Middle Pleistocene palaeolimnology of a dammed tropical river: The Zarzal Formation, Cauca Valley, Colombia

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ABSTRACT

The Plio/Pleistocene Zarzal Formation (ZF) offers one of the few examples of alternation between fully lacustrine to fluvial conditions in a major, tropical, intramontane river in the Northern Andes, i.e., the Cauca River. The ZF is mainly composed of diatomites, mudstones, and tuffaceous sandstones deposited in an intramontane depression located between the Western and Central cordilleras of Colombia and associated with the Cauca-Romeral Fault System. Stratigraphic, sedimentological, micropalaeontological (diatoms), and geochronological analyses (independent (U-Th)/He dating of apatite and zircon) have been performed on two sections of the ZF. These analyses reveal a fluctuation between volcanic, fluvial and lacustrine deposits during the Middle Pleistocene. In addition, the presence of soft-sediment deformation structures reflects the synergetic effect of tectonism and volcanism on the sedimentation patterns in the Cauca River Valley. Our data show that between about 0.48–0.52 Ma (Ionian) depositional facies varied from a fluvial-dominated environment to a palaeo-lake, suggesting the impoundment of the river. Once the lake was formed, full lacustrine conditions were frequently interrupted by river pulses bringing terrigenous and previously deposited volcanic material into the lake. Diatom-based palaeolimnological reconstructions and comparisons with the sedimentological records indicate that river episodes played a decisive role on nutrient supply and sediment input, controlling important ecological dynamics in the newly formed lake. Although we cannot unambiguously pinpoint to the influence of volcanic activity on nutrient cycling within the lake, our data exhibit a strong relationship between volcanic deposits and changes in flora. The latter are possibly linked to the increase in phosphorous availability. The combined effects of tectonism and volcanism had major environmental implications in the Quaternary evolution of the Cauca River causing unprecedented damming of one of the major torrential tropical rivers in northern South America. Therefore, are of utmost importance when considering risk assessment and management for riverine communities and infrastructure such as dam buildings.

1. Introduction

The Zarzal Formation (ZF) is a formal name given by Van der Hammen (1958) to a set of sedimentary layers composed of diatomites, mudstones, and tuffaceous sandstones outcropping near the town of Zarzal in the Cauca Valley, Central Andes of Colombia (Fig. 1A, B) (see also De Porta, 1974). Recent studies have suggested that these rocks were formed under a dynamic depositional environment including lacustrine, floodplain, and fluvial conditions, implying damming episodes of one of the largest rivers in the Northern Andes (Neuwerth et al., 2006; Neuwerth, 2012; Suter et al., 2005, 2008a,b). Although the total thickness of the ZF is still unknown, Zuñiga and Padilla (1993) and Nivia (2001), based on stratigraphic relationships and geophysical studies, have estimated that it can reach up to 30 m. This unit is part of the Cauca Valley sedimentary fill, which has been influenced by volcanism from the Central Cordillera and tectonism related to the continued collision of the Panamá-Chocó Bock (Fig. 1B) (Suter et al., 2008b). The Cauca depression records important fluvial activity in an
Inter-Andean setting probably since the Eocene (Marín-Cerón et al., 2015; Sierra et al., 2004). At present, the Cauca River runs through a deep intramontane depression located between the Western and Central cordilleras. With a total length of ~1400 km, a basin area of ~63,300 km², and mean annual discharge in excess of 2000 m³/s, the Cauca River is a major tropical fluvial system, it is considered the second largest river in Colombia, (Restrepo and Syvitski, 2006; Ocampo-Duque et al., 2013). It ranks among the most densely populated fluvial basins in South America hosting 25% of the Colombian population settled in this valley (Pérez-Valbuena et al., 2015). This study aims at unraveling the Middle Pleistocene palaeoenvironmental history of the Cauca River, focusing on the lacustrine-dominated deposits of two outcropping sections close to Zarzal town (Fig. 1C). Results presented here constitute the oldest record of continental diatoms reported from Colombian geological units.

