Geology of the Tierras Blancas Area in the Southeastern Acambay Graben, Central Mexico

Lonnie T. Mercer
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd
Part of the Geology Commons

BYU ScholarsArchive Citation
https://scholarsarchive.byu.edu/etd/303
GEOLOGY OF THE TIERRAS BLANCAS AREA IN THE SOUTHEASTERN ACAMBAY GRABEN, CENTRAL MEXICO

by

Lonnie T. Mercer

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirement for the degree of

Master of Science

Department of Geology
Brigham Young University
April 2004
of a thesis submitted by

Lonnie T. Mercer

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date Bart J. Kowallis, Chair

Date Eric H. Christiansen

Date Wade E. Miller
As chair of the candidate’s graduate committee, I have read the thesis of Lonnie T. Mercer in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

____________________________ ___________________________________
Date Bart J. Kowallis
Chair, Graduate Committee

Accepted for the Department

____________________________
Jeffrey D. Keith
Department Chair

Accepted for the College

____________________________
G. Rex Bryce
Associate Dean, College of Physical and Mathematical Sciences
ABSTRACT

GEOLOGY OF THE TIERRAS BLANCAS AREA IN THE SOUTHEASTERN ACAMBAY GRABEN, CENTRAL MEXICO

Lonnie T. Mercer
Department of Geology
Master of Science

Pliocene-Pleistocene sediments in the southeastern Acambay graben, central Mexico have yielded mammal fossils, including *Equus simplicidens*, cf. *Rhynchotherium*, ?*Camelops*, *Mammuthus* sp., *Bison* sp., and *Antilocapra* sp. The fossiliferous sediments include a period of lacustrine sedimentation in the late Pliocene-early Pleistocene that interrupted fluvial and alluvial sedimentation during the early Pliocene and Pleistocene. The sediments deposited in this late Pliocene paleolake record a history of lake level fluctuations, shown by lithologic variations in lacustrine sediments and abundance of vertebrate burrows.

Volcanic and tectonic events in the Acambay graben were the major controls on sedimentation during Pliocene-Pleistocene time. Various local volcanic structures produced source rocks for Pliocene-Pleistocene sediments, and intra-arc extensional tectonics caused basin subsidence. Blockage of stream drainages by lava flows or
perhaps increased basin subsidence contributed to the appearance of and fluctuations in 
the lacustrine system during the late Pliocene. Diatom assemblages from lacustrine 
sediments indicate slightly higher precipitation and humidity than present-day conditions 
in the Acambay graben. Therefore, climatic forcing may have also contributed to the 
development of the late Pliocene paleolake in the Acambay graben.

Pliocene-Pleistocene volcanic rocks in this part of the Acambay graben range 
from basaltic andesite to rhyolite. The calc-alkaline composition of these volcanic rocks 
is similar to others in the modern Mexican Volcanic Belt; they have a continental arc 
affinity, which is consistent with a tectonic setting within the Mexican Volcanic Belt. 
The major eruptive episode in the Acambay graben occurred during the early Pliocene, 
although volcanism, represented by small volcanic structures, continued until the late 
Pleistocene. This observed decline in volcanism in the Acambay graben correlates with a 
early Pliocene through Quaternary trenchward migration of volcanism in the Mexican 
Volcanic Belt.
ACKNOWLEDGMENTS

This research has been funded by NSF Grant EAR 9902898. I want to thank all those that I associated with in the Brigham Young University Geology Department. From my first day at BYU, I felt inclusion and friendship in the BYU geology family. I am extremely appreciative of Bart Kowallis for the direction and purpose that he instilled in me. I am also grateful to Wade Miller and Eric Christiansen for patiently answering my numerous questions and providing suggestions to improve the project. I have also benefited from the help of Michael Dorais and David Tingey in laboratory preparation and analysis of rock samples. I am appreciative of the resourcefulness of the geology department staff, especially Kris Mortensen, Marge Morgan, Kim Sullivan, and Joanne Loosli. I also want to thank all of the geology graduate students for support and respect that helped keep me focused in school.

I want to recognize the help of Oscar Carranza (Universidad Nacional Autónoma de México) in providing necessary assistance in the preparations for my fieldwork in central Mexico. Matthew Rojas was my valuable field assistant and translator during a month of fieldwork. I greatly appreciate Jaime Roldán (Universidad Nacional Autónoma de México) for graciously allowing the use of his home in Temascalcingo while we completed fieldwork. I also want to thank the local government leaders and landowners that enabled our access to the study area. I have also benefited from the assistance of Isabel Israde-Alcántara (Universidad Michoacana de San Nicolás de Hidalgo) in diatom
analysis and Sergio Cevallos-Ferriz (Universidad Nacional Autónoma de México) in paleobotanical analysis.

I want to thank my family for their continual support, despite defying family tradition in attending BYU. Finally, I want to thank my future wife, wherever she may be, for waiting until I finished my thesis so that I could focus on graduate school for two years.
# TABLE OF CONTENTS

ABSTRACT ...................................................................................................................... iv
ACKNOWLEDGMENTS ................................................................................................... vi
LIST OF FIGURES .......................................................................................................... ix
INTRODUCTION ............................................................................................................. 1
  Late Cenozoic Mammalian Biostratigraphy of Central Mexico ................................. 1
  Late Cenozoic Climate ............................................................................................... 2
  Regional Geology ....................................................................................................... 3
  Local Geology ............................................................................................................ 5
METHODS ........................................................................................................................ 7
  Fieldwork ..................................................................................................................... 7
  Geologic Map and Stratigraphic Descriptions .......................................................... 7
  Sandstone Petrography and Modal Analysis .............................................................. 8
  Volcanic Lithic Grain Chemistry ............................................................................. 9
  Volcanic Rocks ......................................................................................................... 9
  Diatom Analysis ....................................................................................................... 10
  Mammal Fossils and Leaf Imprints ......................................................................... 11
RESULTS ........................................................................................................................ 12
  Stratigraphy .............................................................................................................. 12
    Mesozoic Tlalpujahua metamorphic-plutonic complex ......................................... 12
    Miocene-Pliocene volcanic rocks (Tv) .................................................................. 13
    Early-Middle Pliocene Lagunita beds (Tl) ............................................................ 13
    Late Pliocene-Early Pleistocene Tierras Blancas beds (Tlb) ................................... 17
    Late Pliocene-Pleistocene volcanic rocks (Tr, Ta) ................................................. 22
    Pleistocene Cementerio beds .............................................................................. 23
    *Quaternary lava flows, alluvium, and colluvium (Qba, Qva, Qc, Qa)* ............... 26
  Structure ..................................................................................................................... 28
DISCUSSION .................................................................................................................... 28
  Miocene-Early Pliocene Volcanism and Extension .................................................. 28
  Pliocene-Pleistocene Sedimentation and Volcanism ............................................... 29
    *Early Pliocene Lagunita sedimentation* ............................................................... 30
    *Late Pliocene-Early Pleistocene Tierras Blancas sedimentation* ....................... 32
    *Late Pliocene-Pleistocene silicic and intermediate volcanism* ......................... 40
    *Pleistocene Cementerio sedimentation* ............................................................. 40
    *Quaternary volcanism and sedimentation* ......................................................... 41
  Quaternary Tectonics ................................................................................................. 42
  Paleoenvironmental Interpretations ........................................................................... 42
CONCLUSIONS ............................................................................................................. 43
REFERENCES ................................................................................................................ 47
LIST OF FIGURES

Figure 1. Index map of Mexican Volcanic Belt..............................................................55
Figure 2. Index map of fossiliferous basins in central Mexico........................................56
Figure 3. Geologic map of the study area in the southeastern Acambay graben..........57
Figure 4. Composite stratigraphic section of the southeastern Acambay graben.........58
Figure 5. Variation diagrams for volcanic rocks and sandstones.................................59
Figure 6. Geochemical discrimination diagrams.........................................................60
Figure 7. Photograph of the Lagunita beds..................................................................61
Figure 8. Photograph of Lagunita-Tierras Blancas angular unconformity......................61
Figure 9. Photograph of Lagunita tuffaceous mudstone..............................................62
Figure 10. Photograph of Lagunita volcaniclastic sandstone..........................................62
Figure 11. Photograph of the Lagunita lapilli tuff.........................................................63
Figure 12. Variation diagrams for volcanic rocks........................................................64
Figure 13. Photograph of Lagunita volcanic breccia.....................................................65
Figure 14. Stereoplots of the Lagunita and Tierras Blancas beds.................................66
Figure 15. Photograph of an upper jaw and skull of Equus simplicidens......................67
Figure 16. Ternary diagrams of sandstones.................................................................68
Figure 17. Photograph of Tierras Blancas diatomaceous mudstone..............................69
Figure 18. Leaf imprint from the Tierras Blancas diatomaceous mudstone...............69
Figure 19. Vertebrate burrow in the Tierras Blancas diatomaceous mudstone.............70
Figure 20. Vertebrate burrows in the Tierras Blancas diatomaceous mudstone..........70
Figure 21. Vertical cross-section of a vertebrate burrow...........................................71
Figure 22. Vertebrate burrows in the Tierras Blancas diatomaceous mudstone...........71
Figure 23. Diagram of Tierras Blancas assemblages....................................................72
Figure 24. Photograph of interbedded Tierras Blancas beds........................................73
Figure 25. Photographs of Tierras Blancas volcaniclastic sandstone.........................74
Figure 26. Photograph of Tierras Blancas volcaniclastic sandstone.........................75
Figure 27. Photograph of tool marks on Tierras Blancas volcaniclastic sandstone........75
Figure 28. Photograph of deformation in the Tierras Blancas beds.............................76
Figure 29. Photograph of deformation in the Tierras Blancas beds.............................76
Figure 30. Photograph of Quaternary andesite overlying Tierras Blancas mudstone....77
Figure 31. Photograph of Cementerio and Tierras Blancas beds................................78
Figure 32. Photograph of Cementerio beds...............................................................78
Figure 33. Photograph of Cementerio tuffaceous sandstone and volcanic ash..........79
Figure 34. Photograph of Cementerio tuffaceous sandstone.......................................80
Figure 35. Variation diagrams of volcanic lithic grains in sandstones........................81
Figure 36. Photograph of Pleistocene basaltic andesite scoria cones..........................82
Figure 37. Photograph of a Pleistocene andesite scoria cone.......................................82
Figure 38. Photograph of the Pastores fault escarpment and andesite scoria cones.......83
Figure 39. Photograph of the Pastores fault...............................................................84
Figure 40. Photograph of a normal fault in the graben..............................................84
Figure 41. Photograph of a slickensided surface of a normal fault in the graben.........85
Figure 42. Schematic cross-section of Pliocene-Pleistocene sediments.......................86
Figure 43. Measured stratigraphic section.................................................................87
Figure 44. Schematic lake-basin type diagram...........................................................88
INTRODUCTION

Late Cenozoic sediments of the Tierras Blancas area lie along the southeastern margin of the Acambay graben, central Mexico (Figure 1), approximately 5-10 km north of Atlacomulco. These sediments have yielded mammal fossils that have contributed to an important and growing collection of late Cenozoic mammal fossils from across central Mexico. This collection has enhanced our understanding of the Great American Biotic Interchange by constraining the timing of the appearance of South American immigrants in North America (Miller and Carranza-Castañeda, 1984, 2001; Carranza-Castañeda and Miller, 1996; Kowallis et al., 1998; Adams, 2001; Flynn et al., in press). Geologic mapping of the Tierras Blancas area supplies a framework for evaluation of the fossiliferous sediments. In addition, a newly established stratigraphic framework for this area provides constraints on the ages of previously unstudied sediments and volcanic rocks. Changes in the character of these late Cenozoic sediments and volcanic rocks give evidence of climatic, tectonic, and volcanic variations in the Acambay graben during Pliocene-Pleistocene time.

Late Cenozoic Mammalian Biostratigraphy of Central Mexico

North American mammalian fossils are valuable in the biochronology of non-marine sediments, and they provide the data base for an understanding late Cenozoic mammal dispersal events (e.g., Lindsay et al., 1984; Webb and Opdyke, 1995). Central Mexico lies in an excellent location for deciphering the timing of the immigration of South American mammals into North America after the formation of the Panamanian land bridge (Miller and Carranza-Castañeda, 2001). Late Cenozoic sediments in small basins of central Mexico (Figure 2) have yielded vertebrate fossils that have significantly
improved late Cenozoic mammalian biostratigraphy of North America by constraining the age of the Hemphillian-Blancan boundary at approximately 4.8 Ma (Miller, 1980; Miller and Carranza-Castañeda, 1982, 1984, 1996, 2001; Carranza-Castañeda and Miller, 1988, 1996; Montellano-Ballesteros, 1992; Kowallis et al., 1998). Layers of glassy volcanic ash are often found interbedded with the fossiliferous sediments and provide radiometric ages that improve chronologic control. Recent studies of the fossils, sediments, and volcanic ashes of these basins have indicated initiation of the Great American Biotic Interchange during the latest Hemphillian and earliest Blancan in central Mexico (Miller and Carranza-Castañeda, 1984, 2001; Carranza-Castañeda and Miller, 1996; Kowallis et al., 1998; Adams, 2001; Flynn et al., in press).

Previous studies have focused on the sedimentary basins in the states of Baja California, Hidalgo, Guanajuato, and Jalisco (Miller, 1980; Miller and Carranza-Castañeda, 1982, 1984, 1996, 2001; Carranza-Castañeda and Miller, 1988, 1996). This study concentrates on the Acambay graben, which lies in the states of Mexico and Michoacán (Figure 2).

**Late Cenozoic Climate**

During the Pliocene (about 2.5 Ma), global climate transitioned from a relatively warm and wet climate to a cooler and drier climate (e.g., Burckle, 1995; PRISM Project Members, 1995). Reconstructions of sea surface temperature, land vegetation, sea level, sea ice, and land ice for an interval of the Pliocene (3.15-2.85 Ma) suggest a relatively warm climate as compared to present-day climate (PRISM Project Members, 1995). In addition, terrestrial biota and lacustrine ostracodes from the western United States indicate that Pliocene climate prior to 2.4 Ma was less seasonal and more humid than
present conditions (Forester, 1991; Thompson, 1991). The same data sets suggest that late Pliocene climate (2.4-1.8 Ma) in the western United States was similar to modern conditions with possibly more precipitation (e.g., Forester, 1991; Thompson, 1991). Late Pliocene-Pleistocene global climate has been characterized by relatively cool, dry conditions marked by high-amplitude, high-frequency fluctuations of interglacial and glacial extremes (e.g., Morley and Dworetzky, 1991; Thompson, 1991).

The Pliocene-Pleistocene climate of central Mexico may have experienced patterns similar to those of the western United States. Although terrestrial mammal fossils suggest that relatively humid conditions persisted in northern Mexico until the late Pleistocene (Webb and Opdyke, 1995), late Pliocene-Pleistocene climate in central Mexico likely experienced significant fluctuations that corresponded to global climate change. The late Pliocene appearance and early Pleistocene disappearance of a paleolake, as shown below, in the southeastern Acambay graben of central Mexico gives possible evidence of climatic variation during the past ~3 Ma. These climatic trends may also help explain the appearance and subsequent disappearance of other lakes in central Mexico during the late Cenozoic (Israde-Alcántara and Garduño-Monroy, 1999; Michaud et al., 2000). Seasonal variations in precipitation characterize the present climate of central Mexico with relatively high rainfall during the summer and stable, dry conditions during the winter (Bradbury, 2000). In addition, the present climate of central Mexico is relatively dry, as compared to middle Pliocene climate (PRISM Project Members, 1995).

Regional Geology

The Mexican Volcanic Belt extends over 1,000 km along an east-west trend across central Mexico (Figure 1; Nixon, 1982; Verma, 1987; Suter et al., 1995; Sheth et
Volcanic rocks of the modern Mexican Volcanic Belt are predominantly medium- to high-K and calc-alkaline (magnesian, in the sense of Frost et al., 2001), although intraplate alkaline rocks comprise a significant volume of the Mexican Volcanic Belt (Nixon, 1982; Nixon et al., 1987; Verma, 1987; Moore et al., 1994; Márquez et al., 1999; Sheth et al., 2000). The coexistence of calc-alkaline and intraplate alkaline volcanism in central Mexico has created considerable controversy concerning the origin of the Mexican Volcanic Belt, but the majority of workers trace its volcanism to subduction of the Cocos and Rivera Plates beneath the North American Plate along the Middle American Trench (Nixon, 1982; Nixon et al., 1987; Verma, 1987; Moore et al., 1994; Márquez et al., 1999; Sheth et al., 2000; Ferrari et al., 2001). The present-day plate tectonic configuration of the Cocos and Rivera Plates subducting beneath North America dates back to the late Miocene (Nixon, 1982; Verma, 1987; Bandy et al., 2000). The onset of volcanism in the Mexican Volcanic Belt initiated in the middle to late Miocene (Nixon et al., 1987; Ferrari et al., 1999; Márquez et al., 1999; Sheth et al., 2000; García-Palomo et al., 2002), and a trenchward migration of volcanism occurred from the late Miocene-early Pliocene to the early Quaternary (Nixon et al., 1987; Ferrari et al., 1999; Figure 1).

Within the Mexican Volcanic Belt, there are a series of east-west trending tectonic depressions that comprise the Chapala-Tula fault zone (Figure 1; Johnson and Harrison, 1990; Suter et al., 1995). These tectonic basins are the result of intra-arc extension within the Mexican Volcanic Belt that began in the late Miocene (Suter et al., 1995; Campos-Enriquez et al., 2000; Suter et al., 2001). The Acambay graben lies in the eastern sector of the Chapala-Tula fault zone and is bounded by the Acambay-Tixmadejé
and Pastores faults on the north and south, respectively (Johnson and Harrison, 1990; Suter et al., 1995; Suter et al., 2001). Central Mexico also lies at the southern boundary of the Basin and Range province, and the Mexican Volcanic Belt was superposed on the preexisting structural fabric of Basin and Range extension (Henry and Aranda-Gomez, 1992).

Late Cenozoic lacustrine systems developed within the intra-arc basins of the Mexican Volcanic Belt (Chacón-Torres and Múzquiz-Iribe, 1997; Israde-Alcántara, 1997; Metcalfe, 1997; Rosas-Elguera and Urrutia-Fucugauchi, 1998; Israde-Alcántara and Garduño-Monroy, 1999; Michaud et al., 2000; Suter et al., 2001). Some of the lakes have persisted to the present, such as Lake Cuitzeo (Israde-Alcántara and Garduño-Monroy, 1999), Lake Chapala (Rosas-Elguera and Urrutia-Fucugauchi, 1998; Michaud et al., 2000), and Lake Pátzcuaro (Chacón-Torres and Múzquiz-Iribe, 1997; Bradbury, 2000), while several other lake systems disappeared (Chacón-Torres and Múzquiz-Iribe, 1997; Israde-Alcántara, 1997; Rosas-Elguera and Urrutia-Fucugauchi, 1998; Israde-Alcántara and Garduño-Monroy, 1999; Michaud et al., 2000).

Local Geology

Aguirre-Díaz et al. (2000) summarized the stratigraphy of the north and south walls of the Acambay graben, which is dominated by Pliocene-Pleistocene volcanic rocks. Suter et al. (1995) determined an age of 0.4 Ma for a “basaltic” lava flow (identified below as andesitic) associated with scoria cones northwest of Atlacomulco. These dated lava flows cover the Pastores fault and extend northward into the study area. Suter et al. (1995) reported an outcrop that exposes the Pastores fault cutting these lava flows, but this relationship is obscured in most locations due to poor exposure of fault
scarps. Several stratovolcanoes, lava domes, and cinder cones with associated lava flows formed within the graben (Norato-Cortez, 1998; Ramírez-Herrera, 1998). However, the stratigraphy and structure within the graben are poorly understood (Suter et al., 1995; Aguirre-Díaz et al., 2000), although it has been reported that the basement consists of Mesozoic metasedimentary rocks that crop out in a few locations along the southern flank of the graben (Norato-Cortez, 1998; Aguirre-Díaz et al., 2000).

Pliocene-Pleistocene fluvial, alluvial, and lacustrine sediments are found within the Acambay graben but have not been studied in detail. The lake deposits have been attributed to tectonic depressions (sag ponds) that formed along the Pastores fault (Suter et al., 1995; Aguirre-Díaz et al., 2000). Suter et al. (1995) and Aguirre-Díaz et al. (2000) referred to lacustrine sediments that outcrop along the Pastores fault, both in the footwall and hanging wall, and they indicated a correlation of all of these lake sediments with the Ixtapantongo Formation of Sánchez-Rubio (1984). While lacustrine sediments in the footwall of the Pastores fault may correlate with the Quaternary Ixtapantongo Formation (radiocarbon age of 23 ka; Sánchez-Rubio, 1984), lacustrine deposits in the hanging wall of the Pastores fault, lying in this study area, cannot be correlative to the Ixtapantongo Formation because they lie stratigraphically below Quaternary lava flows mentioned above (0.4 Ma; Suter et al., 1995). In addition, the lake sediments within the Acambay graben contain Blancan vertebrate fossils from the latest Pliocene and earliest Pleistocene (Wade E. Miller, oral communication, 2002). Identified Blancan vertebrate faunas from the Acambay graben include horses, mastodons, and camels (Mercer et al., 2002). In addition, horse, camel, mastodon, bison, and antilocaprid fossils have been recovered
from Quaternary sediments in the graben (Wade E. Miller, written communication, 2003).

One volcanic ash layer has been found interbedded with lake sediments near the top of the stratigraphic section. The ash layer was sampled by Bart Kowallis (Brigham Young University), and zircon grains were separated and dated by standard fission-track methods. The youngest population of single-crystal zircon fission-track ages yielded a peak age of 1.20 ± 0.13 Ma (Mercer et al., 2002).

**METHODS**

**Fieldwork**

Round-trip travel from the campus of Brigham Young University (Provo, Utah) to the field area in Mexico included over 5,500 driving miles. A GMC Yukon was rented to complete the travel. Passports, visas, Mexican automobile insurance, vehicle documents, trip permits, and a Mexican travel tax were required to travel across the United States-Mexico border. The fieldwork was completed over a period of approximately one month during May and June of 2002.

**Geologic Map and Stratigraphic Descriptions**

Geologic mapping was completed for a 3 minute by 4 minute area in the southeastern sector of the Acambay graben (Figure 3). The geologic map was completed on aerial photographs in the field and then transferred to a 1:50,000 topographic base map using Adobe Illustrator™. Sections were measured, described, and photographed in nine localities throughout the area using a tape and 35-mm camera (Appendix A). Section locations were selected in order to provide complete geographic coverage of the fossiliferous lacustrine sediments and proximity to fossil localities. Field notes and
descriptions were recorded in standard field notebooks. Samples, including volcaniclastic sandstones, mudstones, and volcanic ashes, were collected from each measured section (Appendix A). The sedimentary units were described and photographed in several other locations. Bedding and fault plane attitudes were measured with a Brunton compass and plotted on equal-area stereoplots (using RockWorks™) to characterize structural patterns. Sample and section locations were collected using a Garmin Etrex GPS unit.

