Chapter 2
The Glacial Record of Northern South America

Abstract The Bogotá basin and direct surroundings (eastern Andes in Colombia) holds a long sedimentary sequence that reaches from the present into the Miocene. Palaeo-botanical data indicates tectonic uplift by some 2,000 m during the Late Miocene–Pliocene that probably precluded sufficiently high enough terrain to support glaciers during the time period preceding the Quaternary. The first mountain glaciation as recorded by glaciofluvial sedimentation in the Bogotá basin is dated by fission-track and magnetic polarity dating at ca. 2.6 Ma, whereas a shift towards more extensive glaciations occurred after ca. 0.8 Ma. Moraines preserved in the Bogotá mountains record a series of glacial events for the time interval ca. 43 to 12.5 ka BP. Equilibrium Line Altitude (ELA) depression by ca. 1,300 m is reconstructed for the early Last Glacial Maximum (LGM; ca. 20 ka BP).

Introduction

The Colombian Andes in tropical South America (between latitudes 1–11°N) rises to elevations just over 5,000 m and is presently glaciated only very locally (see Helmens 2004). The total area of glaciated terrain was substantially enlarged during the Pleistocene, estimated to roughly 7.5 % of the total surface area of the Andean mountains (Thouret et al. 1996). The Pleistocene glacial record has been studied in detail in the high plain of the Bogotá area in the eastern Andes (Fig. 1.1). The high plain of Bogotá is situated at an elevation of 2,600 m and represents the bed of a former lake that occupied the tectonic basin of Bogotá during the Late Pliocene–Pleistocene (Fig. 2.1).

The Bogotá area holds an exceptionally long continental sediment sequence that reaches from the present into the Miocene (Van der Hammen et al. 1973; Helmens and Van der Hammen 1994; Van der Hammen and Hooghiemstra 1997). The sequence is near continuous in the Bogotá basin which began to accumulate

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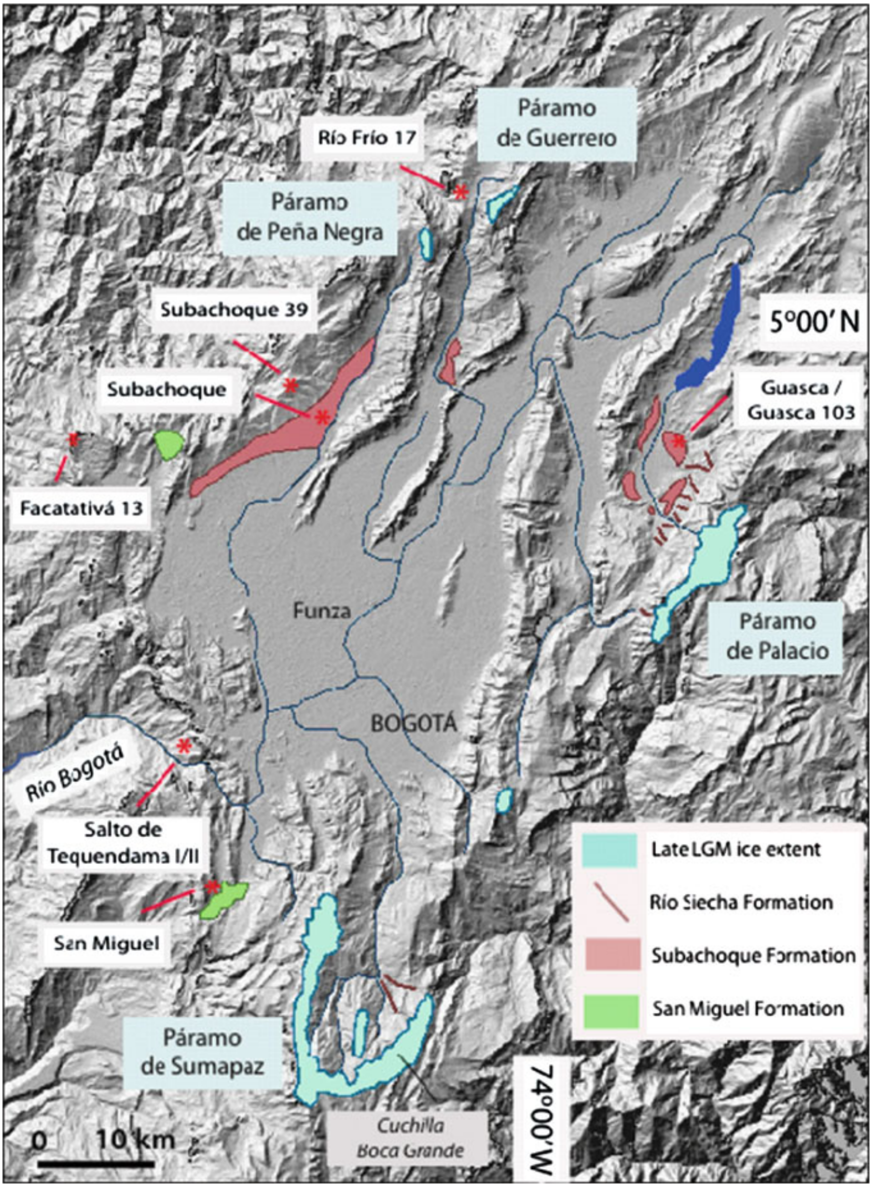