Fig. 1. Location and structural information of the studied area (A). Spatial distribution of the Zarzal Formation and its relationship with surrounding Quaternary units (B). Geological map modified from Neuwerth et al. (2006).
2. Geological framework

The southern portion of the Cauca Valley is bounded by a series of faults with a predominant N-S trend that correspond to the Cauca-Patía and Romeral Fault systems (Fig. 1B). The basin itself has been interpreted as the result of a graben structure (McCourt, 1984; Droux and Delaloye, 1996) or as a transtensional pull-apart basin (Kellogg et al., 1983) (Fig. 1). The studied area is situated where kinematics of the Romeral Fault System change from dextral to sinistral strike-slip due to the active deformation linked to the collision of the Panamá-Chocó Block indenter (Suter et al., 2008b). The ZF is part of the oldest Quaternary sedimentary infill of the Cauca Basin (Fig. 1), and lies on an angular unconformity over the Miocene fluvi-al-volcaniclastic deposits of La Paila Formation (McCourt, 1984; Schwinn, 1969; Van der Hammen, 1958). Earlier sedimentological studies indicate that the ZF was deposited under fluvial and lacustrine conditions as well as under intense seismic activity (Cardona and Ortiz, 1994; Neuwert et al., 2006; Suter et al., 2005, 2008a). The origin of this unit has been connected to the downstream damming of the Cauca River. Two mechanisms have been proposed for this damming: 1) progressive westward migration of volcaniclastic mass flows derived from the activity of the San Diego-Cerro Machín volcanic province in the Central Cordillera (cf. Martínez et al., 2013); these flows, which form the Cartagó and Quindío fans, possibly blocked the Cauca River (Fig. 1C) (Cardona and Ortiz, 1994; Suter et al., 2005; Neuwert et al., 2006); and 2) tectonism induced by uplifting and indentation of older rocks mainly from the Western Cordillera that served as a physical barrier in the central part of the Cauca basin (James, 1986; Suter et al., 2008b). Damming periods in the north of the ZF have also been reported during the Holocene (Page and Mattsson, 1981; García et al., 2011), most likely as a result of tectonism and climate (Schummm et al., 2000; Martínez et al., 2013). The age of the formation of this lacustrine facies is still a matter of controversy, ranging between ~2.8 Ma, based on laser fusion 40Ar/39Ar dating of biotites from ash layers (Neuwert, 2012) and < 0.8 Ma, according to the age of Alinus (Van der Hammen and Hooghiemstra, 1997; Neuwert, 2012).

3. Materials and methods

Two field sections (S1 and S2) located ~550 m apart have been described, mapped and sampled. Outcrops were cleaned and descriptions made on fresh exposure. Sections S1 and S2 are ~12.5 m and 7 m thick, respectively (Fig. 2A). Samples for diatoms were taken at least every 25 cm. The most representative samples for volcaniclastic deposits analysis were collected and the thinner layers described in the field at every 25 cm. The most representative samples for volcaniclastic deposits contain datable organic matter suitable for C-14 dating of Quaternary materials (Noller et al., 2000). Recently, the (U-Th)/He method has been successfully applied to dating young volcanics, i.e., over the Holocene-Pleistocene interval (Min et al., 2006; Farley et al., 2002; Danisik et al., 2012; Cox et al., 2012). From field evidence and previous age constraints, the expected eruption age for the sample studied here is <5 Ma. Therefore, the (U-Th)/He method for dating apatite and zircon crystals has been applied in this study to provide a geochronological constrain for the ZF.

