Interannual Variability in Pollen Dispersal and Deposition on the Tropical Quelccaya Ice Cap*

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Pollen collected from snow samples on the Quelccaya Ice Cap in 2000 and 2001 reveals significant interannual variability in pollen assemblage, concentration, and provenance. Samples from 2000, a La Niña year, contain high pollen concentrations and resemble samples from the Andean forests (Yungas) to the east. Samples from 2001, an El Niño year, contain fewer pollen and resemble those from the Altiplano. We suggest that varying wind patterns under different El Niño/Southern Oscillation (ENSO) conditions may affect the processes of pollen transport over the Altiplano and on the ice cap, although confounding variables such as flowering phenology and sublimation should also be considered **Key Words: biogeography, ice-core palynology, Peru, pollen dispersal, Quelccaya ice cap.**

Introduction

Studies have shown that sensitive records of past vegetation changes can be obtained through the analysis of pollen in nonpolar ice cores (Thompson et al. 1988, 1995; Liu, Yao, and Thompson 1998; Yao 2000; Reese 2003). However, few studies to date have addressed questions concerning the modern dispersal and depositional processes of pollen in these high-alpine areas. Understanding these processes is crucial to the development of a "modern analog," or knowing how the current vegetation is represented in the modern pollen rain on the ice caps. A modern analog is our most powerful calibration tool for the accurate reconstruction of past environments from fossil pollen evidence (Webb, Bartlein, and Kutzbach 1987; Webb et al. 1993). Without these studies, the interpretation of fossil pollen signatures found deep in the ice cores remains speculative (McAndrews 1984; Bourgeois 1986, 1990; Koerner, Bourgeois, and Fisher 1988).

Although pollen dispersal on mountain slopes has been studied (Markgraf 1980; Jackson, 1991; Fall 1992; Horn 1993; Flenley 1996), summit environments or ice caps have received comparatively little attention. Reese and Liu (2002) and Reese, Liu, and Mountain (2003) are the only published studies that have analyzed modern pollen assemblages in surface snow samples from tropical ice caps. The results from the Quelccaya Ice Cap (Reese and Liu 2002) in southern Peru and Mt. Parinacota (Reese, Liu, and Mountain 2003) in southwestern Bolivia showed significant differences in the pollen dispersal and depositional mechanisms on the ice caps. The variability in the pollen data was likely the result of the biophysical differences between the two mountains, and their locations on the Altiplano itself. However, the two studies did confirm that the prevailing wind plays a major role in pollen deposition, with local thermal and mechanical mountain winds controlling the dispersal of pollen once on the ice cap.

From these previous studies, however, two major questions have emerged and remain unanswered. The first is the interannual variability in pollen dispersal and deposition on these tropical ice caps. Reese and Liu (2002) utilized

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shallow surface samples that only represented the current season of accumulation. One goal of this research is to address this question by replicating the Reese and Liu (2002) study (consisting of fifteen samples collected in 2000), one year later, at the Quelccaya Ice Cap in Peru. For this study, nineteen new surface samples were collected from the ice cap in June 2001 and were compared to the previous year's data in terms of pollen assemblage and concentration. The second question concerns pollen provenance on the Quelccaya Ice Cap. To answer this question, discriminant analysis was used to compare the ice cap pollen samples from both years to an extensive network of surface pollen samples taken from the central Andes. These Andean surface samples were collected in June/July of 2001 from the four major vegetation regions in the central Andes. The regions are (1) the puna grasslands of the Altiplano, (2) the scrub deserts of the Southern Bolivian Highlands, (3) the coastal deserts west of the Andes, and (4) the Yungas vegetation on the eastern slopes of the Andes. This network of Andean surface samples has been discussed by Reese (2003) and Reese and Liu (forthcoming).

Study Area

Rising to 5,670 m above sea level, the Quelccaya Ice Cap (13.93°S and 70.83°W) sits atop an ignimbrite plateau (Thompson, Mosley-Thompson, and Morales-Arnao 1984) on the eastern edge of the Andes Mountains in southern Peru (Figure 1). Quelccaya is the single largest glacier in Peru (Zamora and Ames 1977) with an area of 54 km^2 (Morales-Arnao and Hastenrath 1999). The vegetation near Quelccaya is puna, as defined by a global classification of ecoregions (Olson et al. 2001). The name