Fig. 2.1 The high plain of Bogotá and surrounding mountains (Eastern Colombian Andes; Fig. 1.1), showing the late LGM extent of mountain glaciers and the surface distribution of the Río Siecha (outwash fans), Subachoque (glaciofluvial and lake sediments) and San Miguel Formations (slope deposits). Location of exposures/boreholes mentioned in the text is also shown (based on Helmens 1990)

sediments at about 3 Ma. The older part of the sequence occurs as fragmented sections in the hills to the west of the basin. The sediments have been formally defined into 16 lithostratigraphic units and their surface distribution and geomorphic expression have been mapped over a total area of nearly 2,000 km^2 (Helmens 1990). Palynological data obtained from organic-bearing beds in exposed sections and from continuous lacustrine sequences from the central Bogotá basin, including the nearly 600 m long Funza II record (Hooghiemstra and Ran 1994), forms the basis for a biostratigraphic framework of 7 biozones (Van der Hammen et al. 1973; Kuhry and Helmens 1990; Wijninga 1996a). Absolute chronological control is provided through fission-track dating of volcanic ash layers (Helmens 1990; Andriessen et al. 1993; Helmens et al. 1997a), magnetic polarity dating (Helmens et al. 1997a), and radiocarbon dating of sediments and Andosols (summarized in Van der Hammen et al. 1980; Helmens 1990; Helmens and Kuhry 1995).

The palaeo-botanical record of the Bogotá area registers major tectonic uplift for the period between about 6–3 Ma. The uplift is recorded in the sections Salto de Tequendama I/II (Van der Hammen et al. 1973; Wijninga 1996b), Río Frío 17 (Wijninga 1996c), Subachoque 39 (Wijninga and Kuhry 1990), Facatativá 13 (Van der Hammen et al. 1973; Wijninga 1996d) and Guasca 103 (Wijninga and Kuhry 1993) (for locations see Fig. 2.1). Sediments of Middle Miocene age have provided fossil evidence of predominantly warm tropical lowland plant taxa, whereas Late Miocene and Pliocene sediments show increasing proportions of plant taxa associated with high-elevation (Biozones I-III). This trend in vegetation has been primarily interpreted in terms of a gradual tectonic uplift of the Eastern Andes in the Bogotá region by some 2,000 m during the Late Miocene-Pliocene (Van der Hammen et al. 1973; Kuhry and Helmens 1990; Wijninga 1996a). Figure 2.2 shows the inferred elevation at which the analyzed sediment sections were originally deposited, taking into account an estimated uncertainty of about 500 m. The latter corresponds to a range in temperature variation of about 3 °C expected for the Pliocene (Wijninga 1996a). Age control is based on fission-track dating of intercalated tephras (sections Río Frío 17 and Facatativá 13; Helmens 1990) combined with magnetic polarity dating (Guasca 103; Helmens et al. 1997a). The uplift is thought to have ceased, and the high plain of Bogotá area was situated as presently within the Andean forest belt at about 2,500 m, when the central Bogotá basin started to accumulate sediments at about 3 Ma (lower part of Biozone IV near the base of the Funza II pollen record; Hooghiemstra and Ran 1994; Andriessen et al. 1993; Figs. 2.1 and 2.2). The early part of Biozone IV in the Late Pliocene shows the first possible record of proto-páramo or páramo-like vegetation (Van der Hammen et al. 1973; Helmens and Van der Hammen 1994). Páramo vegetation presently forms the tropic-alpine vegetation belt above the Andean forest limit in the northern Andes.