**Sandstone Petrography and Modal Analysis**

Eleven medium- to coarse-grained sandstone samples and four sandy mudstone samples were selected for thin-section preparation and modal analysis. Samples were selected from nearly every measured section in order to account for variations in sandstone petrography throughout the area. Samples were impregnated with epoxy and cut into standard thin sections (prepared by Wagner Petrographic, Provo, Utah). Point counts were accomplished using a petrographic microscope equipped with an automated stage. Three hundred points were counted for each sample using the Gazzi-Dickinson method (Dickinson, 1970; Ingersoll et al., 1984; Ingersoll and Cavazza, 1991). Counted grain types include monocrystalline quartz, plagioclase feldspar, potassium feldspar, dense minerals, miscellaneous minerals, and volcanic lithic fragments (Dickinson, 1970; Ingersoll et al., 1984). Volcanic lithic grains were counted according to the following textures: vitric, lathwork, microlitic, granular, and seriate (Dickinson, 1970; Ingersoll and Cavazza, 1991; Critelli et al., 2002).
Volcanic Lithic Grain Chemistry

Four of the petrographically-analyzed sandstone samples (AG-03-01, AG-06-01, AG-08-01, and AG-04-04) were prepared as polished thin sections for electron microprobe analysis in order to analyze the composition of volcanic lithic grains across the study area. Ten to twenty volcanic lithic grains were analyzed from each thin section and completed at Brigham Young University with a Cameca SX-50 electron microprobe. Vitric volcanic lithic grain analyses used a 10-μm beam with a 15 kV accelerating voltage, 10 nA beam current, and 20-second counting times to minimize volatilization of Na. Analyzed elements include Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and Ba. Ten lathwork and microlitic volcanic lithic grains were also analyzed on one thin section (AG-04-04), which contains a significant portion of these grain types. Lathwork and microlitic volcanic lithic grain analyses used a 50-μm beam with a 15 kV accelerating voltage, 10 nA beam current, and 20-second counting times. Analyzed elements include Si, Ti, Al, Fe, Mn, Mg, Ca, Na, and K. Rhyolitic glass from Yellowstone National Park, Wyoming and hornblende from Kakanui, New Zealand were used as standards for calibration (Appendix B).

Volcanic Rocks

Approximately 20 samples of volcanic rocks were collected throughout the area (Figure 3). Rock chips were powdered in a tungsten carbide shatter box in preparation for X-ray fluorescence analysis.

Volcanic ash samples were collected in 5 localities (Figure 3). These samples were prepared for X-ray fluorescence analysis following the methods of Perkins et al. (1995). The volcanic ash samples were washed repeatedly in water to remove organic
material and clay. After drying overnight, each sample was sieved through 18, 35, 60, 120, and 230 size brass sieves. A glass fraction of >99.5% purity was prepared from the 60-120 fraction by acid digestion to remove carbonate minerals and surficial clay alteration. The samples were digested in 10% HNO$_3$ for 15 minutes and then washed repeatedly in deionized water. Next, the samples were treated in 5% HF using an ultrasonic cleaner, washed repeatedly in deionized water, and then quickly dried using acetone. After cleaning, a Frantz Isodynamic Separator™ was used to remove magnetic and nonmagnetic minerals from the glass fraction. Each glass fraction was checked for purity using a petrographic microscope. Glass fractions of each sample were powdered in a tungsten carbide shatter box.

Glass disks were formed by fusion of 1.00 g of rock powder, 7.00 g of a 50/50 mixture of lithium tetraborate and lithium metaborate, 0.03 g of cesium iodide, and 0.03 g of lithium nitrate for major element analysis. Loss on ignition was measured by heating about 2.0 g of rock powder at 1000 °C in an oven for 4 hours. Two grams of rock powder was pressed into 3.2-cm-diameter pellets backed by Whatman fibrous cellulose for trace element analysis. X-ray fluorescence analysis was completed at Brigham Young University using a Siemens SRS-303 wave length dispersive spectrometer. International reference standards (QLO-1 and JB-2) were analyzed as unknowns to assess accuracy (Appendix B). Analyzed trace elements include S, Sc, V, Cr, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, and Ba.

**Diatom Analysis**

Twenty-nine samples from lacustrine sediments were collected in approximately 0.3-m intervals at the Los Espejos locality (Figure 3 and Appendix A) for diatom
analysis. Diatoms from these samples, along with an additional 9 lacustrine samples from other localities, were prepared and identified by Isabel Israde-Alcántara (Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, Mexico).

Dr. Israde-Alcántara used the method of Scherer (1994) to clean and separate the diatom valves from the sediment and organic material. Deionized water was used to wet and break up approximately 0.5 cm$^3$ of each sediment sample in a 400-ml Pyrex beaker. After breaking up the sediment, twenty cm$^3$ of 30% H$_2$O$_2$ was added. The mixture was heated and boiled at ~150 °C for 30 minutes. Twenty cm$^3$ of HNO$_3$ was then added, and the mixture was boiled for another 30 minutes. The mixture was removed from the heat source and let stand for 60 minutes. The beaker was filled with deionized water and let stand for 6 hours. The water was then decanted, and the process of washing with deionized water was repeated until the solution was no longer cloudy.

To prepare slides for diatom identification, a standardized aliquot (3 µl) of diatoms suspended in water was settled onto cover slips. Clean slides were placed on a metal plate heated by a hot plate to over 100 °C. A Pasteur pipette was used to place Naphrax™, a refractive medium, in the center of each slide to cover an area the size of a cover slip. When the Naphrax™ began to bubble less vigorously, the sediment-laced cover slips were placed sediment-side down on each slide to cover the Naphrax™. The slides were then removed from the hot plate, cooled, and labelled. Diatom valves were identified using optical microscopy.

**Mammal Fossils and Leaf Imprints**

Mammal fossil localities found in the study area were noted, and the fossils then were collected with the assistance of Dr. Oscar Carranza (Universidad Nacional
Autónoma de México). Most of the fossils reside in a collection of the Universidad Nacional Autónoma de México (Mexico City, Mexico). Leaf imprints in the lake sediments were sampled in two localities. The most complete leaf imprints were identified by Dr. Sergio Cevallos-Ferriz (Universidad Nacional Autónoma de México, Mexico City, Mexico) and now reside in a collection of the Universidad Nacional Autónoma de México (Mexico City, Mexico). In addition, several collected leaf imprints are located in storage at Brigham Young University (Provo, Utah).

RESULTS

Stratigraphy

The stratigraphy of the southeastern Acambay graben includes Mesozoic basement rocks, late Tertiary-Quaternary volcanic rocks, and Pliocene-Pleistocene fluvial, alluvial, and lacustrine sediments (Figure 4). The first two stratigraphic names used here are from Aguirre-Díaz et al. (2000), while the other stratigraphic names are used here informally and named after communities and localities where the stratigraphic unit is well-exposed.

Mesozoic Tlalpujahua metamorphic-plutonic complex

The oldest rocks exposed along the southern flank of the Acambay graben are a sequence of slates and slightly metamorphosed shales (Figure 4). These metasedimentary rocks crop out in the footwall of the south-central sector of the Acambay graben and are cut by intermediate to silicic dikes and sills observed inside mines near Tlalpujahua village (Aguirre-Díaz et al., 2000). The Tlalpujahua metamorphic-plutonic complex has an inferred Mesozoic age, based on lithologic similarities to regional sedimentary rocks.
(Aguirre-Díaz et al., 2000). These metasedimentary rocks were not observed in the southeastern Acambay graben but are the probable basement rocks in this area.

Miocene-Pliocene volcanic rocks (Tv)

The footwall of the Pastores fault in the southeastern Acambay graben exposes at least 30 m of undated intermediate to silicic volcanic rocks (Figure 4). Near Tlalpujahua, these volcanic rocks unconformably overlie the Tlalpujahua metasedimentary rocks but are not cut by plutonic rocks, suggesting a Miocene-Pliocene age (Aguirre-Díaz et al., 2000). A low-silica dacite (Figure 5; Curva in Appendix B) was sampled from the undifferentiated units in the footwall of the Pastores fault (Figure 3). It has a light tan to light gray groundmass and lacks phenocrysts. This dacite is medium-K, ferroan (Figure 5), and plots in the volcanic arc region of tectonomagmatic discrimination diagram of Pearce et al. (1984; Figure 6).

Early-Middle Pliocene Lagunita beds (Tl)

The Lagunita beds are the basal stratigraphic unit exposed in the graben and generally show 2-5 m of exposure, except in the northeastern part of the field area where at least 30 m of Lagunita beds are exposed (Figure 7). The Lagunita beds (Figure 4) consist of five lithofacies including tuffaceous mudstone, volcaniclastic sandstone, lapilli tuff (ash flow), tuff (ash-sized pyroclastic fall), and volcanic breccia (debris flow/lahar). Mammal fossils are sparse in the Lagunita beds, as only two horse teeth have been found in volcaniclastic sediments. Radiometric ages have not been determined for volcanic rocks in the Lagunita beds, but Blancan *Equus simplicidens* fossil teeth (Wade E. Miller, oral communication, 2002) constrain the age of deposition to the Pliocene. In addition, an angular unconformity between the Lagunita beds and the overlying late Pliocene-early
Pleistocene Tierras Blancas beds (Figure 8) indicates a probable early Pliocene age for the Lagunita beds, although Lagunita deposition could have continued through the much of the Pliocene.

The tuffaceous mudstone lithofacies is the most abundant of all the Lagunita lithofacies and is commonly interbedded with volcaniclastic sandstones. Bed thickness of the mudstone ranges from 0.5 to 3 m. The tuffaceous mudstone is white and commonly massive with poorly-defined bedding (Figure 9). The tuffaceous mudstone shows blocky weathering and is well-cemented. Volcaniclastic sand and gravel lenses are sparse in these tuffaceous mudstone beds. Bedding contacts of the tuffaceous mudstone commonly form conformable depositional surfaces with other lithofacies of the Lagunita beds.

Using a classification based on mineral components, the Lagunita volcaniclastic sandstones are lithic arenites (Dott, 1964). These sandstones are volcaniclastic sandstones, according to the classification for rocks composed of volcanic fragments (Fisher, 1961). In addition, Boggs (1995) indicates volcaniclastic sandstones that are a specific type of lithic arenite that is mostly composed of volcanic detritus. For simplicity, the Lagunita sandstones are described here as volcaniclastic sandstones. The volcaniclastic sandstone lithofacies consists of fine- to coarse-grained, thinly to thickly bedded sandstones (Figure 10). The sandstone is commonly gray with planar lamination and ripple cross-lamination (1-4 cm). Sand grains are angular to subangular, poorly to moderately sorted, and poorly cemented with zeolite. The sandstones contain a high percentage of epiclastic volcanic lithic and feldspar grains. Gastropod shell fragments (complete shell is estimated to be 2-3 cm in diameter) are found in a few sandstone beds.
Graded beds and cut-and-fill structures (generally 1.5 m in width by 0.2 m in height) are common. The volcaniclastic sandstones are often interbedded with the tuffaceous mudstones and contain mudstone inclusions and rip-up clasts along the basal contact of the sandstone beds.

The lapilli tuff lithofacies is a strongly resistant, 3-m thick ash flow tuff that is exposed laterally about 50 m. It is likely more laterally extensive, except it is cut by a normal fault at one end and disappears into alluvium at the other. The ash flow tuff is white to gray and contains nearly 100% lapilli-sized pumice (Figure 11). The lapilli tuff overlies tuffaceous mudstone with a sharp horizontal contact and is overlain by volcaniclastic sandstone.

The tuff lithofacies was found in two localities (Figure 3). At La Cascada, a 10-cm-thick, brown, cemented pyroclastic fall tuff (AG-2002-12 in Appendix B) is interbedded with tuffaceous mudstones. This tuff lies in the lower part of the exposed Lagunita section (Figure 4) and contains a significant amount of clay, >50% glass, and <10% minerals. Another tuff unit crops out along the dirt road near La Plataforma; this tuff (AG-2002-14 in Appendix B) is a white, poorly cemented pyroclastic fall tuff with glass shards forming at least 90% of the tuff. Although limited exposure obscures its relationship with other lithofacies in the Lagunita beds, it appears to lie a couple of meters stratigraphically below the Lagunita-Tierras Blancas contact and is, therefore, higher in the stratigraphic section than sample AG-2002-12 (Figure 4). These tuffs are distal pyroclastic fall deposits, and glass fractions of the ashes are rhyolitic in composition (Figure 5). The Lagunita tuffs are high-K, ferroan (Figure 5), and, plot in the within plate region of the Pearce discrimination diagram (Figure 6), in contrast to
other silicic rocks in this area. The Lagunita volcanic ashes are distinct and unusual for normal continental arc volcanic rocks due to relatively low Al and Ca as well as relatively high Fe and Zr (Figure 12 and Appendix B), which suggests a marginally peralkaline character.

The volcanic breccia lithofacies includes gray to brown angular breccias (Figure 13) that are not laterally extensive. Volcanic clasts are mixed together, range from basaltic to felsic in composition, and form 50-80% of the breccia. Clast sizes range from 1 to 30 cm in diameter. The matrix consists of brownish clay or gray sandy to silty ash, and the breccias tend to be strongly cemented. The volcanic breccias form erosional contacts with other Lagunita lithofacies, including channel-shaped structures (3-5 m thick).

Deformation is pervasive in the Lagunita beds throughout the field area. In the La Plataforma locality, the Lagunita beds are dipping about 45-50° beneath horizontally bedded Tierras Blancas beds (Figure 8). Tilted bedding of the Lagunita beds is common in other localities, although exposure is generally limited to a few meters obscuring possible larger structures. The Lagunita beds are best exposed in the La Cascada locality, where at least 30 m of Lagunita beds crop out on a hillside exposing a ~10-m-scale fold (Figure 7). Bedding attitudes were measured along the fold, and poles to bedding were plotted on an equal-area stereonet (Figure 14). The stereoplot reveals an east-west trend in the poles to bedding, which indicates a north-south trend of the fold’s axial plane and a near horizontal north-south fold axis. Closely-spaced fractures and joints (<5 cm spacing) are pervasive in the Lagunita beds.
Late Pliocene-Early Pleistocene Tierras Blancas beds (Tbh)

As previously mentioned, the Tierras Blancas beds unconformably overlie the Lagunita beds forming an angular unconformity in areas where the Lagunita beds are deformed (Figure 8). The Tierras Blancas beds (Figure 4) are mudstones (2-15 m thick) with thin interbedded volcaniclastic sandstones (5-30 cm thick). The Tierras Blancas beds consist of four lithofacies including sandy mudstone, diatomaceous mudstone, massive mudstone, and volcaniclastic sandstone. The Tierras Blancas unit is the most productive in terms of mammal fossils yielding *Camelops*, cf. *Rhynchotherium*, and at least 20 elements of *Equus simplicidens*, including an articulated upper jaw and skull (Oscar Carranza-Castañeda and Wade E. Miller, written communication, 2003; Figure 15). Radiometric age determinations have not been obtained from units within the Tierras Blancas beds, but a late Pliocene age-earliest Pleistocene age is assigned with confidence to Tierras Blancas deposition because of key Blancan mammal fossils (Wade E. Miller, oral communication, 2002). The Tierras Blancas diatom assemblage also indicates a Pliocene-early Pleistocene age of deposition, as shown by the presence of *Stephanodiscus excentricus* (Michaud et al., 2000; Isabel Israde-Alcántara, written communication, 2003). The stratigraphic relationship with a dated volcanic ash bed (1.20 ± 0.13 Ma; Mercer et al., 2002) lying less than one meter above the Tierras Blancas beds also suggests late Pliocene-early Pleistocene deposition (Appendix A).

The sandy mudstone lithofacies is the basal unit of the Tierras Blancas beds and ranges in thickness from 1 to 2 m. It has a tan to buff color, is massive and commonly resistant, forming a platform at the base of the Tierras Blancas outcrops (Figure 8). The mudstone is 80-90% tan clay with 10-20% angular to subangular lithic sand grains.
Feldspar minerals and volcanic lithic grains dominate the sand grain assemblages (Appendix C). Quartz, Fe-Ti oxides, pyroxene, and amphibole are accessory minerals that comprise a minor component of the grains (Appendix C). Detrital matrix and zeolite cement are the major interstitial materials and likely formed from very fine volcanic ash. The Tierras Blancas sandy mudstones plot in the transitional arc provenance subdivision of Dickinson et al. (1983; Figure 16). Sparse volcanic pebbles and cobbles are found near the base of the sandy mudstone, which also contains organic material and root traces. At least 15 mammal fossils representing *Equus simplicidens* and cf. *Rhynchotherium* have been recovered from this unit. The sandy mudstone always shows horizontal bedding.

The diatomaceous mudstone lithofacies lies conformably on top of the sandy mudstone and ranges in thickness from 1 to 15 m. This unit thins and pinches out to the northwest, but lateral thinning is difficult to determine in other areas due to limited exposure. The diatomaceous mudstone is commonly horizontally bedded but locally shows significant nonsystematic deformation and slumped bedding. It is white in color, finely laminated to thinly bedded (Figure 17), and generally crops out as a cliff-forming unit above its sharp depositional contact with the sandy mudstone. The mudstone is predominately a diatomite but also contains very fine ashy sediment that dominates some beds. Mammal fossils have been collected from this unit, most importantly the upper jaw and skull of *Equus simplicidens* (Oscar Carranza-Castañeda and Wade E. Miller, written communication, 2003) from the Las Casas locality (Figure 15). Leaf imprints were collected in two locations from the diatomaceous mudstone (Figure 18). The fossil plant material is currently being studied by Dr. Sergio Cevallos-Ferriz (Universidad Nacional
Preliminary results suggest that three species of *Quercus* (oak) and one species of *Salix* (willow) are represented (Sergio Cevallos-Ferriz, written communication, 2003), but further identification and analysis is needed in order to make possible paleoenvironmental interpretations from the leaf imprints. Plant material is abundant along some horizons with a general trend of increasing plant material upsection. The diatomaceous mudstone is also marked in some localities by tubes (~5-10 cm in diameter) that cut across bedding and are partially or completely filled with dark brown, waxy organic debris (Figure 19). These tunnels are interpreted to be vertebrate burrows (Stephen Hasiotis, oral communication, 2002). In fact, small mammalian vertebrates, such as a ground squirrel, are the likely burrowers, based on the burrow size (Wade E. Miller, written communication, 2003). As mentioned, the vertebrate burrows generally are filled with dark brown, waxy organic material, but may also be partly filled with reworked white diatomaceous mudstone. Where this occurs, the mudstone material fills in the lower part of the burrow with organic material in the upper part (Figures 20-21). The vertebrate burrows tend to increase in abundance upsection and also have increased abundance in certain localities (Figure 22).

Diatoms identified by Dr. Isabel Israde-Alcántara (Universidad Michoacana de San Nicolás de Hidalgo, Morélia, Michoacán, Mexico) in the diatomaceous mudstone lithofacies of the Tierras Blancas beds include the following genera: *Aulacoseira, Stephanodiscus, Staurosira, Cocconeis, Cymbella, Gomphonema, Rophalodia,* and *Synedra* (Figure 23). Planktonic genera (*Aulacoseira* and *Stephanodiscus*) dominate the diatom assemblage through most of the lacustrine section. Periphytic diatoms are sparse, and tycoplanktonic genera are mostly absent. An exception is near the base of the
diatomaceous mudstone (sample AG-03-38) where periphytic genera are slightly more abundant than planktonic diatoms and tycoplanktonic genera have their highest abundance.

The massive mudstone lithofacies lies conformably on top of the diatomaceous mudstone forming a gradational contact. It is a brown slope-forming unit (Figure 24). The massive mudstone is also horizontally bedded, except where it is tilted in the same orientation as the underlying diatomaceous mudstone.

Like the volcanioclastic sandstone lithofacies of the Lagunita beds, Tierras Blancas sandstones are described here as volcanioclastic sandstones, according to the classification of Fisher (1961). The volcanioclastic sandstone lithofacies is commonly interbedded with the diatomaceous mudstone and massive mudstone, usually forming a basal contact with the massive mudstone and an upper contact with the diatomaceous mudstone. The volcanioclastic sandstone beds generally maintain the same thickness laterally, although a road cut in San Bartolo Lanzados exposes a volcanioclastic sandstone bed that has a channel structure (Figure 25). The volcanioclastic sandstones are thin (5-30 cm), black to dark gray in color, and laterally extensive. The sandstone is medium- to coarse-grained, moderately sorted, moderately cemented, and has angular to subangular grains. Volcanic lithic grains dominate the sand grain assemblages (Appendix C). Vitric volcanic lithic grains are the most abundant volcanic lithic grain (Appendix C) and include colorless pumice and glass shards. Lathwork and microlitic volcanic lithic grains are a significant component of Tierras Blancas volcanioclastic sandstones (Appendix C) and consist of a dark-colored glassy groundmass with plagioclase phenocrysts and/or visible plagioclase microlites. Monocrystalline grains, such as feldspar, quartz, and Fe-Ti oxides, constitute
a minor component of the grain assemblage (Appendix C). When plotted in a QFL ternary diagram (Figure 16), the Tierras Blancas volcaniclastic sandstones plot in the undissected arc provenance subdivision of Dickinson et al. (1983). The volcaniclastic sandstone beds are normally graded. Along its irregular basal contact with the diatomaceous mudstone, white clay rip-up clasts are common, and white clay interbeds occur within the sandstone (Figure 26). The upper surface of Tierras Blancas volcaniclastic sandstones shows tool marks (Figure 27).

The Tierras Blancas beds generally show horizontal bedding lacking deformation, but deformed bedding also occurs in several outcrops of the Tierras Blancas beds. Where the Lagunita beds show relative deformation uniformity, the tilted bedding of the Tierras Blancas beds is relatively unsystematic. Dipping Tierras Blancas beds commonly are juxtaposed with horizontally bedded strata and display significantly different bedding attitudes over meter-scale distances (Figures 28-29). A stereoplot of poles to bedding of Tierras Blancas sandstones corresponds with the unsystematic deformation viewed in outcrops in that the stereoplot lacks a trend (Figure 14), despite a limited number of points. The pattern of deformed bedding of the Tierras Blancas beds shows similarity to slumped bedding or soft sediment deformation. In areas of slump-like deformation, the volcaniclastic sandstones show soft sediment deformation in the form of centimeter-scale faults and convoluted bedding (Figure 26). Quaternary volcanics always directly overlie the outcrops of deformed Tierras Blancas sediments, and two locations show overlying lava flows that mixed with underlying Tierras Blancas mudstone (Figure 30). Tierras Blancas units commonly are not deformed where lava flows do not occur (Figure 3).
Late Pliocene-Pleistocene volcanic rocks (Tr, Ta)

Several undated volcanic structures lie in the southeastern Acambay graben. A silicic lava dome, named the Cerro Santa Lucía by Norato-Cortez (1998; Figure 4), lies along the western margin of the study area (Figure 3) and is a parasitic lava dome to the inactive San Pedro stratovolcano (Norato-Cortez, 1998). Norato-Cortez (1998) described the Cerro Santa Lucía as part of a post-stratovolcano phase in the Acambay graben in which several dacitic and rhyolitic lava domes erupted. The San Pedro stratovolcano was active during the early Pliocene (Norato-Cortez, 1998), and, therefore, the age of the Cerro Santa Lucía may be constrained to the late Pliocene and/or early Pleistocene.

Silicic lava flows associated with the Cerro Santa Lucía were sampled in three locations (Figure 3) and include two dacites and one low-silica rhyolite (Figure 5). These dacites and rhyolites have light gray groundmasses with 50-80% phenocrysts including plagioclase, quartz, biotite, and amphibole. The dacites and rhyolite are medium- to high-K and magnesian (Figure 5). The dacite and rhyolite group plots in the volcanic arc region of the tectonomagmatic discrimination diagram of Pearce et al (1984; Figure 6). These volcanic rocks, as well as all others that were analyzed as part of this study, show geochemical similarities to XRF analyses reported by Sánchez-Rubio (1984) and Norato-Cortez (1998) for volcanic rocks in the Acambay graben.

