A Paleoenvironmental Investigation of Eolian Influx in Lacustrine Sediments of the Southern Rocky Mountain Region

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A PALEOENVIRONMENTAL INVESTIGATION OF EOLIAN INFUX IN LACUSTRINE SEDIMENTS OF THE SOUTHERN ROCKY MOUNTAIN REGION.

A Thesis
Presented to
the Faculty of Natural Sciences and Mathematics
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In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

by
Rebecca L. Brice
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Advisor: Dr. Donald Sullivan
Abstract

Potential indications of long-term trends in paleoclimate, specifically winds, in the Southern Rocky Mountain region of the United States were tested using lacustrine sediment from South Blue Lake in the Wet Mountains of Colorado. This study builds upon existing eolian and lacustrine research, and investigates paleowind in a location not yet studied in this manner. Variability in sediment laminae, particle size, and mineralogy show similar patterns during the mid-Holocene warm period (ca. 5500 cal. yr BP – ca. 6000 cal. yr BP). These patterns indicate a warmer, drier, windier period that is contrasted by a less variable period in the recent Holocene. Windblown sediment dominates the South Blue Lake core and supports long-term, continuous eolian contribution to sediment of a sub-alpine lake. Results from this study support the hypothesis that dust is transported to the Southern Rocky Mountain region from a distal source (>400km) to the west. Mega-drought conditions in the source region likely provide sediment supply and availability for transport to the Southern Rocky Mountain region.

Keywords: paleowind, Rocky Mountains, dust, Holocene, climate
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Chapter One: Introduction

1.1 Motivating question and study purpose

Paleoclimatology allows us to explore past natural climate variability from ecological and physical perspectives. The value of multi-century to millennial-scale paleoclimatic data lies in the revelation of spatial and temporal patterns long before humans substantially altered Earth’s environmental processes. Natural climatic variability throughout the Quaternary can be studied using marine sediments or terrestrial environmental proxies measured in lacustrine sediments, trees rings, ice cores, speleothems, peat, and others. Comparison of many different environmental proxies strengthens our understanding of climate changes and the way that the climate system responds to external forcings. Such research provides a benchmark of natural climate variability to aid in understanding climates we may expect in the future. Different environmental proxies have different strengths for detecting individual components of the climate system such as atmospheric composition, temperature, and precipitation patterns. For example, we extract physical or chemical data from ice cores that informs our understanding of atmospheric changes over millennia or even extending hundreds of thousands of years into the past. In contrast, tree rings can provide well-calibrated precipitation and temperature information at decadal, centennial, or sometimes millennial scales. While paleoclimate reconstructions have been carried out in the Southern Rocky Mountain (SRM) region (the states of Wyoming, Colorado, New Mexico, and eastern
Utah), the primary paleoclimatic data obtained are typically temperature and precipitation. Researchers studying paleoclimates are calling for additional proxy research that will expand the breadth of climate reconstruction resources in order to anticipate future climate extremes (Routson et al., 2011).

Paleowind proxies may give us a direct record of past atmospheric circulation and may add complexity and accuracy to our current understanding of the climate system. This study seeks to use an environmental proxy that records information about past wind. Finding a wind signal in the paleoclimate record is challenging and raises the following question: Can we reconstruct a paleorecord for near-surface winds during the Holocene in the SRM region and how can this record inform our understanding of regional atmospheric circulation response to climate change in the future? Environmental proxies such as lake sediments may provide an opportunity for us to reconstruct Holocene near-surface winds (Liu and Fearne, 2000).

Effective and calibrated methods for detecting wind in the lacustrine sediment record are limited in the literature for the SRM region. Contextualizing wind prior to the historic record and at a regional scale will contribute to both our understanding of the connection of climate variability with wind patterns and provide a template for future paleowind research in this region. This thesis project intends to explore wind patterns using an environmental proxy approach for a more complete understanding of the spatial and temporal patterns of wind in the SRM region. In an effort to reconstruct long-term changes in the intensity of pre-historic winds, lacustrine sediment was sampled from the South Blue Lake on the west side of the Wet Mountains and downwind from the Great Sand Dunes National Park and Preserve. This study builds upon existing eolian and
lacustrine research in this region and investigates a paleowind record in a location not yet studied in this manner. The hypothesis for this project is that strong prevailing westerly winds will transport sediments, primarily silt, from the San Luis Valley over the Sangre de Cristo Range and deposit them on the lee side (Figure 1). The basis for this hypothesis is that active sand dunes at GSDNPP indicate that wind potential is sufficient for eolian transport in this region. Finer-grained sediments also occur in the San Luis Valley and should record provenance in the sink area. Mineral sediments accumulating in closed basin lakes east of the Sangre de Cristo range are expected to provide information about changes in the intensity and duration of winds. My guiding research question is: will closed basin lakes east of the Sangre de Cristo Range preserve an identifiable record of paleowind activity?

Potential indicators of long-term trends in paleoclimate, specifically winds, in the South Blue Lake core were investigated and calibrated using numerical dating methods. Initial work involved landscape assessment using topographic maps and aerial photographs to identify optimal sites for collection of lake samples. Once potential sites were identified, preliminary field exploration began in June, 2012. Preliminary field assessment confirmed the appropriateness of the selected site, South Blue Lake. An initial stratigraphic assessment was used to identify variations in strata thickness. These variations may indicate wind duration and changes in particle size that should be indicative of wind velocity. I determined bulk density and organic matter content following procedures described by Dean (1974). Higher bulk density values correspond to lower organic matter content and validate that laminae are dominated by eolian transport. I analyzed particle size distribution using a laser diffraction particle size
Figure 1 Illustrated model of the hypothesis. Strong prevailing westerly winds will transport sediments (primarily silt from San Juan Mountain Pliocene-age glaciation) from the San Luis Valley over the Sangre de Cristo Range and deposit them at Blue Lake in the Wet Mountains.
analyzer and used these results to identify key areas of the core for mineralogical analysis. Peaks in magnetic susceptibility correspond to peaks in mafic mineral abundance. Magnetic susceptibility was determined using a Bartington magnetometer. Quantitative mineralogical evaluation was performed using x-ray diffractometry (XRD) and Rock Jock software analysis (Eberl, 2003). Mineralogical fingerprints in South Blue Lake sediment were compared against end members collected from the San Luis Valley west of the lake location (a distal source) and from the Greenhorn complex surrounding the lake (a local source). With these data, I investigated regional near-surface wind patterns in the Southern Rocky Mountain region.

1.2 Problem statement

Climate variability in the coming century is of growing concern to policy makers, governments, and scientists. Current state-of-the-art Earth system models forecast unprecedented temperature changes in the late-21st century as a response to increased greenhouse gas concentrations. It is expected that there will also be changes in large-scale atmospheric circulation patterns (Meehl et al., 2007). These models are also in general agreement that annual mean wind speeds will increase in the mountainous west and southwest United States where it is already considered windy (Figure 2), but a great deal of uncertainty remains (Eichelberger et al. 2008). Confidence in using global models at smaller scales is lacking. The highly dynamic nature of climate variables such as cloud cover and wind means that model accuracy of specific regional and local impacts
resulting from climate change remain a significant uncertainty (IPCC 4th Assessment Report). Relatively short instrumental records for local climatic components and low-density instrumentation networks pose a considerable challenge for placing climate variability into long-term context. The short temporal scale of instrumental records is exacerbated by limited research on paleowinds.

Figure 2 Colorado Annual Average Wind Speed map at 80m. Severe wind potential can be seen in areas of purple, blue, and red. Study sites will be located in south-central Colorado near Walsenberg. National Renewable Energy Laboratory, 2010. http://www.windpoweringamerica.gov/pdfs/wind_maps/co_80m.pdf

The SRM region has an extensive temperature and precipitation paleorecord (e.g. Holliday, 1989; Fall, 1997; Shinker et al., 2006; Routson et al., 2011; Drake et al., 2012), but very little research has been conducted to investigate pre-instrumentation Holocene paleowinds in this area. The contribution of this study is two-fold. First, this study will
address whether eolian sediment is carried to and deposited in mountain environments. Second, this study will consider the role of drought in the availability and supply of eolian sediment.

Indications of eolian activity may be useful in understanding patterns for climate extremes, such as drought and windstorms, so that we may place past events into future context. Existing eolian research has investigated paleowind in the American Southwest (Frank et al., 2008; Phillips and Doesken, 2011; Reheis and Urban, 2011). However, considerable debate about the presence and effectiveness of eolian transport and deposition in the Rocky Mountains persists today. This study has the potential to support or refute the presence of long-term eolian processes in the Southern Rocky Mountain region. Drought is also an important climatological element in the Southern Rocky Mountain region, and is often the driver of environmental disturbances observed in the landscape. Instrumental records of recent droughts are too young to be compared with this study. Many other local environmental proxies do not have resolutions appropriate for chronological comparison to South Blue Lake. However, Routson et al. (2011) found evidence, using in part paleoreconstructions from Bristlecone Pine in the San Juan Mountains, for a multi-century drought in the southwestern United States beginning about 2000 cal. yr BP. Their findings correspond well to other reconstructed climate indices (e.g., PDSI, ENSO) that may affect the southwestern United States. Using correlations between tree-ring derived Palmer Drought Severity Index and OSL ages using SAR protocol for eolian deposition in GSDNPP, Forman et al. (2006) found strong agreement between drought and dune migration in the San Luis Valley corresponding with Routson’s inferred 2nd century drought. If dry conditions increase sediment
availability for transport, this increase should be reflected in the eolian sediments found in South Blue Lake. This research has the potential to support recent studies that postulate the existence of past multi-century droughts in the southwestern United States. Projections for future climate variability in this region anticipate increased duration and severity of drought. This study has the potential to describe how past mega-drought affected the Southern Rocky Mountains and aid in our understanding of what these conditions may mean for the future in this region.
Chapter Two: Previous Studies

2.1 Review of the current state of the science

Windborn dust is largely underutilized as a proxy for paleowind. Entrainment, transport and deposition of wind-carried silt are direct evidence of atmospheric circulation and may be used to infer wind direction and speed in the past. Changes in the influx of silt-sized mineral sediment may mean less vegetation, reduced sediment stabilization, seasonal and decadal climate cycles (ie: ENSO, monsoon, drought), and/or an increase in availability and transport of external eolian material in a source area (Reheis and Urban, 2011).