Our age control has been derived from a sample collected 2.2 m above the base of the S1 section in the ZF, an ash fall deposit (biozone A; Fig. 2). We followed the standard sample preparation and analytical procedures for (U-Th)/He dating (Farley et al., 2002; Reiners, 2005; Restrepo-Moreno et al., 2009). Apatite and zircon separates were obtained through conventional gravimetric and magnetic susceptibility procedures. Uhefral, unfractured, apatite, and zircons grains with a minimum prism thickness of ~65 μm and low elongation ratios were manually selected under a high resolution stereomicroscope. Zircon and apatite grains with similar typologies (i.e., overall form, dominant crystalline faces, and color) were selected to avoid potential mixture of differently sourced materials. Individual grains were scanned for mineral and/or fluid inclusions under a petrographic microscope at magnification 100x. Selected grains for aliquot mounting were digitally measured to generate morphometric parameters for F2 corrections (Farley et al., 1996; Farley, 2000). After grain selection and measurements, single and multigrain aliquots of apatite and zircon were prepared. Zircon aliquots were wrapped in Nb tubes preparing a total of six aliquots, two multigrain and four single grains. For apatite, because of the expected young age of the sample and the potentially low U-Th-Sm concentrations, we packed one multigrain aliquot consisting of 10 individual crystals with similar dimensions/shapes in order to improve yields of 18He and U-Th-Sm signals. All apatite crystals were placed into a single Pt tube. Wrapped sample pellets were transferred to a stainless steel planchette for full degassing via heating individual pellets in an automated, all-metal analytical system under high vacuum conditions. Helium isotopic ratios were measured using a Pfeiffer-Blazers Prisma® quadrupolar mass spectrometer. Degassed packets were retrieved from the planchette to dissolve apatite and zircon grains and measure parent isotope concentrations (235U, 230Th and 149Sm) from a spiked solution of a solution composed of 0.3 g of dried sediments dissolved in 30 ml of distilled water with a few drops of hetamexaphosphate of sodium (10%). The aliquot was poured on a coverslip, placed on a petri-dish, and left to settle at room temperature for 12 h. This procedure was also followed in order to create a photographic record under a Scanning Electron Microscope (FEI QUANTA 250). A minimum of 400 valves were counted under a Nikon Eclipse 55i® microscope. Taxonomical identifications are based on Taylor et al. (2007), Renan et al. (2012), Bicudo and Menezes (2006), and online databases Spaulding et al. (2010) and http://craticula.ncl.ac.uk/EADiatomKey/html/index.html. Diatom preservation was defined by visual estimation and given a number ranging from 0 = very poor, 1 = poor, 2 = moderate to 3 = good. Diatoms per gram were calculated following Flores and Sierra (1997). Relative abundance diagrams have been generated using Tilia 1.7.16® software. Cluster analysis of the diatom information has been carried out with CONISS® (Grimm, 1987). Graphic correlation of the two studied sections is based on lithological and biostratigraphical data according to Shaw's method (Shaw, 1964).

3.2. Volcanic deposits

Volcaniclastic deposits were analyzed for each section following Murcia et al. (2013). This classification depends on the origin of the deposits. Pyroclastic fall deposits (ash fall) include sediments formed by direct accumulation from a pyroclastic fall. Secondary volcaniclastic deposits include reworked volcanic sediments removed by exogenous processes such as gravity, water, air, and/ or ice (e.g., lahars).

