2003

Pollen dispersal and deposition in the high-central Andes, South America

Carl A. Reese
Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Social and Behavioral Sciences Commons

Recommended Citation

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
POLLEN DISPERSAL AND DEPOSITION IN THE HIGH-CENTRAL ANDES, SOUTH AMERICA

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Geography and Anthropology

by

Carl A. Reese
B.A., Louisiana State University, 1998
M.S., Louisiana State University, 2000
August 2003
Once again,

To
Bull and Sue
ACKNOWLEDGMENTS

First and foremost I would like to thank my major professor, Dr. Kam-biu Liu, for his undying support throughout my academic career. From sparking my initial interest in the science of biogeography, he has wisely led me through swamps and hurricanes, from the Amazon to the Atacama, and from sea level to the roof of the world with both patience and grace. I am who I am today because of him, and I want to sincerely thank him for that.

I thank Dr. Robert Rohli for his support and advice throughout my doctoral program. He has not only been a great teacher and advisor to me, but has proved to be a true friend as well. I would also like to thank Drs. Steve Namikas, Nina Lam, and Laurie Anderson for serving on my committee and for their interest in this project. Dr. G. Bruce Williamson deserves special thanks not only for his guidance, but also for the seemingly hundreds of recommendation letters that he so kindly and carefully crafted for me. Thanks also to Mary Lee Eggart and Jason K. Blackburn for their cartographic assistance on this project.

For his priceless help in the field, I thank Dr. Keith R. Mountain. The reason this dissertation exists is because of him and his hard work. At times I asked him to bear an unbearable load, and he never complained, and he never failed me. He is proof positive that, “No hill is too great for a climber”.

I also want to further extend my gratitude to Dr. Lonnie G. Thompson for supplying me with not only research materials and data, but with the invaluable lessons that I have learned from him in the field. He is a world-class researcher, as well as a world-class human being.

I am deeply indebted to the following for their financial support of this project; The National Science Foundation, The Association of American Geographers, The Geological
Society of America, The Sigma-Xi National Research Society, The Department of Geography and Anthropology at Louisiana State University, and once again, Dr. Kam-biu Liu.

Finally, I could not have done this without the support, encouragement, and love from my fiancée, Olivia Drinkwater.
# TABLE OF CONTENTS

DEDICATION.................................................................................................................................................. ii  

ACKNOWLEDGEMENTS................................................................................................................................... iii 

ABSTRACT...................................................................................................................................................... vii 

CHAPTER 1. INTRODUCTION.................................................................................................................................1  
  1.1 Expected Significance...................................................................................................................................... 5  
  1.2 References .................................................................................................................................................... 5  

CHAPTER 2. A 25,000-YEAR HIGH-RESOLUTION POLLEN RECORD FROM THE  
  SAJAMA ICE CAP, BOLIVIA.................................................................................................................................9  
  2.1 Introduction................................................................................................................................................... 9  
  2.2 Background............................................................................................................................................... 11  
    2.2.1 Environment and Vegetation ...................................................................................................................... 11  
  2.3 Methods....................................................................................................................................................... 14  
  2.4 A 39-year Ice-core Pollen Record of El Nino-Southern Oscillation from the Sajama Ice Cap, Bolivia........... 15  
  2.5 A 400-year High-resolution Ice Core Pollen Record from Mt. Sajama, Bolivia.......................................... 20  
  2.6 A 25,000-year High-resolution Pollen Record from the Sajama Ice Cap, Bolivia.................................... 25  
  2.7 Conclusion ................................................................................................................................................... 31  
  2.8 References.................................................................................................................................................... 32  

CHAPTER 3. POLLEN DISPERSAL AND DEPOSITION ON THE QUELCCAYA  
  ICE CAP, PERU............................................................................................................................................... 35  
  3.1 Introduction................................................................................................................................................... 35  
  3.2 Background............................................................................................................................................... 36  
    3.2.1 Vegetation ............................................................................................................................................... 39  
    3.2.2 Wind Patterns......................................................................................................................................... 40  
  3.3 Methods and Materials............................................................................................................................... 41  
  3.4 Results......................................................................................................................................................... 43  
    3.4.1 2000 Results.......................................................................................................................................... 44  
    3.4.2 2001 Results.......................................................................................................................................... 47  
  3.5 Discussion and Conclusion......................................................................................................................... 50  
    3.5.1 The Intra-Annual Results .......................................................................................................................... 50  
    3.5.2 The Inter-Annual Results ........................................................................................................................ 53  
    3.5.3 Conclusions.......................................................................................................................................... 56  
  3.6 References.................................................................................................................................................... 56  

CHAPTER 4. POLLEN DISPERSAL AND DEPOSITION ON THE ICE CAP  
  OF VOLČAN PARINACOTA, SOUTHWESTERN BOLIVIA..................................................................................... 63  
  4.1 Introduction................................................................................................................................................... 63  
  4.2 Background................................................................................................................................................... 64  
  4.3 Materials and Methods............................................................................................................................... 68
4.4 Results..........................................................................................................................70
4.5 Discussion....................................................................................................................72
4.6 References...................................................................................................................75

CHAPTER 5. A MODERN POLLEN-RAIN STUDY FROM THE CENTRAL ANDES REGION OF SOUTH AMERICA..................................................................78
5.1 Introduction...................................................................................................................78
5.2 Study Area ..................................................................................................................79
  5.2.1 Physiography.........................................................................................................79
  5.2.2 Climate and Wind Patterns .....................................................................................81
    5.2.2.1 Surface Winds ...............................................................................................81
    5.2.2.2 Upper-Level Winds .......................................................................................83
  5.2.3 Vegetation...............................................................................................................85
5.3 Methods and Materials...............................................................................................88
5.4 Results........................................................................................................................90
  5.4.1 Pollen Results........................................................................................................94
  5.4.2 Discriminant Analysis on Ice Cap Pollen Data .......................................................97
    5.4.2.1 The Sajama Ice Core ....................................................................................97
    5.4.2.2 The Quelccaya Ice Cap ...............................................................................100
    5.4.2.3 Mt. Parinacota ..............................................................................................104
5.5 Discussion and Conclusion........................................................................................108
5.6 References..................................................................................................................110

CHAPTER 6. SUMMARIES AND CONCLUSIONS................................................................115
6.1 Summary of the Main Research Findings................................................................116
  6.1.1 The 25,000-year Sajama Record ........................................................................116
  6.1.2 Pollen Dispersal on High-Alpine Ice Caps ..........................................................117
  6.1.3 A Modern Pollen-Rain Study From the Central Andes ......................................119
6.2 Directions for Future Research ...............................................................................120

APPENDIX A: LETTER OF PERMISSION FROM PHYSICAL GEOGRAPHY ..................122

APPENDIX B: LETTER OF PERMISSION FROM ARCTIC, ANTARCTIC, AND ALPINE RESEARCH .................................................................123

VITA........................................................................................................................................124
ABSTRACT

This dissertation uses fossil (ice core) and modern pollen samples collected throughout the central Andes to investigate the paleovegetational changes in the area as well as the modern dispersal and depositional characteristics of pollen in this region of South America. The results of the fossil pollen study on Mt. Sajama reveal a vegetation history that closely corresponds to the chemical and physical records already published from the mountain. Pollen becomes abundant after 15,000 B.P. and suggests the occurrence of two distinct phases between 15,000 and 12,000 B.P. (a short interstadial and the Deglacial Climatic Reversal). After 12,000 B.P., there is a steady transition into the Holocene, which has been consistently warm and dry.

However, for the accurate interpretation of the fossil pollen records, it is necessary to understand the dispersal and depositional characteristics of pollen on the ice caps themselves. Modern surface snow samples from two ice caps in the central Andes, the Quelccaya Ice Cap in Peru and Mt. Parinacota in Bolivia, have begun to answer some of these questions. In both cases, the prevailing winds play a major role in the dispersal of pollen onto the ice caps. The uniform pollen assemblages at Quelccaya suggest the majority of its pollen is deposited by “rainout” events originating from the local vegetation and areas farther to the east. Parinacota, on the other hand, seems to experience mechanical deposition from the prevailing winds as well as from local mountain winds. Inter-annual data from Quelccaya show the variability in these pollen assemblages and raise more questions as to the effect of the El Nino/Southern Oscillation cycle, sublimation, and the timing of the flowering season. Lastly, modern surface samples collected throughout the central Andes provide the first comprehensive understanding of the modern pollen-rain in the area, as well as the pollen provenance on central Andean ice caps. This data set is the first of its kind for the central Andes, and it serves to further the effectiveness
of future fossil pollen studies in the central Andes by broadening our understanding of the modern relationships among pollen, vegetation, and climate in the region.
CHAPTER 1. INTRODUCTION

This dissertation is a palynological inquiry. Its aim is to study the dispersal and depositional characteristics of pollen in the high-central Andes region of South America. This region, also known as the Andean Altiplano, is an environment laden with lakes and ice caps that contain detailed records of paleoenvironmental change. These records are ideal candidates for palynological investigation, yet this tool remains largely underutilized in the area. The importance of these records is self-evident when the one takes into account the vast number and variety of ecoregions in close proximity to the area. In certain sections of the Altiplano, the environment changes from high-alpine desert to tropical wet forest in a horizontal distance of 200 km. These steep vegetational gradients, courtesy of the Andes Mountains, are the perfect study sites for paleovegetational research.

Over the years, several studies have used various chemical and physical paleoenvironmental proxies (e.g., oxygen isotopes, accumulation/stratigraphic signals, soluble anions, dust/aerosol loadings) in an attempt to reconstruct the paleoclimates of this region (e.g., Thompson et al., 1985, 1986, 1995, 1998, 2000; Henderson et al., 1999). To date, however, the reconstruction of paleovegetation and vegetation response to climatic change has been presumptuous at best. In order to reconstruct the biological features of paleoenvironments accurately, it is necessary to use biological proxies. Fossil pollen lends itself well to this challenge, as it provides a direct link to past vegetation. Though several high-quality pollen records have been produced from lakes and bogs in the area (Graf, 1981; Hansen et al., 1984, 1994; Markgraf, 1985; Baied and Wheeler, 1993; Schwalb et al., 1999; Paduano et al., 2003), their resolution has been largely inadequate. It is also important to note that these archives are limited in their effectiveness by the environment itself. Climatic change may have repeatedly
desiccated these lakes and bogs throughout their history, compromising both the pollen and the stratigraphy of the record. Furthermore, the tectonic nature of the region adds to the problems with these records, as the long-term effects of uplift can repeatedly alter a lake’s hydrology.

Ice cores, on the other hand, have proven to provide a much more robust archive. These cores also have the potential to produce both long and extremely high-resolution records. For instance, ice cores from the Sajama ice cap in Bolivia yielded yearly to centennial-scale records for much of their 25,000 year history (Thompson et al., 1998). The same is true for the other ice cores in the region; namely the Quelccaya Ice Cap in eastern Peru (Thompson et al., 1985, 1986) and the Huascaran Ice Cap in western Peru (Thompson et al., 1995). Accurate paleovegetational records (i.e., pollen records) from these archives would sharpen our picture of Andean Altiplano paleoenvironmental change, as well as provide a check or validation for the chemical and physical paleoclimatic proxies on which we rely so heavily.

Pollen is the only biological parameter that is consistently present on high-alpine ice caps. Its presence is an open door to numerous research opportunities, the results of which will likely further and strengthen our ability to do quality environmental reconstructions. Though successful studies have been done in the subtropics (Liu et al., 1998), to date, no intensive pollen study has been done on a tropical ice core or ice cap. Exploratory work (Thompson et al., 1988, 1995) conducted on the two Peruvian ice cores of Quelccaya and Huascaran simply proved that the pollen concentrations and pollen assemblages could be ecologically meaningful, and warranted further investigation.

Chapter 2 of this dissertation describes the results from the first, systematic, high-resolution pollen analysis from a tropical ice core. Stratigraphic pollen analysis was performed on the entire 132 m ice core taken from Mt. Sajama, Bolivia in 1997. Sampling resolution
ranged from 0.25 to 5-year intervals in the top 64.84 meters of the core, and 5 to 600-year intervals throughout the rest of the core. The results from this project are broken into three separate studies. They are as follows: 1) An ice-core pollen record of El Nino-Southern Oscillation from the Sajama Ice Cap, Bolivia, 1958-1996; 2) A 400-year high-resolution ice-core pollen record from Mt. Sajama, Bolivia; and 3) A 25,000-year pollen record of climatic change from the Sajama Ice Cap, Bolivia.

It is important to note, however, that in the non-polar ice cores, all pollen studies to date have been conducted without the full understanding of the dispersal and depositional processes on the ice caps themselves. In this regard, the polar regions (especially the Arctic) are decades ahead of the tropics and subtropics. Numerous studies have been conducted on the origins of the pollen found in polar ice caps (Vareschi, 1935; Srodon, 1960; Krenke and Fedorova, 1961; Ritchie and Lichti-Federovich, 1967; Jankovska and Bliss, 1972; Lichti-Federovich, 1973, 1975a; Kalugina et al., 1981; Bourgeois, 1990b; Andreev et al., 1997), the seasonal variations in the ice cap pollen assemblages (Godwin, 1949; Heusser, 1954; Ambach et al., 1966; Lichti-Federovich, 1975b; Short and Holdsworth, 1985; Bourgeois, 1990a, 1990b, 2000), and the global circulation patterns responsible for their dispersal (Bourgeois et al., 1985, 2001). Understanding all of these processes, in relation to the modern climate and vegetation, is essential for the accurate interpretation of the fossil pollen data.

This lack of dispersal and depositional pollen data for the tropical ice caps, along with the extremely limited numbers of published pollen records (both modern surface studies and paleoenvironmental studies) from Bolivia (Graf, 1981, 1992; Paduano et al., 2003) and Peru (Hansen et al., 1984, 1994; Hansen, 1995; Hansen and Rodbell, 1995; Seltzer et al., 2002), have hampered the development of this promising, new science. Currently, no studies have
investigated pollen transport on a high-alpine ice cap, tropical or not. Several studies have been published on high-alpine pollen dispersal (Markgraf, 1980; Jackson, 1991; Fall, 1992; Horn, 1993; Flenley, 1996). However, all of these have dealt with slope transport and deposition and most have stopped well short of the summits or any ice cover.

Chapters 3 and 4 of this dissertation attempt to address this problem by studying the modern patterns and processes of pollen dispersal and deposition on the tropical Andean ice caps of Quelccaya (Peru) and Mt. Parinacota (Bolivia/Chile), respectively. In the austral winter months of 2000, 2001, and 2002, a series of surface snow samples was collected from the two ice caps. These data were used to answer questions on (1) the uniformity of the pollen assemblages and the pollen concentrations found across the ice caps, (2) the intra-annual and inter-annual variability in the ice cap pollen assemblages, (3) the mechanisms that deliver the pollen to the ice cap, and (4) the transport processes which influence the pollen distribution (e.g. the effects of the prevailing winds, glacial winds, the thermally-driven anabatic and katabatic winds, and the mechanical mountain winds).

Chapter 5 will take this question a bit further by analyzing a network of modern surface soil samples collected from different vegetation zones in the region. Over the past three years, an extensive network of modern surface soil samples has been collected from every major vegetation zone in the central Andes. This network extends both latitudinally across the entire Andean Altiplano, and longitudinally from the Pacific Ocean to the Peruvian/Bolivian Amazon. This modern pollen data set will help to determine the large-scale patterns and gradients of modern pollen deposition in the region, and help answer questions concerning pollen provenance on the ice caps.
1.1 Expected Significance

Besides providing the first high-resolution pollen record from a tropical ice cap, these studies will advance the science of ice-core palynology and its ability to serve as an effective paleoclimatic and paleoecological research tool. They will provide the science with crucial information about synoptic-scale atmospheric variability, and the dispersal and deposition processes that influence the distribution of pollen on ice caps. To date, no similar studies have been conducted on a tropical ice cap. This information will also increase our understanding of the pollen dynamics on ice caps, resulting in more accurate interpretations of the fossil pollen record. This study will also further the effectiveness of other South American palynological studies by providing a more complete and systematic network of pollen surface samples for Peru and Bolivia. Our knowledge of the modern analog and modern pollen-rain is vital to the accurate interpretation of all fossil pollen records.

