Chapter 5. Palynology

5.1. Materials and methods

Spanning the entire sedimentary succession of the Tepoztlán Formation, samples were taken both north and south of the type locality (Tepoztlán, 18.59°N, 99.05°W, 1717 m) in the SA1 and 2 and the TEP sections.

For palynological analyses 38 samples of 150 g each were investigated, representing various lithologies of volcaniclastics of which 23 samples turned out to be barren. The best results were attained from the fine-sandy layers of tuffaceous sandstone, very fine-grained clayey layers on top of ignimbrites (co-ignimbrite ash-cloud deposits) that were affected by weathering processes, the fine-grained matrix of lahars and clayey to silty, thinly-bedded layers on top of lahars or fluvial deposits (waning flow deposits; Tab. 8). For the final analysis 15 samples from 1639 m to 2266 m were taken in irregular intervals depending on lithology (Fig. 41).

All samples were processed following the standard palynological processing techniques, which include the treatment with HCl (33%), HF (73%) and heavy liquid separation with $ZnCl_2$ solution. All samples were centrifuged and washed with distilled water after each step. The residue was cleaned by sieving using an 11 µm mesh. For strew mounts Eukitt, a commercial mounting medium on the base of resin, was used. All samples, residues and slides are stored in the Institute of Applied Geosciences at the Technische Universität Darmstadt, Germany.

Table 8: Elevation, lithology and age of the samples taken for palynological analysis.

Stratigraphic Section	**Elevation above sea level**	**Sample No.**	**Lithology**	Age
Tepozteco	2266 m	15	Debris flow deposit (lahar)	**19.0 – 18.8 Ma**
	2076 m	14	Debris flow deposit (lahar)	**20.1 – 19.0 Ma**
	1906.7 m	13	Tuffaceous sandstone (fluvial)	**21.3 – 20.9 Ma**
	1904.7 m	12	Tuffaceous sandstone (fluvial)	
	1904.3 m	11	Tuffaceous sandstone (fluvial)	
	1904 m	10	Tuffaceous sandstone (fluvial)	
	1903.2 m	9	Tuffaceous sandstone (fluvial)	
	1881.5 m	8	Tuffaceous sandstone (fluvial)	**21.8 – 21.3**

	1881 m	7	Tuffaceous sandstone (fluvial)	**Ma**
San Andrés	1848 m	6	Debris-flow deposit (lahar)	**21.9 – 21.8 Ma**
	1843 m	5	Tuff (pyroclastic flow deposit)	
	1820.5 m	4	Tuff (pyroclastic flow deposit)	**22.2 – 21.9 Ma**
	1734.5 m	3	Debris-flow deposit (lahar)	**22.6 – 22.5 Ma**
	1639.7 m	2	Tuffaceous sandstone (fluvial)	**22.8 – 22.6 Ma**
	1639 m	1	Tuffaceous sandstone (fluvial)	

The amount of palynomorphs is low within the samples studied, which is due to the sediment types. The counting is based on max. 100 pollen grains and spores per slide. About 53 individual palynomorphs (pollen and spores, see Tab. 9) were identified and counted at 400x magnification. The identification of palynomorphs is based on the works of Heusser (1971, 1977), Markgraf and D'Antoni (1978), Thiele-Pfeiffer (1980), Wingenroth and Heusser (1983), Mohr (1984), Roubik and Moreno (1991) and Herrmann (2007). The samples reveal a well preserved and diverse pollen and spore assemblage.

Two Tilia diagrams of the San Andrés and the Tepozteco section were constructed from the palynological data. The results are analysed and interpreted to infer their palaeoenvironmental implications.

In addition, the 53 pollen and spore taxa are used to reconstruct the climate with the coexistence approach (Mosbrugger and Utescher, 1997). This method is applied in two steps. The first step includes that for all taxa the nearest living relatives and their climatic tolerances have to be determined with respect to certain climate parameters. In the second step, the interval within which all nearest living relatives of the fossil flora can coexist is calculated for these climate parameters (cf. Mosbrugger and Utescher, 1997). The coexistence interval represents a reasonable estimator of the past climate in which the fossil flora was able to exist. The following climatic parameters are considered: MAT – mean annual temperature (°C); TCM – mean temperature of the coldest month (°C); TWM – mean temperature of the warmest month (°C); and MAP – mean annual precipitation (mm).

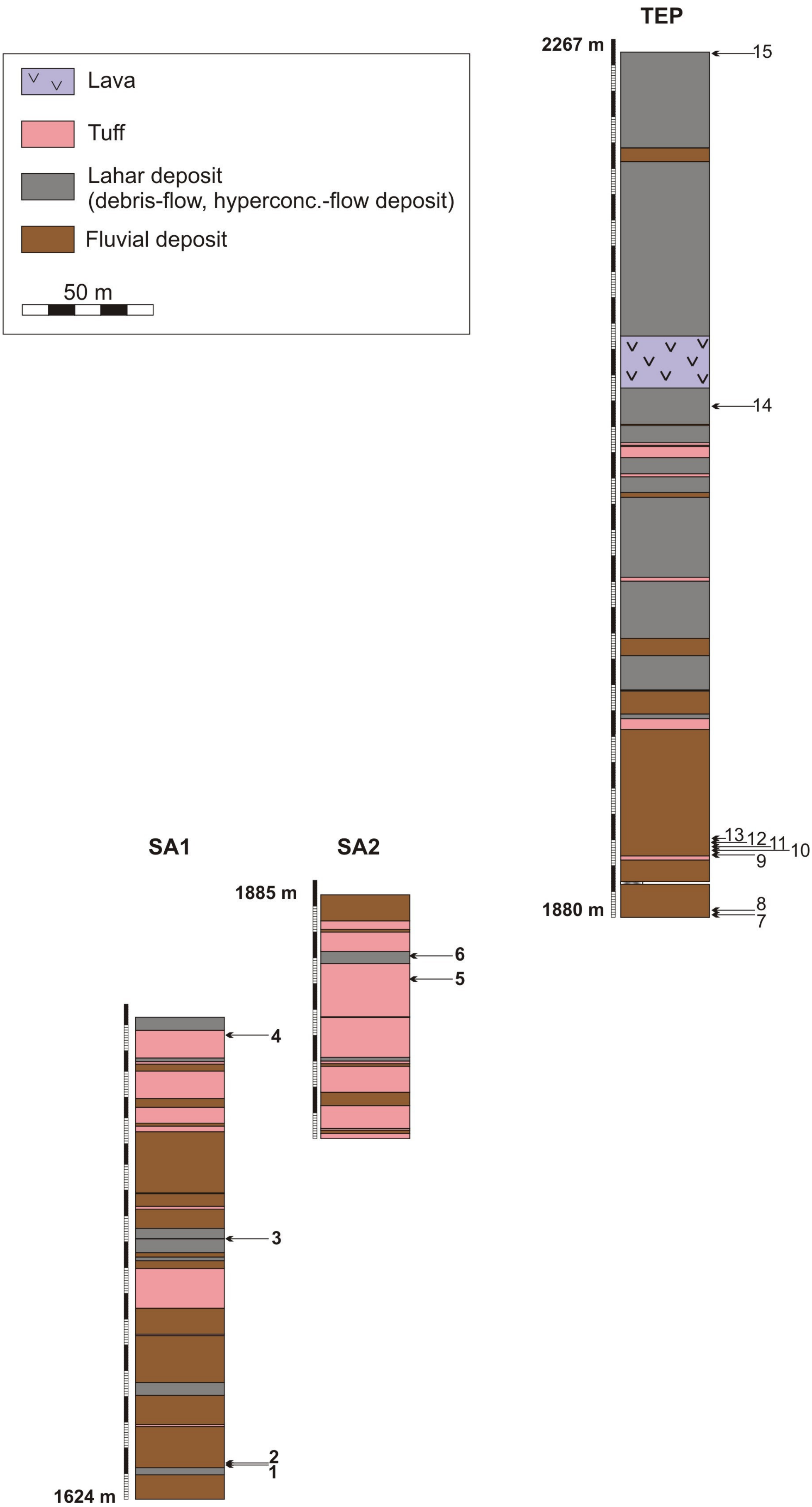

Figure 41. Schematic section of the Tepoztlán Formation to the south and the north to Tepoztlán, showing the sample horizons and their lithologies.