Previous studies of eolian dust (airborne particles less than 100 μm) explore its provenance and transport (Pye, 1987; Smith et al., 2002; Wright, 2001; Lawrence et al., 2010; Lawrence et al., 2011; Muhs, 2013). Provenance indicates wind direction, while proportions of particle sizes indicate the type of transport mechanism (ie: wind, water, etc.), as well as the magnitude (energy) of the transport mechanism. Wind transported material is sorted and redistributed spatially according to size, shape and density. Globally, arid locations like the deserts of China and Africa and the High Plains of the United States are the main source areas of windblown mineral dust (Pye, 1987). Global concentrations of dust are estimated to be as much as 1 g m⁻³. Seasonally arid locations like the American Southwest may also produce windblown mineral dust, albeit at a smaller scale than large desert regions. Smith et al. (2002) posit that windborn dust is not
just spatially significant, it is also important for understanding temporal differences in a landscape because the provenance and transport of eolian material is subject to changes in climate over time. Changing climatic conditions over time is an important consideration when discussing generation, transport, and deposition of dust in the past.

Eolian sediment analysis techniques are often used to determine sediment provenance and, in combination with other local proxies and geochronological techniques, contain valuable information used in reconstructing past environments (Fitzsimmons et al., 2007; Madole et al., 2008; Muhs et al., 2007). Previous geochemical studies have shown that by comparing mineralogical “fingerprints” of local sources for sediment to external sources we may be able to determine transport and provenance of the sediment (Taylor and McLennan 1985; Olivarez et al., 1991; Muhs et al., 2008; Muhs et al., 2013; Dean, 1997). Hutchison (1968) used such an approach to identify several minerals samples from GSDNPP and determine if their source was either the San Juan Mountains or the Sangre de Cristo Mountains. He found that sediment deposited in GSDNPP is predominantly external to the depositional environment and originate from the San Juan Mountains. Sediments of GSDNPP contain high concentrations of iron-rich minerals attributable to the geology of the San Juan Mountains and are distinctly different than sediments derived from the Sangre de Cristo Mountains. Headwaters for the Rio Grande River originate in the San Juan Mountains and are believed to be the greatest contributor to sediment deposition in the San Luis Lakes and “sump” (McCaplin, 2012). Madole (2008) determined that GSDNPP mineralogy is approximately 28% quartz, 52% volcanic rock fragments, and 20% other minerals. Among other minerals such as
sanidine (a high temperature form of potassium feldspar indicative of extrusive igneous rock) and basaltic hornblende, hypersthene is relatively abundant in GSDNPP sediments and is thought to be derived from the San Juan Mountains (Madole, 2008; Hutchison, 1968).

GSDNPP is located at the dramatic change in elevation between the valley and the mountains where winds are funneled through the low passes of the Sangre de Cristo range. The majority of the coarse (sand-sized) eolian sediment transported across the San Luis valley is deposited at GSDNPP. East of GSDNPP, winds are channeled through the low passes of the Sangre de Cristo Mountains. Boundary layer winds accelerate over complex terrain because they are bound above by wind shear and temperature gradient, and bound below by the Earth surface. Wind speed accelerates with compression between these laminae and this creates energy and facilitates transport of particles in suspension.

Investigations into dune activation in North America since the middle Pleistocene reveal that dune activation is spatially and temporally dependent (Muhs, 1985; Muhs et al., 2008; Madole et al. 2008). Dean (1997) investigated accumulation rates in the Great Plains during the middle-Holocene and found cyclic variations in past windiness peaks, indicating windier and dustier periods in 1200-1000 cal. yr BP, 800-600 cal. yr BP, and 400-200 cal. yr BP. Forman et al. (2006) found indications of five separate episodic eolian sand depositional events (ca.1300 cal. yr BP, ca.950 cal. yr BP, ca.700 cal. yr BP, 18th century, 20th century) in the San Luis Valley. Janke (2002)
found that sediment in the dune complex and periphery of GSDNPP are continually mobilized today.

While wind-transported sediment within the San Luis Valley has been the subject of many previous studies (e.g.: Madole et al., 2008; Janke, 2002), the question of whether silt-sized sediment is transported over the Sangre de Cristo Mountains to the Wet Mountains is largely unanswered. Great Sand Dunes National Park and Preserve (GSDNPP) is a unique geologic setting and provides an ideal opportunity to test a new terrestrial proxy for ancient near-surface winds. Research shows that the area known as the “sump” located in the southwest region of the Rio Grande basin is the source for the vast majority of episodic eolian volcanic- and granite-derived sediment transported to the GSDNPP (Madole et al., 2008). The key mechanism for eolian sediment availability and transport from the sump area to the GSDNPP is hydrologic change, such as flooding and water table fluctuation (Madole et al., 2008). Wind transported sediment held in suspension is dominated by silt-sized (~63µ to ~2µ) or clay-sized (<2µ) particles (Muhs et al., 2008). Silt-sized particles held in suspension or reactivated during drier periods may be transported over the Sangre de Cristo mountain range. The sediments may be deposited in the Wet Mountains where decreased wind velocity allows sediment to fall out of suspension. These silt-sized eolian sediments are the interest of this study.
Chapter Three: Study Area

3.1 Physiography

South-central Colorado is part of the Rio Grande Rift System. The San Luis Valley is one of the largest high desert valleys in the world. The San Juan, Sangre de Cristo and Wet Mountain ranges, with peaks reaching above 4000m, flank the low, flat San Luis and Huerfano Valleys. Mid-Tertiary tectonic activity has left distinctive volcanic features in the landscape and has contributed to the high concentrations of mafic rock material in the area (Bauman, 2013).

The San Juan Mountains are a north-south trending range rising gently to the west of the San Luis Valley. The San Juan Mountains are a volcanic remnant and a source of mafic sediments found in the alluvial outwash of the ancient Rio Grande River. The Sangre de Cristo Mountains are a northwest-southeast trending rising dramatically to the east of the San Luis Valley. The Sangre de Cristo range divides the San Luis Valley on the west from the Huerfano Valley on the east. The high elevations of the Sangre de Cristo Mountains are the result of orogenic uplift, and rocks in these mountains are predominately granite and gneiss. The boundary between the San Luis Valley and the Sangre de Cristo Mountains in marked by the Sangre de Cristo fault and is expressed as a sharp contact between valley lowland and high peaks. The Continental Divide runs across the Sangre de Cristo range. Three passes called Mosca, Medano, and Music break up the high relief of the Sangre de Cristos (Figure 3). These passes are clustered toward
Figure 3 Two of the three passes of the Sangre de Cristo mountains. Medano Pass is far left. Medano Pass lies at the center of a natural topographic crescent that channels air flow over this low point. This is attributed to the formation of a vast dune system (Great Sand Dunes National Park and Preserve). Mosca Pass is middle-right.
the south end of the Sangre de Cristos and along the rim of a natural north-south crescent shape in the range. Great Sand Dunes National Park and Preserve (GSDNPP) hugs the western slope where the three passes are clustered. GSDNPP is a unique feature in the SRM region landscape and will be discussed later in more detail.

The Wet Mountain range is the easternmost set of mountains in the study area, the eastern flank of the Huerfano valley, and last mountainous terrain downwind from the San Luis Valley before reaching the vast expanse of the Great Plains to the east. The Wet Mountains have a Precambrian granite core with Eocene and Oligocene age volcanics. These mountains are a northwest-to-southeast trending low-elevation range. The highest peak, Greenhorn Mountain at 3763 m, is at the southern end of the range.

The South Blue Lakes are located on the west facing side of Greenhorn Peak, at the southern end of the Wet Mountains in the San Isabel National Forest (N37 53.812, W105 02.439). The two lakes, North South Blue Lake and South Blue Lake, are approximately 0.5 km apart with South Blue Lake slightly higher in elevation than North South Blue Lake. The South Blue Lakes catchment is approximately 2 km². South Blue Lake is a spring-fed, naturally-occurring closed-basin subalpine lake at approximately 3,458 m above sea level (Figure 4). Rocks surrounding South Blue Lake are andesite flows over granite gneiss, migmatite, and Lit-par-lit gneiss (Boyer, 1962). Observations of talus above treeline, mass wasting “benches” on the eastern slope of South Blue Lake, and evidence of a recent slump event at North South Blue Lake suggest that the South
Blue Lakes are the result of slump or landslide activity occurring on the steep slopes directly to its east. South Blue Lake is a relatively shallow lake with an asymmetrical basin. The average depth is 65cm, ranging from 25 cm at the shallowest to 1 m at the deepest (Figure 5).
Figure 4 Blue Lake with coring raft, view looking north. Blue Lake is a subalpine lake near tree line. Tree line can be seen in the upper right-hand corner of the image. The alpine slope extends east toward Greenhorn Peak.
Figure 5  Site location and bathymetry of Blue Lake, Wet Mountains, Colorado. Bathymetric contour interval is 10cm. A natural spring feeds the lake on the east. Shoreline fluctuates approximately 10-15cm throughout the year. The deepest section of the lake is near the center, toward the natural spring.
Climate in the San Luis Valley and surrounding mountains is influenced by two climate regimes. The SRM region lies on the climatic boundary between the Rocky Mountain winter-dominant precipitation regime and the dry summer-dominant precipitation regime of southwestern deserts and Great Plains of North America. For example, the San Juan Mountains experience a winter dominant precipitation regime, sometimes resulting in the highest snow depth accumulations in the state of Colorado. The San Luis Valley, a high-elevation desert valley (~2300m above sea level), often receives less than 178mm yr\(^{-1}\) of precipitation and primarily during summer monsoon. Topography and dry air create high spatial variability in climate across the complex terrain in the SRM region (Pielke et al., 2003). Strong precipitation gradients occur from valley to peaks so precipitation amounts and timing are in sharp contrast between the flanking mountain ranges and the San Luis Valley (McCaplin, 2012). Temperature gradients in the region also contribute to the differences in climate regimes. Because of this, potential evapotranspiration exceeds precipitation in the valley, while the inverse is true in the mountains.

