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Velez, M.A.

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Chapter 4

Pollen and diatom based environmental history since the Last Glacial Maximum from the Andean core Fúquene-7, Colombia

Maria Isabel Vélez, Henry Hooghiemstra, Sarah Metcalfe, Ignacio Martínez, Herman Mommersteeg

Abstract

The late Pleistocene-Holocene ecological and limnological history of Lake Fúquene (2580 m alt.), in the Colombian Andes, is reconstructed on the basis of diatom, pollen and sediment analyses of the upper 7 m of the core Fúquene-7. Time control is provided by 11 AMS $^{14}$C dates ranging from 19,670±240 to 6040±60 yr BP. In this paper we present the evolution of the lake and its surroundings. Glacial times were cold and dry, lake levels were low and the area was surrounded by paramo and subparamo vegetation. Lateglacial conditions were warm and humid. The El Abra Stadial, a Younger Dryas equivalent, is reflected by a gap in the sedimentary record, a consequence of the cessation of deposition due to a drop in lake level. The early Holocene was warm and humid; at this time the lake reached its maximum extension and was surrounded by Andean forest. The onset of the drier climate prevailing today took place in the Middle Holocene, a process which is reflected earlier in the diatom and sediment records than in the pollen records. In the late Holocene human activity reduced the forest and transformed the landscape. Climate patterns from the Lateglacial and throughout the Holocene, as represented in our record, are similar to other records from Colombia and northern South America (the Caribbean, Venezuela and Panama) and suggest that the changes in lake level were due to precipitation variations driven by latitudinal shifts of the Intertropical Convergence Zone.

1. Introduction
Fluctuations in lake level and water chemistry roughly correspond to long-term changes in the balance between precipitation and evaporation, which in turn, may be interpreted in terms of climate variability. Long-term changes in precipitation at these near equatorial latitudes is generally ascribed to shifts in the average position of the Intertropical Convergence Zone (ITCZ) forced by the 21,000 year precession cycle. Martin et al. (1997) and Haugh et al. (2001) postulated that during the early Holocene (12,400 to 8800 cal yr BP, -10,500 to 7500 extrapolated $^{14}$C ages- and 11,500 to 5,400 cal yr BP, respectively), the increase in precipitation recorded for northern South America, was due to a more northerly position of the ITCZ during the northern hemisphere summer. In the late Holocene, the average position of the ITCZ shifted southwards, decreasing precipitation during summer in the northern part of South America (Haugh et al., 2001).

The littoral location of the core Fúquene-7 makes it a particularly sensitive register of changes in the local flora and aquatic plants due to changes in water level. Other cores from lake Fúquene have been studied palynologically: core Fúquene-1 covers the period of c. 27,000 $^{14}$C yr BP to recent (Van Geel and Van der Hammen, 1973), core Fúquene-2 records the period of c. 32,000 $^{14}$C yr BP to recent (Van Geel and Van der Hammen, 1973), core Fúquene-3 records the period of c. 125,000 yr BP to present (Van der Hammen and Hooghiemstra, 2002), and core Fúquene-7 represents the last c. 70,000 yr BP (Mommersteeg, 1998).

Up to now, water levels of Colombian lakes have been reconstructed on the basis of inferred competition among plant taxa from wet lake shores, shallow water, and deep water. Such a registering system may be quite accurate when the lake shore is close to the coring site. However, in large lakes where coring sites are located far from the shore this monitoring mechanism is less accurate. Van 't Veer and Hooghiemstra (2000) identified five aquatic pollen taxa as indicator of water depth. From deep to shallow water these taxa are: *Isoetes*, Cyperaceae, *Hydrocotyle*, *Ludwigia* and *Myriophyllum*. Other taxa, indicative of lake levels (Hooghiemstra, 1984), are: *Rumex*, *Polygonum*, *Typha*, *Sagittaria*, *Utricularia*, Compositae (e.g. *Bidens*; see Van 't Veer et al., 2000) and *Plantago* (see, e.g., Bosman et al., 1994). Low water levels may expose
organic material giving the opportunity to fungi to start the process of decomposition (see Bosman et al., 1994, on fungi as possible depth indicators). Finally, shrubs and trees characteristic of swampland and poorly drained soils around lakes, such as Myrica and Alnus, can be used to infer lake level changes (Hooghiemstra, 1984; Mommersteeg, 1998).

Other papers focused on lake level reconstructions are the studies of Laguna Verde (Kuhry, 1988) and Van der Hammen and González (1960) on Laguna La América. Van 't Veer et al. (2000) described lake level changes during the El Abra Stadial of Colombia, which is claimed to be the equivalent of the Younger Dryas climate oscillation (Van der Hammen and Hooghiemstra, 1995).

In this paper we take a further step by studying diatoms and magnetic minerals. Diatoms are excellent paleoindicators of lake level fluctuations and changes in water chemistry, and magnetic minerals are used to infer erosion on the surroundings. When integrating palynological and diatom analyses, we demonstrate that although their results are similar, diatoms record earlier changes in water volume, hence the importance of combining different proxies when interpreting climate records.