An undated, poorly-exposed andesite lava flow lies in the west-central part of the study area (Figure 3). Its association with volcanic centers in the area is difficult to constrain due to poor exposure, but it likely erupted from the Cerro Santa Lucía or the San Pedro stratovolcano, based on its geographic proximity to these structures. Therefore, it is likely late Pliocene-Pleistocene in age. This andesite lava flow is
geochemically distinct from other lava flows in the area and shows a high-K, magnesian geochemical signature (Figures 5 and 12).

*Pleistocene Cementerio beds*

Unconformably overlying the Tierras Blancas beds are the Cementerio beds (Figure 4), which include tuffaceous sandstone, mudstone, and tuff lithofacies (ash-sized pyroclastic fall). The Cementerio beds have an erosional contact with the underlying Tierras Blancas beds and range in thickness from 1 to 4 m (Figures 31-32). The Cementerio beds have not been mapped due to limited thickness and vertical exposures in outcrop (Figure 3). While the Cementerio beds are Quaternary in age, they have been separated from other Quaternary sediments because of their distinct tuffaceous character. The Cementerio beds have not yielded any mammal fossils but are important because one ash bed has yielded a zircon fission-track age of $1.20 \pm 0.13$ Ma (Mercer et al., 2002; Figure 33).

Like the Lagunita and Tierras Blancas volcaniclastic sandstones, the sandstones of the Cementerio beds are volcaniclastic sandstones, according to the classification of Fisher (1961). To differentiate volcaniclastic sandstones that are mostly composed of pyroclasts that show little textural modification, Critelli et al. (2002) use the term “tuffaceous sandstones”. Therefore, the Cementerio sandstones are described here as tuffaceous sandstones in order to emphasize the relatively large component of sand pyroclasts in the Cementerio sandstones as compared to the Lagunita and Tierras Blancas volcaniclastic sandstones. The tuffaceous sandstone lithofacies is the most prominent and abundant of the Cementerio lithofacies. It lies unconformably on top of the Tierras Blancas beds and is a cliff-forming unit that often caps the outcrops of Pliocene-
Pleistocene sediments (Figures 31-33). The tuffaceous sandstone is generally thickly bedded and interbedded with thin tuffs and mudstones (Figure 33), although some sections of the Cementerio beds have thinly bedded tuffaceous sandstones interbedded with thinly bedded mudstones (Figure 32). The tuffaceous sandstone is tan to buff to gray in color, medium- to coarse-grained, moderately to poorly sorted, poorly cemented by zeolite, and contains subangular to subrounded grains. Volcanic lithic grains strongly dominate the sand grain assemblages of the Cementerio sandstones (Appendix C). Vitric volcanic lithic grains are the most abundant volcanic lithic grain, while other types of volcanic lithic grains constitute a minor component of the grain assemblage (Figure 16). The Cementerio sandstones contain a significant component of plagioclase feldspar but little quartz, potassium feldspar, and other monocrystalline minerals (Appendix C). The Cementerio sandstones plot in the undissected arc provenance subdivision of Dickinson et al. (1983; Figure 16). Lenses of gravel-sized pumice are common (Figure 34), and sand grains are generally volcanic lithics. Planar lamination, trough cross-lamination (5-10 cm), and normally graded bedding are common. Where tuffaceous sandstones are interbedded with mudstones, soft sediment deformation is present along the erosional contacts between the sandstones and mudstones.

Electron microprobe analyses of vitric volcanic lithic grains of two samples (AG-03-01 and AG-06-01 in Appendices A and B) from the basal tuffaceous Cementerio sandstone bed show a single distinct grouping of high-K, ferroan rhyolite (Figure 5). On geochemical variation diagrams, these high-SiO₂ rhyolites consistently show a tight grouping (Figure 35).
In contrast, samples that were collected from upper tuffaceous sandstones of the Cementerio beds (AG-08-01 and AG-04-04 in Appendices A and B) have vitric volcanic lithic grains with much broader ranges in compositions, varying from dacite to rhyolite for AG-08-01 and from trachydacite to rhyolite for AG-04-04 (Figure 5). In sample AG-08-01, grain compositions are dominantly medium-K and magnesian (Figure 5), while vitric grains in sample AG-04-04 are high-K and dominantly ferroan (Figure 5). Broad ranges in grain compositions for both samples are consistently shown in geochemical variation diagrams (Figure 35). Analyses of lathwork and microlitic volcanic lithic grains were also completed from sample AG-04-04. These grains are typically more mafic than the glassy grains, varying from andesitic to trachydacitic (Figure 5) and show a relatively broad range in variation diagrams (Figure 35). All grains from this sample are dominantly high-K and ferroan (Figure 5). Volcanic lithic grain compositions from the upper Cementerio sandstones are very similar to volcanic rocks associated with the Amealco caldera (Aguirre-Díaz and McDowell, 2000).

The mudstone lithofacies is limited in its extent, found in only three localities. The mudstones are interbedded with tuffaceous sandstones and commonly have thickness of less than a meter (Figure 32). The mudstones are massive, white or brown in color, contain thin (< 1 cm in width) root traces, and are horizontally bedded.

The tuff lithofacies crops out in four localities and is interbedded with tuffaceous sandstones forming gradational contacts (Figures 31-33). The tuff ranges in thickness from 1 to 10 cm and extend laterally through an outcrop, where present. This unit is a distal pyroclastic fall tuff with white to light gray, poorly consolidated, ash-sized grains consisting of >90% glass. Three volcanic ash samples (MX-2000-06, AG-2002-04, and
AG-2002-08 in Appendices A and B) were collected in separate localities from tuff units that lie about 0.5-1 m above the basal contact of the Cementerio beds. The glass fractions of the tuff samples are rhyolitic in composition (Figure 5). These three analyses are high-K, ferroan (Figure 5), and plot closely in all variation diagrams (Figure 12). In addition, because of relatively low Nb content these tuffs plot in the volcanic arc region of the Pearce discrimination diagram (Figure 6). Based on similarities in composition and stratigraphy, these tuff samples represent one tuff unit.

Quaternary lava flows, alluvium, and colluvium (Qba, Qva, Qc, Qa)

The youngest rocks in the southeastern Acambay graben are Quaternary lava flows, alluvium, and colluvium that unconformably overlie Lagunita, Tierras Blancas, and Cementerio beds in various locations (Figures 3-4).

Mafic lava flows and scoria cones in the northern part of the study area (Figure 3) are associated with lavas that were named the Basalto Los Metates by Sánchez-Rubio (1984). These lava flows are associated with small scoria cones in the northeastern part of the study area (Figure 36). Tentatively assigned a Pliocene age by Sánchez-Rubio (1984), Aguirre-Díaz et al. (2000) reported paleomagnetic results to correlate the Basalto Los Metates with the Matuyama chron (2.58-0.78 Ma; Cande and Kent, 1995). The lava flows lie stratigraphically above the 1.2 Ma Cementerio beds in at least one measured section (Línea de Teléfono in Appendix A). Therefore, the age of these lava flows must be constrained to the younger portion of the Matuyama chron (1.1-0.78 Ma). These mafic lava flows were sampled in six locations (Figure 3) and are basaltic andesitic in composition (Figure 5). These basaltic andesites commonly have gray to dark gray
groundmasses with <5% plagioclase and pyroxene phenocrysts. They are medium-K and magnesian (Figure 5) with high Ba/Nb (Figure 6).

Intermediate lava flows lie in the southern part of the study area (Figure 3) and are associated with scoria cones along the Pastores fault (Figures 37-38). Suter et al. (1995) reported an $^{40}$Ar/$^{39}$Ar age of 0.4 ± 0.1 Ma for these lava flows (Figure 4). These Pleistocene lava flows were sampled in nine locations (Figure 3) and have an andesitic composition (Figure 5). The andesites have dark gray to black groundmasses with 5-10% plagioclase phenocrysts and sparse pyroxene. The andesites are distinctly more potassic than the basaltic andesites and straddle the dividing line between the medium- and high-K series (Figure 5). Like the basaltic andesites, the andesites are magnesian (Figure 5) and have relatively high Ba/Nb ratios (Figure 6). One of the samples (Garabato in Appendix B) that is grouped with the andesites is a trachyandesite (because of its high Na$_2$O content) that only slightly differs from the general geochemical trend of andesites in variation diagrams (Figure 12). It likely differs in geochemistry due to post-eruptive alteration that enriched Na$_2$O content. Another sample (San Bartolo in Appendix B) is a low-silica dacite (Figure 5) that follows the geochemical trend of andesites (Figure 12).

Alluvium covers a large portion of the field area, specifically in the stream valley and areas of agricultural use (Figure 3). Alluvium described at the El Durazno locality includes clay and sandstones (Appendix B). The clays are dark brown, massive, and slope-formers with ~10% sand-sized minerals, such as feldspars. Resistant sandstones interbedded with the clays are light brown to brown, massive, and medium- to coarse-grained. Colluvium covers the slopes of volcanic domes, scoria cones, and the Pastores fault scarp (Figure 3).
Mammal fossils have not been recovered from the Quaternary section in the study area but have been recovered from other Quaternary sediments near Acambay (Antonio Luiz, oral communication, 2002). These fossils include horse, camel, mastodon, antilopcaprid, and bison (Wade E. Miller, oral communication, 2002). All of this fossil material currently resides in a municipal museum of archeology in Acambay (Antonio Luiz, director).

Structure

The Pastores fault is an east-west trending normal fault that dips between 50-70° to the north and is the southern boundary of the Acambay graben (Suter et al., 1995; Figure 3). A 150-m escarpment has formed along the Pastores fault at the southeastern part of the field area (Figure 38). The Pastores fault is covered in the southwestern part of the field area by the Pleistocene andesitic lava flows and scoria cones (Suter et al., 1995; Figures 3 and 38-39). Minor normal faults cut the sedimentary units in the field area, have approximate offsets of 5-20 m, and have trends that are subparallel to the Pastores fault (Figures 3 and 40-41). Only the largest of these normal faults has sufficient displacement to be mapped.

DISCUSSION

Miocene-Early Pliocene Volcanism and Extension

Mesozoic metasedimentary rocks form the pre-Miocene basement of the Acambay graben (Aguirre-Díaz et al., 2000). The development of the Mexican Volcanic Belt began in the middle to late Miocene (Nixon et al., 1987; Ferrari et al., 1999; Márquez et al., 1999; García-Palomino et al., 2002), which roughly corresponds with the initiation of intra-arc extension in the central sector of the belt. Arc-parallel extensional
faulting began in late Miocene-early Pliocene time (between 8 and 5 Ma) in several areas of the central Mexican Volcanic Belt and approximately 6 Ma in the Acambay graben, based on the Holocene slip rate of Acambay-Tixmadejé fault and its estimated throw (Suter et al., 2001). The Acambay graben has been interpreted as an intra-arc basin of the Mexican Volcanic Belt (Suter et al., 1995; Campos-Enriquez et al., 2000; Suter et al., 2001).

Silicic to intermediate volcanism characterizes the late Miocene and early Pliocene of the Acambay graben, as evidenced by the eruption of the Amealco caldera (4.7 Ma; Aguirre-Díaz and McDowell, 2000), the formation of the San Pedro stratovolcano (early Pliocene; Norato-Cortez, 1998), and the occurrence of Miocene-Pliocene volcanic rocks exposed along the flanks of the graben (Aguirre-Díaz et al., 2000). One dacite sample (Figure 3; Curva in Appendix B) collected from the footwall of the Pastores fault suggests that late Miocene-early Pliocene volcanism in the Acambay graben had a continental arc affinity (Figure 6) with an unusual ferroan geochemistry (Figure 5). Early Pliocene volcanic rocks associated with the Amealco caldera (Aguirre-Díaz and McDowell, 2000) show geochemical similarity to this dacite, including a ferroan geochemical signature.

**Pliocene-Pleistocene Sedimentation and Volcanism**

The Pliocene-Pleistocene stratigraphic succession of the southeastern Acambay graben records a period of significant changes in sedimentation and volcanism. Early Pliocene fluvial and alluvial sedimentation, as represented by the Lagunita beds, transitioned to Tierras Blancas lacustrine deposition in the late Pliocene and early
Pleistocene (Figure 42). Fluvial and alluvial sedimentation of the Cementerio beds returned in the Pleistocene and continues to the present.

During the Pliocene and Pleistocene, volcanism continued but resulted in the formation of small volcanic structures, such as silicic lava domes, mafic to intermediate scoria cones, and associated lava flows. The decrease in size of volcanic structures during the Pliocene and Pleistocene corresponds with a trenchward migration in volcanism throughout the Mexican Volcanic Belt.

*Early Pliocene Lagunita sedimentation*

Relatively coarse-grained sediment is characteristic of Lagunita deposition. Volcaniclastic sedimentary composition and texture as well as fluvial sedimentary structures indicate near-source fluvial and alluvial sedimentation. Local volcanism likely sourced the volcaniclastic sediments and strongly influenced Lagunita deposition, as evidenced by several volcanic breccias, pyroclastic fall tuffs, ash flow tuff, and volcaniclastic sediments. Early Pliocene eruptions from the Amealco caldera and the San Pedro stratovolcano produced volcanic rocks that are the probable sources of Lagunita sediments.

The Pliocene Lagunita tuffs are distal pyroclastic fall deposits and show a marginally peralkaline character that is atypical of continental arc volcanism and generally associated with extensional tectonics (Figure 6). Peralkaline volcanic centers have been found throughout the Mexican Volcanic Belt (Nixon, 1982; Nixon et al., 1987; Verma, 1987; Moore et al., 1994; Márquez et al., 1999; Sheth et al., 2000). In addition, marginally peralkaline volcanic ashes have been found in Guanajuato, which also lies in the central sector of the Mexican Volcanic Belt (Adams, 2001). Therefore, it is very
plausible for the marginally peralkaline Lagunita tuffs to be eruptive products of peralkaline volcanic centers in distant areas of the Mexican Volcanic Belt.

Overburdening of Lagunita sediments by lava flow or ash-flow tuff emplacement may have produced folding and bed deformation in the Lagunita beds, as Lagunita sedimentation corresponds with a period of voluminous volcanism in the Acambay graben. Folding on the same scale (100-m width and 30-m depth) has been observed in the Huckleberry Ridge Tuff in eastern Idaho (Embree, 1999; Embree and Hoggan, 1999). This folding of the Huckleberry Ridge Tuff occurred in response to gravity sliding of the tuff during emplacement on water-saturated, partially-consolidated sediments (Embree, 1999; Embree and Hoggan, 1999). Therefore, folding of the Lagunita beds similar to that of the Huckleberry Ridge Tuff would have required lava flow or ash-flow tuff emplacement in a setting with paleotopographic relief and water-saturated, partially-consolidated sediments, which are conditions that could have existed in fluvial sediments in a graben that was active during the Pliocene. Lagunita deformation differs from the Huckleberry Ridge Tuff folding in that sediments are folded in the Lagunita beds while the ash-flow tuff is the deformed unit in the Huckleberry Ridge Tuff.

Fault-related folding is possible in extensional settings (Schlische, 1995), such as the Acambay graben. A subhorizontal, north-south trending fold axis of the Lagunita fold (Figure 14) is approximately perpendicular to the Pastores fault as well as a fault that is antithetic to the Pastores fault and lies in the graben (Figure 3). Therefore, the Lagunita fold as well as other Lagunita deformation could have formed from transverse folding associated with the Pastores fault and antithetic faults in the graben. Poor understanding of subsurface geology and faults within the Acambay graben and limited
exposure of the Lagunita beds creates difficulty in interpreting the possible relationships of transverse folds with the Pastores fault and intragraben faults.

*Late Pliocene-Early Pleistocene Tierras Blancas sedimentation*

Tierras Blancas sedimentation transitioned from Lagunita fluvial and alluvial processes to dominantly lacustrine deposition (Figure 42). Relatively fine-grained deposition was characteristic of Tierras Blancas sedimentation, as mudstones dominated. The basal sandy mudstone lithofacies corresponds to a period of transition from Lagunita fluvial and alluvial deposition to Tierras Blancas lacustrine sedimentation. Diatomaceous mudstones and massive mudstones dominate the Tierras Blancas stratigraphy and represent periods of relatively deep lacustrine and marginal lacustrine deposition, respectively.

The Tierras Blancas paleolake was likely restricted to a relatively small area (~15 km²), as lacustrine mudstone outcrops are primarily confined to the study area with minor outcrops lying outside the map area by a few kilometers to the west (Figure 3). Previous studies of Neogene lake systems in the Mexican Volcanic Belt describe lacustrine sediments similar to the Tierras Blancas beds but have significantly larger geographic areas (Rosas-Elguera and Urrutia-Fucugauchi, 1998; Isabel-Alcántara and Garduño-Monroy, 1999; Michaud et al., 2000). Despite its small size, the Tierras Blancas paleolake recorded a detailed history of lacustrine sedimentation highlighted by distinct lake level rises and falls.

The interbedded character of the lacustrine and marginal lacustrine mudstones gives stratigraphic evidence of major lake level fluctuations. Volcaniclastic sandstones interbedded with lacustrine mudstones also demonstrate changes in lake level. The
volcaniclastic sandstones have a fluvial character in some areas, as shown by channel-like structures (Figure 25) and normally graded beds, but generally lack common fluvial sedimentary structures. In either case, the volcaniclastic sandstones would not have been deposited in a lacustrine environment but rather in river/stream system or as large sheet flows into the basin.

A common stratigraphic stacking pattern (Figure 43) for the mudstones and sandstones is diatomaceous mudstone (lacustrine), massive mudstone (marginal lacustrine), volcaniclastic sandstone (fluvial/sheet flow), and diatomaceous mudstone (from bottom to top). The gradational contacts between the mudstones indicate relatively gradual changes in lake level at these boundaries (Figure 24). Erosion marks the contacts between sandstones and mudstones, as shown by the sharp irregular contacts (Figure 25). Tool marks on the upper surface of volcaniclastic sandstones suggest erosion followed by a rapid transition to lacustrine deposition, which corresponds with an abrupt rise in lake level (Figure 27). These stratigraphic patterns indicate gradual lake level falls and rapid lake level rises.

Vertebrate burrows also indicate lake level fluctuations because the burrows were likely excavated by small terrestrial rodents (Stephen Hasiotis, oral communication, 2002; Figures 19-22) during periods of very low lake level or temporary disappearance of the lake. After rapid lake level rise, the burrows were subsequently filled with mudstone material washing into the burrows and then organic material from plant development in the lake (Stephen Hasiotis, oral communication, 2002; Figures 20-21). A gradual trend of increased vertebrate burrows and plant material upsection in the lacustrine mudstones suggests a shallowing trend of the lake throughout its history.
As mentioned previously, the volcanic setting of the Tierras Blancas paleolake favored diatom development (Isabel Israde-Alcántara, written communication, 2003). Due to the sensitivity of diatoms to physical and chemical environmental conditions, diatom analysis enables the determination of paleolake conditions (Israde-Alcántara and Garduño-Monroy, 1999; Bradbury, 2000; Michaud et al., 2000). The dominance of planktonic genera (*Aulacoseira* and *Stephanodiscus*) in the diatomaceous mudstones (Figure 23) indicates the paleolake remained a relatively deep, freshwater body through most of its history (Isabel-Alcántara and Garduño-Monroy, 1999; Bradbury, 2000; Michaud et al., 2000). The ratios of planktonic to periphytic genera abundance suggest water depths in excess of 10 m (Barker et al., 1994). Only one sample (AG-03-38) near the base of the lacustrine section gives evidence of relatively low lake level (water depth<10 m; Barker et al., 1994), marked by relatively high abundances of periphytic and tycoplanktonic genera (*Cocconeis*, *Synedra*, *Rophalodia*, *Cymbella*, and *Staurosira*) and relatively low abundances of planktonic taxa (*Aulacoseira* and *Stephanodiscus*) (Figure 23). This diatom assemblage suggests a littoral habitat with high aquatic vegetation because *Cocconeis placentula* and *Synedra ulna* require more light penetration than *Aulacoseira* taxa, and with lake level controlling light penetration, a short period of relatively low lake level must have occurred (Isabel Israde-Alcántara, written communication, 2003). Relatively low lake level at a stratigraphic level near the base of the lacustrine section is expected, as lake level could easily fluctuate during filling and initial establishment of the lake.

Diatom analysis indicating a lacustrine history strongly dominated by a relatively stable, perennial lake appears to contradict stratigraphic and sedimentologic evidence of
major lake level fluctuations. Actually, the apparent lake level stability represented in the diatom analysis probably reflects a sampling bias, where diatoms were only analyzed from samples of Tierras Blancas diatomaceous mudstones. Both sedimentological and diatom evidence suggest a relatively deep lacustrine depositional environment for the diatomaceous mudstone lithofacies. On the other hand, the diatom record might yield evidence of several periods of relatively low lake level if diatoms were analyzed from Tierras Blancas massive mudstones, which represent marginal lacustrine deposition. Therefore, the Tierras Blancas stratigraphic and sedimentologic record best represents the occurrence of lake level fluctuations, while the analyzed diatom record adds to an understanding of depositional environments and paleolake conditions, specifically during periods of relatively high lake level. In addition, the analyzed diatom record demonstrates the stability of high lake level periods, which are then slowly modified by gradual lake level falls.

Based on dominantly mudstone and sparse sandstone lithologies, Tierras Blancas stratigraphy fits the fluvial-lacustrine facies association and, therefore, overfilled lake basin type of Carroll and Bohacs (1999; Figure 44). Carroll and Bohacs (1999) presented facies associations common in lacustrine strata, controls on lacustrine systems, and lake-basin models that are useful in analyzing lacustrine sedimentation. They suggested that tectonic basin subsidence and/or uplift of drainage barriers allow for potential accommodation to produce lake development and associated deposits (Figure 44). In addition, climate controls the supply of sediment and water to a basin and, therefore, strongly affects lake occurrence and character (Figure 44).
In the Pliocene Acambay graben, potential accommodation for lake development may have been produced by basin subsidence (i.e., extensional faulting and graben formation). According to the model of Carroll and Bohacs (1999; Figure 44), relatively high slip rates along basin-bounding faults lead to relatively high rates of basin subsidence, which creates potential accommodation and may cause a transition from fluvial to lacustrine sedimentation. Decreasing fault slip rates and basin subsidence could, in turn, lead to a change from lacustrine to fluvial sedimentation as the basin fills with sediments. In other words, a change in the character of sediments may coincide with variations in basin subsidence (i.e., fault slip rates). Extensional tectonics has been cited as the major control on lake distribution and evolution in other areas of the Mexican Volcanic Belt, including Cuitzeo basin (Israde-Alcántara and Garduño-Monroy, 1999) and the Jalisco triple junction (Rosas-Elguera and Urrutia-Fucugauchi, 1998; Michaud et al., 2000).

In a paleoseismic study of the Acambay-Tixmadejé fault, Langridge et al. (2000) calculated a Holocene slip rate of 0.17 mm/yr based on displacements of sediments exposed in fault trench sites and caused by four late Pleistocene and Holocene ground-rupturing earthquakes. Holocene and Pleistocene sediments, such as the fluvial and alluvial Cementerio beds, likely suggest a period of relatively stable fault slip rates (~0.17 mm/yr), as evidenced by their consistent sedimentary character. The Tierras Blancas beds may represent a brief period of higher fault slip rates (possibly as high as 0.5 mm/yr) during the late Pliocene, as indicated by lacustrine sedimentation (Figure 42). The early Pliocene may be characterized by lower fault slip rates that were similar to the
Holocene, as the Lagunita beds indicate fluvial and alluvial deposition similar to Quaternary deposition.