1.2 References


2.1 Introduction

The stratigraphic pollen analysis of ice cores has proven to be a sensitive and effective tool in the reconstruction of paleoenvironments. Though previous research efforts have focused primarily on polar (Lichti-Federovich, 1975; Mc Andrews, 1984; Bourgeois et al., 1985, 2000; Bourgeois, 1986, 1990a, 1990b, 2000; Andreev et al., 1997) and sub-tropical (Liu et al., 1998) ice caps, preliminary studies on tropical Andean (Thompson et al., 1988, 1995) ice caps have also shown similar promise. The close proximity of these tropical ice caps to pollen sources, along with the climatically sensitive nature of the tropics, makes them good candidates for a high-resolution pollen study.

To date, the reconstruction of tropical paleovegetation has only been estimated through the results of chemical and physical proxies found within ice cores (e.g. $\delta^{18}$O; soluble aerosols such as NH$_4$, Cl$^-$, NO$_3^-$, and SO$_4^{2-}$; and trapped gasses such as CO$_2$ and methane). Without a direct relationship to the past vegetation, however, interpretation of these proxies is tenuous. In order to approximate paleovegetation and paleovegetational change more accurately, it is necessary to use biological proxies directly produced from these fossil plant communities. Pollen is the best candidate for this task, because it provides a direct link to the past vegetation and is the only biological parameter consistently found in tropical ice cores.

However, it is important to remember that pollen are proxy data, and the interpretation of the fossil pollen assemblages, along with the entire science of palynology is based on a series of uniformitarian assumptions. They are as follows (Birks and Birks, 1980):

1) The modern ecology of the plants represented in the pollen taxa is well understood.
2) Present plant distributions are in equilibrium with their controlling variables.
3) Former plant distributions were in equilibrium with their controlling variables.
4) Former plants have modern analog in the modern flora.
5) The ecological tolerance and preferences of plants have not changed or evolved.
6) The fossil assemblage is a truthful representation of the death assemblage.
7) The origin of the taphonomy can be established.
8) The fossil remains can be identified to a sufficiently low taxonomic level.

All of these assumptions must be considered true for this science to be valid. However, despite these limitations, the science of palynology has proven to be a very useful and sensitive technique for detecting environmental change.

This project is the first systematic, high-resolution pollen study from a tropical ice core. Presented in this paper are the results from 249 ice core samples taken from the Sajama Ice Cap in southwestern Bolivia. This 132-meter core contains a 25,000-year record of environmental change in the region. This record has been divided into three separate studies for the dissemination of the results in this paper. The first study is a 39-year record presented at one-year resolution. These annual samples show that ice-core pollen is a sensitive indicator of short-interval climatic change, especially the climate fluctuations associated with El Nino/Southern Oscillation (ENSO). The second study is a 400-year record reported at 5-year resolution. These 149 samples have recorded the vegetation responses of the Andean Altiplano to climatic change through the Little Ice Age. The last section of this paper contains the entire 25,000-year record from Sajama. All 249 samples were combined to yield a record at ~500-year resolution. Here the pollen establishes itself as a sensitive proxy for paleoenvironmental vegetation change. These data closely match the 25,000-year chemical record that has already been published from Sajama (Thompson et al., 1998). These pollen data also support the paleoenvironmental
reconstructions derived from the traditional chemical ice-core proxies, some of which have been called into question because they are open to equivocal interpretations.

2.2 Background

Mt. Sajama (18°06’ S, 68°53’ W, at 6,542 m above sea level), Bolivia’s highest peak, is an extinct stratovolcano located on the drier, western side of the Andean Altiplano in southwestern Bolivia (Figure 2.2.1). The ice cap that sits at the summit of Sajama varies from 121-177 m in thickness, as determined from short-pulse radar readings (Thompson et al., 1998) (Figure 2.2.2). In 1997, four cores (two short cores and two long cores to bedrock) were drilled and extracted from the summit. The two long cores (C-1 and C-2), which are parallel cores drilled 3 m apart, were used for our palynological investigation. Although C-2 was primarily used for pollen sampling, samples were taken from C-1 in instances where sections of the primary core had already been heavily sampled. Dating control for the two long cores came from a combination of techniques including $^3$H (tritium) analysis, physical layer counts, tephra-layer correlations with known volcanic eruptions (i.e. Huaynaputina), $^{14}$C AMS dating, and stratigraphic $\delta^{18}$O correlations with the GISP 2 core from Greenland.

2.2.1 Environment and Vegetation

The Andean Altiplano, upon which Sajama sits, is the second largest plateau in the world and averages nearly 4,000 m in height (Hastenrath, 1985). It is a dry and windswept environment that straddles the rainshadow of the Andes Mountains, and occupies approximately 100,000 km$^2$ in the countries of Peru, Bolivia, and Chile. The average annual temperature at Sajama is roughly 1°C (Schwalb et al., 1999). The yearly mean precipitation at the base of Sajama is around 316 mm per year (Hardy et al., 1998), as recorded at nearby Sajama Village.
Figure 2.2.1. Map of the central Andes showing the location of Mt. Sajama and the other ice caps mentioned in the text.
Figure 2.2.2. Photo of Mt. Sajama from the east.
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 per year (Hardy et al., 1998). However, the precipitation regime is highly seasonal at Sajama 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 six-month dry season (May-October), however, easterly flow dominates in the wet season (December-March) (D. Hardy, personal communication, 2002). November 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 vegetation that comprises the western Altiplano, and the area immediately surrounding Sajama, is a vegetation assemblage known as puna, or “puna-brava” (Tosi, 1960). The main characteristic of puna is the preponderance of bunch grasses (Gramineae). Other common plants include Compositae shrubs and herbs (e.g. Gynoxys and Baccharis), rosette species (Polylepis), cushion plants (Yareta, Umbelliferae), and a host of other xerophytic shrubs and herbs including Ephedra, Cactaceae, Euphorbiaceae, Caryophyllaceae, and Solanaceae (Hansen et al., 1984). Low-lying areas of the western Altiplano can often support peat bog habitats known locally as “bofedales” (Baied and Wheeler, 1993). These habitats support a wide variety of hydrophilous plants as well as large populations of Yareta.

2.3 Methods

After collection in 1997, the ice cores from Sajama were brought back frozen to the Byrd Polar Research Center at Ohio State University for storage. All samples used in this study were cut directly from the frozen cores and placed into leakproof Nalgene sample bottles. The ice was allowed to melt naturally and then shipped to Louisiana State University for pollen processing.
and analysis. The samples were collected at bi-yearly or tri-yearly resolution from AD 1996 to the tritium peak at AD 1964. Samples from AD 1963 to AD 1600 ranged in resolution from 1 to 5 years. The remaining samples ranged in resolution from 5 to 550 years in some cases. The amount of meltwater for each sample varied from 400 to 1100 ml. Each sample was processed for pollen following the standard methods for meltwater processing (Liu et al., 1998; Reese and Liu, 2002). This method involves the evaporation of the meltwater down to 50 ml of water. The remaining liquid was spiked with *Lycopodium* marker spores (Stockmarr, 1972), and then treated with acetolysis solution to remove any organic materials. The remainder was stained and mounted on microscope slides for analysis. All pollen and spores were identified until a minimum of 1000 *Lycopodium* marker spores were counted. Charcoal particles were counted and reported regardless of size. For each study, the data were standardized by aggregating the samples into equal units of time for the unbiased comparison of the results. In the 39-year study, the results are reported in 1-year time aggregates. The samples for the 400-year Little Ice Age study were aggregated into 5-year intervals. For the complete 25,000-year record, equal aggregates were impossible, therefore the sample resolution is ~500 years (+/- 50 years). The pollen percentages and pollen and charcoal concentrations were calculated using the TILIA computing software. All concentrations and percentages were based on a pollen sum that consists of all pollen and fern spores. TILIA GRAPH WINDOWS was used to generate the pollen diagrams for the display of the results.

### 2.4 A 39-year Ice-core Pollen Record of El Nino-Southern Oscillation from the Sajama Ice Cap, Bolivia, 1958-1996

The aim of this study was to test the sensitivity of the Sajama pollen record to short-interval climate change (e.g. ENSO Events) on the Andean Altiplano. The ENSO cycle is an important phenomenon that greatly influences the climate in this region of the world. During the
warm phase, or El Nino conditions, the western Altiplano endures very dry, windy, and generally warmer conditions (L.G. Thompson, personal correspondence, 2002). The opposite is true during the cold phase, or La Nina conditions, when the climate is normal to slightly wetter. The pollen in the environment should be a good indicator of these conditions as plants incur high levels of stress during the dry El Nino events, possibly altering the types and concentrations of pollen found on the Sajama Ice Cap. In this study, pollen concentration and pollen percentage data were compared to the Southern Oscillation Index (SOI, hereafter) to determine whether any significant correlations exist. The charcoal content of the core was also analyzed to test for a correlation between natural fire and El Nino events.

This section of the study involves the analysis of the top 28.3 meters of the ice core, which comprises the first 70 samples. Again, the samples vary in resolution from 4 months to 1 year, but all were standardized and grouped into 1-year aggregates for unbiased comparison throughout the record. The primary dating control for this 39-year record was the physical counts of the distinct seasonal layers within the core, calibrated with the tritium peak at 1964.

The yearly SOI data, plotted along with the results of the pollen analysis are shown in Figure 2.4.1. The Southern Oscillation Index (SOI) (according to the climate research unit at East Anglia University) is defined as:

\[
\text{Mean Sea Level Pressure (monthly) at Papeete, Tahiti - Darwin, Australia} \\
\text{Long-term Running Mean (monthly)}
\]

The results of this analysis are typically reported as monthly averages. The annual SOI data reported in this study were calculated by averaging the 12 monthly means for each particular year.

Pollen concentrations in the annual layers from 1958 to 1996 range from 792 to 5000 grains per liter, with an average of 2,614 grains per liter. These values are comparable to modern
Figure 2.4.1. Pollen percentage diagram showing the results of the 39-year pollen analysis plotted with the SOI.
surface snow samples collected at the Quelccaya ice cap in the Peruvian Andes (Reese and Liu, 2002) and Mt. Parinacota, 22 km southwest of Sajama (Reese unpublished data, see Chapter 4). However, these values are about 2-3 times higher than those reported from the annual layers from the Dunde ice cores for a comparable period, 1957-1986 (Liu et al., 1998).

On the whole, the pollen from Altiplano plant taxa dominate the 39-year pollen record from the Sajama ice core. Compositae (Tubuliflorae-type, sensu McAndrews et al., 1973) and Gramineae account for an average of 31.9 % and 32.3% of all the pollen and spores counted, respectively. However, significant inter-annual variability exists, ranging from 5-75% for Compositae and 10-85% for Gramineae from one annual layer to another. Other ecologically important pollen taxa include Polylepis, Dodonaea, Urticaceae/ Moraceae, Umbelliferae, Plantago, Chenopodiaceae, and Cyperaceae, but their frequencies are generally <10%. Minor taxa include Podocarpus, Leguminoseae, Verbenaceae, and fern spores. The miscellaneous pollen category represents 23 different taxa of pollen, all of which are common to the Andean Altiplano. However, their percentages never exceed 1% of the total pollen count in any of the samples. Charcoal particles range in abundance from 350 to 2,400 particles per liter but do not seem to follow any trend.

In fact, none of the pollen data seem to show any clear trends or patterns throughout the 39-year period of study. To test the null hypothesis of no relationship between pollen data and SOI during the 39-year study period, a bi-variate (Pearson’s) correlation was run between each of the pollen percentage variables and the SOI. Results show no significant correlation between any of the pollen percentage (taxa) data and the SOI. Likewise, no significant correlation exists between the charcoal content and the SOI. However, a significant and strong negative
correlation exists between the pollen concentration and the SOI. The results show the two variables have a Pearson’s R of –0.798, significant at the 0.01 level (2-tailed).

This negative correlation means that as the SOI becomes more negative (El Nino conditions) the pollen concentration on the ice cap increases. At first, these results seem to contradict logical thinking. As the environment becomes more stressful for plants, they seemingly produce more pollen. However, the best explanation for this correlation has nothing to do with the plants, or their levels of stress. The most likely justification for this phenomenon is the process of sublimation on the ice cap itself.

Sublimation is the process in which a solid-state substance (i.e., ice) changes directly into a gas (i.e., water vapor). It has been known for some time that high alpine ice caps (including Sajama) do not melt (L.G. Thompson, personal communication, 2002). Instead they lose mass through the process of sublimation. Though we know little about the sublimation process on these ice caps, it is believed that warmer and drier conditions tend to increase sublimation rates (Hardy et al., 1998). In fact, unpublished data (1996-1997) from the satellite-linked weather station atop Mt. Sajama show that during the 1997 El Nino year, wet season accumulation was negated by the dry season loss due to sublimation (D. Hardy, personal communication, 2002). If this is indeed the rule, then the conditions brought on by El Nino (warmer, drier, and windier) should tend to exacerbate sublimation. This factor alone is enough to concentrate the pollen in the ice core records.

Assuming equal accumulation and a constant amount of available pollen in the environment, each annual ice cap layer would have an equal amount of pollen trapped in suspension. However, if a high rate of sublimation occurred during a particular year, then that same amount of pollen would be contained in a smaller volume of ice. The end result is a higher
pollen concentration based on sublimation alone. This is the most likely explanation for the correlation between pollen concentration and the ENSO cycle in the Sajama ice cores.

Though no relationship was found between the actual vegetation and the climatic effects of ENSO, these results are significant and invite additional analysis. The high correlation between the two records (SOI and pollen concentration) could be used in the future to possibly reconstruct paleo-El Nino events and possibly extend the SOI record back in time, as far as annual resolution is obtainable in the ice core.

2.5 A 400-year High-resolution Ice Core Pollen Record from Mt Sajama, Bolivia

This aspect of the study shows the sensitive nature of tropical ice-core pollen records and their ability to record vegetation responses to climate fluctuations on the centennial time scale accurately. In this paper 149 samples, ranging in dates from AD 1996 to AD 1600, were analyzed for pollen and charcoal content to reconstruct the vegetation responses of the Bolivian Altiplano through the Little Ice Age. This study utilizes the top 64.84 meters of the Sajama Ice Core. Sample resolution ranges from 4 months to 5 years, but all of the data were standardized by grouping the results into 5-year time aggregates. Therefore all parts of the record can be compared without bias. Dating control for this section of the core include physical layer counts calibrated with the tritium horizon, $^{14}$C dating of plant macrofossils, and the ash layer produced from the eruption of Huaynaputina in A.D. 1600 (Thompson et al., 1998).

Results of the pollen analysis show the dominance of grasses (Gramineae) and Compositae plants on the Andean Altiplano (Figure 2.5.1). Compositae (29-79%) is a family of dry-loving plants that range in size from small shrubs to trees reaching 10 m or more in height (i.e. *Gynoxys oleifolia*). The grasses are slightly less common in the pollen count, ranging from 8-49%. *Polylepis* (1-47%), locally known as Quenoa (Baied and Wheeler, 1993), is a tree
Figure 2.5.1. Results from the 400-year Little Ice Age pollen study, plotted in 5-year intervals.
common to the area and can be found from 3,000 m to over 5,100 m at Sajama (Kessler, 1995; Braun, 1997). The spurious spike in *Polylepis* around 1860 can easily be explained by the occurrence of a *Polylepis* anther in the sample that simply over-represented its presence. Normal values of this pollen type range from 1-23%. Of the minor pollen taxa (normally <10% abundance), all are consistent with the vegetation of the Altiplano or the upper Andean slopes. Of these types, the Urticaceae/Moraceae (2-15%) families are the most common, and range in distribution from the Amazon lowlands to the lower Altiplano.

