This change has been observed in the volcanism all-over central Mexico and has been interpreted as the limit between SMO and the TMVB (Ferrari et al., 1994a; 1999). Ferrari et al. (2000b) describe this hiatus, lasting for about 10 Ma, to be mostly of Middle Miocene time and refers to the time of termination of the SMO volcanism, fitting well with the waning of the subduction off Baja California, which, at this latitude, took place between 14 and 12 Ma (Lonsdale, 1991). However, Gómez-Tuena et al., (2007) and Alaniz-Álvarez and Nieto-Samaniego (2007**)** note that this hiatus in volcanism was documented in several different locations throughout the TMVB during different times. In the Taxco-Tepoztlán area, the volcanic hiatus between the predominantly rhyolitic volcanism of the SMO and the andesitic to basaltic volcanism of the TMVB appeared between about 31 and 21 Ma (Alaniz-Álvarez and Nieto-Samaniego, 2007). Here, the Teneria Formation with rhyolitic domes and pyroclastic flows represents the youngest volcanic rocks of the SMO, having a K-Ar age of 31.6 Ma (Alaniz-Álvarez et al., 2002). The volcanic material of the

Balsas Group, underlying the Tepoztlán Formation in Malinalco and San Andrés would therefore be related to the SMO volcanism. K-Ar ages obtained from intercalated volcanic rocks in the Tilzapotla-Taxco region, south of the study area, show that the main episodes of deposition occurred during the Eocene (35.2, 38.5 and 44 Ma; Morán-Zenteno et al., 2007).
So far, with 22.7 Ma, the Tepoztlán Formation can be considered the oldest formation of the TMVB and its volcanic activity as the beginning of intermediate to mafic volcanism after a hiatus of 9 Ma. However, this does still not explain the tectonic and geodynamic circumstances under which the TMVB formed.

Today, geophysical evidence clearly indicates that the Cocos and Rivera oceanic plates are currently being subducted under the continent in the direction of the TMVB (Urrutia-Fucugauchi and Del Castillo, 1977; Urrutia-Fucugauchi and Böhnel, 1987; Pardo and Suárez, 1993, 1995). For this reason, most researchers consider that magma genesis in the TMVB, as well as the oblique orientation to the trench, must be related in some way to the subduction process (Gómez-Tuena et al., 2007). Some researchers doubt this relation because of the unusual presence of an extensional tectonic regime, accompanied with the existence of rocks with compositional similarity with ocean-island basalts (OIB) and mid-ocean ridge basalts (MORB; Márquez et al., 1999; Verma, 1999; Sheth et al., 2000; Verma, 2000, 2002). However, the overall geochemical, geochronological, and geological evidence suggests that even these questionable volcanic fields were to some extent influenced by the Pacific subduction regime (Negendank et al., 1985; López-Infanzón, 1991; Gómez-Tuena et al., 2003; Ferrari et al., 2005; Orozco-Esquivel et al., 2007). The arc magmas are supposed to represent some sort of recycling of materials derived from the mantle, the subducted crust, and the overriding plate. At the latest, during Middle to Late Miocene times, it has to be considered that the subduction zone was controlled by two independent oceanic plates with different ages, compositions, convergence velocities, and subduction dip angles, gradually varying along the Middle America Trench. Moreover, the arc was emplaced over a geologically diverse continental crust with different ages, thicknesses, and compositions. The results of this study support this theory, stating that the source of the magmas of the Tepoztlán Formation was probably a heterogeneous mantle and that the magmas evolved by assimilation of country rock and further fractional crystallization in the upper crust (Torres-Alvarado, in prep.).

Global plate reconstructions indicate that the Cocos plate was formed at about 23 Ma when the Farallon plate fragmented into two plates, which also created the Nazca plate to the south (Atwater and Stock, 1998; Lonsdale, 2005). This time coincides with the end of a time of reduced volcanic activity and with the beginning of increased volcanism of intermediate to mafic composition in the Taxco-Tepoztlán area. It may also explain the development of the initial phase of the TMVB. The progressive collision of the East Pacific Rise with the North America Plate at around 21 Ma (Demant et al., 1989) could furthermore explain an increased magma production within the newly formed magmatic arc and the phase of high production rate of pyroclastic and effusive material within the Tepoztlán Formation during the San Andrés Member (22.2 – 21.3 Ma). Ferrari et al. (2003) suggest that the velocity of subduction was the main factor in controlling both the volcanic flux and the strain rate in the western TMVB.

Each sector of the arc is controlled by a complex state of stress and deformation history that involves extensional and strike-slip faulting that has been acting concurrently with magmatism. As mentioned before, especially this extensional faulting is regarded by some authors as a sign for a rifting as the cause for the development of the TMVB. However, Henry and Aranda-Gómez (1992) suggest this extension to have taken place in a backarc setting and Ferrari et al. (2003) describe that the extensional faulting, the signs of rifting and even back-arc spreading are related to the subduction of very old lithosphere with a high dip angle.