The formation of drainage barriers, including natural dams produced by lava flow emplacement, also may have created potential accommodation for lacustrine development (Carroll and Bohacs, 1999). This scenario is plausible for the Pliocene Acambay graben given the volcanic arc setting of the graben. In fact, volcanic blockage of stream drainages has caused the occurrence of various lakes in the Mexican Volcanic Belt, including modern Lakes Cuitzeo, Pátzcuaro, and Zirahuén (Chacón-Torres and Múzquiz-Iribe, 1997). The strong influence of volcanism on Tierras Blancas deposition is evidenced by lacustrine mudstones that are dominated by diatomite but include layers rich in ashy material, which likely represent pulses of volcanic activity. In addition, the volcanlastic sandstones of the Tierras Blancas beds are immature and were deposited near their volcanic source rocks. Therefore, sandstone deposition during Tierras Blancas sedimentation was closely related to local volcanism.

The relationship of thin volcanlastic sandstones to local volcanic events points to volcanic forcing as the cause of lake level fluctuation. Volcanic forcing of lake level fluctuation could also explain the pattern of rapid lake level rises and gradual lake level falls during Tierras Blancas sedimentation. Upon emplacement of a lava flow acting as a natural dam, lake level rise and the establishment of a lake would be relatively rapid (Figure 42). Erosion of the natural dam would occur over a longer period of time, allowing for a gradual fall in lake level. Deposition of volcanlastic sand corresponds to the lowest lake level (or temporary lake disappearance), which is followed by the emplacement of another damming lava flow and subsequent resurgence of the lake. An
overall shallowing trend of the lake, evidenced by increased abundance of vertebrate burrows and plant material in the upper Tierras Blancas beds, also suggests volcanic barriers as the cause of lake development because gradual shallowing could correspond to slow erosion of a natural dam. The final disappearance of the lake may have occurred as volcanism ceased to disrupt stream drainages.

Assuming late Pliocene stream drainage patterns in the southeastern Acambay graben were similar to those of the present, lava flow dams would have been located along the southern margin of the graben because present-day streams drain to the southwest (Figure 3) towards the Lerma River. These lava flows likely were associated with volcanism along the southern and western flanks of the San Pedro stratovolcano, including the Cerro Santa Lucía. It is difficult to determine the exact location of these lava flow dams due to erosion.

Climatic variations can potentially play a major role in the development of a lacustrine system (Figure 44). In fact, the role of climate has been evaluated in the development of many Pleistocene lakes in the Mexican Volcanic Belt, including Lake Chapala (Clements, 1962; Tereshchenko et al., 2002) and Lake Pátzcuaro (Bradbury, 2000). The overfilled lake-basin model indicates the Tierras Blancas paleolake was hydrologically open and water inflows from fluvial systems were relatively high (Carroll and Bohacs, 1999; Bohacs et al., 2000). Climatic forcing of lake level in overfilled lake basins is minimal due to open hydrology (Carroll and Bohacs, 1999; Bohacs et al., 2000). Therefore, the role of climate in the establishment of the Tierras Blancas paleolake was likely secondary to those of basin subsidence and volcanic drainage barriers, and the diatom record gives evidence of the role that climate may have contributed. Both
*Aulacoseira ambigu*a and *Aulacoseira granulata*, which are abundant in the Tierras Blancas diatomaceous mudstones, need abundant silica fluxes and tolerate well-mixed, turbid waters (Gasse, 1986). Therefore, *Aulacoseira* taxa indicate flooding episodes and marginally higher lake levels (Bradbury, 2000). In addition, the Tierras Blancas diatoms lack evidence of saline conditions during the lacustrine depositional period.

Consequently, Tierras Blancas diatom assemblages give evidence of paleolake conditions that require a climate with slightly higher precipitation and humidity than present-day conditions in central Mexico (Isabel Israde-Alcántara, written communication, 2003).

Soft sediment and bed deformation in the Tierras Blancas beds records another important aspect of early Pleistocene sedimentation in the study area. The relationship of Tierras Blancas deformation with overlying Quaternary lava flows points to emplacement of volcanics on overburdened, water-saturated, partially-consolidated sediments as the cause of deformation. This type of deformation is similar to Lagunita deformation, noted above, although Lagunita deformation is relatively systematic and more extensive. The nonsystematic character of Tierras Blancas deformation indicates slumping occurred in areas where Quaternary lava flowed over Tierras Blancas sediment on an erosional surface with paleotopographic relief. Mixing of a Quaternary andesite with underlying diatomaceous mudstone in at least two locations lends further support to Quaternary lava flows causing Tierras Blancas deformation (Figure 30). In addition, deformation is generally confined to the upper part of the Tierras Blancas section, and deformation is not present where Quaternary lava flows do not overlie the Tierras Blancas beds. Oriented forces (i.e., faults producing folding) likely did not produce Tierras Blancas bed deformation because deformed bedding orientations lack a systematic pattern (Figure 14).
**Late Pliocene-Pleistocene silicic and intermediate volcanism**

Eruption of silicic (dacites and rhyolites of the Cerro Santa Lucía) and intermediate (undated andesite lava flow) volcanic rocks occurred during the late Pliocene and Pleistocene in the southeastern Acambay graben. These volcanic rocks mark a period of medium- to high-K, magnesian volcanism (Figure 5) with continental arc affinity (Figure 6).

**Pleistocene Cementerio sedimentation**

After late Pliocene-early Pleistocene lacustrine deposition, sedimentation returned to fluvial and alluvial deposition in the Pleistocene, as represented by the sandstones and mudstones of the Cementerio beds (Figure 42).

Volcanism continued to play a major role in sedimentation in Pleistocene time. Tuffaceous sandstones in the Cementerio beds consist of reworked volcanic ash and may consist of detrital vitric volcanic lithic grains from a single source or multiple sources. The two samples from the basal Cementerio sandstone (AG-03-01 and AG-06-01) lie in the stratigraphic interval that includes the Cementerio volcanic ash bed (samples MX-2000-06, AG-2002-04, and AG-2002-08). XRF analyses of the glass fractions of the Cementerio tuff correlate well with electron microprobe analyses of vitric volcanic lithic grains from the basal tuffaceous sandstone bed (Figures 5, 12, and 35). The similarity in glass compositions of the basal tuffaceous sandstone and the tuff indicates the vitric volcanic lithic grains in the sandstone were wholly derived from the Cementerio tuff. The Cementerio tuff and basal tuffaceous sandstones have a high-K, ferroan geochemical signature (Figure 5) but still have other features that correspond with normal continental arc rocks (Figure 6).
Samples (AG-08-01 and AG-04-04) from upper tuffaceous sandstones of the Cementerio beds show broad ranges of volcanic lithic grain compositions (Figures 5 and 35), suggesting derivation of grains from multiple sources. Compositional similarity and geographic proximity to volcanic rocks associated with the Amealco caldera suggests that the sandstones were derived from Amealco-related source rocks. A lack of volcanic lithic grains of basaltic andesite composition provides evidence that the basaltic andesite lava flows are younger than the Cementerio beds. The upper Cementerio sands have a mixed geochemical signature with medium- to high-K, ferroan to magnesian grains (Figure 5), much like Amealco volcanic rocks.

**Quaternary volcanism and sedimentation**

During the Pleistocene, mafic to intermediate volcanic rocks erupted in the southeastern Acambay graben. The basaltic andesites erupted from several vents, as indicated by multiple scoria cones (Figures 3 and 36), but have a close association shown by a consistently tight geochemical grouping (Figures 5 and 12). Like the basaltic andesites, andesite lava flows show a tight geochemical grouping (Figures 5 and 12) indicating an eruptive association, despite multiple scoria cones acting as vents (Figures 3 and 38). Geochemistry of the basaltic andesites and andesites indicates a period of normal continental arc volcanism (Figure 6) with a dominantly medium-K, magnesian geochemical signature (Figure 5).

As a result of the abundance of lava flows, Quaternary alluvium and colluvium contain relatively high percentages of volcanic mineral and lithic grains. Quaternary alluvium and colluvium represent continued fluvial and alluvial sedimentation throughout the Pleistocene and to the present in the Acambay graben.
**Quaternary Tectonics**

As evidenced by the 19 November 1912, $M_s = 6.7$ Acambay earthquake, active normal faulting in the Acambay graben continues to the present (Suter et al., 2001). Minor normal faults in the study area are also active, as they cut Quaternary alluvium (Figures 40-41). These faults are antithetic to the Pastores fault (Figure 3). The southeastern Acambay graben lacks evidence of faults with orientations that suggest a relationship to NE-SW trending Basin and Range extensional structures, such as those in the western Acambay graben (Suter et al., 1995; Aguirre-Díaz et al., 2000).

**Paleoenvironmental Interpretations**

The late Pliocene-early Pleistocene Tierras Blancas beds provide the best data for paleoenvironmental interpretations for the late Cenozoic Acambay graben. As mentioned previously, the Tierras Blancas diatom record suggests that late Pliocene-early Pleistocene climate in the Acambay graben was slightly more humid than the relatively dry present-day climate. Planktonic taxa, such as *Aulacoseira* and *Stephanodiscus*, dominate the diatom assemblage (Figure 23), suggesting relatively high precipitation (Bradbury, 2000). *Aulacoseira ambigua* and *Aulacoseira granulata* bloom in spring and early summer presently in Lake Pátzcuaro and likely followed similar bloom cycles during the Pliocene (Bradbury, 2000). *Stephanodiscus* taxa bloom in fall and winter after the rainy season delivers increased phosphorus to the lake because high phosphorus levels and reduced insolation (e.g., low light conditions) favor *Stephanodiscus* development (Bradbury, 2000). In addition, the Tierras Blancas lacustrine sediments do not contain evaporite deposits and yield few periphytic and tycoplanktonic diatoms, which indicates a lack of saline conditions during the existence of the Tierras Blancas
paleolake (Israde-Alcántara, written communication, 2003). Diatom analysis of the Tierras Blancas beds does not yield any information about possible temperatures of the paleolake.

**CONCLUSIONS**

With the fragmentation of the proto-Cocos Plate into the present-day Rivera and Cocos Plates at about 7 Ma (late Miocene), the modern plate tectonic configuration in central Mexico was established (Nixon, 1982; Verma, 1987; Bandy et al., 2000). Resulting from subduction of the Rivera and Cocos Plates beneath the North American Plate, continental arc volcanism initiated in the middle to late Miocene with the establishment of the Mexican Volcanic Belt (Nixon et al., 1987; Ferrari et al., 1999; Márquez et al., 1999; Sheth et al., 2000; García-Palomo et al., 2002). From the late Miocene-early Pliocene to the early Quaternary, volcanism in the Mexican Volcanic Belt migrated trenchward (Nixon et al., 1987; Ferrari et al., 1999). This southward migration is evident in the region surrounding the Acambay graben because the major eruptive episode in the Acambay graben occurred during the early Pliocene, highlighted by the eruption of the Amealco caldera (Aguirre-Díaz and McDowell, 2000) and the formation of the San Pedro stratovolcano (Norato-Cortez, 1998). Volcanic rocks exposed in the footwall of the Pastores fault erupted during the late Miocene and early Pliocene and coincide with the major eruptive episode in the Acambay graben. Late Pliocene and Pleistocene volcanic structures, such as the Cerro Santa Lucía dacitic dome and intermediate scoria cones, formed in the Acambay graben but are significantly less voluminous than early Pliocene volcanic structures in the graben. Voluminous
Pleistocene volcanism occurred approximately 100 km to the south of the Acambay graben with the development of the Nevado de Toluca stratovolcano (Nixon et al., 1987).

Volcanic rocks erupted in the southeastern Acambay graben show continental arc affinity and generally are typical of volcanic rocks in the Mexican Volcanic Belt (Nixon, 1982; Nixon et al., 1987; Ferrari et al., 2001). The Lagunita tuffs, on the other hand, have a marginally peralkaline character that is unusual for a continental arc setting. These tuffs are distal pyroclastic fall tuffs that are likely associated with peralkaline volcanic centers that have been found in the Mexican Volcanic Belt (Nixon et al., 1987; Verma, 1987; Márquez et al., 1999; Sheth et al., 2000). A ferroan geochemical signature, which is also atypical of a continental arc setting, is shown by Miocene-Pliocene volcanic rocks exposed in the footwall of the Pastores fault and is similar to volcanic rocks associated with the Amealco caldera (Aguirre-Díaz and McDowell, 2000). Ferroan geochemistry is also exhibited by volcanic lithic grains from the Pleistocene Cementerio tuff and tuffaceous sandstones. The Cementerio tuff is a distal pyroclastic fall tuff that is likely associated with a distant volcanic center in the Mexican Volcanic Belt, while the Cementerio tuffaceous sandstones were derived from the volcanic source rocks associated with the Amealco caldera.

Volcanism strongly affected Pliocene-Pleistocene sedimentation, as shown by the dominance of volcaniclastic sediments throughout this time interval, the abundance of diatoms during lacustrine deposition, and variations in sedimentary character influenced by volcanic blockage of stream drainages.

Since the late Miocene and early Pliocene, intra-arc tectonics caused the formation of several arc-parallel graben and half-graben structures in the central sector of
the Mexican Volcanic Belt (Suter et al., 1995; Campos-Enriquez et al., 2000; Suter et al., 2001). The Acambay graben is one of these intra-arc basins, and extensional faulting in the Acambay graben began approximately 6 Ma (Suter et al., 2001). Normal faulting continues to the present in the Acambay graben, as shown by large fault escarpments, Quaternary alluvium cut by faulting, and surface rupture of faults in historic time (Suter et al., 1995; Suter et al., 2001).

Development of the Acambay graben allowed for Pliocene-Pleistocene sedimentation in the southeastern Acambay graben that records an interesting history, including the interruption of alluvial and fluvial deposition by lacustrine sedimentation during the late Pliocene and earliest Pleistocene (Figure 42). Volcanism and tectonics produce the appearance and disappearance of the late Pliocene Tierras Blancas paleolake through volcanic blockage of stream drainages and increased basin subsidence. Despite the small size (~15 km$^2$) and short history (~15 m thick lacustrine section) of the paleolake, the Tierras Blancas lacustrine sediments record lake level fluctuations, which were also probably produced by volcanic and tectonic forces. Nonetheless, climate played a role in the establishment of the Acambay paleolake, as climatic variations are pervasive during late Pliocene-Pleistocene time (Morley and Dworetzky, 1991; Thompson, 1991). In addition, diatom assemblages from the lacustrine sediments indicates a paleoclimate with slightly higher precipitation and humidity than present-day conditions (Isabel Israde-Alcántara, written communication, 2003). Due to the open hydrology of the Acambay paleolake, climatic forcing likely played a secondary role to volcanic and tectonic forcing in the appearance and disappearance of the paleolake.
Blancan (Pliocene) mammal fossils recovered in the Acambay graben add to an important collection of late Cenozoic mammal fossils from central Mexico. This collection contributes to an understanding of the Great American Biotic Interchange by constraining the age of the appearance of South American immigrants into North America (Miller and Carranza-Castañeda, 1984, 2001; Carranza-Castañeda and Miller, 1996; Kowallis et al., 1998; Adams, 2001; Flynn et al., in press).
REFERENCES


Embree, G. F., 1999, Secondary deformation within the Huckleberry Ridge Tuff and subjacent Pliocene units near the Teton Dam, northeastern end of the Snake River plain, Idaho: Geological Society of America Abstracts with Programs, v. 31, no. 4, p. 11.


Márquez, A., Oyarzun, R., Doblas, M., and Verma, S. P., 1999, Alkaline (ocean-island basalt type) and calc-alkaline volcanism in the Mexican Volcanic Belt: A case for plume-related magmatism and propagating rifting at an active margin?: Geology, v. 27, no. 1, p. 51-54.


Figure 1. Index map of major volcanoes, calderas, and fault systems in the Mexican Volcanic Belt. The Acambay graben is in the central portion of the Mexican Volcanic Belt and forms the eastern part of the east-west trending Chapala-Tula fault system. Inset shows regional map of the Mexican Volcanic Belt. Modified after Aguirre-Diaz and McDowell (2000).
Figure 2. Index map of central Mexico showing late Cenozoic basins that yield mammal fossils. Areas in green mark basins that have been studied previously, and the area in red marks the Acambay graben. Modified after Kowallis (oral communication, 2003).
Figure 3. Geologic map of the Tierras Blancas area in the southeastern Acambay graben. Cross-section along line A-A’ was selected to represent the stratigraphic context of the lacustrine Tierras Blancas beds. The numbers of the volcanic samples correspond to the numbering of volcanic rocks in Appendix B. Locality names: LA: Las Arenas, LC: Las Casas, LE: Los Espejos, CE: Cementerio de San Bartolo, SB: San Bartolo, LR: Las Represas, ED: El Durazno, TE: Línea de Teléfono, LP: La Plataforma, CA: La Cascada.
Quaternary alluvium and colluvium


Pleistocene basaltic andesite lava flows associated with scoria cones. Reverse magnetic polarity correlated to the Matuyama chron (1.1-0.78 Ma). Volcanic rock samples: Cascada, Cerrito, Metates, Mondragon, Rio, TB.


Late Pliocene-Pleistocene silicic/intermediate lava flows from a parasitic lava dome (Cerro Santa Lucia) on the eastern flank of the early Pliocene San Pedro stratovolcano (Norato-Cortez, 1998). Volcanic rock samples: D1, D2, DSB, Loma.

Pleistocene Cementerio beds

Pleistocene basaltic andesite lava flows associated with scoria cones. Reverse magnetic polarity correlated to the Matuyama chron (1.1-0.78 Ma).

Late Pliocene-Early Pleistocene Tierras Blancas beds:
Diatomaceous mudstone - white, laminated lacustrine sediments. All samples for diatom analysis.
Volcaniclastic sandstone - thin (5-30 cm) dark gray fluvial/sheet sandstone. Sandstone samples: AG-02-02, AG-02-03, AG-03-02, AG-05-02.
Massive mudstone - brown, massive marginal lacustrine deposits.
Diatomaceous mudstone - white, laminated lacustrine sediments.
Sandy mudstone - tan, massive sandy mudstone. Samples: AG-06-03, AG-10-03.

Early Pliocene Lagunita beds:
Volcanic breccias - gray to brown, lahar/debris flow breccias
Tuff - white, distal pyroclastic fall deposit.
Tuffaceous mudstones and volcaniclastic sandstones - interbedded fluvial and alluvial sediments
Lapilli tuff - thin (3 m) ash flow tuff
Tuff - brown, distal pyroclastic fall deposit.
Volcanic ash sample: AG-2002-12.

Miocene-Pliocene (?) intermediate to silicic volcanic rocks exposed in the footwall of the Pastores fault (Aguirre-Díaz et al., 2000). Volcanic rock sample: Curva.

Mesozoic Tlalpujahua metamorphic-plutonic complex:

Figure 4. Composite stratigraphic section of the southeastern Acambay graben.
Figure 5. XRF analyses for volcanic rocks and electron microprobe analyses for volcanic lithic grains from sandstones. The data are from Appendix B.
Figure 6. (A) Rb versus Y+Nb discrimination diagram for silicic volcanic rocks from the study area (modified after Pearce et al., 1984). (B) Ba versus Nb discrimination diagram of mafic to intermediate volcanic rocks from the study area (modified after Nelson and Tingey, 1997). The data are from Appendix B.
Figure 7. Looking north from the central part of the map area towards a large exposure of Lagunita beds (>30 m thick) in the background. An anticline crops out along the hill in the background. The hill is part of the La Cascada locality.

Figure 8. Photograph of the angular unconformity between the dipping Lagunita beds (foreground) and the horizontal Tierras Blancas beds (background) at the La Plataforma locality. At least 5-6 horse (*Equus simplicidens*) teeth were collected from the sandy mudstone bed of the Tierras Blancas beds here. Hammer for scale.
Figure 9. Tuffaceous mudstone lithofacies of the Lagunita beds in the La Cascada locality. Beds dip at about 60°. White color is characteristic of tuffaceous mudstones, and bedding is not well-defined. The bed in the foreground is approximately 0.5 m thick.

Figure 10. Volcaniclastic sandstone lithofacies of the Lagunita beds in the La Cascada locality. The sandstone is coarse-grained, moderately sorted, and thinly bedded. The yellow notebook is about 20 cm long.
Figure 11. Lapilli tuff lithofacies of the Lagunita beds in the La Cascada locality. The ash flow tuff is almost entirely composed of lapilli-sized pumice. The tuff is cut by a meter-scale normal fault at the right-hand side of the photograph. The ruler on the notebook is 15 cm long.
Figure 12. XRF analyses for volcanic rocks in the study area. The data are from Appendix B.
Figure 13. Volcanic breccia lithofacies of the Lagunita beds in the El Durazno locality. The matrix is light brown, and clast compositions generally range from intermediate to mafic. Camera lens cap for scale.
Figure 14. (A) Equal-area stereoplot of poles to bedding planes from Lagunita beds in the La Cascada locality (see Figures 3 and 7). The east-west trending great circle indicates the trend of the poles. The axial plane of the fold is not plotted but has a north-south trend. (B) Equal-area stereoplot of poles to bedding planes from deformed Tierras Blancas beds throughout the study area. The scatter of the data indicates the deformation in the Tierras Blancas beds is unsystematic.
Figure 15. Lateral and ventral views of the upper jaw and skull of Equus simplicidens found in the Las Casas locality (see Figure 3). The skull was found in the diatomaceous mudstone lithofacies of the Tierras Blancas beds.
Figure 17. Diatomaceous mudstone lithofacies of the Tierras Blancas beds in the Los Espejos locality. White color and fine laminations to thin bedding are characteristic of the diatomaceous mudstone. Pencil for scale.

Figure 18. Leaf imprint, representing *Quercus* sp., collected from the Tierras Blancas diatomaceous mudstone lithofacies. Nearly all of the leaf imprints found and collected (including this sample) as part of this study were taken from an outcrop near the community of San José Toxi, which is located about 4-5 km west of the map area (see Appendix A).
Figure 19. Vertebrate burrow cutting across Tierras Blancas diatomaceous mudstone bedding and filled with dark brown organic material. Photograph taken at the outcrop in San José Toxi. Camera lens cap for scale.

Figure 20. Vertebrate burrows in the Tierras Blancas diatomaceous mudstone. Note the burrow that cuts diagonally across the center of the photograph. The lower portion of the burrow is filled with white material (diatomaceous mudstone sediment), and the upper portion of the burrow is filled with brown organic material. Camera lens cap for scale.
Figure 21. Vertical cross-sectional cut of a vertebrate burrow with diatomaceous mudstone sediment filling the lower half of the burrow and brown organic material filling the upper half. The small vertebrates (probably ground squirrels) used their teeth and/or claws to dig through the sediment, creating the cuspsate edges of the burrow. Pen for scale.