As a result of the tectonic uplift, the Andes in the Bogotá area possibly lacked sufficiently high enough terrain to support glaciers during the time period preceding the Quaternary. The first mountain glaciation, with glaciofluvial deposition in the Bogotá basin, is recorded near the Gauss/Matuyama magnetic reversal at 2.6 Ma (Helmens et al. 1997a). Since the Funza II pollen record indicates a considerable lowering in the regional forest limit just after ~2.7 Ma (start of

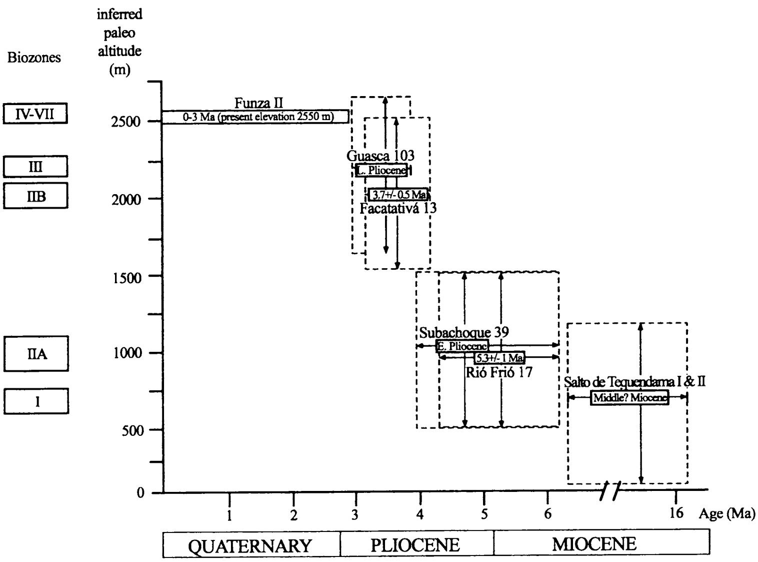

Fig. 2.2 Elevations of past depositional environments, estimated by comparing paleo-floras with present-day equivalents, for a series of sediment sections and the Funza II borehole in the Bogotá area (for locations see Fig. 2.2). Vertical arrows correspond to an estimated uncertainty of ca. 500 m in inferred paleo-altitude. Absolute ages are fission-track dates on intercalated volcanic ashes. Sections make a diagonal in this paleo-altitude versus age diagram, indicating tectonic uplift of the Bogotá region during the Late Miocene and Pliocene prior to ca. 3 Ma. Modified after Wijninga (1996a) and taken from Hooghiemstra et al. (2006)

Biozone IV, upper part; Hooghiemstra and Ran 1994; Andriessen et al. 1993), the first recorded glaciation was most probably related to the global cooling at the base of the Quaternary. An early Matuyama age for the onset of major glaciation in the Bogotá mountains closely corresponds to that obtained for the Bolivian Andes in central South-America, as established by magneto-stratigraphic dating of glacial deposits in the La Paz Basin (Thouveny and Servant 1989).

Major cooling in the Bogotá mountains near the base of the Quaternary is additionally suggested by the occurrence of wide-spread, down-slope movement of old tropical weathering products (Van der Hammen et al. 1973; Helmens 1990). Pollen data obtained from organic intercalations in these slope deposits (San Miguel Formation in Fig. 2.1) show a cold pollen flora corresponding to Biozone IV (upper part) and V (Kuhry and Helmens 1990). The base of the San Miguel Formation has been bracketed by fission-track dates on tephra between 2.8 ± 0.2 and 2.5 ± 0.3 Ma (San Miguel section in Fig. 2.1; P.A.M. Andriessen, K. F. Helmens and R. W. Barendregt, unpublished data).

In the Bogotá area, glacial deposits are restricted to the highest mountain ranges bordering the Bogotá basin, with elevations reaching over 3,600 m. Here a series of moraine complexes dated to the later part of the last glacial cycle, including the Last Glacial Maximum (LGM) at about 20 ka, have been preserved (Helmens et al. 1997b).