2. Environmental setting of Lake Fúquene

2.1 Geography and climate

Lake Fúquene (5°27'N, 73°46'W) is located in the Eastern Cordillera of Colombia at 2580 m above sea level (Fig. 1). The present lake is the remnant of a larger Pleistocene lake that covered the Ubaté-Chiquinquirá high plain. Maximum thickness of the lacustrine sediments in the Fúquene basin is unknown; however the longest core recovered up to now is the 43-m deep core Fúquene-3 (Van der Hammen and Hooghiemstra, 2002) that represents the last c. 124,000 yr BP. The area of the present lake is 35 km²; it is 8 km long, 4 km wide, and for the most part between 2 and 5 m deep (Mommersteeg, 1998), with seasonal fluctuations of about 1 m (Van Geel and Van der Hammen, 1973; Mommersteeg, 1998). There are several rivers and creeks that empty into the lake; Rio Suarez is its only outlet (Donato et al., 1987).
The annual migration of the ITCZ controls the modern precipitation regime in the region. There are two rainy seasons and two dry seasons. The dry periods are from December to February and from June to August, and the rainy seasons are from March to May and from September to November (Eidt, 1952). Monthly precipitation ranges from c. 36 mm to 208 mm, with minimum and maximum values of 0 mm and 699 mm, respectively. Due to the shallowness of lake Fúquene, minor changes in net precipitation result in significant fluctuations of the lake level (Mommersteeg, 1998). The region is relatively isothermic during most of the year because of its location at low latitude and the stabilising presence of big water bodies (lakes Fúquene and Cucunubá; Eidt, 1952). Average annual temperature is about 13° to 14°C, but the daily temperature range is wide and night frost may even occur during the dry periods (Van Geel and Van der Hammen, 1973).

2.2. Regional and local vegetation

The gradient in precipitation and altitude in the Fúquene basin allows the simultaneous presence of dry montane forest (500-1000 mm annual precipitation) and wet montane forest (1000-2000 mm annual precipitation) (Van Geel and Van der Hammen, 1973). Floristic surveys of remnants of original vegetation in a wide area around lake Fúquene are available (a.o. Cleef, 1981; Cleef and Hooghiemstra, 1984), as are calibrations of pollen records based on the relationship between modern vegetation and modern pollen rain (Van der Hammen and González, 1960, 1963; Grabandt, 1980, 1985; Melief, 1984; Van 't Veer and Hooghiemstra, 2000). The major taxa of these vegetation belts are given below; the majority of them were recognised in the pollen spectra of core Fúquene-7.

The subandean (or lower montane) forest belt is present from 1000 to 2300-2500 m altitude. Annual precipitation is 1500-2700 mm; mean annual temperature ranges from 19° to 23°C in the lower zones, and from 14° to 19°C in higher altitudes. The main floristic elements are Acalypha, Alchornea and Urticaceae/Moraceae.

The Andean (or upper montane) forest belt is present from 2300-2500 to 3200-3500 m altitude. Annual precipitation is 700-1400 mm in
the dry interandean valleys and 1000-3000 mm on the outer slopes; mean annual temperature ranges from 9° to 16° C. The main floristic elements are Alnus, Cedrela, Clethra, Daphnopsis, Dodonaea, Eugenia, Hedyosmum, Ilex, Juglans, Miconia, other Melastomataceae, Myrica, Myrsine (= Rapanea), other Myrtaceae, Podocarpus, Polylepis, Quercus, Symplocos, Vallea and Weinmannia. The upper forest line is located at about 3200 m altitude; arboreal taxa such as Melastomataceae, Polylepis, Quercus, and Weinmannia may be dominant in these ecotone forests.

The subparamo belt is present from about 3200-3500 to 3500-3700 m altitude. Annual precipitation is 700-2500 mm; mean annual temperature ranges between 6° and 9°C. The main floristic elements are Hypericum, Ericaceae (which cannot be identified to the generic level but include important genera such as Befaria, Gaultheria, Gnaphalium, Macleania, Pernettya, and Vaccinium), and Compositae (which cannot be identified to the generic level either, but include important genera such as Baccharis, Diplostephium, Espeletia, Oritrophium, and Senecio).

The grassparamo belt is present from 3500-3700 m to 4200-4300 m altitude. Annual precipitation is 700-2500 mm; mean annual temperature is 3-6 °C. The main floristic elements are Gramineae (which cannot be identified to the generic level but include important genera such as Agrostis, Calamagrostis, Festuca, Muhlenbergia, and Chusquea) and a number of shrubs and herbs such as Aragoa, Geranium, Halenia, Loricaria, Lupinus, Lysipomia, Paepalanthus, Plantago, Puya, Rhizocephalum, and Valeriana.

The superparamo belt is present from about 4200-4300 m to the perennial snow cap. Species of Caryophyllaceae (such as Arenaria, Cerastium) and Cruciferae (Draba), mosses and cyanobacteria are characteristic. The vegetation cover is incomplete due to night frost, creeping soil, and mechanical damage to vegetation by downslope chutes of rocks and boulders.

Lakes in the Andean forest belt, and in the paramo belt in particular, may often have Isoetes, Azolla, Ludwigia, Potamogeton and Myriophyllum, with Polygonum, Typha and Carex reedswamp occurring around the margins.

The altitudinal zonation of the vegetation belts is largely determined by the mean annual temperature: the upper forest line corresponds to the
9.5°C annual isotherm. The gradient of change in temperature is some 0.6°C per 100 m vertical displacement, but as high as c. 0.78°C/100 m during dry glacial conditions (Wille et al., 2001). Changes in mean annual precipitation have little impact on temperature reconstructions (Van der Hammen and González, 1960, 1963; Hooghiemstra, 1984) and their contribution is estimated on the basis of the forest composition and lake level status. Recent research suggests that low atmospheric pCO$_2$ during a glacial stage may cause the position of the upper forest line to be lower than it is under present-day pCO$_2$ values, independent of temperature (Boom et al., 2001 and references therein). This effect cannot be quantified yet and may be compensated for by a steeper glacial lapse rate (see the discussion in Wille et al., 2001).