Pollen concentration remains relatively uniform throughout the 400 years, ranging from 800-8,200 grains per liter. The spike at AD 1735 should be disregarded. Again, this spike can be explained by a whole plant anther (Compositae) being present in a single sample. The consistency of the concentration numbers suggests that the amount of vegetation on the Altiplano has remained relatively constant. Therefore, as a response to climatic change, it can be assumed that the vegetation assemblage does not change so much in density as it does in composition. It should be noted that this interpretation of the pollen concentration data does not incorporate the effect of sublimation on the concentration values. Though sublimation is undoubtedly a factor in these data, no study has addressed these questions on this time scale. However, the effect does seem to be reduced with the aggregation (into larger time intervals) of the data.

As for the charcoal results, the particles per liter of meltwater remain well below 5,000 for most of the time, with typical amounts in the range of 800-4,000. One noticeable exception occurs around 1615 and corresponds to the eruption of Volcán Huaynaputina in Peru. Though the eruption is estimated to have taken place in the year AD 1600, the bulk of the ash layer was not deposited in Bolivia until some years later. The charcoal in this layer is also accompanied by large amounts of volcanic tephra (Dugmore et al., 1996; Dwyer and Mitchell, 1997; Boygle,
of note is the increase in charcoal beginning just before AD 1950 and ending in the 1980s. This rise is a likely result of an expanding railroad industry and increasing mining operations that were the result of economic and social changes after the Bolivian national revolution of 1952 (Malloy and Thorn, 1971).

The most interesting finding in the data, however, concerns the ratio of (Gramineae+Cyperaceae)/Compositae. This ratio was used as a proxy for wetness. Grasses and sedges (Cyperaceae) are typically shallow-rooted plants that tend to proliferate in wetter conditions. On the contrary, the Compositae plants are xerophytic, deeply rooted plants that prosper in drier environments. Higher ratio numbers, nearing and above 1.0, show the dominance of grasses and sedges and, therefore, presumably wetter conditions. The lower the ratio, the greater the dominance of the Compositae plants and presumably drier conditions.

Although the pollen concentration numbers provide no clear indication of environmental change, the contrast in dominance between these environmentally-different plant types should. For the years before AD 1700, the average wetness index ratio equals 0.884. During the period from AD 1700 through AD 1880, the average wetness index ratio is significantly lower at 0.290. For the post AD 1880 period, the average is again near the pre-1700 levels at 0.831. When this vegetation-derived index is compared to the wetness (accumulation) record from the Quelccaya Ice Cap (350 km to the north of Sajama), we find a striking similarity between the two.

Thompson et al. first published the Quelccaya accumulation data in 1986. The results hinted at a two-phased Little Ice Age event, in which cold and wet conditions occurred before AD 1700 and cold and drier conditions occurred between AD 1700 and AD 1880. After the end of the Little Ice Age around 1880, relatively wet conditions resumed along with temperature amelioration. Since this time, new oxygen isotopic and accumulation data from other ice caps in
the central Andes agree that the Little Ice Age was indeed a two-phase event in this region (Thompson et al., 1985, 1986, 1988, 1995). Even lake core evidence from the region agrees with these findings, albeit rather inconclusively (Schwalb et al., 1999). What had yet to be discovered was the magnitude of these events and the actual impact they had on the environment. Questions have always remained as to the sensitivity of oxygen isotopes in the tropics and the ability of ice core evidence to reflect the environmental (vegetational) conditions accurately. The pollen evidence herein clearly shows that the vegetation of the western Altiplano responded dramatically to the effects of a two-phase Little Ice Age. The response was not a change in plant density, but rather a change in assemblage, as grasses and sedges dominated the wetter periods and Compositae plant dominated the drier.

This two-phased Little Ice Age is probably due to the failure of the South American summer monsoon (hereafter SASM) (Zhou and Lou, 1998) resulting from the cold temperatures characteristic of the Little Ice Age. One component of the SASM is the presence of an upper-level, high-pressure cell that locks in over the Altiplano during the summer months due to intense convection brought on by summer insolation (Zhou and Lou, 1998). This high-pressure system reverses the general circulation in the region and brings the warm and moist air from the Amazon to the Altiplano; providing the high amount of rainfall during the summer. However, once the Little Ice Age became established, the resulting cooler land temperature likely prohibited the development of this strong high-pressure system and prevented the advection of Amazonian air masses, which resulted in the drier conditions after AD 1700.

The results of this study clearly show the ability of ice caps to record the vegetation responses to climate fluctuations at centennial-scale resolutions. The pollen data not only give validation to the chemical and physical ice core data, but being the only biological parameter
present in ice cores, also provide a direct link to the past vegetation. The fact that a pollen record (an independent proxy from the chemical and physical parameters) from a completely different ice cap, located approximately 350 km away from Sajama, shows the same paleoclimatic trend reflects the strength of both the pollen and the more traditional proxies and suggests that environmental response to atmospheric forcing occurred at the macro-scale. This research has widened the effective scope of ice core research and has shown ice cores to be an even more versatile and precious archive.

2.6 A 25,000-year High-resolution Pollen Record from the Sajama Ice Cap, Bolivia

Because annual and centennial-scale variability were evident from the previous analysis (sections 2.4 and 2.5), this aspect of the study was conducted to test the sensitivity of the Sajama ice core pollen record to millennial-scale climatic fluctuations. The pollen data were also tested against the 25,000-year chemical proxy record, which have already been published from Sajama (Thompson et al., 1998). The results for this record were obtained from the 249 ice samples that comprise the entirety of the 132 m Sajama ice core. Samples from the core range in resolution from 4 months to 550 years of accumulation. To standardize the record, the pollen data were grouped into ~500-year time aggregates. Though it was impossible to create equal time aggregates throughout the core, all aggregates fall within +/- 50 years of the 500-year interval. This aggregation allows the entire record to be compared without bias. Again, dating control for the core was established through a combination of methods including physical layer counts, tritium, volcanic ash layers, $^{14}$C dating of insect remains and plant macrofossils, and the correlation of the $\delta^{18}$O records from Sajama and the well-dated GISP 2 core from Camp Century, Greenland.
The pollen record for this study was divided into zones derived from the pollen data to facilitate the explanation of the results (Figure 2.6.1). However, as the results will show, they closely match the zones derived independently from the chemical record already established at Sajama (to be discussed later in Figure 2.6.2).

Firstly, it is important to note that the Sajama pollen record (Figure 2.6.1) only extends back 15,000 B.P. From 15,000 B.P. to the start of the ice core record at 25,000 B.P., pollen was absent or only present in small amounts (less than 8 grains per sample). This lack of pollen is probably the result of the Late Glacial Stage (LGS, hereafter) conditions that were known to exist in the region. The Altiplano was heavily glaciated during this period, which most likely decimated the local plant communities and/or pushed them farther away from the ice cap. Regardless, the ice core pollen record is not sensitive to climatic change during the LGS.

The Sajama pollen record begins around 15,000 B.P. After the last glacial maximum around 18,000 B.P., it is believed that climatic conditions began to ameliorate. However, results suggest that the plant populations did not begin to rebound until about 3,000 years later. The first significant rise in pollen comes at 15,000 B.P. with low concentrations (<200 grains/l) of primarily grass (Gramineae, 48%). Compositae plants (25%) and Polylepis (14%) were also present along with one grain of Podocarpus and one grain of Myrica. The pollen evidence, with the preponderance of grass, suggests that the end of the LGS was primarily a wet and cold environment.

From 14,500 to 14,000 B.P., however, a dramatic climatic reversal is reflected in the pollen assemblage. This short interstadial was a warm and dry period that is dominated by Compositae (68%). When there is a complete turnover from grass to the Composite plants, such as the reversal that occurred between 15,000 and 14,500 B.P., it is a clear sign of an
Figure 2.6.1. Results of the pollen analysis for the last 15,000 years at Sajama. Note: Pollen was absent in the record from 25,000-15,000 B.P., and therefore are not reported here.
Figure 2.6.2. 25,000-year chemical/physical record from Sajama plotted with the pollen and charcoal data.
environmental change from wet to dry. Other pollen taxa present in the Short Interstadial zone are the grasses (22%) and one to two grains of *Polylepis*, Umbelliferae, and *Podocarpus*. Also of note in this zone is the first appearance of the Chenopodiaceae/Amaranthaceae plant families and *Ephedra*. Both of these plants are adapted for life in harshly dry environments. This again supports the notion that this short interstadial is a true climatic reversal, and not just an anomaly in the pollen data. In this zone a slight peak in pollen concentration is evident, which ranges from 280 to 945 grains/l.

After this short interglacial we see yet another rapid shift in the climate of the Andean Altiplano. Thompson et al. (1998) called this phenomenon the Deglacial Climatic Reversal (DCR, hereafter). This period occurs in the pollen data between 14,000 and 12,000 B.P. and is characterized as a return to the climate of the LGS. This period is marked by the domination of grass (40-74%) coinciding with a marked decrease in Compositae plants (7-34%). Other minor taxa in this zone include *Polylepis*, Umbelliferae, Caryophyllaceae, and *Myrica*. Also of significance are the first signs of *Plantago*, the Cyperaceae (sedge) family, and the highest percentages of fern spores. All of these are wet loving plants that confirm the return of the wetter LGS conditions. This zone also loosely corresponds to the Younger Dryas (YD) stadial that is well-documented for the North Atlantic, but still controversial for the Southern Hemisphere (Markgraf, 1991; Thompson et al, 1995).

After 12,000 B.P. the climate shifted again for the last time, and Holocene-like conditions began to emerge. Pollen concentration rose markedly, never falling below 1,100 grain/l again. The Compositae plants began to increase and stabilize around 10,000 B.P. at 44-62%. The grasses decreased from their DCR highs and also stabilized around 10,000 B.P. at 18-30%. The warm and dry Holocene conditions are also marked by the consistent presence of arboreal taxa
such as *Polylepis*, *Dodonaea*, and the Urticaceae/Moraceae family, as well as a wide array of xerophytic shrubs and herbs (e.g. *Plantago*, Chenopodiaceae/Amaranthaceae). The consistent but small presence of hydrophilous plants like Umbelliferae and Cyperaceae can be explained by the “bofedales” communities which are common of the Holocene western Altiplano. Of the minor taxa, all of the plants are common components of the Andean Altiplano and can be found in abundance throughout the region. Fern spores slowly decreased in abundance throughout the DCR, but disappeared almost entirely around 10,000 B.P. and are rarely found since.

The charcoal results from this analysis are as to be expected. Charcoal was absent during the wet LGS and the DCR, but a small peak is seen during the short, dry interstadial from 14,500-14,000 B.P. Charcoal forms a steady baseline during the dry Holocene (5,000-51,000 particles/l), but skyrockets in the last 500 years to 247,230 particles/l. World industrialization over the last 200 years is the most likely explanation for this spike.

When the pollen results are compared to the 25,000-year record derived from chemical and physical parameters (Figure 2.6.2), the two records match very closely. According to Thompson et al. (1998), the LGS lasted from 25,000 to 15,500 B.P. The LGS is a cold and wet period which is characterized by high accumulation, depleted $^{18}$O values, and low amounts of the soluble anions and dust. The notable exception occurs between 22,000 and 21,000 B.P. when high chloride and sulfate values are present. Thompson et al. (1998) explained this event as the temporary desiccation of the salt lakes which are abundant throughout the southern Altiplano. This stage corresponds to the pollen poor section of our record when pollen was either missing or barely present due to the effects of glaciation.

After the LGS, the short interstadial event began at 15,500 B.P. and ended around 14,000 B.P. This zone is marked with extremely enriched $^{18}$O levels (higher than the Holocene), the
lowest accumulation seen in the previous ten centuries, and spikes in dust and the soluble anions. At the beginning of this zone is the first occurrence of any significant amount of pollen in the pollen record. This climatic reversal to warm and dry conditions marks the end of full glacial conditions on the Andean Altiplano. The height of this short interstadial occurred around 14,750 B.P. according to the chemical/physical record. However, the vegetation response to the climatic shift did not materialize in the pollen record for another 250 years. This lag should represent the time needed for the western Altiplano vegetation assemblage to completely turn over from wet to dry conditions.

After the short interstadial event, the DCR ran from 14,000 to 12,000 B.P. in both the pollen and chemical/physical record. The chemical parameters shifted back to LGS values in $^{18}$O, dust, and the soluble anions. Effects of this colder and wetter stadial can also be seen in the pollen assemblage, which reverts back to the domination of grass, last seen in the LGS.

The climatic shift that started the Holocene period began at 12,000 B.P. and continued to the present. Though the accumulation, oxygen isotope, and pollen concentration records suggest this change as a rapid event, it took nearly 2,000 years for the pollen assemblage to shift from a wet assemblage to the dry assemblage that defines the Holocene period. Palynologically speaking, the Holocene is a relatively homogeneous period consistently dominated by Compositae. Though the dust, soluble anions, and charcoal records suggest a mid-Holocene warm period (from 6.0-2.5 ka), no such event is reflected in the pollen. The Holocene has been a relatively stable period of warm and dry conditions.

2.7 Conclusion

The results of this study show the sensitive and versatile nature of pollen to climatic change over a wide range of time scales. The pollen record, as a completely independent proxy,
also provides validation to the more traditional chemical/physical ice core proxies. Over the past thirty years, the results of the chemical ice core proxies have often been called into question. Although the science has not been challenged, the ability of these proxies to accurately estimate the actual environmental conditions, sometimes occurring thousands of feet below the ice cap, has (L.G. Thompson, personal communication, 2002). The pollen results from this study have not only strengthened the previous ice core records from Sajama, but have provided new depth to their meaning. These results bode well for the future of ice core palynology by warranting the continued use and development of this paleoenvironmental research tool.

2.8 References


CHAPTER 3. POLLEN DISPERSAL AND DEPOSITION ON THE QUELCCAYA ICE CAP, PERU

Note: The bulk of this chapter has been previously published in Physical Geography. The citation is as follows:


3.1 Introduction

To date, ice cores represent one of our best-known sources for long-term and high-resolution paleoenvironmental data. Biological as well as abiotic evidence of our past environments is preserved in the glacial ice of polar and alpine areas, creating an excellent opportunity for Quaternary paleoenvironmental study through the use of proxy data. The climatic records produced from polar as well as tropical and subtropical alpine ice cores have been well documented in the literature (Dansgaard et al., 1969; Lorius et al., 1979; Thompson et al., 1985, 1986, 1989, 1995, 1997, 1998, 2000a, 2000b; Oeschger and Langway, 1989; Hammer et al., 1997).

However, the majority of the data extracted from these cores have been derived from physical or chemical parameters, such as atmospheric dust (Thompson et al., 1988; Cole-Dai et al., 1997, 1999), oxygen isotopes (Thompson et al., 1986, 1995, 1998; Yao et al., 1997; Henderson et al., 1999), and accumulation/stratigraphic signatures (Anklin et al., 1998; Van der Veen et al., 1999a, 1999b). Although proven to be quite promising, few studies have utilized these ice cores for palynological investigation (Ambach et al., 1966; Lichti-Federovich, 1975a; McAndrews, 1984; Bourgeois et al., 1985, 2000; Bourgeois, 1986, 1990a, 1990b, 2000; Andreev et al., 1997). Even fewer palynological studies exist on tropical and subtropical ice cores (Thompson et al., 1988, 1995; Liu et al., 1998; Yao, 2000). However, through these studies, it
has been shown that sensitive pollen records of past climatic and vegetational changes can be obtained.

