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ABSOLUTE CHRONOLOGY OF THE PLIOCENE-QUATERNARY SEDIMENT SEQUENCE OF THE BOGOTÁ AREA, COLOMBIA

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A revised geochronological framework is presented for the sequence of unconsolidated sediments present in the Bogotá area (Eastern Cordillera, Colombia). This is based on 11 fission track dates on zircons that were obtained both from exposed ash layers and from a series of ashes from the Funza II borehole, which reached 586 m below the surface of the high plain. The 3 dates obtained from the exposed ash layers provide control for the older part of the sequence (6–2.5 Ma). The 8 dates from the Funza II core give control for the younger part of the sequence (3–0 Ma). Acceptance of these new fission track dates on volcanic zircons means that many of the tephra dates obtained from the Funza I core (that included fission track dates on glass shards and K-Ar dates using the mineral fractions in the ashes, published in 1984), are rejected. It also confirms earlier climate-stratigraphical dating.

The Neogene-Quaternary sediments of the Bogotá area span a period of at least the last 6 Ma. The fluvial-lacustrine sediment record registers major tectonic uplift of the Eastern Cordillera for the period between 5 and 3 Ma, the development of the large sedimentary basin of Bogotá after 3.5 Ma, with an important phase of tectonic adjustment at about 1 Ma, and a long period of strong climatic fluctuations that started shortly after 2.7 Ma.

INTRODUCTION

Previous Studies

The thick sequence of unconsolidated sediments of the Bogotá area has long been investigated by palynological and stratigraphical research. The high plain of Bogotá is situated at an altitude of ca. 2550 m in the Eastern Cordillera of Colombia (latitude 4° 30'–5° 10'N, longitude 73° 45'–74° 25'W) and represents the bed of a former lake. This subsided during the Late Pliocene and Pleistocene and, as an intramontane basin, accumulated about 600 m of mainly lake sediments. The high plain is surrounded by mountains that reach altitudes of up to 4000 m. The only fluvial outlet is situated in the southwest (Fig. 1).

The first pollen record from the basin of Bogotá came from a 195 m long borehole collected in the campus area of the 'Universidad Nacional' at Bogotá (section Ciudad Universitaria X–Y in Fig. 1), and reached bedrock. A long sequence of glacial and interglacial cycles was shown in tropical South America for the first time (Van der Hammen and Gonzalez, 1960, 1963) and the potential of palynological studies in this basin became evident. The 195 m long pollen record was

compared with the European stratigraphic record (e.g. Van der Hammen *et al.*, 1971) and the biostratigraphy was correlated provisionally with the sequence from Waalian to recent (Van der Hammen and Gonzalez, 1964); thus it represented the last 0.9 Ma.

Sediments exposed in the marginal valleys of the high plain area and on the surrounding slopes were the subject of stratigraphical studies (Scheibe, 1933; Stirton, 1953; Hubach, 1957; Van der Hammen, 1957, 1965, 1966; de Porta, 1961; Julivert, 1961). In Van der Hammen *et al.* (1973), lithological data were combined with palynological data of organic-rich intercalations and with the long pollen record of the Ciudad Universitaria X–Y core, that allowed the authors to establish a lithostratigraphic sequence of three formations and a biostratigraphic sequence of seven biozones. The general chronostratigraphy as provisionally proposed by Van der Hammen *et al.* (1973) was based mainly on the interpretation of the palynological and lithological data and subsequent correlation with European stratigraphic climatic subdivisions. The base of biozone IV, that shows considerable climatic cooling, was provisionally correlated with the base of the Pretigian (Pliocene–Pleistocene boundary), at approximately 2.5 Ma. The changes in vegetation cover in biozones V–VII were related to the climatic fluctuations of the Quaternary. Only one age estimate was provided for the older sediments. The

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FIG. 1. The high plain of Bogotá in the Eastern Cordillera of Colombia. Locations of sections discussed in the text are indicated. The thick black line limits the area covered by the Neogene-Quaternary geological maps (see Fig. 9).

volcanic ash of the Mondoñedo 8 section was K-Ar dated at 4.0 Ma. The ash is intercalated in a sequence of strongly weathered kaolinitic clays and the sediments were considered to have been deposited in a tropical lowland environment before the final major upheaval of the Eastern Cordillera (biozone I). Tectonic uplift of the Cordillera (biozones II and III) was correlated with the (Late) Pliocene.

A second coring program was carried out in the centre of the basin of Bogotá near the village of Funza (section Funza I in Fig. 1) with the objective of recovering a complete sequence through the basin. The first core recovered the interval 0–150 m and a second one (1976), at the same location, recovered undisturbed sediments from 140 to 357 m, where technical problems terminated drilling. Pollen analysis of 1230 samples between 2 and 357 m core depth revealed a long sequence of glacial and interglacial cycles and showed part of the evolutionary history of the Andean forest belt and paramo vegetation (Hooghiemstra, 1984, 1989). Time control of this Funza I record was principally based on the many intercalated volcanic ash layers, which were dated by fission track dating of volcanic glass shards and K-Ar dating, using mainly the mineral fraction, of the ashes (Hooghiemstra *et al.*, 1984; Hooghiemstra, 1989). The geochronology was not without problems and the core was estimated, at that time, to represent about 3.5 Ma. Using this time scale, a distinct long and cold period in the Funza I record (pollen zones 28 and 29) was dated between 2.5 and 2.2 Ma. Correlation with the Pretigian, dated about 2.5–2.2 Ma (Zagwijn and Doppert, 1978) seemed plausible. Provisional correlation was also made between the Funza I pollen record and the oxygen isotope stratigraphy of V28-239 (Shackleton and Opdyke, 1976). The Funza I pollen record starts in biozone V. From the geochronology of the Funza I record, cold glacial conditions may have existed in the Colombian Andes during the Early Pliocene (biozone IV). Thus, based on Funza I geochronology, that of Van der Hammen *et al.* (1973) was revised because the sediment sequence was apparently older. The Funza I geochronology was used in several subsequent publications (Van der Hammen and Cleef, 1986; Van der Hammen, 1988; Hooghiemstra, 1989).