5.2. Results

The Tepoztlán palynoflora is predominantly composed of 38 angiosperm and seven gymnosperm pollen taxa. Additionally, eight pteridophyte and bryophyte spore taxa occur, showing low abundance (see Tab. 9). The taxa can be assigned to the following plant communities: riparian forest, deciduous forest and mixed coniferous-broadleaved forest. Cosmopolitan taxa can exist in all of these plant communities. The only exception is Palmae, existing in subtropical to tropical arid areas.

Table 9: List of pollen and spore taxa and their corresponding plant communities

Palynomorphs	Recent plant	Plant community/ vegetation unit
	Pteridophyta / Bryophyta	
Pteridophyta sp.	Dennstaedtiaceae cf. *Dennstaedtia sp.*	Riparian/ deciduous forest
Sporopollenites sp. 1	Indet	-
Sporopollenites sp. 2	indet 2	-
Verrucingulatisporites sp.	Pteridaceae	Cosmopolitan
Retitriletes sp.	Lycopodiaceae *Lycopodium* sp.	Deciduous forest
cf. *Stereisporites* sp.	Sphagnaceae cf. *Sphagnum* sp.	Wetland/ Riparian/ deciduous forest
Perinomonoletes sp.	Polypodiaceae cf. *Blechnum* sp. cf. *Asplenium* sp.	Deciduous forest
Laevigatosporites sp.	Thelypteridaceae	Wetland/ Riparian forest
	Gymnosperms	
Inaperturopollenites sp.1	Cupressaceae	Deciduous forest
Pinuspollenites sp. 1-5	Pinaceae *Pinus* sp.	Coniferous/Mixed coniferous-broadleaved forest
cf. *Cedripites* sp	Pinaceae *Cedrus* sp.	Deciduous forest
Inaperturopollenites sp.2	Taxodiaceae *cf. Sequoia sp.*	Riparian forest
cf. *Piceapollis* sp	Pinaceae *Picea* sp.	Mixed coniferous-broadleaved forest
Abiespollenites sp.	Pinacaceae *Abies* sp.	Coniferous/Mixed coniferous-broadleaved forest
Ephedripites sp.	Ephedraceae *Ephedra* sp.	Cosmopolitan
	Angiosperms	
Cyperaceaepollis sp.	Cyperaceae	Riparian forest
Graminidites sp.	Poaceae	Cosmopolitan
Monocolpopollenites sp.	Liliaceae	Wetland/ riparian forest
Trivestibulopollenites betuloides	Betulaceae *Betula* sp.	Riparian forest
Momipites sp.	Juglandaceae *Engelhardia* sp.	Deciduous forest
Triporopollenites sp. 1	indet 1	-
Triporopollenites sp. 2	Apocyanaceae cf. *Prestoria* sp.	Riparian forest
Carpinidites sp.	Betulaceae *Carpinus* sp. *(Carpinus cf. tropicalis* subsp. *Mexicana)*	Deciduous forest
Periporopollenites sp. 1	indet 2	-

Alnipollenites verus	Betulaceae *Alnus* sp.	Riparian forest
Chenopodipollis sp. 1+2	Amaranthaceae cf. *Iresine* sp. 1+2	Cosmopolitan
Periporopollenites sp. 2	Plantaginaceae *cf. Plantago* sp.	Cosmopolitan/ wetland
Tricolpopollenites sp. 1	cf. Brassicaceae	Cosmopolitan
Quercoidites sp. 1	Fagaceae *Quercus* sp. *1*	Deciduous forest
Tricolpopollenites sp. 2	indet 3	-
cf. *Ilexpollenites* sp.	Aquifoliaceae *cf. Ilex* sp.	Deciduous forest
Tricolpopollenites sp. 3	indet 4	-
Tricolpopollenites sp. 4	cf. Brassicaceae, cf. Oleaceae	Cosmopolitan
Quercoidites sp. 2	Fagaceae *Quercus* sp. *2*	Deciduous forest
Quercoidites sp. 3	Fagaceae *Quercus* sp. *3*	Deciduous forest
Tricolporopollenites sp. 1	Fagaceae *Castanea* sp.	Deciduous forest
Tricolporopollenites sp. 2	indet 5	-
Tricolporopollenites sp. 3+4	Rutaceae 1+2 *cf. Zanthaxylon* sp. *1+2*	Cosmopolitan
Tricolporopollenites sp. 5	indet 6	-
Compositoipollenites sp. 1	Compositae 1	Cosmopolitan
Chenopodipollis sp. 3	Chenopodiaceae *Chenopodium* sp.	Cosmopolitan
Polyporopollenites undulosus	Ulmaceae *Ulmus* cf. *mexicana*	Deciduous forest
Tricolporopollenites sp. 5	indet 7	-
Caryapollenites sp.	Juglandaceae *Carya* sp.	Riparian forest
Tetracolporopollenites sp. 1	indet 8	-
Tricolporopollenites sp. 6	indet 9	-
Intratriporopollenites sp	Tiliaceae *Tilia* sp. (*T. americana* var. *mexicana*)	Deciduous forest
Artemisiapollenites sp.	Compositae *Artemisia sp.*	Cosmopolitan
Monocolpopollenites sp. 2	Palmae	Subtropical/ tropical
Periporopollenites sp. 3	indet 10	-
Tricolporopollenites sp. 3	indet 11	-
Tricolporopollenites sp. 6	indet 12	-
Faguspollenites sp.	Fagaceae *Fagus* sp.	Deciduous forest

5.2.1. Zoning of samples

Two Tilia diagrams document the palynomorphs of the San Andrés and Tepozteco sections (Figs. 42 and 43) and illustrate the changes in pollen and spore content within the Tepoztlán area. Pollen and spores are shown in percent of total sum (pollen + spores), charcoal particles are shown in their absolute numbers within a sample slide. The diagrams were divided into six zones with eight sub-zones, described below and are based on variations in the abundance of the dominant microflora taxa as well as the stratigraphical order in which samples have been taken. Furthermore, zones and sub-zones are characterised by their affiliation to a certain plant community or vegetation unit.

San Andrés section

Zone A: 22.8 - 21.9 Ma

Sub Zone A1 (strat. level: 1639.0 - 1639.7 m; age: 22.8-22.6 Ma)
This subzone is characterised by a dominance of cf. Rutaceae, Poaceae and *Pinus* (>10%). *Betula*, *Compositae sp.*, Cupressaceae/ Taxodiaceae, Cyperaceae and *Alnus* are common constituents, making up 4.3 – 8.5% of the total content of pollen and spores. *Carya*, cf. Cruciferae, Chenopodiaceae, *Castanea*, cf. *Iresine*, cf. *Prestoria* and *Quercus* are minor elements (< 2%). Charcoal particles reach a number of 156 particles per slide (p/s) on average.

Sub Zone A2 (strat. level: 1734.5- 1820.5 m; age: 22.6-21.9 Ma)
This subzone is characterised by a dominance of Poaceae, Cyperaceae, *Betula*, *Alnus* and *Pinus* (>10%). Cupressaceae/ Taxodiaceae, *Tilia*, *Compositae sp.* and *Carpinus* are common constituents, making up 2.9-6.3% of the total content of pollen and spores. Cf. Cruciferae, *Quercus* and cf. Rutaceae are minor elements (< 2%). Charcoal particles reach a number of 46 (p/s) in average.

Zone B: 21.9-21.8 Ma

Zone B (strat. level: 1843 m; age: 21.9-21.8 Ma)
This zone is represented by only one sample and is characterised by a dominance of *Betula*, *Quercus* and *Pinus* (>10%). Alnus makes up 3.6% of the total content of pollen and spores. No minor elements occurred. Charcoal particles reach a number of 110 (p/s).

Zone C: 21.9 - 21.8 Ma

Zone C (strat. level: 1848 m; age: 21.9-21.8 Ma)

This zone, represented by only one sample, is characterised by the dominance of *Compositae sp.*, *Betula*, *Quercus* and *Alnus* (>10%). *Pinus*, Poaceae and Cupressaceae/ Taxodiaceae are common constituents, making up 2.5-9.3% of the total content of pollen and spores. *Tilia*, Cyperaceae, *Carpinus*, *Castanaea*, *Carya*, Taxodiaceae, *Artemisia* and *Fagus* are minor elements (< 2%). Charcoal particles reach a number of 520 (p/s) on average.