2.3 Water chemistry
Fúquene lake is currently enriched with nutrients through runoff carrying fertilisers and extra sediments as a consequence of human activities in the catchment area. Once in the lake, water is retained between 6 to 9 months (CAR, 1974a; CARb, 1974 in Donato et al., 1987). Water chemistry in the lake is strongly influenced by ground
Figure 1. Map showing the location of Lake Fúquene in the Eastern Cordillera of Colombia and the coring site for Fúquene-2, Fúquene-3 and Fúquene-7. The geographical position of this map is indicated in the inset figure by the small rectangle in the province of Cundinamarca, in the centre of Colombia (Figure modified after Van der Hammen and Hooghiemstra, 2002).

water, springs and local aquifers rich in HCO₃, Cl, SO₄ and Mg, and its hardness, often indicated by the concentration of the calcium ion, oscillates between 22 and 3000 ppm (De Speelman (1982) in Donato et al., 1987). The north-south orientation of the lake and its valley and the shallowness of the lake favour the impact of the trade winds, which prevent the waters from stratifying (Donato et al., 1987). Water turbulence leads to some resuspension of minerogenic material and nutrients. The thermocline and nutriclines are only ephemeral limnological features, i.e., epilimnion and hypolimnion are seldom well-established.

3. Methods

3.1 Core recovery, pollen analysis and time control
The 14-meter long Fúquene-7 core was drilled in the north-east margin of the lake using a hand-operated Dachnovsky corer. The sediment cores were transported to Amsterdam and stored in a dark cold room. Pollen samples were collected at 5-cm intervals along the core. Standard preparation techniques (Faegri and Iversen, 1975) were applied, including treatment with 10% KOH, natriumpyrophosphate, HCl (10%), and acetolysis mixtures following Erdtman (1960). Gravitational separation was applied with a bromoform alcohol mixture. Finally, the samples were mounted with glycerine jelly. Pollen concentration values were calculated by adding a known number of *Lycopodium* spores to each sample. About 300 pollen grains were counted. The pollen sum includes the following ecological groups: subandean forest, Andean forest, subparamo, grassparamo, and superparamo. *Alnus* was excluded from the pollen sum as it represents mainly azonal swamp forest on wet soils around the lake (Hooghiemstra, 1984). Representation of lake shore taxa, shallow water taxa, and deep water taxa is expressed on the pollen sum. The software TILIA and TILIAGRAPH were used to calculate percentages and to construct the pollen diagram. For more details concerning pollen analysis see Mommersteeg (1998).

Accelerator mass spectrometry (AMS) radiocarbon dates were obtained from 11 bulk samples of organic rich clay for time control (Mommersteeg, 1998; Van 't Veer *et al.*, 2000) (Table 1). For depths above 349 cm a linear extrapolation of radiocarbon dates was used.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>¹⁴C date</th>
</tr>
</thead>
<tbody>
<tr>
<td>349-350</td>
<td>6040±60</td>
</tr>
<tr>
<td>403-404</td>
<td>7070±50</td>
</tr>
<tr>
<td>448-449</td>
<td>7780±60</td>
</tr>
<tr>
<td>467-468</td>
<td>7850±70</td>
</tr>
<tr>
<td>481-482</td>
<td>7890±60</td>
</tr>
<tr>
<td>491-492</td>
<td>7970±80</td>
</tr>
<tr>
<td>504-505</td>
<td>8680±60</td>
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<tr>
<td>521-522</td>
<td>13,110±120</td>
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<tr>
<td>543-544</td>
<td>14,200±120</td>
</tr>
<tr>
<td>651-652</td>
<td>17,990 60</td>
</tr>
<tr>
<td>699-700</td>
<td>19,670±240</td>
</tr>
</tbody>
</table>

**Table 1.** List of radiocarbon dates of core Fúquene-7 (after Mommersteeg, 1998)
3.2 Diatom analysis

We collected 52 samples for diatom analysis at 20 cm intervals along the core. Diatoms were extracted from the sediments by standard procedures (Battarbee, 1986). Permanent slides were mounted in Naphrax, r.i. 1.70 and examined at 1000x magnification with an Olympus BX40 microscope. A minimum of 400 valves were counted per slide. The software TILIA and TILIAGRAPH were used to calculate percentages and to construct the diatom diagrams. Detrended correspondence analysis (DCA) was carried out using CANOCO (Ter Braak, 1986). Samples between 215 and 248 cm depth did not contain diatoms and were excluded. 40 samples yielded good quality results. 'Calibrate' version 0.82 (Juggins, 1998) based on the modern diatom data base of Gasse et al. (1995) was used to reconstruct pH and conductivity. We recorded 51 diatom species, of which 36 were present in the African data set. As the percentages of matches between the two data were above 70%, the reconstructed pH and conductivity for Füquene can be accepted with confidence. The interval between 99 to 120 cm had low percentages of matches of about 32%, therefore we did not trust the reconstructed pH and conductivity at that interval (see section 4.1). We used the following literature for the diatom identification and ecological interpretations: Germain (1981), Patrick and Reimer (1966), Krammer and Lange-Bertalot (1986, 1991) and Gasse (1980, 1986).

3.3 Magnetic minerals

In total 36 samples of wet sediment –taken at 20 cm intervals along the core- were used to gauge mineral magnetic properties. Samples were magnetised in a magnetic field at room temperature. Saturation Isothermal Remnant Magnetisation (SIRM) readings were taken for each sample. SIRM indicates the level at which 'Isothermal Remnant Magnetisation' (IRM) stabilises, independently of the increases of the magnetic field. According to Lowe and Walker (1997) IRM is the magnetic moment activated and retained by a sample placed in a magnetic field at room temperature.