Early questioning of the Funza I geochronology was expressed by Van der Hammen (*pers. commun.*) who suggested that the frequency change observed in the Funza I sequence resembled that at 0.8 Ma in deep sea cores; and later by Helmens and Kuhry (1986) on the basis of data obtained from a 13 m long borehole collected in the mountains northwest of the high plain of Bogotá (section Páramo de Agua Blanca I in Fig. 1). Using a combination of the radiocarbon dates for the upper part of the borehole and pollen concentration numbers for the remaining lower part of the pollen record, the Páramo de Agua Blanca I section was estimated to represent the last 0.45 Ma. In the Páramo de Agua Blanca I pollen record, the beginning of the continuous curve of *Quercus* (oak)

at 7 m was thought to register the immigration of this tree into the area. According to the pollen density time frame (Middeldorp, 1982, 1986), the first appearance of this originally northern hemisphere genus into the Bogotá area occurred at about 0.2 Ma, corresponding to the original age of Van der Hammen *et al.* (1973), correlated with the Holsteinian-Saalian boundary. On the basis of these differences with the glass fission track dates of Funza I, a discussion started (Helmens and Kuhry, 1986; Hooghiemstra, 1988) that was solved by the new fission track dates of Funza II and other sites. These confirmed the validity of the original stratigraphical framework and geochronology of the sediment sequence of the Bogotá area of Van der Hammen *et al.* (1973).

Recent Studies

In 1988 another attempt was carried out near Funza to recover the complete basin infill (section Funza II in Fig. 1). At a depth of 586 m sandstone was recovered but subsequently a broken drilling extension rod prevented further penetration. It seems that bedrock had been reached and a complete sequence of sediments recovered at Funza I and Funza II. The first results of the pollen record were presented in Hooghiemstra and Sarmiento (1991), further in Hooghiemstra and Cleef (*submitted*) and Hooghiemstra and Ran (1994). The sediments recovered by the Funza I and II cores were deposited at present-day elevations, i.e. after the final major upheaval of the Eastern Cordillera had ceased and under relatively warm climatic conditions (540–468 m), under considerably colder climatic conditions (468–ca. 260 m), and finally under a strong glacial–interglacial rhythm (ca. 260–2 m). Although less volcanic ash intercalations were recognized in the Funza II core, eight layers between 67 and 506 m provided fission track data on zircon ranging from 0.20 to 2.74 Ma. These ages are, from a technical point of view, of good quality and have placed the Funza I dates in some doubt. Additional support for the validity of the four lowermost dated horizons (between 298 and 506 m) comes from recent experiments in which the Funza I pollen record has been graphically paralleled and tentatively correlated with a high-resolution oxygen isotope record from the Eastern Pacific (Shackleton and Hooghiemstra, *unpublished data*; Hooghiemstra and Sarmiento, 1991; Hooghiemstra *et al.*, 1993). Smaller scale uncertainties for the upper part of the Funza record remained, as the beginning of the *Quercus* pollen record is tentatively dated at ca. 0.35 Ma according to this provisional land–sea correlation. Very recently, however, a plausible interpretation of the migration of *Quercus* into the area of Bogotá was discussed (Hooghiemstra and Ran, (1994). Also, the results of frequency analysis of the Funza I data set (Hooghiemstra and Mélice, 1991, 1994; Hooghiemstra *et al.*, 1993) support the time control of the lower part of the Funza records.

During the last decade, extensive data have become available from the outer valleys of the high plain of Bogotá. As part of a mapping program established

by Van der Hammen, preliminary geomorphological/geological maps were made for various parts of the area using aerial photo-interpretation and field survey (Robertson, 1981; Helmens, 1984; Bakker and Van der Wiel, 1984; Bekker, 1985; Schurink, 1987). Recently, the area of investigation was extended to cover the major portion of the upper drainage basin of the Río Bogotá (Fig. 1). Aerial photo-interpretation, field observations and laboratory analyses (palynology, mineralogy/micromorphology, ^{14}C and fission track dates) and a compilation of existing data have resulted in a set of Neogene–Quaternary geological maps (Helmens, 1990). In Helmens (1990), the lithostratigraphic framework of Van der Hammen *et al.* (1973) is amplified. Thirteen formations and three members have been described. New important palynological/macrobiostratigraphic evidence has been added to the existing biostratigraphic framework (Kuhry and Helmens, 1990). From the exposed sediment sequences, three volcanic ash layers were fission track dated on zircon, i.e. from sections 17 and 31 (Helmens *et al.*, 1990) and section Subachoque 121 (Bekker *et al.*, *submitted*). The ages of 5.33, 3.67 and 2.77 Ma for sediments that are considered to have been deposited before, at the beginning and shortly after the final major upheaval of the Eastern Cordillera, respectively, are consistent with fission track ages for the lower part of the Funza II core. Finally, an integration of evidence has made possible a reconstruction, in space and time,

of sedimentation and landscape evolution in the Bogotá area through Neogene–Quaternary times, related to tectonics, climate and glacial history (Helmens, 1990; Helmens and Van der Hammen, *submitted*).

The objective of this paper is to integrate the recently collected data with earlier published papers and to provide a synthesis. The current concept of the geochronology of the sediments of the Bogotá area is similar to the original one of Van der Hammen and Gonzalez (1960, 1964) and Van der Hammen *et al.* (1973).

TEPHRA AGES

Airfall tephrae are increasingly used for dating stratigraphic sequences in addition to bio- and lithostratigraphic, environmental and geomorphologic studies. The use of distal airborne tephrae for correlation and subdivision in mountainous regions provides more complications than in deep-sea environments (Fig. 2).

Distinct individual ash layers, representing an undisturbed reflection of a complete eruption phase or event (Fig. 3), were seldom recognized in the cores from the basin of Bogotá. Pure volcanic ash was only found as globule-, disc- and streak-shaped inclusions occasionally arranged layerwise in a clayey matrix. The volcanic ash layers or laminae mostly appeared to be frequently disturbed or reworked. Admixture with detrital material was frequent upon closer microscopic

FIG. 2. Flow chart illustrating paths and categories of variables capable of affecting the character of airborne pyroclasts between formation from erupting magma and exposure in terrestrial sediment sequences.

FIG. 3. Volcanic ash layers in the Tarragona core (near the city of Bogotá), at a depth of about 71 m. Note ash infill of fissures (burrows or mud cracks?) in the silty-clay substratum and the size-, density- and colour-grading of the fall-out layer.

inspection. This is, of course, inevitable because the ash had to settle through a considerable water column in a large lake. The occurrence of pure tephra material containing only pyrogenetic components and derived from one eruption (phase) was exceptional in this active area. An additional complication is that when a region is frequently subjected to ashfalls during a long period of time, recognition and correlation of individual tephra layers is difficult.