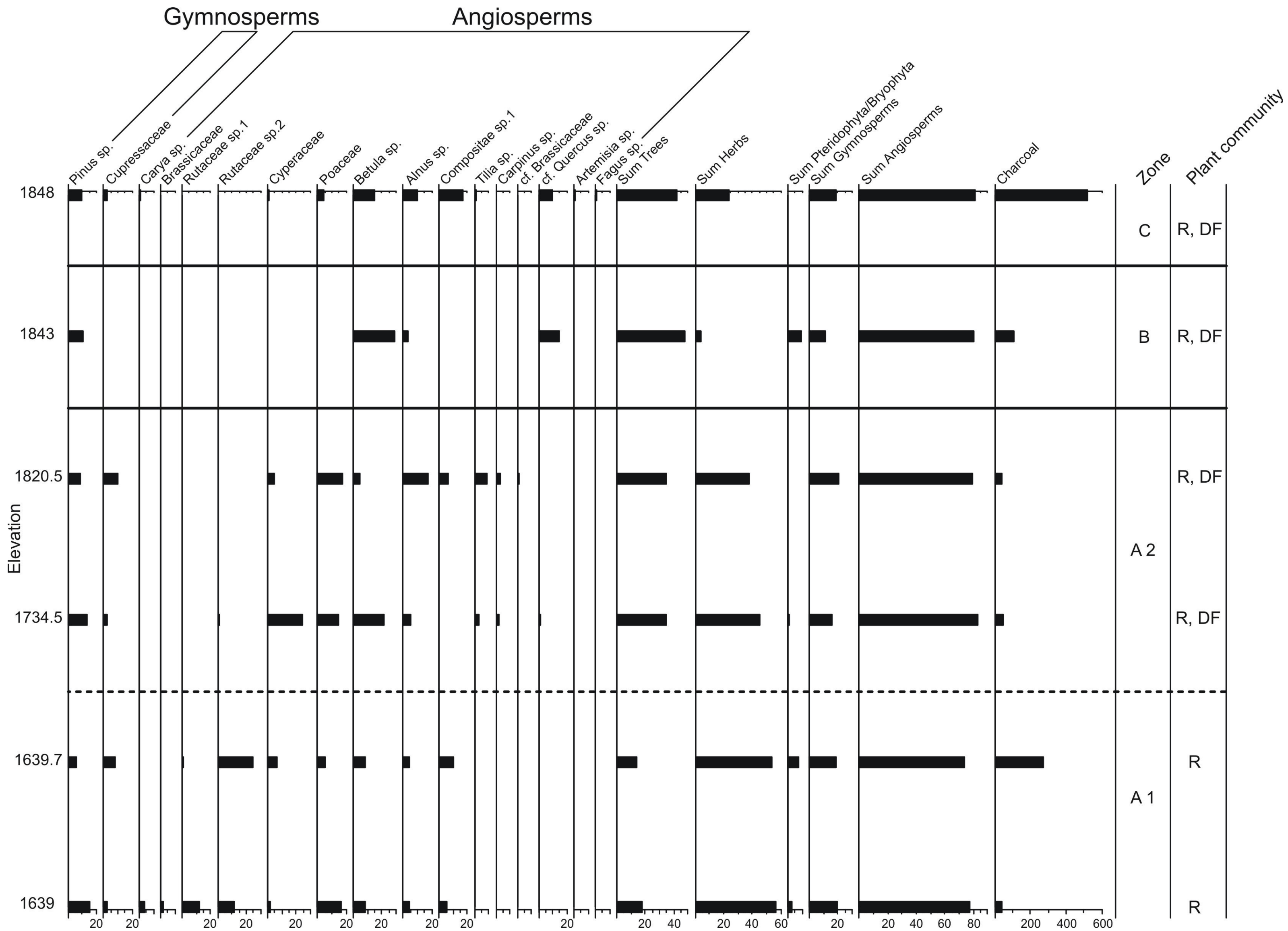

Figure 42. Tilia diagram, showing the percentages of palynomorphs within the San Andrés sections SA1 and SA2.

Summary of palynological data of the San Andrés section

The San Andrés section represents 1.5 Ma of deposition (22.8 - 21.3 Ma). The base of the section (Sub Zone A1) is characterised by the presence of *Pinus*, Cupressaceae, *Carya*, Rutaceae, Cyperaceae, Poaceae, *Betula*, *Alnus* and *Compositae* sp. The percentage of *Pinus* within the samples is relatively constant throughout the section. However, Cupressaceae show an increase in content through A1 and A2 and a sudden decline to zero percent in Zone B, and a re-appearance in Zone C with 2.5%. *Carya* appears only once in the lower part of the section (A1) and then again at the top of the section in Zone C. Rutaceae show an increase over Sub Zone A1 and a decrease in A2. In samples from younger strata Rutaceae are absent.
Cyperaceae are increasing from the basis of the section into A2, then they decrease and are completely absent in B. However, they are found again in Zone C. Poaceae behave in a similar way throughout the section. They also increase in A1 and A2, are absent in B and then reappear in Zone C. With a slight setback in A2 but an over all increase from A1 to C, *Betula* shows its highest content in B. Similar to the latter taxa is *Alnus*. Showing an increasing trend over A1 and A2 it is weak but still present in B and from there show an increase to C. In contrast, *Compositae sp.* shows an increase over A1 and A2 but is completely absent in B. However, it reoccurs in Zone C. The first appearance of *Tilia* and *Carpinus* takes place in A2 where they show a slight increase over this sub zone. In B *Tilia* and *Carpinus* are absent before they again appear in Zone C. *Quercus* also had its first appearance in A2 but is characterised by a steady increase over A2 and B to Zone C. Finally *Artemisia* and *Fagus* all have their first appearance in Zone C. The sum of gymnosperms and angiosperms also shows some changes throughout the section. Percentages of gymnosperm pollen taxa range between 10.9-20.7%, angiosperms between 73.9 - 82.8%. A steady increase in sum of tree pollen from Sub Zone A1 to Zone B can be noticed while, in contrast, there is a steady decrease in sum of herb pollen within the same Sub Zones. Beginning from Zone C this process is reversed again, showing an increase in herb pollen and a slight decrease in tree pollen. The content of charcoal is increasing through Zone A1, and then shows a sudden break with much lower values before it is steadily increasing from Zone A2 to C, again. Charcoal particles in Zones A1 and C (10 particles each) were measured and analysed. The mean length in Zone A1 is 42.5 µm, the mean width 19.1 µm (ratio 2.29) while the mean area is 860 μm^2. In Zone C the mean length of the charcoal particles is 43 µm, the mean width 21.4 µm (ratio 1.96) while the mean area is 1000 μm^2. The charcoal particles within the samples are dark brown to black in colour, sometimes with a brownish margin. A successive trend in the pollen content of the sample slides can be clearly noticed and is characterised by the initiation and absence of certain pollen and spore taxa within time as shown in the Tilia diagram (Fig. 42). This trend is reflected by a successive change of vegetation units, from riparian forest vegetation (Zone A1) to deciduous forest elements (Zone A2). Both elements dominate until Zone C.

Tepozteco section

Zone D marks the beginning of the Tepozteco section. Due to low thicknesses of single strata samples were taken in relatively small intervals in the lower part of the section. Clusters of samples, taken in close spatial intervals have been grouped together (Zone D and E). With increasing thicknesses of single strata up to 10s of meters in the case of debris flow deposits and decreasing accessibility of the outcrops only few samples could be taken (Zone F).

Zone D: 21.8 - 21.3 Ma

Zone D (strat. level: 1881.0-1881.5 m; age: 21.8-21.3 Ma)
This zone is characterised by a dominance of *Pinus* and Poaceae (>10%). *Tilia*, Cupressaceae/ Taxodiaceae, *Betula* and Cyperaceae are common constituents, making up 2.1-7.3% of the total content of pollen and spores. *Alnus*, Taxodiaceae, cf. *Prestoria*, *Carpinus*, cf. Cruciferae, *Compositae sp.*, *Cedrus* and *Artemisia* are minor elements (< 2%). Charcoal particles reach a number of 12 particles on average.