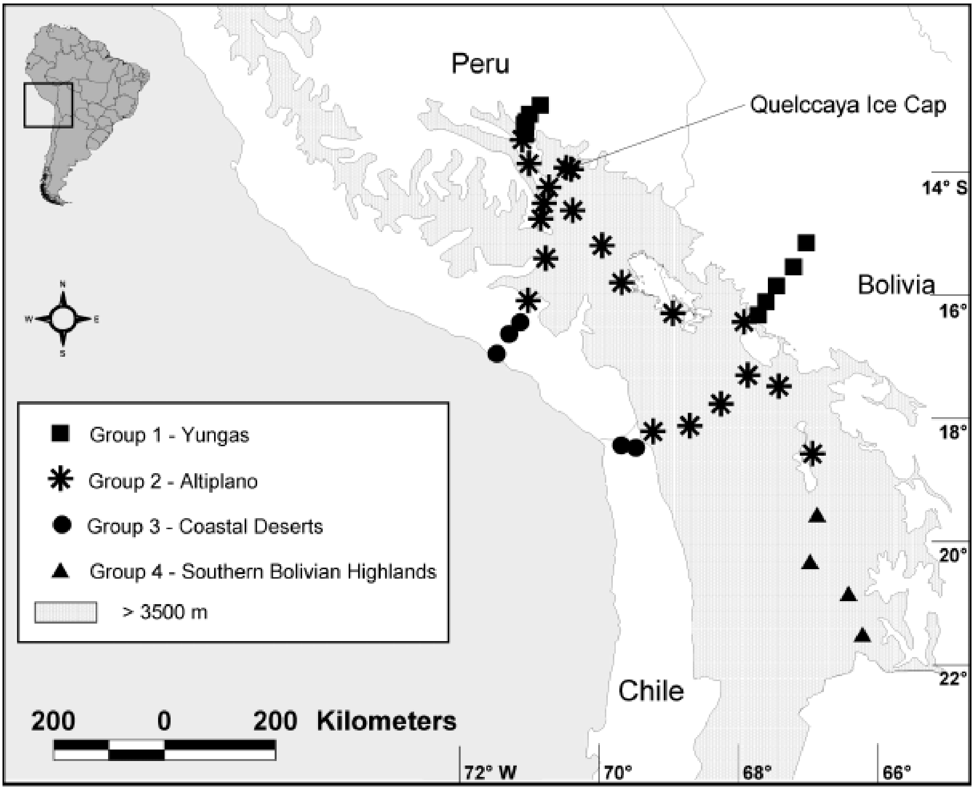

Figure 1 *Map of the central Andes showing the location of the Quelccaya Ice Cap and the forty surface samples used in the discriminant analysis.*

puna comes from the "puna-brava" (Tosi 1960) vegetation assemblage that defines the Andean Altiplano. Puna is found between 5,000 and 3,300 m above sea level (Hansen, Wright, and Bradbury 1984) and is primarily a dry grassland community dominated by bunch grasses like *Festuca*, *Stipa*, *Calamagrostis*, and *Agrostis* (Poaceae) (Young et al. 1997) (Figure 2A). Other common plants include Asteraceae (e.g., *Baccharis*, *Werneria*, *Gynoxys*), *Plantago*, *Polylepis*, *Dodonaea*, and *Alnus* (Hansen, Wright, and Bradbury 1984; Young et al. 1997).

A distinct northeast to southwest precipitation gradient exists on the Altiplano, with precipitation totals diminishing toward the Atacama Desert to the southwest. Though the puna is relatively homogenous throughout its extent, this precipitation gradient affects the vegetational composition of the ecosystem. Palynological studies have repeatedly shown that the abundance of grass pollen is a good indicator of this precipitation gradient across the Altiplano, as the percentage of grass tends to increase with increased precipitation (Meserve and Glanz 1978; Betancourt et al. 2000; Latorre et al. 2002, 2003). Reese (2003) showed the Altiplano grasses to have an inverse relationship with the deep-rooted, xerophytic Asteraceae family; the latter tends to increase in abundance as precipitation decreases. Precipitation over the puna grasslands ranges from 400–800 mm annually in the northern and easternmost extents, nearly twice the amount in the drier southwest (Garreaud, Vuille, and Clement 2003). The higher precipitation accounts for a fivefold increase in species richness and a twofold increase in ground cover, as compared to the southwestern Altiplano (Arroyo, Armesto, and Villagran 1988).

In the southernmost reaches of the Altiplano, south of roughly 19° S latitude is an area of the Bolivian Altiplano that we refer to as the Southern Bolivian Highlands. Though still technically classified as puna on a global-scale map (Olson et al. 2001), this region differs markedly from the puna of the northern and central Altiplano in both landform and vegetation. This arid region is home to several paleo-salt lakes and exposed sedimentary rock formations that date back to the Cretaceous Period (Holmgren et al. 2001). The vegetation assemblage also changes from a grass-dominated landscape to a scrub desert (Arroyo, Armesto, and Villagran