Wind regimes can be expressed on hourly, diurnal, seasonal, annual and decadal scales. Many atmospheric and surface conditions contribute to the location, duration, and intensity of wind. This study will focus on near-surface winds found along the boundary
layer in the SRM region. Wind roses generated from wind speed and wind direction data collected between 2004 and 2013 at the GSDNPP RAWS weather station (37 43’ 36” N, 105 30’ 39”W) indicate a dominant west-southwesterly wind direction in all seasons (Figure 6). Wind speeds vary by season, with greatest wind speed occurrence in spring (March-April-May). Davis and Walker (1992) found similar seasonality to wind intensity and occurrence in the western United States, attributing it primarily to the north-south migration of the Polar Front. GSDNPP wind roses show that spring is the season with the highest frequency of wind speeds greater than 6 m s\(^{-1}\). In late winter and spring, the subtropical jet strengthens in the southwest, as well as the persistence of a western Colorado Ridge (Davis and Walker, 1992; Frank et al., 2008). These synoptic conditions increase the southwesterly flow aloft. The Great Basin ridge precedes these conditions, a blocking high that displaces the polar jet to the north, and results in high wintertime temperatures.
Figure 6: Wind roses of wind speed and direction observations collected from 2004-2013 at Great Sand Dunes National Park and Preserve (data courtesy of RAWS). Individual plates show from left to right winter, spring, summer, fall and annual averages. Calm threshold was fixed at 6 m/s.
Chapter Four: Methods

4.1 Field collection

Three lake sediment cores (BL12-1, BL12-2, BL12-3) were collected from the deepest part of South Blue Lake using a square rod piston corer (Wright et al., 1984). Each 1-meter core segment was wrapped in plastic wrap and foil, then placed in a halved PVC pipe for transport to the lab. Lake bathymetry was determined using paddle-boat and a rope marked by depth with a weight. Soil samples were collected in east-west transects in the San Luis Valley, and in the area around South Blue Lake. Figure 7 shows where the San Luis Valley source sediment samples were collected. Sample locations were selected to best represent locations upwind, and from the expected locations of ancient and current Rio Grande River silt deposits. Locations were recorded with GPS in the ancestral Rio Grande River floodplain (SLV12-3), the current Rio Grande River floodplain (SLV12-2), at the San Luis Lakes also called the “sump”; (SLV12-1), and at GSDNPP (SD12-1). Figure 8 shows where the South Blue Lake local source samples were collected. Sample locations in the South Blue Lake basin were selected to represent local bedrock geology. Local source samples were collected from mineral soil. Locations were recorded with GPS along a transect on the downwind slope of South Blue Lake. Samples were collected in the tree stand (BLG12-3), at tree line (BLG12-2), and above treeline (BLG12-1). A solid rock sample was collected from the talus slope above South Blue Lake (BLG1-1GT).
Figure 7 Illustration on the study area. The location of the four source sediment samples is shown with red markers. SLV12-1 is located in the “sump” area, known today as the San Luis Lakes. SLV 12-2 is located near the town of Del Norte along the course of the current Rio Grande River. Source sediment sample SD12-1 was collected at Great Sand Dunes National Park and Preserve. Yellow markers represent the location of Lipman (1975) and Lawrence et al. (2010) comparisons.
Figure 8 Base Camp (Garmin GPS software) image of study site. Blue Lake is indicated with a blue flag and labeled BL12-1. The location of the three local sediment samples is shown with blue flags. BLG12-3 is forested, BLG12-2 is at tree line, and BLG12-3 is above tree line. BLG1-1GT rock sample was collected at BLG12-1. Greenhorn peak is to the southeast of Blue Lake.
4.2 Lab methods

4.2.1 Numerical dating

Radiocarbon ages were determined for three organic samples from BL12-3 at depths of 250 cm, 314 cm, and 423 cm. Samples were submitted to the Accelerator Mass Spectrometry Laboratory, University of Arizona, Tucson. Reported ages were provided in $^{14}$C age BP. Ages were calibrated as described by Fairbanks et al. (2005) and verified using Calib Rev 6.1.0 (Stuiver and Reimer, 2006 (version 5.0)).

4.2.2 Stratigraphy

All three lacustrine sediment cores (BL12-1, BL12-2, and BL12-3) were sliced in half lengthwise, and the cores logged. Sediment color was determined using Munsell Soil Color Chart and visual assessment of color and textural changes throughout the core were noted. Zones of abrupt change in particle size and areas where organic matter is concentrated were identified in the stratigraphic sequence. Random samples were examined under a microscope to check for the presence of diatoms. Dilute hydrochloric acid drops were placed at several locations along the stratigraphic column to check for the presence of carbonates. Mass accumulation rates (MAR) were determined using the following equation:

$$MAR = (S \times BDd) \times silt\%$$

Where S is sediment accumulation (m kyr$^{-1}$), BDd is bulk density, and silt% is average silt percentage. MAR was calculated between the three calibrated ages.
4.2.3 Loss on ignition and bulk density

Bulk density (BD) describes the dry volume of soil expressed in g cm$^{-3}$. Organic matter content (OC) describes the percentage of organic material in the lake sediments. OC and BD were determined using loss on ignition (LOI) according to Dean (1974). Continuous three cubic centimeters of sediment from each core were sampled at 1 cm intervals beginning at a depth of 100 cm. Shallower depths were not collect for BL12-3. Samples were heated to 100$^\circ$ C for 2 hours and then weighed. Heated sample weight was subtracted from initial sample weight, along with the 3 cc volume, to determine BD measurements. The sample was then heated to 550$^\circ$ C for 1.5 hours, weighed, and the post-heated weight was subtracted from the 100$^\circ$ C weight to obtain organic matter content measurements.

4.2.4 Magnetic susceptibility

Sediment with provenance from the San Juan Mountains is expected to show higher magnetic susceptibility because of the high magnetite content owing to the volcanic mafic origin of the sediments. Magnetic susceptibility was determined at 10 cm intervals using a Bartington MS2C meter. To maximize the number of measurements of magnetic susceptibility, core segments from both BL12-1 (100-500) and BL12-3 (500-610) were used. Technical Specifications for the MS2C sensor are listed in Table 1 (Source: Operating Manual for MS2 Magnetic Susceptibility System, Bartington Instruments Ltd). Measurements were recorded as SI units.
Table 1 Technical detail of the Bartington MS2C meter.

<table>
<thead>
<tr>
<th>Loop internal diameter</th>
<th>30, 36, 40, 45, 60, 72, 80, 90, 100, 110, 125, 130, 135, 140, 145, 150, 160 or 162mm. Intermediate sizes can be provided.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration accuracy 5% (calibration sample provided)</td>
<td>5% (calibration sample provided)</td>
</tr>
<tr>
<td>Measurement period: x1 range, X0.1 range</td>
<td>1.1s SI (0.9s CGS), 11s SI (9s CGS)</td>
</tr>
<tr>
<td>Amplitude of applied field 250T peak 10%</td>
<td>250T peak 10%</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>20mm</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>0.565 kHz</td>
</tr>
<tr>
<td>Drift at 20°C</td>
<td>&lt;2 x 10^-5 SI (&lt;2 x 10^-6 CGS) (vol) in 10 minutes after 5 minutes operation</td>
</tr>
<tr>
<td>Enclosure material</td>
<td>white polyacetal</td>
</tr>
<tr>
<td>Weight</td>
<td>2 – 2.65kg depending on diameter</td>
</tr>
<tr>
<td>Dimensions</td>
<td>290 x 200 x 160mm</td>
</tr>
</tbody>
</table>

4.2.5 Particle size analysis

Approximately 3 cc of sediment was collected at even-numbered intervals from BL12-3. Following Singer and Janitzky (1986), each sample was placed a 100 ml bath of 35wt% hydrogen peroxide solution until the organic matter oxidation reaction ceased. The samples, in liquid suspension with dispersant were placed in a Beckman and Coulter LS13 320 Laser Diffraction Particle Size Analyzer instrument and used to obtain particle size distribution measurements. Particle size percentiles (range breaks) for initial statistics were predetermined at <2 μm, <3.91 μm, <7.8 μm, <15.6 μm, <31.25 μm, < 62.5 μm, <125 μm, and <250 μm according to common size fraction ranges (Wentworth, 1922). Relative percentages for each fraction were used to determine the proportion of three Wentworth size classes: Very Fine Sand (125 μm – 62.5 μm), Medium Silt (31 μm – 15.6 μm), and Very Fine Silt (7.8 μm – 3.9 μm). Assumptions for this analysis are that
Very Find Sand 125 μm – 62.5 μm) is only locally derived. Silt, medium to very fine, is predominantly eolian. Descriptive statistics for each sample were calculated using Beckman Coulter © software (e.g.: Appendix A), and for the entire core using SPSS statistical software.

4.2.6 Mineralogy

Particle size analysis results were used to determine mineralogy. The basis of this mineralogical analysis is the assumption that local and external sediments will show distinctively different mineralogy. This assumption is based on the predominantly mafic volcanic composition of the San Juan Mountains, which deliver sediments to the San Luis Valley in contrast to the predominantly granitic Wet Mountains. Measurements that exceeded two standard deviations from the mean in each Wentworth size class from the particle size analysis results (very fine sand, medium silt, very fine silt) were resampled from the core to determine mineralogy. The basis of the mineralogical analysis is the assumption that local and external sediments will show distinctively different mineralogy. Bulk sample from core depths at the three highest standard deviations and three lowest standard deviations in each class were then pretreated for mineralogical analysis. Selected core depths were: Medium silt - 126 cm, 168 cm, 298 cm, 378 cm, 408 cm, 488 cm; Very Fine Sand - 184 cm, 310 cm, 404 cm, 460 cm, 482 cm, 534 cm; Very Fine Silt - 264 cm, 344 cm, 428 cm, 478 cm, 494 cm, 608 cm.

Three bulk samples from the San Luis Valley, three bulk samples from surrounding South Blue Lake, one sample from GSDNPP, and one bedrock sample from the South Blue Lake basin were also pretreated and analyzed. Each bulk sample was first
soaked in a bath of 35wt% hydrogen peroxide to remove organic matter. After oxidation, fine silt and clay particles were separated from sand and coarse sand using a 38 μm sieve. Remaining silt and clay fractions were treated with sodium hexametaphosphate to enhance dispersion (Muhs et al., 2008).

Clay-sized fractions were removed from each sample following a modified Stokes settling velocity method. Samples and water were placed in a centrifuge for 6 minutes at 2500 rpm. Supernatant fluid was decanted and more water was added. The sample was replaced into the centrifuge for another 6 minutes. These steps were repeated until decanted water was clear (Soukup et al., 2008). The result is a sample comprised of 38-2 μm-sized particles.