Figure 22. Photo showing density of vertebrate burrows in the Tierras Blancas diatomaceous mudstone. The abundance of vertebrate burrows in this outcrop is relatively high. Note the thin layer of Quaternary alluvium lying unconformably above the Tierras Blancas beds. Photograph was taken in the Las Arenas locality (see Figure 3). Notebook with 15-cm ruler for scale.
Samples | Aulacoseira ambiguа | A. granulata var. angustissima | A. granulata | A. italica | Stephanodiscus excentricus | S. niagarae | Staurosira construens var. venter | Cocconeis placenta var. placentula | Cymbella helmckei | Gomphonema affine | Rophalodia gibba | Synedra ulna | Planktonic | Tycoplanktonic | Periphytic | Total
---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---
AG-01-02 | | | | | | | | | | | | | | 20 | 40 | 20 | 20
AG-02-04 | | | | | | | | | | | | | | 40 | 60 | 20 | 40
AG-03-11 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-12 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-13 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-14 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-15 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-17 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-18 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-19 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-20 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-21 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-22 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-23 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-24 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-25 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-26 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-27 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-28 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-29 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-30 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-31 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-32 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-33 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-34 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-35 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-36 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-37 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-38 | | | | | | | | | | | | | | 20 | 40 | 60 | 80
AG-03-39 | | | | | | | | | | | | | | 20 | 40 | 60 | 80

Figure 23. Diatom assemblages from the Tierras Blancas diatomaceous mudstone lithofacies. The diagrams show counts of each species and totals of planktonic, tycoplanktonic, and periphytic taxa. Modified after Israde-Alcántara (written communication, 2003).
Figure 24. Tierras Blancas beds in the San Bartolo locality. The diatomaceous mudstone lithofacies (white) lies at the base of the outcrop and grades upward into the massive mudstone lithofacies (brown). A thin volcaniclastic sandstone bed (resistant bed) lies on top of the massive mudstone. Diatomaceous mudstone caps the outcrop, lying above the volcaniclastic sandstone.
Figure 25. Photographs of the Tierras Blancas volcaniclastic sandstone bed along a road cut near the San Bartolo locality (see Figure 3). The sandstone is interbedded with diatomaceous mudstone. The basal contact of the sandstone bed is sharp and irregular, indicating erosion of the underlying mudstone. The sandstone bed has a channel-like shape, pinching outward to a very thin bed. The channel shape indicates fluvial deposition, which interrupts lacustrine deposition of the diatomaceous mudstone. Hammer for scale.
Figure 26. Centimeter-scale faulting and convolute bedding in a Tierras Blancas volcaniclastic sandstone bed at the Cementerio de San Bartolo locality. Pencil for scale.

Figure 27. Tool marks on the upper contact of a Tierras Blancas volcaniclastic sandstone bed. The tool marks trend in a NNW-SSE direction and were caused by erosion along the upper contact of the volcaniclastic sandstone during a lake level rise. Photograph was taken in the San Bartolo locality. Pen for scale.
Figure 28. Deformed bedding of the Tierras Blancas section in the San Bartolo locality. On the right-hand side of the photograph, bedding has a subvertical orientation, while bedding on the left-hand side shows horizontal bedding. The bedding orientations are best shown by the dark gray volcaniclastic sandstones. The white sediments are diatomaceous mudstones, and the light brown sediments are massive mudstones.

Figure 29. Deformed Tierras Blancas beds in the Las Casas locality. The white diatomaceous mudstones are dipping at about 30°-40° to the right in the photo, while a thin (15 cm) dark gray volcaniclastic sandstone lying at the base of the diatomaceous mudstone is horizontal.
Figure 30. Quaternary andesite flow overlying Tierras Blancas diatomaceous mudstone in the San Bartolo locality. The andesite flow mixed with the underlying, unconsolidated mudstone during emplacement. Hammer for scale.
Figure 31. Resistant Cementerio beds (gray) capping Tierras Blancas beds (white) in the Línea de Teléfono locality. In this photograph, tuffaceous sandstones comprise most of the Cementerio beds with a volcanic ash bed in lowest part. The exposed Tierras Blancas beds are relatively thin here.

Figure 32. Cementerio beds lying unconformably on top of the Tierras Blancas beds in the Cementerio de San Bartolo locality. Note the interbedded character of the sandstones, mudstones, and volcanic ash beds of the Cementerio section. The volcanic ash (AG-2002-04) was collected from this locality. The total thickness of the sediments in the photograph is approximately 3 m.
Figure 33. Tuffaceous sandstone (tan to buff color) and volcanic ash (white) from the Cementerio beds in the Los Espejos locality. The volcanic ash yielded a zircon fission-track age of 1.20 ± 0.13 Ma (Mercer et al., 2002). The Cementerio-Tierras Blancas contact lies less than one meter below the volcanic ash bed. Hammer for scale.
Figure 34. Coarse-grained tuffaceous sandstone from the Cementerio beds in the San Bartolo locality. Note the lenses of gravel-sized pumice throughout the sandstone. Camera lens cap for scale.
Figure 35. Electron microprobe analyses from volcanic lithic grains in sandstones. The data are in Appendix B.
Figure 36. Looking southwest from the La Cascada locality. Basaltic andesite scoria cones and lava flows dominate the east-central part of the map area (see Figure 5). The La Cascada locality has the thickest exposure of Lagunita beds (see Figure 11).

Figure 37. Quarry in an andesitic scoria cone in the footwall of the Pastores fault in the southern part of the map area (see Figures 3 and 38).
Figure 38. Looking south-southwest towards the field area in the southeastern Acambay graben. The photograph was taken from the north-central park of the field area. The Pastores fault forms the ridge along the horizon with a large escarpment (150 m high) to the left-hand side of the photograph (as marked). The Pastores fault forms a gradual rise towards the right-hand side of the photograph where andesite flows and associated scoria cones obscure fault scarps. Lava flows near these scoria cones have yielded an $^{40}$Ar/$^{39}$Ar age of $0.4 \pm 0.1$ Ma (Suter et al., 1995). A basaltic andesite lava flow crops out in the left-hand foreground of the photograph. Fossiliferous lacustrine sediments lie in the low-lying areas in the middle part of the photograph.
Figure 39. Looking west along the Pastores fault. The photograph was taken from the southwestern part of the field area. The floor of the Acambay graben is the flat farmland in the right-hand side of the photograph, and the footwall of the Pastores fault is in the left-hand side of the photograph. In the foreground, the Pastores fault is not as prominent as the escarpment in the background due to Quaternary andesite lava flows that obscure the fault.

Figure 40. Looking west along the unnamed normal fault mapped in the central part of the field area. The person in the photograph is standing along the plane of the fault, and the Cementerio sandstone bed to the left of the person bends upward near the fault due to fault drag. The eastern flank of the Cerro Santa Lucía lies in the background.
Figure 41. Slickensided surface along the normal fault mapped in the central part of the map area. Faint slickenlines show nearly pure dip-slip movement along the fault. The ruler on the notebook is 15 cm long. The fault is the same as the fault shown in Figure 40, although Figure 40 was photographed near the Línea de Teléfono locality while this photograph was taken in the La Cascada locality (see Figure 3).
Figure 42. Northwest-southeast schematic cross section of Pliocene-Pleistocene sediments in the southeastern Acambay graben, central Mexico. Interpreted volcanic and tectonic forcing events are outlined to the right of the figure.
Figure 43. Measured stratigraphic section from the San Bartolo locality (see Figure 3 and Appendix A). The stratigraphic stacking pattern in the Tierras Blancas beds shown here is typical of Tierras Blancas stratigraphy throughout the study area.
Figure 44. Schematic lake-basin type diagram showing existence and character of nonmarine strata in general and lacustrine strata in particular as a function of both sediment+water supply and potential accommodation. Potential accommodation is the space available for sediment accumulation below the basin's outlet or spillpoint, and it is mainly influenced by basin tectonics and drainage barriers. Sediment+water supply is primarily a function of climatic humidity, along with seasonality, local relief, and bedrock geology. Modified after Bohacs et al. (2000).
Las Arenas (LA)
AG-2002-01
Total thickness: 8.0 m
GPS latitude/longitude:
19°51.357’ N
99°51.897’ W

Locality directions and description: Exit highway 55 at the community of San Bartolo Las Arenas. A farmer’s dirt road leads to the north from San Bartolo Las Arenas across a lava flow that forms a low-lying plateau. The locality lies along the eastern edge of the plateau and downhill from the road. The outcrop generally has a white appearance due to the predominance of the diatomaceous mudstone. A thin layer (~30 cm) of alluvium and volcanic boulders lie on top of the outcrop, which forms a meter-sized ledge and then grades into a shallow slope. The base of the outcrop grades into alluvium and corn fields. Vegetation is generally sparse in the diatomaceous mudstone but grassy in alluvium with surrounding farmland. Local farmers told us the diatomaceous mudstone is not valuable for farming because it is difficult to grow crops in the soil immediately on and next to the diatomaceous mudstone (or “tierra blanca”). Bedding is very irregular with random bed orientations.

Unit A
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 285 cm thick. White color, feels chalky, friable, abundant plant material, few vertebrate burrows, slumped bedding.

Unit B
Tierras Blancas beds. Massive mudstone. 100 cm thick. Coffee brown color, slope-former, gradational contact with Unit A, slumped bedding.

Unit C
Tierras Blancas beds. Sandstone. 15 cm thick. Black color, moderately cemented, 70-80% black lithic sand grains, coarse sand, poorly developed interbeds of black sands and white clay-rich layers, erosional contact with Unit B, laterally discontinuous due to slumped bedding.

Unit D
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 100 cm thick. White color, feels chalky, friable, abundant plant material, abundant vertebrate burrows (10-40 cm in diameter and filled with dark brown, waxy organic material), sharp contact with Unit C, slumped bedding.

Unit E
Cementerio beds. Sandstone. 300 cm thick. Tan to buff color, medium to very coarse sand, gravel lenses, poorly to moderately sorted, angular grains, moderately cemented, 60-70% feldspar, 20-30% quartz, 5-10% lithics, horizontal banding, normal grading, few
trough cross-beds (< 5 cm), soft sediment deformation along contact with Unit D, erosional contact with Unit D in channel-like structure, slumped bedding.
Las Casas (LC)  
AG-2002-02  
Total thickness: 19.1 m  
GPS latitude/longitude:  
19º51.896’ N  
99º51.995’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection, where a left turn leads to the Las Casas locality. The locality lies downhill from a small cluster of homes, from which the locality derives its name. The stratigraphy was measured near a small retention pond. The outcrops generally have a white appearance due to the predominance of the diatomaceous mudstone. A thin layer (~30 cm) of alluvium lies on top of the outcrops, which form a 1-3 m ledge and then grade into a slope. The base of the outcrop grades into alluvium and corn fields. Vegetation is generally sparse in the diatomaceous mudstone but grassy in alluvium with surrounding farmland. Nearly all of the bedding is horizontal with a few tilted slump blocks.

Unit A  
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. >600 cm thick. White color, feels chalky, friable, upper jaw and a few loose teeth of *Equus* were found near the retention pond, plant material is sparse lower in the section and becomes significantly more abundant near brown mudstone, sparse vertebrate burrows.

Unit B  
Tierras Blancas beds. Massive mudstone. 180 cm thick. Coffee brown color, slope-former, gradational contact with Unit A.

Unit C  
Tierras Blancas beds. Sandstone. 15 cm thick. Black color, moderately cemented, 70-80% black lithic sand grains, coarse sand, poorly developed interbeds of black sands and white clay-rich layers, erosional contact with Unit B, laterally continuous where bedding is horizontal, some areas of slumped bedding.

Unit D  
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 300 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant near brown mudstone, sparse vertebrate burrows, sharp contact with Unit C, some areas of slumped bedding.

Unit E  
Tierras Blancas beds. Massive mudstone. 250 cm thick. Coffee brown color, slope-former, gradational contact with Unit D.
Unit F
Tierras Blancas beds. Sandstone. 15 cm thick. Black color, moderately cemented, 70-80% black lithic sand grains, coarse sand, poorly developed interbeds of black sands and white clay-rich layers, erosional contact with Unit E, laterally continuous where bedding is horizontal, some areas of slumped bedding.

Unit G
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 300 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant near upper contact, sparse vertebrate burrows, sharp depositional contact with Unit F, slumped bedding.

Unit H
Cementerio beds. Sandstone. 250 cm thick. Gray color, coarse sand, pumice gravel lenses, poorly to moderately sorted, angular grains, moderately cemented, few trough cross-beds (< 5 cm), erosional contact with Unit G.
Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken

Note: Section was measured in an area with soft sediment deformation. The repeated mudstone and sandstone here may be a result of repetition due to deformation.
Los Espejos (LE)  
AG-2002-03  
Total thickness: 17.2 m  
GPS latitude/longitude:  
19º52.094’ N  
99º52.191’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection. Drive straight ahead through the intersection to continue on the road to the Los Espejos locality. The locality lies to the south of the road near a group of small retention ponds, from which the locality derives its name. The locality is located on the ranch of Sr. Mondragon. The outcrops generally have a white to light gray appearance due to the predominance of the diatomaceous mudstone. The outcrops form a 1-3 m ledge in the upper part of the section and then grade into a slope in the basal part of the section. The base of the outcrop grades into alluvium. Volcanic cobbles and boulders lie in the central part of the drainage and are scattered over some sediment outcrops. Vegetation is grassy throughout with some trees in alluvium that overlies the outcrops. Nearly all of the bedding is horizontal. A east-west trending, west dipping normal fault (~5 m offset) cuts the section but is too small to be mappable. Small springs, fault breccia (1 m zone), and a slickensided surface (115, 75 attitude) with dip slip indicators are evidence of the fault.

Unit A  
Lagunita beds. Tuffaceous mudstone. White color, massive, blocky weathering, ashy.  
Volcanic breccia. Angular volcanic clasts (1-30 cm), clasts have basaltic-andesitic composition, 50% sandy-silty matrix, pumice gravels, strongly cemented, volcanic breccia forms a channel-like structure (2 m high by 4 m wide) in the Tuffaceous mudstone. >300 cm thick.

Unit B  
Tierras Blancas beds. Sandy mudstone. 150 cm thick. Tan color, massive, vertebrate fossils including *Equus* and *Camelops*, unconformably overlies Unit A.

Unit C  
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 760 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, sparse vertebrate burrows, sharp contact with Unit B, horizontal bedding.

Unit D  
Tierras Blancas beds. Sandstone. 30 cm thick. Black color, moderately cemented, 70% black lithic sand grains, 20% quartz grains, 10% other grains, coarse sand, angular to subangular grains, moderately sorted, poorly developed interbeds of black sands and white clay-rich layers, vertebrate fossils including cf. *Rhynchotherium*, erosional contact.
with Unit C with clay rip-up clasts, soft sediment deformation, fines upward to silty sandstone, laterally discontinuous.

Unit E
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 190 cm thick. White color, feels chalky, friable, plant material increases in abundance upsection, sparse vertebrate burrows, sharp depositional contact with Unit D, horizontal bedding.

Unit F
Tierras Blancas beds. Massive mudstone. 110 cm thick. Coffee brown color, slope-former, gradational contact with Unit E.

Unit G
Cementerio beds. Sandstone. 55 cm thick. White to light tan color, coarse sand, pumice, lithic fragments, subangular to subrounded grains, poorly to moderately sorted, poorly developed bedding to massive, some ashy interbeds (~1 cm thick), erosional contact with Unit F with soft sediment deformation in basal part of sandstone.

Unit H
Cementerio beds. Air fall tuff. 5 cm thick. White color, fine-grained glass, pumice, poorly cemented, gradational contact with Unit G, sampled by Dr. Kowallis in 2000 as sample number MX-2000-06.

Unit I
Cementerio beds. Sandstone. 120 cm thick. Tan to gray color, coarse sand, gravel lenses, nearly 100% lithic fragments, pumice (1-10 mm), moderately sorted, subangular to subrounded grains, moderately cemented, trough cross-beds (5-10 cm), gradational contact with Unit H.
Cementerio de San Bartolo (CE)
AG-2002-04
Total thickness: 15.7 m
GPS latitude/longitude:
19º52.116’ N
99º53.151’ W

Locality directions and description: There are a number of routes to arrive at this locality that take about the same time so I will describe one of them. Exit highway 55 at the community of San Bartolo Las Arenas. A road winds to the northwest through Las Arenas towards the community of San Bartolo Lanzados and passes several outcrops of Tierras Blancas beds, including the San Bartolo locality. Continue on the road until you pass over a small bridge and reach a school that lies at the base of a hill. From here, take a right turn towards the San Bartolo Lanzados cemetery, which is in considerable disrepair. (The outer walls of a new cemetery (or panteón) were under construction while we were completing the field work. The new cemetery lies close to the San Bartolo locality.) The locality lies to the north of the road and northeast of the cemetery, from which the locality derives its name. The outcrops generally have a white appearance due to the predominance of the diatomaceous mudstone. The outcrops generally form a 1-3 m ledge in the upper part of the section and then grade into a slope in the basal part of the section. The base of the outcrop grades into alluvium. The section was measured in an arroyo that exposes a ~10 m section. Vegetation is grassy throughout with some trees and brush in the arroyo. The bedding is horizontal.

Unit A
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. >760 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, sparse vertebrate burrows but increase in abundance at top of section, horizontal bedding.

Unit B
Tierras Blancas beds. Massive mudstone. 110 cm thick. Coffee brown color, slope-former, vertebrate fossils including *Equus*, gradational contact with Unit A.

Unit C
Tierras Blancas beds. Sandstone. 15 cm thick. Black color, moderately cemented, coarse sand, angular to subangular grains, moderately sorted, poorly developed interbeds of black sands and white clay-rich layers, erosional contact with Unit B with clay rip-up clasts, soft sediment deformation, laterally continuous.

Unit D
Tierras Blancas beds. Massive mudstone. 275 cm thick. White to tan color, lacks sand and laminations, slope-former, sparse sandstone lenses, sharp depositional contact with Unit C.
Unit E
Cementerio beds. Bedded sandstone. 30 cm thick. Light gray color, coarse sand, ashy sands with thin fine-grained ash interbeds (~1 cm thick), subangular to subrounded grains, moderately sorted, poorly cemented, erosional contact with Unit D with soft sediment deformation in basal part of sandstone.

Unit F
Cementerio beds. Air fall tuff. 40 cm thick. Light gray to white color, fine-grained glass, poorly cemented, gradational contact with Unit E.

Unit G
Cementerio beds. Bedded sandstone. 50 cm thick. Light gray to white color, medium-to fine-grained sand, thin ash interbeds (<1 cm thick), poorly to moderately sorted, poorly cemented, gradational contact with Unit F.

Unit H
Cementerio beds. Massive mudstone. 30 cm thick. White color, sharp depositional contact with Unit G.

Unit I
Cementerio beds. Interbedded sandstones and mudstones. 150 cm thick. Sandstones have gray color with black sands and pumice, coarse sand, moderately sorted, subrounded grains, moderately cemented, some soft sediment deformation along bedding contacts. Mudstones have white color, massive, thin interbeds (1 cm). Erosional contact with Unit H.

Unit J
Cementerio beds. Laminated mudstone. 30 cm thick. White color, finely laminated, sharp depositional contact with Unit I.

Unit K
Cementerio beds. Silty mudstone. 110 cm thick. White to gray color, massive, very fine-grained, soft sediment deformation near basal contact, flute casts on basal contact, sharp erosional contact with Unit J.
Cementerio of San Bartolo (CE)
AG - 04

Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken
San Bartolo (SB)
AG-2002-05
Total thickness: 14.7 m
GPS latitude/longitude:
19º51.768’ N
99º53.119’ W

Locality directions and description: There are a couple of routes to arrive at this locality that take about the same time so I will describe one of them. Exit highway 55 at the community of San Bartolo Las Arenas. A road winds to the northwest through Las Arenas towards the community of San Bartolo Lanzados and passes several outcrops of Tierras Blancas beds. The locality lies to the south of the road in a drainage with scattered volcanic cobbles and boulders. The outcrops generally have a white appearance due to the predominance of the diatomaceous mudstone. The outcrops generally plateau in the upper part of the section and then grade into a slope in the basal part of the section. Vegetation is sparse with some grassy areas. The bedding is extremely deformed and, therefore, the section was measured from several adjacent locations.

Unit A
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. >915 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, sparse vertebrate burrows but increase in abundance at top of section, small horizontal burrows (~1 cm), bedding is generally horizontal in the lower part of the section and is increasingly deformed upsection.

Unit B
Tierras Blancas beds. Massive mudstone. 150 cm thick. Coffee brown color, slope-former, small yellow nodules (1-3 cm), vertebrate fossils including Equus, gradational contact with Unit A.

Unit C
Tierras Blancas beds. Sandstone. 15 cm thick. Black color, moderately cemented, coarse sand, angular to subangular grains, moderately sorted, tool marks on upper contact, erosional contact with Unit B with clay rip-up clasts, soft sediment deformation, laterally continuous but locally discontinuous due to bed deformation.

Unit D
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 300 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, irregular bed attitudes of deformed bedding, sharp depositional contact with Unit C.

Unit E
Cementerio beds. Sandstone. 250 cm thick. Gray color, coarse sand, pumice gravel lenses, poorly sorted, subangular grains, poorly cemented, clay rip-up clasts along contact with Unit D, angular unconformity and erosional contact with Unit D.
Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken
Las Represas (LR)
AG-2002-06
Total thickness: 6.0 m
GPS latitude/longitude:
19º52.497’ N
99º52.812’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection. Drive straight ahead through the intersection to continue on the road where you will pass the Los Espejos locality. Continue on the road as it winds to the northwest, passes through the valley, and up the next plateau. The locality lies to the northeast of the road beyond some corn fields near a drainage with dammed retention ponds. A small ranch road passes next to the outcrop where we measured the section. The outcrops generally have a white to tan appearance. The outcrops form a small ledge (2-3 m) and grade into a slope which steepens towards the stream valley. Vegetation is grassy with some trees and brush. The bedding is horizontal.

Unit A
Lagunita beds. Volcanic breccia. >330 cm thick. Dacitic to andesitic clasts, mostly covered by vegetation.

Unit B
Tierras Blancas beds. Sandy mudstone. 60 cm thick. Tan color, subangular to angular sand grains, massive, unconformably overlies Unit A.

Unit C
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 120 cm thick. White color, feels chalky, friable, abundant plant material, sparse vertebrate burrows, sharp depositional contact with Unit B.

Unit D
Cementerio beds. Sandstone. 85 cm thick. Tan to gray color, medium to coarse sand, fines upward, pumice grains, sorted, moderately cemented, erosional contact with Unit C.

Unit E
Cementerio beds. Air fall tuff. 5 cm thick. White color, fine-grained, sorted, poorly cemented, gradational contact with Unit D.
Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken

Las Represas (LR)
AG - 06

Sedimentary Units
Land Mammal Ages
EPOCH

- BLANCAN
- IRVINGTONIAN

Unconformity

AG-06-01
AG-06-02
AG-06-03

Thickness (cm)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>330</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
</tr>
<tr>
<td>C</td>
<td>120</td>
</tr>
<tr>
<td>D</td>
<td>85</td>
</tr>
<tr>
<td>E</td>
<td>5</td>
</tr>
</tbody>
</table>

Unconformity

Cementerio beds
Tierras Blancas beds
Lagunita beds

PLIOcene
PLEISTOCENE

UNIT
El Durazno (ED)
AG-2002-07
Total thickness: 10.0 m
GPS latitude/longitude:
19º52.643’ N
99º53.129’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection. Drive straight ahead through the intersection to continue on the road where you will pass the Los Espejos locality. Continue on the road as it winds to the northwest, passes through the valley, and up the next plateau passing the Las Represas locality. The locality lies to the northeast of the road downhill from a small peach tree. The colluvium exposures generally have a dark brown appearance. The outcrops form small ridges (2-3 m high) that slope down into the drainage. The bedding of the colluvium dips in the same attitude as the present slope. The Lagunita outcrops are exposed in an arroyo (5-10 m deep). Vegetation is grassy with scattered trees.

