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Astronomical tuning of long pollen records reveals the dynamic history of montane biomes and lake levels in the tropical high Andes during the Quaternary

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ABSTRACT

Long pollen records from two sediment cores of the basin of Bogotá (Colombia) are presented, reflecting the dynamic history of environmental and vegetation changes in the tropical high Andes during the Quaternary. An astronomically tuned age model has been developed by using the visual correlation of the temperature-constrained record of *Alnus* with the benthic $\delta^{18}O$ stacked record of ODP Site 846 and 849 for the last 1 million year (Ma). In addition, spectral analysis of the arboreal pollen percentages (AP%) prior to 1 Ma shows two consistent peaks at 7.6 and 9.5 m, which could either be interpreted as reflecting the 19 and 23-kyr components of the precession cycle or the 41-kyr cycle of obliquity. Evidence for precession forcing comes from the sum of the filtered 7.6 and 9.5 m cycles, revealing a long-term modulation that can be linked to the short-term (100-kyr) and long-term (400-kyr) eccentricity cycles. A precession-forced scenario, however, is not consistent with zircon fission-track ages and is difficult to explain in terms of climate forcing mechanisms. On the contrary, an obliquity control of the AP% record is consistent with the fission-track ages and with glacial–interglacial-bound temperature changes within the study region. Accordingly, it appears that the Funza09 record extends back to ~2.25 Ma during which four periods with distinct different depositional environments could be identified, following a chronological poorly constrained interval of fluvial and fluvio-lacustrine sediments. From ~2.25 to ~1.47 Ma sediment deposition occurred in an area of wetlands dissected by fluvial channels and swamps. The strongest subsidence of the basin occurred between ~1.47 and ~1.23 Ma when a proper lake developed. Lacustrine sediments accumulated in water up to 50 m deep between ~1.23 and ~0.86 Ma. Hereafter, water depth was generally lower than 50 m, but fluctuated in conjunction with the 100-kyr dominated glacial–interglacial variability during the middle and late Pleistocene. The evolutionary changes of the páramo and montane forest biomes are described in terms of five characteristic stages. Most of the Pleistocene vegetation has no analogue to modern assemblages principally due to the late immigration events of *Alnus* (1.01 Ma) and *Quercus* (0.43 Ma) and we conclude that forest composition similar to modern was not established until the Last Interglacial. However, modern ecological constraints of suites of taxa that formed the vegetation of the pre-MIS 5 part of the record allow a reconstruction of environmental and climate change.

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1. Introduction

One of the major achievements in the study of Earth system history is the reconstruction of global climate change over millions of years derived from deep sea sedimentary archives (Zachos et al., 2001; Walker and Lowe, 2007). In addition, ice archives from tropical glaciers (Thompson et al., 1998) and high-latitude ice sheets (Grootes et al., 1993; Jouzel et al., 2007; Loulergue et al., 2008) have provided a thorough picture of Pleistocene climate variability in unprecedented detail. There is a dearth, however, of designated climate records from terrestrial archives, and in particular from tropical areas, which prohibit a full understanding of the driving mechanisms behind long-term climate change and its impact on terrestrial biota. Though terrestrial pollen records were among the first to show a major step in global climate cooling about ~2.6 million years ago (Ma) associated with the build-up and

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retreat of the large Northern Hemisphere ice caps (e.g. Godwin, 1956; Frenzel, 1968; Van der Hammen et al., 1971; Zagwijn, 1975), the fragmented character of continental records have hampered attempts to develop Quaternary reference sequences of terrestrial changes, partly due to the absence of robust and independent age constraints (e.g. Tzedakis et al., 2006). Land-based pollen sequences are therefore often compared with marine records on the basis of climatostratigraphic correlations (e.g. Tzedakis et al., 1997, 2001, 2004; Ruddiman, 2006; Bailey, 2009), while pollen records derived from strategically-placed marine sequences have allowed a direct marine–continental correlation on both orbital and millennial timescales, which refined our understanding of phase relationships between different components of the Earth system during the middle to late Pleistocene (e.g. Tzedakis et al., 2004; Margari et al., 2010).

Here we will elaborate on long pollen records derived from two sediment cores, Funza-1 and Funza-2, of the Bogotá basin (4°N, 2550 m altitude) in the tropical high Andes (Fig. 1). At present, the high plain of Bogotá represents the floor of a Pleistocene lake, which has been studied now for five decades, yielding a comprehensive data set of pollen and sediment fractions (Van der Hammen and González, 1960, 1963; Hooghiemstra, 1984, 1989; Hooghiemstra and Sarmiento, 1991; Van Veer and Hooghiemstra, 2000; Torres et al., 2005; Torres, 2006). The Bogotá basin consolidated after the strongest uplifting phase of the Eastern Cordillera in the Northern Andes (Van der Hammen et al., 1973; Helmens, 1990; Wijninga, 1996; Mora et al., 2008, 2010; Hoorn et al., 2010; Helmens, 2011). Although the lower part of the Funza-2 core (586–485 m) is interpreted as fluvial and may contain gaps in sedimentary record, sediments seem to have accumulated on a long-term scale without major interruptions (Hooghiemstra, 1984; Torres et al., 2005). At approximately 27 ka the basin lost its permanent lake; most plausibly the basin was overfilled with sediments giving rise to a large wetland area on the basin floor (Hooghiemstra, 1984). Much of the present-day high plain has been drained.