The resultant sample was dried in a 50° C oven was then prepared for quantitative X-ray Diffraction Analysis (XRD) according to Eberl (2003) and modified from Srodon et al. (2001). One gram of each silt fraction sample was combined with 0.25 g of a corundum standard and 4 ml of ethanol, then pulverized for 5 minutes in a McCrone micronizing mill. The mixture was dried in a 60° C oven overnight. The dry sample was sieved at 500 μm and shaken for 5 minutes with fluorohydrocarbon. Samples were packed into the XRD holder and X-rayed in a Siemens Kristalloflex 805 machine from 5 to 65 degrees two-theta using Cu K-alpha radiation, and with a step size of 0.02 degree two theta. X-ray peak heights were converted to mineral abundance in RockJock© software. Quartz, orthoclase, anorthite, calcite, muscovite, and kaolinite were selected for RockJock quantification using semi-quantitative assessment of mineral dispersion through each sample’s XRD pattern results.
Chapter Five: Results

5.1 Field collection

Three cores were collected from South Blue Lake. BL12-1 had a total length of 495 cm. BL12-2 had a total length of 321 cm (100 cm-421 cm). BL12-3 had a total length of 516 cm (100 cm-616 cm). The cores were collected in three separate but adjacent holes near the east-central part of the lake where lake bathymetric results showed the deepest water (N37 53.811 W105 02.411). Soil sample locations are listed in Table 2. South Blue Lake basin bedrock was collected as solid rock from the same location as BLG12-3.

Table 2 Mineralogy sample numbers, locality, and GPS coordinates for comparison samples.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Locality</th>
<th>GPS coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 12-1</td>
<td>GSDNPP</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>SLV 12-1</td>
<td>San Luis Valley - San Luis Lakes, middle sump</td>
<td>N37 40.878 W105 44.054</td>
</tr>
<tr>
<td>SLV 12-2</td>
<td>San Luis Valley - Floodplain of current Rio Grande, near Del Norte</td>
<td>N37 41.164 W106 21.236</td>
</tr>
<tr>
<td>SLV 12-3</td>
<td>San Luis Valley - Floodplain of ancient Rio Grande, north of Del Norte</td>
<td>N39 52.757 W105 59.136</td>
</tr>
<tr>
<td>BLG 12-1</td>
<td>Blue Lake/Greenhorn - Above treeline</td>
<td>N37 53.691 W105 02.181</td>
</tr>
<tr>
<td>BLG 12-2</td>
<td>Blue Lake/Greenhorn - At treeline</td>
<td>N37 53.710 W105 02.239</td>
</tr>
<tr>
<td>BLG 12-3 /bedrock</td>
<td>Blue Lake/Greenhorn - Mid-slope, forested</td>
<td>N37 54.028 W105 2.372</td>
</tr>
</tbody>
</table>
5.2 Numerical dating

Radiocarbon ages were obtained from plant remnant material collected from BL12-3, and submitted to the University of Arizona AMS laboratory in Tucson, Arizona. Three radiocarbon dates taken from 250 cm, 314 cm, and 423 cm depth in the core were calibrated to calendar years before present 2727+/-38 cal. yr BP, 3252+/-67 cal. yr BP, and 5490+/-44 cal. yr BP respectively (Table 3).

Table 3 Radiocarbon and calendar ages for BL12-3. Ages calibrated to calendar years before present according to Fairbanks et al. (2005) and verified using Calib Rev 6.1.0 (Stuiver and Reimer, 1993).

<table>
<thead>
<tr>
<th>Lab Sample Number</th>
<th>Sample Number</th>
<th>Depth in Core</th>
<th>14C Age</th>
<th>Calibrated Age Range (1SD) Cal BP</th>
<th>Relative Area Under the Distribution</th>
<th>Calibration Data</th>
<th>Sediment Accumulation (m/kyr)</th>
<th>MAR = (T x BDDt) x silt% (g/m2/kyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA100515</td>
<td>BL12-3 250</td>
<td>250 cm</td>
<td>2590+/-39</td>
<td>2758-2623</td>
<td>0.949975</td>
<td>(Reimer et al, 2004)</td>
<td>2727+/-38</td>
<td>0.90</td>
</tr>
<tr>
<td>AA105516</td>
<td>BL12-3 314</td>
<td>314 cm</td>
<td>3038+/-45</td>
<td>3336-3174</td>
<td>0.958612</td>
<td>(Reimer et al, 2004)</td>
<td>3252+/-67</td>
<td>1.20</td>
</tr>
<tr>
<td>AA100517</td>
<td>BL12-3 423</td>
<td>423 cm</td>
<td>4745+/-44</td>
<td>5583-5333</td>
<td>0.745138</td>
<td>(Reimer et al, 2004)</td>
<td>5490+/-44</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Sedimentation rate is relatively consistent throughout the core and is an average of 0.89 m yr⁻¹. The basal age (616 cm) was estimated to be between 8545 cal. yr BP and 9390 cal. yr BP based upon the average sedimentation rate between the last radiocarbon dated depths. The basal age range was calculated as a range because it is only an approximation. Sedimentation between 423 cm and 314 cm is 0.50 m kyr⁻¹. Between 314 cm and 250 cm, the sedimentation rate increases to 1.20 m kyr⁻¹. Between 250 cm and 0 cm, the sedimentation rate is 0.90 m kyr⁻¹ (Figure 10).
5.3 Stratigraphy

South Blue Lake sediment stratigraphy is predominately mottled, clayey homogenized sediment interspersed with faint to moderately distinct laminae and very distinctive alternating dark and light paired laminae (Figures 9 and 11). Layering occurs between 556 cm and 553 cm, 484 cm and 460 cm, and then again between 432 cm and 397 cm. The most distinct layering occurs at 276 cm until 250 cm. Between 396 cm and 370 cm sediment texture becomes noticeably more coarse. This is a unique feature in the column. On five occasions (at 502 cm, 457 cm, 432 cm, 396 cm, and 311 cm) the color and texture changed dramatically in single laminae approximately 2-4 cm thick. These laminae are characterized by a very dark organic sheet with appearance of charcoal overlain by light colored, coarse-grained sediment with the appearance of sand. Charcoal is a common occurrence throughout the core, but appears to be concentrated between 500 and 300 cm. Organic material is prevalent throughout the column in the form of charcoal, plant remnant material, fibrous debris, and wood. Wood is concentrated near the center of the column, between 520 cm and 450 cm.

5.4 Bulk density and organic matter content

Bulk density (BD) of samples from BL12-3 ranges from 1.05 g cm$^{-3}$ at a depth of 488 cm 0.15 g cm$^{-3}$ to at a depth of 160 cm (Figure 12). Bulk density is elevated (mean=0.41 g cm$^{-3}$) with increased variability between 572 cm and 320 cm (max=1.0 g cm$^{-3}$; min=0.20 g cm$^{-3}$). A low BD measurement at 320 cm (0.20 g cm$^{-3}$) is followed by a distinct peak at a depth of 314 cm (0.87 g cm$^{-3}$). A dramatic increase begins with a higher but steady BD between 400 cm and 300 cm. This corresponds roughly to the
Figure 9 Photo of a portion of BL12-3 indicating mottling, faint laminations, and charcoal and coarse sediment flux.
Figure 10 Age-depth model for South Blue Lake. Radiocarbon ages have been calibrated to calendar years before present (cal yr BP). The deepest age indicated (8537-9390 cal. yr BP) is an extrapolated basal age range from mean sediment accumulation rate.
Figure 11 Stratigraphic column for Blue Lake indicating color and textural changes with depth. Horizontal dashed lines indicate the location of ages in cal. yr BP.
Figure 12  Bulk density (BD) for BL12-3. Ages are calendar years before present.
middle radiocarbon date, and has an approximate calendar age of 3254 cal. yr BP. At 250 cm until 200 cm, BD falls to a sustained low level (mean=0.20 g cm\(^{-3}\)). BD is relatively stable between 189 cm and 100 cm (mean=0.33 g cm\(^{-3}\); min= 0.16 g cm\(^{-3}\); max=0.48 g cm\(^{-3}\)).

South Blue Lake organic matter content (OC) ranges between 7% at 488 cm and 79% at a depth of 150 cm (Figure 13). OC variability appears to increase between 600 cm and 422 cm. Organic matter content remains near 70% until a series of dramatic reductions that occur at 488 cm, 400 cm, and 300 cm. Highest OC is at the top 200 cm of the core. It is initially at 62% at 222 cm, then drops to 24% between 214 cm and 200 cm.

BD and OC results from the two replicate cores are included in the Appendix A. Gaps in data for each curve in this analysis represent physical gaps in the sediments that are commonly the result of multiple insertions of the piston corer. The top meter of BL12-1 is not included in results for BL12-3 because it was a different core and it did not provide enough sediment for all analyses.

5.5 Magnetic susceptibility

Magnetic susceptibility (MS) measurements ranged from 0.0 SI to 8.8 SI in BL12-2 and BL12-3. The highest MS measurement was 8.8 SI at a depth of 488 cm. The lowest measurement (0.0 SI) was taken at a depth of 120 cm. A sustained interval of high variability occurs between 510 cm and 380 cm, where values range from 0.1 SI to
Figure 13  Organic matter content (OC) for BL12-3. Ages are calendar years before present.
8.8 SI during this period (Appendix B). A bi-modal MS peak also occurs between 320 cm and 270 cm (Figure 14).

5.6 Particle size analysis

Particle size analysis (PSA) was designed to identify the distribution of sediment in South Blue Lake that can most likely be attributed to eolian processes. Particle size histograms showed bi-modal distribution or tri-modal distribution (Figure 25). The way in which particle size was distributed in each sample varied at individual depths throughout BL12-3. The particle size mode in BL12-3 is 14.94 µm, just slightly smaller than the fraction cut-off for medium silt. Figures 15, 16, and 17 shows particle size distribution in BL12-3 as individual size fractions with means and standard deviations. Very fine sand (125 µm-62.5 µm) ranges between 0.40% of total particles at a depth of 232 cm and 17.00% at a depth of 184 cm. The mean relative percentage for very fine sand is 7.27% and +2 or -2 standard deviations 10.01% and 4.53% respectively. Medium silt (31 µm-15.6 µm) ranges from 20.10% at 478 cm and 7.45% of total particles at a depth of 314 cm. The mean relative percentage for medium silt is 21.69% and +2 or -2 standard deviations 24.77% and 18.62% respectively. Very fine silt (7.8 µm-3.9 µm) ranges from 10.21% of total particles at a depth of 428 cm and 29.30% at two places, 488 cm and 408 cm. The mean relative percentage for medium silt is 12.74% and +2 or -2 standard deviations 15.05% and 10.44% respectively (Table 4). Medium silt has the highest mean relative volume (21.69%) in BL12-3.
Figure 14: Magnetic susceptibility (SI) with depth in Blue Lake for BL12-2 and BL12-3.
Figure 15 Percentage of distribution for very fine sand by depth in BL12-3. Blue line represents the mean within the fraction. Orange lines represent +/-2 standard deviations from the mean.
Figure 16 Percentage of distribution for medium silt by depth in BL12-3. Blue line represents the mean within the fraction. Orange lines represent +/-2 standard deviations from the mean.
Figure 17 Percentage of distribution for fine silt by depth in BL12-3. Blue line represents the mean within the fraction. Orange lines represent +/-2 standard deviations from the mean.
Table 4 Particle size distribution means and standard deviations.

