AN ABSTRACT OF THE THESIS OF

Jonathan Vopata for the Master of Science Degree in Physical Sciences presented on November 30, 2004.

Title: A Study of Patterned Ground at Trinchera Peak, Colorado

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In 2000, patterned ground was discovered on Trinchera Peak (4120 m), Culebra Range, Sangre de Cristo Mountains, southernmost Colorado. Subsequently, another site of similar patterned ground was discovered on a ridge (3905 m), just north of Trinchera Peak. An initial overview of the study sites revealed the patterned ground is better formed at Trinchera Peak than at Site 2. At Trinchera Peak the most distinct polygons range between 3 and 5 meters in diameter. The polygons are sorted with the margins of the polygons composed of stones and the polygon centers consisting of finer sediment and turf. The patterned ground of Trinchera Peak is remarkably similar to patterned ground at other sites around the world. This preliminary study is an attempt at determining a minimum age of the patterned ground formation. Methods included photographing the site, recording measurements of lichens (*Rhizocarpon geographicum*), collecting soil samples, and recording soil temperatures. Lichen measurements from both patterned ground study areas were compared to lichen growth rate curves developed by Benedict (1967) from the Indian Peaks area in the Colorado Front Range.

The median lichen diameters at Trinchera Peak and Site 2 indicate a minimum time range for patterned ground activity to be ~ AD 1350 for Trinchera Peak and ~ AD 1750 for Site 2. Using only the five largest lichens of both study sites a minimum age of patterned ground formation was calculated to ~AD 850. These lichen ages are considerably younger than expected, thus lichenometry results may suggest episodes of snowkill rather than periods of patterned ground activity. Additionally, lichen dates obtained may be erroneous due to differences in substrate, climate, moisture, and length of the growing season between the Indian Peaks Region of Colorado and Trinchera Peak.

Advanced soil development, large lichens, and the relatively mild climate of the Holocene indicate the polygonal patterned ground may have developed initially as far back as the Pleistocene. Variability in lichen sizes, frost boil, and current revegetation of Trinchera Peak indicate periods of patterned ground activity as well as episodes of snowkill during the Holocene. Patterned ground activity may have occurred during the Neoglaciation (prior to AD 850) and then been partly reactivated during the Little Ice Age (~ AD 1300-1900). The recent climatic warming trend has led to revegetation and stability of Trinchera Peak patterned ground.

A STUDY OF PATTERNED GROUND AT TRINCHERA PEAK, COLORADO

A Thesis

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Chapter 1

Introduction

While conducting extended field observations on Trinchera Peak, southernmost Colorado in 2000, Drs. James Aber and Volli Kalm made a joint discovery of relict patterned ground. Subsequently, Aber discovered another site of similar patterned ground on a ridge just north of Trinchera Peak (Aber and Kalm, 2001). In 2001, Jet Tilton conducted preliminary lichen measurements of the patterned ground to determine the surface stability of periglacial features at Trinchera Peak. He concluded that the patterned stone nets of Trinchera Peak were the oldest stable periglacial landform examined (Tilton, 2003). Exactly when and how the patterned ground had developed is still unclear. This thesis is an attempt at determining an age range for the patterned ground on Trinchera Peak, using general field observations, lichenometry, soil data, and temperature data.

Overview of the Study Area

Trinchera Peak is about 12 kilometers southwest of Cuchara, Colorado and approximately 290 kilometers south of Denver, Colorado (Veatch, 2000). As depicted in Figure 1, the mountain is divided between Costilla, Huerfano, and Las Animas counties. For this study, both the patterned ground of Trinchera Peak and the patterned ground on a ridge approximately 2 kilometers due north of Trinchera were analyzed to determine an age of formation. Trinchera Peak was the primary site and the northern ridge functioned as a secondary field site. Figure 2 is a photograph taken from the north, showing the locations of both study sites. The patterned ground at Trinchera Peak rests on an alpine