Age Determinations of Tephra Beds

Reliable age determinations of distal tephra beds are difficult to obtain for several reasons: for example fine grain-size, or low abundance of material suitable for age determination, or occurrence of hydration processes involving exchange of elements, thereby disturbing the radiometric systems. One of the major problems, however, is contamination by the presence of detrital grains. Especially for K-Ar and $^{39}\text{Ar}/^{40}\text{Ar}$ analysis of very young rocks, involving a minimum amount of material, this may become a serious problem when the sediment has been reworked. Glass shards in distal tephra beds may have intrinsic properties that raise questions about their ages. These include the

open system behaviour of K and/or radiogenic Ar, and partial fading of fission tracks at ambient temperatures (Cerling *et al.*, 1985; McDougall and Harrison, 1988; Wagner, 1979; Naeser *et al.*, 1980; Westgate, 1989; Walter, 1989).

Fission track analysis has been successfully applied in tephrochronology using zircons. When tephra experiences simple thermal history, with ambient temperatures of $< 80^\circ\text{C}$, hydrated glass shards are suitable for fission track age determination after establishing correction procedures (Westgate, 1989). The fission track method has the particular advantage of being grain-specific and, therefore, contamination is minimized. The disadvantage, however, is the large error, up to 100%, in age determination of glass shards and zircons of tephra beds younger than 100,000 years, because of the few spontaneous fission tracks that are being produced over such a short time. Although zircon has a much higher U-content than glass shards and, therefore, is less-time consuming to date zircons, the total number of spontaneous fission tracks remains rather low for young tephra beds. The applications of fission track dating of zircons in Quaternary tephtras has been discussed by Naeser *et al.* (1981), Naeser and Naeser (1984) and Walter (1989).

TABLE 1. Zircon fission track analytical data from the Funza II core (high plain of Bogota) and outcropping tephra at the localities Rio Frio (TT 20) and Facativá (FAC 250)

Sample ¹ (depth in m)	Mineral	ρ_s^2 ($\times 10^3$ t/cm ²)	ρ_i^3 ($\times 10^6$ t/cm ²)	t ($\times 10^6$ year)	1σ ($\times 10^6$ year)	Number of grains	ρ_d^4 ($\times 10^5$ t/cm ²)	Z ⁵	χ^2 (%)	Uranium (ppm)
Fun II/1 (67.76–67.79)	zircon	16.4 (3)	10.11 (925)	0.20	0.12	13	0.2058 (2269)	308.1	<5	302
Fun II/2 (239.00–239.09)	zircon	25.79 (3)	63.44 (369)	0.26	0.18	10	0.2058 (2269)	308.1	82	190
Fun II/3 (250.66)	zircon	70.21 (11)	16.24 (1272)	0.27	0.11	15	0.2058 (2269)	308.1	34	486
Fun II/4 (270.6–277.5)	zircon	141.5 (26)	17.27 (1547)	0.53	0.15	16	0.2058 (2269)	308.1	56	517
Fun II/5 (298.42–307.96)	zircon	226.9 (53)	14.13 (1650)	1.02	0.23	15	0.2058 (2269)	308.1	86	423
Fun II/6 (317.22–317.55)	zircon	181.3 (42)	9.77 (1132)	1.44	0.33	15	0.2058 (2269)	308.1	<5	292
Fun II/7 (322.5)	zircon	315.1 (64)	19.76 (2007)	1.01	0.21	15	0.2058 (2269)	308.1	6	592
Fun II/10 (506.2)	zircon	294.9 (57)	6.83 (660)	2.74	0.63	15	0.2058 (2269)	308.1	62	204
TT 220	zircon	381.7 (118)	4.12 (637)	5.33	1.02	11	0.1868 (2883)	308.1	96	136
FAC 250	zircon	864.5 (304)	13.56 (2385)	3.67	0.50	11	0.1868 (2883)	308.1	87	447

¹Depth in m.² ρ_s : Density of spontaneous fission tracks; in parenthesis is given the number of actually counted tracks.³ ρ_i : Density of induced fission tracks; in parenthesis is given the number of actually counted tracks.⁴ ρ_d : Density of fissions tracks in standard glass NBS 962; in parenthesis is given the number of actually counted tracks.⁵Empirically derived constant based upon repeated analysis of Fish Canyon, 84-1 and 88-1 zircon standards.

Analytical Procedures, Constants and Calibration

In view of possible contamination, individual zircon crystals were dated by the fission track method, selecting only crystals with a glass mantle, because these are considered to be juvenile and not detrital minerals.

Standard laboratory techniques were applied for separation of zircons. Fission track dating techniques follow Andriessen and Bos (1986) and use the external detector method for zircon. A zeta-calibration factor of 308.1 in combination with NBS glass 962 was used for the age calculation. Fish Canyon zircon was used as a standard and revealed an age of 27.3 ± 4.3 Ma (Table 1). When the pooled data passed the Chi-square test at 5%, the error for the fission track ages was computed using the conventional method of Green (1981); otherwise the mean age and standard error of the individual grains was calculated.

Geochronology of the Funza II Record

From the tephra in the Funza II core only eight of the unpure ash beds appeared to contain sufficient amounts of zircons. Zircon fission track analytical data (Table 1) and the age estimates provide the tephrochronological framework (Fig. 4). This new framework is considerably different from the one based on age data from the Funza I core (Hooghiemstra *et al.*, 1984; Hooghiemstra, 1989).

The ash layers analyzed represent the interval between 67.76 and 506.2 m. The time-span of the 0–506.2 m core interval is 2.74 ± 0.63 Ma. The upper part of the core is only represented by one

FIG. 4. Fission track dating results of volcanic zircons obtained from the Funza II core.

volcanic ash at 67.76–67.79 m. The next sample, at 239.00–239.09 m, leaves an interval of 171 m without direct age control. Within the core between 239 and 322 m are six dated volcanic ash layers. A further age determination comes from a depth of 506.2 m, leaving

an interval of 183.7 m, from 322.5 to 506.2 m, and an interval of 79.8 m, from 506.2 to 586 m, without direct time-control. Thus time-control is only available between 239 and 322 m.

Tephra Ages on the High Plain of Bogotá

Hitherto, tephra exposures in the marginal valleys of the high plain of Bogotá and in the surrounding hills and mountains have only been dated at two localities. The first, in a deep erosional gully in the hills southwest of the village of Mosquera (section Mondoñedo 8 in Fig. 1), exposes thin layers of white silty ash interbedded with kaolinitic clays and strongly decomposed lignites. K-Ar analysis of biotite yielded an age of 4.0 ± 0.4 Ma (Van der Hammen *et al.*, 1973). The second, on the high plain area itself southwest of the village of Guasca (section Guasca in Fig. 1), exposes silty ash in a lacustrine-fluvial sediment sequence of clays and silts. Fission track dating of shards from this ash gave an age of 3.62 ± 0.67 Ma (Van der Hammen *et al.*, 1980).