Zone E: 21.3 – 20.9 Ma

Sub Zone E1 (strat. level: 1903.2-1906.7 m; age: 21.3-20.9 Ma)
This subzone is characterised by a dominance of *Betula*, Cyperaceae and *Pinus* (>10%). *Quercus*, *Castanea*, *Alnus*, Cupressaceae/ Taxodiaceae, *Tilia*, Poaceae and *Compositae sp.* are common constituents, making up 2.1-8.0% % of the total content of pollen and spores. *Carpinus*, cf. Cruciferae, cf. *Prestoria* and *Ilex* are minor elements (< 2%). Charcoal particles reach a number of 120 (p/s) on average.

Sub Zone E2 (strat. level: 1904.3-1906.7 m; age: 21.3-20.9 Ma)
This subzone is characterised by a dominance of *Betula*, *Alnus*, Cyperaceae and Poaceae (>10%). *Pinus*, *Quercus*, *Tilia*, *Compositae sp.*, cf. Cruciferae and cf. Rutaceae are common constituents, making up 2.1-9.6% of the total content of pollen and spores. *Carpinus*, Cupressaceae/ Taxodiaceae and Chenopodiaceae are minor elements (< 2%). Charcoal particles reach a number of 120 (p/s) on average.

Zone F: 20.1 – 18.8 Ma

Zone F (strat. level: 2076.5- 2266 m; age: 20.1-18.8 Ma)
This zone is characterised by a dominance of *Pinus* and *Quercus* (>10%). Poaceae, *Betula*, *Artemisia*, *Tilia* and *Alnus* are common constituents, making up 4.0-8.1% of the total content of pollen and spores. *Carpinus*, Cyperaceae, cf. Rutaceae, *Castanea*, *Picea* and *Compositae sp.* are minor elements (< 2%). Charcoal particles reach a number of 351 (p/s) on average.

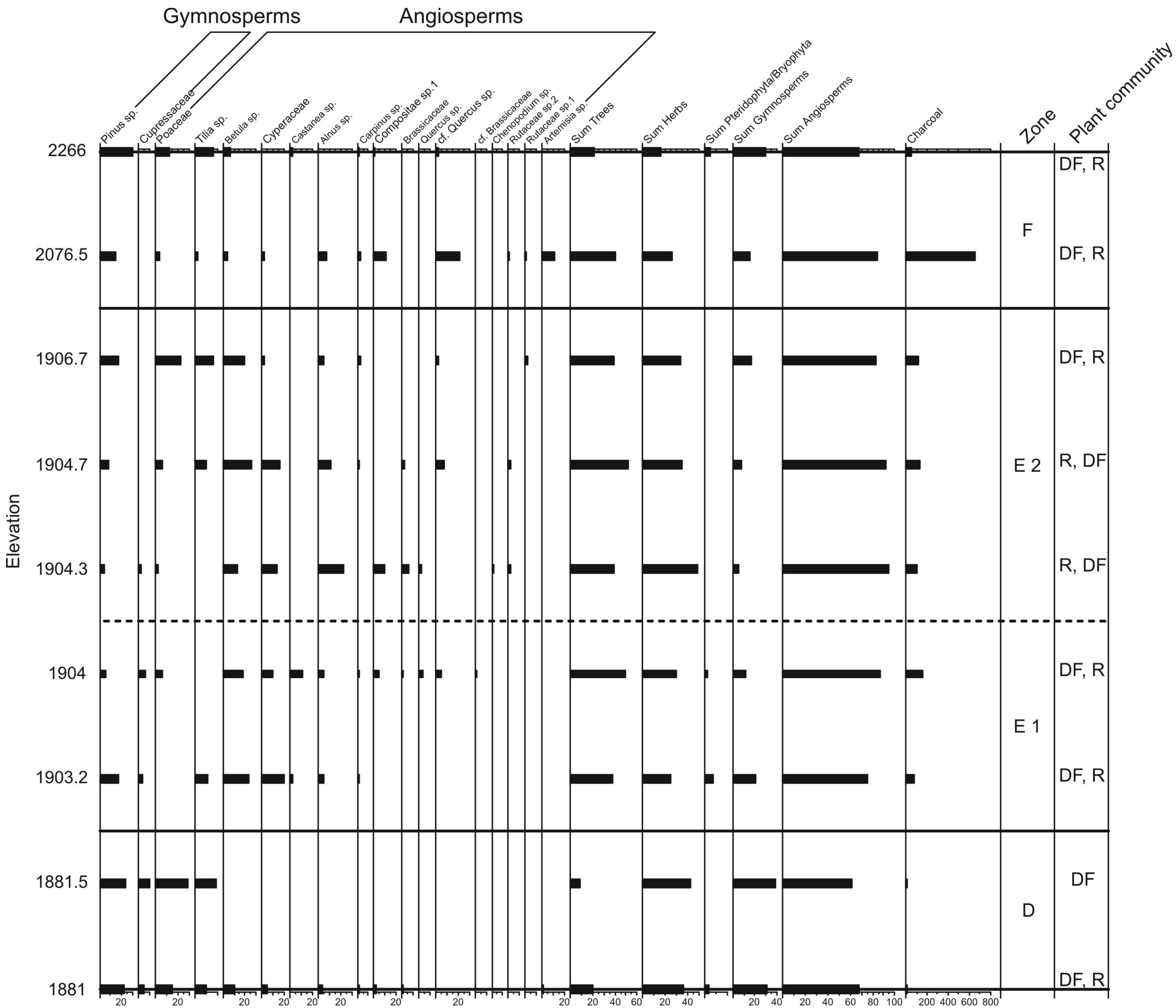

Figure 43. Tilia diagram, showing the percentages of palynomorphs within the Tepozteco section TEP.

Summary of palynological data of the Tepozteco section

The Tepozteco section represents 3 Ma of deposition (21.8 - 18.8 Ma). The base of the section (Zone D) is characterised by the presence of *Pinus*, Cupressaceae, Poaceae, *Tilia*, *Betula*, Cyperaceae, *Alnus*, *Carpinus*, *Compositae* sp. and *Artemisia*. *Pinus*, appearing in all samples, is characterised by a decrease from D to E2 (1904.3 m), and followed by an increase to F. Cupressaceae are steadily decreasing to E2 from whereas they are absent in the following samples. Poaceae are present in all samples besides one at 1903.2 m**,** with changing percentages and an increasing trend in each sub zone. Just as Poaceae, *Tilia* is present in all samples except at 1904 m. An increase in D can be noticed, followed by a decrease in E1 which in turn is followed by an increase in E2 and F, again. *Betula* is present in all samples except at 1881.5 m, thus showing a decrease in Zone D. After a reoccurrence in E1 and a decrease through this zone, *Betula* percentages are relatively steady throughout E2 and finally increase again in Zone F. Cyperaceae are not present at 1881.5 m in D. They are characterised by relatively high values at the base of each sub zone and a decrease to the top of each zone. *Castanea* has its first appearance in E1. It is absent in E2 and can only be found within the last sample at top of F, again. *Alnus* is present with a very small percentage at the base of A, then is absent at 1881.5 m. The steady values in E1 change to a decreasing trend through E2 and F until it finally fails to appear again at top of F.

Carpinus is characterised by more or less steady values in all samples except one taken at 1881.5 m. *Compositae* sp. appears at base of D, then is absent at 1881.5 m and 1903.2 m but reoccurs at the top of E1. From an increasing trend to E2 can be noticed which is ended by an absence until F from where another decrease can be seen. *Quercus* is absent at the top of Zone D, then reappears at 1904 m in E1, showing an increase until 2076.5 m in F from where another decrease can be noticed. *Chenopodium* sp. appears only at 1904.3 m in E2. Rutaceae also have their first appearance in E2. From there they are characterised by relatively steady values. *Artemisia* finally only occurs in Zone F. The sum and ratio of gymnosperms and angiosperms also shows some changes throughout the section. Percentages of gymnosperm pollen taxa range between 5.8 - 38.1%, angiosperms between 61.9 - 94.1%. The two pollen types show converse trends with a decrease from D to E2, followed by an increase to F in the case of gymnosperms. In contrast, angiosperms show an increase from Zone D to E2 and a decrease from E2 to Zone F. A similar trend of opposing sine curves is shown by the appearance of tree and herb taxa. The content of charcoal is steady increasing from Zone D to F. This is a sign for an increase in fires within the study area, caused by volcanic activity. Charcoal particles in Zone F (10 particles) were measured and analysed. The mean length pf the particles is 33 μm, the mean width 19.2 μm (ratio 1.67) while the mean area is 677.5 μm^2. Comparable to the San Andrés section, the charcoal particles within the samples are dark brown to black in colour, sometimes with a brownish margin. Although sub zones E1 and E2 encompass less time as the samples have been taken in relatively short stratigraphic intervals (even not as distinctive as in the San Andrés section), a successive trend in the pollen content of sample slides can also be noticed within the Tepozteco section (Fig. 43). The different successive vegetation units within this section are described as follows: Zone D is characterised by a change from deciduous and riparian to a single deciduous forest whereas in Zone E1 deciduous and riparian elements re-appear together. This does not change in Zone E2 although riparian elements clearly dominate in the lower two samples before deciduous taxa prevail again through Zone F.

