"Solving a piece of the puzzle". Reconstruction of millennial-scale environmental and climatic change in the northern Andes during the last glacial cycle: An integration of biotic and abiotic proxy-information
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Chapter 1: General introduction

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Chapter 1

General Introduction

1. Climate change: the past is the key to the present

In recent years, there has been an on-going discussion on climate change. In particular temperature change and its effects on the natural and human environments in the future received much attention. According to the IPCC’s Fourth Assessment Report (IPCC, 2007; Impacts, Adaptation and Vulnerability) warming of the climate system is unequivocal, but discussion remains on whether this warming is natural or anthropogenic. Studies on past climate change also show alternating cold and warm periods without anthropogenic forces.

Model studies have attempted to predict future climate change, however it is noted that there is a notable lack of geographical balance in data and literature on observed/measured changes making model outcomes subject to discussion. As an alternative for studying modern climate data, exploration and analysis past climate change is potentially beneficial to a better understanding of future climate change. Because climate change will cause alterations in ecosystems, investigating past reorganisations in ecosystems will give insight in past climate dynamics.

However, most understanding of climate history finds its source in Earth systems from the uninhabited parts of the globe, while the impact of climate change on the environments of the inhabited parts of the globe is poorly understood (IPCC, 2007; Impacts, Adaptation and Vulnerability).

2. Palaeoecological research in the tropics

Records of past climate change are mainly inferred from ice cores of Greenland and Antarctica (e.g. GRIP-Members, 1993; Grootes et al., 1993; Jouzel et al., 2007; NGRIP-Members, 2004; Parrenin et al., 2007; Svensson et al., 2008), marine sediments (e.g. Bond et al., 1993; Martrat et al., 2007; Peterson et al., 2000), and speleothems (e.g. Cheng et al., 2009; Wang et al., 2008). However, for terrestrial ecosystems such studies on the long-term evolution and millennial-scale variability are rare (e.g. Allen et al., 1999; Wijmstra, 1969; Heusser and Heusser, 1990; Reille and De Beaulieu, 1990; Guiot et al., 1989; Tzedakis et al., 1997, 2001, 2004, 2006). Particularly, in tropical settings only few comparable investigations are known (e.g. Kershaw, 1986; Mayle et al., 2000; Torres et al., in review; González-Carranza et al., 2012). In general, past reorganisations in terrestrial environments are rather difficult to interpret, because the terrestrial records are notorious for discontinuities in sediment accumulation and erosion of the sediment archive.

At the moment, focus of climate- and palaeoecological research again has been directed towards the low latitudes, because the tropics have the potential to alter the global oceanic heat and fresh water balance and they play a role as a source of water vapour to the atmosphere. In addition, high altitude regions in the tropics appear to be particularly sensitive to current climate changes (Thompson et al., 2003; Urrutia and Vuille, 2009) and are therefore ideally suited to investigate the environmental response (i.e. glaciations, hydrology and ecosystem integrity) to greenhouse gas forcing and glacial-induced ice volume variations, rather than their surrounding lowlands. Moreover, research on
sediment sequences in lake basins in tropical mountains has shown high potential to archive past climate change with high precision. Until recently, these high altitude tropical settings lacked the necessary high-resolution and accurate records to fully explore the operating mechanisms of the Earth’s climate system over long periods of time.

This thesis focuses on the northern Andes, and on the Fúquene Basin (5°27’N, 73°46’W) in particular. This basin is situated in the Eastern Cordillera of Colombia at 2540 m elevation and is covered by Quaternary lacustrine sediments. Presently, only part of the basin is covered by a water body, Lake Fúquene.

The surface of the sedimentary basin is close to the midpoint of the amplitude of the migration of the upper forest line (UFL) during a glacial-interglacial cycle. This implies that during the warmest period of the last interglacial (MIS 5e) the highest position of the UFL was at 3400 m, while during the coldest period of the last glacial (MIS 2) the UFL was at ca. 2000 m altitude (Van der Hammen, 1974; Hooghiemstra, 1984, Hooghiemstra, 1989; Van’t Veer and Hooghiemstra, 2000; Boom et al., 2001; Hooghiemstra and Van der Hammen, 2004; Torres, 2006). These changes in the altitudinal distribution of the vegetation are mainly temperature driven. Therefore, pollen records from these sediments are a sensitive recorder of temperature change, a proxy that is also frequently measured in marine sediments and ice cores allowing global comparisons (op. cit.).

Because previous studies from sediment cores collected at marginal sites of the lake showed a rich archive of vegetation and climate change (Van Geel and Van der Hammen, 1973; Van der Hammen & Hooghiemstra, 2003; Mommersteeg, 1998), sediment cores taken from more central sites of the lake were investigated in this study. As sediment cores from marginal sites showed discontinuities, it was reasoned that sediment cores from a central part of the lake would yield a more complete sediment accumulation due to the more stable sedimentary conditions. Therefore, two parallel 60 m-deep cores were drilled in the deepest part of the lake and they form the basis for the research presented in this thesis.