Fission track analysis has now also been applied to zircons from tephra exposures at three further localities (Table 1). One is an exposure on the main water divide west of the Rio Frío (section 17 in Fig. 1) where tephra is a 7 cm green silty ash bed within an organic- and diatom-rich clay within the lower part of a ca. 10 m sequence of fluvial gravels (Fig. 5). Its age is 5.33 ± 1.02 Ma (Helmens *et al.*, 1990). The second is also a roadcut on the main water divide, northwest of the village of Facatativá (section 31 in Fig. 1) which corresponds to section Facatativá 13 by Van der Hammen *et al.*, (1973). The white silty ash bed is a few millimetres thick and occurs intercalated in a (ca. 4 m) compact peat/lignite unit. Its age is 3.67 ± 0.50 Ma (Helmens *et al.*, 1990). The third is an ash exposed in a fluvial cut on the high plain area southwest of the village of Subachoque (section Subachoque 121 in Fig. 1). The ca. 1 m tephra-rich layer, that displays yellow and pink colours, occurs in the lower part of a lacustrine-fluvial sequence of clays, silts and sands. Its age is 2.77 ± 0.50 Ma (Bekker *et al.*, submitted).

FIG. 5. Section 17 on the western main water divide of the Bogotá area. The arrow indicates the silty ash bed intercalated between dark-coloured organic clays and light-coloured diatom clays.

THE PALYNOLOGICAL RECORD OF THE FUNZA I AND II CORES

The vegetation in the Eastern Cordillera shows a clear altitudinal zonation (Fig. 6) with the following vegetation zones: tropical lowland vegetation, up to ca. 1000 m altitude, subandean forest belt, from 1000

FIG. 6. Present (interglacial) and last glacial (20,000–14,000 BP) altitudinal distribution of the zonal vegetation belts in the Colombian Eastern Cordillera, shown schematically. (After Van der Hammen, 1974).

FIG. 7. Main pollen diagrams of the cores Funza I (after Hooghiemstra, 1984, 1989) and Funza II (after Hooghiemstra and Cleef, *submitted*; Hooghiemstra and Ran, 1994). Core depth (m) and estimated ages (ka) for 36 horizons are indicated. Estimated ages have been based on (1) correlation of Funza I with the fission track-dated core Funza II (this study) and (2) land–sea correlation between the arboreal pollen record of Funza I and oxygen isotope record of ODP Site 677 (Hooghiemstra *et al.*, 1993; Shackleton and Hooghiemstra, *unpublished data*). The 36 horizons in fact correspond to the control points of this land–sea correlation (see Hooghiemstra and Sarmiento, 1991; Hooghiemstra *et al.*, 1993). Core Funza I was drilled in two parts with the depth interval 140–150 m as an overlap, which interval is shown in both part of the pollen record. For full data concerning pollen zones, lithology and reconstruction of vegetational and climatic change is referred to Hooghiemstra and Cleef (*submitted*) and Hooghiemstra and Ran (1994). Pollen analysis of core Funza II to reach ca. 1200 years time resolution and further studies on land sea correlation are in progress.

to 2300–2500 m; and the Andean forest belt, from 2300–2500 m to the upper forest line at 3200–3500 m. Above the upper forest line, open alpine vegetation types are present: the subparamo belt containing scrub and patches of dwarf forest from 3200–3500 to 3400–3600 m; the grassparamo belt with stem rosettes of *Espeletia* from about 3500 to 4000–4100 m; and the superparamo belt, that has an incomplete vegetation cover and much frost action in the soil, from 4000–4100 to 4500 m. The subnival zone (4500 to 4800 m) is practically devoid of vegetation. At present, perennial snow cover is only found on the highest peaks (≥ 4800 m) of the Sierra Nevada del Cocuy, ca. 200 km north of the Bogotá area.

Situated at an altitude of about 2550 m, the former lake of Bogotá received pollen from the subandean forest belt, the Andean forest belt, the subparamo belt and the grassparamo belt (pollen production in the superparamo belt is relatively low). The pollen diagrams Funza I (2–357 m core depth) and Funza II (2–540 m core depth) represent the most complete pollen record of the sedimentary basin of Bogotá. Figure 7 shows the main pollen diagrams of these cores: Funza I after Hooghiemstra (1984), Funza II after Hooghiemstra and Cleef (*submitted*) and Hooghiemstra and Ran (1994). The contribution of each of the four vegetation belts to the pollen rain is expressed as a percentage of the total, and graphed from left to right. The estimated ages are based on the fission track dates of the Funza II core at 67, 298–307, 317, 322 and 506 m (Table 1) and an experimental correlation between the Funza I pollen record and the oxygen-isotope record of ODP Site 677 (Shackleton and Hooghiemstra, *unpublished data*; Hooghiemstra and Sarmiento, 1991; Hooghiemstra *et al.*, 1993).

Pollen Sequence and Climatic Implications

The high-resolution pollen diagram Funza I (Hooghiemstra, 1984, 1989) and the first palynological results of the Funza II core, viz. pollen diagram with 1 m sample distance from 2 m through 540 m core depth (Hooghiemstra and Sarmiento, 1991; Hooghiemstra and Cleef, *submitted*; Hooghiemstra and Ran, 1994), are briefly discussed below (Fig. 7). The interval between 541 and 586 m in the Funza II core contained hardly any pollen grains, or at best a few badly preserved ones. Lithological data (Fig. 7) provides additional evidence for the interpretation of the palynological record (Helmens, 1990).

On average, high arboreal pollen percentages in core interval 540–465 m of Funza II seem indicative of warmer climatic conditions than those prevailing during the time interval represented by the rest of the core. The arboreal pollen record, however, occasionally shows strong fluctuations. A number of arboreal taxa that reach very high percentages, i.e. *Ilex*, *Rapanea*, *Myrica* and *Eugenia*, have certain pioneer qualities. These, together with an important contribution of the shrub *Borreria* and some high maxima of Gramineae, indicate a more open character of the Andean forest.

The probable presence of azonal forests and more open azonal vegetation types might be explained by the dynamic local environment in the developing basin of Bogotá, including frequently fluctuating water levels, variable sedimentation patterns and large-scale colluviation, as represented in the irregular sequence of clays, silts and sands in this lower part of the core. A more detailed discussion of the 540–465 m core interval is presented in Hooghiemstra and Cleef (*submitted*).