<table>
<thead>
<tr>
<th></th>
<th>μm %volume very fine sand (125-62.5)</th>
<th>μm %volume medium silt (31-15.6)</th>
<th>μm %volume very fine silt (7.8-3.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean:</td>
<td>7.27</td>
<td>21.69</td>
<td>12.74</td>
</tr>
<tr>
<td>+2 SD</td>
<td>10.01</td>
<td>24.77</td>
<td>15.04</td>
</tr>
<tr>
<td>-2 SD</td>
<td>4.53</td>
<td>18.62</td>
<td>10.43</td>
</tr>
</tbody>
</table>

Results for particle size analysis are mostly continuous until the bottom 1.5 meters. Between 530 cm and 500 cm the LS13 320 Laser Diffraction Particle Size Analyzer instrument stopped functioning properly and the problem could not be resolved in the time accommodated to complete this thesis. Between 600 cm and 575 cm the volume of BL12-3 was insufficient to do this analysis.

Laser particle size analysis assumes that particle orientation in suspension is random. Replicate analysis was performed with the Laser Diffraction Particle Size Analyzer on select samples from BL12-2, even-numbered intervals in BL12-3, and dry sample to test viability of particle size results. The bi-modal patterns observed in the histograms from the BL12-3 core is evident in the comparison samples as well. High peaks for the eolian-sized fractions are common among these replicates. Histograms for these replicates are found in Appendix A.
5.7 Mineralogy

Mineral composition in BL12-3 was determined using x-ray diffraction (XRD) and RockJock quantitative mineralogy software (Eberl, 2003). For the mineralogy, I resampled depths in the core where the three highest and three lowest percentages of each fraction occurred in the PSA (Tables 2 and 5).

Table 5 Mineralogy core samples, locality, and GPS coordinates for samples collected at Blue Lake.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Locality</th>
<th>GPS coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>168</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>298</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>378</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>408</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>488</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>184</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>310</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>404</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>460</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>482</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>534</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>264</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>344</td>
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<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>428</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>478</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>494</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
<tr>
<td>608</td>
<td>BL12-3</td>
<td>N37 53.811 W105 02.411</td>
</tr>
</tbody>
</table>
The full XRD patterns for all samples, percentage distribution charts, and tabular information for each individual sample are included in Appendix D. Full XRD patterns were used to select dominant minerals by relative abundance in each sample. Of the suite of minerals provided to RockJock for analysis quartz was on average the dominant mineral in all core samples with a mean percentage of 10.2%. Mean plagioclase and potassium-feldspar abundances are 5.4% and 6.6%, respectively.

Madole et al. (2008) found GSDNPP dune composition to be 28% quartz, 52% volcanic rock fragments, and 20% other minerals. Other authors have used XRD and quartz:plagioclase (Q:P) ratios to identify sediment influx in a system, as well as to estimate provenance of the sediment (eg: Muhs et al, 2003; Moros et al., 2004; Muhs et al, 2008; etc.). When local basalt is dominant in a source area, as the silt deposits are in the San Luis Valley, quartz abundance should be considerably less than plagioclase. For this reason, a quartz-to-plagioclase comparison was utilized to determine sediment provenance at South Blue Lake. The Q:P ratio was plotted for the core. Q:P ratio between 0.5 and 1.0 defines the Q:P region for the San Luis Valley/GSDNPP. A Q:P value between 1.5 and 3.0 defines the South Blue Lake sediments (Figure 18). South Blue Lake basin bedrock has a Q:P ratio of 1.4. For comparison, a quartz:orthoclase (Q:O) relationship was plotted separately. Local Q:O ratios fall between 1.2 and 2.2. San Luis Valley/GSDNPP source values on this plot range between 0.4 and 0.9. South Blue Lake basin bedrock has an O:P ratio of 0.4.

Relative abundance of quartz, plagioclase, and potassium feldspar were plotted on ternary plots. Relative abundance of these minerals in dust sampled in the San Juan
Mountains (Lawrence et al., 2010) was compared to: 1) the South Blue Lake core; 2) the San Luis Valley/GSDNPP samples, SLV12-2, SLV12-3, and SD12-1; 3) local bedrock of the San Juan Mountains (Lipman 1978); and 4) South Blue Lake bedrock sample BLG1-1GT (Figure 19). The South Blue Lake quartz:plagioclase:k-spar is most similar to the dust found in the San Juan Mountains by Lawrence.
Figure 18  Quartz to plagioclase ration for Blue Lake, San Luis Valley source samples, and Blue Lake basin bedrock.
Figure 19 Ternary diagrams for mineral components (quartz; K-spar; plagioclase) of potential eolian source areas. a) Blue Lake core plotted against dust collected in the San Juan mountains (Lawrence et al, 2010). b) San Juan dust compared to San Luis Valley samples. c) San Juan dust compared to San Juan bedrock (Lipman, 1975). d) San Juan dust compared to bedrock of the Blue Lake basin.
Chapter Six: Discussion

6.1 Evidence of drought

Large swings in sediment composition and sediment influx in South Blue Lake indicate a more variable environment. Increases in silt-sized mineral sediment may mean less vegetation, reduced sediment stabilization, seasonal and decadal climate cycles (ie: ENSO, monsoon), and/or an increase in availability and transport of external eolian material (Reheis and Urban, 2011). Routson et al. (2011) and Forman et al. (2006) found evidence for a multi-century drought in the southwestern United States beginning about 2000 cal. cal. yr BP. However, mineralogical ratios for silt-sized sediment in South Blue Lake from the end of the inferred 2\textsuperscript{nd} century drought time period (ca. 1800 cal. cal. yr BP to ca. 1300 cal. cal. yr BP; 200 cm to 100 cm) do not match the quartz:plagioclase values associated with the samples taken from the San Luis Valley, GSDNPP, or the normative mineralogy from the San Juan Mountains, suggesting that almost all of the eolian sediment received at South Blue Lake was not from the study region. Dry conditions appear to have increased sediment availability for transport during the 2\textsuperscript{nd} century drought, but the higher influx of predominantly quartz silt in South Blue Lake still appears to be the result of drier and consequently more active eolian conditions outside of the study region.
6.2 Fine particle production in the SRM region

Environmental mechanisms capable of producing silt-sized particles (63 μm – 2 μm) that contribute to eolian deposits around the world are still debated in the literature. Proposed mechanisms for silt-production are: glacial grinding, fluvial comminution, eolian abrasion (ballistic impact during saltation), salt weathering, and chemical weathering. But, combined environmental factors specific to location such as glacial grinding and fluvial comminution are better attributed to the production and mobilization of eolian sediment (Wright, 2001; Sun, 2002). Because these silt-producing mechanisms are largely controlled by geography, it is possible to eliminate those that are not plausible for this study area.

Silt generation from eolian abrasion of saltating sand grains on desert margins is still contested in the literature and is the subject of ongoing research (Smith et al., 2002). Once silt-size sediment is produced in arid environments, discussion remains about the relative contribution of ballistic impact of saltating sand to activation and entrainment of dust in atmospheric flow. Distinguishing one silt-generating mechanism from another in the Southern Rocky Mountain region is beyond the scope of this study, but the San Luis Valley provides an interesting venue to test proportions of silt-generation from varying mechanisms.

The Southern Rocky Mountain (SRM) region is relatively cold because of combined latitudinal and elevational characteristics. Chemical weathering is most effective in tropical environments and so is not a viable silt producing mechanism in the SRM region. Additionally, while the SRM region is subject to prolonged periods of
drought, any periodic wetting and drying in the San Luis Valley, and more importantly in the San Juan Mountains, is likely not sufficient for extensive salt weathering. Smalley and Vita-Finzi (1968) relate that glacial grinding is by far the most effective mechanism for creating silt, and that extensive silt deposits are located on the periphery of Pleistocene glaciated areas. Evidence supports glaciation in the San Juan Mountains through the late Pleistocene (Madole et al., 2008). Glacial grinding in the San Juan Mountains could have produced large amounts of silt. Glacial and fluvial related silt deposits should coincide geographically (Pye, 1987; Smith et al., 2002; Wright, 2001).

The Rio Grande River flows from the San Juans into the San Luis Valley. It is commonly accepted that fluvial transport is responsible for bringing post-glacial silt from the San Juan Mountains to the San Luis Valley. Through comminution, fluvial transport could have potentially produced additional silt en route to the valley floor, where it was deposited. As the Rio Grande changed course over time, exposed silt deposits dried out and became subject to eolian action. An important point is that the presence of loess deposits is the result of a coupled relationship between silt availability and depositional opportunity (Smith et al., 2002; Wright, 2001). While the production and entrainment of silt particles is important to dust transport, dust traps are essential for collection of settling particles. This may be one reason for the paucity of loess deposits downwind of the San Luis Valley and GSDNPP. While silt is present and mobile, topography and vegetation may encourage rapid and well-dispersed deposition that results in widespread, thinly layered deposits of loess. This may also explain why South Blue Lake sediment,
while it is predominately eolian, does not appear to come from the San Juan Mountains or the San Luis Valley.