3.4 Interpretation and comparison of the proxy records
Fluctuations in lake level were inferred from the pollen and the diatom records. Ecological ranges of diatoms were obtained from the publications listed above. Dominance of littoral and planktonic diatoms were indicative of low and high lake levels, respectively. Changes in pH - as reflected in the diatom assemblages- are indicative of the interaction between spring waters, local input of aquifers and the volume of the lake. The record of pollen-based lake level changes (Mommersteeg, 1998, Van ‘t Veer et al., 2000) was visually compared with the diatom-based record of lake level oscillations. The regional vegetation history of the Fúquene area is taken from Mommersteeg (1998) and is principally based on the record of altitudinal shifts of the upper forest line. Changes of magnetic mineral concentration were used to infer rates of erosion: high concentrations represent periods of increased sedimentation (or soil erosion) whereas low concentrations reflect reduced sedimentation (Lowe and Walker, 1997).

4. Results and interpretation

4.1. Stratigraphy of the core

The following sedimentary sequence was observed in the core:

0-25 cm: Grey clay matrix with detrital material
25-275 cm: Black organogenic material (peat)
275-700 cm: Dark brown clay matrix with organic and detrital material intercalated with grey sediments of silt and fine sand at 350-360 cm, 375 cm, 440-450 cm, 515-520 cm, 547-and 550 cm.

4.2 Analysis of diatoms and other proxies

Diatoms present in the lake today include: Cyclotella bodanica, Aulacoseira granulata, A. italica, Fragilaria construens, Tabellaria flocculosa, Navicula capitata, N. rynchocoeptala, Navicula sp. Cymbellia ventricosa, Gomphonema parvulum and Epithemia zebra (Donato et al., 1987). Samples collected in January 2000 showed that in the littoral zone Fragilaria spp. and Tabellaria flocculosa are dominant, whereas the surface sediments in the centre of the lake are dominated by Epithemia
sorex, Fragilaria spp. and Aulacoseira distans. Good analogues for fossil assemblages are difficult to find due to the pollution of the lake water.

Downcore changes in the diatom assemblages are shown in Fig. 2. The records of SIRM, reconstructed pH and conductivity, and the record of lake level changes are presented in Fig. 3. Some aspects of the reconstructed pH and conductivity are discussed below.

The similarity between the curve of the first axis of the DCA analysis (eigenvalue of 0.666) plotted against depth, and the pH obtained from 'Calibrate' (Fig. 4), suggests that pH could be the main chemical variable determining the distribution of the diatoms in the record. For the interval from 99 to 120 cm 'Calibrate' indicates a maximum pH of 8. However, the low match in 'Calibrate' (about 32%) for this interval and the dominance of Aulacoseira distans cf. laevissima suggest that the pH was around 6.8 (E. Haworth personal communication; Gasse, 1986). The conductivity for the interval of 99 to 120 cm was probably lower than the value obtained from 'Calibrate', as suggested again by the presence of A. distans cf. laevissima, which inhabits environments of low to very low conductivity (<300 μS/cm; E. Haworth personal communication).

The most conspicuous relationships between pH and diatom assemblages are seen in zone 1 (Figs. 2 and 3) where high pH corresponds to the dominance of F. pinnata and F. brevistriata, and zones 2 to 6, where lower pH values correspond to the dominance of C. stelligera and A. ambigua assemblages. The marked change in assemblage composition, pH and conductivity at about 550 cm core depth reflects an important re-organisation of the lake hydrology, as will be discussed below.

4.3 Description of the diatom record

Diatom zonation was based on visual inspection of the percentage diagram and determined according to changes in dominance of certain taxa (> 50% of the total valves counted per depth). The ecological ranges of the diatom species are presented in Table 2. We recognised the following zones (FUQ-1 to FUQ-7):
Zone FUQ-1 (699-550 cm; estimated period from 19,700 to c. 14,200 $^{14}$C yr BP) is dominated by the genus *Fragilaria* in particular *F. brevistriata* (40-60%) and *F. pinnata* (30-45%). Average sedimentation rate is about 29 cm/kyr. Magnetic minerals peak at 555 cm depth and decrease rapidly to remain relatively low. This zone includes radiocarbon ages of 19,670±240 $^{14}$C yr BP at 699 cm, and 17,990±60 $^{14}$C yr BP at 651 cm.

Zone FUQ-2 (550-510 cm; estimated period from c. 14,200 $^{14}$C yr BP to c. 8680 $^{14}$C yr BP) is dominated by *F. pinnata* (60%) followed by *F. construens* (10%). *F. brevistriata* decreases to 5-10% relative to the lower zone. New elements, such as *Cocconeis placentula*, *Gomphonema truncatum*, *Navicula radiosa* and *Epithemia turgida* appear in this zone. *Aulacoseira ambigua* starts to increase. The average sedimentation rate changes from 29 cm/kyr at the bottom to 4 cm/kyr at the top of the zone. At the top of the zone between c. 521 and 504 cm, radiocarbon dates indicate a gap in the sediment record.

Zone FUQ-3 (510-410 cm, estimated period c. 8680 to c. 7070 $^{14}$C yr BP) shows a conspicuous increase in *Aulacoseira ambigua* (70-75%), particularly at the beginning and at the end of the zone, and a decrease in *Fragilaria* spp. Other common diatoms are *Cymbella microcephala*, *Epithemia turgida*, *Achnanthes minutissima* and *Navicula minuscula var. muralis* which increase between 460 and 440 cm. At the beginning of the zone the sedimentation rates are high and concentrations of magnetic minerals are low. At the top of the zone the concentration of magnetic minerals increases and sedimentation rates start to decrease.