Unit A
Lagunita beds. Volcanic breccia and tuffaceous mudstones. >640 cm thick. Brown to orange-brown color, clasts of various compositions (basaltic to silicic), 70-80% angular breccia (1cm-1m), 20-30% clay matrix.

Unit B
Colluvium. Massive muds. 150 cm thick. Dark brown color, some feldspar and quartz grains, unconformably overlies Unit A.

Unit C
Colluvium. Sandstone. 30 cm thick. Light brown color, medium to coarse sand, sharp depositional contact with Unit B, laterally continuous.

Unit D
Colluvium. Sandstone. 30 cm thick. Brown color, coarse sand, depositional contact with Unit C, laterally discontinuous.

Unit E
Colluvium. Massive muds. 150 cm thick. Dark brown color, 10% feldspar and quartz grains, 90% clay, depositional contact with Unit D.
El Durazno (ED)
AG - 07

Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken
Línea de Teléfono (TE)
AG-2002-08
Total thickness: 12.9 m
GPS latitude/longitude:
19º52.610’ N
99º52.554’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection. Take a right turn at the intersection to follow a road that winds north and northeast along the southern flank of a scoria cone, passing a quarry where scoria is mined for road base. Continue on the road until it approaches a second scoria cone to the north and reaches an intersection. Take a left turn to follow a road that winds southwest by the La Cascada locality and to a ranch. The locality lies to the north of the road near a telephone line, from which the locality derives its name. The outcrops generally have a white appearance due to the predominance of the diatomaceous mudstone. A lava flow covers the slope uphill from the outcrops of Tierras Blancas beds. The outcrops generally form a 1-2 m ledge in the upper part of the section and then grade into a slope in the basal part of the section. The base of the outcrop grades into alluvium. Vegetation is grassy throughout with some trees and brush. The bedding is horizontal.

Unit A
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. >300 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, sparse vertebrate burrows, horizontal bedding, upper part of section lacks laminations.

Unit B
Cementerio beds. Bedded sandstone. 60 cm thick. Light gray to white color, medium to coarse sand, tuffaceous sand, poorly cemented, white mudstone interbeds (1 cm), erosional contact with Unit A.

Unit C
Cementerio beds. Massive mudstone. 30 cm thick. White color, sharp depositional contact with Unit B.

Unit D
Cementerio beds. Interbedded sandstones and mudstones. 150 cm thick. Sandstones have gray color with black sands and pumice, coarse sand, moderately sorted, subrounded grains, moderately cemented, some soft sediment deformation along bedding contacts. Mudstones have white color, massive, thin interbeds (1 cm). Erosional contact with Unit C.

Unit E
Cementerio beds. Massive mudstone. 150 cm thick. White color, fractured, cemented, sharp depositional contact with Unit D.
Unit F
Cementerio beds. Sandy mudstone. 60 cm thick. Tan color, massive, moderately cemented, depositional contact with Unit E.

Unit G
Cementerio beds. Massive mudstone. 150 cm thick. Brown color, slope former, poorly cemented, gradational contact with Unit F.

Unit H
Cementerio beds. Sandstone. 90 cm thick. Gray color, coarse sand, pumice gravel, lithic fragments, quartz grains, sorted, faint bedding, erosional contact with Unit G.

Unit I
Lava flow. Basaltic andesite. >300 cm thick. Cobbles and boulders have washed downhill.
Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken
La Plataforma (LP)
AG-2002-10
Total thickness: 12.3 m
GPS latitude/longitude:
19º52.000’ N
99º52.000’ W

Locality directions and description: Exit highway 55 at the community of Tierras Blancas. A cement road winds downhill to the west through Tierras Blancas until it reaches an intersection. Drive straight ahead through the intersection to continue on the road where you will pass the Los Espejos locality. Continue on the road as it winds to the northwest, passes through the valley, and up the next plateau. The locality lies to the north of the road near a sharp turn in the road as it reaches the top of the plateau. The outcrops generally have a white to light gray appearance due to the predominance of the diatomaceous mudstone. The outcrops form a 1-3 m ledge in the upper part of the section and then grade into a slope in the basal part of the section. The base of the outcrop forms a 10-m wide platform ends with a steep slope to the stream valley. Vegetation is grassy with scattered trees and brush. Nearly all of the bedding is horizontal.

Unit A
Lagunita beds. Volcaniclastic sandstone. Light gray color, felsic lithic fragments, moderately sorted, angular grains, bed thickness is 0.5 m, faint bedding, fining upward cycles. Tuffaceous mudstone. White color, massive, blocky weathering, ashy. Volcanic breccia. Angular volcanic clasts (1-30 cm), primarily silicic clasts, 20-40% sandy-silty matrix, pumice gravels, strongly cemented. Lagunita beds are tilted. >300 cm thick.

Unit B
Tierras Blancas beds. Sandy mudstone. 150 cm thick. Tan color, massive, vertebrate fossils including *Equus*, root casts, 10-20% sand-sized lithic fragments, volcanic clasts (10 cm) near lower contact, moderately cemented, fines upward, unconformably overlies Unit A.

Unit C
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 450 cm thick. White color, feels chalky, friable, plant material is sparse lower in the section and becomes significantly more abundant upsection, sparse vertebrate burrows in lower part of section and increasing in abundance in upper part of section, sharp depositional contact with Unit B, horizontal bedding, 1 thin discontinuous sandstone interbed (1 cm thick).

Unit D
Tierras Blancas beds. Massive mudstone. 150 cm thick. Brown color, slope former, gradational contact with Unit C.
Unit E
Cementerio beds. Sandstone. 180 cm thick. Gray to black to tan color, medium to coarse sand, nearly 100% lithic fragments, pumice (1-10 mm), gravel lenses, moderately sorted, subangular to subrounded grains, moderately cemented, trough cross-beds (5-10 cm), erosional contact with Unit D.
La Plataforma (LP)
AG - 10

Key to Lithology and Symbols
- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken

Sedimentary Units
- Land Mammal Ages
- EPOCH
- Unconformity

<table>
<thead>
<tr>
<th>EPOCH</th>
<th>Land Mammal Ages</th>
<th>Sedimentary Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLEISTOCENE</td>
<td>Irvingtonian</td>
<td>Tierras Blancas beds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lagunita beds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blancan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLEISTOCENE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLEISTOCENE</td>
</tr>
</tbody>
</table>

- Tierras Blancas beds
- Lagunita beds
- Blancan

Unconformity

Unit
- Tierras Blancas beds
- Lagunita beds
- Blancan

Thickness (cm)
- 300
- 150
- 450
- 150
- 180

Sample collected

Photograph taken

AG-10-01
AG-10-02
AG-10-03
San José Toxi
AG-2002-11
Total thickness: 5.0 m
GPS latitude/longitude:
19°51.968’ N
099°56.330’ W

Locality directions and description: Exit the circular highway around Atlacomulco towards Shomegé. The highway will lead towards the community of San José Toxi, which is located about 10 km northwest of Atlacomulco. The locality lies to the north of the road near a school and cemetery. The outcrops generally have a white to light gray appearance from the Tierras Blancas diatomaceous mudstone. The outcrops lie in a quarry, which exposes a vertical section of the mudstones.

Unit A
Tierras Blancas beds. Finely laminated, diatomaceous mudstone. 500 cm thick. White color, feels chalky, friable, plant material is abundant throughout the section, vertebrate burrows are abundant throughout the section, horizontal bedding, leaf imprints were found in abundance along some horizons.
Key to Lithology and Symbols

- Massive coarse sands
- Bedded sands
- Cross-bedded sands
- Cross-stratified sands and gravels
- Tuffaceous sands and gravels
- Volcanic ash bed
- Massive muds
- Diatomaceous, laminated mudstones
- Sandy muds
- Tuffaceous, massive mudstones
- Volcanic breccia
- Vertebrates
- Vertebrate burrows
- Slumped bedding
- Plant material
- Sample collected
- Photograph taken
### Appendix B. XRF Analyses for Volcanic Rocks and Ashes (normalized to 100% on a volatile-free basis)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Symbol</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3^*$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>Total</th>
<th>LOI</th>
<th>Anal Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-2000-06</td>
<td>1</td>
<td>75.62</td>
<td>0.12</td>
<td>13.64</td>
<td>1.48</td>
<td>0.04</td>
<td>0.13</td>
<td>1.10</td>
<td>3.23</td>
<td>4.60</td>
<td>0.05</td>
<td>100</td>
<td>3.91</td>
<td>99.41</td>
</tr>
<tr>
<td>AG-2002-04</td>
<td>2</td>
<td>75.49</td>
<td>0.11</td>
<td>13.63</td>
<td>1.49</td>
<td>0.04</td>
<td>0.21</td>
<td>1.14</td>
<td>3.40</td>
<td>4.44</td>
<td>0.04</td>
<td>100</td>
<td>3.86</td>
<td>99.52</td>
</tr>
<tr>
<td>AG-2002-08</td>
<td>3</td>
<td>75.63</td>
<td>0.09</td>
<td>13.56</td>
<td>1.55</td>
<td>0.04</td>
<td>0.11</td>
<td>1.09</td>
<td>3.26</td>
<td>4.63</td>
<td>0.03</td>
<td>100</td>
<td>3.82</td>
<td>99.82</td>
</tr>
<tr>
<td>AG-2002-12</td>
<td>4</td>
<td>76.01</td>
<td>0.16</td>
<td>11.70</td>
<td>2.76</td>
<td>0.05</td>
<td>0.17</td>
<td>0.27</td>
<td>3.35</td>
<td>5.52</td>
<td>0.00</td>
<td>100</td>
<td>4.88</td>
<td>100.31</td>
</tr>
<tr>
<td>AG-2002-14</td>
<td>5</td>
<td>76.75</td>
<td>0.18</td>
<td>11.94</td>
<td>1.73</td>
<td>0.05</td>
<td>0.06</td>
<td>0.24</td>
<td>2.94</td>
<td>6.08</td>
<td>0.02</td>
<td>100</td>
<td>4.42</td>
<td>100.11</td>
</tr>
<tr>
<td>ARENAS</td>
<td>6</td>
<td>62.62</td>
<td>1.14</td>
<td>15.90</td>
<td>6.01</td>
<td>0.10</td>
<td>2.77</td>
<td>5.22</td>
<td>3.45</td>
<td>2.52</td>
<td>0.27</td>
<td>100</td>
<td>0.82</td>
<td>99.74</td>
</tr>
<tr>
<td>CERRO</td>
<td>7</td>
<td>62.75</td>
<td>1.14</td>
<td>15.85</td>
<td>5.91</td>
<td>0.10</td>
<td>2.71</td>
<td>5.17</td>
<td>3.51</td>
<td>2.57</td>
<td>0.29</td>
<td>100</td>
<td>0.89</td>
<td>100.24</td>
</tr>
<tr>
<td>CHOSTO</td>
<td>8</td>
<td>62.78</td>
<td>1.12</td>
<td>15.82</td>
<td>6.02</td>
<td>0.10</td>
<td>2.69</td>
<td>5.15</td>
<td>3.58</td>
<td>2.48</td>
<td>0.26</td>
<td>100</td>
<td>0.89</td>
<td>100.32</td>
</tr>
<tr>
<td>EJIDO</td>
<td>9</td>
<td>62.08</td>
<td>1.20</td>
<td>15.74</td>
<td>6.22</td>
<td>0.10</td>
<td>2.87</td>
<td>5.50</td>
<td>3.54</td>
<td>2.46</td>
<td>0.29</td>
<td>100</td>
<td>0.72</td>
<td>98.86</td>
</tr>
<tr>
<td>GARABATO</td>
<td>10</td>
<td>61.03</td>
<td>1.11</td>
<td>15.66</td>
<td>5.81</td>
<td>0.10</td>
<td>2.67</td>
<td>5.10</td>
<td>5.68</td>
<td>2.63</td>
<td>0.21</td>
<td>100</td>
<td>0.64</td>
<td>101.63</td>
</tr>
<tr>
<td>LANCHADOS</td>
<td>11</td>
<td>62.64</td>
<td>1.13</td>
<td>15.90</td>
<td>6.01</td>
<td>0.10</td>
<td>2.67</td>
<td>5.16</td>
<td>3.57</td>
<td>2.55</td>
<td>0.27</td>
<td>100</td>
<td>0.72</td>
<td>100.44</td>
</tr>
<tr>
<td>LOMA</td>
<td>12</td>
<td>59.57</td>
<td>1.07</td>
<td>17.98</td>
<td>6.80</td>
<td>0.11</td>
<td>2.74</td>
<td>6.30</td>
<td>3.86</td>
<td>1.29</td>
<td>0.28</td>
<td>100</td>
<td>0.40</td>
<td>100.87</td>
</tr>
<tr>
<td>SAN BARTOLO</td>
<td>13</td>
<td>63.13</td>
<td>1.11</td>
<td>15.88</td>
<td>5.76</td>
<td>0.09</td>
<td>2.57</td>
<td>5.08</td>
<td>3.59</td>
<td>2.51</td>
<td>0.28</td>
<td>100</td>
<td>0.71</td>
<td>99.40</td>
</tr>
<tr>
<td>SUR</td>
<td>14</td>
<td>62.45</td>
<td>1.14</td>
<td>15.96</td>
<td>6.04</td>
<td>0.10</td>
<td>2.77</td>
<td>5.25</td>
<td>3.32</td>
<td>2.67</td>
<td>0.29</td>
<td>100</td>
<td>0.89</td>
<td>99.24</td>
</tr>
<tr>
<td>TEJOCOTE</td>
<td>15</td>
<td>62.34</td>
<td>1.18</td>
<td>15.99</td>
<td>6.00</td>
<td>0.10</td>
<td>2.85</td>
<td>5.39</td>
<td>3.45</td>
<td>2.43</td>
<td>0.28</td>
<td>100</td>
<td>0.78</td>
<td>99.15</td>
</tr>
<tr>
<td>CASCADA</td>
<td>16</td>
<td>56.06</td>
<td>1.55</td>
<td>16.69</td>
<td>8.05</td>
<td>0.13</td>
<td>4.36</td>
<td>8.44</td>
<td>3.20</td>
<td>1.21</td>
<td>0.31</td>
<td>100</td>
<td>0.76</td>
<td>99.45</td>
</tr>
<tr>
<td>CERRITO</td>
<td>17</td>
<td>53.81</td>
<td>1.72</td>
<td>16.11</td>
<td>9.19</td>
<td>0.15</td>
<td>6.52</td>
<td>8.01</td>
<td>3.16</td>
<td>0.93</td>
<td>0.39</td>
<td>100</td>
<td>0.29</td>
<td>99.30</td>
</tr>
<tr>
<td>METATES</td>
<td>18</td>
<td>56.56</td>
<td>1.54</td>
<td>16.80</td>
<td>7.69</td>
<td>0.12</td>
<td>4.20</td>
<td>8.24</td>
<td>3.42</td>
<td>1.12</td>
<td>0.32</td>
<td>100</td>
<td>0.34</td>
<td>98.43</td>
</tr>
<tr>
<td>MONDRAGON</td>
<td>19</td>
<td>55.28</td>
<td>1.61</td>
<td>16.82</td>
<td>8.39</td>
<td>0.13</td>
<td>4.19</td>
<td>8.96</td>
<td>3.24</td>
<td>1.03</td>
<td>0.34</td>
<td>100</td>
<td>1.95</td>
<td>99.99</td>
</tr>
<tr>
<td>RIO</td>
<td>20</td>
<td>54.53</td>
<td>1.50</td>
<td>16.15</td>
<td>8.31</td>
<td>0.11</td>
<td>5.00</td>
<td>9.85</td>
<td>3.12</td>
<td>1.12</td>
<td>0.29</td>
<td>100</td>
<td>2.99</td>
<td>100.31</td>
</tr>
<tr>
<td>TB</td>
<td>21</td>
<td>54.70</td>
<td>1.57</td>
<td>16.36</td>
<td>8.73</td>
<td>0.14</td>
<td>5.57</td>
<td>8.38</td>
<td>3.22</td>
<td>1.02</td>
<td>0.33</td>
<td>100</td>
<td>-0.01</td>
<td>100.14</td>
</tr>
<tr>
<td>CURVA</td>
<td>22</td>
<td>64.97</td>
<td>0.76</td>
<td>17.41</td>
<td>4.82</td>
<td>0.03</td>
<td>1.09</td>
<td>5.90</td>
<td>3.60</td>
<td>1.27</td>
<td>0.14</td>
<td>100</td>
<td>2.57</td>
<td>99.16</td>
</tr>
<tr>
<td>D1</td>
<td>23</td>
<td>71.37</td>
<td>0.38</td>
<td>14.74</td>
<td>2.59</td>
<td>0.05</td>
<td>0.93</td>
<td>2.80</td>
<td>3.42</td>
<td>3.62</td>
<td>0.10</td>
<td>100</td>
<td>1.67</td>
<td>100.28</td>
</tr>
<tr>
<td>D2</td>
<td>24</td>
<td>68.69</td>
<td>0.69</td>
<td>17.48</td>
<td>4.16</td>
<td>0.06</td>
<td>1.42</td>
<td>2.13</td>
<td>2.77</td>
<td>2.57</td>
<td>0.03</td>
<td>100</td>
<td>4.01</td>
<td>100.71</td>
</tr>
<tr>
<td>DSB</td>
<td>25</td>
<td>68.25</td>
<td>0.61</td>
<td>16.01</td>
<td>3.67</td>
<td>0.06</td>
<td>1.00</td>
<td>4.14</td>
<td>3.72</td>
<td>2.37</td>
<td>0.16</td>
<td>100</td>
<td>0.93</td>
<td>99.61</td>
</tr>
</tbody>
</table>

Note: Reported oxide data are in wt%. XRF = X-ray fluorescence spectrometry.
Appendix B. XRF Analyses for Volcanic Rocks and Ashes

<table>
<thead>
<tr>
<th>Sample</th>
<th>S</th>
<th>Sc</th>
<th>V</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Rb</th>
<th>Sr</th>
<th>Y</th>
<th>Zr</th>
<th>Nb</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-2000-06</td>
<td>34</td>
<td>1.3</td>
<td>0</td>
<td>19</td>
<td>18</td>
<td>0</td>
<td>42</td>
<td>152</td>
<td>124</td>
<td>27</td>
<td>128</td>
<td>14</td>
<td>635</td>
</tr>
<tr>
<td>AG-2002-04</td>
<td>28</td>
<td>0.0</td>
<td>0</td>
<td>17</td>
<td>17</td>
<td>0</td>
<td>40</td>
<td>150</td>
<td>131</td>
<td>27</td>
<td>130</td>
<td>13</td>
<td>662</td>
</tr>
<tr>
<td>AG-2002-08</td>
<td>31</td>
<td>1.2</td>
<td>0</td>
<td>17</td>
<td>16</td>
<td>0</td>
<td>36</td>
<td>151</td>
<td>122</td>
<td>27</td>
<td>126</td>
<td>13</td>
<td>624</td>
</tr>
<tr>
<td>AG-2002-12</td>
<td>38</td>
<td>0.0</td>
<td>1</td>
<td>18</td>
<td>20</td>
<td>0</td>
<td>131</td>
<td>178</td>
<td>20</td>
<td>99</td>
<td>717</td>
<td>49</td>
<td>39</td>
</tr>
<tr>
<td>AG-2002-14</td>
<td>33</td>
<td>0.0</td>
<td>0</td>
<td>19</td>
<td>18</td>
<td>0</td>
<td>67</td>
<td>171</td>
<td>10</td>
<td>66</td>
<td>384</td>
<td>43</td>
<td>40</td>
</tr>
<tr>
<td>ARENAS</td>
<td>40</td>
<td>16.9</td>
<td>81</td>
<td>60</td>
<td>35</td>
<td>12</td>
<td>66</td>
<td>67</td>
<td>405</td>
<td>26</td>
<td>207</td>
<td>10</td>
<td>485</td>
</tr>
<tr>
<td>CERRO</td>
<td>41</td>
<td>16.1</td>
<td>81</td>
<td>63</td>
<td>37</td>
<td>14</td>
<td>69</td>
<td>68</td>
<td>412</td>
<td>32</td>
<td>209</td>
<td>11</td>
<td>503</td>
</tr>
<tr>
<td>CHOSTO</td>
<td>45</td>
<td>15.5</td>
<td>85</td>
<td>58</td>
<td>34</td>
<td>11</td>
<td>67</td>
<td>67</td>
<td>396</td>
<td>26</td>
<td>207</td>
<td>11</td>
<td>471</td>
</tr>
<tr>
<td>EJIDO</td>
<td>41</td>
<td>16.0</td>
<td>89</td>
<td>65</td>
<td>39</td>
<td>17</td>
<td>73</td>
<td>63</td>
<td>435</td>
<td>29</td>
<td>216</td>
<td>14</td>
<td>488</td>
</tr>
<tr>
<td>GARABATO</td>
<td>39</td>
<td>14.1</td>
<td>80</td>
<td>62</td>
<td>36</td>
<td>14</td>
<td>70</td>
<td>69</td>
<td>412</td>
<td>29</td>
<td>206</td>
<td>12</td>
<td>495</td>
</tr>
<tr>
<td>LANCHAS</td>
<td>92</td>
<td>16.7</td>
<td>82</td>
<td>58</td>
<td>36</td>
<td>12</td>
<td>70</td>
<td>67</td>
<td>420</td>
<td>28</td>
<td>208</td>
<td>16</td>
<td>492</td>
</tr>
<tr>
<td>LOMA</td>
<td>39</td>
<td>21.0</td>
<td>63</td>
<td>37</td>
<td>24</td>
<td>10</td>
<td>82</td>
<td>14</td>
<td>579</td>
<td>17</td>
<td>114</td>
<td>5</td>
<td>429</td>
</tr>
<tr>
<td>SAN BARTOLO</td>
<td>38</td>
<td>17.3</td>
<td>79</td>
<td>58</td>
<td>34</td>
<td>11</td>
<td>67</td>
<td>70</td>
<td>407</td>
<td>28</td>
<td>207</td>
<td>14</td>
<td>511</td>
</tr>
<tr>
<td>SUR</td>
<td>34</td>
<td>15.4</td>
<td>81</td>
<td>61</td>
<td>38</td>
<td>17</td>
<td>73</td>
<td>66</td>
<td>424</td>
<td>34</td>
<td>210</td>
<td>11</td>
<td>509</td>
</tr>
<tr>
<td>TEJOCOTEO</td>
<td>38</td>
<td>16.6</td>
<td>86</td>
<td>63</td>
<td>39</td>
<td>15</td>
<td>74</td>
<td>66</td>
<td>439</td>
<td>29</td>
<td>212</td>
<td>12</td>
<td>515</td>
</tr>
<tr>
<td>CASCADA</td>
<td>42</td>
<td>25.8</td>
<td>152</td>
<td>140</td>
<td>32</td>
<td>13</td>
<td>80</td>
<td>23</td>
<td>717</td>
<td>30</td>
<td>117</td>
<td>7</td>
<td>310</td>
</tr>
<tr>
<td>CERRITO</td>
<td>49</td>
<td>29.3</td>
<td>153</td>
<td>285</td>
<td>76</td>
<td>15</td>
<td>80</td>
<td>12</td>
<td>580</td>
<td>25</td>
<td>167</td>
<td>5</td>
<td>328</td>
</tr>
<tr>
<td>METATES</td>
<td>45</td>
<td>26.6</td>
<td>156</td>
<td>120</td>
<td>26</td>
<td>8</td>
<td>73</td>
<td>23</td>
<td>688</td>
<td>30</td>
<td>123</td>
<td>4</td>
<td>321</td>
</tr>
<tr>
<td>MONDRAGON</td>
<td>96</td>
<td>30.4</td>
<td>161</td>
<td>161</td>
<td>37</td>
<td>14</td>
<td>80</td>
<td>18</td>
<td>716</td>
<td>28</td>
<td>127</td>
<td>8</td>
<td>716</td>
</tr>
<tr>
<td>RIO</td>
<td>59</td>
<td>35.0</td>
<td>155</td>
<td>188</td>
<td>42</td>
<td>13</td>
<td>78</td>
<td>22</td>
<td>670</td>
<td>26</td>
<td>118</td>
<td>7</td>
<td>280</td>
</tr>
<tr>
<td>TB</td>
<td>47</td>
<td>29.7</td>
<td>157</td>
<td>201</td>
<td>43</td>
<td>12</td>
<td>76</td>
<td>17</td>
<td>642</td>
<td>25</td>
<td>129</td>
<td>4</td>
<td>277</td>
</tr>
<tr>
<td>CURVA</td>
<td>50</td>
<td>15.0</td>
<td>64</td>
<td>36</td>
<td>19</td>
<td>4</td>
<td>59</td>
<td>14</td>
<td>700</td>
<td>12</td>
<td>38</td>
<td>0</td>
<td>275</td>
</tr>
<tr>
<td>D1</td>
<td>41</td>
<td>5.8</td>
<td>26</td>
<td>24</td>
<td>20</td>
<td>0</td>
<td>41</td>
<td>105</td>
<td>426</td>
<td>21</td>
<td>85</td>
<td>11</td>
<td>524</td>
</tr>
<tr>
<td>D2</td>
<td>65</td>
<td>4.7</td>
<td>44</td>
<td>30</td>
<td>27</td>
<td>0</td>
<td>37</td>
<td>59</td>
<td>372</td>
<td>8</td>
<td>114</td>
<td>9</td>
<td>768</td>
</tr>
<tr>
<td>DSB</td>
<td>52</td>
<td>11.4</td>
<td>49</td>
<td>27</td>
<td>22</td>
<td>0</td>
<td>27</td>
<td>53</td>
<td>803</td>
<td>15</td>
<td>28</td>
<td>6</td>
<td>468</td>
</tr>
</tbody>
</table>