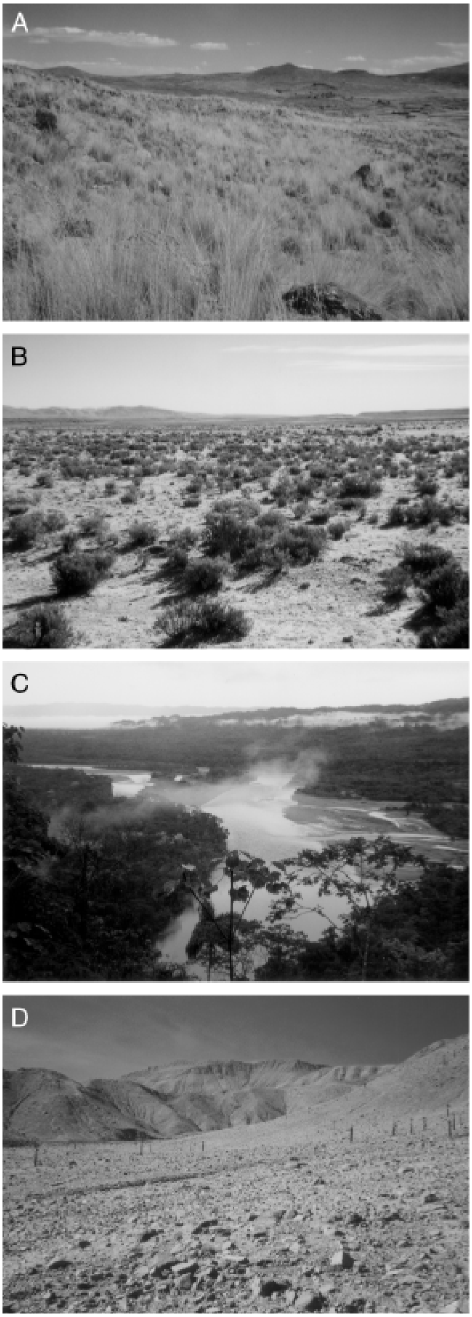

Figure 2 *Field photographs showing the contrasts among the four principal landform and vegetation types in the Central Andes: (A) puna, (B) Southern Bolivian Highlands, (C) Yungas, (D) coastal desert.*

1988), where the Solanaceae family (e.g. *Fabiana*) is dominant between 3,200–4,000 m (Latorre et al. 2002) (Figure 2B). Other common plant families include Asteraceae, Chenopodiaceae, Amaranthaceae, and Euphorbiaceae.

Less than 50 km to the east of Quelccaya lies the edge of the Altiplano and the steep environmental gradient of the eastern Andean slopes. The vegetation here is categorized as Yungas (Weberbauer 1936, 1945; Olson et al. 2001). Yungas is a mixed deciduous and broadleaf evergreen forest, dense with arboreal ferns, lianas, and trees, which typically occur between 400–3,500 m above sea level (Olson et al. 2001) (Figure 2C). Common tree species include *Alnus*, *Myrica*, *Podocarpus*, *Weinmannia*, and members of the Apocynaceae, Ericaceae, Myrtaceae, Melastomataceae, and the Urticaceae and Moraceae (especially *Cecropia*) families. Aside from patches of disturbance (which may allow for downslope invasion), all puna species are absent (Hansen, Wright, and Bradbury 1984).

The markedly drier slopes of the western Andes are a stark contrast to the Yungas vegetation on the eastern flank. In many areas, the puna grasslands (especially the xerophytic elements such as the Asteraceae, Chenopodiaceae, and Amaranthaceae families) are allowed to extend all the way to the Pacific Ocean (Reese and Liu 2002). True desert vegetation like the Cactaceae family and the genus *Ephedra* are also more prevalent (Figure 2D). In some sections of the Atacama and Sechura Deserts, in Chile and Peru, respectively, the landscape is completely without vegetation or significant rainfall.

Methods and Materials

In August of 2000, fifteen surface snow samples (from nine different locations) were collected along an east–west transect across the Quelccaya ice cap (samples # 1–15, see Figure 3) (Reese and Liu 2002). An additional nineteen samples were collected in June 2001 (samples # 16–34, see Figure 3). Among these thirty-four samples were nine pairs of samples taken to test for within-site variability. The two samples within each pair were taken no more than 1 m from each other. For each sample, regardless of year, surface snow was directly transferred into 500 ml Nalgene leakproof sample bottles. Only the top 5 cm of snow was sampled at each site. This uppermost layer should represent the accumulation of the current season. After collection, the bottles were sealed and readied for transport back to Louisiana State University for processing.

The amount of meltwater varied for each sample, but all ranged between 200 and 500 ml. All meltwater samples were processed following the procedure outlined in Reese and Liu (2002). For the identification of the pollen, each slide was scanned at 200X using a Nikon Optiphot microscope. The pollen was identified under 400X magnification and was verified with several pollen keys (van der Hammen and Gonzalez 1960; Heusser 1971; Markgraf and D'Antoni 1978; Roubik and Moreno 1991; Colinvaux, De Oliveira, and Moreno 1999). For all samples, pollen and spores were identified and counted until a total of 300 was obtained. Charcoal particles were counted and reported regardless of size, and their concentration values (number of particles per liter of meltwater) were calculated in the same manner as the pollen concentration values.

Statistical Analyses

To answer the question of pollen provenance on the ice cap, we compared the 2000 and 2001 Quelccaya snow samples to a network of surface samples taken from central Andes using discriminant analysis. In June/July of 2001, forty surface samples were collected from topsoil and moss polsters along three different transects running through the central Andes (Figure 1) (Reese 2003; Reese and Liu forthcoming). Two of the transects run west to east across the Andes, from the Pacific coasts of Peru and Chile, across the Altiplano, and descend the eastern slopes of the Andes, finally terminating in the lower reaches of the Yungas. The third transect starts north of Cusco, Peru, and continues southward through the Altiplano, terminating in the heart of the Southern Bolivian Highlands. These transects were selected because the samples represent every major vegetation zone in the central Andes region of South America. All surface samples were processed for pollen following the standard procedures (Faegri and Iversen 1975), as described in Reese and Liu (forthcoming).