The basic premise for silt generating mechanisms may be used to disqualify particular source locations for South Blue Lake eolian sediment (Figure 20). The Sangre de Cristo Mountains are also a potential source for granitic eolian sediment in South Blue Lake. The Sangre de Cristos were glaciated in the Pleistocene and coupled glacial grinding-fluvial transport conditions exist in this mountain range. However, the expected distance travelled for 15 μm silt (the modal particle size in South Blue Lake) is greater than the distance of the Sangre de Cristo Mountains to South Blue Lake. 15 μm particles are typically held in suspension for long distances, at times greater than 400 km. The Sangre de Cristo Mountains are 50 km southwest, and only 35 km directly west of South Blue Lake. The distance-decay models used commonly in the literature suggest greater coarse silt and fine sand-sized particles for this distance to source relationship.

Figure 21 shows the overlay of Wet Mountain granite mineralogy on the ternary provenance diagrams (Cullers et al, 1992). These data do not permit the exclusion of either the Wet Mountain granite or the Sangre de Cristo bedrock, but the likelihood of these locations as sources for South Blue Lake sediment can be reduced. While the Wet Mountain granite might be considered the source of the eolian material in South Blue Lake, the contradiction between distance-from-source and particle size does not support this. The Wet Mountain range is only about 65 km in length, too close to South Blue Lake for the mean and modal particle sizes. The Wet Mountains were never glaciated, so the quantity and supply of silt-sized particles are also not available. Additionally, grus -
Figure 20 - Revised cartoon model of the hypothesis. The mean particle size relative to the distance from source model does not support the hypothesis that eolian sediment in South Blue Lake is from the Sangre de Cristo Mountains (option 1) or from the Wet Mountains (option 2). There has been no silt making machine like glaciers in the Wet Mountains and average particle size is too large for what is found in South Blue Lake. Mineralogy data don’t permit the elimination of the Sangre de Cristos as a potential source, despite their close proximity to the lake.
Figure 21 Ternary diagrams for mineral components (quartz;K-spar;plagioclase) of potential eolian source areas. a) Blue Lake core plotted against dust collected in the San Juan mountains (Lawrence et al, 2010). b) San Juan dust compared to San Luis Valley samples. c) San Juan dust compared to San Juan bedrock (Lipman, 1975). d) San Juan dust compared to bedrock of the Blue Lake basin. The green circles represent mineralogical characteristics of Wet Mountain granite.
weathered granite not attributed to glacial grinding - is typically sand-sized or larger particles. Sand-sized particles do not dominate the particle size fraction in South Blue Lake, and particles of this size cannot travel distances up to 65 km. This distance from source versus particle size situation does not suggest that the silt in Blue Lake is from such a close source, according to the commonly used distance-decay models for loess, but rather it travels a much farther distance.

6.3 Dust movement

Dust transport and deposition are dependent upon changes in atmospheric circulation over time and can be reconstructed from present and past particle size and mineralogical signatures. Dust gets activated at the surface and then forced upward and entrained in atmospheric flow. According to Pye (1987), several studies have explored wind velocity required to entrain dust. The actual velocity requirement will vary spatially, but Clements et al. (1963) found that on desert surfaces the wind velocity necessary to entrain dust ranges from 6 m s\(^{-1}\) to more than 16 m s\(^{-1}\). Hall (1981) found similar wind speeds to effectively hold particles in suspension at specific locations in Arizona and Colorado, averaging 11 m s\(^{-1}\) and gusting to more than 16 m s\(^{-1}\). Reheis states that their results, as well as the results of Engelstaedter and Washington (2007) using satellite data, showed that gustiness is better correlated with dust emissions than average wind speed.
Wind roses generated from wind speed and wind direction data collected between 2004 and 2013 at the GSDNPP RAWS weather station (37° 43’ 36” N, 105° 30’ 39”W) indicate a dominant west-southwesterly wind direction in all seasons (Figure 6). Wind speeds vary by season, with greatest wind speed occurrence in spring (March-April-May). Davis and Walker (1992) found similar seasonality to wind intensity and occurrence in the western United States, attributing it primarily to the north-south migration of the Polar Front. GSDNPP wind roses show that spring is the season with the highest frequency of wind speeds greater than 6 m s⁻¹ (occurring 12.1% of the time), however Reheis and Urban (2011) found a statistically significant (p = 0.01) correlation between silt-clay flux on the eastern Colorado Plateau and average wind speeds throughout the year. In late winter and spring, the subtropical jet strengthens in the southwest, as well as the persistence of a western Colorado Ridge (Davis and Walker, 1992; Frank et al., 2008). These synoptic conditions increase the southwesterly flow aloft. This is preceded by the Great Basin ridge, a blocking high that displaces the polar jet to the north, and results in high wintertime temperatures. Pre-drying followed by a windy period may be an important sequence allowing for greater sediment availability. Time series reveal that the frequency of high wind days share a relationship with phases of the Southern Oscillation Index (SOI) and ENSO variability. The best correlation between high wind frequency and SOI was during January through April (Phillips and Doesken, 2011). Although this correlation is not statistically significant, which the authors attribute to the limited spatial and temporal resolution of wind data available in this region, it is notable and merits further research. The timing and direction of these
winds are evidence for particle activation and entrainment because of the reduced vegetation cover of early spring and because the potential source is the arid to semi-arid southwestern United States.

Silt-sized quartz particles less than 63 μm are shown to often travel predictable distances, and studies have found that decreasing particle size corresponds to increasing distance from the source. Numerous past studies have estimated the relationship between particle size and distance from the source, with many showing that dust transported more than a few hundred kilometers is generally less than 30 μm in size (Pitty, 1968; Prospero and Bonatti, 1969; Porter et al., 2001; Mason et al., 2011). Relative abundance of South Blue Lake particles less than 63 μm (sand-silt fraction boundary) is shown in Figure 22. According to estimates made by Ding et al. (2005) and Muhs (2013) silt abundance less than 20% indicates basin-dominant deposition. No portion of the South Blue Lake core particle size proportion <63 μm falls into this category. The majority of particles in South Blue Lake <63 μm (70%-99% of the core) indicate that South Blue Lake sediment flux is mostly eolian.

Results from Tsoar and Pye (1987) show that once particles finer than 20 μm are entrained in the atmosphere, they are likely to stay in suspension for a long period of time. But, medium to coarse silts are more likely to fall out of the atmospheric flow a short distance from the initiation point. Pye (1987) noted that dust will be deposited closer to its source if the wind carrying the sediment is variable. Distribution of airborne particle sizes as well as deposition of transported particle sizes is strongly controlled by the location of transport and deposition (Smith et al., 2002). Prevailing winds in the
Figure 22 Particle size range indicative of eolian origin (Ding et al, 2005; Muhs 2013) for the relative abundance of particles less than 63 micrometers (sand-silt fraction boundary). Silt abundance less than 20% indicates basin dominant deposition (shaded green). Silt abundance between 70-83% indicates that airborne particles have traveled approximately 100 km from their source (shaded peach). Silt abundance between 85-95% suggests that particles have traveled approximately 200 km (shaded blue). Silt abundance between 92-99% suggests that particles have traveled a distance greater than 300 km (shaded pink).
study area are south/southwesterly. The complex basin and range topography of the San Luis Valley and surrounding mountains interfere with unidirectional winds, causing shifting surface winds. Smaller particles entrained in the boundary layer jet stream coming from the prevailing direction may transport dust a farther distance before it settles out above South Blue Lake, whereas surface winds acting on a local scale may not transport sediments as far thus restricting transport from the San Luis Valley. Using the distance to source examples above and particle size distribution in South Blue Lake, it is possible to estimate the distance that silt-sized sediment traveled before being deposited. The distance from the San Juan Mountains (primary source) and the San Luis Valley (secondary source) to South Blue Lake is between 100-200 km. Since most of South Blue Lake sediments that are less than sand-sized (%<63 µm) are within the 70-92% range, they should indicate an expected transport distance of between 100-200 km.

However, mean particle size in South Blue Lake for the proportion less than 63 µm ranges between 5.4 and 24.5 µm (Figure 23). With the exception of the single occurrence of 24.5 µm at a depth of 502 cm, all of the particle size means by depth are less than 15.7 µm. Particles under long-term, long-distance suspension are typically less than 20 µm (Pye, 1987). Yang and Ding (2004) used a median particle size to distance function to examine Chinese desert loess. Their results show a distance-decay relationship between particle size and distance from source that supports long-distance
Figure 23 Mean particle size for the $< 63 \mu m$ proportion of South Blue Lake. Mean particle size of this eolian proportion indicates primarily long-distance transport.
transport (>200 km) of particles less than 20 μm. Particle-sizes less than 10 μm are shown to travel farther than 400 km.

Lawrence et al. (2009) categorize the particle size to distance from source relationship differently (Figure 24). But, data from South Blue Lake still conform to the general relationship and are in agreement with the Ding et al. approach. Where 50% or less of the distribution is comprised of silt, Lawrence et al. (2009) suggest that sediment flux is dominated by a local source (0-10 km away). Between 422 cm and 442 cm, silt proportions indicate local flux into South Blue Lake. Silt proportion around 60% implies a regional source (10-1000 km away). The South Blue Lake silt proportion is more frequently in this category; occurring at 312 cm, 292 cm, 164 cm, and with greatest frequency between 500 cm and 400 cm. By and large, the proportion of silt in South Blue Lake is near or above 70%. Silt proportions above 70% suggest far-traveled dust (>1000 km) and imply global-scale entrainment of the particles. A large portion of the South Blue Lake exceeds this proportion. Mass accumulation rate (MAR) can also be used to confirm particle size results as they relate to distance from source. Lawrence et al. (2009) reports that changes in MAR for dust is reflective of provenance. MAR of 5-100 g m\(^{-2}\) kyr\(^{-1}\) indicates local origin, MAR of 1-50 g m\(^{-2}\) kyr\(^{-1}\) indicates regional origin, and MAR of 0-1 g m\(^{-2}\) kyr\(^{-1}\) indicates global origin (Figure 24). Using the MAR for South Blue Lake to determine distance from source is less accurate than using particle size proportion because the predetermined range indicating local or regional flux is very
Figure 24  a) Silt fraction (2 μm-63 μm) relative to estimated distance from source (Lawrence et al., 2009). Silt proportion that suggests a 1) locally dominant source (0-10 km) in green, 2) regional source (10-1000 km) in red, and 3) global source (>1000 km) in blue. b) Mass accumulation rate (MAR) in g/m²/kyr for Blue Lake core (red line) and for the silt fraction only (black line) relative to estimated distance from source (Lawrence et al., 2009). MAR that suggests 1) local origin (5-100 g/m²/kyr) in peach shaded box, 2) regional origin (1-50 g/m²/kyr) in blue shaded box, and 3) global origin (0-1 g/m²/kyr) in pink shaded box.
large (5-100 g m\(^{-2}\) kyr\(^{-1}\)) with a large overlap between 8 and 50 g m\(^{-2}\) kyr\(^{-1}\). However, most of the calculated South Blue Lake MAR is less than 10 g m\(^{-2}\) kyr\(^{-1}\), and is occasionally completely within the global-distance range (0-1 g m\(^{-2}\) kyr\(^{-1}\)).