Unlike in polar ice caps (Ritchie and Lichti-Federovich, 1967; Lichti-Federovich, 1973, 1975b; Kalugina et al., 1981; Bourgeois et al., 2001), all pollen studies to date on tropical and subtropical ice cores have been conducted without the full understanding of the dispersal and depositional processes on the ice caps themselves. Understanding these processes, in relation to the modern patterns of climate and vegetation, is essential for the interpretation of the fossil pollen signatures being detected within the deeper ice cores (McAndrews, 1984; Bourgeois, 1986, 1990a; Koerner et al., 1988). This, along with the limited numbers of published pollen records (both surface samples and pollen stratigraphies) from Bolivia (Graf, 1981, 1992) and Peru (Hansen et al., 1984, 1994; Hansen, 1995; Hansen and Rodbell, 1995), have hampered the development of this promising, new science in the central Andes. Currently, there are no data on the patterns and processes of pollen deposition on any high-alpine ice cap. Several studies have been published on high-alpine pollen dispersal (Markgraf, 1980; Jackson, 1991; Fall, 1992; Horn, 1993; Flenley, 1996), but all of these have considered the pollen deposition gradient on mountain slopes and most have stopped well short of the summits or any ice cover. This study attempts to utilize 34 surface snow samples, taken on the Quelccaya Ice Cap in the austral winter of 2000 and 2001, to answer some basic questions about pollen dispersal and deposition on tropical Andean ice caps.

### 3.2 Background

The Quelccaya Ice Cap (13° 56’ S and 70° 50’ W; at 5670 m above sea level) is located in southern Peru on the eastern side of the Andean Altiplano in the Cordillera Vilcanota (Fig. 3.2.1). The ice cap covers over 55 km² and sits atop a flat ignimbrite plateau (Thompson et al.,
Figure 3.2.1. Map of Peru showing the location of the Quelccaya Ice Cap. Adapted from Mercer et al., 1975.
Figure 3.2.2. Aerial view of the Quelccaya Ice Cap looking from the south/southwest.
The average annual temperature at Quelccaya is –3°C (Thompson et al., 1985). The annual precipitation around Quelccaya ranges between 700 and 1500 mm per year (water equivalent), or an annual accumulation of snow between two to three meters (Mercer et al., 1975; Thompson and Dansgaard, 1975; Thompson et al., 1984, 1985; Morales-Arnao and Hastenrath, 1999). However, a strong seasonality exists in the precipitation regime of the area, resulting in distinct wet and dry seasons. During the five-month wet season from November to April, the area receives over 80% of its total annual rainfall (Johnson, 1976; Sarmiento, 1986).

3.2.1 Vegetation

The Altiplano, upon which the Quelccaya Ice Cap sits, averages 3700 m above sea level and is primarily dominated by “puna-brava” vegetation (Tosi, 1960). Puna is characterized as a dry grassland, dominated by bunch grasses (Gramineae). Rosette plants, cushion plants, *Gynoxys* and other Compositae, *Polylepis* trees, along with a host of other desert shrubs and herbs are also commonly found (Hansen et al., 1984). On the eastern slopes of the Andes, puna proper occurs between 3900 and 4500 m (Tosi, 1960). Above this formation lies another vegetation zone known as the super-puna (4500 m to snowline). The super-puna is primarily dominated by *Plantago*, and other herbs and shrubs that are adapted to colder (annually less than 5°C) and drier surroundings (Hansen et al., 1984). Krummholz vegetation adaptations are common among the small trees and shrubs like *Polylepis*, which grows to the edge of the ice cap at Quelccaya. Below the super-puna and puna is a sharp vertical vegetation gradient, which changes from sub-puna (grassland) vegetation to tropical wet forest in a horizontal distance of 200 km in some places. Sub-puna (3300 to 3900 m) is very similar to puna, except that a greater number of trees (esp. *Alnus*) are often found. Below the three puna zones, humid montane forest (3300 to 1800 m) and humid subtropical forest (1800 to 300 m) occur in regions receiving well
over 1500 mm of annual precipitation and are usually dominated by trees (e.g. *Podocarpus*), lianas, and ferns (Weberbauer, 1936; Tosi, 1960; Hansen et al., 1984; Young, 1993). Below these areas, where human disturbance has not encroached, tropical wet forest occurs.

On the western slopes of the Altiplano, the vegetation zones are much less complex. This area straddles the rainshadow of the Andes and is dry to only moderately wet all year around. Features of the puna grasslands of the Altiplano extend all the way to the western coast of the continent. Although trees such as *Prosopis* are abundant in certain sections of the western coast below 1500 m, they hardly ever form dense stands.

As for the reproductive patterns of these central Andean plants, little is known about the exact seasonality of the pollination process. Although year-round pollination is possible (Monasterio and Vuilleumier, 1986), neither wet nor dry season is ideal for pollen dispersal. During the wet season, the frequent precipitation in the area hinders this process, while during the dry season, stress inhibits its effectiveness. Therefore, for most plants (e.g., *Espeletia*) the height of pollen release occurs in September and October, between the dry and wet seasons (Monasterio, 1986). Thus the pollen is dispersed before the onset of the rains, using the extra insolation and ground moisture during the summer/wet season to enhance seed development and growth.

### 3.2.2 Wind Patterns

The circulation patterns around Quelccaya and the eastern ridge of the central Andes fall under the influence of the South American summer monsoon (Zhou and Lau, 1998). Winds are typically out of the west all year around, however, during the austral summer months, the winds come primarily from the east and northeast. This dramatic shift in summer circulation is caused by the intense summer heating of the tropical highlands, which forms a warm-cored anticyclone.
over the Altiplano in the upper troposphere. In return, at the lower levels, moist air masses are advected from the east and northeast causing strong convection, condensation, and precipitation. Thus, the resulting latent heat release provides the means by which the warm-cored anticyclone is maintained (Schwerdtfeger, 1961, 1976; Gutman and Schwerdtfeger, 1965; Kreuels et al., 1975; Virji, 1981; Zhou and Lau, 1998). This seasonal switch in the prevailing winds, in conjunction with the diurnal and glacial winds, should have a marked impact on the dispersal of pollen on the ice cap.

3.3 Methods and Materials

In August (austral winter/dry season) of 2000, 15 surface snow samples (from nine different locations), were collected along an east/west transect across the ice cap, following the normal summit route from the Quelccaya base camp (samples # 1-15, see Fig. 3.3.1). An additional 19 samples were collected in June 2001 from the western edge of Quelccaya, the southern dome, and the summit (samples # 16-34, see Fig. 3.3.1). Among these 34 samples were nine pairs of samples taken to test for within-site variability. The two samples within each pair were taken no more than one meter from each other. For each sample, regardless of year, a small square-nosed shovel was used to collect the snow. Only the top 5 cm of snow was sampled at each site. This uppermost layer should primarily represent accumulation of the current season or year. After collection, the snow was immediately transferred into sealed plastic bags and then allowed to melt naturally. The meltwater was then transferred into leak-proof Nalgene bottles for transport back to Louisiana State University. The amounts of meltwater varied for each sample, but all ranged between 200 to 500 ml. All meltwater samples were processed following the procedure outlined in Liu et al. (1998). This involved the evaporation of the meltwater on a hot plate, down to 100 ml of water. The remaining sample was spiked with *Lycopodium* marker...
Figure 3.3.1. Map of the Quelccaya Ice Cap (shaded) showing the 34 sample locations and seasonally prevailing winds (arrows). Numbers 7 and 8 are located at the true summit. Adapted from Thompson, 1980.
spores (Stockmarr, 1972), centrifuged, then treated with acetolysis solution to remove organic matter. The residue was stained, and mounted on slides with silicone oil. Pollen grains were identified and counted until a total of 300 grains was obtained, or a minimum of 1000 marker spores was reached. Pollen percentages and concentrations were calculated using the TILIA computer software, and were based on a pollen sum consisting of all pollen grains and spores. TILIA GRAPH was used to generate pollen diagrams for the display of results. 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.

3.4 Results

Results of the pollen analysis show that the pollen assemblages and concentrations between the 2000 and 2001 samples are statistically very different. The statistical program SPSS 8.0 was used to run a discriminant analysis between the data collected for each year. The canonical discriminant function used in the analysis had a correlation value of 0.994, was significant at the 0.000 level, and was able to explain 100% of the variance. When self-validated, this function correctly classified all 34 samples into their appropriate group, with Group 1 being the 2000 samples and Group 2 being the 2001 samples. The mean for Group 1 was 10.71 (with a standard deviation of 0.91) while Group 2’s mean fell at –8.45 (with a standard deviation of 1.07) along the canonical discriminant function. These results show that this inter-annual data are statistically too different to be compared to each other, therefore, the results section of this study has been divided into two parts. Section 3.4.1 will discuss the results of the 2000 data, while Section 3.4.2 will discuss the data from 2001. The consequences of these initial findings will be discussed in full in Section 3.5.
3.4.1 2000 Results

Results from the pollen analysis show remarkable uniformity among the fifteen surface samples (Fig. 3.4.1.1). No significant variations in pollen percentages occur between any of the surface samples, whether paired or individual. *Plantago* is the most abundant pollen type in nearly all samples, ranging between 19.3-27%. This genus of wind-pollinated herbs and shrubs is well-represented on the high Altiplano (e.g. *Plantago major* and *P. tubulosa*) (Gentry, 1993). *Alnus* (probably *A. jorullensis*) is also well-represented (13.3-23%) in the samples. *Alnus* is abundant in the sub-puna and humid montane forests between 2500 and 4000 m (Cassinelli, 2000). Other major pollen types include the Urticaceae/Moraceae group, a common montane forest and lowland taxon. These wind-pollinated pollen families are effective at long-distance transport and are most likely originated from the eastern Andean slopes. Gramineae (grass) pollen are also common (5.5-11%), reflecting the dominance of puna grasses around the ice cap and the Altiplano in general.

Likewise, no significant differences occur between the minor pollen groups. An unknown inaperturate-scabrate pollen is the most abundant among the minor pollen taxa (3-12%). This grain resembles *Populus* in size and appearance. Extensive areas of the Altiplano have been planted with exotic species (mainly *Cupressus macrocarpa*, *Eucalyptus globulus*, and *Pinus radiata*), but the presence of this tree in the Peruvian Andes cannot be confirmed. Compositae (long-spine or Tubuliflorae-type) is another common minor pollen taxon, ranging from 2.5-10%. *Ambrosia*-type (short-spine Compositae) was found in most of the samples, however, their abundance is never greater than 2%. The Compositae group of plants can range from small xerophytic shrubs to trees reaching more than 10 m in height (e.g. *Gynoxys*
Figure 3.4.1.1. Pollen percentage diagram showing the results of the 15 surface snow samples taken at Quelccaya in August 2000. Sample numbers joined by brackets are paired samples taken at the same location to test for within-site variability.
oleifolia), and are well-represented on the high Altiplano. The weedy genus Cuphea is present in all samples (<2-6%), as well as Cupressaceae (<2-5%). Cupressus macrocarpa, the likely source of Cupressaceae pollen, is a native North American species that is widely planted in 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 the ice cap. However, the pollen of this genus is usually under-represented in pollen assemblages.

Other minor pollen types (ranging from 0-3%) include Polylepis, a widely abundant tree that can be found in Krummholz form growing in small populations up to the edge of the ice cap. Also present are Dodonaea viscosa, another common Altiplano species between 1000-3500 m, as well as Ericaceae, Myrica, and Podocarpus. The latter three taxa are common plants of the humid upper-montane forests located along the eastern slopes of the Andes (3,300-1800 m above sea level). Lastly, the miscellaneous pollen category contains pollen from 22 different plant taxa, whose overall abundance does not exceed 2 grains per sample. Of this group, Weinmannia, Cyperaceae, Umbelliferae, Myrtaceae, and the Cheno/Am family (Chenopodiaceae and Amaranthaceae) are the most frequent.

The biggest difference among the samples lies in the pollen concentration values. The highest concentrations occur at sites 1-6 on the western slopes of the ice cap. These concentrations range between 30,100 and 55,400 grains per liter, the highest concentrations found in any tropical or non-tropical ice cap. The magnitude of these numbers can only be appreciated when compared to other surface snow samples from around the globe. Surface samples from Greenland and the Canadian Arctic range in pollen concentration from 1 grain/l near the pole to 5280 grains/l in the low Canadian Arctic (Bourgeois et al., 2001). Using the uppermost (modern) levels in Arctic ice cores, McAndrews (1984) reported an average of 7.4
grains/l from the Devon Island ice cap, while similar results (approx. 8 grains/l) were found at the Agassiz Ice Cap on Ellesmere Island (Bourgeois, 1986). In Antarctica, Linskens et al. (1993) reported an average pollen concentration of 0.12 grain/cm$^3$ (approx. 120 grains/l) from surface moss turfs and cushions. From core-tops in the mid-latitudes, Liu et al. (1998) found a pollen concentration of 800 grains/l on the Dunde Ice Cap, while Yao (2000) reported concentration values around 1000 grains/l at the Guliya Ice Cap, both in the Qinghai-Tibetan Plateau, China. It is also important to note that these concentration values from the Quelccaya snow samples are markedly greater than the preliminary work done 1980 Quelccaya ice cores (Thompson et al., 1988). In that study, a pollen concentration of 1600 grains/l was found from one sample, the AD 920 level in the ice core. This raises the question of how pollen concentration changes down an ice core as a function of compaction and ablation. However, this remains an unresolved question at this point.

The lowest concentration values on the Quelccaya surface (17,250 grains/l) occur at sites 7 and 8, the true summit. Similarly low values are found at sites 9, 10 and 13, 14, on the summit dome above 5600 m. Toward the easternmost sites (11, 12, and 15) the concentrations seem to increase slightly again (22,500-24,000).

The charcoal concentrations range from 1,100 to 6,000 particles/l. They tend to follow a similar pattern as the pollen concentrations. The highest values are reached at the western sites, decreasing toward the summit, and increasing again at the easternmost sample locations.

3.4.2 2001 Results

As with the 2000 samples, the results from the 2001 pollen analysis show remarkable uniformity among the 19 ice cap surface samples (Figure 3.4.2.1). Again, no significant variations in pollen percentages occur between any of the surface samples, whether paired or
Figure 3.4.2.1. Pollen percentage diagram showing the results of the 19 surface snow samples taken at Quelccaya in June/July 2001. Sample numbers joined by brackets are paired samples taken at the same location to test for within-site variability.
Grass (Gramineae) pollen was the dominant pollen taxon in these samples, with percentages ranging from 19-40%. Other major taxa include Plantago (6-19%), Alnus (5-19%), Compositae (5-18%), fern spores (4-27%), and Saxifragaceae (1-10%). Minor pollen types (less than 5% in all samples) include Podocarpus, Quercus, Rumex, Cupressus, Polylepis, the Urticaceae/Moraceae families, and an unknown Inaperturate-Scabrate pollen grain. This is the same unknown pollen grain that was also present in the 2000 samples. It is most likely Populus. The miscellaneous pollen group contains grains from 14 other genus/families, however, their abundance never exceeds 1% of the total pollen assemblage. These pollen include Loranthaceae, Carya, Weinmannia, Myrica, the Chenopodiaceae/Amaranthaceae families, Dodonaea, Juglandaceae, Myrtaceae, Melastomataceae, Leguminoseae, Caryophyllaceae, Apocynaceae, Ulmaceae, and Tribulus-type. With the exception of the Populus grains, all pollen types are local and can be commonly found in the eastern Altiplano or the eastern Andean slopes.

Once again, the biggest differences between the samples lies in the pollen concentration values. The samples taken along the edges and slopes 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 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 meters, still 200 meters lower in elevation than the true summit. The three samples (#’s 32, 33, 34) from the south dome 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 as they increase in elevation. The south dome’s charcoal content ranged from 1,200-1,900 particles/l, while the lowest values are again reached at the south dome (700-830 particles/l).

3.5 Discussion and Conclusion

3.5.1 The Intra-Annual Results

The similarities in the pollen percentages within the yearly samples are most likely a result of uniformly mixed air masses above, and advecting into the ice cap. This is not unexpected, as the high Altiplano is an open, wind-swept environment without many effective barriers. Once over the Andean slopes and on the plateau, winds are allowed to mix freely with each other aided by the strong convective forces characteristic of the region (Schwerdtfeger, 1976). However, it is also possible that the homogeneous pollen assemblage is a result of the depth in our sampling. Since our samples were no deeper than 5 cm, it is possible that the entire surface snow layer, and part of its pollen content, was deposited in one or perhaps a few precipitation events.