In preparation for the discriminant analysis, the forty surface soil samples were divided into four groups based on their location and

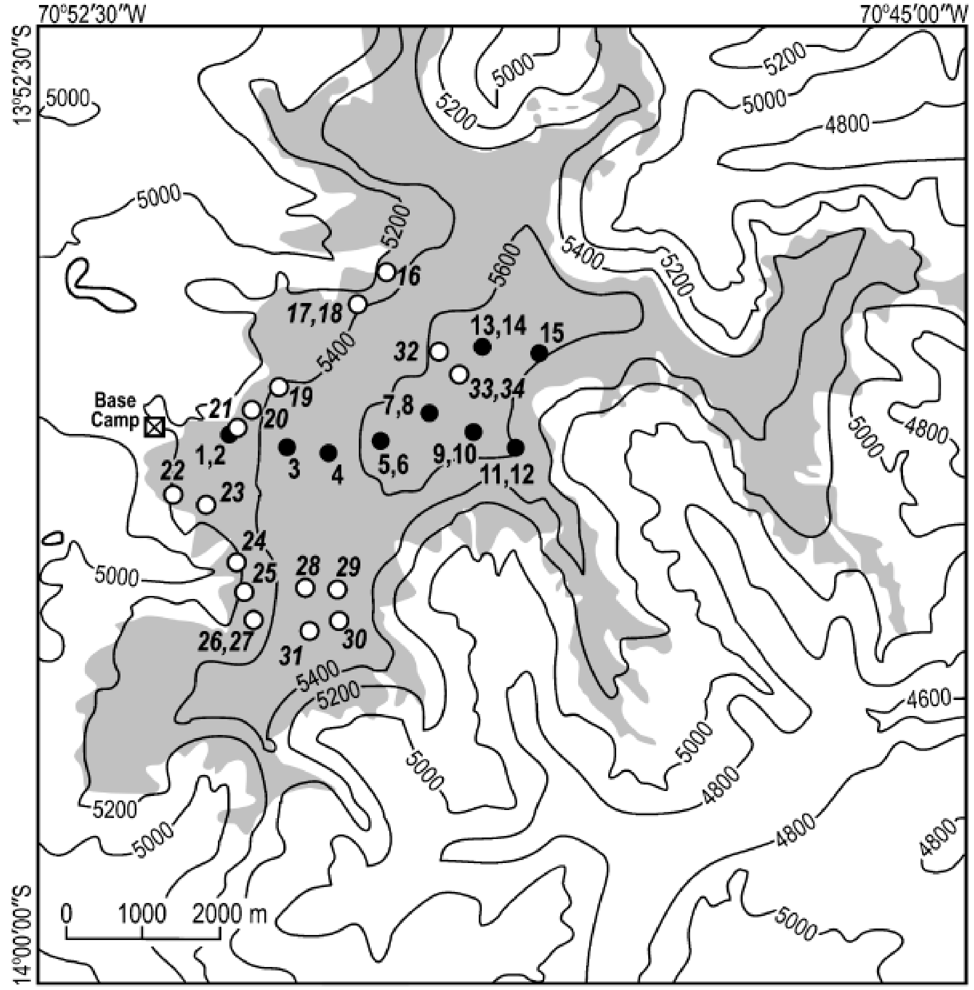

Figure 3 *Map of the Quelccaya Ice Cap (shaded), showing the fifteen samples (black) taken in 2000 and the nineteen samples (white) taken from 2001 (adapted from Reese and Liu 2002). Sample numbers 7 and 8 are located on the true summit.*

corresponding ecoregion (ecoregions defined by the World Wildlife Fund; Olson et al. 2001) (Figure 1). Group 1 corresponds to the eleven soil samples taken from the eastern Andean slopes (Yungas). Group 2 includes twenty samples taken from the puna grasslands of the Andean Altiplano. Group 3 consists of five samples taken from the Atacama and Sechura deserts on the west coast of South America, while Group 4 includes four samples located in the scrub desert of the Southern Bolivian Highlands. Following the methodology of Liu and Lam (1985), discriminant analysis was performed on the pollen percentage data using SPSS version 11.5.

The results from this pollen analysis have been discussed in Reese and Liu (forthcoming). Table 1 shows that the modern pollen rain in each region is representative of the local vegetation found there. After grouping these samples, discriminant analysis (SPSS) was used objectively to evaluate the strength of these groups based on their pollen content (Liu and Lam 1985). Twelve taxa were entered into the discriminant function: Solanaceae, the

Table 1 *Mean Pollen Percentages (Bold) and Ranges (in Parentheses) of the Twelve Pollen Taxa Used in the Discriminant Analysis, in the Four Central Andean Vegetation Zones*

Pollen Taxon	**Vegetation Zones**			
	Andean Yungas	**Altiplano**	**Coastal Deserts**	**Southern Bolivian Highlands**
Fern Spores	**31.2** (5.0–67.0)	**2.9** (0.0–8.0)	**0.0** (0.0–0.0)	**0.0** (0.0–0.0)
Poaceae	**22.1** (5.7–57.3)	**55.0** (15.0–80.0)	**41.0** (25.0–61.0)	**25.7** (10.0–33.7)
Asteraceae	**6.2** (1.0–20.7)	**18.9** (3.0–79.7)	**20.6** (6.3–52.7)	**14.5** (8.3–30.0)
Plantago	**0.9** (0.0–2.7)	**5.2** (0.0–19.7)	**1.5** (0.0–3.3)	**0.5** (0.0–1.7)
Cheno/Am	**2.0** (0.0–11.7)	**2.1** (0.0–6.7)	**14.4** (7.3–28.7)	**9.1** (2.0–30.0)
Solanaceae	**0.0** (0.0–0.0)	**0.7** (0.0–5.3)	**9.9** (6.3–13.0)	**45.0** (30.0–54.3)
Urt/Mor	**25.7** (8.0–41.7)	**4.5** (0.0–18.0)	**0.1** (0.0–0.3)	**0.0** (0.0–0.0)
Myrica	**0.0** (0.0–0.0)	**0.1** (0.0–0.7)	**3.0** (0.0–11.3)	**0.0** (0.0–0.0)
Euphorbiaceae	**0.0** (0.0–0.0)	**0.2** (0.0–3.0)	**1.3** (0.0–4.0)	**0.3** (0.0–0.7)
Myrtaceae	**0.6** (0.0–4.0)	**0.2** (0.0–2.0)	**1.0** (0.0–5.0)	**0.0** (0.0–0.0)
Ericaceae	**0.1** (0.0–1.0)	**0.0** (0.0–0.0)	**0.0** (0.0–0.0)	**0.0** (0.0–0.0)
Palmae	**0.1** (0.0–0.7)	**0.0** (0.0–0.0)	**0.0** (0.0–0.0)	**0.0** (0.0–0.0)

