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Pollen Dispersal and Deposition on the Ice Cap of Volćan Parinacota, Southwestern Bolivia

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Abstract

Pollen, a regular component of tropical ice cores, has been shown to have great potential as a sensitive paleoenvironmental proxy in ice-core research. However, questions remain as to the modern dispersal and depositional patterns of pollen on high-alpine tropical ice caps. This information is vital to the accurate interpretation of the environmental reconstructions being derived from fossil pollen. In this study, 11 surface snow samples were collected around the caldera rim at the summit of Mt. Parinacota along the Bolivian-Chilean border. Results show that pollen concentration and assemblage are uniform in samples taken from the southwestern quadrant and the entire eastern half of the mountain. However, the pollen signatures are significantly different in the northwestern quadrant, probably due to long-distance transport of xerophytic Compositae shrub pollen from the prevailing winds. The sections of the mountain not directly impacted by the prevailing northwesterlies reflect a more locally influenced pollen assemblage dominated by grasses. These results are consistent with previous findings from the Quelccaya Ice Cap and confirm the importance of the prevailing winds in the dispersal and deposition of pollen on these high-alpine tropical ice caps.

Introduction

Over the past 30 yr, tropical ice caps have produced a wealth of information about our paleoenvironments through the detailed analysis of ice cores retrieved from them (e.g., Mercer et al., 1975; Thompson and Dansgaard, 1975; Thompson, 1980; Thompson et al., 1984, 1985, 1986, 1988, 1995, 1998, 2000; Henderson et al., 1999). These data, mostly derived from chemical and physical proxies, have been primarily used to reconstruct the physical characteristics of our past environments (e.g., paleotemperature, paleoprecipitation, and paleocirculation). From these methods, however, the reconstruction of biological features such as paleovegetation has been tenuous. In order to accurately reconstruct paleovegetation from these ice cores, it is necessary to use biological proxies.

Fossil pollen grains are abundant and ubiquitous components of tropical ice cores and are ideal for paleovegetational investigation because they serve as a direct link to past vegetation. In previous studies, pollen has proven to be a very sensitive tool for this endeavor (Thompson et al., 1988, 1995; Liu et al., 1998; Yao, 2000). However, little is known about the modern dispersal and depositional characteristics of pollen on these high-alpine tropical ice caps. Accurate interpretation of the ice-core pollen records is dependent on the full understanding of this modern analogue.

Reese and Liu (2002) have made initial strides in understanding this phenomenon. They analyzed 15 surface snow samples from the Quelccaya Ice Cap in southern Peru. Their results showed uniform pollen assemblages in every sample regardless of location on the ice cap, though major differences existed in pollen concentration. Their research identified the importance of the prevailing wind as the primary transportation agent for the pollen found on the ice cap. Local-scale winds also played an important role, but only in redistributing the pollen locally over the ice cap itself. To date, this is the only paper that has studied this aspect of pollen on tropical ice caps.

The aim of this research is to test these previous findings by replicating the study on a different ice cap in the Andean Altiplano, Mt. Parinacota. Although these two mountains are in the same geographical region, they differ significantly in their geomorphic settings and environmental conditions. Quelccaya is located on the wetter, eastern edge of the Altiplano, whereas Parinacota is located in southwestern Bolivia on the drier, western edge (Garreaud et al., 2003) (Fig. 1). The comparison of these findings will help to further our knowledge of the patterns of pollen dispersal and deposition in the high tropical Andes and also reveal the differences in pollen provenance between the two regions of the Altiplano.