The most interesting finding thus far concerns the pollen concentrations found among the yearly surface samples. Winds and advecting air masses are the primary vehicle for the dispersal and deposition of pollen on the surface of an ice cap. Thus, the key to understanding this question lies in the general circulation and micro-scale wind patterns around the ice cap itself. These samples were collected during the peak climbing season (austral winter), when the prevailing winds are out of the west. These prevailing westerlies dominate the general circulation and drive the air masses, which are the major source of the pollen brought to the ice
cap. Accordingly, the highest concentrations of pollen were found along the western slopes of Quelccaya. However, the micro-scale, thermally-driven mountain winds, which also influence pollen dispersal, are much more complex than this. Though the prevailing winds may deliver the majority of pollen to the ice cap, it is the interplay between the diurnal and glacial winds that scatter them unevenly across the surface.

The glacial wind, or “snow patch wind” (Ohata, 1989a) is a katabatic wind caused by the contrast in temperature between the air in contact with the ice surface and the ambient air adjacent to it (Strenten and Wendler, 1967; Martin, 1975; Manins and Sawford, 1979; Whiteman, 2000). When the air temperature above the ice surface is higher than 0°C, the air layer at the surface will be cooled, resulting in an inversion that starts the katabatic flow (Geiger, 1965; Ohata, 1989b). This nearly constant downhill flow is stronger on sunny summer days with weak upper-air winds (Obleitner, 1994) and can be as thick as 100 m (Patagonia Ice Field, Ohata, 1989a), with winds that can exceed 22 m/s (50 mph) (Cape Denison, Antarctica, Whiteman, 2000). These should not be confused with the nocturnal katabatic winds, which are a result of a different cooling mechanism. These glacial winds are more prevalent during the summer months, when the temperature inversion is the strongest. However, as long as the air temperature above the ice is greater than 0°C, they can exist 24 hours a day (Geiger, 1965) and year-round. This wind could significantly impede deposition of an airborne pollen grain on the summit or summit dome, as the wind is constantly pushing these airborne particles off the summit and down the slopes. This could explain the low pollen and charcoal concentrations found at the summit of Quelccaya (e.g. samples 7 and 8). This wind quickly diminishes as it moves down slope and nears the ice’s edge, as the heat release from the land surface around the ice cap warms the air and breaks up the inversion (Whiteman, 1990, 2000). This break in the
flow could result in increased deposition of pollen toward the edges of the ice cap on all sides, and help to explain the results we have found in this study.

Another set of thermally-driven winds are the daytime upslope (anabatic) and nighttime downslope (katabatic) winds. These diurnal winds are a product of the temperature differences between the air in contact with the slope and the ambient air over the surrounding valley (Whiteman, 1990, 2000; Clements, 1999). During daytime, the air over the slope is generally hotter than the air at the same elevation over the valley. This causes the column of air over the valley to sink and forces an upslope movement of air. Conversely, during nighttime, the air over the slope loses heat energy more quickly and becomes cooler than the air at the same level over the valley. This in turn causes a shallow downslope current of air. These diurnal slope winds typically range between 1-5 m/s (Whiteman, 2000). Obleitner (1994), in a study of the glacier and valley winds at the Hintereisferner (Otztal Alps, Austria), found that the daytime anabatic winds reach the edge of the glacier, but penetrate no further than the tongue before dissipating. This is due to the inversion layer over the ice surface that will reverse the temperature gradient and weaken the upslope movement. Thus, the pollen-carrying winds would tend to stall over the ice cap’s edge, possibly causing the deposition of the airborne particles that they are carrying. This would further explain the greater concentration of pollen and charcoal toward the edges of the ice cap.

Other factors that could increase pollen deposition, especially on the edges of the lee slopes are horizontal roll vortices and vertical axis eddies. Horizontal roll vortices, or rotors, are products of lee-side mountain waves, which form as an air mass is forced over a mountain. They are characterized by very fast and turbulent winds, which rotate in the direction of the general flow and about an axis parallel to the mountain (Carney et al., 1996; Whiteman, 2000). Their
winds produce an eddy that can force winds to move upslope and back onto the ice cap. Vertical-axis eddies occur when fast-moving, stable air is forced around a barrier rather than over it. As the wind flows around the mountain, the interior (or mountain-side) of the airstream receives more friction as it passes by the barrier (Orgill, 1981). This friction slows down the wind speed and literally turns the airstream back toward the mountain. If the winds are strong and persistent, a continuous spin (eddy) will occur on the backside of the mountain (Forchtgott, 1969), forcing air to return back onto the ice cap, concentrating the pollen toward the edges.

All of these factors, including pollen deposition as a result of precipitation events, work in conjunction with each other to disperse pollen and charcoal in this uneven manner. With all this discussion on wind movements, it is important to note that the pollen being transported to the ice cap is not exclusive to that of wind-pollinated species. Insects and insect parts are a common component of glacial ice, and the surface of the Quelccaya Ice Cap is no exception. Insect remains were present in every sample though no significant amounts of pollen from obligatory insect-pollinated species were found.

3.5.2 The Inter-Annual Results

Results from the pollen analysis revealed that the pollen assemblages differ greatly between the 2000 and 2001 samples. The 2000 samples are dominated by Plantago, Alnus, and Urticaceae/Moraceae pollen, while grass is only a minor taxon. The opposite is the case in 2001 when grass dominates the pollen spectra along with high percentages of fern spores. Though little is know about the exact flowering season in the central Andes, this is the most likely explanation for these results. Monasterio (1986) claims that the height of the flowering season for most Altiplano plants (e.g., Espeletia) 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/early July 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.

Another major difference between the two years is the amount of pollen that was found on the ice cap. The 2000 samples had concentrations ranging between 17,250-55,400 grains per liter of meltwater. The 2001 concentrations were markedly less with values between 3,300-21,000 grains/l. One possible explanation is the influence that the ENSO cycle has on the plants on the Altiplano. During El Nino events, conditions on the Andean Altiplano are generally warmer and much drier than with normal or La Nina conditions (Thompson et al., 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 Nino years. These stresses would have an effect on the amount of pollen that a plant could produce and release during the year. Therefore it is a logical conclusion that the amount of pollen in the environment (available for transport to the ice cap) greatly depends on this cycle.

If this scenario were true, it would explain the differences in pollen concentration for the two years in question. The Southern Oscillation Index (SOI), as computed by the Climatic Research Unit at East Anglia University, 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 Nina conditions existed (annual average of 7.80 on the SOI). La Nina events represent amiable conditions on the Altiplano, and less stressful conditions for plant growth and development. In these years it is believed that more pollen is available in the atmosphere, which translates into higher pollen concentrations on the ice cap. The opposite was 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 Nino conditions. Therefore, in 2001 the Altiplano plants were likely to be more stressed than the previous year, resulting in lower pollen production. This concurs with our findings of low concentration values on the ice cap for 2001.

Another possible explanation for the inter-annual differences in the pollen concentration values could be the timing of the samples, with respect to the flowering season. Since the 2000 samples were collected in August during this transitional period between dry and wet seasons (the primary flowering season on the Altiplano, Monasterio, 1986) and the 2001 samples were collected in June/early July during the height of the winter dry season, large variations in the concentration values would be expected between the two groups. The 2000 samples could simply contain more because there was more pollen available in the atmosphere (due to flowering) at the time of collection. Also, the fact that only the top 5 cm of snow was collected for each sample would allow for the detection of these seasonal differences (literally happening weeks apart). However, more data are needed to fully substantiate this hypothesis.

Finally, the process of sublimation could also have an effect on the pollen concentration values found on the ice cap. It has been known for some time that the surface ice on Quelccaya does not melt, however, it experiences dry season ice loss due to sublimation (L.G. Thompson, personal communication, 2002). The term sublimation refers to the process that occurs when a solid (ice) changes directly into a gas (water vapor), skipping the liquid phase. 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 (L.G. Thompson, personal communication). During years when sublimation rates are higher, more loss of ice will be
experienced, concentrating the pollen even further. Unfortunately, no data from Quelccaya exists that refutes or supports this supposition.

3.5.3 Conclusions

This project has been the first attempt to study the pollen dispersal and depositional processes on tropical ice caps. The results from the paper have answered a few basic questions, but in turn have also raised even more. These processes are an essential piece to the puzzle of ice-core palynology. With additional research, especially multi-seasonal and multi-year studies, the advancement of this science could add another accurate and valuable tool for unlocking the mystery of our paleoenvironments.

3.6 References


CHAPTER 4. POLLEN DISPERSAL AND DEPOSITION ON THE ICE CAP OF VOLČAN PARINACOTA, SOUTHWESTERN BOLIVIA

Note: This chapter is currently in press in Arctic, Antarctic, and Alpine Research. The expected citation is as follows:


4.1 Introduction

Over the past 30 years, 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, has 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 like paleovegetation, has been presumptuous at best. 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). 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 analog.
Reese and Liu (2002) have made the initial strides in understanding this phenomenon. In their paper, they analyzed fifteen 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, however, 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, while Parinacota is located in southwestern Bolivia on the drier, western edge (Garreaud et al., 2003) (Figure 4.1.1). The comparison of these findings will help to further our knowledge on 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.

4.2 Background

Mt. Parinacota (18° 10’ S and 69° 08’ W; at 6,348 m above sea level) is a composite volcano located along the Bolivian/Chilean border on the western side of the Andean Altiplano (refer back to Figure 4.1.1). The approximately 12 km² ice cap sits atop a geologically-young secondary cone, which was formed in the last 13,500 years from primarily andesitic aa lava flows (Wörner et al., 1988) (Figure 4.2.1). The average annual temperature at Parinacota is roughly 1°C (Schwalb et al., 1999). The yearly mean precipitation at the base of Parinacota is
Figure 4.1.1. Map of the central Andes showing the location of Mt. Parinacota and other ice caps mentioned in the text.
Figure 4.2.1. Mt Parinacota from the south/southwest.
around 316 mm per year, 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 (6,542 m above sea level) 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 per year (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 six-month dry season (May-October), however, easterly flow dominates in the wet season (December-March) (D. Hardy, personal communication, 2002). November 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 3000-4500 m, but 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).

4.3 Materials and Methods

In August (dry season) of 2002, 11 surface snow samples (from nine locations) were collected around the caldera rim at the summit of Mt. Parinacota (Figure 4.3.1). 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 leakproof Nalgene sample bottle. These bottles were sealed at the site and remained closed until processing at Louisiana State University. For each sample, the volume of meltwater varied, but all ranged from 200-400 ml. 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, 1972), then evaporating the meltwater on a hot plate until 50 ml remain. The sample is then 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 were counted. 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 TILIA GRAPH.
Figure 4.3.1. Aerial view of Parinacota showing the locations of the 11 surface snow samples. Source: http://volcano.indstate.edu/cvz/pariimg.html.
4.4 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 (Figure 4.4.1). The pollen concentration values for all of the samples in the study ranged from 2,500 to 17,500 grains per liter of meltwater. However, the higher values are located in the northwestern sector of the mountain (samples 1-4) and range from 6,000-17,500 grains/liter. Compositae pollen, consisting of *Artemisia*-type grains (25-41%), long-spine Tubuliflorae (7-12%), and short-spine *Ambrosia*-type (1-3%), are the most abundant pollen group in these 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 55-77%, 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/liter.

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 3,000-4,500 m, but are found in dwarf form as high as 5,100 m. *Alnus* is another genus of trees found in conjunction with or just below *Polylepis* at elevations between 2,500-4,000 m (Cassinelli, 2000). The Urticaceae and Moraceae group comprises two large families of plants common to the lowlands and montane slopes of the Andes, but certain species can also be found in high-
Figure 4.4.1. 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 to test for intra-site variability.
alpine environments. 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 in occurrence (<3 grains in all samples), but are all components of the regional vegetation.

Charcoal ranged between 1,100-3,500 particles per liter 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 intra-site variability.

4.5 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/liter of meltwater (Reese and Liu, 2002). The values at Parinacota (2,500 to 17,500 grains/liter) 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 (i.e. the sub-puna and upper montane forests) zones than Parinacota, and is therefore more 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 flat 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. On the other hand, 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 remains if the majority of pollen being deposited on the ice cap was
mechanically carried to the ice cap by wind, or if the pollen deposition was a result of “washout”
events 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.

4.6 References


CHAPTER 5. A MODERN POLLEN-RAIN STUDY FROM THE CENTRAL ANDES REGION OF SOUTH AMERICA

5.1 Introduction

In order for palynologists to reconstruct past environments accurately with fossil pollen evidence, it is necessary to first understand how the current vegetation is represented in the modern pollen-rain of the study area (Webb et al., 1987, 1993). In the central Andes region of South America, however, no comprehensive study of this nature exists. Of the dozen or so fossil pollen studies that exist from the area (e.g. Graf, 1981; Hansen et al., 1984, 1994; Markgraf, 1985; Baied and Wheeler, 1993; Hansen and Rodbell, 1995; Schwab et al., 1999), only a few have incorporated a modern surface pollen data set into their work (i.e. Graf, 1981; Hansen et al., 1984; Hansen and Rodbell, 1995). However, these three surface studies are neither intensive nor extensive, though they are very representative of the areas immediately surrounding their respective core sites. Comprehensive studies do exist in Colombia (Grandon, 1980) and southern Chile (Markgraf et al., 2002), but they are too far removed from the Andean Altiplano to offer much assistance.

This research is the first systematic and comprehensive analysis of the modern pollen-rain in the central Andes region of South America. The results are derived from 40 surface soil samples collected from the Peru, Bolivia, and Chile in August 2000 and June/July 2001. These data will help address questions of dispersal patterns, pollen provenance, and regional pollen-rain signatures for the central Andes. Statistical comparison to regional ice core and ice cap pollen data will also show the sensitivity of the ice-core pollen records in the region, and how these factors are reflected in the distribution and assemblages of pollen found on nearby Andean ice caps. Not only is this
research fundamental to advancing the rapidly-growing science of ice-core palynology, but it will also serve to further the effectiveness of future fossil pollen studies in the central Andes by broadening our understanding of the modern relationships among pollen, vegetation, and climate in the region, thus laying the groundwork for the derivation of pollen-climate transfer functions and response surfaces.

5.2 Study Area

5.2.1 Physiography

The study area, encompassing the 40 surface soil samples, lies roughly between 13° S and 22° S latitude and between 67° W and 72° W longitude (Figure 5.2.1.1). At the center of the study area is the Andean Altiplano. This highland area is the second-highest plateau in the world and covers an area of some 100,000 km² across Peru, Bolivia, and Chile. It is a dry and windswept environment that straddles the rainshadow of the Andes Mountains, and averages roughly 4,000 m in elevation (Hastenrath, 1985). To either side of the plateau are steep environmental gradients, which become increasingly wetter on the eastern slopes and increasingly drier toward the west. Though the majority of the Altiplano is a relatively flat region, some areas have an extremely complex topography. Numerous mountain ranges litter the landscape, some of which support peaks that reach 6000 m in elevation. Toward the southern extent of the Altiplano is an area that will be referred to as the Southern Bolivian Highlands. This is by far the most remote portion of the Altiplano. The environment is dotted with salt lakes and sedimentary rock formations, some of which date back to the Cretaceous Period.

The 40 surface samples were collected along three different transects (Figure 5.2.1.1). Two of the transects run from the Pacific coasts of Peru and Chile, through the
Figure 5.2.1.1. Map of the central Andes showing the location of the surface samples collected for this study. Ecoregions modified from ESRI ©/ WWF 1999.
Sechura and Atacama Deserts, respectively, and up the western slopes of the Andes. From there they both continue across the Altiplano and descend the eastern slopes of the Andes, finally terminating in the Amazon lowlands. The third transect begins just north of Cusco, Peru and winds southward through the Altiplano, terminating at San Vicente, Bolivia in the heart of the Southern Bolivian Highlands. These transects were chosen because they dissect every major vegetation zone in the central Andes. The surface samples are comprehensive in their range and provide the first modern pollen-rain data for many of these ecological regions.