Zone FUQ-4 (410-248 cm, estimated period from c. 7070 to 4300 $^{14}$C yr BP) shows a dominance of *A. ambigua* and *Cyclotella stelligera*. Along with the dominant *A. ambigua*, there are also *Cymbella microcephala*, *Gomphonema angustatum* and *Nitzschia amphibia*. At the beginning of the zone the concentrations of magnetic minerals are the highest in the entire core; in the middle and upper part of this period values are minimal.

Zone FUQ-5 (248-215 cm, estimated period from c. 4300 to 3700 $^{14}$C yr BP based on extrapolation of radiocarbon dates) features an absence of
diatoms except for some corroded valves of *Fragilaria* spp., *Aulacoseira* spp., *Cyclotella* spp. and *Brachysira* sp. Concentration of magnetic minerals is low.

Zone FUQ-6 (215-90 cm, estimated period from c. 3700 to 1600 $^{14}$C yr BP age based on extrapolation of radiocarbon dates) is dominated by *Cyclotella stelligera* and *Fragilaria brevistriata* at the bottom, whereas *A. distans* cf. *laevissima* and *Brachysira brebissonii* dominate at the top. There are low percentages of *A. ambigua*, *F. pinnata*, *B. brebissonii*, *C. stelligera* and *F. construens*. The low values of magnetic minerals of the zone below are maintained.

Zone FUQ-7 (90-0 cm, c. 1600 $^{14}$C yr BP to recent, age based on extrapolation of radiocarbon dates) is dominated by *Cyclotella stelligera* and *Aulacoseira ambigua*. Common diatoms are *Gomphonema gracile*, *Brachysira brebissonii*, *Aulacoseira granulata* var. *angustissima*, *Aulacoseira crenulata*, *Cymbella silesiaca*, *Cymbella gracile*, *Brachysira vitrea*, *Eunotia serra* var. *serra*, *Eunotia soleirolii*, *Eunotia flexuosa*, *Tabellaria flocculosa*, *Fragilaria construens* and *Synedra ulna*. The concentration of magnetic minerals is still very low.
Figure 2. Diatom percentage diagram of the upper 7 m of Fúquene-7 showing the most important taxa, >5%
Figure 3. Limnological reconstruction of Lake Fúquene based on diatom analysis. From left to right: radiocarbon ages, diatom zones, inferred lake-level, reconstructed pH and conductivity, record of magnetic mineral concentration, sedimentation rates and lithology of the core.
Figure 4. Comparison between the results from DCA and reconstructed pH for the core Fúquene-7.

4.4 Interpretation of the diatom record

The dominance of littoral (*Fragilaria* spp) diatoms during the period from 19,700 to c. 14,200 $^{14}$C yr BP (FUQ-1) suggests that the lake was shallow at the time. The pH ranged between 7.6 and 7.8. The conductivity shows a decrease from 250 $\mu$S/cm at the bottom to 170 $\mu$S/cm at the top. There is an increase of epiphytic, aerophilous and planktonic diatoms at c. 14,200 $^{14}$C yr BP (FUQ-2). Their increase may indicate an increase or decrease in the lake level (i.e. an increase in lake level would increase the extension of the lake and hence of the littoral area available those diatoms to colonise; a decrease in lake level would cause the littoral area to be closer to the coring site, and hence to cause an increase in the proportion of those diatoms in the samples). However, on the basis of the increase in the planktonic *Aulacoseira ambiguа* and of the fact that the epiphytic and
aerophilous diatom species are highly represented during high lake levels (see FUQ-3 and FUQ-4), we conclude that the lake level started to increase (rather than decrease) c. 14,200 BP. The decline in magnetic mineral concentration suggests a decrease in erosion, probably as a consequence of an increase in lake level and/or vegetation cover. The pH reaches 8-8.2 at the time of the increase in lake level. This period is followed by a gap in the sediment record; the period from c. 13,110 to c. 8680 14C yr BP is not represented.

The diatom zone FUQ-3 is dominated by planktonic *A. ambigua*; the relative increase of other planktonic species, and the decrease in littoral species suggest that the lake reached its maximum extension. However, an increase in epiphytic and littoral species along with a decrease in planktonic taxa at c. 7780 14C yr BP suggest a temporary decrease in lake level. During this period the pH values decreased from 8.2 (zone below) to 7.4 suggesting a major influence of runoff and local aquifers into the lake carrying more acidic water due to dissolution of CaCO3 and oxidation of Fe2S from the surrounding rocks (Caruccio and Geidel, 1978). Both minerals are found in Cretaceous marine outcrops in the area (Martínez, 1995). An increase in water turbulence and silica content are suggested by the dominance of the genus *Aulacoseira* (Kilham, 1971; Kilham *et al*., 1986; Bradbury, 2000). Conductivity oscillated between 140 µS/cm and 310 µS/cm. These oscillations may correspond to instability of the lake level, but they may also point to variations in salinity caused by the influence of ground water and/or river runoff into the lake. The low concentration of magnetic minerals combined with high sedimentation rates is indicative of additional and/or different sources of sediments.

In zone FUQ-4 the increasing abundance of epiphytic and littoral diatom species (Fig. 2) suggests a gradual decrease in lake level. Reconstructed pH values fluctuate between 7.6 and 7.8 (Figs. 3 and 4). Conductivity - and salinity- were higher than in the zones below and correspond to a steady decrease in lake level, pointing to small volume of water with high salinity, i.e. a higher concentration of solutes. pH values are higher than in the previous period, suggesting that the water input from local aquifers was lower. The presence of *Aulacoseira* spp. suggests an increase in
water turbulence and in silica content (Van Landingham, 1964). The decline in both the magnetic mineral concentration and lake level, suggests a correlation between sediment input and lake size.