Background

Mt. Parinacota (18°10′S and 69°08′W, 6348 m a.s.l.) is a composite volcano located along the Bolivian-Chilean border on the western side of the Andean Altiplano (Fig. 1). The approximately 12-km^2 ice cap sits atop a geologically young secondary cone, which was formed in the last 13,500 yr from primarily andesitic aa lava flows (Wörner et al., 1988) (Fig. 2). The average annual temperature at Parinacota is roughly 1°C (Schwalb et al., 1999). The yearly mean precipitation at the base of Parinacota is around 316 mm yr^{-1}, as recorded at nearby Sajama Village approximately 22 km away (Hardy et al., 1998). Precise weather data from the summit of Parinacota are unavailable; however, they can be estimated from a satellite-linked automated weather station at the summit of Mt. Sajama (6542 m a.s.l.) approximately 25 km away. The summit temperatures at Sajama range from –7.5°C in January to –14.0°C in June, with 440 mm (water equivalent) of precipitation yr^{-1} (Hardy et al., 1998).

The precipitation regime is highly seasonal at Parinacota, with over 80% of the annual precipitation falling in the summer wet season between December and March (Johnson, 1976; Hardy et al., 1998; Vuille et al., 1998; Garreaud et al., 2003). The prevailing winds in the region are typically from the west during the 6-mo dry season (May–October); however, easterly flow dominates in the wet season (December–March) (D. Hardy, personal communication). November

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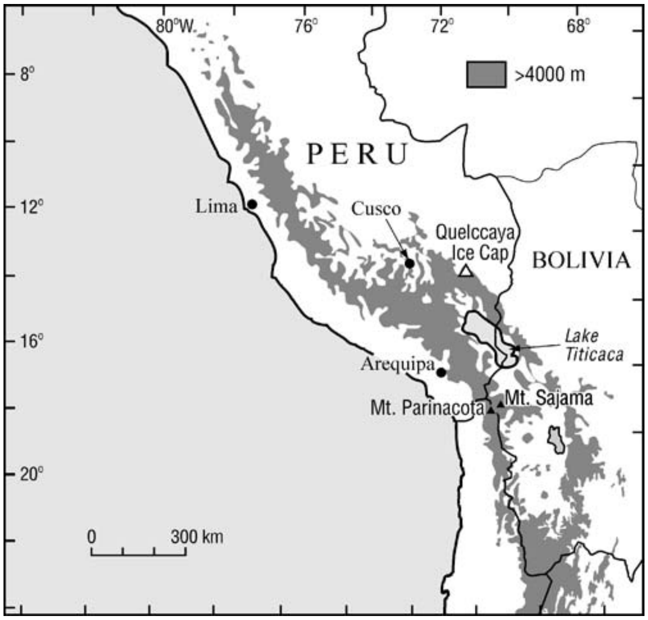

FIGURE 1. Map of the Central Andes showing the location of Mt. Parinacota and other ice caps mentioned in the text.

and April serve as transitional months in this dynamic circulation regime that is dominated by the South American summer monsoon (Zhou and Lau, 1998; Vuille et al., 1998).

The flora of the Altiplano surrounding Parinacota is principally composed of the "puna-brava"-type vegetation assemblage (Tosi, 1960). Puna is a dry grassland, primarily composed of bunch grasses (Gramineae), Compositae plants, rosette plants, cushion plants, and other xeric shrubs and herbs (Hansen et al., 1984; Schwalb et al., 1999). However, in low-lying areas and near sources of water, the marsh-like *Bofedales* community may be common (Baied and Wheeler, 1993). *Polylepis* trees are also abundant between 3000 and 4500 m and can be found as high as 5100 m near Parinacota (Kessler, 1995; Braun, 1997). To the west of Parinacota lies the Atacama desert and much drier conditions. Here, Compositae plants are generally more abundant, along with Cactaceae and *Euphorbia* (Heusser, 1971), although aspects of the puna grasslands can extend all the way to the Pacific Ocean (Reese and Liu, 2002). To the east of Parinacota, the puna assemblage extends for another 300 km before a sharp vegetation gradient begins at the easternmost edge of the Andes. From here, the vegetation can change from puna grasses to tropical wet forest in a horizontal distance of 200 km in some places (Reese and Liu, 2002).