4.2.2. Climate analysis

Quantitative palaeoclimatic results derived from the CA based on the palynological assemblages are presented here. The palaeoclimatic data are shown in Figs. 44 – 45 where they are approximately plotted next to the magnetostratigraphic time-scale. In this study, intervals for MAT (mean annual temperature), TCM (temperature of the coldest month), TWM (temperature of the warmest month), MAP (mean annual precipitation), PWaM (precipitation of the warmest month), PDM (precipitation of the driest month) and PWeM (precipitation of the wettest month) are calculated. The climate curves are tentatively interpolated, using the means of the coexistence intervals as suggested by Mosbrugger et al. (2005).

San Andrés section

The MAT of the San Andrés section (Fig. 44) range between 6.7 and 16.4°C, in contrast to contemporary 20°C. Between 22.75 and 21.86 Ma we notice a cooling from 16.4 – 6.7°C, whereas there is an increasing trend in temperature between 21.86 and 21.77 Ma (6.7 – 16.4°C). These trends can also be noticed in the TCM and TWM curves (Fig.44a).

In general, the climate parameters of the San Andrés section (22.75 - 21.32 Ma) show up to 10°C lower MAT values than what is measured nowadays in this area. This is due to lower temperatures during the winter season (TCM). However, compared to recent times, the temperatures of the summer (TWM) are often even higher. Colder winters and warmer summers compared to modern temperatures suggest a stronger seasonality during the Lower Miocene. With ca. 1200 mm the annual rainfall calculated for the San Andrés section is almost twice as much as it is today (Fig. 44b). Most of the annual precipitation falls during the warm summer months suggesting that the rainfall is triggered by monsoonal activity, defined by hot and rainy summers and relatively dry winters as it can be seen in the climate diagrams (Fig. 44c). The classification according to the Köppen-Geiger system (Tab. 10; Peel et al., 2007) shows that temperate and cold climates with dry winters and hot or warm summers are alternating, whereas the temperate climates are generally dominating (Tab. 11).

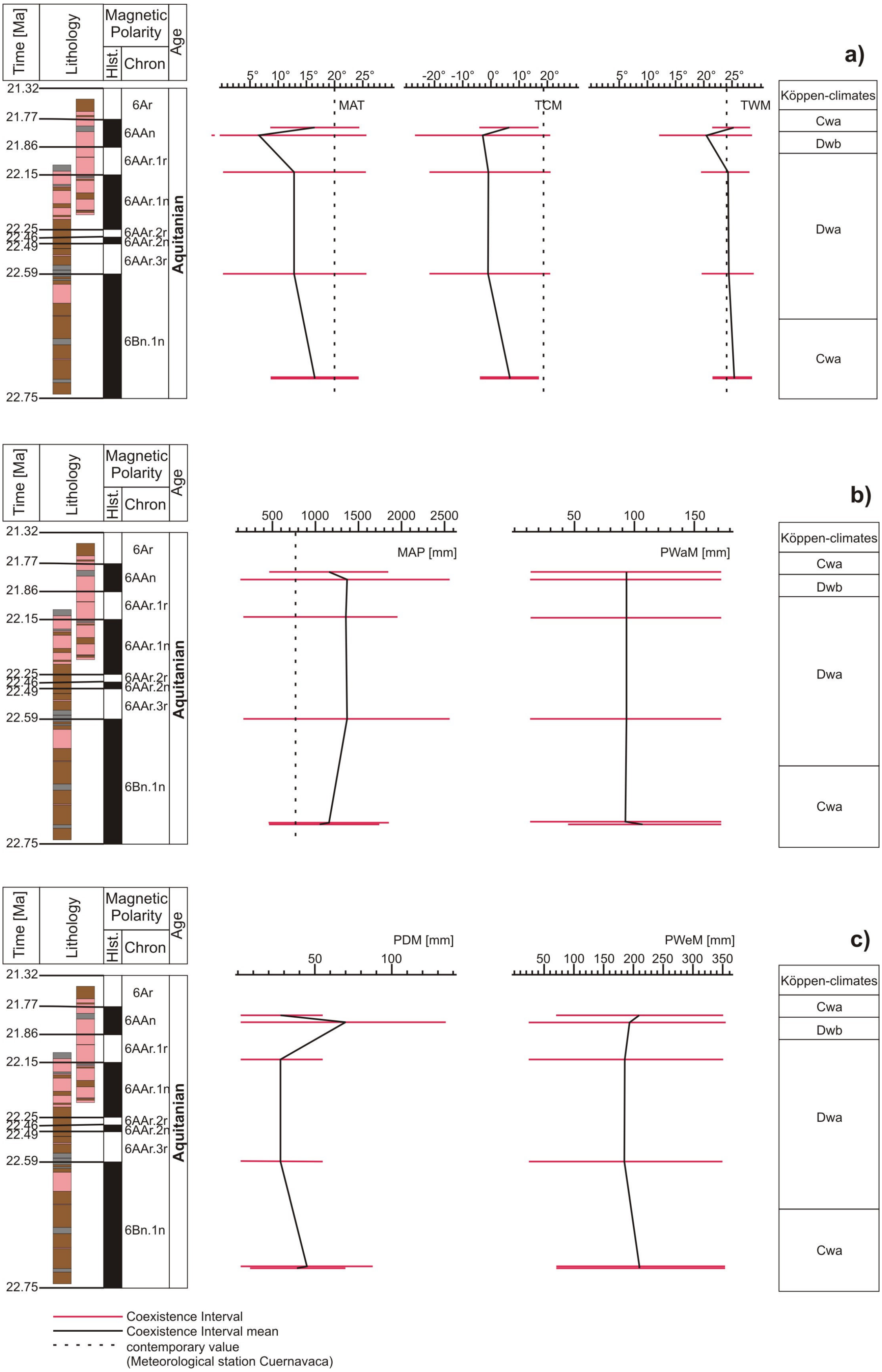

Figure 44. Climate diagrams of the San Andrés section showing a) MAT, TCM, TWM; b) MAP, PwaM; c) PDM, PWeM and the Köppen climate classification.

Table 10: Description of Köppen climate symbols and defining criteria (Peel et al., 2007).

1st	2nd	3rd	Description	Criteria
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- dry winter	$P_{wdry} < P_{swet}/10$
	f		- without dry season	Not (Cs) or (Cw)
		a	- hot summer	$T_{hot} \geq 22$
		b	- warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- cold summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- warm summer	$P_{wdry} < P_{swet}/10$
	f		- without dry season	Not (Ds) or (Dw)
		a	- hot summer	$T_{hot} \geq 22$
		b	- warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- cold summer	Not (a, b or d)
		d	- very cold summer	Not (a or b) & $T_{cold} < -38$

T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter

Table 11: Calculated climate parameters for the San Andrés and Tepozteco section together with the contemporary values measured by the meteorological weatherstation in Cuernavaca. The Köppen-Geiger classification of the climates was carried out after Peel et al. (2007).