After the deformational phases belonging to the Laramide orogeny and lasting until the Eocene with E-W or WSW-ENE oriented extension and Basin-and-Range type tectonics, since the Oligocene, the tectonic activity and contemporaneous volcanism of the TMVB was focused to several fault systems with N-S oriented extension. In the western sector this tectonic activity was mainly represented by the E-W trending Chapala rift system (Johnson and Harrison, 1990; Garduno et al., 1993), in the central sector, between the Chapala Lake and the Popocateptl-Ixtaccihuatl, where the study area is located, by the E-W trending La Pera fault system.

The type of deformation that occurred in the initial stages of the formation of the TMVB is difficult to describe, because most of the structures produced at that time are covered by a volcanic layer up to 4 km deep. However, deep wells drilled by PEMEX (Petróleos Mexicanos) in the Mexico City basin reaching 4000 m give evidence on the La Pera fault system (Marsal and Graue, 1969; Oviedo, 1970; Pérez-Cruz, 1988). Furthermore, gravimetric anomalies reported in Urrutia-Fucugauchi and Flores-Ruiz (1996) and Ferrari et al. (2002) support the existence of this structure which is thought to have developed in Eocene-Oligocene times. The La Pera fault system is thought to be mainly located under the Sierra de Chichinautzin (Ferrari et al., 2002; Siebe et al., 2004; Delgado-Granados et al., 1995) and seems to have also controlled the monogenetic volcanism in the Sierra Chichinautzin volcanic field (Márquez et al., 1999). The extension to the north of this system corresponds to normal faults with a northern inclination found near Malinalco (González-Cervantes, 2004) and Tenango (Márquez et al., 1999; García-Palomo et al., 2000). This is particularly of interest with regard to the development of the Tepoztlán Formation within the study area as the La Pera fault system, existing since pre-Miocene times, explains the E-W trending axial braided-river system and also the assumed E-W trending alignment of stratovolcanoes and lava domes. Studies throughout the TMVB suggest that emplacement of magmatism always occurred in the maximum extensional strain zones (Alaniz-Álvarez et al., 1998; García-

Palomo et al., 2000). These zones acted as weakness zones through which the melts could ascend to form the early volcanic arc (Mooser, 1972). In this way, the development of the E-W trending fault system could have significantly influenced the shifting from a N-S to an E-W trending volcanism at the end of the SMO and the initial phase of the TMVB through a docking of the magmatic arc volcanism to the newly developed fault system.

Within the study area, an eastward shift in volcanic activity from Malinalco to Tepoztlán and Tlayacapan from 22.7 to 18.7 Ma was detected, pointing to an eastward shift of extensional faulting and contemporaneous volcanism. However, comparable data are still lacking, especially in the central sector of the TMVB. Furthermore, so far, no comparable data are available about the palaeoelevations of the early TMVB which could prove the elevations as suggested by the palynological results of this study.