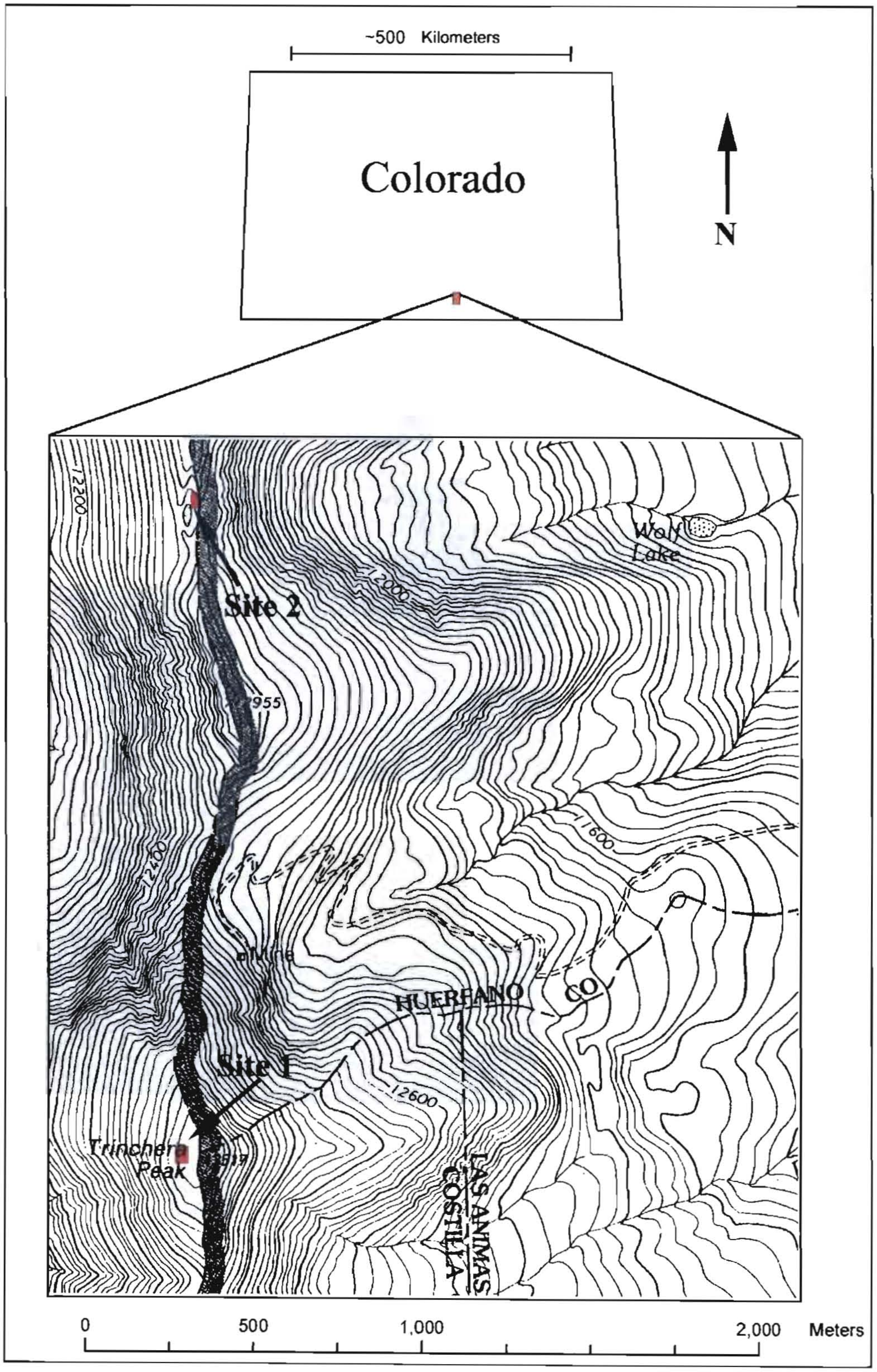


Figure 1. Location of study sites 1 and 2 in Colorado.

(Modified from Trinchera Peak Quadrangle 7.5-minute series 1994.)