At 465 m, climatic conditions became much colder. Under the influence of climatic fluctuations, the upper forest line shifted along the slopes of the Cordillera, and the basin of Bogotá became alternatively covered with Andean forest and open paramo vegetation (465–2 m in the Funza II core and 357–2 m in the Funza I core). This important change in climate occurred close to the ash horizon at 506 m, dated 2.7 ± 0.63 Ma, and is provisionally estimated ca. 2.7 Ma (Hooghiemstra and Cleef, *submitted*). This cooling was accompanied by the onset of glaciation in the mountains surrounding the basin of Bogotá. A regular input of glacially derived coarse-grained sediment into the central basin, together with fluctuations in lake level, resulted in the alternation of clays, peat/lignites and sands between 465 and 320 m in the Funza II core, and between 357 and 320 m in the Funza I core.

Another important change in climate is registered at 233 m in both Funza pollen diagrams when climatic oscillations become longer and of greater amplitude. The upper 233 m of the records show ten major climatic cycles. The forest line shifted between approximately 3400 and 1800 m, which made the high plain of Bogotá at 2550 m a sensitive area for preserving evidence for the changing climate. Mean annual temperature estimates fluctuate between about 6 and 15 °C; the present mean annual temperature in the area is about 14 °C. Three fission track ages of ca. 1 Ma (322 to 298 m in the Funza II core) in combination with estimates based on land–sea correlation suggest that the first cold period has an age of ca. 0.8 Ma. In the Funza I core (Hooghiemstra, 1984, 1989), this was originally correlated with the Pretiglian (2.5–2.2 Ma). The climatic change at 233 m in the Funza cores follows an abrupt change in sedimentation at 320 m. Above 320 m, mainly lacustrine clays were deposited in the centre of the basin of Bogotá. This change towards a deeper lacustrine environment seems to be caused by tectonic movement in the basin.

PRESENT STATE OF STRATIGRAPHIC SUCCESSION CONCEPTS AND CHRONOLOGY

Lithostratigraphy

In Van der Hammen *et al.* (1973), three major lithostratigraphic units of formation rank were proposed: Tilatá Formation, Subachoque Formation and Sabana Formation. The Tilatá and Sabana Formations were adapted from Scheibe (e.g. 1933) and Hubach (1957), respectively. Van der Hammen *et al.* (1973)

defined the intermediate Subachoque Formation. Lithostratigraphic subdivision was based on general lithology shown by the sediments. Altitudinal/geomorphic position of sediment sequences and tectonic disturbance of strata, were important additional criteria. The Tilatá Formation, and sediments that were correlated with the type Tilatá, is especially found on the slopes surrounding the high plain of Bogotá. Their beds are often tectonically disturbed. A Pliocene age was suggested for the formation. The Subachoque and

Sabana Formations cover the high plain area itself. These formations were associated with a large lake that occupied the basin of Bogotá during the Pleistocene. The coarser fractions of the Subachoque Formation were interpreted as indicative of glacial conditions. Generally, strata of both formations are tectonically undisturbed.

As a result of the field and mapping data collected since 1980, it became possible to amplify and add to the original formations and to distinguish several

FIG. 8. Lithostratigraphy, biostratigraphy and chronostratigraphy of the unconsolidated sediment sequence of the Bogotá area. The Pliocene–Pleistocene boundary corresponds to 2.4 Ma. After Helmens (1990).

members. Additional formations could be recognized on the basis of considerable lithological differences between sediments and according to their geographical/geomorphic position. These lie along the main rivers that cross the high plain of Bogotá, along the footslopes bordering the high plain area and in the surrounding mountains. Figure 8 gives the updated lithostratigraphic column and table for the sediments of the Bogotá area (Helmens, 1990); four main depositional environments are represented:

(1) An environment unrelated to present-day topography (Miocene–Lower Pliocene). The mainly fluvial sediments of the Marichuela and Lower Tilatá Formations were deposited beyond the present high plain of Bogotá.

(2) A lacustrine-fluvial environment related to the large tectonic-sedimentary basin of Bogotá (Upper Pliocene–Quaternary) represented by the Upper Tilatá, Subachoque, Sabana, Río Tunjuelito and Chia Formations. The fluvial sediments of the Río

FIG. 9. Surface distribution of the different Neogene–Quaternary lithostratigraphic units in the Bogotá area. For the topographic base see Fig. 1. After Helmens and Van der Hammen (*submitted*).

Tunjuelito and Chía Formations were deposited along the main rivers that cross the basin of Bogotá. Pleistocene sedimentation was influenced by glacial conditions (Subachoque, Sabana and Río Tunjuelito Formations). The almost 600 m thick sediment sequence of the central basin of Bogotá (Fig. 8) is based on the lithological data of the Funza II core (Fig. 7).

(3) A footslope environment with gravity flow deposition (Pliocene) shown by the Chorrera Formation; and fluvio-glacial deposition (Pleistocene) shown by the Río Siecha Formation.

(4) A mountain environment with slope deposition (Pliocene–Quaternary) shown by the Balsillas, San Miguel and Mondoñedo Formations; and glacial deposition (Pleistocene) shown by the Río Chisacá Formation.

Formal descriptions of the new lithostratigraphic units are provided in Helmens (1990). The lithological data are derived from sediment sequences exposed in the marginal valleys of the high plain of Bogotá and in the surrounding hills and mountains; the deep Ciudad Universitaria X–Y, Funza I and Funza II boreholes; and from the many borings and geo-electric profiles carried out in the basin of Bogotá for hydrological and industrial purposes (Fandiño, 1967; EPAM, 1985; Lobo-Guerrero, 1985a, b).

The surface distribution of the lithostratigraphic units is shown in Fig. 9. This map is a generalized version

of the two 1 : 80.000 Neogene–Quaternary geological maps (Helmens, 1990).

Biostratigraphy

The biostratigraphic sequence of Van der Hammen *et al.* (1973) included seven biozones (I–VII). This zonation (Fig. 10) was based principally on the successive immigration of four important arboreal taxa into the Bogotá area (*Hedyosmum*, *Myrica*, *Alnus* and *Quercus*). A second important criterion in the biostratigraphic zonation was the regional ecoclimatic zone in which the sediments were deposited (lower tropical, subandean, Andean or paramo). This was established by distinctive pollen assemblages, including taxa representative of the four previously mentioned vegetation belts. The present altitudinal distribution of these vegetation belts is shown schematically in Fig. 6.

In Fig. 8, the biostratigraphic data of Van der Hammen *et al.* (1973) have been supplemented with palynological/macrob botanical data from several new exposures, and with palynological data from the Funza I and Funza II curves (Hooghiemstra and Cleef, submitted; Hooghiemstra and Ran, 1994) and the Páramo de Agua Blanca I core (Kuhry and Helmens, 1990).