Location	Elevation [m.a.s.l.]	MAT [°C]	TCM [°C]	TWM [°C]	MAP [mm]	PWaM [mm]	PDM [mm]	PWeM [mm]	Köppen-Geiger classification
Tepozteco	2266	12,95	-0,8	24,15	1351,5	92,5	29	186,5	Dwa
Tepozteco	2076.5	15,2	5,85	25,15	1165	99,5	31,5	196,5	Cwa
Tepozteco	1906.7	12,95	-0,8	24,15	1361,5	92,5	29	186,5	Dwa
Tepozteco	1904.7	11,65	-2,2	23,85	1165,5	108,5	32	152	Dwa
Tepozteco	1904.3	12,95	-0,8	21,65	1079,5	92,5	44	199,5	Dwa
Tepozteco	1904	14,45	5,8	23,95	1600	92,5	30	224	Dwb
Tepozteco	1903.2	14,75	4,7	24,85	1165	108,5	32	153	Dwb
Tepozteco	1881.5	11,65	-2,2	21,55	1165,5	120	39,5	152	Cwa
Tepozteco	1881	15	6,1	24,15	871	92,5	22	152,5	Cwa
San Andrés	1848	16,45	6,4	25,15	1165	92,5	29	210	Cwa
San Andrés	1843	6,7	-2,85	20,35	1334,5	92,5	69	188	Dwb
San Andrés	1820.5	12,95	-0,8	24,15	1361,5	92,5	29	186,5	Dwa
San Andrés	1734.5	12,95	-0,8	24,15	1361,5	92,5	29	186,5	Dwa
San Andrés	1639.7	16,45	6,4	25,15	1165	92,5	45,5	211,5	Cwa
San Andrés	1639	16,45	6,4	25,15	1098,5	108,5	39	211,5	Cwa
Cuernavaca	1628	20.0	19.3	24.0	770	n.d.	n.d.	n.d.	Cwb

Cwa, Cwb, Dwa, Dwb (description in Table 2), n.d. (no data available)

Tepozteco section

The MAT of the Tepozteco section (Fig. 45a) ranges between 11.6 and 15.2°C. Due to close intervals of sampling, more changes in MAT can be noticed at the base of the section (21.77 -

20.99 Ma), ranging from 11.6 – 15.0°C. Until 20.13 Ma, an increase in MAT to 15.2°C can be noticed, followed by a decrease to 12.9°C until 18.78 Ma. As in the San Andrés section before, a stronger seasonality compared to recent conditions can be seen, also showing lower temperatures in the cold season and higher temperatures in the warm season.

The annual rainfall was similar to the values in the San Andrés section before (Fig. 45b). The MAP ranged from 871 – 1600 mm (mean 1213 mm). As in the San Andrés section, the highest rates of rainfall are also noticed during the warm summer months, suggesting a strong influence of the monsoon (Fig. 45c). The classification according to the Köppen-Geiger system shows that temperate and cold climates with dry winters and hot or warm summers are alternating. The dominating climate is the temperate one with preferential hot summers (Tab. 11).

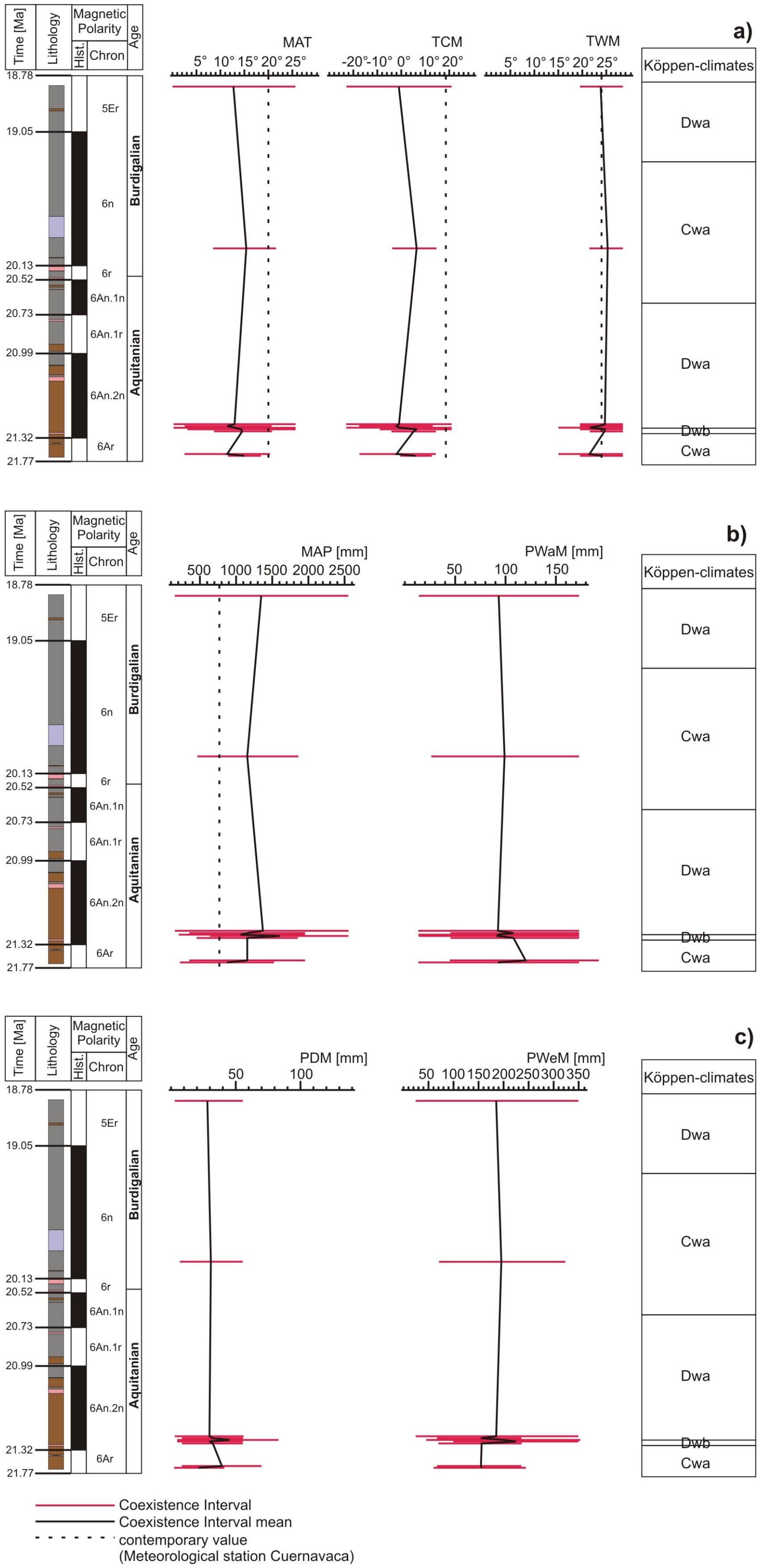

Figure 45. Climate diagrams of the Tepozteco section showing a) MAT, TCM, TWM; b) MAP, PwaM; c) PDM, PWeM and the Köppen climate classification.

5.3. Discussion

Palaeoenvironmental implications

The entire succession records various stages of recovery of vegetation related to a wide variety of disturbance factors and mechanisms. During the whole period of deposition of the Tepoztlán Formation, mixed mesophytic forests appear to have been widespread in the lowlands along streams and mid-altitude uplands surrounding the valley. Pollen assemblages were repeatedly reset by volcanic eruptions or their secondary effects (lahars) to more limited assemblages with gradual recoveries to the initial stages before the eruption. This is in accordance with similar floras and recovery stages after volcanic eruptions that are described in lahar dammed (MacGinitie, 1953; Meyer, 2003) and caldera lakes (Wolfe and Schorn, 1989; Graham, 1963) from North America.

Palynomorph assemblages of most samples analysed point to streamside assemblages bordered by moist volcanic highlands and patches of grassland. Forest elements can be divided into a deciduous vegetation on hillslopes and riparian vegetation along rivers. Species of *Pinus* and *Quercus* dominated in the hillslope forests, accompanied by *Alnus* and *Carpinus*. The inferred palaeotopography in an evolving volcanic setting suggests the existence of mixed coniferous-hardwood forests on elevated areas. Signs for their existence could be *Picea* and *Abies*. The presence of *Picea* is particularly interesting since it no longer occurs in central or southern Mexico (Graham, 1989). In modern Latin America, *Carpinus* and *Ilex* can be found at elevations above 1500 m (Marchant et al., 2002). In association with *Pinus* and *Quercus* they formed the Miocene analogue of a Quercus-Pine dominated forest, growing at elevations between 1500 and 2800 m in today's Mexico (cf. Graham, 1989).

Swamp or riparian forests growing along rivers were dominated by Cyperaceae, Cupressaceae/Taxodiaceae and *Carya*. Cyperaceae provide evidence for a swamp area. *Alnus*, also belonging to the pioneer vegetation, prefers wetland areas but is also a common element of Quercus-Pine dominated forests.