Urticaceae/Moraceae group, the Chenopodiaceae/Amaranthaceae group, fern spores, *Myrica*, Euphorbiaceae, Myrtaceae, Ericaceae, Palmae, Poaceae, Asteraceae, and *Plantago* (Reese and Liu forthcoming). After the analysis, 100 percent of the samples were correctly classified into their respective groups, with discriminant functions 1 and 2 explaining 98.9 percent of the variance (Figure 5). These results suggest that the surface sample groups are statistically robust and accurately represent these pollen data.

Using these four vegetation groups derived from the surface pollen data, discriminant analysis was used to statistically predict which group (vegetation zone) the 2000 and 2001 Quelccaya ice cap samples would fall into, or best represent. The results were then used to infer from what vegetation zone (group) the pollen found on Quelccaya is derived. Differences in pollen provenance between years could reflect variability in general circulation patterns or in the prevailing winds (Reese and Liu 2002; Reese, Liu, and Mountain 2003).

Results

2000 Pollen Results

The results from the fifteen surface samples collected on the Quelccaya Ice Cap in 2000 have been previously discussed in Reese and Liu (2002). In general, these pollen data show great uniformity (Figure 4). No major differences in assemblage or percentages are found between any of the samples, whether paired or individual. *Plantago* (19 percent–27 percent) and *Alnus* (13 percent–23 percent) are the most abundant pollen types in all samples. *Plantago major* and *P. tubulosa* are two common species found on the Altiplano, especially at the higher elevations (Gentry 1993). The large quantities of *Plantago* pollen are to be expected, as these two species are wind-pollinated herbs that are known to be prolific pollen producers. *Alnus* (probably, *A. jorullensis*) is found in the central Andes between 2,500 and 4,000 m (Cassinelli 2000) and ranges from the lower elevations of the puna ecosystem to the upper reaches of the Yungas on the eastern Andean slopes. Another major pollen taxa is the Urticaceae/Moraceae group. These two wind-pollinated families are common components of the Yungas and are effective at long-distance (regional) transport. Poaceae pollen is also common (5.7 percent–11 percent) and reflects the dominance of the puna grassland around the ice cap and the Altiplano in general. An unknown inaperturate-scabrate pollen grain (3 percent–12 percent) is consistently found throughout the samples as well. This grain closely resembles *Populus* in size and appearance, although the existence of this tree in the central Andes cannot be confirmed.

Of the minor (< 10 percent) pollen taxa, Asteraceae (i.e., long-spine or Tubuliflorae-type) is common, as well as *Ambrosia*-type (short-spine Asteraceae) pollen (2.5 percent–10 percent and < 2 percent, respectively). The Asteraceae group of plants can range from small xerophytic shrubs to trees reaching more than 10 m in height (e.g., *Gynoxys oleifolia*) and are a regular component of the puna ecosystem. The herb *Cuphea* is present in all samples (< 2 percent–6 percent), as well as Cupressaceae

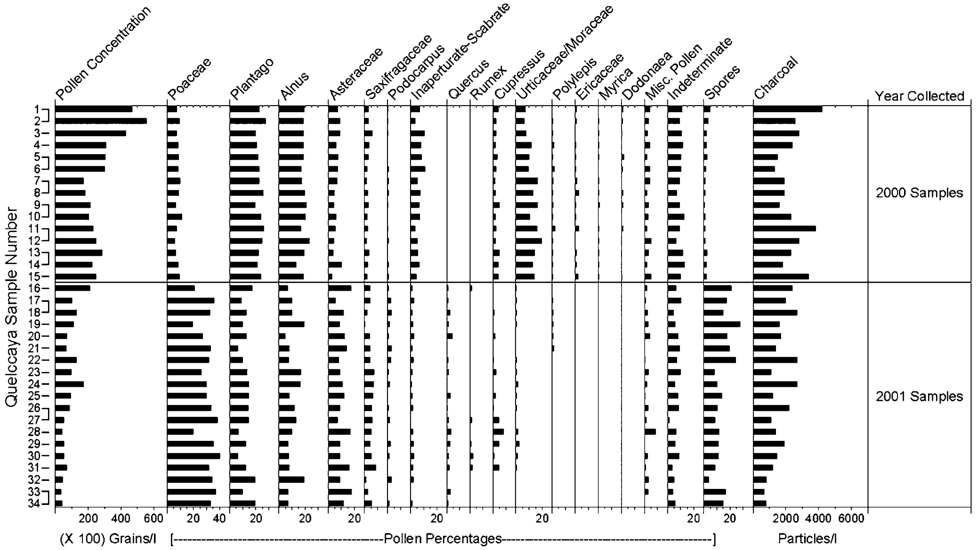

Figure 4 *Pollen percentage diagram of the thirty-four surface samples taken from the Quelccaya Ice Cap in 2000 and 2001. Paired samples in brackets were taken no more than a meter apart to test for within-site variability.*