Biozone I represents lower elevation tropical vegetation types, biozone II lower tropical to lower subandean vegetation types and biozone III upper subandean vegetation types. *Hedyosmum* migrated into the area

Mauritia Amaranthaceae Iriarteaceae Bombacaceae Rapanea Myrica Umbelliferae Valeriana Plantago Aragoia Polyplepis Myriophyllum Geranium Caryophyllaceae Lycopodium Alnus Quercus	Provisional Pollen Zones	Tentative correlation with Europe	Estimated approximate age (1973)	Ages from zircon fission track (this study)
	VII	UPPER	Holocene	
			Weichselian	
			Termin	
			Saalian	0.2–0.3 Ma
			Holsteinian	
			Elsterian	
	VI	MIDDLE	III Cromerian	
			I Complex	
	V	LOWER	Menapian	c. 1.0 Ma
			Waalian	
			Eburonian	
	IV		Tiglian	2 Ma
			Pretiglian	2.74±0.63 Ma
	III			
	II		Reuverian	3 Ma
				4 Ma
	I		(Brunssumian ?)	5.33±1.02 Ma

FIG. 10. Original establishment and (climate-)stratigraphical dating of the biozones and the stratigraphical sequence of the high plain of Bogotá (Van der Hammen *et al.*, 1973), compared to the new zircon fission track dates presented in this paper. In the European stratigraphical table the cold phases have been placed at the right side of the column, the warm phases at the left. The range of selected pollen taxa has been updated.

at the beginning of biozone II and *Myrica* at the beginning of biozone III. Biozone IV is characterized by Andean (lower part of biozone IV) and alternately Andean and paramo vegetation types (upper part of biozone IV), and, in addition, by the consistently high representation of *Borreria*. Its upper boundary has been provisionally defined on the basis of the preliminary pollen results of the Funza II core and may be expected to be defined definitively once the final Funza II pollen diagram is ready. Biozones V–VII also represent an alternation of Andean and paramo vegetation types. *Alnus* migrated into the area at the beginning of biozone VI and *Quercus* at the beginning of biozone VII.

There are several factors that are thought to have influenced vegetation cover during biozones I to VII (Van der Hammen *et al.*, 1973; Kuhry and Helmens, 1990; Wijninga and Kuhry, 1990, 1993). The replacement of a tropical lowland flora (biozone I) with floras of intermediate altitudes (biozones II and III) and with a high-mountain flora (biozone IV, lower part), are related to the tectonic uplift of the Eastern Cordillera in the Pliocene. The major altitudinal shifts of the zonal vegetation belts along the slopes of the Cordillera in biozones IV (upper part) and V–VII are related to major climatic fluctuations during the Quaternary. Regarding the whole interval of biozone IV, some distinctive aspects of the pollen assemblages of biozone IV (Hooghiemstra and Cleef, 1994, *submitted*) may be related to the adaptation of the Andean flora to new environmental conditions at the end of uplift, and to local sedimentological conditions associated with the development of the sedimentary basin of Bogotá.

Geochronology

Age estimates of the stratigraphic sequence shown in Fig. 8 are based on zircon fission track dates of sections 17 and 31 (Helmen *et al.*, 1990) and Subachoque 121 (Bekker *et al.*, *submitted*), the four lowermost fission track dates of the Funza II core (between 298 and 506 m core depth) and radiocarbon-dated sediments and paleosols of up to about 50,000 years in age (see Helmen, 1990). In addition, indirect time control, such as the pollen density time framework of the Paramo de Agua Blanca I core (Helmen and Kuhry, 1986; Kuhry, *in preparation*) and ages based on land-sea correlations (Shackleton and Hooghiemstra, *unpublished data*; see also Hooghiemstra and Sarmiento, 1991; Hooghiemstra *et al.*, 1993) were used.

THE GEOLOGICAL–ENVIRONMENTAL HISTORY OF THE BOGOTÁ AREA DURING NEOGENE–QUATERNARY TIMES

The environmental conditions under which sedimentation took place in the Bogotá area during the Neogene–Quaternary periods are now discussed. The history of former sedimentary environments,

vegetation and climate could be reconstructed through an integration of the litho- and biostratigraphic evidence, the absolute chronological data, mineralogical/micro-morphological data of sediments and paleosols and a detailed mapping of glacial landforms.

The sequence starts with the Marichuela Formation (Figs 8 and 9) which represent very large debris flows and gravity flows, with clasts up to boulder size, that aggraded on broad alluvial plains and lakes. The deposition of very coarse-grained material is interpreted to be related to a period of increased regional tectonic activity which, together with the locally strong tectonic deformation of strata, suggest a synorogenic origin for the formation, i.e. probably one of the last phases of Miocene folding and faulting (Van der Hammen, 1961).

The Tequendama Member, of the Lower Tilatá Formation, represents a period of relatively quiet fluvial sedimentation. The river system, that more or less followed the borders of what is now the upper drainage basin of the Río Bogotá, deposited sands and gravels, while in local lakes and marshes (organic) clays and peat accumulated. The forest vegetation was of tropical lowland type, with extensive stands of *Mauritia* (biozone I). The altitude of deposition presumably did not exceed 500 m. The fission track age (section 17) of 5.33 ± 1.02 Ma places it in the earliest Pliocene.

The fluvial sediments of the Tibagota Member, of the Lower Tilatá Formation, were deposited at the beginning of the final major upheaval of the Eastern Cordillera. Sedimentation still mainly occurred outside the area of the present high plain of Bogotá. Along part of the northwestern border of the area, deposition took place in a large alluvial fan system that extended towards the west. Gravels and sands were deposited, while away from the hills or mountains clays and peaty sediments accumulated. Under the influence of persisting warm conditions, the gravelly sequences became deeply brownish and reddish coloured. Palynological and macrobotanical data for the Tibagota Member point to a depositional environment in the lower tropical to lower subandean forest belt, between ca. 1000 and 1500 m. *Hedyosmum* was present at this stage, but *Myrica* was still absent (biozone II). The fission track age of 3.67 ± 0.50 Ma in section 31 indicates an early Pliocene age.