The absence of diatoms in zone FUQ-5 may be caused by valve dissolution due to the peaty character of the sediment and/or to an exposure of the sediments to the atmosphere as a consequence of a drop in the lake level. The absence of magnetic minerals suggests very low levels of erosion from the surrounding catchment. Because of the insufficient time control from this time on, we have not determined sedimentation rates.

The change in diatom composition at zone FUQ-6, compared to zone FUQ-4, can be interpreted as revealing low lake level conditions. Littoral diatoms (*Fragilaria* spp.) are rare, there is abundance of *A. distans* cf. *laevissima*, a diatom common in shallow lakes (E. Haworth, pers. comm). As indicated above, pH and conductivity reconstructed from “Calibrate“ should be interpreted with caution due the low percentage of matches (32%). In fact, the dominance of *A. distans* cf. *laevissima* rather suggests (1) low pH values in the order of 6.8 (in contrast to 8 indicated by “Calibrate”) and, (2) lower conductivity than in the period of the zone FUQ-4 (Fig. 3). The dominance of *A. distans* cf. *laevissima* over *A. ambigua* may indicate a decrease of dissolved phosphorus in the water (Kilham *et al.*, 1986). P and pH variations may suggest a change in the trophic structure of the lake.

The dominance of *C. stelligera* in zone FUQ-7 suggests that the lake level was relatively shallow, but deeper than at the end of the previous period. At about 690 yr BP (extrapolated) the peak in planktonic species indicates an increased water depth. pH was between 7.4 and 7.6. Conductivity decreased from 350 µS/cm during the earliest part of the period to 150 µS/cm, and then stabilised at the latter value (Fig. 3). The 350 µS/cm value suggests an increased salinity. The reappearance of *A. ambigua* and the near disappearance of *A. distans* cf. *laevissima* may suggest an increase in phosphorous, turbulence or pH. As indicated before, DCA suggests that pH might be the main environmental variable determining the diatom distribution. Hence, it is probable that a return to alkaline conditions was the cause of the reappearance of *A. ambigua*. The reduced
magnetic mineral concentration during this period suggests low sediment input.

<table>
<thead>
<tr>
<th>Species</th>
<th>Habitat</th>
<th>Salinity</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclotella stelligera Cleve and Grunow 1882</td>
<td>X</td>
<td>e b a p</td>
<td>O m e Hf Ac</td>
</tr>
<tr>
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<td>X</td>
<td>x x</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Aulacosira granulata (Ehrenberg) Simonsen, 1979</td>
<td>x x</td>
<td></td>
<td></td>
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<tr>
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<td>x x</td>
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<td></td>
</tr>
<tr>
<td>Aulacosira distans cf. leevissima</td>
<td></td>
<td></td>
<td>pH 6.8; alkalinity 185 meq/l (Haworth, personal communication)</td>
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<tr>
<td>Aulacosira leevissima (Grunow) Krammer 1990</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fragilaria construens (Ehrenberg) Grunow, 1862</td>
<td>x x</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td>Fragilaria construens variety</td>
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<td>x x</td>
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<td>Brachysira vitrea (Grunow) Ross in Halley, 1986</td>
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<td>Low pH-dilute biotopes (Gasse, 1986)</td>
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<td>Brachysira brevisisoni Ross in Hartley, 1986</td>
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<tr>
<td>Cymbella gracilis (Ehrenberg 1843) Kützing, 1844</td>
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<td>Subaereal, cold-acidic waters (Gasse, 1986)</td>
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<td></td>
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<td>x x</td>
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<td>Gomphonema angustum Agardh, 1834</td>
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<tr>
<td>Gomphonema gracile Ehrenberg, 1838</td>
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</table>

**Table 2.** List of diatom taxa found in the Fúquene-7 core and their ecological preference. Abbreviations: L = littoral; e = epiphytic, algae; b = benthic; c = crenophytic; a = aerophyous; p = planktonic; O = oligohalobous; m = mesohalobous; e = euhalobous; Hf = halophobous; Ac = acidophilous; I = indifferent or circumneutral; Af = alkaliophilous; Ab = alkaliibiontic.
### Table 2. Continued

#### 4.5 Summary of the pollen-based reconstruction

The relevant part of the pollen record of core Füquene-7, over the last c. 24,000 $^{14}$C yr, is summarised in Fig. 5. The following four pollen zones were recognised in the core interval from 700 to 280 cm. For more details see Mommersteeg (1998).

During pollen zone Y (780-535 cm; period of 24,035 to 13,925 $^{14}$C yr BP) the regional vegetation is dominated by grassparamo. In the last phase of this period Andean forest increased slightly. *Hydrocotyle* was a common element in the margins of the lake, indicative of low lake level. Pollen from this interval suggests low lake levels and extensive dry vegetation.

During pollen zone Z1 (535-415 cm; period of 13,925 to 7225 $^{14}$C yr BP, including a hiatus) the regional vegetation was composed of humid *Quercus*-dominated forest. This indicates that wet conditions must have prevailed; however in the middle of this period the oak forest was partly replaced by grassy vegetation i.e. the upper forest line moved down slope. This is indicative of a temporary return to drier and cooler conditions that
could explain the hiatus corresponding to the interval between 13,110-7780 \(^{14}\text{C} \) yr BP.

During pollen zone Z2 (415-325 cm; period of 7225 to 5540 \(^{14}\text{C} \) yr BP) Quercus-dominated forest continued to be the most abundant around lake. The increase of Potamogeton was probably related to higher temperatures.

During pollen zone Z3 (325-280 cm; period of 5540 \(^{14}\text{C} \) yr BP to recent) the lake, as well as its surroundings, were subject to human impact. For this reason Mommersteeg (1998) did not analyse this period. However, the pollen diagram (Fig. 5) shows an increase in subparamo, marsh and aquatic elements, and a decrease in Quercus and Alnus.