Materials and Methods

In August (dry season) of 2002, 11 surface snow samples (from 9 locations) were collected around the caldera rim at the summit of Mt. Parinacota (Fig. 3). The two paired samples, numbers 3/4 and 9/10, were collected at the same location, no more than 1 m apart to test for within-site variability. At each site, the top 5 cm of snow was scraped and transferred directly into a 500-mL, leak-proof Nalgene sample bottle. These bottles were sealed at the site and remained closed until the samples were processed at Louisiana State University. For each sample, the volume of meltwater varied, but all ranged from 200 to 400 mL.

FIGURE 2. Mt. Parinacota from the south/southwest (taken August 2001).

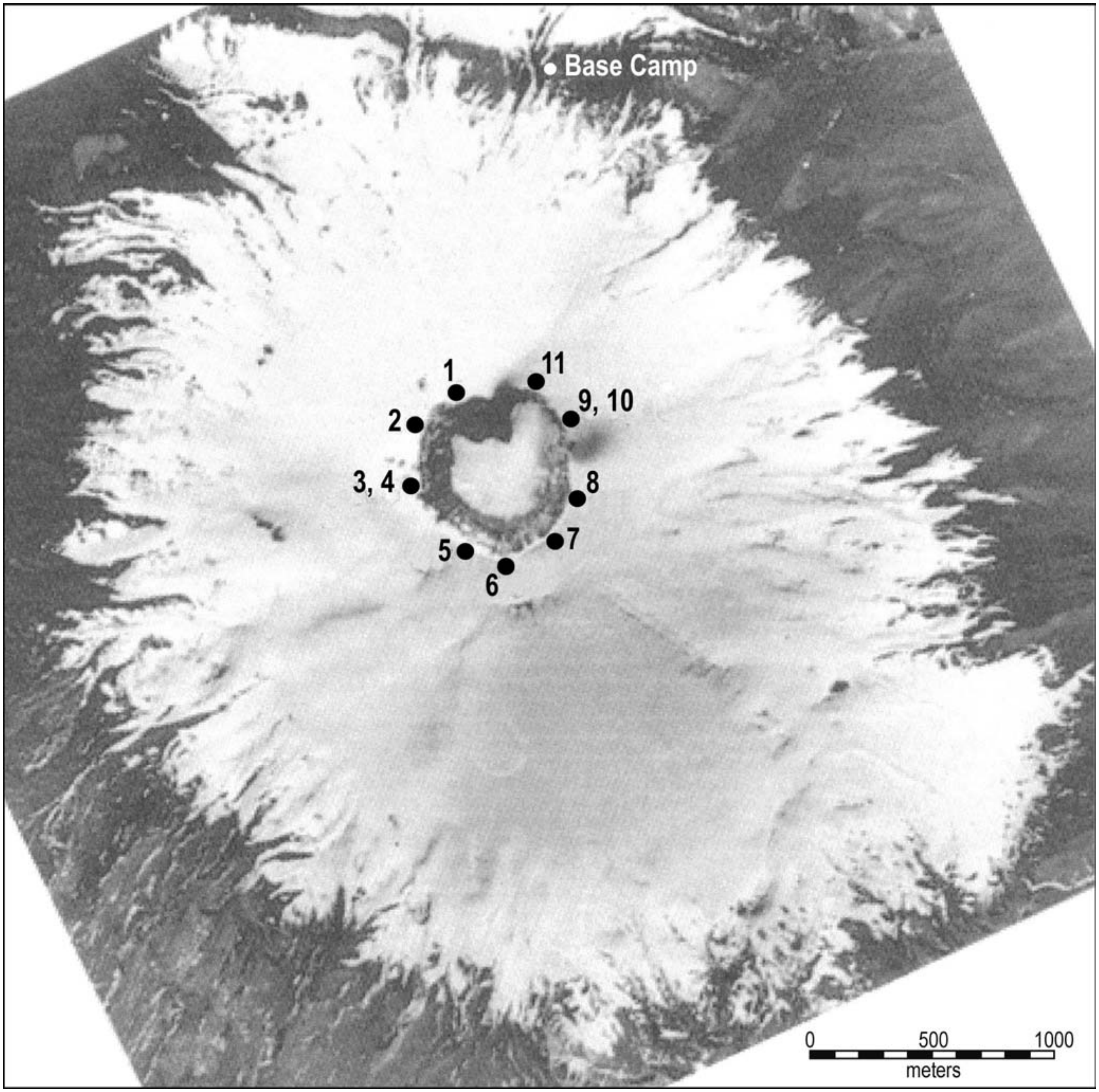

FIGURE 3. Aerial view of the Parinacota Ice Cap showing the locations of the 11 surface snow samples. Source: http://volcano.indstate.edu/cvz/pariimg.html

The pollen was extracted from the meltwater following the standard procedure (Liu et al., 1998; Reese and Liu, 2002). This method involves spiking the meltwater with *Lycopodium* marker spores (Stockmarr, 1971), then evaporating the meltwater on a hot plate until 50 mL remain. Next, the sample is transferred into test tubes by carefully centrifuging and decanting the extraneous water. The residue is then treated with Acetolysis solution (to remove organics), stained, and mounted on slides with silicon oil. All pollen and spores were identified until a minimum of 1000 marker spores was counted. The total pollen sums ranged from 35 grains (in samples 5, 9, and 10) to 281 grains (in sample 2). For most samples, the pollen sum exceeded 75 grains. Tilia computer software was used to calculate all pollen percentages and concentrations. These figures were based on a total sum of all pollen and spores. Charcoal particles were counted regardless of size, and the raw values are reported as particles per liter of meltwater. All results were displayed using TiliaGraph.

Results

The results of the pollen analysis show a distinct difference between the samples taken from the northwestern quadrant of the mountain and the other samples (Fig. 4). The pollen concentration values for all of the samples in the study ranged from 2,500 to 17,500 grains L^{-1} of meltwater. However, the higher values are located in the northwestern sector of the mountain (samples 1–4) and range from 6,000 to 17,500 grains L^{-1}. Compositae pollen, consisting of *Artemisia*-type grains (25–41%), long-spine Tubuliflorae (7–12%), and short-spine *Ambrosia*-type (1–3%), is the most abundant pollen group in these