5.2.2 Climate and Wind Patterns

The Andean Altiplano lies in an area of the world that is greatly influenced by the Hadley cell circulation and the seasonal shift of the Inter-tropical Convergence Zone (ITCZ, hereafter). However, this influence is primarily restricted to the lower-level winds, as the upper-level winds are almost always westerly (Virji, 1981). This upper-level flow is the most important component of the general circulation for the Altiplano simply because of its elevation. At 4,000 m above sea level, the normal atmospheric pressure at the Altiplano’s surface is roughly 500 hPa, well above any low-level circulation. However, the Andean slopes to either side of the Altiplano are greatly affected by the surface flow and therefore a brief discussion of surface winds in the region will be included.

5.2.2.1 Surface Winds

The Andes Mountains are an effective barrier for the primarily zonal circulation in this region and help to create two distinct environments on either side of the mountain chain (Cerveny, 1998). To the west, the Pacific coasts of Peru and Chile are extremely
dry. Arica, Chile holds the record for the world’s lowest average annual precipitation (0.03 inches per year) (Krause and Flood, 1997), though some sections of the Atacama Desert are rumored to have never recorded any precipitation in all of recorded history. Though the precipitation totals are extremely low, this coastal area has an enormous amount of atmospheric moisture coming in from the Pacific Ocean, usually in the form of low stratus clouds and fog (Cerveny, 1998). This atmospheric moisture, as well as the Pacific Ocean, moderates the temperature of this coastal region. Arica, for example, has an average annual temperature of 19° C, with a variance of 3° C (source: International Station Meteorological Climate Summary, Version 4.0).

Due to the break-up of the zonal flow in the region, the circulation feature that dominates the West Coast of South America is the South Pacific High. As a result, the Pacific coast of Peru and Chile are dominated year around by south-southwesterly winds that are pushed around this high-pressure cell (counterclockwise) and then onshore (Zhou and Lau, 1998). Johnson (1976) reported that Lima, Peru experiences a southerly component in wind direction at all times throughout the year. Though this air is moisture-laden, with its source region over the Pacific, the semi-permanent anticyclone in the eastern South Pacific produces strong subsidence and prevents convection and rainfall of any kind.

The eastern slopes of the Andes have a much different story, which is more complex than the drier western slopes. Unlike the western slopes, the Hadley cell circulation dominates the flow in this area. In the austral winter months (approximately May through October), when the Hadley cell is shifted north of the equator, the eastern Andes experience the southeasterly trades, which blow into the ITCZ. Although this is
the established dry season, precipitation is highly variable and unpredictable, as the
advecting air masses (originating over the Atlantic and the Amazon) are moisture laden
(Marengo and Hastenrath, 1993). Local orographic effects are the primary controls for
precipitation on the eastern slopes.

In summer, however (November through April), when the ITCZ is in the southern
hemisphere, the eastern slopes receive northeasterly winds in the form of the
countertrades. The source region for these advecting air masses is again the Atlantic
Ocean and the Amazon, but more precipitation falls because of the intense surface
heating and convection that occurs during this summer season.

5.2.2.2 Upper-Level Winds

The upper level circulation patterns around the Altiplano are one of the most
debated topics in the scientific literature of the region. Due to the altitude of the
Altiplano, the upper-level flow is the most important component of the circulation, and
has a dramatic impact on the weather in the area. Because of the influence of the Hadley
cell circulation, the upper-level winds are westerly nearly all year around. These
westerlies are the result of the upper-level return flow in the Hadley circulation, which is
poleward, away from the ITCZ. As this air flows south, it is deflected to the left by the
Coriolis force, resulting in the westerlies that dominate for roughly nine months (March
through November) of the year (Virji, 1981). However, during the height of the austral
summer (December through February), a reversal occurs in this upper-level flow. This
under-studied, but heavily-debated issue is often referred to as the South American
summer monsoon (SASM, hereafter) (Zhou and Lau, 1998).
The SASM was a term coined by Zhou and Lau (1998) to describe the reversal of the upper-level circulation over the Altiplano, from westerly to easterly flow during the summer months. This reversal is caused by a zone of upper-level high pressure that forms over the Altiplano, which is often referred to as the Bolivian High (Schwerdtfeger, 1961). The counterclockwise flow of air off this seasonal anticyclone pulls in moisture-laden easterly winds from the Amazon, and ultimately from the South Atlantic Ocean.

Considerable debate exists over the cause of the phenomenon, however. The question about the origin of the Bolivian High was first raised by Schwerdtfeger (1961). He claimed that the high was thermally-induced and ultimately spawned from the intense sensible heating of the Altiplano during the austral summer. Once formed, this upper-level high pressure cell is supported by the latent heat release from the frequent severe thunderstorms which are common in the area in summertime (Schwerdtfeger, 1961; Gutman and Schwerdtfeger, 1965; Ramage, 1968). Subsequent studies that confirm these findings can be found in Dean (1971), Kreuels et al. (1975), Rao and Erdogan (1989), and Lenters and Cook (1995).

This theory about the formation of the Bolivian High was first challenged by Silva Dias et al. (1983) who claimed that the semi-permanent upper-level high pressure cell over the northeastern Amazon (Kiladis and Wheeler, 1995; Kalnay et al., 1986) simply shifted farther south during the summer months and relocated over the Altiplano. Therefore, the Bolivian High was no longer its own separate entity, but simply was the summer position of a transient upper-level Amazon High. A wealth of literature was to follow, also confirming and expanding this hypothesis (De Maria, 1985; Buchmann et al.,
Regardless of its formation, the Bolivian High and the resultant easterly reversal of winds is undisputed. The result of this circulation is the moisture-enriched easterlies, which provide more available moisture for precipitation on the Altiplano during the hot, highly convective summer months. In fact, over 80% of the total annual precipitation for the Altiplano falls in the three months between December and March (Vuille et al., 1998). It is important to note that although there is available moisture over this region in summer, this in no way produces a wet surface climate. Figure 5.2.2.2.1 shows the mean monthly precipitation at four weather stations across the central Andes.

5.2.3 Vegetation

The vegetation of the Altiplano is most often categorized as puna, or dominated by the “puna-brava” vegetation assemblage (Tosi, 1960). Puna, and its variants, commonly occur between 5,000 and 3,300 m, and are characterized as dry grasslands dominated by bunch grasses like Festuca and Stipa (Gramineae) (Hansen et al., 1984). In depressions or low-lying areas near sources of water, the marsh-like “bofedales” community can occur (Baied and Wheeler, 1993). Bofedales is a cushion-peat bog habitat that supports a wide range of hydrophilous plants, including the tussock grasses (Gramineae), cushion plants (Azorella, Umbelliferae), Cyperaceae, Juncaceae, and water plants like Isoetes and Myriophyllum (Haloragidaceae).

Although the puna ecosystem is relatively homogeneous throughout its extent, it is commonly divided into three subregions. The upper reaches of the puna, known as
Figure 5.2.2.2.1. Mean monthly precipitation (in mm) at four stations across the Altiplano. Taken from Vuille et al., 1998.
superpuna, occur between roughly 5,000 (~snowline) and 4,300 m (Hansen et al., 1984). Superpuna as a region averages approximately 4° C annually with freezing temperatures occurring almost daily (Tosi, 1960). Annual precipitation averages close to 750 mm, but 50-85% of this is lost to runoff (Hansen et al., 1984). The plants that dominate the superpuna are very adapted to this harsh environment and include Plantago, Ephedra, Caryophyllaceae, Composites such as Gynoxys and Baccharis, Azorella, and as always a wide host of bunch grasses. Polylepis, the small Rosaceae tree, can also occur up to 5,100 m (Kessler, 1995; Braun, 1997), though this elevation is obviously out of its optimal range.

Standard puna commonly occurs between 4,300 and 3,900 m (Tosi, 1960; Cuatrecasas, 1968). This subregion is similar to the superpuna, however, trees and shrubs like Polylepis, Ericaceae, and Cupressus are much more common. Its mean annual temperature is slightly warmer at 7° C, while precipitation totals remain about the same at 800 mm per year (Hansen et al., 1984). Below the puna proper lies the subpuna (roughly 3,900 to 3,300 m). Subpuna is primarily limited to the eastern, or wetter side of the Andean Altiplano, where Dodonaea, Rapanea, and Alnus become common elements of the ecosystem.

To the east of the Altiplano, below the subpuna, lies a steep environmental gradient that can often range from puna to tropical wet forest (AF in the Köppen classification system) in a horizontal distance of 200 km in some areas (Reese and Liu, 2002). Below 3,000 meters in the cloud forests (Weberbauer, 1936), nearly all puna species are absent and the vegetation is dense with ferns, lianas, and trees. Typical tree species include Alnus, Myrica, Podocarpus, Juglans, and members of the Apocynaceae,
Ericaceae, Myrtaceae, and Melastomataceae families. Though no one genus or family dominates this environment, the Urticaceae and Moraceae families come close, especially the tropical tree *Cecropia*. Below this vegetation zone, where human disturbance has not encroached, tropical wet forest occurs. Extensive research has been done on the amazing biodiversity of this ecosystem (e.g. Gentry, 1993), however, plant families such as Bignoniaceae, Melastomataceae, Piperaceae, Malpighiaceae, and Palmae are common.

On the western slopes of the Andean Altiplano, the vegetation is quite different and much less complex than on the eastern slopes. There, elements of the puna ecosystems extend to the Pacific Ocean in some areas. Desert taxa, such as Chenopodiaceae (Goosefoot family), Amaranthaceae (Amaranth family), Compositae, Cactaceae, Euphorbiaceae, *Plantago*, and *Ephedra* are also common. Although trees such as *Prosopis* are abundant in the wetter sections of the western coast below 1500 m, they rarely form dense stands (Reese and Liu, 2002). The western Andean slopes and the deserts share a common vegetation assemblage with the southern Bolivian Highlands, which comprise the southernmost tip of the Andean Altiplano. This shrub desert also has an abundance of Chenopodiaceae, Amaranthaceae, Compositae, and Euphorbiaceae, however, the Solanaceae family is quite dominant.

### 5.3 Methods and Materials

In August 2000 and June/July 2001, 135 surface soil samples were collected along three transects running through the central Andes region of Peru, Bolivia, and Chile. In all cases, surface soil and/or mosses were collected and sealed into Whirlpack plastic bags. Of the 135 samples taken, roughly 80 were samples of *Azorella*, known locally as yareta (a species of Umbelliferae). This plant is a cushion plant that is
common to the area, and was mistaken by the author as a species of moss (moss is an ideal pollen collector). Therefore, these samples were discarded and not used in this study. Of the 55 remaining samples (some of which were taken from less than desirable locations), the 40 best samples were chosen that guaranteed complete spatial coverage of the area (refer back to Figure 5.2.1.1).

All samples were processed for pollen following the standard procedures (Faegri and Iversen, 1975). Approximately 0.9 cc of sediment was used for the majority of the surface samples, however for extremely sandy samples, 10 cc of material was selected and put through a pollen separation technique using sodium pyrophosphate (Cwynar et al., 1979). Regardless, two *Lycopodium* marker spores were added to every sample before the start of processing to obtain pollen concentration values (Stockmarr, 1972). After these initial steps, the samples were treated with a series of acids and strong bases, namely hydrochloric acid (to remove carbonates), potassium hydroxide (to remove organics), hydrofluoric acid (to remove silicates), and acetolysis solution (nine parts acetic anhydride to one part concentrated sulfuric acid) to remove cellulose. After these treatments, the residue was stained with safranin and mounted onto microscope slides with silicone oil. Pollen grains and fern spores were counted until a minimum of 200 were identified, or until a minimum of 1000 marker spores was reached. The pollen results were reported using the Hutchinson taxonomic classification system (Hutchinson, 1959; Fernald, 1987). Pollen percentages were calculated using TILIA computer software, and were based on a sum of all pollen and spores. TILIA GRAPH for Windows was used to generate all pollen diagrams. Statistical analysis was performed on the pollen percentage data using SPSS version 8.0.
5.4 Results

Using field data, the 40 surface soil samples (Figure 5.4.1) were divided into four basic groups based on location (Figure 5.4.2). Group 1 (Samples 1-11) corresponds to the soil samples taken from the eastern Andean slopes (cloud forests and Yungus) and the Amazonian lowlands. Group 2 (Samples 12-23) included the samples taken from the eastern, wetter portion of the Andean Altiplano. Group 3 (Samples 24-36) was a large group that consisted of western Altiplano sites and true desert samples from the Atacama and Sechura Deserts. Group 4 (Samples 37-40) consisted of the four samples located in the shrub deserts of the southern Bolivian Highlands, where the Solanaceae plant family is dominant.

After these four groups were created, discriminant analysis (SPSS) was used to validate the data. Discriminant analysis is a very effective tool when used to objectively evaluate the prior classification of surface samples into groups (Liu and Lam, 1985). Figure 5.4.3 shows the groups of samples plotted in statistical space (plotted against Discriminant Functions 1 and 2). A total of 36 out of 40, or 90% of the samples were correctly classified into their respective groups. However, discriminant analysis can go one step further and statistically test the strength of each of the groups. Using a self-validation technique, discriminant analysis removes each sample individually and tests the likelihood that it will fall back into its original group. The program then uses the discriminant functions to predict the likelihood (probability of group membership) that each sample will fall into its original group. When this self-validation was run, 90% of the samples were still correctly classified into their groups, with high probabilities of modern analog (an average of 0.614). These high values suggest that each of the
Figure 5.4.1. Location data for the 40 Andean surface samples.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Latitude (°S)</th>
<th>Longitude (°W)</th>
<th>Altitude (ft.)</th>
<th>Material</th>
<th>Vegetation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.449</td>
<td>71.654</td>
<td>12,820</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>2</td>
<td>13.369</td>
<td>71.604</td>
<td>11,320</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>3</td>
<td>13.275</td>
<td>71.596</td>
<td>9,763</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>4</td>
<td>13.205</td>
<td>71.617</td>
<td>10,921</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>5</td>
<td>13.156</td>
<td>71.588</td>
<td>7,640</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>6</td>
<td>13.036</td>
<td>71.524</td>
<td>4,169</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>7</td>
<td>12.889</td>
<td>71.361</td>
<td>1,518</td>
<td>Topsoil</td>
<td>Lowland forest</td>
</tr>
<tr>
<td>8</td>
<td>16.088</td>
<td>67.697</td>
<td>11,491</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>9</td>
<td>15.983</td>
<td>67.517</td>
<td>13,480</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>10</td>
<td>15.517</td>
<td>67.245</td>
<td>2,006</td>
<td>Topsoil</td>
<td>Lowland forest</td>
</tr>
<tr>
<td>11</td>
<td>15.128</td>
<td>67.042</td>
<td>753</td>
<td>Topsoil</td>
<td>Lowland forest</td>
</tr>
<tr>
<td>12</td>
<td>13.841</td>
<td>71.541</td>
<td>13,330</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>13</td>
<td>14.486</td>
<td>71.297</td>
<td>13,683</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>14</td>
<td>14.737</td>
<td>71.351</td>
<td>13,159</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>15</td>
<td>15.382</td>
<td>71.271</td>
<td>14,114</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>16</td>
<td>14.601</td>
<td>70.832</td>
<td>13,130</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>17</td>
<td>15.171</td>
<td>70.358</td>
<td>12,763</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>18</td>
<td>15.777</td>
<td>70.035</td>
<td>12,747</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>19</td>
<td>13.930</td>
<td>70.857</td>
<td>16,760</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>20</td>
<td>13.907</td>
<td>70.940</td>
<td>15,353</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>21</td>
<td>14.225</td>
<td>71.217</td>
<td>12,413</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>22</td>
<td>16.414</td>
<td>68.053</td>
<td>14,228</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>23</td>
<td>16.299</td>
<td>67.819</td>
<td>9,800</td>
<td>Topsoil</td>
<td>Yungus</td>
</tr>
<tr>
<td>24</td>
<td>16.070</td>
<td>71.557</td>
<td>12,775</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>25</td>
<td>16.425</td>
<td>71.677</td>
<td>6,420</td>
<td>Sand</td>
<td>Desert</td>
</tr>
<tr>
<td>26</td>
<td>16.613</td>
<td>71.864</td>
<td>4,570</td>
<td>Sand</td>
<td>Desert</td>
</tr>
<tr>
<td>27</td>
<td>16.935</td>
<td>72.060</td>
<td>2,289</td>
<td>Sand</td>
<td>Desert</td>
</tr>
<tr>
<td>28</td>
<td>18.425</td>
<td>70.042</td>
<td>2,407</td>
<td>Sand</td>
<td>Desert</td>
</tr>
<tr>
<td>29</td>
<td>18.464</td>
<td>69.804</td>
<td>7,186</td>
<td>Sand</td>
<td>Desert</td>
</tr>
<tr>
<td>30</td>
<td>18.196</td>
<td>69.529</td>
<td>13,087</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>31</td>
<td>18.107</td>
<td>68.934</td>
<td>15,026</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>32</td>
<td>17.750</td>
<td>68.430</td>
<td>13,066</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>33</td>
<td>17.282</td>
<td>67.991</td>
<td>12,462</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>34</td>
<td>17.460</td>
<td>67.488</td>
<td>12,528</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>35</td>
<td>18.560</td>
<td>66.946</td>
<td>12,244</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>36</td>
<td>16.273</td>
<td>69.209</td>
<td>12,649</td>
<td>Topsoil</td>
<td>Altiplano</td>
</tr>
<tr>
<td>37</td>
<td>19.557</td>
<td>66.866</td>
<td>12,533</td>
<td>Topsoil</td>
<td>Shrub Desert</td>
</tr>
<tr>
<td>38</td>
<td>20.316</td>
<td>66.981</td>
<td>12,026</td>
<td>Topsoil</td>
<td>Shrub Desert</td>
</tr>
<tr>
<td>39</td>
<td>20.840</td>
<td>66.357</td>
<td>12,902</td>
<td>Topsoil</td>
<td>Shrub Desert</td>
</tr>
<tr>
<td>40</td>
<td>21.503</td>
<td>66.131</td>
<td>13,215</td>
<td>Topsoil</td>
<td>Shrub Desert</td>
</tr>
</tbody>
</table>
Figure 5.4.2. Locations of the four, statistically-derived pollen regions. Ecoregions modified from ESRI ©/WWF 1999.
Figure 5.4.3. Surface sample groups plotted against canonical Discriminant Functions 1 and 2. Discriminant Functions 1 and 2 account for 96.7% of the total variance in the data set.
groups are statistically strong, and do a good job in accurately representing these pollen data.