5. Environmental reconstruction based on multi-proxy approach

In this section we present the history of environmental and climatic changes in Lake Fúquene and its surroundings. The reconstruction of the lake history is based on evidence from diatoms, pollen records of lake shore and aquatic taxa, radiocarbon dating and sediment analysis. The development of the lake is placed in the regional context on the basis of regional information from the pollen record. Figure 6 shows the different periods that resulted from superimposing the diatom and the pollen zonation and the comparison with the climatic periods of Van 't Veer et al., (2000). From both proxies the following discrete periods we recognised:

From 19,700 to 14,200 \(^{14}\text{C} \) yr BP (period 1): all proxies showed stable dry and cold glacial conditions. The lake was low and chemically stable; it was probably a closed hydrological system. Paramo and grassparamo vegetation surrounded the lake and the temperature was about 4 to 6 °C lower than today's (Mommersteeg, 1998; Van 't Veer et al., 2000). Although data from the same period are scarce in Colombia, Wille et al. (2000) recorded dry and cold conditions in the southern part of the Western Cordillera of Colombia. This period is correlated with pollen zone W (c. 22,000-14,200 \(^{14}\text{C} \) yr BP) from Van 't Veer et al. (2000), zone Y from Mommersteeg (1998), zone W5 from Van Geel and Van der Hammen (1973), and diatom zone FUQ-1.
From c. 14,200 to c. 13,925–13,110 $^{14}$C yr BP (period 2) this period records transitional conditions from a dry cold glacial to a warmer and a more humid Lateglacial. The lake level started to increase and probably the water became more dilute as a consequence of increasing volume. It was a period of changes in land cover, presence of open rocky soil, and erosion as reflected in the increase in the coarser sediments and in *Dodonaea* (Van 't Veer et al., 2000); eventually, however, a *Quercus*-dominated forest became established in the area. This interval includes the transition from pollen zone Y to Z1 from Mommersteeg (1998), Y1 pollen zone from Van 't Veer et al. (2000), and FUQ-2 diatom zone. This period of increased temperatures and humid conditions is known in Colombia as the Guantiva Interstadial (Van Geel and Van der Hammen, 1973; Mommersteeg, 1998; Van 't Veer et al., 2000).

From 13,110 to 8680 $^{14}$C yr BP (period 3): there are no records for the period from 13,110 to 8680 $^{14}$C yr BP due to a gap in the sedimentary record. The stratigraphy of the core shows a sharp contact between underlying dark fine sediments and light and coarser sediments. According to Van 't Veer et al. (2000) and Mommersteeg (1998) this hiatus occurred at the transition from the Guantiva Interstadial to the El Abra Stadial and covers the full El Abra Stadial. The El Abra Stadial, which corresponds to the Younger Dryas event, features a decrease in effective precipitation (Van 't Veer et al., 2000). During this event the Andes of Colombia had a cold and dry climate (Van 't Veer et al., 2000), hence, the sedimentary gap in Fúquene-7 reflects a drop in lake level to somewhere below the coring site. In the Cauca Valley, in the southwest of Colombia, Berrió et al. (2002a) report dry and warm climates at c. 10,500 $^{14}$C yr BP. In the Llanos Orientales, Behling and Hooghiemstra (1998) record a drop in temperature from 10,700 to 10,000 $^{14}$C yr BP. The Younger Dryas (11,000-10,000 $^{14}$C yr BP) in the north of South America was, in general terms, cold and dry, as reported by Muhls and Zárate (2001) for eastern Colombia and Venezuela, by Marchant et al. (2002) for a synthesis of Colombian sites, by Fritz et al. (2001) for the Caribbean and Lake Valencia (Venezuela), and by Haug et al. (2001) for the Cariaco Basin (northern shelf of Venezuela). This period also includes the transition from the dry and cold El Abra Stadial (Younger Dryas) to a
widely recognised warm and wet early Holocene (Martin et al., 1997; Haugh et al., 2001). This period correspond to the diatom zone FUQ-2.

From 8680 to 7070 $^{14}$C yr BP (period 4): all proxies indicate warm and humid climatic conditions. During this period the lake reached the highest level recorded since 19,700 $^{14}$C yr BP. It presented a stable water chemistry. The surroundings were colonised by humid Quercus dominated forest and the upper forest line was between 3200 and 3300 meters of altitude. Martin et al. (1997) and Haugh et al. (2001) suggest that the abundant precipitation recorded in the north of South America was due to a more northern positioning of the ITCZ. This period is included in the Z2 pollen zone of Van 't Veer et al. (2000), zones Z1 and Z2 from Mommersteeg (1998) and diatom zone FUQ-3. A temporary drier phase occurred at c. 7780 $^{14}$C yr BP, causing a drop in lake level. This drier period was also recorded in sediments from the south west of Colombia, where maximum dryness was reached by 7500 $^{14}$C yr BP (Berrío et al., 2002a). Other records from the eastern savannas of the Llanos Orientales indicate similar conditions (Behling and Hooghiemstra, 1998; Behling and Hooghiemstra, 2000; Berrío et al., 2002b).

From 7070 to c. 5500 $^{14}$C yr BP (period 5): decreasing lake levels, unstable sedimentation and water chemistry, increased presence of rocky soil (Dodonaea) and greater abundance of Urticaceae point to a period of instability and the onset of drier climates. Dry conditions were already present at this time in the savannas of the Llanos Orientales and in the Cauca Valley in the southwest of Colombia (Berrío et al., 2002a,b). Haugh et al. (2001) attribute the change to a drier climate in the Holocene as consequence of the southward shift of the ITCZ. This shift, prevailing today, causes drier climates in the Cariaco basin (north Venezuela) and brings more precipitation in the Amazon region. This period is correlated with Z2 pollen zones from Van 't Veer et al. (2000), and Mommersteeg (1998) and diatom zone FUQ-4.