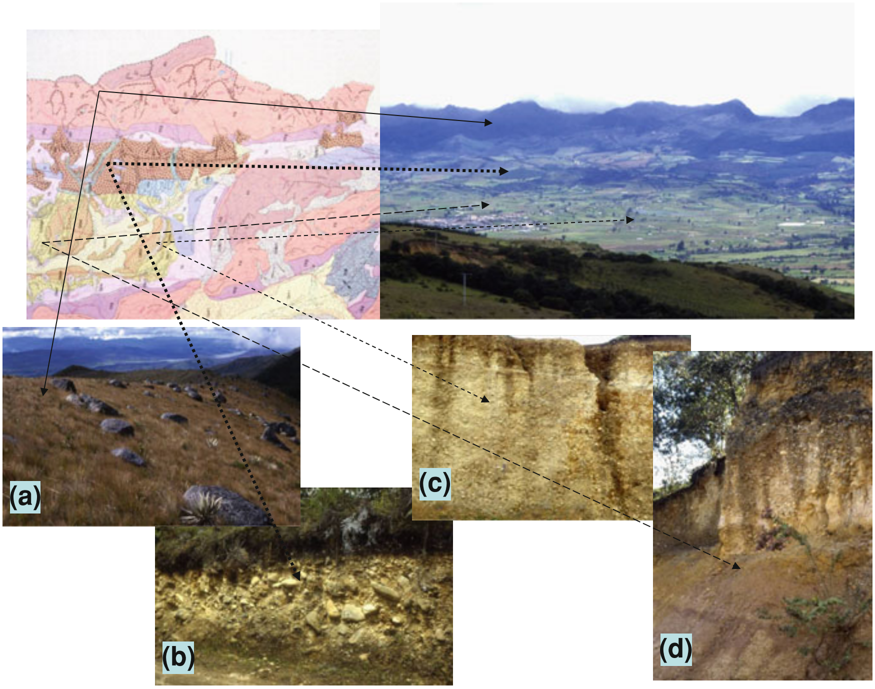

Fig. 2.3 Map fragment (Helmens 1990) and photos illustrating moraines (**a**) and the Río Siecha (**b**: outwash), Río Tunjuelito (**c**: glaciofluvial) and Subachoque Formations (**d**: glaciofluvial alternating with lake sediments) along the western slopes of the Páramo de Palacio and in the adjacent Bogotá basin (Fig. 2.1). Taken from Helmens (2011)

Glaciation During the Early Pleistocene (Matuyama Chron)

In the marginal valleys of the high plain of Bogotá, a distinct, gradual lithological change can be observed from moraine deposits on the higher mountain slopes to glaciofluvial accumulations in the Bogotá basin (Figs. 2.1 and 2.3). The coarse and angular boulders of which the moraines are composed (Fig. 2.3a) pass into more rounded boulders and gravels in a series of large coalescing outwash fans directly at the foot of the formally glaciated mountain slopes (Río Siecha Formation; Figs. 2.1 and 2.3b). The latter deposits grade, within the Bogotá basin, into thick sequences of rounded gravel (Río Tunjuelito Formation; Fig. 2.3c), which in their turn grade into a series of sand and gravel units away from the main rivers that enter the basin. The sand and gravel units alternate with, and in places truncate, more fine-grained sediment beds of mostly lacustrine origin (Subachoque Formation; Figs. 2.1 and 2.3d).

Palynological records from the lacustrine intercalations in the Subachoque Formation, from thin organic beds in the Río Tunjuelito Formation, and from thick sequences of clays interbedded with peaty and sandy sediment in the deeper parts of the central Bogotá basin (which have been correlated with the type Subachoque), reflect the changing climatic conditions of the Pleistocene. These pollen assemblages (Biozone IV, upper part, to Biozone VI) indicate that during deposition of the Subachoque and Río Tunjuelito Formations the slopes surrounding the Bogotá basin were alternately covered by Andean forest vegetation, representing interglacial (or interstadial) conditions, and treeless páramo vegetation that indicate glacial (stadial) conditions. The sand and gravel interbedded in the Subachoque Formation, and the gravels of the Tunjuelito Formation, are interpreted to represent the coldest intervals of the Pleistocene when the surrounding mountains were glaciated (Van der Hammen et al. 1973; Helmens 1990). The glaciers caused the outer valleys of the Bogotá basin to be infilled by glaciofluvial sediment, restricting the Bogotá Lake to the central part of the basin. Radiocarbon dates from the Tunjuelito Formation and from organic-rich sediments and paleosols found associated with the moraines in the Bogotá mountains suggest synchrony between the deposition of gravels in the Bogotá basin and glacial events in the mountains for the Late Pleistocene (Van der Hammen et al. 1980/81; Van der Hammen 1986).