3. Use of multiple proxies

Pollen records, showing changing abundances in, for example, tree- and grass pollen, are indicative of temporal changes in, respectively, forest and grassland vegetation. As vegetation change is for a large part related to temperature, while precipitation, greenhouse gasses, and other variables play a minor role, vegetation change can be interpreted as changes in climate in a particular area. Although plants have their taxon-specific ecological envelope and taxa respond individually to climate change, many taxa respond in unison to environmental- and climate changes. Therefore, taxa showing similar responses can be considered as an altitudinal-constrained plant association, or ‘vegetation belt’. While, it is noted that such ‘vegetation belts’ always reflect an abstraction, studies have shown the effective use of vegetation belts for interpretation of climate- and environmental change.

Here, we follow the altitudinal vegetation zonation for the northern Andes put forward by Cuatrecasas (1958) and Van der Hammen (1974) and further elaborated in Hooghiemstra (1984), Van ‘t Veer and Hooghiemstra (2000) and Bogotá-A et al. (2011b). We
Chapter 1

recognised the following vegetation belts: subandean forest (1000-2300 m), Andean forest (2300-3200 m), subpáramo vegetation (3200-3500 m), and grasspáramo vegetation (3500-4200 m).

To develop a record of past temperature, the altitudinal migrations of the UFL have been reconstructed by following the relationship between arboreal pollen percentages (AP%) and the position of the UFL as elaborated by Hooghiemstra (1984) and Groot et al. (2011, this thesis). The highest occurrence of closed Andean forest is taken as the UFL (by convention) and the Mean Annual Temperature (MAT) over there is 9.5°C . By using a temperature gradient of 0.6°C per 100 m vertical forest displacement, migrations of the UFL over time can then be read as changes in MAT. The modeling study in Groot et al. (2011, this thesis) showed that changes in atmospheric pCO₂ also have an unquantified but significant impact on the position of the UFL supporting earlier evidence for this conclusion by Boom et al. (2001).

Aquatic pollen taxa can be used to reconstruct water levels and lake size and thus can be interpreted as a measure for precipitation and/or evaporation in the lake area. In this study, the proportions of successional plant associations to estimate water depth described by Van ‘t Veer and Hooghiemstra (2000), Torres et al. (2006) and Bogotá-A et al. (2011) are used (Fig. 4 from pollen paper). Thus, here Isoëtes and Potamogeton infer deep water; Ludwigia, Myriophyllum, Hydrocotyle, Typha, Apiaceae, and Ranunculaceae infer shallow water; Cyperaceae infers swamp conditions; and Rumex and Polygonum infer wet shore conditions.

By combining information from the aquatic vegetation change and grain size data (GSD) from the sediments, the reconstruction of changes in the local environment is fine-tuned.

To have a meaningful interpretation of the GSD, first the data has to be unravelled into its elementary components. As the more than 60 m thick sediment sequence in the basin is produced by erosion of the various rock formations in the area (Sarmiento et al., 2008) and riverine transport of sediments, sediments from Lake Fúquene are mixtures of sediment populations derived from different sources, and they have been transported to the site of deposition by different mechanisms (Weltje and Prins, 2003). Unmixing of these sediments can be accomplished with the End-Member Modelling Algorithm (EMMA; Holz et al., 2004, 2007; Stuut and Lamy, 2004; Vriend and Prins, 2005; Prins et al., 2007; Prins and Vriend, 2007; Vriend et al., 2012, this thesis). The unmixing results obtained from sediment populations in the GSD are then shown as End-Members (EMs). These modelled sediment components (EMs) can be tied to specific sediment transport processes and/or sediment source. Absence of an estimate for the abundance of organic matter in EMMA is problematical for reconstructing lacustrine environments. A fifth EM is created artificially on the basis of Loss-on-Ignition (LOI) data mainly indicating the presence of peat.

The relationship between downcore proportions of end-members (EMs) and vegetation associations of the hydrosere gives insight in the changing depositional environments.
Chapter 1

4. Developing an age model

For long sediment records from terrestrial environments, developing robust age models is a challenging task. Chronologies of long terrestrial sequences that extend beyond radiocarbon time control are well-known for insufficient robustness and therefore the age models of these records are subject to change. Only few terrestrial records include data from paleomagnetism (Tzedakis et al., 2006), well-dated tephra beds (Shane et al., 2002; Lowe et al., 2008), or show annual laminations over a long period of time (Brauer et al., 1999; Brauer et al., 2001).