Near the end of the tectonic uplift of the Cordillera, the locus of sediment accumulation gradually moved towards the area of the present high plain of Bogotá from its margins. Sedimentation started in the outer valleys of the present high plain area, in what seem to be small marginal basins (Guasca Member s.s. of the Upper Tilatá Formation). Palynological data for the Guasca Member point to deposition in the upper subandean forest belt, at an elevation of ca. 2200 m. *Myrica* had now migrated into the area, but *Alnus* was still absent (biozone III). Later on, when the main uplift of the Eastern Cordillera had ceased, sedimentation also took place in the central part of the present high plain of Bogotá (unnamed Upper Member of

the Upper Tilatá Formation). The area now lay within the Andean forest belt, at ca. 2600 m (lower part of biozone IV). The depositional environment for both the Guasca Member and the unnamed Upper Member seems to have been partly fluvial, partly lacustrine. Rivers deposited sands and some gravel, whereas in extensive lakes and marshes clays, diatom clays, organic clays and peat could accumulate. Lacustrine/fluvial sedimentation alternated with important phases of colluviation (deposition of silts). A sequence of 110 m of (greenish) clays, silts and sands accumulated in this way in the central basin (580–465 m in the Funza II core). The fission track ages of sections Subachoque 121, 2.77 ± 0.52 Ma, and Funza II (506 m core depth) 2.74 ± 0.63 Ma, indicate a Late Pliocene age for the Upper Tilatá Formation.

During deposition of the Subachoque Formation, there was a gradual development of a large sedimentary basin in which sediments were spread out over an increasing area. Lacustrine/fluvial sedimentation now took place under alternately 'glacial' and 'interglacial' conditions. The changes in climatic conditions resulted in altitudinal shifts of the vegetation belts along the slopes of the Cordillera and were accompanied by fluctuations of the water level in the basin of Bogotá. Generally, relatively high lake levels prevailed when open paramo vegetation types dominated the area ('glacial' periods). Low lake levels were common during phases with Andean forest types covering the area ('interglacial–interstadial' periods). The fluctuations in lake level may be explained by differences in evaporation under warm and cold climatic conditions, and by differences in interception, evapotranspiration and waterstorage of forest and open vegetation. In the central basin, low lake levels of warm 'interglacial' periods often resulted in the development of marshes in which peat accumulated. In the marginal valleys, it seems that during these periods fluvial incision dominated. Glaciations in the surrounding mountains formed another important factor influencing sedimentation during this period. With glaciers in the upper watersheds causing a sudden large supply of sediment, the marginal valleys became occupied by broad sandy floodplains in which gravels of fluvio-glacial origin were deposited in minor stream channels (Subachoque Formation) and, more specifically, along the main river courses of today (Río Tunjuelito Formation). During these coldest periods the lake was restricted to the central basin. During the time interval corresponding to the upper part of biozone IV and the lower part of biozone V, a sequence of some 150 m of clays, peat and sands accumulated in the centre of the basin (465–320 m in the Funza II core). The fission track age of 2.74 ± 0.63 Ma, at 506 m in the Funza II core, together with three dates of ca. 1 Ma between core depths 322 and 298 m suggest an Early Pleistocene age for the Subachoque sediments in the central basin of Bogotá. Sedimentation of the Subachoque Formation continued in the marginal valleys into biozone VI. At

the beginning of biozone VI *Alnus* had migrated into the Bogotá area.

During deposition of the Sabana Formation, the area corresponding, more or less, to the central part of the present high plain of Bogotá (limited approximately at 2600 m) was occupied by a large lake for most of the time. The area surrounding the lake was, under the influence of alternately 'glacial' and 'interglacial' conditions, covered by open paramo vegetation or Andean forest. The changes in vegetation cover were accompanied by fluctuations in lake level, in which the low lake levels of the warm 'interglacial' periods allowed peat accumulation in marshy shore vegetations. During the coldest periods, with glaciers in the surrounding mountains, sands and some gravels were deposited locally into the marginal zones of the lake. In the southeast, a large supply of sediment by the Río Tunjuelito resulted in the formation of a broad delta plain that built out for several kilometres into the lake. Gravels, derived from glaciers in the high mountain range of the Páramo de Sumapaz, accumulated in thick sequences in the centre of the delta (Río Tunjuelito Formation). During the time interval corresponding to the upper part of biozone V and biozones VI–VII, a sequence of some 320 m of mainly clays accumulated in the centre of the lake (320–2 m in the Funza I and II cores). At the beginning of biozone VII *Quercus* had migrated into the area.

A marked lowering in water level during the upper part of the Last Glacial period eventually led to the disappearance of the lake. Radiocarbon data indicate that the lake retreated from the marginal parts of the basin ca. 40,000 years ago and drained into the central basin about 28,000 years ago. The former lake bottom was subsequently incised by the Río Bogotá and its tributaries. Radiocarbon ages indicate that the fine-grained fluvial sediments of the floodplains of these rivers (Chía Formation) are mostly Holocene in age.

DISCUSSION AND CONCLUSIONS

The tephra dating results of the Funza I core were difficult to interpret. The fission track dates on glass shards had a minimum of counting statistics, whereas the K-Ar dates showed a large age range within short intervals. The large age range indicated by the K-Ar dates suggested contamination of the ash with older detrital material (Hooghiemstra *et al.*, 1984; Hooghiemstra, 1989).

The new fission track ages on zircon from the Funza II core and the three exposures provide a more consistent framework and confirm the earlier stratigraphic concept of Van der Hammen *et al.* (1973). No technical problems were encountered. These tephra ages allow us to place some major events, that influenced both sedimentation and vegetation cover in the Bogotá area during Pliocene–Quaternary times, on a geochronological time scale that corresponds exactly

with the original climate–stratigraphic correlation and dating by Van der Hammen *et al.* (1973) (Fig. 10).

The dating results of sections 17 and 31, together with the lowermost tephra ages of the Funza II core (at 506 m), place the final major tectonic uplift of the Eastern Cordillera in the Bogotá area between ca. 5 and 3 Ma. The fluvial sediments of section 17, with an age of 5.33 ± 1.02 Ma, are considered a probable equivalent of the Tequendama Member of the Lower Tilitá Formation. The tropical flora encountered in the type Tequendama indicates that the fluvial sediments were probably deposited at an elevation that did not exceed 500 m (biozone I). The thick peat deposit of section 31 accumulated at the beginning of the upheaval of the Cordillera, in a lower subandean environment at ca. 1500 m or slightly higher (biozone II). The intercalated ash bed was dated at 3.67 ± 0.50 Ma. Deposition of the lower fluvial-lacustrine sediments of the Funza II core, with an age of 2.74 ± 0.63 Ma, took place in the Andean forest belt at approximately present-day elevations of ca. 2600 m (lower part of biozone IV). A similar amount of uplift, of ca. 2000 m, has been recorded from the northern continuation of the Eastern Cordillera in Venezuela, the Sierra de Mérida area, for the period between 5 and 2 Ma (Kohn *et al.*, 1984).