(<2 percent–5 percent). The Cupressaceae pollen is most likely *Cupressus macrocarpa*. This species is native to North America, but is widely planted on the Altiplano and ranges from a shrub in the drier regions to a tree of over 30 m (Cassinelli 2000). Large areas of *Cupressus* can be found less than 50 km from Quelccaya. The low amounts of *Cupressus* pollen are to be expected, as this genus is typically underrepresented in pollen assemblages.

Other minor pollen types include *Polylepis*, *Dodonaea viscosa*, *Myrica*, *Podocarpus*, and the Ericaceae family (all under 3 percent). The latter three taxa are common to the upper Yungas on the eastern slopes of the Andes between 1,800 and 3,300 m above sea level. Lastly, the miscellaneous pollen category contains pollen from twenty-two different plant taxa, whose overall abundance never exceeds two grains per sample (<1 percent). Of this group, *Weinmannia*, Cyperaceae, Apiaceae, Myrtaceae, and the Cheno/Am family (Chenopodiaceae and Amaranthaceae) are the most frequent.

The biggest difference between the fifteen samples is in the pollen concentration values. The highest concentrations can be found in samples 1–6, located on the western edge of the ice cap. These concentrations range between 30,100 and 55,400 grains per liter, the highest concentrations found in any tropical or nontropical ice cap (as discussed in Reese and Liu 2002). The lowest concentration values on the entire ice cap (17,250 grains/l) occur at sites 7 and 8, the true summit. Similarly low values are found at pairs 9 and 10 and 13 and 14, all located on the summit dome above 5,600 m. Toward the eastern slopes (samples 11, 12, and 15) the concentrations seem to increase again, albeit very slightly (22,500–24,000 grains/l). The charcoal concentrations range from 1,100 to 6,000 particles/l and follow a similar pattern to that of the pollen concentrations. The highest values are located on the western slopes of Quelccaya, decreasing to a minimum at the summit and increasing again slightly in the easternmost samples.

2001 Pollen Results

Similar to the 2000 samples, the results from the 2001 pollen analysis show remarkable uniformity among the nineteen ice-cap surface samples (Figure 4). Again, no major variations in pollen percentage occur between any of the surface samples, whether paired or individual. Poaceae pollen is the dominant pollen taxon in these samples, with percentages ranging from 19 percent to 40 percent. Other major taxa include *Plantago* (6 percent–19 percent), *Alnus* (5 percent–19 percent), Asteraceae (5 percent–18 percent), and Polypodiaceae fern spores (4 percent–27 percent). The number of monolete and trilete fern spores found in the samples was roughly equal. Minor pollen types (<10 percent in all samples) include Saxifragaceae, *Podocarpus*, *Quercus*, *Rumex*, *Cupressus*, *Polylepis*, the Urticaceae/Moraceae families, and the same unknown Inaperturate-Scabrate pollen grain as in the 2000 samples, probably *Populus*. The miscellaneous pollen group contains grains from fourteen other taxa; however, their abundance never exceeds 1 percent of the total pollen assemblage. These pollen include Loranthaceae, *Carya*, *Weinmannia*, *Myrica*, the Chenopodiaceae/Amaranthaceae familes, *Dodonaea*, Juglandaceae, Myrtaceae, Melastomataceae, Fabaceae, Caryophyllaceae, Apocynaceae, Ulmaceae, and *Tribulus*-type. With the exception of the probable *Populus* grains, all pollen types are local and can be commonly found in the eastern Altiplano or the eastern Andean slopes.

As with the 2000 samples, the biggest difference within the 2001 samples is the pollen concentration values. The samples taken along the western edge of the ice cap (samples 16–27) display the highest concentrations, ranging from 6,250–21,000 grains per liter. Compared to these samples, the south dome (samples 28–31) of the Quelccaya Ice Cap has markedly lower pollen concentrations (4,000–6,000 grains/l). The south dome acts like a second summit to the ice cap, particularly for the southern half of the ice cap, below roughly 13° 56' S latitude. However, the elevation of this south dome is approximately 5,500 m, still 200 m lower in elevation than the true summit. The three samples from the true summit (samples 32, 33, and 34) are the lowest of the 2001 samples with concentrations between 3,200 and 4,000 grains per liter. Charcoal concentration follows the same general pattern as the pollen. Concentrations reach their highest values (1,100–2,800 particles/l) along the slopes and edges and steadily decrease with increasing elevation. The south dome's charcoal content ranges from 1,200–1,900 particles/l, while the lowest values are again reached at the summit (700–830 particles/l).