3.3. Age control

Young volcanic samples often represent a challenge for radiometric dating (Davidson et al., 2004). Typical geochronometers such as U/Pb or C-14 can determine ages either older than ~5 Ma (U/Pb) or younger than ~50 ka (C-14). Furthermore, not all sedimentary and volcaniclastic deposits contain datable organic matter suitable for C-14 dating of Quaternary materials (Noller et al., 2000). Our age control has been derived from a sample collected 2.2 m above the base of the S1 section in the ZF, an ash fall deposit (biozone A; Fig. 2). We followed the standard sample preparation and analytical procedures for (U-Th)/He dating (Farley et al., 2002; Reiners, 2005; Restrepo-Moreno et al., 2009). Apatite and zircon separates were obtained through conventional gravimetric and magnetic susceptibility procedures. U-He, unfractured, apatite, and zircons grains with a minimum prism thickness of ~65 μm and low elongation ratios were manually selected under a high resolution stereomicroscope. Zircon and apatite grains with similar typologies (i.e., overall form, dominant crystalline faces, and color) were selected to avoid potential mixture of differently sourced materials. Individual grains were scanned for mineral and/or fluid inclusions under a petrographic microscope at magnification 100x. Selected grains for aliquot mounting were digitally measured to generate morphometric parameters for F2 corrections (Farley et al., 1996; Farley, 2000). After grain selection and measurements, single and multigrain aliquots of apatite and zircon were prepared. Zircon aliquots were wrapped in Nb tubes preparing a total of six aliquots, two multigrain and four single grains. For apatite, because of the expected young age of the sample and the potentially low U-Th-Sm concentrations, we packed one multigrain aliquot consisting of 10 individual crystals with similar dimensions/shapes in order to improve yields of He and U-Th-Sm signals. All apatite crystals were placed into a single Pt tube. Wrapped sample packets were transferred to a stainless steel planchette for full degassing via heating individual packets in an automated, all-metal analytical system under high vacuum conditions. Helium isotopic ratios were measured using a Pfeiffer-Blazers Prisma® quadrupolar mass spectrometer. Degassed packets were retrieved from the planchette to dissolve apatite and zircon grains and measure parent isotope concentrations (235U, 230Th and 149Sm) from a spiked solution using a Thermo Finnigan Element® ICP-MS. Ages were calculated using the HefloPlot software® (Vermeesch, 2010). Alpha-recoil F2 corrections were performed following Farley et al. (1996). Errors are reported at 1σ level including both analytical and F2 corrections as part of error calculations. Durango apatite (Farley, 2000) and Fish Canyon Tuff
zircon (Reiners, 2005) were used as monitoring standards for apatite and zircon, respectively. These standards were measured every nine unknowns. Procedural hot and cold blanks were routinely measured during the sequence of analysis. The standard age equation used for (U-Th)/He dating is based on an assumption that the intermediate daughter isotopes in the U-Th decay chain have reached secular equilibrium. However, for a very young volcanic sample (< ~1 Ma), this assumption is invalid, requiring a more complex age calculation. For such samples, the correct (U-Th)/He ages are commonly older than those calculated from the standard equation by a few tens of percentage depending on age, D230, etc. (Cox et al., 2012; Danisik et al., 2012). For this correction, we have used the equation of Farley et al. (2002) with an assumption that our zircon samples have D230 value (definition) of 0.2 which is the average of terrestrial zircon samples. More detailed analytical procedures are available in Electronic Supplementary Material.

4. Results

4.1. Lithofacies and diatoms

Five diatom biozones were identified in section S1 (A–E) (Fig. 3), whereas section S2 contains only the three upper biozones (C–E) (Figs. 2 and 4). Lithological descriptions are provided for each of the diatom biozones.

4.1.1. Biozone A (0–2 m, section S1)

Thick tabular beds marked by thin of interlayering of siltstone laminae and very fine sandstones with parallel, lenticular, and climbing ripple laminations. Convolute bedding and water escape structures, including dish-and-pillar, can be locally observed (Subzone A1; Fig. 3). In the upper segment of this interval, there is a ~ 70 cm thick massive bed of beige mudstone with abundant root traces and small wood logs (Subzone A2; Fig. 3). Diatoms consist of benthic and aerophil species including (average relative abundance in parenthesis): Achnanthidium minutissimum (23,4%) (Fig. 5K), Diadesmis confervacea (21,6%) (Fig. 5G), Nitzschia amphibia (9%) and Staurosira construens (7,5%) the
latter peaks in this interval. Planktonic *Aulacoseira ambigua* (Fig. 5A) is also common (10.3%). Low abundance of diatoms precluded the estimation of valve concentration.

### 4.1.2. Biozone B (2–5 m, section S1)

This biozone records a sharp change in lithology and diatom composition (Fig. 3). The lithology consists of thick tabular beds of structureless white diatomites interbedded with thin beds and laminae of gray, fine to coarse grained sandstones, rich, primarily, in hornblende, pyroxene, and plagioclase crystals, and pumice. It is interpreted as an ash fall and secondary volcaniclastic deposits, which can display normal grading. Mud cracks and sand dykes intruding the diatomite layers are also identified at the base of this biozone (Fig. 3). Diatoms assemblages are composed of planktonic species *A. ambigua* and *A. granulata* (Fig. 5B) with averages of 50.6% and 41.9% respectively, and some appearances of *Fragilaria crotonensis* as well as planktonic *Discostella stelligera* (Fig. 5D) at the top (Fig. 3). Valve concentration is of $3 \times 10^8$ valves/g (Fig. 3).