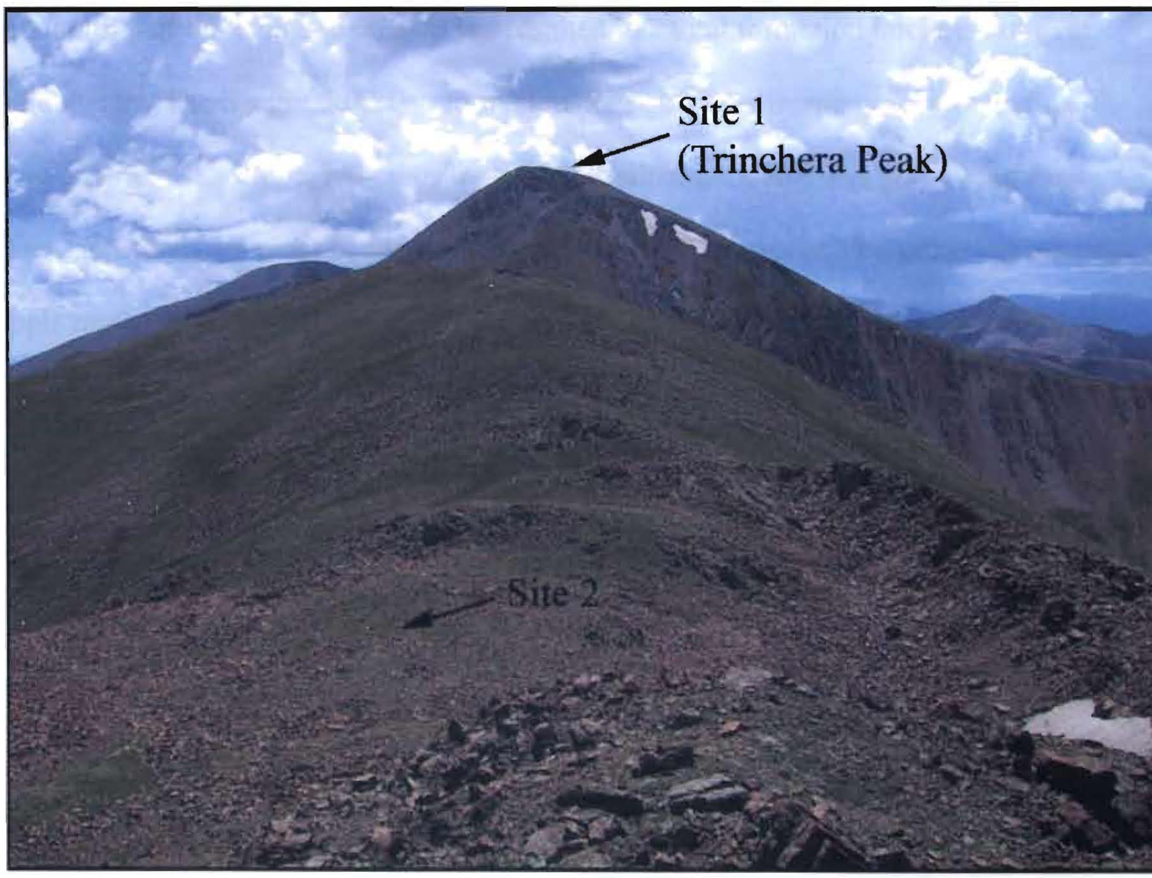


Figure 2. Photograph taken from the north showing the locations of study sites 1 and 2

plateau just west of the mountain summit. The patterned ground of site 2 lies in the saddle of a mountain ridge. The Trinchera Peak study site is approximately 4120 meters above sea level, whereas site 2 is lower at about 3900 meters.

The bedrock of both study sites is part of the Sangre de Cristo Formation. The Sangre de Cristo Formation is Middle Pennsylvanian to Early Permian in age. Folding and faulting of the Sangre de Cristo has resulted in a total formation thickness of over 4000 meters. The Sangre de Cristo formation consists of sedimentary rock including conglomeratic sandstone, red arkosic sandstone, siltstone, shale, and gray limestone. "The sandstones are cross bedded and the siltstones and shales exhibit cross laminations, ripple marks, mudcracks, and small burrows, and plant fragment impressions are found locally" (Wallace and Lindsey, 1996). The mountain ridge is supported by near-vertical beds of gray, quartzite sandstone at the base of the Sangre de Cristo Formation.

Trinchera Peak is part of the Culebra Range in the Sangre de Cristo Mountains. The Sangre de Cristo Mountains extend from central New Mexico to central Colorado (McAlpin, 1983). The Culebra mountain range formed by crustal uplifting during the Laramide Orogeny. The Laramide Orogeny began in the late Cretaceous and lasted until the early Tertiary (Penn and Lindsey, 1996). The Laramide orogeny was a period of strong crustal compression causing Proterozoic crust to thrust over Paleozoic and younger strata. This thrusting created numerous thrust and reverse faults in the Culebra Range. Tectonic activity of the Sangre de Cristo Mountains eventually faded out between the late Tertiary and Quaternary periods (Aber, 2002).