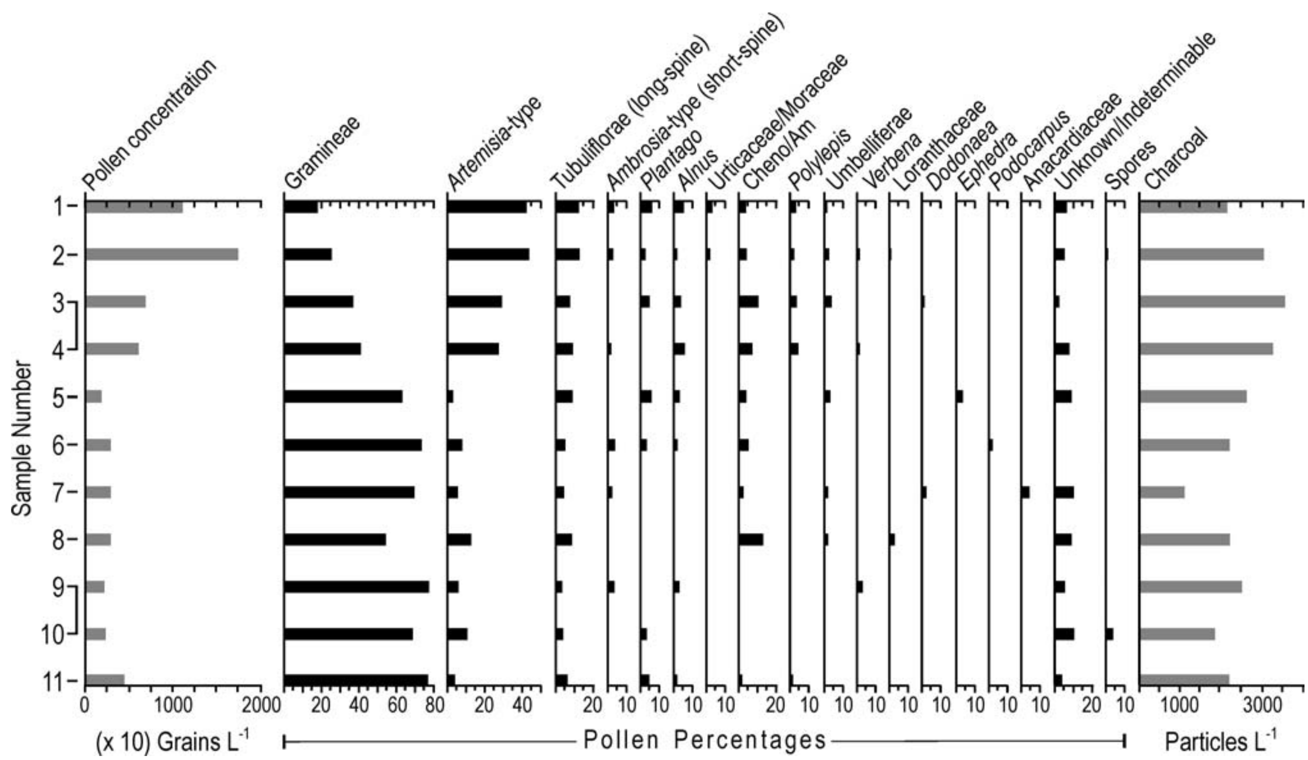

FIGURE 4. Pollen percentage diagram showing the results of the 11 surface snow samples taken at Mt. Parinacota. Sample numbers joined by brackets are paired samples taken at the same location to test for intrasite variability.

samples. This family of plants, mostly small xerophytic shrubs and herbs, is well represented on the Altiplano and the drier surrounding regions (e.g., Atacama). Gramineae (grass) pollen is also common, but slightly less so (19–41%). However, in the samples collected from the rest of the caldera (samples 5–11), the opposite is true. Gramineae pollen dominates the assemblage, ranging from 55 to 77%, while Compositae is reduced to a minor taxon with percentages rarely exceeding 10%. Pollen concentration is also diminished in these latter samples with numbers that never exceed 4,500 grains L^{-1}.

Of the minor (<10% abundance) taxa found in the samples, all are relatively common components of the Altiplano or the surrounding vegetation regions. *Plantago* is a genus of wind-pollinated herbs and shrubs that are widespread on the Altiplano (Gentry, 1993). *Polylepis* trees, locally known as Quenoa (Baied and Wheeler, 1993), are common in the region between 3000 and 4500 m but are found in dwarf form as high as 5100 m. *Alnus* is another genus of trees found in conjunction with or just below *Polylepis* at elevations between 2500 and 3800 m (Cassinelli, 2000). The Urticaceae/Moraceae group comprises these two large families of plants common to the montane slopes of the Andes, bordering the Altiplano. The Chenopodiaceae/Amaranthaceae (Cheno/Am) group is another large group of plants consisting of the amaranth and goosefoot families. These taxa are also very diverse and widespread but tend to be herbs and shrubs that are xerophytic in nature. The Umbelliferae pollen (probably *Azorella*) is a cushion plant associated with the puna vegetation assemblage. The other pollen types (*Verbena*, Loranthaceae, *Dodonaea*, *Ephedra*, *Podocarpus*, and Anacardiaceae) and fern spores were rare (<3 grains in all samples) but are all components of the regional vegetation.

Charcoal ranged between 1100 and 3500 particles L^{-1} of meltwater, which is comparable to other ice caps in the region (Reese and Liu, 2002). Though no distinct pattern exists, the charcoal tends to follow the same pattern as the pollen in terms of concentration, with the highest values occurring in the northwestern samples (samples 1–4). Also of note: no significant differences were found between the paired samples 3/4 and 9/10, suggesting no intrasite variability.