### 4.1.3. Biozone C (5–7.6 m, section S1; 0–2.8 m, section S2)

This is the lowest biozone registered in both sections (Figs. 2 and 4). The lithology is similar to that of the previous interval, but volcaniclastic deposits become less frequent (Fig. 3). In terms of diatom assemblages *A. ambigua* disappears from the record while other species of *Aulacoseira* such as *A. pusilla* (18%), *A. granulata* v. *angustissima* (18,2%), and *A. muzzanensis* (7,4%) become more abundant (Fig. 3). Planktonic diatoms *F. crotonensis* is present with a maximum of 7%, and *D. stelligera* shows peaks of high abundances (max 40%) (Fig. 3). The highest diatom concentration occurs in this biozone with values up to $3 \times 10^8$ valves/g.

### 4.1.4. Biozone D (7.6–10.4 m, section S1; 2.8–5.3 m, section S2)

The lithology of this interval is characterized by an increase in thin diatomite and mudstone interbeds. Seven thin beds of gray sandstones either massive or with normal grading can be observed. According to the composition and structure, we have classified these layers as secondary volcaniclastic (particularly at the base) and pyroclastic fall deposits (Fig. 3). Particles of Fe oxide, which are concordant with the stratification, are common in this zone. Diatomites are mixed with detrital sediments and several samples lack diatoms (Fig. 3). Dish-and-pillar and soft-sediment deformation structures are common and are helpful features for correlation between volcaniclastic deposits in both sections (Fig. 2). The diatom signal includes the first and last occurrence of *Stephanodiscus* cf. *minutulus* (Fig. 5C) (average 11.4%, max 30%), and abundant *S. construens* (max 19%) and *S. pinnata* (max 16,5%) (Figs. 3 and 4). *Aulacoseira* spp. decreases (57%) and *D. stelligera* disappears completely from the record. Diatom concentration is reduced substantially to $3 \times 10^8$ valves/g (Fig. 3).

### 4.1.5. Biozone E (10.4–12.5 m, section S1; 5.3–7 m, section S2)

This interval is made largely of laminated mudstones which are interbedded with some diatomite laminae. Two thin beds of volcaniclastic sandstones can be observed at the top (Fig. 3). *A. granulata* (73,8%), *S. construens* (14,1%), and *S. pinnata* (8,2%) dominate this biozone. Diatom production shows a decline ($\sim 1.3 \times 10^8$ valves/g), and evident fragmentation of *Aulacoseira* valves is observed (Figs. 3 and 4).

### 4.2. Radiometric dating

The new (U-Th)/He data obtained from apatite and zircon samples...
are available in Tables 1 and 2, respectively. One multigrain apatite aliquot (10 apatite grains; Toba Ap) yielded corrected (U-Th)/He age of 2.1 ± 0.3 Ma with Th/U ratio of 2.5. Two multigrain zircon aliquots generated corrected dates of 1.9 ± 0.2 (Toba Zr_Multi 1) and 0.60 ± 0.08 Ma (Toba Zr_Multi 2). Four out of five single grain zircon aliquots yielded corrected ages ranging from 0.20 ± 0.38 to 0.67 ± 0.47, all of which are internally consistent within 2-sigma uncertainty. These ages are virtually identical to one multigrain zircon aliquot (Toba Zr Multi 2; 0.60 ± 0.08 Ma). The five single grain zircon ages and one multigrain zircon age (Toba Zr Multi 2) generate a weighted mean of 0.53 ± 0.06 Ma with MSWD of 0.5.

5. Discussion

5.1. Geochronology and stratigraphical correlations

Except for two multigrain aliquots of apatite (Toba Ap, 2.1 ± 0.4 Ma at 2σ), and zircon (Toba Zr Multi 1, 1.8 ± 0.2 Ma at 2σ), all the remaining aliquots yielded consistent (U-Th)/He ages in the range 0.20–0.60 Ma with a weighted mean of 0.53 ± 0.12 Ma at 2σ.
and. We suggest that the latter represents the most likely timing of eruption for this volcanic unit and consequently that our sample dates back to the Middle Pleistocene (Ionian stage) (Gibbard et al., 2010). This new and independent chronological estimate for the ZF is in agreement with an age of < 0.8 Ma based on palynological observations, i.e., the presence of _Alnus_ (Hooghienstra and Sarmiento, 1991; Andriessen et al., 1993; Van der Hammen and Hooghienstra, 1997; Suter et al., 2009a; Neuwirth, 2012), but differs from previously reported ⁴⁰Ar/³⁹Ar Gelasian ages for this same unit (Neuwirth, 2012).