Basin sedimentation in the high plain of Bogotá area proper started after 3.7 Ma when sedimentation was initiated in small marginal basins. When the main uplift of the Cordillera ceased, i.e. before 2.7 Ma, sedimentation also took place in the central high plain area (start of the Funza II record). During the next 1.5–2 Ma there was a gradual development of a large sedimentary basin in which sediments were spread out over increasing areas (start of the Ciudad Universitaria X–Y pollen record).

An important change in the depositional environment of the basin, associated with a sudden cooling of the climate, was recorded shortly after 2.74 ± 0.63 (Funza II core) and 2.77 ± 0.52 Ma (section Subachoque 121). This change, from the clays, silts and sands of the Upper Tilitá Formation towards the alternation of clays, peat/lignites, sands and locally gravels characterizing the Subachoque Formation, was caused by fluctuations of the water level in the basin of Bogotá, triggered by changing climatic/vegetational conditions ('glacial–interglacial' periods), and by repeated inputs of coarse-grained sediment into the basin from glaciers in the surrounding mountains.

The three fission track dates from between 322 and 298 m in the Funza II core indicate that, in the central basin, the change from the lacustrine-fluvial sediments of the Subachoque Formation towards the lacustrine clays of the Sabana Formation took place at ca. 1 Ma. Sedimentation of the Subachoque Formation continued for some time in the marginal valleys, eventually coming to an end when the lake level dropped. The change towards a deeper central lacustrine environment seems to be related to a phase of important tectonic adjustments in the basin of Bogotá.

This period of increased tectonic activity in the Bogotá area was followed by another important change in climate when the climatic oscillations became longer and of greater amplitude (Hooghiemstra and Melice, 1994; Hooghiemstra *et al.*, 1993).

Correlation of the high-resolution pollen record of the Funza I core with the high-resolution oxygen-isotope record of core ODP 677 from the Eastern Pacific (Shackleton and Hooghiemstra, *unpublished data*; Hooghiemstra and Sarmiento, 1991; Hooghiemstra *et al.*, 1993) showed that the major climatic cooling recorded at 465 m in the Funza II core, and the change in frequency and amplitude of the 'glacial–interglacial' cycles as recorded at ca. 233 m in both the Funza I and II cores, were given ages of about 2.7 and 0.9 Ma, respectively. The age of 2.7 Ma corresponds with the first incidence of ice-rafted debris corresponding with the initiation of moderate-sized ice sheets in the northern hemisphere (e.g. Ruddiman and Raymo, 1988). It corresponds with the Pliocene–Pleistocene boundary used by many terrestrial stratigraphers (Zagwijn, 1975, 1992; Van der Hammen *et al.*, 1973). The age of 0.9 Ma in the deep-sea records marks a significant change in the character of the climatic cycles, when the cycles changed from high-frequency and low-amplitude (41 ka cycles) to low-frequency and high-amplitude oscillations (100 ka cycles) (Ruddiman and Raymo, 1988). On the basis of the land–sea correlation (above), the change towards a deeper central lacustrine environment in the tectonic basin of Bogotá, recorded at 320 m in both Funza cores, occurred at about 1.3 Ma. For the purposes of the land–sea correlation only the four lowest fission track ages from the Funza II core (298–506 m) were used. Using these dates, a realistic correlation of the respective land-based and ocean-based paleoclimatic records was achieved. The three fission track dates for the depth interval 239 to 277 m in the Funza II core were considered to be underestimates. The fission track age of 0.2 ± 0.12 Ma at 67 m fits well in the geochronological framework.

The new fission track dates on zircon place the immigration of *Hedyosmum* (base of biozone II) and *Myrica* (base of biozone III) into the Bogotá area between 5.3 and 3.7 Ma and between 3.7 and 2.7 Ma, respectively. The immigration of *Alnus* (base of biozone VI), recorded at 257 m in both Funza cores, took place on the basis of the land–sea correlation model at about 1 Ma. The age range of ca. 0.35–0.20 Ma for the migration of *Quercus* into the area (base of biozone VII), as provisionally suggested by Van der Hammen *et al.* (1973) and as obtained from the Funza I and II pollen records and the Páramo de Agua Blanca I pollen record (Helmens and Kuhry, 1986; Kuhry, *in preparation*), accords with the uppermost fission track age from the Funza II core (67 m) at 0.20 ± 0.12 Ma.

An additional line of evidence that corroborates the revised time scale of the sediments of the Bogotá area is based on frequency analysis of the Funza I pollen record. Using the list of control points provided by the land–sea

correlation model, frequency analysis (Hooghiemstra and Mélice, 1991, 1994; Hooghiemstra *et al.*, 1993) showed that the results are similar to many time-series analyses of Quaternary paleoclimatic records (Berger, 1989; Crowley and North, 1991). Orbital forcing is clearly demonstrated by the presence of eccentricity, obliquity and precession periodicities, as well as known high frequency oscillations in the 14 ka through 10.5 ka bands.

It is especially interesting to note that the chronology presented here is essentially in agreement with the one originally proposed by Van der Hammen *et al.* (1973), that was based on climate–stratigraphic correlation of the Bogotá sequence with the European one; on radiocarbon dates for the last 50,000 years, on one date for the Pliocene sequence; and on other geological/palynological correlations and considerations (Fig. 10). It is a warning not to accept age determinations if they are not consistent with lithostratigraphic and biostratigraphic data. Furthermore, sample quality must always be considered carefully.

The following biostratigraphical/chronostratigraphical correlations published in 1973 (Fig. 10) are consistent with the new dates:

- base of biozone VII (beginning of *Quercus* record) — boundary Holsteinian–Saalian 0.2 Ma;
- base of biozone VI (beginning of *Alnus* record) — boundary Menapian–Cromerian complex 0.8 Ma;
- base of biozone V $\pm$ boundary Eburonian–Waalian 1.2 Ma;
- base of biozone IV $\pm$ base of Pleistocene, Pretiglian 2.3 (2.5) Ma;
- base of biozone III (beginning of *Myrica* record) 3 (3.2) Ma;
- base of biozone II (beginning of *Hedyosmum* record) 4 (4.2) Ma;
- base of biozone I ca. 5 Ma.

It is estimated that the main upheaval of the Eastern Cordillera of Colombia took place between approximately 5 and 3 Ma which is close to the estimate of Van der Hammen *et al.* (1973) who placed it between 4.5 and 2.5 Ma.

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