Frank et al. (2008) conducted a synoptic climatology analysis, using the ULSC model, of atmospheric transport of White Pine blister rust spores from California to the SRM region. Blister rust spores are roughly the same size as fine silt (10-20 μm), so this synoptic climatology may be used to infer fine silt transport to South Blue Lake as well. The feasibility of upper-level transport of silt-sized particles from the Great Basin (and farther west) to the Sangre de Cristo and Wet Mountains was demonstrated in the Frank et al. (2008) study. A summer (April-July) trough in the western United States develops about 14.8% of the time and creates a zone of high wind speeds over California capable of transporting eolian-sized particles to the SRM region. Modeled potential (considered “very high”) of California blister rust infestation in the Sangre de Cristo and Wet Mountains confirm the potential transport and deposition of particles from a distance greater than 1000 km to the west (Frank et al., 2008).

The wide and rapidly changing particle size distribution reflected in Figure 22 between 500 cm and 400 cm shows that eolian input into South Blue Lake between ca. 8000 cal. yr BP and ca. 5500 cal. yr BP varied between globally dominated and locally dominated source in rapid transition. This pattern is also exhibited in Figure 22 where a distinctly different eolian input pattern between 500 cm and 400 cm reflect rapid
changes in sedimentation ranging from 40% silt, suggesting a sediment source within 0-
10 km, to 80-90% silt suggesting a global source. MAR of both bulk core sediment and
of the silt fraction suggest regional and global origin (a distance from 10 to >1000 km)
for the vast majority of the South Blue Lake core.

However, ternary diagrams of quartz:plagioclase:k-spar ratios that compare South
Blue Lake sediment mineralogy to the mineralogy of potential source areas confirm that
the source of silt-sized material in South Blue Lake is from outside of the lake basin.
However, the mineralogy refutes the hypothesis that this sediment is from either the San
Luis Valley or the San Juan Mountain bedrock. It is most similar to eolian dust deposited
in the San Juan Mountains (Figure 19). Whereas provenance of this dust has not yet been
confirmed, Lawrence et al. (2010) use strontium and neodymium isotopic data to suggest
that it results from a combination of regional and global sources. Regionally, the dust is
likely from dust plumbs in the Colorado Plateau, the Great Basin, and the Mojave Desert.
More recently, combined meteorological data and satellite imagery show that the primary
source of recent dust events in the San Juan Mountains is the arid basins of the Colorado
Plateau (Phillips and Doesken, 2011). Sediment is available at these source sites, and
southwesterly synoptic scale wind patterns should be able to entrain and transport
sediment northeastward to the Southern Rocky Mountains.

Pye (1987) proposes that dust sampled at continental sites is typically a mix of
local and far-travelled material because coarser material can be picked up in vertical
surface convection or with unstable atmospheric conditions, and this results in a bimodal
grain-size distribution. Most of the particle size distribution histograms from South Blue
Lake are bi-modal, indicating locally derived and mixed eolian sediment. Figure 25 shows how the bi-modal distribution varies by meter in BL12-3. Average particle size distribution for 612 cm to 500 cm is the exception showing a negatively skewed curve. This section of the core, which corresponds to approximately 8545 cal. yr BP to 7000 cal. yr BP, appears to be almost entirely eolian. The mean particle size is 16 μm, a particle size indicative of long-distance transport. The other meter-segments of the core, by contrast, show the bi-modal distribution referred to in the literature. Beginning at 500 cm (7000 yr BP) both regional eolian and local influx of sediment is occurring at South Blue Lake with the highest influx of local sediment taking place between approximately 5000 cal. yr BP and 3000 cal. yr BP.

6.4 Loess deposits

Loess deposits around the world are often associated with oscillations between glacial and interglacial periods. Although loess stratigraphy in the High Plains and Southern Rocky Mountain region does not show the same link to glaciation as is observed at adjacent regions of North America that were directly affected by the Laurentide ice sheet, episodic loess deposition in Nebraska, Kansas and Colorado is closely tied to periods of drought and dune activation (Muhs, 2013). Such deposits are connected to dune activity because of their location downwind of dunes, and the representative tapering of loess depth with distance from the dunes. Recent ideas about dune activity suggest that the impact of saltating sand grains in dune fields plays a key role in the atmospheric entrainment of silt-sized material (Crouvi et al., 2010). Furthermore, the silt-sized particles release with the reactivations of previously immobile
Figure 25  Histograms for particle size distribution by meter in Blue Lake (BL12-3). The top four histograms show bi-modal particle size distribution for 100 cm through 500 cm. The bottom histogram shows a negatively skewed eolian dominant particle size distribution for 500 cm through the bottom of the core.
Dune fields may contribute more to atmospheric dust that continuously active sand (Pye 1987).

Madole et al. (2008) estimate that the age of the Great Sand Dunes is late-Pleistocene and that the dunes have exhibited periodic stabilization and reactivation throughout the Holocene. These bursts and breaks in dune activity may be contributing silt to atmospheric circulation of loess. Because the dune fields of GSDNPP follow the periodic saltation pattern conducive to silt development and activation described by Pye and Crouvi, and we might expect to see loess deposits downwind of GSDNPP in the Huerfano Valley, and along the slopes of the Sangre de Cristo and Wet Mountains. On the contrary, large loess deposits have not been identified or documented downwind from GSDNPP as explained above. Furthermore, mineralogical results from the South Blue Lake core do not demonstrate that most of silt sediment accumulating in the lake is from GSDNPP or from the San Luis Valley. Topography and vegetative cover may be blurring the eolian distribution of material originating to the west. The unique topographic setting in the region may also play a role in limiting silt transport from the dunes. Sparse vegetation facilitates dune activation and movement and vegetation along the margins of GSDNPP is increasing, thus stabilizing the some of the most active regions of the dune field along the margins. As compared to large loess regions around the world like those found in central Asia and China, which are downwind from large desert regions, South Blue Lake is downwind from a relatively small arid region and
dune system. For this reason, it would make sense that the volume of deposits would reflect the scaled-down size of the source.

6.5 Particle size analysis zones

Particle size fluctuations in South Blue Lake were grouped into three zones (PSA Zone I, 500 cm–420 cm, ca. 7000–5400 cal. yr BP; PSA Zone II, 400 cm–315 cm, ca. 5000–3252 yr BP; PSA Zone III, 298 cm–184 cm, ca. 3100–2000 cal. yr BP) based on observed patterns in the particle size distribution results (Figure 26). These zones were compared with other studies of climate and windiness during the Holocene, and with other results from this study.

6.5.1 Zone I

Previous paleowind studies have generalized North American circulation during the Holocene based upon lake studies conducted in Minnesota (Dean 1997; Mayewski et al., 2004). According to these authors, the mid-Holocene is considered to be a time of increased, sustained windiness in North America. Prevailing North American westerlies are thought to have been particularly strong between ca. 6000 cal. yr. BP and ca. 5000 cal. yr. BP. High concentration and mass accumulation rates of aluminum in varved lake sediments between ca. 7800 yr. BP and ca. 5500 yr. BP (seven times greater than in the last 3000 years BP) also indicate that generally wind was of greater intensity in the mid-Holocene (Dean 1997). Using generalized paleoclimate studies to make inferences about a specific location merits caution, however. Fall (1997) indicated that there are important differences in the literature among climatological interpretations for the Holocene. The complex physical characteristics we observe today, particularly in areas like the SRM
Figure 26 Particle size analysis zones (PSA Zone I, PSA Zone II, PSA Zone III) determined from results comparison of sedimentation rate, particle size, and mineralogy. Zone I corresponds to approximately 7000 yr BP to 5400 yr BP. Zone II corresponds to approximately 5000 yr BP to 3252 yr BP. Zone III corresponds to approximately 3100 yr BP to 2000 yr BP.
region, existed during the Holocene as well and complicate the study and interpretation of past climates. Paleoclimate studies conducted in the mountains and deserts of the American Southwest (e.g., Betancourt 1984; Waters, 1989; Betancourt, 1990; Van Devender, 1990; Fall, 1997; Wurster et al., 2008) will be included in the following discussion for this reason.

Beginning ca. 9000 cal. yr BP until ca. 4000 cal. yr BP, upper and lower tree lines in the Southern Rocky Mountains expanded above and below current elevations. This expansion in tree lines is indicative of warmer temperatures and increased precipitation (Fall, 1997). High lake levels in Arizona and New Mexico, greater estimated effective moisture on the Colorado Plateau around 6000 cal. yr BP, and enhanced monsoonal precipitation between 9000 cal. yr BP and 4000 cal. yr BP indicate a wetter period in the American Southwest during the early- to mid-Holocene (Waters, 1989; Betancourt, 1990; Van Devender, 1990). Antevs (1948, 1955), by contrast, inferred a warmer but drier period in the Great Basin between ca. 7500 cal. yr BP to ca. 4000 cal. yr BP (Fall, 1997). Drake et al. (2012) also point to increased aridity in the southwest using pollen, packrat midden, and macrobotanical evidence in the San Juan Basin, New Mexico during the mid-Holocene (ca. 5300 cal. yr BP).

This time period overlaps well with PSA Zone I (ca. 7000 cal. yr. BP – ca. 5400 cal. yr. BP), an area of exceptional variability in South Blue Lake mineralogy, medium silt accumulation, bulk density intensity, and pronounced stratigraphic layering. Particle
size during this period shows a divergence in sand (decreased proportion) and very fine silt (increased proportion), with medium silt being highly variable. Frequent statistically-low intervals of medium silt proportion relative to the total particle size distribution are unique in this zone (Figures 15-17). The minor proportion of sand, and the dominance of both medium (31-15.6 μm) to fine (7.8-3.9 μm) silt fractions, implies that atmospheric conditions favored regional- and long-distance particle transport and deposition in South Blue Lake rather than a local contribution. Distinctive variability in magnetic susceptibility occurs between ca. 7000 cal. yr BP and ca. 5000 cal. yr BP where an apparent cyclical pattern of near average magnetic susceptibility is punctuated by very high influx of magnetic material. This persists from ca.7100 cal. yr BP to ca. 4800 cal. yr BP. These peaks in magnetic susceptibility correspond well to high points in the silt-sized fractions. Apart from similar heightened variability during this period, less temporal agreement exists between magnetic susceptibility and mineralogy.