From c. 5500 to 4300 $^{14}$C yr BP (period 6): lower lake levels and drier climates prevailed during this period. The Andean forest moved downslope again and elements from the subparamo were frequent in the basin. Van Geel and Van der Hammen (1973) suggested that the increase
in dryness was first felt in the southern part of the lake and eventually in the northern part. Van Geel and Van der Hammen (1973) and Mommersteeg (1998) suggested land occupation by humans caused forest destruction and soil erosion. This period is correlated with pollen zone Z3 (Mommersteeg, 1998) and Z2 (Van Geel and Van der Hammen, 1973) and diatom zone FUQ-4.

From c. 4300 to c. 3700 \(^{14}C\) yr BP (period 7): during this period there is a change in the stratigraphy of the core from detrital material to a peat. The absence of diatoms and the peaty sediments suggest a lowered lake level and occasional desiccation. This period corresponds to the Z2 pollen zone from Fúquene-2.

From c. 3700 to c. 1600 \(^{14}C\) yr BP (period 8): during this period drier and cooler conditions were established in the basin. The lake level was relatively low and water became more acidified and nutrient rich. The increase in erosion in the catchment is indicated by all proxies, confirming human influence. This period is correlated with diatom zone FUQ-6 and pollen zones Z2-Z3 from Fúquene-2.

From c. 1600 \(^{14}C\) yr BP to present (period 9): climatic conditions similar to the previous period were maintained. Some changes in hydrochemistry and in lake level are indicated by diatoms and sediments, however it is difficult to know whether they were caused by human influence or by changes in climate. This period corresponds to diatom zone FUQ-7 and pollen zone Z3 from Fúquene-2.
Figure 5. Pollen percentage diagram of the upper 7 m of core Fúquene-7 showing selected taxa that are most relevant for the present comparison of the diatom-based and pollen-based lake-level histories. Adapted after Mommersteeg (1998).

6. Conclusions

We conclude that diatom and pollen assemblages recorded synchronously most of the environmental changes occurred in the basin since c. 19,700 $^{14}$C yr BP. The onset of drier conditions during the middle Holocene (c. 7070 $^{14}$C yr BP), however, appear earlier in the diatom and sedimentary record than in the pollen record.

The climate patterns from the Lateglacial and the Holocene in our new record from Lake Fúquene are similar to other records from Panama, Venezuela and the Caribbean (Fritz et al., 2001; Bradbury et al., 2001; Haugh et al., 2001). Relatively dry climates predominated during glacial times. A marked dry and cold El Abra Stadial (equivalent to the Younger Dryas in Europe) was registered in Fúquene-7 by a hiatus occurring
sometime between about 13,000 and 8700 $^{14}$C yr BP and recorded in Laguna Los Lirios between 11,300 to 9800 $^{14}$C (Bradbury et al., 2001), in Lake Valencia from c. 10,000 to c. 9000 $^{14}$C yr BP (Fritz et al., 2001), and in the Cariaco basin (Haugh et al., 2001) from c.12,600 to 11,500 cal. yr BP (corresponding to 10,500 to c. 10,000 $^{14}$C yr BP). During the early Holocene, characterised by humid and warm climates, the lake reached its maximum extension. This increase in precipitation in the north of South America was the consequence of a northern position of the ITCZ during this period (Martin et al., 1997; Haugh et al., 2001). The onset of drier climates occurred in Fúquene at c. 7070 $^{14}$C yr BP and prevail until today. These middle Holocene drier climates are registered in other places in the savannas of the Llanos Orientales and the Cauca Valley in Colombia (Berrio et al., 2002a,b). Marchant et al. (2001, 2002) show a general change in the vegetation of Colombia as a consequence of drier climatic conditions between 6500 and 5000 $^{14}$C yr BP. In Panama (Lake La Yeguada) limnological records suggest a dry phase between 7000 and 3800 $^{14}$C yr BP (Fritz et al., 2001) and in Venezuela (Lake Valencia) a drier phase was recorded between 7000 and 6000 $^{14}$C yr BP (Fritz et al., 2001). According to Haugh et al. (2001) this drier climate phase is due to the southward shift of the ITCZ to its current average position. We conclude that the environmental and lake level changes recorded in this core are driven by changes in precipitation due to shifts of the ITCZ.
<table>
<thead>
<tr>
<th>(^{14} \text{C} ) dates ( \text{yr BP} )</th>
<th>( \text{Zones} )</th>
<th>( \text{Diatom} ) ( \text{zones} )</th>
<th>( \text{Pollen} ) ( \text{zones} )</th>
<th>( \text{Extrapolated} \ \text{^C} \text{yr BP} )</th>
<th>( \text{Pollen} ) ( \text{zones} )</th>
<th>( \text{Van’t Veer et al., (2000)} )</th>
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</thead>
<tbody>
<tr>
<td>6040±60</td>
<td>FUQ-1</td>
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<td>19,670±240</td>
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</table>

### Figure 6. Synthesis of diatom-based and pollen-based records of environmental change and its zonation based on cores Füquene-7 and Füquene-2. From left to right: column A compares pollen-based and diatom-based zones from cores Füquene-7 and Füquene-2 (Van Geel and Van der Hammen, 1973; Mommersteeg, 1998). In column B we present the climatic periods recognised by Van’t Veer et al. (2000), and column C shows the different environmental periods that result from the overlap of diatom and pollen zones.

### 7. Acknowledgements

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