The two multigrain aliquots (Toba Ap_Multi and Toba Zr_Multi 1) with significantly older ages than the rest of our aliquots probably contain “exotic” detrital grains from nearby layers. This demonstrates the importance of single grain analysis particularly for sedimentary and volcanoclastic samples. Despite efforts to select un-reworked apatite and zircon grains with unvarying typologies, the grains within these aliquots may not be exclusively derived from the grains originating from the corresponding eruption, but from a mixture of grains from previous volcanic and tectonic episodes. It remains unclear why two of the analyzed multigrain aliquots yielded an identical age within their 2σ uncertainties ( ~2 Ma). One possible explanation is that the 0.5 Ma eruption episode was predated by an additional 2 Ma volcanic eruption and that the level sampled in this study could be made by a mixture of ash fall-out of the Ionian volcanic event plus the contribution of some Gelasian and Calabrian (Early Pleistocene) grains from previous events.

In the temporal context provided by our helium ages, sections S1 and S2 are correlated using lithological features, cluster analyses, eruptions, i.e., the presence of soft-sediment deformation structures, reworked diatom biozones, and a 45° slope in the Shaw’s graph (Fig. 2B). Biozones and S2 are correlated using lithological features, cluster analyses, and S2 is correlated using diatom biozones, and a 45° slope in the Shaw’s graph (Fig. 2B).

Table 1
Summary of apatite (U-Th)/He data for sample TOBA.

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<tbody>
<tr>
<td>Durango</td>
<td>130</td>
<td>4.8</td>
<td>546</td>
<td>9.2</td>
<td>12,200</td>
<td>127.7</td>
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<td>3.2</td>
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<td>18.5</td>
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¹ U-disequilibrium uncorrected.
² U-disequilibrium corrected.

These _Aulacoseira_ species are common in floodplain shallow lakes with a dynamic mixing regime, high concentrations of silica and high turbidity (Hotzel and Crome, 1996; Liu et al., 2012). The high abundance of _A. ambigua_ in the lower part of the zone and is decrease in the upper part of biozone B (Fig. 2) indicates a gradual decrease in river influence. A subaerial period is revealed by mud cracks at 3.5 m with no obvious changes in the lithological record (Fig. 3), suggesting that shallow conditions and bottom lake exposure occurred. After this subaerial interval, high water levels returned as it is indicated by the abundance of _A. granulata, D. stelligera, F. crotonensis_ and _A. pusilla_ (upper part of biozone B and biozone C) (Fig. 3). _D. stelligera_ and _F. crotonensis_ are good indicators of abundant nitrogen (N) and limited phosphorus (P) (Saros et al., 2011; Saros and Anderson, 2015), suggest high water levels rich in these elements. Moreover, _F. crotonensis_ is known to increase when silica content (Si) is moderate to high (Saros et al., 2011).