The Subachoque Formation, and sediments of the underlying Guasca Member of the Upper Tilatá Formation, have been lithologically described in detail and provided with fission-track dates on volcanic zircons and geomagnetic polarity dates in two major outcrops, i.e. the Guasca and Subachoque sections along the eastern and western margins of the Bogotá basin (Fig. 2.1). The clays and silts of the Guasca Member represent the oldest sediments in the marginal valleys of the Bogotá basin (Helmens 1990). The simplified lithology and absolute chronology of the Guasca and Subachoque sections (Helmens et al. 1997a) are given in Fig. 2.4. The polarity records obtained from these sediments was not expected to mimic the global geomagnetic polarity reference timescale considering that the alternating glaciofluvial and lacustrine/paludal sediments of the Subachoque and Upper Tilatá Formations accumulated at different rates, and periods of sedimentation alternated with periods of erosion. The paleomagnetic correlation made by Helmens et al. (1997a) takes into account the discontinuity of sedimentation, as well as the error limits of the fission-track dates.

The sudden influx of sands and gravels in the marginal parts of the Bogotá basin recorded at the base of the Subachoque Formation (Fig. 2.4) is interpreted as reflecting the onset of glaciation in the adjacent Bogotá mountains (Helmens 1990; Helmens and Van der Hammen 1994). The sudden influx of more coarse-grained sediment is accompanied by an increase in the magnitude of the magnetic susceptibility (MS) signal. Helmens et al. (1997a) use MS as a proxy for periglacial and glacial erosion in the Bogotá mountains, which resulted in a high influx of magnetite-rich sediments into the basin. The major lithological change at the base of the Subachoque Formation is bracketed by fission-track dates of 2.9 ± 0.4 Ma and 2.5 ± 0.3 Ma and according to geomagnetic polarity is dated near the Guass-Matuyama polarity reversal at 2.6 Ma. Glaciations are recorded throughout the Matuyama Chron. However, the low resolution and fragmentary nature of the glacial record provided by the Subachoque sediments, and the limited chronological control, hamper reconstruction of the total number of glaciations in the Bogotá mountains during the Matuyama as well as detailed land-sea

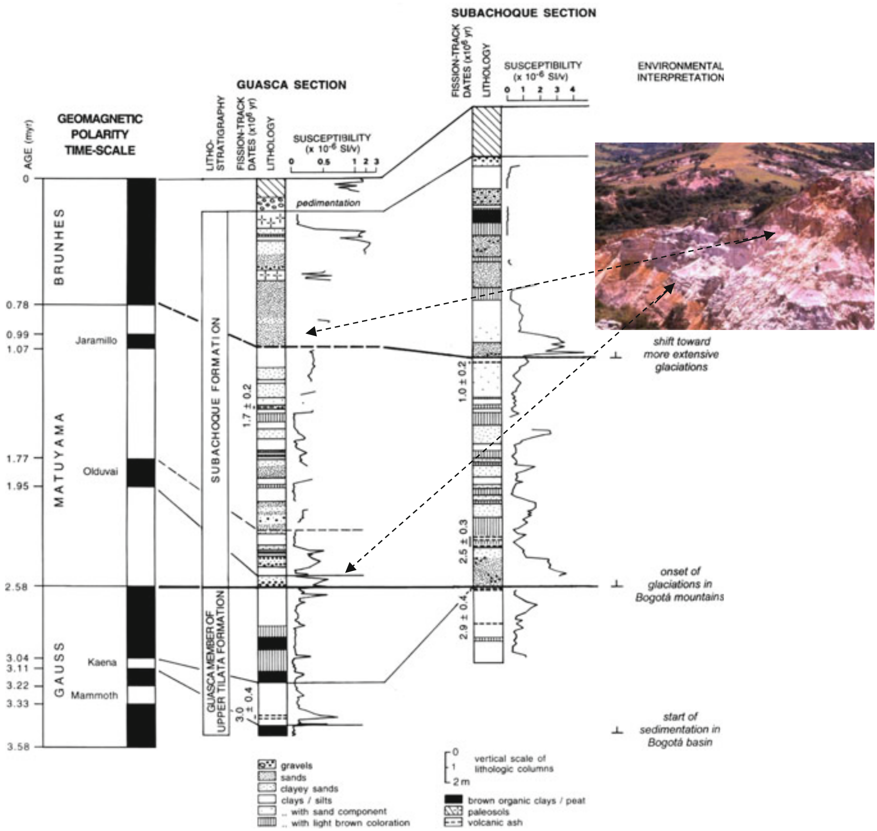

Fig. 2.4 The Late Pliocene-Quaternary environmental record of the Guasca Member of the Upper Tilatá Formation and the Subachoque Formation in the marginal valleys of the Bogotá basin, based on magnetostratigraphy, fission-track chronology, lithology and magnetic susceptibility of the Guasca and Subachoque sections (Fig. 2.1). The geomagnetic reversal chronology is based on Cande and Kent (1995). Vertical scale of lithological columns is linear. The sand and gravel interbeds in the Subachoque Formation represent glaciofluvial sediment derived from glaciers in the higher mountain ranges surrounding the Bogotá basin (Helmens et al. 1997a). The photo shows the Guasca section. Taken from Helmens (2011)

correlation. Distinct peaks in the MS sequence suggest at least five glaciations occurred during the Matuyama Chron.