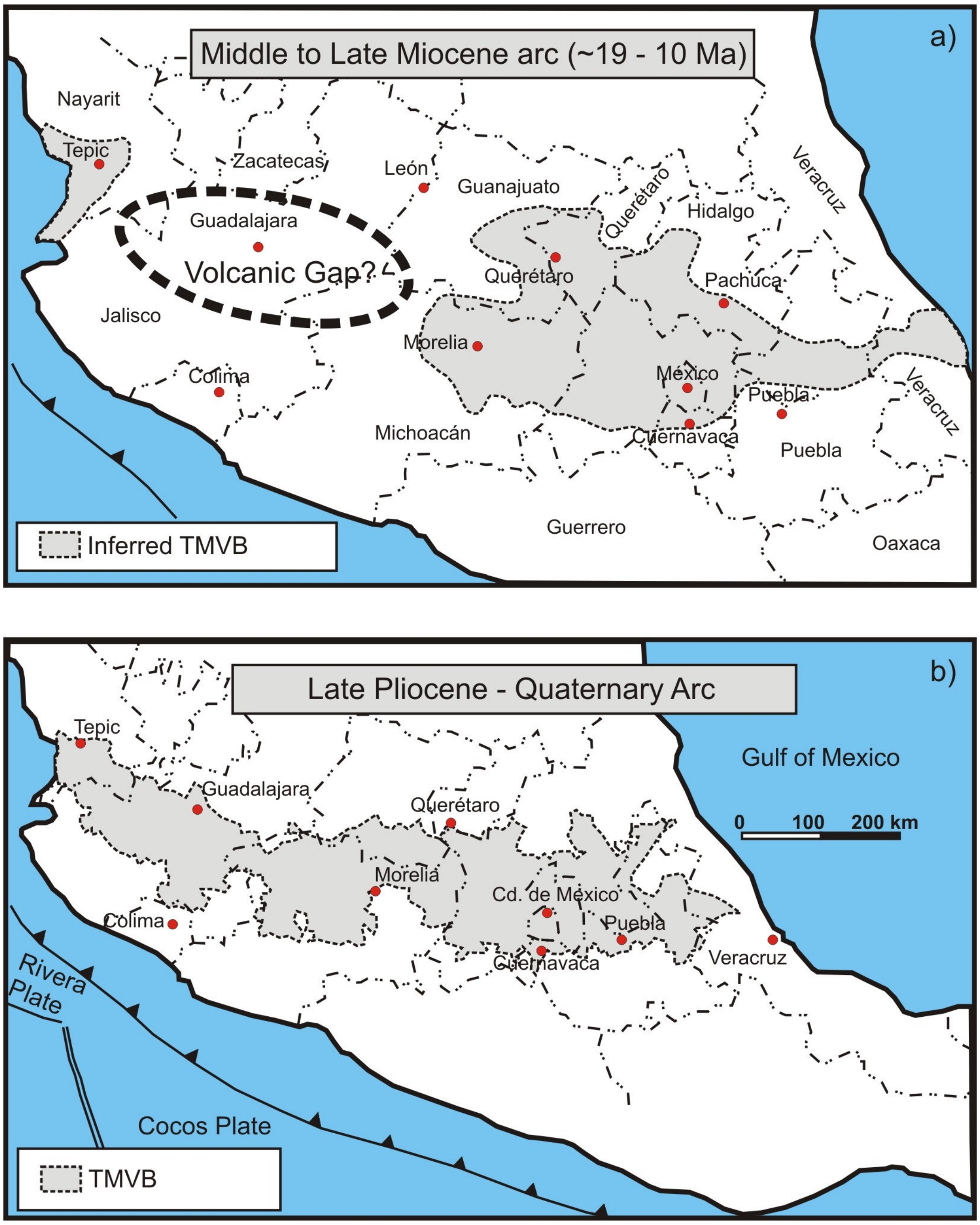

Figure 47. The distribution of the TMVB a) in the Miocene, b) since the Pliocene (Gómez-Tuena, 2007).

Outlook

Within this study a detailed description and interpretation of the circumstances leading to the development of the Tepoztlán Formation as part of the initial phase of the TMVB is presented. However, understanding the complex geologic situation during the early arc development requires more detailed studies of the region and an interdisciplinary approach, integrating geology, geochemistry, geophysics and palynology. First of all, future studies on the initial phase of the TMVB should involve a detailed compilation and description of all known Early and Middle Miocene volcanic outcrops within the borders of the early arc. This will include the Mexican states of Michoacán, Querétaro, Guanajuato, México, Morelos, Hidalgo and Puebla. The few existing studies on Early Miocene rocks within Central Mexico are far from being comprehensive and geochronological and geochemical data of many of these rocks are still lacking. One starting point for more detailed studies should involve the Miocene volcaniclastics from drill cores (PEMEX) of the Valley of Mexico and from the basis of the Nevado de Toluca which are supposed to be of the same age as the Tepoztlán Formation and thus belong to the first rocks produced during the development of the TMVB. The results are supposed to give important insights on the genetic relationships of these deposits with the Tepoztlán Formation and probably give further insights on the magmatic source. Special emphasis should also be set on tectonic studies within the central sector of the TMVB and should involve field work as well as analyses of the existing seismic transects, which may give evidence for the Early Miocene stress regimes, and provide implications about the tectonic situation during this time. The results would be especially interesting with regard to the proposed eastward shift of deformation and contemporaneous volcanic activity which is indicated by the presented depositional model.

Additionally, further studies should include detailed palynological investigations on a transect of Miocene key sections from Central Mexico to the Gulf of Mexico. The results of this study are seen to broaden the knowledge about elevational effects on the Miocene palaeoflora and thus enable to calibrate climatological data that were attained by means of the coexistence approach. Tectonic as well as palynological studies should focus on the detection of the existence of an early uplift of the TMVB region, explaining the strong monsoonal activity as suggested by the here presented palynological data.

Furthermore, it would be interesting to get to know more about the time between the shifting of volcanic activity from the SMO to the TMVB. Here, studies on the Balsas Group, south of Malinalco and Tepoztlán, would be particularly of interest. This group of deposits, probably ranging in age from the Cretaceous to the Oligocene but still lacking detailed geochronology and geochemical data, still contains the least studied rocks in Central Mexico. Therefore, it is supposed to provide valuable information about the development of the SMO and especially the situation during the volcanic hiatus preceding the initial phase of the TMVB.

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