The herbaceous plants are mainly composed of Poaceae, Compositae and Chenopodiaceae. The maximum distribution of herbaceous vegetation is recorded in the lower part of the San Andrés section with higher proportions of its components. This vegetation can either be attributed to patches of open grass- and shrubland or the lower levels of the forest vegetation (open forest). The general increase of species associated with a Pinus-Quercus forest shows a growing influence of hillslope vegetation on the pollen record whereas a general decrease in riparian vegetation is noticed within the two stratigraphic sections.

All sediments of the sections studied are locally derived and were deposited in proximal to median distances from the source area. With only few exceptions all pollen taxa group in one of the vegetation units described in Table 9, suggesting that they were also locally derived without any sign of transport, e.g. by wind from distal areas. Exceptions are tropical taxa such as Palmae and *Engelhardia* which were excluded from the analyses. These taxa are most likely derived from lower altitudes that are influenced by tropical climates and vegetation. Graham (1988) describes Palmae *(Cryosophia* and *Manicaria* type) and *Engelhardia* in the Lower Miocene Cucaracha Formation of Panama and suggests their ecology to be a fern marsh with associated palms community of mangrove *(Rhizophora)* and tropical wet and premontane forests. From the same period Palacios and Rzedowski (1993) describe the existence of a cloud forest with *Engelhardia* in Chiapas. Closer to the study area but of Middle Pliocene age, the Paraje Solo Formation (Machain-Castillo, 1985) near Veracruz provides a record of vegetation extending from coastal mangrove swamps, to upland *Quercus-Liquidambar* and *Quercus-Pinus* forests, to highland communities of *Abies-Pinus* in the eastern Transmexican Volcanic Belt.

The vegetational units deciphered in the Tepoztlán Formation seem to be independent of the sedimentology, indicated by continuity of riparian and deciduous forest vegetation throughout all lithologies. Within the San Andrés section Zones A1 and A2 are characterised by fluvial, mass flow and pyroclastic sediments. While there is riparian forest vegetation in A1 exclusively, A2 shows additional elements of a deciduous forest, indicating that the vegetation which was formerly concentrated near the stream at the riverbanks, spreaded out of the valley and began to populate the planes and hillslopes where a deciduous forest formed. Due to the deposition of the A2 sediments by mass flow and pyroclastic flow processes, the appearance of taxa growing outside the river valley could alternatively be interpreted as the result of sediment transport from higher regions on the volcanic slopes. However, no significant increase, neither in the number of palynomorphs nor in taxa, and no taxa from high elevations could be documented which would be expected after a sediment transport from high elevations. The influence of higher-elevation taxa on the pollen assemblage due to mass flow transport processes on the flanks of the volcano is thus considered as minor.

Zone B is characterised by a fine, only several mm thick, purple paleosol on top of an ash-flow deposit. Here, the effect of a volcanic eruption on vegetation is documented within the pollen assemblage. The variety of taxi within this zone is very restricted and limited to ferns, *Altus*, *Betel*, *Quarks* and *Pinups*. Ferns are among the typical early colonizers of volcanic sites and could be documented in the aftermath of many eruptions (Richards, 1996; Harrison et al., 2001). *Altus* has the capability to fix nitrogen and can even grow on pure sand. Just like *Betel* it is found in disturbed riparian sites in Alaska (Shellfire, 1963) and on volcanic ash in Japan (Tarawa, 1964). The presence of oaks, not actually belonging to the pioneer vegetation can be explained as follows: The destruction of certain forest elements in the valley due to volcanic eruptions and the deposition of pyroclastic sediments within the valley would result in a reduction of these pollen, while forest elements on adjacent slopes were largely unaffected, resulting in a peak of these pollen as described by Taggart and Cross (1982) from Oregon. The limited variety within this zone raises the question why there is a lack of herbaceous taxi which should appear right after the inhabitation of the ferns. Taggart and Cross (1974, 1980, 1982) carried out some studies on the consequences of direct volcanic disturbance at Succour Creek, Oregon/Idaho. Here, samples taken above the volcanic disturbance events are dominated by herbaceous divots (Composite, Malacca, Chenopodiaceous, and Amaranthaceous) and grasses, typically followed by pine parkland which could be an explanation for the *Pinups* pollen, found within the Tepoztlán samples.

Zone C, characterised by debris flow deposits results from a Lahar that was initiated after the eruption. During that period, the vegetation was already recovering and back to a greater variety, following the general trend to a dominating dry, deciduous forest with riparian elements. This corresponds to the studies by Linter and Torrance (2007) carried out on Papua New Guinea. Each successional process is interrupted by the next eruptive episode before the vegetation starts to follow a general trend, again. In areas with less volcanic impact, regeneration starts at a more advanced level. In general, the pollen diagram of the San Andres section shows that the deciduous forest vegetation became denser in the course of the succession. On the other hand, the environment became drier as documented in the decrease of taxa such as Cyperaceae. Nevertheless, the dominating vegetation unit remained a riparian forest vegetation.

Within the Tepozteco section, Zones D to E2 are characterised by fluvial sediments while Zone F shows predominantly lahars and thus being a direct indicator for explosive eruptions in the near past and vicinity. Due to closer sampling intervals at the base and more distant sampling to the top, trends are not as obvious within this section. The trend of increasing elevations due to growth of the volcanic edifice and steepening of the relief (see chapter 4) can not be seen in a change of vegetation units. However, increasing elevations can be assumed from the climatic tolerances of certain taxa and will be discussed in detail in the following sub-chapter. Nevertheless, a continuity of the deciduous forest vegetation together with riparian elements is documented. The San Andrés and Tepozteco sections both show significant similarities in their vegetational development, especially in the area of temporal overlap at the top of the San Andrés section and the base of the Tepozteco section, respectively.

The colour of the pollen grains and spores ranges from a light brown to black, sometimes similar to the brown charcoal particles described by Umbanhowar Jr. and McGrath (1998), a sign that they were exposed to high temperatures. As it is mentioned by Umbanhowar Jr. and McGrath (1998), charcoal created at 400°C and 350°C attains a dark black colour whereas charcoal burned at 300°C is brown. Thus, the particles studied may result from burning temperatures of about 300°C to 350°C. Umbanhowar Jr. and McGrath (1998) compared the length/wide ratios of charcoal particles of different origins (grass, leaves and wood from deciduous trees). The results of their study were as follows: Grass has a mean length/wide ratio of about 3.62, wood 2.13 and leaves 1.91. Keeping these values in mind, the mean values of the three analysed slides show that mostly wood was burned near the base of the San Andrés section while it was mostly leaves that formed the charcoal particles in the upper part of the San Andrés as well as the Tepozteco section. Clark (1988), who analysed the source areas of charcoal particles states, that small charcoal particles are transported over wide areas due to fires with large columns and strong winds. Only relatively large particles (>50 μm) represent local fires (Clark and Royall, 1995). This would suggest that 23% of the found particles are clearly locally derived whereas for the remaining 77% the origin is still questionable and could be derived from more distant areas. On the other hand, Pitkänen et al. (1999) discuss that an abundance of microscopic charcoal may indicate proximal fires with low-intensity within a few km distance from the place of deposition. Duffin et al. (2008) studied charcoal particles after fires in Kruger National Park, South Africa and demonstrated that large charcoal particles > 50 μm are transported between 0 and 5 km from their source area, particles < 50 μm between 10 and 15 km.

It should be kept in mind, that there might be a loss in the pollen and spore content due to the poor preservation potential within the deposits from high-energy braided rivers and hot ash-flows. Many palynomorphs have become indeterminable, are folded or appear only in fragments, resulting from the transport and the grinding mechanisms within the relatively coarse sediments. These factors might have resulted in a decrease of diversity in taxa and a fractionation of the palynomorph spectra, especially of those pollen and spores that are not capable in surviving the harsh treatments from source to deposition. It can be assumed that palynomorphs, transported by lahars, had to suffer much less from mechanical stress than palynomorphs in the high-energy system of the braided stream. Thus, the vegetation units could be composed of less taxa than primarily present. On the other hand, Taggert and Cross (1990) describe the positive effect of local volcanic activity in facilitating fossil preservation which is the immense quantity of fine volcanic ash produced by proximal volcanic centres. These sediments supplement the often meagre supply of normal clastics by reworking of poorly consolidated ash initially deposited on surrounding watersheds. Thus, the potential for preservation of a fossil assemblage becomes high with the activation of a local volcanic centre as there is a higher deposition rate and thus also a higher possibility of a fast covering and protection of the palynomorphs against erosion by the stream.