Glaciation During the Middle-Late Pleistocene (Brunhes Chron)

A change in lithology in the upper part of the Subachoque Formation, accompanied by a further increase in the MS signal, is dated at <1.0 ± 0.2 Ma and placed near the Matuyama/Brunhes polarity reversal at 0.8 Ma (Fig. 2.4). Sand and gravel units in the upper part of the Subachoque Formation dated to the Brunhes Chron are distinctly more coarse-grained than those dated to the Matuyama Chron; additionally, peaty horizons and paleosols are found interbedded with the sands and gravels of Brunhes age. Helmens et al. (1997a) interpret the lithological change in the Subachoque Formation near the Matuyama/Brunhes boundary as representing a shift towards more extensive glaciations, which caused rapidly aggrading floodplains to leave a distinct series of coarse-grained sand and gravel layers in the Bogotá basin. Additionally, episodes with conditions warmer than during the Matuyama Chron, and higher evaporation and evapotranspiration rates (Hooghiemstra 1984; Kuhry 1991), probably resulted in lower lake levels, and peat accumulation, and, in the orographically dry Guasca valley, in periods of soil formation (Helmens et al. 1997a). Several glaciations seem to be recorded during the Brunhes Chron.

A shift towards higher magnitude climate oscillations is also recorded in the Funza pollen sequence at ca. 0.8 Ma (Andriessen et al. 1993; Hooghiemstra et al. 1993; Hooghiemstra and Ran 1994). This change has been found associated with a distinct change in the frequency of oscillations from 41 to 100 ka climate cycles (Hooghiemstra et al. 1993).

The Late Pleistocene (Last Glacial Cycle: Brunhes Chron)

Detailed mapping of glacial landforms in the Páramos de Palacio, Sumapáz, Peña Negra and Guerrero (Fig. 2.1) has allowed the identification of four moraine complexes with distinct differences in morphology and degree of denudation (Helmens 1988). Dating of the moraines, and of still older glacial deposits without moraine morphology, using ^{14}C dating on basal lake sediments, peaty horizons and organic-rich paleosols, have dated glacial advances between about 43 and 38 ka BP (in radiocarbon years), 36–31 ka BP, 23.5–19.5 ka BP, 18.0–15.5 ka BP, and 13.5–12.5 ka BP (Helmens 1988; Helmens et al. 1997b).

The most extensive glaciations occurred during the Late Pleistocene in the Middle Wisconsinan probably under the influence of cool and humid conditions (Van der Hammen et al. 1980; Van der Hammen 1981; Helmens and Kuhry 1995). The moraines dated to 18.0–15.5 ka BP (late LGM) show the most impressive morainic morphology of the different morainic complexes recognized. The arcuate, multiple ridge system rises tens of meters above the valley floors and the related maximum ice extent can be continuously traced throughout the mountain ranges studied (Helmens 1988; Fig. 2.1).

Glaciers reached some 100 m further down valley during the early part of the LGM (23.5–19.5 ka BP). The early LGM moraines have been used by Mark and Helmens (2005) to reconstruct paleo-glacier surfaces and equilibrium line altitudes using the area-altitude balance ratio (AABR) method. An overall lowering in ELA from modern values to early LGM of ca. 1,300 m was reconstructed, indicating considerable LGM cooling in the Bogotá mountains. Mark and Helmens (2005), however, do report a large amount of intra-regional variance in LGM ELA that is ascribed to topography and its indirect effect on precipitation, cloudiness and/or glacier form, with lower headwall elevations being correlated to larger accumulation area and lower ELAs. The lowering in ELA of ca. 1,300 m is of similar magnitude to the pollen-based inferred lowering in forest limit in the Bogotá area, implying a drop in mean annual temperature during the early LGM by some 8 °C (Van Geel and Van der Hammen 1973; Kuhry 1988; Helmens et al. 1996).

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