Between 494 cm (ca. 6800 cal. yr. BP) and 460 cm (ca. 6300 yr. BP) variability in the Q:P ratio varies from very high (3.0) where quartz relative abundance is much higher, to very low (1.5) where plagioclase dominates. Periods of higher quartz may indicate lulling in westerly winds. The high variability in quartz versus plagioclase between 608 cm (ca. 8000 cal. yr. BP) and 408 cm (ca. 5500 cal. yr. BP) could also be indicative of a more turbulent time for orographically driven surface winds. The North American Monsoon (NAM) is believed to have intensified around 8000 cal. yr BP resulting in an abrupt change in atmospheric circulation and an increase in convective storms in the region. Rapid fluctuations in local versus external sediment flux into South Blue Lake
may have been influenced by this increased storminess. Organic content trends upward in South Blue Lake from the basal depth around 616 cm (ca. 8545 cal. yr. BP) to around 400 cm (ca. 5000 cal. yr. BP). This supports in part the hypothesis put forth by Shuman et al. (2010) that the first half of the Holocene is a mega-drought (from ca. 8900 cal. yr. BP to ca. 3700 cal. yr. BP). Increasing variability in medium silt fraction over this time period may also indicate increasing sediment availability through drying and vegetation reduction. Frequent laminae of charcoal indicating fire, followed by coarse sediment influx in the core (Figure 17), suggest that warmer, dryer conditions may have magnified in the mid-Holocene and persisted with time (Shuman et al., 2010; Wagner et al., 2005). Increasing variability in the silt fraction over this time period also suggests increasing sediment entrainment, possibly the result of drying and vegetation reduction. Higher variability in every aspect of the South Blue Lake analyses may indicate periodic fluctuations in wind intensity as well as drought. Results from PSA Zone I support the notion that the first half of the Holocene is an extended warm period with low effective precipitation in the Southern Rocky Mountain region (Holliday, 1989). Significant periodic fluctuations in wind intensity imply a highly dynamic climatic interval until ca. 5000 cal. yr BP.

6.5.2 Zone II

PSA Zone II (ca. 5000 cal. yr. BP – ca. 3252 cal. yr. BP) shows a divergence of the silt fractions (decreased relative abundance and reduced range of variability in very fine silt) and an increase in fine sand. Between 380 cm (ca. 4200 cal. yr. BP) and 350 cm (ca. 3500 cal. yr. BP) is considered to be a time of exceptionally strong westerly winds
over North America (Mayewski et al, 2004). Fall (1997) considered ca. 6000 cal. yr BP to ca. 4000 cal. yr BP to be a period of transition from thermal maximum of the mid-Holocene to cooler conditions. Tree lines began to retreat ca. 4000 cal. yr BP as temperatures cooled and precipitation previously dominated by summer monsoon changed over to winter. Fall also noted that between 4000 cal. yr BP and 2600 cal. yr BP, the climate of the Southern Rocky Mountains was drying out. The greater relative abundance of very fine silt may support this hypothesis, especially if strong upper-level westerlies (as suggested by Mayewski) are carrying large amounts of very small silt particles greater distances. Dorner (1998) collected 200cm of sediment dating to ca. 6313 cal. yr BP from Goosedam Meadow located approximately 49km southwest of South Blue Lake. Pollen diagrams and loss on ignition comparisons from the sediments collected at Goosedam Meadow show high organic matter content and increases in arboreal species during PSA II (Dorner, 1998). Coarse sediment influx in the stratigraphic column could be indicative of a period of decreased wind intensity; however, this layer could be more closely related to instability in PSA Zone I. A dramatic spike in sand and in BD at 315 cm (ca. 3100 cal. yr. BP) marks the youngest part of PSA Zone II and could be related to a short-term lull in wind speeds. But, it is more likely showing a short-term event in the local landscape such as wildfire.

6.5.3 Zone III

Beginning at around 320 cm (ca. 3100 cal. yr BP) until about 180 cm (ca. 2000 cal. yr BP) - PSA Zone III - very low relative percentages of sand and high relative percentages of silts are evident. Medium silt once again shows increased variability and
frequency in changes in relative abundance. Very fine silt shows one distinctive peak between 278 cm (ca. 3000 cal. yr BP) and 250 cm (ca. 2800 cal. yr BP).

Quartz:plagioclase ratios are stable, but favoring an external sediment source. Mayewski et al. (2004) found this to be a time of decreased windiness in the northern hemisphere.

In preliminary analysis using pollen, organic matter content, bulk density, and sedimentation rates the Goosedam Meadow sediments tell a story of cooler conditions in this part of the Southern Rocky Mountains from ca. 3000 cal. yr BP to ca. 750 cal. yr BP. Cooler conditions beginning around 3000 cal. yr BP may explain the relative stability of eolian influx and quartz:plagioclase ratios, as well as falling organic content in South Blue Lake until ca. 2000 cal. yr BP. However, the large change in South Blue Lake mineralogy and rebounding organic content percentages in the latter half of the Dorner (1998) time period does not support sediment stability and cooler conditions. Greater agreement appears to remain with Fall (1997), Mayewski et al. (2004), and Routson et al. (2011) conclusions that between 2000 cal. yr BP and 1500 cal. yr BP the Southern Rocky Mountain region was becoming warmer, drier, and windier.

A bimodal peak in the magnetic susceptibility curve between ca. 3250 cal. yr BP and ca. 3000 cal. yr BP is noteworthy because Dorner (1998) found a similar pattern in the same chronological region at Goosedam Meadow. The bimodal peak falls between the boundaries for PSA Zone I and PSA Zone II. The peak overlaps with a large increase in the relative proportion of very fine silt early in the chronology. Very fine silt peaks in PSA Zone I also follow a similar pattern to peaks in magnetic susceptibility. This may
suggest a shift in climatic instability, or it may signal an influx of eolian material from an external source to the entire region.

Another hypothesis for the bimodal peak is that between ca. 3500 cal. yr BP and ca. 3000 cal. yr BP the El Niño/Southern Oscillation (ENSO) showed increased variability. ENSO variability adds pulses of higher-than-normal cool season moisture to the Southern Rocky Mountains in the warm ENSO phase, and can exacerbate dry conditions in the cold ENSO phase (Enloe and Smith, 2004; Wagner et al., 2005; Drake et al, 2012). St. George and Wolfe (2009) found that interannual variability related to ENSO is a major component of near surface wind dynamics and they suggest that El Niño “stilling” may also affect other parts of North America, like the Southern Rocky Mountains, known to be teleconnected to the ENSO system. The unusual bimodal magnetic susceptibility peak observed in both Goosedam Meadow and South Blue Lake may be highlighting this active ENSO period. No other portion of magnetic susceptibility corresponds well to the Goosedam Meadow core so this agreement between the two sites is possibly indicating relatively short-term, localized variability in climate or wind. The inverse is true, particularly between ca. 7000 cal. yr BP and ca. 5000 cal. yr BP, where differences in magnetic susceptibility curves mark spatial differences in environmental conditions between the two sites during the mid-Holocene.
Chapter Seven: Conclusion

Sediment from an external source dominates the silt fraction of the South Blue Lake core. Very fine silt when compared with other analyses used in this study shows the greatest indication of eolian activity. Variations in eolian contribution correspond to durations of increased wind and dry conditions as noted in the literature. A change in bulk density and organic matter content coupled with stabilization of particle size distribution and quartz to plagioclase ratios mark a very distinct shift in eolian influx and inferred large-scale circulation patterns beginning about ca. 5000 cal. yr BP. Earlier in the record fluctuating results imply a dynamic climate in the Southern Rocky Mountain region related to early- to mid-Holocene warming. The ca. 5000 cal. yr BP shift may mark the end of the “Climatic Optimum” and initiation of cooling in the more recent Holocene. Based on these observation, I expect natural variability in the future to be similar to that observed during the mid-Holocene. And, heightened greenhouse warming may enhance this natural variability (Cook et al., 2013).

Paleodrought conditions that have been generalized for the southwestern United States may have a greater impact on sediment availability outside of this study region. While there appears to be a relationship between eolian sediment influx in South Blue Lake and warmer, drier conditions, the sediment isn’t coming from the San Luis Valley or San Juan Mountains. Perhaps the deserts west of the study area are more sensitive to climate changes and therefore a good source proxy for wind (Figure 27). Variable winds
Figure 27 - Revised cartoon model of the hypothesis. Probable long-distance source that is farther (>400 km) west than the San Juan Mountains.
in the mountainous environments may restrict eolian transport from the San Luis Valley. However, during the very active monsoon period of the mid-Holocene storminess may have activated more sediment and allowed greater transport from local sources and nearby sources.

This study highlights the temporal richness and spatial complexity of wind in the Southern Rocky Mountain region. Closed basin lakes east of the Sangre de Cristo Mountains appear to preserve an identifiable record of paleowind, but the potential that this is an exceptionally limited and localized record is noteworthy. South Blue Lake provides evidence for continuous dust deposition in a mountain environment throughout most of the Holocene. Paleowind is identifiable in a combination of proxy evidence, however the direct relationship between changes in wind and climatic variation requires further investigation. This is a preliminary deduction and further studies should be conducted using isotopic analysis on this study’s samples as well as comparison samples from other locations in the region (Sangre de Cristo Mountains, New Mexico, Great Basin, and Colorado Plateau) to confirm provenance. Additionally, radiometric dating of mineral samples could prove useful in determining local to regional provenance. Future investigations using South Blue Lake sediment should incorporate diatoms, fire history, and charcoal and pollen analysis. Based upon the timing and amplitude of variability patterns in South Blue Lake, this lake appears to be particularly sensitive to eolian inputs and is a good location for paleoenvironmental studies.
References


Appendix B

Table of magnetic susceptibility measurements by depth (SI).

<table>
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Appendix C

BL12-2: Laser Diffraction Particle Size Analyzer histogram for replicates.
Appendix D

Normalized pattern data from quantitative mineralogy analysis.

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