Note: Reported results are in parts per million (ppm). XRF = X-ray fluorescence spectrometry.
## Appendix B. Locations for Volcanic Rock Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock Type</th>
<th>Lat (N)</th>
<th>Long (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-2000-06</td>
<td>Rhyolite ash</td>
<td>19°52'05.6&quot;</td>
<td>099°52'11.5&quot;</td>
</tr>
<tr>
<td>AG-2002-04</td>
<td>Rhyolite ash</td>
<td>19°52'07.0&quot;</td>
<td>099°53'09.1&quot;</td>
</tr>
<tr>
<td>AG-2002-08</td>
<td>Rhyolite ash</td>
<td>19°52'36.6&quot;</td>
<td>099°52'33.2&quot;</td>
</tr>
<tr>
<td>AG-2002-12</td>
<td>Rhyolite ash</td>
<td>19°52'50.1&quot;</td>
<td>099°52'58.7&quot;</td>
</tr>
<tr>
<td>AG-2002-14</td>
<td>Rhyolite ash</td>
<td>19°52'07.5&quot;</td>
<td>099°52'39.4&quot;</td>
</tr>
<tr>
<td>ARENAS</td>
<td>Andesite</td>
<td>19°51'40.3&quot;</td>
<td>099°51'54.3&quot;</td>
</tr>
<tr>
<td>CERRO</td>
<td>Andesite</td>
<td>19°50'57.2&quot;</td>
<td>099°53'09.8&quot;</td>
</tr>
<tr>
<td>CHOSTO</td>
<td>Andesite</td>
<td>19°51'24.2&quot;</td>
<td>099°54'20.1&quot;</td>
</tr>
<tr>
<td>EJIDO</td>
<td>Andesite</td>
<td>19°50'18.2&quot;</td>
<td>099°52'53.7&quot;</td>
</tr>
<tr>
<td>GARABATO</td>
<td>Andesite</td>
<td>19°51'16.7&quot;</td>
<td>099°52'31.9&quot;</td>
</tr>
<tr>
<td>LANZADOS</td>
<td>Andesite</td>
<td>19°51'34.4&quot;</td>
<td>099°52'54.9&quot;</td>
</tr>
<tr>
<td>LOMA</td>
<td>Andesite</td>
<td>19°52'36.0&quot;</td>
<td>099°53'17.7&quot;</td>
</tr>
<tr>
<td>SAN BARTOLO</td>
<td>Andesite</td>
<td>19°51'46.1&quot;</td>
<td>099°53'07.2&quot;</td>
</tr>
<tr>
<td>SUR</td>
<td>Andesite</td>
<td>19°50'49.5&quot;</td>
<td>099°53'55.4&quot;</td>
</tr>
<tr>
<td>TEJOCOTE</td>
<td>Andesite</td>
<td>19°51'23.5&quot;</td>
<td>099°53'46.8&quot;</td>
</tr>
<tr>
<td>CASCADA</td>
<td>Basaltic andesite</td>
<td>19°52'49.9&quot;</td>
<td>099°52'40.7&quot;</td>
</tr>
<tr>
<td>CERRITO</td>
<td>Basaltic andesite</td>
<td>19°52'30.4&quot;</td>
<td>099°51'48.7&quot;</td>
</tr>
<tr>
<td>METATES</td>
<td>Basaltic andesite</td>
<td>19°53'41.0&quot;</td>
<td>099°51'19.3&quot;</td>
</tr>
<tr>
<td>MONDRAGON</td>
<td>Basaltic andesite</td>
<td>19°52'31.1&quot;</td>
<td>099°52'23.8&quot;</td>
</tr>
<tr>
<td>RIO</td>
<td>Basaltic andesite</td>
<td>19°52'51.3&quot;</td>
<td>099°52'42.6&quot;</td>
</tr>
<tr>
<td>TB</td>
<td>Basaltic andesite</td>
<td>19°52'03.8&quot;</td>
<td>099°51'35.9&quot;</td>
</tr>
<tr>
<td>CURVA</td>
<td>Dacite</td>
<td>19°50'43.1&quot;</td>
<td>099°51'30.0&quot;</td>
</tr>
<tr>
<td>D1</td>
<td>Rhyolite</td>
<td>19°52'47.8&quot;</td>
<td>099°53'10.6&quot;</td>
</tr>
<tr>
<td>D2</td>
<td>Dacite</td>
<td>19°53'10.9&quot;</td>
<td>099°53'16.3&quot;</td>
</tr>
<tr>
<td>DSB</td>
<td>Dacite</td>
<td>19°52'00.9&quot;</td>
<td>099°53'57.1&quot;</td>
</tr>
</tbody>
</table>
## Appendix B. XRF Analyses for Standards (normalized to 100% on a volatile-free basis)

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>Total</th>
<th>Anal Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLO-1</td>
<td>65.92</td>
<td>0.62</td>
<td>16.07</td>
<td>4.34</td>
<td>0.09</td>
<td>1.07</td>
<td>3.20</td>
<td>4.76</td>
<td>3.65</td>
<td>0.27</td>
<td>100</td>
<td>99.99</td>
</tr>
<tr>
<td>QLO-1</td>
<td>65.92</td>
<td>0.61</td>
<td>16.10</td>
<td>4.32</td>
<td>0.09</td>
<td>1.08</td>
<td>3.20</td>
<td>4.76</td>
<td>3.65</td>
<td>0.27</td>
<td>100</td>
<td>99.86</td>
</tr>
<tr>
<td>QLO-1</td>
<td>65.99</td>
<td>0.62</td>
<td>16.10</td>
<td>4.33</td>
<td>0.09</td>
<td>1.06</td>
<td>3.20</td>
<td>4.67</td>
<td>3.65</td>
<td>0.27</td>
<td>100</td>
<td>100.06</td>
</tr>
<tr>
<td>QLO-1 (mean)</td>
<td>65.94</td>
<td>0.62</td>
<td>16.09</td>
<td>4.33</td>
<td>0.09</td>
<td>1.07</td>
<td>3.20</td>
<td>4.73</td>
<td>3.65</td>
<td>0.27</td>
<td>100</td>
<td>99.97</td>
</tr>
<tr>
<td>QLO-1 (st dev)</td>
<td>0.044</td>
<td>0.0052</td>
<td>0.017</td>
<td>0.008</td>
<td>0.001</td>
<td>0.007</td>
<td>0.003</td>
<td>0.0502</td>
<td>0.003</td>
<td>0.0003</td>
<td>0</td>
<td>0.10</td>
</tr>
<tr>
<td>QLO-1 (accepted)</td>
<td>66.20</td>
<td>0.63</td>
<td>16.34</td>
<td>4.39</td>
<td>0.09</td>
<td>1.01</td>
<td>3.20</td>
<td>4.24</td>
<td>3.64</td>
<td>0.26</td>
<td>100</td>
<td>99.02</td>
</tr>
</tbody>
</table>

Note: Reported oxide data are in wt%. XRF = X-ray fluorescence spectrometry.
## Appendix B. XRF Analyses for Standards

<table>
<thead>
<tr>
<th>Sample</th>
<th>S</th>
<th>Sc</th>
<th>V</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Rb</th>
<th>Sr</th>
<th>Y</th>
<th>Zr</th>
<th>Nb</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLO-1</td>
<td>56</td>
<td>7.5</td>
<td>39</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>56</td>
<td>73</td>
<td>334</td>
<td>23</td>
<td>168</td>
<td>9</td>
<td>1406</td>
</tr>
<tr>
<td>QLO-1</td>
<td>63</td>
<td>8.9</td>
<td>41</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>57</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>169</td>
<td>9</td>
<td>1403</td>
</tr>
<tr>
<td>QLO-1</td>
<td>62</td>
<td>10.0</td>
<td>38</td>
<td>20</td>
<td>19</td>
<td>21</td>
<td>57</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>170</td>
<td>9</td>
<td>1408</td>
</tr>
<tr>
<td>QLO-1</td>
<td>62</td>
<td>9.2</td>
<td>38</td>
<td>21</td>
<td>19</td>
<td>19</td>
<td>56</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>169</td>
<td>9</td>
<td>1400</td>
</tr>
<tr>
<td>QLO-1</td>
<td>62</td>
<td>9.1</td>
<td>37</td>
<td>20</td>
<td>19</td>
<td>20</td>
<td>57</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>169</td>
<td>9</td>
<td>1430</td>
</tr>
<tr>
<td>QLO-1</td>
<td>56</td>
<td>7.5</td>
<td>39</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>56</td>
<td>73</td>
<td>334</td>
<td>23</td>
<td>168</td>
<td>9</td>
<td>1406</td>
</tr>
<tr>
<td>QLO-1 (mean)</td>
<td>60</td>
<td>9</td>
<td>39</td>
<td>20</td>
<td>19</td>
<td>20</td>
<td>57</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>169</td>
<td>9</td>
<td>1409</td>
</tr>
<tr>
<td>QLO-1 (st dev)</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>QLO-1 (accepted)</td>
<td>30</td>
<td>8.9</td>
<td>54</td>
<td>3.2</td>
<td>5.8</td>
<td>29</td>
<td>61</td>
<td>74</td>
<td>336</td>
<td>24</td>
<td>185</td>
<td>10.3</td>
<td>1370</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>S</th>
<th>Sc</th>
<th>V</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Rb</th>
<th>Sr</th>
<th>Y</th>
<th>Zr</th>
<th>Nb</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>JB-2</td>
<td>126</td>
<td>36.6</td>
<td>594</td>
<td>63</td>
<td>28</td>
<td>199</td>
<td>99</td>
<td>6</td>
<td>167</td>
<td>16</td>
<td>58</td>
<td>0</td>
<td>206</td>
</tr>
<tr>
<td>JB-2</td>
<td>122</td>
<td>36.4</td>
<td>592</td>
<td>62</td>
<td>28</td>
<td>200</td>
<td>100</td>
<td>6</td>
<td>168</td>
<td>17</td>
<td>58</td>
<td>0</td>
<td>205</td>
</tr>
<tr>
<td>JB-2</td>
<td>124</td>
<td>36.2</td>
<td>594</td>
<td>62</td>
<td>29</td>
<td>199</td>
<td>100</td>
<td>7</td>
<td>167</td>
<td>16</td>
<td>58</td>
<td>0</td>
<td>207</td>
</tr>
<tr>
<td>JB-2</td>
<td>121</td>
<td>36.5</td>
<td>592</td>
<td>64</td>
<td>29</td>
<td>199</td>
<td>100</td>
<td>6</td>
<td>168</td>
<td>16</td>
<td>57</td>
<td>0</td>
<td>209</td>
</tr>
<tr>
<td>JB-2 (mean)</td>
<td>123</td>
<td>36</td>
<td>593</td>
<td>63</td>
<td>29</td>
<td>199</td>
<td>100</td>
<td>6</td>
<td>168</td>
<td>16</td>
<td>58</td>
<td>0</td>
<td>207</td>
</tr>
<tr>
<td>JB-2 (st dev)</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>JB-2 (accepted)</td>
<td>17.9</td>
<td>53.5</td>
<td>575</td>
<td>28.1</td>
<td>16.6</td>
<td>225</td>
<td>108</td>
<td>7.37</td>
<td>178</td>
<td>24.9</td>
<td>51.2</td>
<td>1.58</td>
<td>222</td>
</tr>
</tbody>
</table>

Note: Reported results are in parts per million (ppm). XRF = X-ray fluorescence spectrometry.
## Appendix B. Electron Microprobe Analyses for Volcanic Lithic Grains from Sandstones (normalized to 100% on a volatile-free basis)

<table>
<thead>
<tr>
<th>Grain</th>
<th>Sample</th>
<th>Type</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃⁺</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Total</th>
<th>Anal Total</th>
<th>BaO</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>76.00</td>
<td>0.09</td>
<td>13.77</td>
<td>1.35</td>
<td>0.02</td>
<td>0.09</td>
<td>0.89</td>
<td>3.40</td>
<td>4.39</td>
<td>100.00</td>
<td>96.61</td>
<td>0.09</td>
<td>833</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.91</td>
<td>0.10</td>
<td>13.58</td>
<td>1.39</td>
<td>0.03</td>
<td>0.07</td>
<td>0.94</td>
<td>3.53</td>
<td>4.44</td>
<td>100.00</td>
<td>95.59</td>
<td>0.03</td>
<td>242</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.75</td>
<td>0.10</td>
<td>13.64</td>
<td>1.43</td>
<td>0.03</td>
<td>0.09</td>
<td>0.89</td>
<td>3.59</td>
<td>4.48</td>
<td>100.00</td>
<td>95.98</td>
<td>0.04</td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.75</td>
<td>0.09</td>
<td>13.75</td>
<td>1.24</td>
<td>0.04</td>
<td>0.10</td>
<td>0.93</td>
<td>3.67</td>
<td>4.43</td>
<td>100.00</td>
<td>96.17</td>
<td>0.05</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.48</td>
<td>0.08</td>
<td>13.71</td>
<td>1.48</td>
<td>0.07</td>
<td>0.13</td>
<td>1.03</td>
<td>3.48</td>
<td>4.55</td>
<td>100.00</td>
<td>96.25</td>
<td>0.07</td>
<td>591</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.95</td>
<td>0.05</td>
<td>13.37</td>
<td>1.39</td>
<td>0.00</td>
<td>0.09</td>
<td>0.92</td>
<td>3.74</td>
<td>4.49</td>
<td>100.00</td>
<td>96.55</td>
<td>0.11</td>
<td>967</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.36</td>
<td>0.09</td>
<td>13.66</td>
<td>1.58</td>
<td>0.07</td>
<td>0.09</td>
<td>1.01</td>
<td>3.77</td>
<td>4.38</td>
<td>100.00</td>
<td>96.91</td>
<td>0.03</td>
<td>242</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.58</td>
<td>0.07</td>
<td>13.58</td>
<td>1.54</td>
<td>0.08</td>
<td>0.11</td>
<td>1.01</td>
<td>3.76</td>
<td>4.28</td>
<td>100.00</td>
<td>97.14</td>
<td>0.04</td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.28</td>
<td>0.11</td>
<td>13.81</td>
<td>1.47</td>
<td>0.06</td>
<td>0.09</td>
<td>0.99</td>
<td>3.78</td>
<td>4.41</td>
<td>100.00</td>
<td>99.59</td>
<td>0.11</td>
<td>967</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.47</td>
<td>0.11</td>
<td>13.65</td>
<td>1.50</td>
<td>0.05</td>
<td>0.09</td>
<td>1.01</td>
<td>3.63</td>
<td>4.50</td>
<td>100.00</td>
<td>96.29</td>
<td>0.05</td>
<td>484</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.64</td>
<td>0.12</td>
<td>13.58</td>
<td>1.43</td>
<td>0.04</td>
<td>0.07</td>
<td>0.96</td>
<td>3.65</td>
<td>4.51</td>
<td>100.00</td>
<td>95.66</td>
<td>0.01</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.62</td>
<td>0.09</td>
<td>13.76</td>
<td>1.34</td>
<td>0.04</td>
<td>0.08</td>
<td>0.92</td>
<td>3.72</td>
<td>4.43</td>
<td>100.00</td>
<td>96.40</td>
<td>0.10</td>
<td>896</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.50</td>
<td>0.12</td>
<td>13.63</td>
<td>1.52</td>
<td>0.07</td>
<td>0.14</td>
<td>0.98</td>
<td>3.70</td>
<td>4.35</td>
<td>100.00</td>
<td>95.74</td>
<td>0.20</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.72</td>
<td>0.11</td>
<td>13.56</td>
<td>1.30</td>
<td>0.02</td>
<td>0.08</td>
<td>0.86</td>
<td>3.79</td>
<td>4.56</td>
<td>100.00</td>
<td>98.52</td>
<td>0.10</td>
<td>914</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>76.01</td>
<td>0.12</td>
<td>13.35</td>
<td>1.36</td>
<td>0.03</td>
<td>0.10</td>
<td>0.79</td>
<td>3.52</td>
<td>4.72</td>
<td>100.00</td>
<td>96.54</td>
<td>0.09</td>
<td>761</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>76.01</td>
<td>0.07</td>
<td>13.49</td>
<td>1.32</td>
<td>0.07</td>
<td>0.09</td>
<td>0.84</td>
<td>3.61</td>
<td>4.50</td>
<td>100.00</td>
<td>96.62</td>
<td>0.09</td>
<td>761</td>
<td></td>
</tr>
<tr>
<td>AG-03-01</td>
<td>Lvv</td>
<td>75.92</td>
<td>0.04</td>
<td>13.45</td>
<td>1.32</td>
<td>0.05</td>
<td>0.09</td>
<td>0.91</td>
<td>3.69</td>
<td>4.53</td>
<td>100.00</td>
<td>97.05</td>
<td>0.03</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.79</td>
<td>0.08</td>
<td>13.70</td>
<td>1.27</td>
<td>0.00</td>
<td>0.07</td>
<td>0.90</td>
<td>3.61</td>
<td>4.58</td>
<td>100.00</td>
<td>96.53</td>
<td>0.06</td>
<td>502</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.71</td>
<td>0.13</td>
<td>13.56</td>
<td>1.39</td>
<td>0.08</td>
<td>0.09</td>
<td>0.91</td>
<td>3.87</td>
<td>4.26</td>
<td>100.00</td>
<td>98.22</td>
<td>0.11</td>
<td>967</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.80</td>
<td>0.12</td>
<td>13.59</td>
<td>1.29</td>
<td>0.06</td>
<td>0.07</td>
<td>0.92</td>
<td>3.79</td>
<td>4.36</td>
<td>100.00</td>
<td>99.72</td>
<td>0.01</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.66</td>
<td>0.05</td>
<td>13.64</td>
<td>1.40</td>
<td>0.04</td>
<td>0.08</td>
<td>0.94</td>
<td>3.77</td>
<td>4.42</td>
<td>100.00</td>
<td>97.48</td>
<td>0.12</td>
<td>1075</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.81</td>
<td>0.07</td>
<td>13.55</td>
<td>1.32</td>
<td>0.06</td>
<td>0.07</td>
<td>0.91</td>
<td>3.70</td>
<td>4.52</td>
<td>100.00</td>
<td>96.56</td>
<td>0.07</td>
<td>654</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.81</td>
<td>0.05</td>
<td>13.63</td>
<td>1.35</td>
<td>0.02</td>
<td>0.09</td>
<td>0.85</td>
<td>3.80</td>
<td>4.42</td>
<td>100.00</td>
<td>96.82</td>
<td>0.04</td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.92</td>
<td>0.08</td>
<td>13.59</td>
<td>1.32</td>
<td>0.01</td>
<td>0.05</td>
<td>0.83</td>
<td>3.73</td>
<td>4.47</td>
<td>100.00</td>
<td>97.12</td>
<td>0.15</td>
<td>1317</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>76.17</td>
<td>0.04</td>
<td>13.31</td>
<td>1.32</td>
<td>0.01</td>
<td>0.08</td>
<td>0.93</td>
<td>3.57</td>
<td>4.57</td>
<td>100.00</td>
<td>95.01</td>
<td>0.10</td>
<td>931</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.52</td>
<td>0.07</td>
<td>13.66</td>
<td>1.33</td>
<td>0.02</td>
<td>0.11</td>
<td>0.92</td>
<td>3.60</td>
<td>4.77</td>
<td>100.00</td>
<td>96.34</td>
<td>0.12</td>
<td>1057</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>76.16</td>
<td>0.09</td>
<td>13.42</td>
<td>1.32</td>
<td>0.05</td>
<td>0.08</td>
<td>0.86</td>
<td>3.64</td>
<td>4.37</td>
<td>100.00</td>
<td>96.08</td>
<td>0.04</td>
<td>349</td>
<td></td>
</tr>
</tbody>
</table>

Note: Reported oxide data are in wt%. Reported Ba data are in parts per million (ppm).
## Appendix B. Electron Microprobe Analyses for Volcanic Lithic Grains from Sandstones (normalized to 100% on a volatile-free basis)