### 5.4.1 Pollen Results

The results of the pollen data are shown in Figure 5.4.1.1. Overall, the pollen found in each of the four groups was indicative of the vegetation that is found locally in each of the regions. The Andean Forest group (Group 1) was dominated by fern spores (5-67%) primarily of the Polypodiaceae type. Polypodiaceae is a very common family in the tropical lowlands, usually found in the form of epiphytes (Mabberley, 1987). Although grass (Gramineae) was the taxon with the next highest percentages (5-57%) in the group, it is not a regular component of the region. The occurrence of grass can be explained by our sampling locations, which often times were near roads or other areas of human disturbance. Where natural or human-induced gaps occur in the tropical vegetation, grass is usually one of the first colonizers and proliferates in just a short time. Grass is also a prolific pollen-producer and is known to be over-represented in pollen assemblages, especially in tropical areas where most of the plant species are not wind-pollinated (Colinvaux et al., 1988). Other major taxa include the Urticaceae/Moraceae families and the Andean slope taxon *Alnus* (0-13%). Other disturbance indicators can be seen in the small amounts of Compositae (1-20%), the Chenopodiaceae/Amaranthaceae families (0-11%), and *Plantago* (0-5%). The minor taxa found in this group include trace amounts of pollen from a host of typical lowland families such as Melastomataceae, Apocynaceae, Piperaceae, Bignoniaceae, Malpighiaceae, Palmae, Myrtaceae, and *Begonia*. Most, if not all, of the plants in these families are animal-pollinated and
Figure 5.4.1.1. Pollen percentage diagram of the 40 surface soil sample.
therefore produce much less pollen than other wind-pollinated species. Thus, they are under-represented in the pollen assemblages.

The Eastern Altiplano group (Group 2), not surprisingly, is dominated by the grasses, which make up 39-80% of the pollen assemblage. The other major taxa found in this group are all typical components of the region and can be found in abundance. They are Compositae (2-40%), Plantago (1-13%), Cupressus (0-7%), fern spores (1-15%), Urticaceae/Moraceae (1-18%), and Caryophyllaceae (0-8%). The minor pollen taxa include trace amounts of Alnus, Myrica, Umbelliferae, Myrtaceae, Saxifragaceae, Polylepis, Cyperaceae, and Leguminoseae.

Group 3, the Western Altiplano and Deserts, has a pollen assemblage that is similar to Group 2. However, the increasing dominance of the xerophytic shrubs and herbs is very apparent. For example, percentages of Compositae (8-80%), and Chenopodiaceae/Amaranthaceae (1-30%) increase significantly. In this group we also see the first signs of desert plant families like Solanaceae (0-13%), Cactaceae (0-5%), Euphorbiaceae (0-4%), and Ephedra (0-2%). However, the grasses still dominate the pollen assemblage with percentages between 15-64%.

The shrub desert of the southern Bolivian Highlands (Group 4) is a very distinctive group. Percentages of grass (10-33%) and Compositae (9-29%) are diminished, while the Solanaceae family (30-56%) begins to dominate. Minor taxa include Chenopodiaceae/Amaranthaceae (2-30%), and Cactaceae, Euphorbiaceae, and Plantago all under 5% of the total pollen sum. The plant families and genera typical of the puna ecosystems (e.g. Cupressus, Polylepis, and Umbelliferae) are all but absent in this group.
5.4.2 Discriminant Analysis of Ice Cap Pollen Data

Over the past three years, the author has completed a series of pollen studies in the central Andes with both fossil and modern data sets. The fossil pollen study (Chapter 2 in this dissertation) was a 25,000-year ice-core record of vegetation change from Mt. Sajama in western Bolivia. The two modern studies focus on the dispersal and depositional patterns and processes of pollen on tropical Andean ice caps; the Quelccaya Ice Cap in southern Peru, and Mt. Parinacota in western Bolivia (Chapters 3 and 4 in this dissertation, respectively). To date, these data remain unpublished except for a small portion of the Quelccaya ice cap data (Reese and Liu, 2002). However, one lingering question remains to be answered regarding these pollen studies. Where is the pollen coming from that is found on each of these ice caps? In other words, what vegetation region/zone do these ice cap pollen assemblages accurately represent? Using the four vegetation groups derived from the surface pollen data, discriminant analysis was used to statistically predict which group (vegetation zone) the ice cap samples would fall into, or best represent. The results are as follows.

5.4.2.1 The Sajama Ice Core

Figures 5.4.2.1.1 and 5.4.2.1.2 show the results of the discriminant analysis on the 218 ice-core samples taken from the Sajama ice cap in western Bolivia (refer to Figure 5.4.2 for a location map). Of these 218 samples, 193 or 88.5% were statistically similar to Group 3, the western Altiplano. The average probability of modern analog, P(DG), for these samples is 0.365. Of the 25 remaining samples, 24 samples (11%) were classified as Group 2, and 1 sample (0.5%) was classified as Group 1. There is no clear
Figure 5.4.2.1.1. The 218 Sajama ice-core samples plotted against Discriminant Functions 1 and 2, along with the Andean surface sample groups.
**Classification Results**

<table>
<thead>
<tr>
<th>GROUP</th>
<th>Predicted Group Membership</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Original Count</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ungrouped cases</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>%</td>
<td>90.9</td>
<td>9.1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>91.7</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>15.4</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ungrouped cases</td>
<td>5</td>
<td>11.0</td>
</tr>
</tbody>
</table>

**Cross-validated Count**

<table>
<thead>
<tr>
<th>GROUP</th>
<th>Predicted Group Membership</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>1.00</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>%</td>
<td>90.9</td>
<td>9.1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>91.7</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>15.4</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ungrouped cases</td>
<td>5</td>
<td>11.0</td>
</tr>
</tbody>
</table>

b. 90.0% of original grouped cases correctly classified.
c. 90.0% of cross-validated grouped cases correctly classified.

Figure 5.4.2.1.2. Classification results of the discriminant analysis performed on the 218 ice-core samples from Mt. Sajama.
pattern among the 24 samples classified as Group 2, as they are scattered throughout the record and range in age from AD 1996 to 24,500 B.P.

The results of this analysis suggest that throughout the 25,000-year ice-core record, Mt. Sajama has received the majority of its pollen from the local, western Altiplano vegetation zone. This is to be expected as Sajama is located in the middle of this vegetation zone and is influenced by prevailing westerlies for the majority of the year (Hardy et al., 1998). So from these statistical results, it appears that the fossil ice-core pollen data from Mt. Sajama accurately represents the vegetation in the western Altiplano and around the ice cap. Therefore, any reference to vegetation change, or vegetation response to climate change, made from these data (Chapter 2 in this dissertation) will reflect the environmental changes in the western Altiplano.

5.4.2.2 The Quelccaya Ice Cap

Figure 5.4.2.2.1 shows the results of the discriminant analysis on the 34 Quelccaya surface ice samples taken over a two-year period in August 2000 and June/July 2001 (see Figure 5.4.2 for a location map). Of the 34 ungrouped (Quelccaya) samples, 16 (47.1%) were statistically similar to Group 1, the Andean Forest samples. Eighteen (52.9%) of the Quelccaya data fell into Group 2, the Eastern Altiplano samples. Among these samples there was a distinct division between the 15 samples collected in 2000 and the 19 samples collected in 2001. Fourteen of the 15 samples from 2000 were classified as Group 2 (eastern Altiplano), while 15 of the 19 samples from 2001 classified as Group 1 (Andean Forest). Regardless, 100% of the Quelccaya ice samples are statistically similar to Groups 1 and 2. This is to be expected as Quelccaya lies in the
Figure 5.4.2.2.1. Classification results from the discriminant analysis performed on the 34 surface snow samples from the Quelccaya Ice Cap.
heart of the Eastern Altiplano (Group 2), and within 50 km of the Andean Forest pollen zone (Group 1) to the east. However, this data set also gives a better indication how the majority of the pollen is being transported onto the ice cap itself. The wind direction during the four-month wet season comes from the Amazon to the east of Quelccaya (Group 1). From this it can be inferred that most of the pollen found on the Quelccaya ice cap is a result of “rainout” events during the wet season. If pollen were being mechanically blown onto the ice cap the pollen assemblage should be representative of Groups 3 and 4. This is due to the fact that the region is dominated by prevailing westerly flow for 8 to 9 months out of the year (D. Hardy, personal communication, 2002). If this were the case, pollen would be blown in from the west (Groups 3 and 4) and be mechanically deposited onto the ice. This is seemingly not the case.

We can take this analysis one step further, and see how each of the samples is plotted in statistical space. Figure 5.4.2.2.2 shows this plot, using Discriminant Function 1 and 2 as the axes. The vast majority of the 2001 samples are statistically similar to Group 1 than any other group. This means that in 2001, the majority of the pollen found on the ice cap originated from the Andean Forest. On the other hand, we see that the majority of the 2000 samples were statistically similar to Group 2, the Eastern Altiplano.

One possible explanation for this could be the effect of ENSO on the region. During the warm-phase (El Nino), conditions on the Altiplano are generally warmer and drier than with normal or La Nina conditions (Thompson et al., 1984; Hardy et al., 1998). In 2000, the Southern Oscillation Index (SOI) had an annual mean of 7.8, indicating strong La Nina conditions. In 2001, the opposite was true as the annual mean was –2.3,
Figure 5.4.2.2.2. Plot of the Quelccaya surface samples in relation to the four pollen zones. This data is plotted in statistical space against Discriminant Functions 1 and 2.
or El Nino conditions. During El Nino, the Bolivian High that usually brings winds (wet season) from the east to Quelccaya should be strengthened as a result of increased surface convection in the warmer and drier El Nino conditions. Though no study has yet to confirm this claim, it is consistent with the properties of a typical warm-cored low that is associated with relatively high pressure (for its elevation) aloft (Robert Rohli, personal communication, 2003), like the Bolivian High (Schwerdtfeger, 1961). If this is true, then in 2001 during El Nino conditions the increased strength of the Bolivian High (easterly wind flow) could have facilitated the import of pollen from greater distances, such as the Andean Forest (Group 1) farther to the east. However, during 2000 (La Nina conditions) when the Bolivian High is relatively weaker, this ability to transport pollen from long distances would be hampered. This would explain why the 2000 samples reflect the local (Group 2) eastern Altiplano vegetation rather than the vegetation of the Andean Forest.

5.4.2.3 Mt. Parinacota

In August 2002, 11 surface samples were collected from around the summit crater of Mt. Parinacota (refer back to Figure 5.4.2 for geographic location, and Figure 4.3.1 for sample locations). Results from the discriminant analysis (Figure 5.4.2.3.1) showed that 7, or 63.6% of the ungrouped (ice cap) samples were classified into Group 2, the Eastern Altiplano. The remaining 4 samples, or 36.4% were classified into Group 3, the Western Altiplano and Deserts. All of the samples had good P(DG) values (average of 0.623). Though Parinacota lies in the heart of Group 3, the vegetation to the eastern side of the mountain is primarily a “bofedales” peat bog community. Many grasses and hydrophilous plants are common in this area, which is very similar palynologically to Group 2, the Eastern Altiplano.
### Classification Results\(^b,c\)

<table>
<thead>
<tr>
<th>GROUP</th>
<th>Predicted Group Membership</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Original</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count 1.00</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ungrouped cases</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>%</td>
<td>90.9</td>
<td>9.1</td>
</tr>
<tr>
<td>Cross-validated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count 1.00</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2.00</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>3.00</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ungrouped cases</td>
<td>0</td>
<td>63.6</td>
</tr>
<tr>
<td>%</td>
<td>90.9</td>
<td>9.1</td>
</tr>
</tbody>
</table>

\(^b\) 90.0% of original grouped cases correctly classified.

\(^c\) 90.0% of cross-validated grouped cases correctly classified.

Figure 5.4.2.3.1. Classification results from the discriminant analysis of the 11 surface snow samples from Mt. Parinacota.
Again, when the samples are plotted in statistical space using Discriminant Functions 1 and 2 as axes, more detailed information can be gleaned. Figure 5.4.2.3.2 shows this plot. Ice samples 1-4 (on the northwestern edge of the mountain) are the samples that were categorized into Group 3. The rest of the samples from the mountain were all categorized as Group 2. Since Parinacota is bombarded by northwesterly winds for most of the year, it is not surprising that the majority of the pollen originating in this section of the mountain is from Group 3 (Western Altiplano and Deserts). However, it appears as if this influence from the prevailing winds stops there. The rest of the mountain most likely receives the majority of its pollen from the local vegetation to the southeast and east (the peat bog communities). In this case the mountain acts as its own wind barrier, which impedes the northwesterly (prevailing) winds from depositing its pollen on the other slopes of the mountain. Without this influence, the local thermally-driven, and mechanical mountain winds are able to bring local pollen up to the summit from the south and east.