Dating of volcanic ash beds from previous analysis has repeatedly changed the age model of the studied sediments, because the wind-transported finest ash fractions were heavily contaminated with lacustrine deposits giving largely uncertain results (Andriessen et al., 1993). In this paper, we will focus on the cyclostratigraphic aspects, i.e. identification of the main astronomical-related frequencies in the composite pollen-based records of Funza-1 and Funza-2 to build a tuned time scale for the Quaternary sediments of Bogotá basin. Such an approach was successful in the adjacent Fúquene basin where a 60-m deep composite record reflecting the last 284,000 years (284 ka) was studied (Groot et al., 2011; Bogotá-A et al., 2011a,b; Vriend et al., 2012). Our time scale will give constraints on the time series of grain size analysis and aquatic vegetation, which will shed new light upon the development of sedimentary environments through time. In particular, we re-visit the history of the lake and show that the lake had not developed before 1.25–1.47 Ma. This led to a re-interpretation of the lower part of the pollen record. We show that the previously postulated hypothesis of an essentially different temperature-constrained altitudinal vegetation distribution is unnecessary to explain the record and we give a new environmental interpretation to the lower part of the pollen record. Finally, we will place the Pleistocene evolution of the montane forest and páramo biomes of the northern Andes into our new time framework.

2. Materials and methods

Funza-1 and Funza-2 were drilled near the village of Funza (4°50′N, 74°12′W, 2550 m.a.s.l.) located at the deepest part of the Bogotá basin (Fig. 1). Core Funza-1 was collected with rotary drilling from a mobile Portadrill truck. The site lies some 600 m from a wetland area bordering the small Bogotá River. Cores were collected in 50 cm increments and 6 cm diameter. The core reached to 357 m depth where technical problems with over-pressured ground water prevented deeper sediments from being collected. The 0–140 m interval was sampled at 25 cm increments and the 140–357 m interval at 20 cm increments. A total of 1230 pollen samples were analysed by H. Hooghiemstra between 140 and 357 m and by O. Hulshof between 0 and 140 m (Hooghiemstra, 1984, 1989).

Funza-2 was retrieved in 1988 with Longyear rotary drilling equipment placed on a concrete platform. The drilling site lies ~1 km from the Funza-1 site and 40 m from a wetland area bordering the Bogotá River. It recovered an entire unconsolidated sedimentary sequence of 586 m (Hooghiemstra and Sarmiento, 1991). Cores were collected in segments of 150 cm length with a diameter of 7 cm in the 0–380 m interval, 5 cm in the 380–450 m interval, and 4 cm in the 540–586 m interval. The bedrock of the Bogotá basin was reached at 586 m below the surface. The interval of 158–204 m could not be collected due to technical problems with over-pressured ground water. With increasing depth hard clayey sediments with a low water content prevailed. Sediments from these intervals were intensively fractured during core recovery. Coarse-grained sediment intervals often contained a substantial proportion of water and these core increments were semi-fluid in the worst cases. Where sediment recovery was up to 75%, samples were evenly distributed to simulate a continuous 20 cm sample distance, exaggerating the linearity of sediment accumulation. Where sediment recovery was less than 75%, sediment recovery gaps were registered. The interval of 204–586 m shows only small gaps in sediment recovery. The full record was first analysed at 1 m increments, and subsequently at 20 cm intervals for pollen analysis, organic carbon content (by means of loss-on-ignition; LOI) and grain size distributions (GSDs). Sediments below 540 m contain either few or no palynomorphs. In total 2010 pollen samples were counted of the intervals 2–158 and 204–540 m. Pollen analysis was carried out by H. Hooghiemstra, E. Ran, and V. Torres. GSD were analysed up to 586 m core depth by V. Torres; in total 2200 samples were analysed.

For methods used for standard pollen preparation, pollen identification, calculation of pollen percentages, plotting of pollen diagrams, and grain size analysis we refer to Torres et al. (2005). Pollen taxa making up the regional vegetation are included in the pollen sum. The grouping of taxa into ecological meaningful groups follows the studies by Van der Hammen (1974), Hooghiemstra (1984, 1989), Van 't Veer and Hooghiemstra (2000) and Bogotá-A et al. (2011b). The pollen sum includes taxa from páramo, subpáramo, Andean forest, and subandean forest; the latter two groups form the arboreal pollen percentage (AP%) record (Fig. 2). For methods used in GSD we refer to Vriend et al. (2012).

We used the Funza-1 pollen data set complemented with more than 880 new pollen counts from the lower part of the Funza-2 record to construct a composite record, called Funza09. The time series of pollen reach to 546 m depth and that of GSD to 586 m depth. We developed the composite pollen record Funza09 by linking the first appearance datum (FAD) of *Alnus* in cores Funza-1 and Funza-2 (Fig. 2). *Alnus* is a prolific pollen producer and the first 20% of representation of this tree is considered as background noise (Hooghiemstra, 1984; Grabandt, 1985; Soepboer et al., 2007). *Alnus* forms abundant swamp forest around the lake making it very plausible that the FAD at 257.60 m in core Funza-1 and at 255.20 m in core Funza-2 are stratigraphically significant and isochronous (Fig. 2). For frequency analysis and astronomical tuning we used the composite pollen record between 2 and 485 m core depth. The uppermost 2 m reflects a soil profile (Hooghiemstra, 1984), and pollen recovery in the lower part is discontinuous due to the increasing proportions of sand (Torres, 2006; Torres et al., 2005).