Although radiocarbon dating has evolved into the most widely applied and accepted means of establishing chronological control for late Quaternary sediments, the radiocarbon dating method is limited to the last ~50 ka. Also, this dating method requires calibration to produce absolute (i.e. calibrated) dates (Reimer et al., 2009). In addition, the method obviously depends on the availability of good quality organic carbon, and contamination with allochtonous carbon may cause deviations (Blaauw et al., 2011). Sediments from Lake Fúquene used in this study did not contain usable plant macrofossils, which prevented direct dating of plant-specific materials. Therefore, the most carbon-rich intervals were visually identified and 46 bulk samples were collected for Accelerator Mass Spectrometry (AMS) radiocarbon dating. Results show that the sediments discussed in this thesis are partly within the range of the radiocarbon dating method (< 50 ka), however not all radiocarbon dates were considered useful due to different reasons (Groot et al., in review; this thesis). The radiocarbon dating results of the studied sediments were difficult to interpret because of their low carbon content, absence of the usual datable residual fraction, and the old age of the samples (close to the limit of dating).

In the absence of adequate time control it is a common practice to compare records of climate change by visual curve matching (VCM). The signature of the proxy record during the Holocene and the last glacial maximum (LGM) is mostly used to characterise the interglacial and glacial conditions, and consequently, these signatures are used to identify stratigraphically older glacial and interglacial episodes. However, the robust designation of antecedent glacial-interglacial cycles is difficult because doing so is based on the preconceptions of the meaning of the proxy record, and that the proxy record preserves a signature of change. The method of VCM was applied between the records from Lake Fúquene and Cariaco Trench located offshore of the Venezuelan Andes. The AP%-based temperature record from Lake Fúquene was compared to the colour reflectance-based temperature record from the Cariaco Basin (Peterson et al., 2000; Hughen et al., 2004). This exercise did generate an age model for the Fúquene sediments and results were compared with the method of cyclostratigraphy (CS) (Groot et al., in review; this thesis). The latter methodology was developed in marine micropaleontology, but hardly applied to long pollen records (Groot et al., 2011; this thesis).

The age model derived from the cyclostratigraphy-method was developed by using frequency analysis on the AP% in the depth domain, identification of orbital drivers of climate change, and tuning of the arboreal pollen (AP) record to the marine LR04
Chapter 1

benthic stack of δ¹⁸O records (Lisiecki and Raymo, 2005) (Groot et al., 2011; this thesis).
The frequency analysis showed highly significant power at ~9.07 and ~22.65 m; this
reflects the imprint of the 41-kyr obliquity cycle and the ~100-kyr eccentricity cycle,
respectively. As the most significant frequency peak is at ~9.07 m, it appeared that the
main driver of UFL shifts is obliquity. Subsequently, the 41-kyr cycle was filtered from
the arboreal pollen record (reflecting temperature change most closely) and tuned to the
filtered 41-kyr cycle from the marine benthic standard LR04 δ¹⁸O record (Lisiecki and
Raymo, 2005). Using cyclostratigraphy as a method to establish a chronology resulted in
a tuned and effective age model (Groot et al., 2011; this thesis).

5. Aim of this study

This thesis focuses on the last interglacial-glacial cycle, reflecting marine isotope stages
5 to 2. The interglacial-glacial cycle before the Eemian interglacial, thus reflecting
The sediments of the composite core Fq-9C were investigated at 1-cm intervals for the
following proxies: pollen, grain size distributions, organic matter content (LOI), and
geochemical composition of the sediments (Bogotá-Angel, 2011).

The objectives of this thesis were:
1. To improve the temporal resolution with an order of magnitude compared to the
   highest resolution pollen record at the turn of the century
2. To obtain a robust age model for the Fúquene sediments that allows establishing
   paleoclimate comparisons with marine sediment and ice core records.
3. To reconstruct downcore changes in grain size distributions and changes in the local
   vegetation to evaluate how the biotic and abiotic changes in the lake basin are associated
   in terms of source of sediments, energetic conditions for sediment transport, and lake
   size/level fluctuations.
4. To reconstruct past vegetation change in the study area and to infer climate change at
   orbital, millennial, and submillennial time-scales.
5. To compare climate change in the northern Andes at submillennial time-scales with
   records of climate change from Greenland and Antarctic ice records, and from marine
   sediment records.

The results are presented in chapters 2 to 5 of this thesis. Chapter 2 presents the age
model for the Fq-9C record which is based on a new approach in the study of long
continental Quaternary records, and highlights the sensitivity of the Andean ecosystems
in recording abrupt temperature change. Correlation with records from marine sediments and
Greenland and Antarctic ice cores, and implication of the role of atmospheric CO₂
concentrations in climate change is shown. Chapter 3 focuses on developing the steps
toward a robust age model for a lacustrine record of climate change, in particular for age
intervals beyond radiocarbon time control. In this chapter, different methods for obtaining
a chronology are compared and the model outcomes are discussed. Chapter 4 shows
the evolution of vegetation and climate representative for the northern Andes, during the
Chapter 1

period from 130 to 27 ka. In Chapter 5 the EMMA algorithm was applied to grain size data of lacustrine sediments. This algorithm is able to unmix GSDs of lacustrine sediments in a genetically meaningful way. This chapter provides an integrated reconstruction of the evolution of the basin with focus on changes in regional and local vegetation, grain size classes of the sediments, geochemical composition, and organic matter accumulation. Chapter 6 presents a general synthesis of results.

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