It is important to note here that Parinacota appears to differ greatly from the Quelccaya Ice Cap in the manner that it receives its pollen. Quelccaya has uniform pollen assemblages (intra-annual) across the ice cap, which appear to originate from the east. “Rainout” events are the most likely method of pollen dispersal that would result in this type of assemblage. However, Parinacota has very different pollen assemblages around its ice cap, which also appear to also have very different origins. If “rainout” events were an important factor, then the pollen assemblages would be uniform, as all of the ice cap would receive pollen from the same source (thunderstorms). Nevertheless, additional data are needed to confirm or deny any of these statements.
Figure 5.4.2.3.2. Plot of the Parinacota ice cap samples in relation to the four pollen zones. These data are plotted in statistical space against the canonical discriminant functions 1 and 2.
5.5 Discussion and Conclusion

It can be concluded from this surface sample study that distinct palynological signatures characterize the major vegetation zones of the central Andes region of South America. Statistically, the surface samples can be divided into four discrete regions. The results from this study imply that the modern pollen-rain in each region is representative of the local vegetation. These results also provide the first modern pollen-rain data for this region. This information will serve to further the effectiveness of future fossil pollen studies in the central Andes by broadening our understanding of the modern relationships among pollen, vegetation, and climate in the region, thus laying the groundwork for the derivation of pollen-climate transfer functions and response surfaces. To date, nearly all of the fossil pollen studies from this area have been conducted without the benefit of this information.

These data have also helped to answer many lingering questions about the dispersal and depositional processes of pollen on Andean ice caps. Over the past 30 years, non-polar ice cores from around the world have yielded some of the best paleoenvironmental records to date. The ice cores taken from the central Andes are no exception. However, in order to accurately reconstruct past environments from fossil pollen records, it is important to have a good understanding of the modern relationship between the pollen on the ice cap and the vegetation in the surrounding environments.

Using discriminant analysis, results from this study show that the prevailing winds play a major role in the transport of pollen to the ice caps. In addition, the ice cap pollen from Quelccaya seems to be deposited on the ice caps through “rainout” events, rather than being mechanically blown onto the ice surface. Airborne pollen is likely
collected in cloud formations due to the intense convection that occurs during the summer months throughout the region. As these clouds advect over the ice cap, they cool and precipitate the pollen in suspension. Also, airborne pollen grains make effective condensation nuclei, and are no doubt key elements in the condensation of water vapor in the clouds.

From the pollen evidence, the Quelccaya Ice Cap likely receives its pollen from the east. This is in accordance to the circulation patterns over the Andes during the wet season (when 80% of the annual precipitation occurs). However, the range and extent of this influence is controlled by the climate fluctuations brought on by the ENSO. During El Nino years, the easterly winds are stronger, and allow pollen from the Andean Forest to be transported up slope to the ice cap. During La Nina 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. So the answer to the questions about pollen provenance on the Quelccaya Ice Cap seems to have been answered with yet more questions. The pollen on the ice cap can represent either the Eastern Altiplano zone or the Andean Forest zone depending on the strength of the Bolivian High and the El Nino/La Nina cycle.

The pollen evidence from Mt. Parinacota also suggests that the prevailing winds (here from the northwest) are a major factor in pollen transport to the ice cap. But unlike Quelccaya, which is a flat ice cap, the prevailing northwesterlies are not allowed to distribute pollen over the entire mountain. Parinacota is a mountain ice cap, not flat like Quelccaya. Therefore, the mountain acts as its own barrier and shelters the rest of the mountain from the prevailing winds. This allows the local, mechanical mountain winds,
and the thermally-driven mountain winds to influence the rest of the mountain. In these cases, local pollen seems to dominate the ice cap pollen assemblages.

The results of this chapter have helped to answer some long-awaited questions in the palynological community of the central Andes. And though they have furthered the science of both palynology and ice-core palynology in region, more questions have arisen from these data. More data, especially multi-year data, are needed to understand the full effect of local climatological phenomena (e.g., ENSO) and the impacts that they have on the modern pollen-rain of the high-central Andes.

5.6 References


Dean, G.A.  1971.  The three-dimensional wind structure over South America and associated rainfall over Brazil.  Report LAFE-164, Department of Meteorology, Florida State University.


International Station Meteorological Climate Summary, Version 4.0. 1996. National Climate Data Center, Naval Oceanography Command Detachment, Asheville, NC.


112


CHAPTER 6. SUMMARIES AND CONCLUSIONS

The aim of this dissertation has been to enhance our understanding of paleoenvironments in the central Andes region of South America using palynology. The individual papers in this dissertation have focused on the paleoenvironmental reconstructions derived from fossil pollen found in ice cores, the dispersal and depositional processes of pollen on high-alpine ice caps, and the modern pollen-rain of the central Andes. Lingering questions about this basic palynological information have hampered the development of this science in the region. Therefore, pollen analysis has remained an extremely underutilized paleoenvironmental research tool. The results from these studies have established pollen as a powerful, versatile, and sensitive paleoenvironmental proxy. The ice cap pollen studies are the first of their kind and have shown their merit by providing an independent and reliable record of paleoenvironmental change, but have also served to validate the more traditional chemical/physical proxy records. These findings will advance this new and exciting science of ice-core palynology. The modern pollen data, on the other hand, have helped to determine the large-scale patterns and gradients of modern pollen deposition in the region, and also helped answer questions concerning pollen provenance on the ice caps. These studies will also further the effectiveness of other South American palynological studies (i.e. lake cores) by providing a more complete and systematic network of pollen surface samples for Peru and Bolivia. Our knowledge of the modern analog and modern pollen-rain is vital to the accurate interpretation of all fossil pollen records. These findings should provide the groundwork that has been missing for the region. Perhaps these studies will act as the cornerstone for the future research that needs to be conducted on the Altiplano.
6.1 Summary of the Main Research Findings

6.1.1. The 25,000-year Sajama Record

The 25,000-year pollen record from the Sajama Ice Cap (Chapter 2) provides an indication of the vegetational responses to climatic change over a variety of temporal scales. The results from the 39-year record show a highly negative correlation between the pollen concentration values and the El Nino/Southern Oscillation (ENSO) cycle. Though the most likely explanation is the differing rates of sublimation on the ice cap, the pollen provides the lens through which we view this phenomenon. El Nino years were typically marked by relatively high concentration values, while the opposite was true for La Nina conditions. Sublimation is thought to increase during warm and dry conditions (characteristic of El Nino years), thereby decreasing the total annual accumulation and concentrating the pollen in suspension.

The pollen results from the 400-year Little Ice Age (LIA) study revealed the two-phased LIA that had been detected in the accumulation records from the Quelccaya Ice Cap in southern Peru. The pollen has not only validated this finding, but has established the vegetation response that has resulted from this event. Grass and the sedge family dominated the wet period of the LIA from roughly A.D. 1600-1700. Once the climate shifted to drier conditions after A.D. 1700, the Compositae plants began to dominate the pollen spectra. These distinct wet/dry stages are probably the result of the failure of the South American summer monsoon (SASM) in the region. This circulation phenomenon feeds off the high temperatures and high insolation that are characteristic of the Andean Altiplano during the summer months. The cooler temperatures that resulted from the LIA
probably hampered the development of the SASM and cold and dry conditions persisted in the later half of the LIA (A.D. 1700-1880).

The pollen data from the 25,000-year record again show striking similarities with the chemical/physical proxy record. Pollen is absent during the bulk of the Late Glacial Stage (LGS) from 25,000 to 15,000 B.P. when full glacial conditions existed. Once pollen emerged in the record it documented a short interstadial (15,000-14,000 B.P.) event, the Deglacial Climatic Reversal stadial (14,000-12,000 B.P.), and the transition into the warm and dry Holocene conditions. Throughout the record, the pollen serve best as a wetness or moisture indicator as climatic conditions changed. Wet periods are typically dominated by the grasses, while drier events are marked by the Compositae plants and other minor xerophytic taxa (e.g. the Chenopodiaceae/Amaranthaceae families). Once again the pollen proves itself as a viable independent proxy, as well as a reliable means of validating the chemical/physical proxy record.

6.1.2 Pollen Dispersal on High-Alpine Ice Caps

Chapters 3 and 4 of this dissertation examined the dispersal and depositional patterns and processes on high-alpine Andean ice caps. Chapter 3 was a palynological study of ice cap surface samples collected from the Quelccaya Ice Cap in southern Peru. In this study, 34 surface snow samples were collected over a two-year period from the ice cap. Results show that intra-annual pollen assemblages remain fairly uniform across the ice surface, suggesting a uniform mixing of the air masses and their pollen contents over the ice cap. These findings also suggest “rainout” events as the primary method of pollen deposition on the ice cap. Intra-annual pollen concentrations are highest towards the western edge of the ice cap,
suggesting that the prevailing winds may have a greater influence on pollen dispersal than other diurnal winds.

Inter-annual pollen assemblages and concentrations, on the other hand, are statistically very different. The pollen concentrations from the samples collected in August 2000 range between 17,250 to 55,400 grains/liter, and are the highest found within a tropical or non-tropical ice cap. Concentrations from the June 2001 samples range between 3,300 to 21,000 grains/liter, significantly lower than the previous-year samples. These differences are explained by the markedly drier conditions present in 2001, possibly driven by the ENSO. These results are the first step in understanding the fundamental questions of modern pollen-rain and depositional processes on a tropical ice cap, which are essential for reliable and accurate interpretation of ice-core pollen data.

Chapter 4 was a similar study conducted on Mt. Parinacota on the Bolivian/Chilean border in the western Altiplano. In this study, eleven surface snow samples were collected around the caldera rim at the summit of mountain. 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 ice caps.
6.1.3 A Modern Pollen-Rain Study From the Central Andes

An extensive network of surface samples from the central Andes region of South America provides the first comprehensive understanding of the modern pollen-rain in the area. Statistical (discriminant) analysis of the 40 surface samples revealed four palynologically distinct areas, (1) the Andean Forest on the eastern slopes of the Andes, (2) the Eastern Altiplano, (3) the Western Altiplano and Coastal Deserts, and (4) the Southern Bolivian Highlands. These surface pollen data were then used to study the pollen provenance on three tropical Andean ice caps; the Quelccaya ice cap, in southeastern Peru, and Mt. Sajama and Mt. Parinacota in western Bolivia. The results of the discriminant analysis show that the prevailing winds are a major factor in the transport of pollen to the ice caps. Fossil pollen from the Sajama Ice Cap reflects a local (western Altiplano) pollen signature throughout most of its 25,000-year history. The uniform pollen assemblages (intra-annual) found on the Quelccaya Ice Cap are likely deposited by “rainout” events that seem to originate from the either the local vegetation or from areas further to the east. However, the ENSO cycle plays a role in the extent of this influence, and seems to be a major factor in both the concentration and types of pollen found on the ice cap from year to year. The prevailing winds are also responsible for delivering pollen to the Parinacota Ice Cap, however, only to the windward side of the mountain. Without this influence, the rest of the mountain experiences deposition from local winds (i.e., thermally-driven slope and valley winds, and mechanical mountain winds like rotors and vertical-axis eddies). Unlike Quelccaya, the surface pollen assemblages are not uniform and seem to be delivered by mechanical means and not by any “rainout” events. However, additional data are needed to confirm these results.
6.2 Directions for Future Research

The research in this dissertation has provided the building blocks for the future of effective palynological research in the central Andes. It has not only shown the potential for using fossil pollen to reconstruct paleovegetation from tropical ice cores, but also demonstrated the need for it. More pollen studies need to accompany the chemical and physical proxy records that are being developed from ice core research around the world. These records are corroborated when done in conjunction with the pollen analysis. Present ice core studies in the central Andes, in which the pollen work has not been done, includes the Quelccaya Ice Cap in southern Peru and the Huascaran Ice Cap in western Peru. Quality pollen work on these cores would be beneficial.

The ice cap surface sample studies provided necessary information about the sensitivity of the potential ice core records. Though these studies could have benefited from additional research, they have answered many lingering questions. Quelccaya, being a flat ice cap, needs to be pit sampled in the future to answer questions about our sampling method. Since only the top 5 cm of ice was collected for each sample, does this layer represent a significant part of the seasonal accumulation, or does it only represent one or two individual storm events? Pit samples that extended further into the season would provide the necessary data to answer this question.

Along these same lines, Parinacota also needs additional sampling. Only so many questions can be addressed with 11 summit samples. Additional samples from the slopes, as well as pit samples could expand our current knowledge of the dispersal and depositional patterns on this ice cap.
The modern surface soil samples proved indispensable sources of information. Every fossil pollen study (whether ice cap, lake, or bog cores) in this region to date has been conducted without this vital information. Knowing what the pollen found in the fossil record represents is impossible without the full understanding of the modern pollen-rain (modern analog) for the region. Consequently, these results will benefit every future palynological study in the region. However, more surface samples collected from a wider network of areas, over a multitude of seasons and years, could only improve these results. Additional pollen data would explain more variation in the natural environment, resulting in new and more accurate vegetation zones. Regardless, these results should have a positive effect on all future pollen studies in the central Andean region of South America.
APPENDIX A: LETTER OF PERMISSION FROM PHYSICAL GEOGRAPHY

Dear Carl:

There is absolutely no problem with the use of your Physical Geography paper in your dissertation. A dissertation is not a formally published document (i.e., through a publishing house) and we publish many manuscripts that form parts of dissertations. Thus there is no need for formal permission - but you may care to keep this message for reassurance.

Best wishes,

Tony Orme

Antony Orme,
Editor-in-Chief, Physical Geography,
Department of Geography,
University of California,
Los Angeles, CA 90095

----------Original Message----------

Dear Dr. Orme,

I am writing in regards to the following manuscript:


I am writing to request a signed release from Physical Geography, so that I may use this manuscript in my dissertation. I expect to defend my dissertation in July of this year.

The release can be sent to: Carl Reese, 5684 Ducros Dr., Baton Rouge, LA, 70820.

Thank you for your help.

Carl Reese
APPENDIX B: LETTER OF PERMISSION FROM ARCTIC, ANTARCTIC, AND ALPINE RESEARCH

Dear Carl Reese:

You have our permission to include in your dissertation the paper "Pollen Dispersal and Deposition on the Ice Cap of Volcán Parinacota, Southwestern Bolivia" by Reese, Liu, and Mountain, tentatively scheduled for Volume 35, No. 4 (November 2003) of Arctic, Antarctic, and Alpine Research. We request that you credit the journal; until publication the article should be cited as "in press."

Cordially,

Connie Oehring
Managing Editor
Arctic, Antarctic, and Alpine Research
INSTAAR
450 UCB, University of Colorado
Boulder CO 80309-0450
U.S.A.
(303) 492-3765
Fax: (303) 492-6388

--------Original Message--------

Hi Connie,

Great news! After I receive the reviews, I'll make the necessary corrections and return the manuscript as soon as possible.

However, I have another favor to ask. I'm finishing my dissertation and I'm scheduled to graduate in August. I'm writing to ask permission to include the newly accepted AAAR paper, "Pollen Dispersal and Deposition on the Ice Cap of Volcán Parinacota, Southwestern Bolivia", in my dissertation. You can either mail me an official letter of permission, or send me an email stating that permission has been granted. If you choose to send a letter, my mailing address is:

Carl Reese
5684 Ducros Dr.
Baton Rouge, LA 70820

Thanks.

Carl Reese
VITA

Carl Andrew Reese was born on February 28, 1976, in Lawrence, Kansas. As the son of a college football coach, he moved frequently during his adolescence, finally landing in Nashville, Tennessee, where he completed his high school education. After a one-year stint at the University of Missouri, he transferred to Louisiana State University and was awarded his Bachelor of Arts degree in geography in May of 1998. Immediately after graduation, he began his graduate studies at Louisiana State University in biogeography. During his master’s program he served as a teaching assistant, as well as a research assistant for Dr. Kam-biu Liu. He was awarded the Master of Science in geography in May of 2000. Once again after graduation, Carl stayed at Louisiana State University and immediately began a doctoral program. He continued in his position as Dr. Kam-biu Liu’s research assistant, and was able to fund his dissertation research with a series of both external and internal grants. He expects to receive his Doctor of Philosophy in geography in August 2003.