In biozone D, an increase in volcanic activity is inferred from the several layers of pyroclastic material product of direct fall and volcanoclastic flows (Fig. 2A). The sudden increase of _S. minuta, Staurosira construens_, and _S. pinnata_ is on top of the volcanoclastic deposits (Figs. 3 and 4), evidences new limnic conditions, most likely as a result of volcanism affecting the physical and chemical characteristics of the water. Volcanism can alter the chemistry of the water and/or can form barriers for water circulation (Barker et al., 2003; Solovieva et al., 2015). Both species of _Staurosira_ are known for being aggressive colonizers (Urrutia et al., 2010), thus suggesting a change from previous ecological conditions. The increase of _S. minuta_ is normally associated with waters rich in P (Wang et al., 2012), most likely indicates an enrichment in P. In higher latitude lakes that suffer thermal stratification, _S. minuta_ is more abundant with the spring increases in P, but its appearances in tropical waters, where seasonal variations are not important, is a matter of debate. According to Vilaclara et al. (2010), its appearance is correlated with strong perturbation in the ecosystem as a result of volcanism, while Solovieva et al. (2015) have explained the increase of dissolved silica from tephras as one of the possible causes for _S. minuta_ appearance. In Zarzal Formation, the abundance of _Aulacoseira_ spp. throughout the record, suggest that silica was always abundant and available, since this species required high concentrations of it (Kilham et al., 1996). So far, in freshwater environments modern studies have been conducted to understand the relationship between P and volcanism. In marine environments it has been observed that dissolve P increases during frequent influxes of volcanic materials (Frogner et al., 2001). In the case of the ZF, it is possible that volcanoclastic flows could have brought more P into the system and/or altered circulation, enhancing remobilization of P, but more studies are necessary to find out the effects of volcanism in the trophic state of lakes. Following this quiet period, the Cauca River started flooding the lake once again (biozone E) as suggested by the presence of abundant terrigenous components, the physical fragmentation of valves, and the occurrence of benthic and facultative planktonic diatoms. Continuous fluvial discharges most likely diluted nutrients which negatively affected the previous flora (_S. minuta_) and favored the establishment of a new one (Fig. 3). In summary, a higher production of diatom valves was recorded in the lacustrine facies when the interaction with the river...
Table 2

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<td>2670</td>
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<td>0.48</td>
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<td>79</td>
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a U-disequilibrium uncorrected.

b U-disequilibrium corrected.

was minor, and the proportion of Si and most probably the ratio of N:P increased.

5.3. Origin of the lacustrine conditions in the Zarzal Fm

Our results reveal that lake conditions were reached about 0.5 Ma ago (Figs. 1 and 3). Reported damming episodes of the Cauca River are known (Suter et al., 2008a, b), and thus seem to be the more plausible explanation for the lacustrine environments recorded in sections S1 and S2. Cause (s) for this impoundment are still poorly understood. Although our studied sections are located away from the presumed zone of damming (Fig. 1C), the 30 cm ash fall layer at transition between biozones A and B demonstrates active volcanism at the time of impoundment (Fig. 3). The ZF is mainly dominated by fine-grained lithologies with continuous planar-tabular stratification layered with sporadic coarse-grained sandstones and tuffs derived from the volcanic activity from the Central Cordillera (Suter et al., 2005, 2008a). Alternatively, these characteristics might indicate that great relief contrast generated by tectonic-driven uplift and subsidence controlled most of the sedimentation through fluvial tributaries generating lacustrine conditions similar to those of ria lakes (Schumm et al., 2000). In fact, structural analyses suggest that tectonism has been an important controlling factor on the sedimentation in the Cauca and Quindío-Risaralda basins during the Quaternary (Suter et al., 2008b; López et al., 2009). Based on all of these characteristics, we consider that the damming of the Cauca River most likely involves tectonic and volcanic processes creating accommodation space for volcanic and lacustrine sediments to accumulate with sporadic influence of the river. In order to test this hypothesis, provenance and structural geology studies are required, particularly focusing on downstream segments of the Cauca River, where potential barrier outcrops might be present.

6. Conclusions

The ZF records a long-term Middle Pleistocene damming of one of the most important rivers of the Northern Andes. Damming of this magnitude is unprecedented for a torrential tropical river. Our studies based on diatoms, sedimentary facies, and U-Th/He thermochronology document that tectonism and volcanoism had major implications in the pre-Quaternary and Quaternary evolution of the Cauca River. Fluvial pulses and volcanic activity had important roles on the ecological dynamics of the lake by altering nutrient availability, water circulation or light penetration. Although we cannot unambiguously pinpoint to the influence of volcanic activity on nutrient cycling in the lake, our results exhibit a strong relationship between volcanic deposits and changes in flora, potentially linked to the increase in phosphorous availability.

This study illustrates that the combined effects of tectonism and volcanism play an important role in the dynamics of intra-mountain rivers. Consequently, these aspects have to be considered in risk assessment exercises for the management of local riverine activities, and civil infrastructures on the Cauca River.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.