The present study already gives some valuable evidence on the environmental conditions in the Tepoztlán area during Lower Miocene times. However, the results have to be critically reviewed, and, because of a lack of comparable studies in that area of even time frame, can only be seen as a pilot study. It is still unclear to which extend the palynomorph content is modified due to long-distance transport by mass flow processes and by means of fractionation in high-energy streams. Therefore, further palynological studies in Central Mexican Lower Miocene sediments are needed to verify the significance of the present data.

Climatic implications

A characteristic vegetation pattern of the Tepoztlán Formation is the dominance of arctotertiary elements (such as *Betula*, *Alnus*, *Carpinus*, *Fagus* and *Tilia*) suggesting cool-temperate climate in the Tepoztlán area within the Lower Miocene. On the other hand, *Carya* and Fagaceae as warm climate indicators, imply warm-temperate forests. Tropical (Palmae and *Engelhardia*) as well as cosmopolitan taxa, existing in all climate zones, such as *Pinus* were excluded from the analysis.

Although time resolution of the climate curves obtained is limited, major trends in temperature and precipitation are well represented by the data (Fig. 44 and 45). However, as already mentioned, the results have to be critically reviewed, and, because of a lack of comparable studies can only be seen as a pilot study. Especially pioneer vegetation (see Fig. 44), because of a lack in variety of taxa, can only provide relatively wide coexistence intervals which might result in unusual peaks of temperature and precipitation. These unusual peaks do not necessarily mean that there has to be a contamination with pollen and spores from higher regions and thus be explained as due to changes in sedimentary facies and transport processes. An explanation could be the scarcity of taxa and the wide climatic compatibleness of the identified palynomorphs representing pioneer vegetation.

Cwa climates represent humid temperate climates, characterised by hot, humid summers and cold winters, showing a monsoon-like pattern (McKnight and Hess, 2007). Nowadays, Cwa climates can still be found in the Transmexican Volcanic Belt and the Sierra Madre Occidental. Cwb climates represent oceanic or maritime climates which are characterised by a narrower annual range of temperatures than Cwa climates and which can also be found in tropical highlands, even at considerable distance from a coastline (McKnight and Hess, 2007). In these areas altitudes are high enough to have at least one month with temperatures below 18°C. Dwa climates represent humid continental climates which are marked by a large seasonal temperature variance with dry winters and monsoonal type rainfall (McKnight and Hess, 2007). Dwb is another dry winter variant of this climate. An interesting aspect of the Dwa and Dwb climates is that they are representing cold climate regions that are affected by the monsoon, i.e. climates that are very rare on earth nowadays. In fact, according to Peel et al. (2007), these climate zones nowadays are limited to North and South Korea and parts of southern China. According to palaeogeographic maps by Scotese (1990), in Miocene times, Central Mexico reached already its present-day position (18–21°N). Exact polar wander curves of Central Mexico are still lacking, though, why this hypothesis still cannot be proved without doubt. Nevertheless, the latitudinal position can be excluded as a cause for these climate zones, keeping in mind the present-day position of North and South Korea (35–42°N). Beside from any global or palaeogeographic explanations, the colder temperatures noticed within the two sections are rather to be explained with an increase in elevation during the local development of volcanic edifices to heights comparable to nowadays and the evolution of the TMVB. The formation of the TMVB could also be an explanation for the monsoon-like climate during the time of deposition of the Tepoztlán Formation which is nowadays due to shift in wind patterns under intense solar heating near the Mexican Plateau (Douglas et al., 1993). An explanation for the stronger seasonality could be the different distribution of land and sea masses during the Lower Miocene. The Central American Seaway (Fig. 46), separating North and South America, was not closed until the Pliocene and thus could enhance seasonal changes by bringing warm winds with more moisture during the summer months. In turn, the smaller landmasses could not produce enough heat through solar heating during the winter months, resulting in lower temperatures in winter. Another explanation for the colder temperatures in winter could be the less developed TMVB as a topographic barrier. Whereas cold winds from the north are nowadays prevented by the TMVB to drive forward to the southern part of Mexico, in Miocene times they could advance almost unhindered to the southern edge of the present-day TMVB.

Keeping in mind an elevation of 1628 m for the meteorological station in Cuernavaca where the 20°C of present-day MAT was measured, and a cooling rate of 0.6°C per 100 m (Lauer and Klaus, 1975; Wille et al., 2001), the mean MAT of the San Andrés section (13.7°C) would coincide with a mean elevation of 2670 m for that section. Therefore, a decrease in mean MAT to 13.5°C within the Tepozteco section could be due to an increase in elevation to a calculated 2700 m. These elevations, about 800 m higher compared with the modern elevations within the study area, are interpreted to be caused by allochthonous processes, i.e. the growth of volcanic edifices and a related volcanic induced alluvial fan system. The calculations are in accordance with climate data taken from the Zempoala area (2800 m a.s.l.) to the west of the study area, dominated by a mixed lower montane forest (1800-2800 m). Here, the climate is characterised by an average annual temperature of 5–12°C and monthly precipitation of 1720 mm (García, 1988).

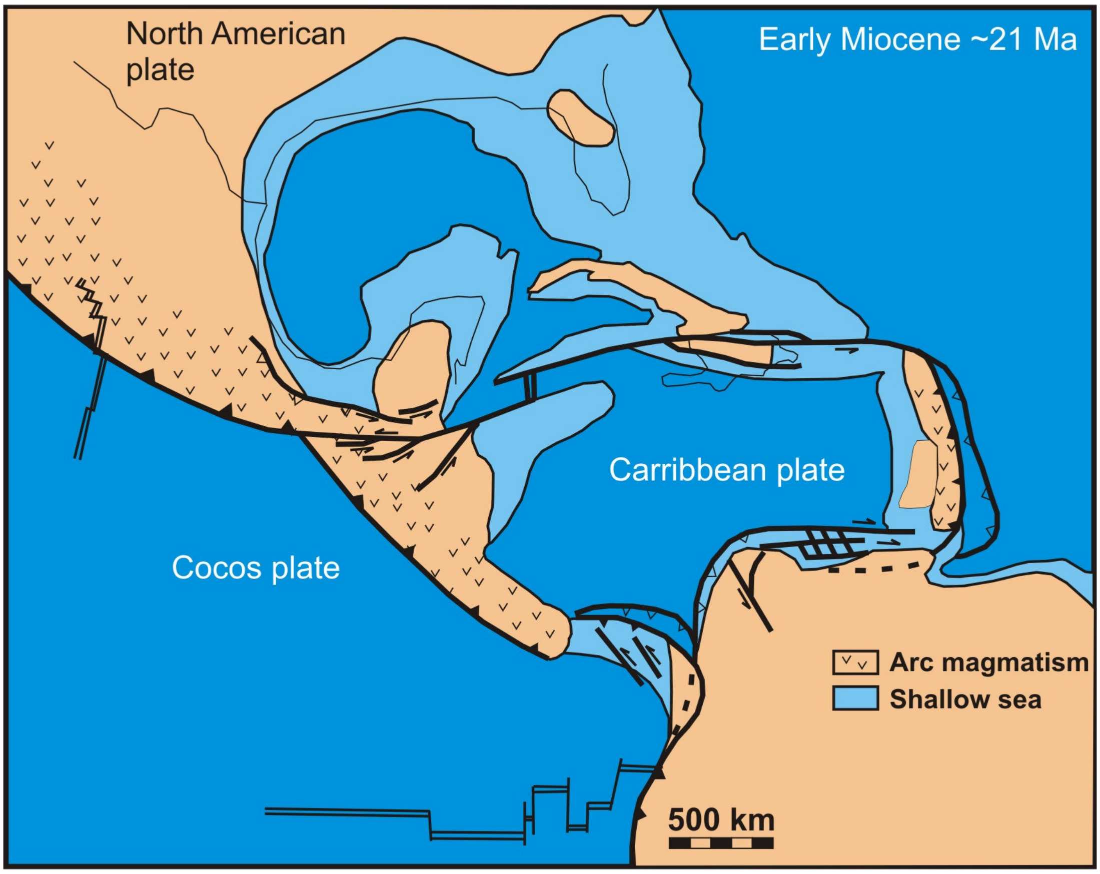

Figure 46. Palaeogeographic map of Central America, showing the distribution of land and sea masses and the Central American Seaway during the Miocene (Pindell, 1994).