Discriminant Analysis

Figure 5 shows the results of the discriminant analysis on the thirty-four Quelccaya surface ice samples, together with the four groups of forty Andean surface soil samples. Of the thirty-four ungrouped (Quelccaya) samples, fourteen (41.2 percent) are statistically similar to Group 1

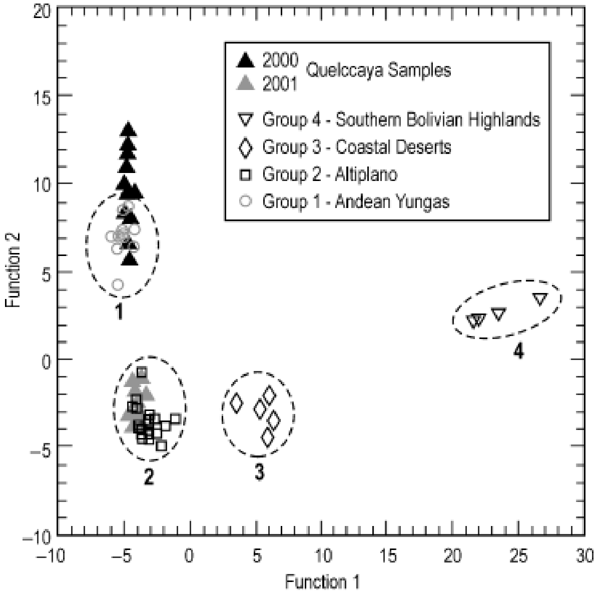

Figure 5 *Plot of the Quelccaya surface samples in relation to the four central Andean pollen zones. The data are plotted against discriminant functions 1 and 2.*

(Yungas), while twenty (58.8 percent) fall into Group 2 (Altiplano). Among these samples, there is a distinct division between the fifteen samples collected in 2000 and the nineteen samples collected in 2001. Fourteen of the fifteen samples from 2000 are classified as Group 1 (Yungas), and all of the nineteen samples from 2001 were classified as Group 2 (Altiplano). These statistical results suggest that the 2000 and 2001 pollen assemblages are different from each other, implying that they are derived from different vegetation sources or are transported by different wind patterns or depositional mechanisms.

Discussion

Temporal Variability in Pollen Composition

Results from the pollen analysis revealed that the pollen assemblages and concentrations differ greatly between the 2000 and 2001 samples. The 2000 samples are dominated by *Plantago*, *Alnus*, and Urticaceae/Moraceae pollen, while Poaceae is only a minor taxon. The opposite occurs in 2001, when Poaceae dominates the pollen spectra along with high percentages of fern spores. Though little is known about the exact flowering season in the central Andes, difference in the sampling dates between these two years may explain these results. Monasterio and Vuilleumier (1986) claim that the height of the flowering season for most Altiplano plants occurs sometime between the dry and the wet seasons (August to October). The 2000 samples were collected in August during this transitional period between dry and wet seasons, while the 2001 samples were collected in June, during the height of the winter dry season. If this is indeed the case, then it should be no surprise that the two samples look significantly different in terms of pollen assemblage.

The samples between these two years also differ greatly in their pollen concentrations. The 2000 samples had concentrations ranging between 17,250–55,400 grains per liter of meltwater. The 2001 concentrations were almost an order of magnitude less in some instances, with values between 3,300–21,000 grains/l. Again, the difference in pollen concentration may simply be due to different sampling dates relative to the flowering seasonality. The 2000 samples could simply contain more pollen because there was more pollen available in the atmosphere (due to flowering) at the time of collection. However, more data are needed to evaluate this hypothesis.

Another possible explanation is the influence that the ENSO cycle has on the plants on the Altiplano. During El Niño events, conditions on the Andean Altiplano are generally warmer and much drier than with normal or La Niña conditions (Thompson, Mosley-Thompson, and Morales-Arnao 1984; Hardy et al. 1998). Though no studies have been done on this phenomenon, it is likely that Altiplano plants endure extreme stress (both moisture and physical) during El Niño years. These stresses would have an effect on the amount of pollen that a plant could produce and release during the year. Therefore, the amount of pollen in the environment (available for transport to the ice cap) may greatly depend on this cycle. Regardless of the effects of ENSO on the pollen productivity of Andean plants, major differences in weather conditions between the two years could possibly explain the differences in pollen concentration.

The Southern Oscillation Index (SOI), as computed by the Climatic Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/soi.htm), records the intensity of ENSO events in the South Pacific. The data are measured daily and are generally reported as monthly and annual averages. In 2000, when the pollen concentrations were high, strong La Niña conditions existed (annual average of 7.80 on the SOI). La Niña events represent amiable conditions on the Altiplano and less stressful conditions for plant growth and development. Our data have led us to believe that more pollen is available in the atmosphere during La Niña, which translates into higher pollen concentrations on the ice cap. The opposite is true for the year 2001. The mean SOI value for this year was −0.51, with a seasonal (April–July) average of −2.30. These values translate as slight to moderate El Niño conditions. Therefore, in 2001, the Altiplano plants were likely to be more stressed than in the previous year, which resulted in lower pollen concentrations according to our data.