<table>
<thead>
<tr>
<th>Grain</th>
<th>Sample</th>
<th>Type</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>Total</th>
<th>Anal Total</th>
<th>BaO</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.79</td>
<td>0.07</td>
<td>13.50</td>
<td>1.39</td>
<td>0.03</td>
<td>0.09</td>
<td>0.86</td>
<td>3.69</td>
<td>4.58</td>
<td>100.00</td>
<td>99.02</td>
<td>0.09</td>
<td>797</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.79</td>
<td>0.08</td>
<td>13.63</td>
<td>1.47</td>
<td>0.06</td>
<td>0.07</td>
<td>0.86</td>
<td>3.75</td>
<td>4.31</td>
<td>100.00</td>
<td>96.43</td>
<td>0.05</td>
<td>412</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.67</td>
<td>0.08</td>
<td>13.67</td>
<td>1.35</td>
<td>0.04</td>
<td>0.09</td>
<td>0.89</td>
<td>3.80</td>
<td>4.42</td>
<td>100.00</td>
<td>99.61</td>
<td>0.02</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>75.86</td>
<td>0.08</td>
<td>13.36</td>
<td>1.35</td>
<td>0.07</td>
<td>0.09</td>
<td>0.94</td>
<td>3.68</td>
<td>4.58</td>
<td>100.00</td>
<td>96.14</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AG-06-01</td>
<td>Lvv</td>
<td>76.03</td>
<td>0.06</td>
<td>13.47</td>
<td>1.38</td>
<td>0.03</td>
<td>0.09</td>
<td>0.85</td>
<td>3.70</td>
<td>4.39</td>
<td>100.00</td>
<td>95.60</td>
<td>0.02</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>64.50</td>
<td>0.99</td>
<td>17.03</td>
<td>4.84</td>
<td>0.05</td>
<td>1.27</td>
<td>4.55</td>
<td>4.58</td>
<td>2.19</td>
<td>100.01</td>
<td>99.77</td>
<td>0.07</td>
<td>609</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>62.58</td>
<td>1.28</td>
<td>16.48</td>
<td>5.88</td>
<td>0.09</td>
<td>2.15</td>
<td>5.05</td>
<td>4.16</td>
<td>2.33</td>
<td>100.01</td>
<td>100.16</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>77.13</td>
<td>0.11</td>
<td>13.40</td>
<td>0.79</td>
<td>0.02</td>
<td>0.14</td>
<td>1.08</td>
<td>4.13</td>
<td>3.22</td>
<td>100.00</td>
<td>96.83</td>
<td>0.16</td>
<td>1460</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.00</td>
<td>0.20</td>
<td>14.56</td>
<td>1.31</td>
<td>0.04</td>
<td>0.33</td>
<td>1.84</td>
<td>3.93</td>
<td>2.80</td>
<td>100.00</td>
<td>96.04</td>
<td>0.10</td>
<td>905</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.41</td>
<td>0.14</td>
<td>14.73</td>
<td>1.23</td>
<td>0.00</td>
<td>0.28</td>
<td>1.81</td>
<td>3.58</td>
<td>2.83</td>
<td>100.00</td>
<td>96.01</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>63.08</td>
<td>1.14</td>
<td>18.31</td>
<td>4.20</td>
<td>0.06</td>
<td>0.94</td>
<td>5.35</td>
<td>4.83</td>
<td>2.09</td>
<td>100.01</td>
<td>98.03</td>
<td>0.06</td>
<td>511</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.69</td>
<td>0.11</td>
<td>13.71</td>
<td>1.45</td>
<td>0.04</td>
<td>0.10</td>
<td>0.93</td>
<td>3.57</td>
<td>4.41</td>
<td>100.00</td>
<td>95.97</td>
<td>0.06</td>
<td>502</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>72.82</td>
<td>0.51</td>
<td>15.40</td>
<td>1.57</td>
<td>0.03</td>
<td>0.14</td>
<td>3.52</td>
<td>5.32</td>
<td>0.69</td>
<td>100.00</td>
<td>100.13</td>
<td>0.02</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>74.18</td>
<td>0.14</td>
<td>14.98</td>
<td>1.49</td>
<td>0.05</td>
<td>0.46</td>
<td>2.09</td>
<td>4.01</td>
<td>2.59</td>
<td>100.00</td>
<td>94.26</td>
<td>0.10</td>
<td>887</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>77.63</td>
<td>0.17</td>
<td>12.56</td>
<td>1.07</td>
<td>0.05</td>
<td>0.16</td>
<td>0.99</td>
<td>3.58</td>
<td>3.81</td>
<td>100.00</td>
<td>95.29</td>
<td>0.10</td>
<td>905</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.82</td>
<td>0.11</td>
<td>13.52</td>
<td>1.33</td>
<td>0.06</td>
<td>0.08</td>
<td>0.88</td>
<td>3.71</td>
<td>4.48</td>
<td>100.00</td>
<td>95.58</td>
<td>0.11</td>
<td>1021</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>65.63</td>
<td>0.99</td>
<td>16.25</td>
<td>4.91</td>
<td>0.08</td>
<td>1.26</td>
<td>3.84</td>
<td>4.29</td>
<td>2.76</td>
<td>100.01</td>
<td>98.81</td>
<td>0.12</td>
<td>1084</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>74.94</td>
<td>0.16</td>
<td>14.58</td>
<td>1.18</td>
<td>0.02</td>
<td>0.30</td>
<td>1.81</td>
<td>4.07</td>
<td>2.93</td>
<td>100.00</td>
<td>95.02</td>
<td>0.11</td>
<td>1021</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.94</td>
<td>0.08</td>
<td>13.31</td>
<td>1.47</td>
<td>0.04</td>
<td>0.10</td>
<td>0.86</td>
<td>3.72</td>
<td>4.49</td>
<td>100.00</td>
<td>96.47</td>
<td>0.04</td>
<td>367</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.80</td>
<td>0.09</td>
<td>13.55</td>
<td>1.35</td>
<td>0.05</td>
<td>0.07</td>
<td>0.93</td>
<td>3.55</td>
<td>4.60</td>
<td>100.00</td>
<td>95.96</td>
<td>0.04</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>AG-08-01</td>
<td>Lvv</td>
<td>75.96</td>
<td>0.10</td>
<td>13.57</td>
<td>1.29</td>
<td>0.05</td>
<td>0.07</td>
<td>0.88</td>
<td>3.70</td>
<td>4.39</td>
<td>100.00</td>
<td>96.19</td>
<td>0.05</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>64.66</td>
<td>0.46</td>
<td>18.82</td>
<td>2.93</td>
<td>0.04</td>
<td>0.55</td>
<td>4.87</td>
<td>4.81</td>
<td>2.86</td>
<td>100.00</td>
<td>98.14</td>
<td>0.07</td>
<td>663</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>66.88</td>
<td>1.17</td>
<td>14.58</td>
<td>5.74</td>
<td>0.09</td>
<td>0.77</td>
<td>2.84</td>
<td>4.34</td>
<td>3.60</td>
<td>100.01</td>
<td>95.94</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>67.10</td>
<td>0.84</td>
<td>16.47</td>
<td>4.07</td>
<td>0.06</td>
<td>0.57</td>
<td>3.18</td>
<td>4.12</td>
<td>3.60</td>
<td>100.01</td>
<td>95.52</td>
<td>0.03</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>66.22</td>
<td>1.28</td>
<td>15.68</td>
<td>5.06</td>
<td>0.07</td>
<td>0.66</td>
<td>3.20</td>
<td>4.22</td>
<td>3.62</td>
<td>100.01</td>
<td>95.42</td>
<td>0.05</td>
<td>475</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>67.91</td>
<td>1.25</td>
<td>14.51</td>
<td>5.49</td>
<td>0.05</td>
<td>0.63</td>
<td>2.23</td>
<td>4.02</td>
<td>3.91</td>
<td>100.01</td>
<td>95.69</td>
<td>0.10</td>
<td>896</td>
<td></td>
</tr>
<tr>
<td>AG-04-04</td>
<td>Lvv</td>
<td>63.96</td>
<td>1.09</td>
<td>17.27</td>
<td>4.78</td>
<td>0.08</td>
<td>0.76</td>
<td>4.25</td>
<td>4.88</td>
<td>2.94</td>
<td>100.01</td>
<td>97.64</td>
<td>0.00</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Reported oxide data are in wt%. Reported Ba data are in parts per million (ppm).
### Appendix B. Electron Microprobe Analyses for Volcanic Lithic Grains from Sandstones (normalized to 100% on a volatile-free basis)

<table>
<thead>
<tr>
<th>Grain</th>
<th>Sample</th>
<th>Type</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Total</th>
<th>Anal Total</th>
<th>BaO</th>
<th>Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AG-04-04</td>
<td>Lvv</td>
<td>76.60</td>
<td>0.21</td>
<td>12.96</td>
<td>1.23</td>
<td>0.03</td>
<td>0.17</td>
<td>0.85</td>
<td>3.87</td>
<td>4.09</td>
<td>100</td>
<td>95.83</td>
<td>0.04</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>Lvv</td>
<td>76.75</td>
<td>0.16</td>
<td>12.96</td>
<td>1.16</td>
<td>0.01</td>
<td>0.14</td>
<td>0.87</td>
<td>3.87</td>
<td>4.07</td>
<td>100</td>
<td>95.31</td>
<td>0.06</td>
<td>555</td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>Lvv</td>
<td>76.99</td>
<td>0.19</td>
<td>13.02</td>
<td>1.05</td>
<td>0.03</td>
<td>0.15</td>
<td>0.88</td>
<td>3.72</td>
<td>3.98</td>
<td>100</td>
<td>94.48</td>
<td>0.13</td>
<td>1129</td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>Lvv</td>
<td>67.98</td>
<td>1.02</td>
<td>15.53</td>
<td>4.28</td>
<td>0.06</td>
<td>0.40</td>
<td>2.69</td>
<td>4.38</td>
<td>3.66</td>
<td>100</td>
<td>95.52</td>
<td>0.11</td>
<td>994</td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>Lvv</td>
<td>76.69</td>
<td>0.14</td>
<td>13.02</td>
<td>1.19</td>
<td>0.03</td>
<td>0.19</td>
<td>0.82</td>
<td>3.81</td>
<td>4.12</td>
<td>100</td>
<td>95.39</td>
<td>0.02</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.69</td>
<td>1.39</td>
<td>16.30</td>
<td>6.32</td>
<td>0.12</td>
<td>1.31</td>
<td>4.34</td>
<td>4.57</td>
<td>2.97</td>
<td>100</td>
<td>98.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>61.98</td>
<td>1.39</td>
<td>16.96</td>
<td>6.30</td>
<td>0.10</td>
<td>1.49</td>
<td>4.64</td>
<td>4.43</td>
<td>2.73</td>
<td>100</td>
<td>99.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>59.85</td>
<td>1.04</td>
<td>18.19</td>
<td>5.87</td>
<td>0.10</td>
<td>3.00</td>
<td>5.84</td>
<td>4.18</td>
<td>1.95</td>
<td>100</td>
<td>97.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.38</td>
<td>1.37</td>
<td>15.63</td>
<td>6.87</td>
<td>0.09</td>
<td>2.15</td>
<td>4.19</td>
<td>4.34</td>
<td>2.98</td>
<td>100</td>
<td>98.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>60.72</td>
<td>0.92</td>
<td>21.28</td>
<td>3.07</td>
<td>0.04</td>
<td>0.48</td>
<td>6.37</td>
<td>4.68</td>
<td>2.44</td>
<td>100</td>
<td>98.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.76</td>
<td>1.36</td>
<td>16.74</td>
<td>5.71</td>
<td>0.07</td>
<td>1.51</td>
<td>4.32</td>
<td>4.62</td>
<td>2.92</td>
<td>100</td>
<td>97.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.48</td>
<td>1.23</td>
<td>17.68</td>
<td>5.33</td>
<td>0.06</td>
<td>1.43</td>
<td>4.75</td>
<td>4.29</td>
<td>2.76</td>
<td>100</td>
<td>96.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>63.37</td>
<td>1.42</td>
<td>16.46</td>
<td>6.04</td>
<td>0.10</td>
<td>1.06</td>
<td>3.98</td>
<td>4.44</td>
<td>3.14</td>
<td>100</td>
<td>96.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.27</td>
<td>1.23</td>
<td>17.85</td>
<td>5.37</td>
<td>0.08</td>
<td>1.10</td>
<td>4.96</td>
<td>4.58</td>
<td>2.57</td>
<td>100</td>
<td>96.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>62.93</td>
<td>1.36</td>
<td>16.69</td>
<td>5.66</td>
<td>0.06</td>
<td>1.10</td>
<td>4.43</td>
<td>4.79</td>
<td>2.98</td>
<td>100</td>
<td>98.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AG-04-04</td>
<td>LvmL</td>
<td>63.80</td>
<td>1.58</td>
<td>16.34</td>
<td>5.61</td>
<td>0.09</td>
<td>0.79</td>
<td>3.79</td>
<td>4.65</td>
<td>3.37</td>
<td>100</td>
<td>96.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rhyolite standard</td>
<td></td>
<td>77.41</td>
<td>0.12</td>
<td>12.24</td>
<td>1.17</td>
<td>0.01</td>
<td>0.05</td>
<td>0.46</td>
<td>3.63</td>
<td>4.90</td>
<td>100</td>
<td>99.52</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rhyolite standard</td>
<td></td>
<td>77.32</td>
<td>0.08</td>
<td>12.27</td>
<td>1.15</td>
<td>0.01</td>
<td>0.02</td>
<td>0.43</td>
<td>3.74</td>
<td>4.98</td>
<td>100</td>
<td>99.68</td>
<td>0.04</td>
<td>385</td>
</tr>
<tr>
<td></td>
<td>Rhyolite standard (mean)</td>
<td></td>
<td>77.37</td>
<td>0.10</td>
<td>12.26</td>
<td>1.16</td>
<td>0.01</td>
<td>0.03</td>
<td>0.44</td>
<td>3.69</td>
<td>4.94</td>
<td>100</td>
<td>99.60</td>
<td>0.02</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Rhyolite standard (st dev)</td>
<td></td>
<td>0.06</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.07</td>
<td>0.06</td>
<td>0</td>
<td>0.11</td>
<td>0.03</td>
<td>272</td>
</tr>
<tr>
<td></td>
<td>Rhyolite standard (accepted)</td>
<td></td>
<td>77.07</td>
<td>0.12</td>
<td>12.12</td>
<td>1.38</td>
<td>0.03</td>
<td>0.10</td>
<td>0.50</td>
<td>3.77</td>
<td>4.91</td>
<td>100</td>
<td>99.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kakanui standard</td>
<td></td>
<td>40.76</td>
<td>4.75</td>
<td>14.71</td>
<td>12.21</td>
<td>0.09</td>
<td>12.62</td>
<td>10.06</td>
<td>2.68</td>
<td>2.13</td>
<td>100</td>
<td>100.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kakanui standard (accepted)</td>
<td></td>
<td>40.38</td>
<td>4.72</td>
<td>14.90</td>
<td>12.14</td>
<td>0.09</td>
<td>12.80</td>
<td>10.30</td>
<td>2.60</td>
<td>2.05</td>
<td>100</td>
<td>99.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Reported oxide data are in wt%. Reported Ba data are in parts per million (ppm). The numbers of the standards are USNM 72854 VG-568 for the rhyolite standard and USNM 143965 for the Kakanui standard.
APPENDIX C
## Appendix C. Raw Grain-Type Point Count Data

<table>
<thead>
<tr>
<th>Sample</th>
<th>Locality</th>
<th>Type</th>
<th>Qm</th>
<th>P</th>
<th>K</th>
<th>D</th>
<th>M</th>
<th>Lvv</th>
<th>Lvg</th>
<th>Lvm</th>
<th>Lvl</th>
<th>Lvs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-01-01</td>
<td>LA</td>
<td>Css</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>271</td>
<td>12</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>AG-02-02</td>
<td>LC</td>
<td>TBss</td>
<td>3</td>
<td>27</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>182</td>
<td>14</td>
<td>48</td>
<td>5</td>
<td>15</td>
<td>300</td>
</tr>
<tr>
<td>AG-02-03</td>
<td>LC</td>
<td>TBss</td>
<td>5</td>
<td>32</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>169</td>
<td>34</td>
<td>32</td>
<td>2</td>
<td>17</td>
<td>300</td>
</tr>
<tr>
<td>AG-03-01</td>
<td>LE</td>
<td>Css</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>268</td>
<td>14</td>
<td>4</td>
<td>0</td>
<td>11</td>
<td>300</td>
</tr>
<tr>
<td>AG-03-02</td>
<td>LE</td>
<td>TBss</td>
<td>5</td>
<td>38</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>177</td>
<td>19</td>
<td>44</td>
<td>2</td>
<td>11</td>
<td>300</td>
</tr>
<tr>
<td>AG-04-03</td>
<td>CE</td>
<td>Css</td>
<td>6</td>
<td>35</td>
<td>2</td>
<td>13</td>
<td>5</td>
<td>168</td>
<td>17</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>300</td>
</tr>
<tr>
<td>AG-04-04</td>
<td>CE</td>
<td>Css</td>
<td>3</td>
<td>18</td>
<td>1</td>
<td>12</td>
<td>2</td>
<td>195</td>
<td>18</td>
<td>28</td>
<td>20</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>AG-05-02</td>
<td>SB</td>
<td>TBss</td>
<td>4</td>
<td>24</td>
<td>7</td>
<td>3</td>
<td>7</td>
<td>198</td>
<td>13</td>
<td>16</td>
<td>25</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>AG-06-01</td>
<td>LR</td>
<td>Csms</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>265</td>
<td>19</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>300</td>
</tr>
<tr>
<td>AG-06-03</td>
<td>LR</td>
<td>TBsms</td>
<td>24</td>
<td>97</td>
<td>33</td>
<td>36</td>
<td>8</td>
<td>38</td>
<td>21</td>
<td>34</td>
<td>5</td>
<td>4</td>
<td>300</td>
</tr>
<tr>
<td>AG-08-01</td>
<td>TE</td>
<td>Css</td>
<td>3</td>
<td>80</td>
<td>0</td>
<td>9</td>
<td>30</td>
<td>123</td>
<td>11</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td>300</td>
</tr>
<tr>
<td>AG-08-02</td>
<td>TE</td>
<td>Csms</td>
<td>8</td>
<td>127</td>
<td>0</td>
<td>10</td>
<td>9</td>
<td>77</td>
<td>9</td>
<td>47</td>
<td>5</td>
<td>8</td>
<td>300</td>
</tr>
<tr>
<td>AG-08-03</td>
<td>TE</td>
<td>Csms</td>
<td>2</td>
<td>52</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>158</td>
<td>6</td>
<td>33</td>
<td>31</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>AG-10-01</td>
<td>LP</td>
<td>Css</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>4</td>
<td>7</td>
<td>213</td>
<td>1</td>
<td>31</td>
<td>19</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>AG-10-03</td>
<td>LP</td>
<td>TBsms</td>
<td>15</td>
<td>112</td>
<td>37</td>
<td>24</td>
<td>9</td>
<td>51</td>
<td>12</td>
<td>15</td>
<td>16</td>
<td>9</td>
<td>300</td>
</tr>
</tbody>
</table>

### KEY

**Localities**

- LA: Las Arenas
- LC: Las Casas
- LE: Los Espejos
- CE: Cementerio de San Bartolo
- SB: San Bartolo
- LR: Las Represas
- TE: Línea de Teléfono
- LP: La Plataforma

**Rock Types**

- Css: Cementerio sandstone
- Csms: Cementerio sandy mudstone
- TBss: Tierras Blancas sandstone
- TBsms: Tierras Blancas sandy mudstone

**Grain Types**

- Qm: Monocrystalline quartz
- P: Plagioclase feldspar
- K: Potassium feldspar
- D: Dense minerals
- M: Miscellaneous minerals
- Lvv: Vitric volcanic lithic
- Lvg: Granular volcanic lithic
- Lvm: Microlitic volcanic lithic
- Lvl: Lathwork volcanic lithic
- Lvs: Seriate volcanic lithic
Appendix C. Recalculated Parameters from Grain-Type Point Count Data

<table>
<thead>
<tr>
<th>Sample</th>
<th>Locality</th>
<th>Type</th>
<th>Q</th>
<th>F</th>
<th>L</th>
<th>Lvv</th>
<th>Lvm</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-01-01</td>
<td>LA</td>
<td>Css</td>
<td>0.0</td>
<td>1.3</td>
<td>98.7</td>
<td>97.5</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>AG-02-02</td>
<td>LC</td>
<td>TBss</td>
<td>1.0</td>
<td>11.0</td>
<td>88.0</td>
<td>77.4</td>
<td>20.4</td>
<td>2.1</td>
</tr>
<tr>
<td>AG-02-03</td>
<td>LC</td>
<td>TBss</td>
<td>1.7</td>
<td>13.7</td>
<td>84.7</td>
<td>83.3</td>
<td>15.8</td>
<td>1.0</td>
</tr>
<tr>
<td>AG-03-01</td>
<td>LE</td>
<td>Css</td>
<td>0.0</td>
<td>1.0</td>
<td>99.0</td>
<td>98.5</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>AG-03-02</td>
<td>LE</td>
<td>TBss</td>
<td>1.7</td>
<td>13.7</td>
<td>84.6</td>
<td>79.4</td>
<td>19.7</td>
<td>0.9</td>
</tr>
<tr>
<td>AG-04-03</td>
<td>CE</td>
<td>Css</td>
<td>2.1</td>
<td>13.1</td>
<td>84.8</td>
<td>80.8</td>
<td>11.5</td>
<td>7.7</td>
</tr>
<tr>
<td>AG-04-04</td>
<td>CE</td>
<td>Css</td>
<td>1.0</td>
<td>6.6</td>
<td>92.3</td>
<td>80.2</td>
<td>11.5</td>
<td>8.2</td>
</tr>
<tr>
<td>AG-05-02</td>
<td>SB</td>
<td>TBss</td>
<td>1.4</td>
<td>10.7</td>
<td>87.9</td>
<td>82.8</td>
<td>6.7</td>
<td>10.5</td>
</tr>
<tr>
<td>AG-06-01</td>
<td>LR</td>
<td>Css</td>
<td>0.0</td>
<td>1.0</td>
<td>99.0</td>
<td>97.4</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>AG-06-03</td>
<td>LR</td>
<td>Tbsms</td>
<td>9.4</td>
<td>50.8</td>
<td>39.8</td>
<td>49.4</td>
<td>44.2</td>
<td>6.5</td>
</tr>
<tr>
<td>AG-08-01</td>
<td>TE</td>
<td>Css</td>
<td>1.1</td>
<td>30.7</td>
<td>68.2</td>
<td>81.5</td>
<td>10.6</td>
<td>7.9</td>
</tr>
<tr>
<td>AG-08-02</td>
<td>TE</td>
<td>Csms</td>
<td>2.8</td>
<td>45.2</td>
<td>52.0</td>
<td>59.7</td>
<td>36.4</td>
<td>3.9</td>
</tr>
<tr>
<td>AG-08-03</td>
<td>TE</td>
<td>Csms</td>
<td>0.7</td>
<td>18.4</td>
<td>80.9</td>
<td>71.2</td>
<td>14.9</td>
<td>14.0</td>
</tr>
<tr>
<td>AG-10-01</td>
<td>LP</td>
<td>Css</td>
<td>0.0</td>
<td>8.7</td>
<td>91.3</td>
<td>81.0</td>
<td>11.8</td>
<td>7.2</td>
</tr>
<tr>
<td>AG-10-03</td>
<td>LP</td>
<td>Tbsms</td>
<td>5.6</td>
<td>55.8</td>
<td>38.6</td>
<td>62.2</td>
<td>18.3</td>
<td>19.5</td>
</tr>
</tbody>
</table>

**KEY**

Localities

- **LA:** Las Arenas
- **LC:** Las Casas
- **LE:** Los Espejos
- **CE:** Cementerio de San Bartolo
- **SB:** San Bartolo
- **LR:** Las Represas
- **TE:** Línea de Teléfono
- **LP:** La Plataforma

Recalculated Parameters

- **Q = Qm**
- **F = P + K**
- **L = Lvv + Lvm + Lvl + Lvg + Lvs**
- **QFL%Q = 100*Q/(Q + F + L)**
- **QFL%F = 100*F/(Q + F + L)**
- **QFL%L = 100*L/(Q + F + L)**
- **LvvLvmLvl%Lvv = 100*Lvv/(Lvv + Lvm + Lvl)**
- **LvvLvmLvl%Lvm = 100*Lvm/(Lvv + Lvm + Lvl)**
- **LvvLvmLvl%Lvl = 100*Lvl/(Lvv + Lvm + Lvl)**

Rock Types

- **Css:** Cementerio sandstone
- **Csms:** Cementerio sandy mudstone
- **TBss:** Tierras Blancas sandstone
- **TBsms:** Tierras Blancas sandy mudstone