Discussion

The results from Mt. Parinacota share many similarities with the Quelccaya Ice Cap study in southern Peru. However, many interesting differences exist as well. At both Quelccaya and Mt. Parinacota the highest concentration of pollen occurs on the western/northwestern side of the ice caps. This is not unexpected as both studies were conducted in August (dry season), when the prevailing winds in the region are from the west/northwest. These results reaffirm the importance of the prevailing wind as a major agent for pollen transport to these tropical ice caps. However, more samples need to be taken during the wet season, or during the transitional parts of the year to fully confirm the extent of this phenomenon.

One major difference that occurred between the two ice caps was in the pollen concentration values. The concentration values at Quelccaya ranged from 17,500 to 55,400 grains L^{-1} of meltwater (Reese and Liu, 2002). The values at Parinacota (2500 to 17,500 grains L^{-1}) were an order of magnitude lower in some cases. It is likely that these results are due to the different environmental conditions that surround the ice caps. Quelccaya, located on the wetter, more vegetated side of the Andean Altiplano, is in close proximity to denser vegetation (the subpuna and upper montane forests) zones than Parinacota and is therefore likely to receive larger amounts of pollen. Near Parinacota, the Altiplano is much more sparsely vegetated and quickly tapers to desert toward the west. This vegetation assemblage is not likely to deliver large quantities of pollen to the ice cap at Parinacota.

Another main difference between the two studies was in the pollen assemblages. In the Quelccaya study, the pollen assemblages are uniform across the ice cap. No significant differences in pollen composition existed between any of the samples on the ice cap regardless of location. However, in this study we find that the northwestern quadrant of the mountain has a significantly different assemblage than the rest of the mountain. One possible explanation lies in the physical differences in the ice caps themselves.

The Quelccaya Ice Cap is a true ice cap. It sits atop a plateau in the Cordillera Vilcanota and is not associated with any particular individual mountain. The surface of the ice cap is flat, with no major barriers to pollen mixing, thus allowing the pollen to disperse to all areas of the ice cap. Parinacota is a mountain ice cap associated with an individual peak. In this case, the mountain serves as its own barrier that would prevent a dominant pollen-laden wind from directly impacting all sides of the ice cap. Therefore, the northwestern quadrant of the mountain receives its pollen from the prevailing winds coming ultimately from the Pacific coast of Chile and the Atacama (consistent with the pollen assemblage). However, because of the mountain, this pollen-laden wind cannot directly impact the other faces of the mountain, including the lee, and local winds (e.g., thermally driven mountain winds or other local-scale circulation) are the main sources of pollen for the rest of the mountain. This is again consistent with the pollen assemblages from Parinacota, as samples 5–11 more closely reflect the vegetation immediately surrounding the mountain.

These findings have also helped to answer another important question regarding the deposition of pollen on these high-alpine ice caps. After the Quelccaya study (Reese and Liu, 2002) the question remained whether the majority of pollen being deposited on the ice cap was mechanically carried to the ice cap by wind, or whether the pollen deposition was a result of "washout" from thunderstorms or other precipitation events. The results from Parinacota suggest that the pollen is indeed being mechanically transported to the ice cap primarily from these prevailing winds and not as a result of precipitation. If "washout" were the leading source of pollen, then the pollen assemblages at Parinacota would have been more uniform. Thunderstorm cells have thoroughly mixed air, and therefore thoroughly mixed pollen. A precipitation event would have covered the ice cap with snowfall that was uniform in its pollen content. The pollen found on the Parinacota Ice Cap is a reflection of the winds that directly impact that particular section of the ice.

The results from these studies are beginning to answer questions that have hampered this emerging science of ice core palynology. With this knowledge, we can now ask questions about pollen provenance and pollen sensitivity in ice core research. However, as more questions are answered, more detailed questions take their place. Though this research has laid the initial groundwork for these investigations, more studies are needed in the future to fully answer remaining questions about pollen dispersal and deposition on these high-alpine tropical ice caps.

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