Finally, the process of sublimation could also have an effect on the pollen concentration values found on the ice cap. While the temperature at the Quelccaya summit is too low for melting to occur, sublimation may result in the loss of snow on the ice cap surface (L. G. Thompson, personal communication, 2002). Though the process of sublimation is not fully understood on the Quelccaya Ice Cap, it is believed that this process must have some effect on the pollen concentrations. During years when drier weather conditions prevail (as would be expected during the 2001 El Niño), more snow will be lost due to higher sublimation rates, resulting in higher pollen concentration values. If this is true, then the original pollen concentrations in the 2001 samples would have been even lower. Unfortunately, no data from Quelccaya exists to directly evaluate this hypothesis.

Pollen Provenance

One possible explanation for interannual shift in pollen provenance at the Quelccaya Ice Cap could be the effect of ENSO on the region. The atmospheric circulation patterns around Quelccaya are primarily controlled by a warm-cored cell of semipermanent high pressure (the Bolivian High) that hovers over the Altiplano during the summer/wet season from December to March (Schwerdtfeger 1961, 1976; Kreuels, Fraedrich, and Ruprecht 1975; Virji 1981). The resulting counterclockwise flow is a phenomenon known as the South American Summer Monsoon (Zhou and Lau 1998), which brings easterly winds and over 80 percent of the annual precipitation totals to the ice cap. Prevailing winds for the remainder of the year are westerly (Virji 1981; Hardy et al. 1998; Vuille et al. 1998; Garreaud, Vuille, and Clement 2003), influenced by the upper-level return flow in the Hadley Cell.

During the warm phase (El Niño), conditions on the Altiplano are generally warmer and drier than with normal or La Niña conditions (Thompson, Mosley-Thompson, and Morales-Arnao 1984; Hardy et al. 1998). During the El Niño of 2001, the Bolivian High that usually brings winds (wet season) from the east to Quelccaya should be weakened as a result of decreased thunderstorm activity, which fuels this upper-level high through the release of latent heat (Schwerdtfeger 1961; Gutman and Schwerdtfeger 1965; Ramage 1968; Dean 1971; Kreuels, Fraedrich, and Ruprecht 1975; Rao and Erdogan 1989; Lenters and Cook 1995). If this is true, the weakened condition of the Bolivian High in 2001 could have hampered the ability to transport pollen from longer distances. This would explain why the 2001 samples reflect the local Altiplano (Group 2) vegetation rather than the vegetation of the Yungas farther away. However, during 2000 (La Niña), when the Bolivian High is relatively stronger, conditions would facilitate the import of pollen from greater distances, especially from environments to the east like the Yungas (Group 1). In addition to wind transport, we suspect that "washout" events due to thunderstorms, as well as biological agents such as insects and birds, may also play a role in pollen deposition on the ice cap. The relatively high percentages of fern spores in the 2001 samples compared with those of 2000, for example, may invoke some transport mechanism that remains to be explained.

Conclusion

This is the first study of the interannual variability of pollen deposition in a tropical ice cap. We analyzed pollen samples collected from surface snow on the Quelccaya Ice Cap in 2000 and 2001, representing a year of strong La Niña conditions and a year of moderate El Niño conditions, respectively. The pollen data reveal significant interannual variability in pollen assemblage, concentration, and provenance. Samples from August 2000 contain high pollen concentrations and relatively high percentages of *Plantago*, *Alnus*, Urticaceae/Moraceae, and an unknown inaperturate-scabrate pollen. Samples from June 2001 are characterized by having lower pollen concentrations and relatively high pollen percentages of Poaceae, Asteraceae, and fern spores. Comparison of the annual samples to Andean surface samples using discriminant analysis shows that the pollen assemblages from 2000, a La Niña year, resemble those from the Andean forests (Yungas) to the east. Samples from 2001, an El Niño year, resemble those from the Altiplano.

The significant interannual variability in pollen signatures between these two years may be explained by different pollen dispersal and depositional processes on the Quelccaya Ice Cap related to ENSO weather conditions. From the pollen evidence, the Quelccaya Ice Cap likely receives the majority of its pollen from the east. This is consistent with the prevailing easterly circulation pattern over the Andes during the wet season (when 80 percent of the annual precipitation occurs). However, the range and extent of this influence may be controlled by the climate fluctuations brought on by the ENSO. During normal or La Niña years, the easterly winds are stronger and allow pollen from the Yungas to be transported to the ice cap. During El Niño years, the opposite is true, as the Bolivian High becomes weaker and the resulting easterly flow is diminished, resulting in a more local pollen assemblage.

The results of this study have significant implications for the emerging field of ice-core palynology. Our data, albeit from only two years, show that the pollen concentrations and pollen assemblages from a La Niña year are distinctly different from those of an El Niño year. If similar differences are found to occur consistently in other years representing La Niña and El Niño conditions, then high-resolution pollen studies of tropical ice cores can provide a means of reconstructing the occurrence of paleo-ENSO conditions in tropical highlands.

Questions remain regarding the temporal resolution of the samples. Since only the top 5 cm of snow was collected at each location, it is impossible to know if this deposition reflects the past several months, or just the last storm event. Without this information it is difficult to separate the variability in pollen assemblage due to weather events, and the seasonal variability as a result of the flowering season. More data, especially multiyear, high-resolution data, are needed to understand the full effect of these phenomena (especially the local effects of ENSO) and the impacts they have on the modern pollen-rain on high-central Andean ice caps. New fieldwork in the summer of 2004 has yielded stratigraphic subsamples of snow collected at subseasonal (monthly) intervals from the summit of the Quelccaya Ice Cap. ■

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