The Pleistocene Epoch, 1 million to 10,000 years ago, brought about a colder climate and the formation of small glaciers in the Trinchera Peak vicinity. These glaciers created many new landforms including cirques, kettle lakes, moraines, and arêtes. The glaciers even eroded the sides of Trinchera Peak creating an alpine horn. Nearly all remaining glacial deposits date from the last glacial stage known as the Pinedale (Aber, 2002).

Today, the alpine zone (above 3,600 meters) at Trinchera Peak is in a climatic warming trend, but it is still a harsh environment (Veatch, 2000). The average annual temperature is below freezing and the frost free season is only one to two months long. Extreme wind velocities in the winter months can create gusts over 160 kilometers per hour. Winter snowfall is the dominant type of precipitation with approximately 2 to 5 meters falling annually. Despite these severe conditions shrubs, wild flowers, grasses, and other small forbs flourish in the alpine tundra. These plants grow almost everywhere from the gently sloping meadows to small crevices in the rock cliffs (Mutel and Emerick, 1992). This alpine vegetation also draws many animals; including big horn sheep, bears, marmots, and numerous insects, to feed high above timberline. The current warmer alpine climate signifies that patterned ground formation is probably no longer active, since patterned ground development requires extremely deep seasonal ground freezing, if not permafrost (Aber and Kalm, 2001).

Patterned Ground

Patterned ground refers to the natural arrangement of surface materials into geometric shapes such as circles, stripes, and polygons (Krantz et al., 1988). Patterned ground has been discovered in a variety of environments and in various forms. For the purpose of this thesis, only periglacial patterned ground will be discussed. Periglacial patterned ground is formed in cold climates by frost-action processes. Cyclic freezing and thawing of the ground causes surface sediments to shift into distinct geometric patterns (Kessler and Werner, 2003). Patterned ground formation requires significant soil moisture and cyclic freezing and thawing. Also, research indicates that snow, vegetative cover, exposure, water drainage, slope, and soil properties all influence patterned ground development (Krantz, 1990). The patterned ground phenomenon is complex and not yet fully understood.

In 1956 A.L. Washburn proposed that patterned ground be classified by two basic criteria: (1) the geometric patterns formed and (2) whether or not sorting had occurred (Washburn, 1956). The patterns formed can include circles, nets, polygons, steps, and stripes. These patterns can range from a few centimeters to several meters in diameter or width. The gradient of the surface is the primary factor in determining which pattern will develop. Circles, nets, and polygons will form only on horizontal or gently sloping land. As the slope increases the circles, nets, and polygons become elongated and transform into steps and stripes. A slope of over 30 degrees is too steep for patterns to develop (Embleton and King, 1975). Once a developed pattern is acknowledged, one may note whether sorting of the sediment had occurred. Sorting is the separating of larger stones from the fine particles. Sorted patterned ground typically displays the edges of the polygon, net, etc. with larger rocks, while the centers consist only of fine material. Sorting in this manner is achieved by larger particles elevated to the surface and shifted outward (Bloom, 1998). Sorted patterned ground occurs most frequently in places of intense freeze-thaw activity, such as wet, cold mountain plateaus (Budel, 1982).

It is still unclear what mechanism or mechanisms are the driving forces for the movement of sediment into visible patterns. It is likely that several combinations of processes act together to create numerous forms of patterned ground in various environments. The sorting of sediments in patterned ground may be achieved by frost heaving, frost-push, frost-pull, or convective activity driven by buoyancy differences (Washburn, 1973). Frost heave is an upward distortion of surface soils and structures due to subsurface freezing of water and growth of ice masses (Bates and Jackson, 1984). As water freezes and expands it lifts particles to the surface creating domes of sediment (Kessler and Werner, 2003). This same principal frost mechanism is responsible for frost push and frost pull. The freezing and thawing sediments expand and contract, pushing and pulling particles into sorted positions. Other research suggests that a convective model set in motion by buoyancy differences may create soil circulation and separation of the large stones from the finer particles. Soil circulation may result from variability in water and/or soil density, due to annual freezing and thawing of the active layer (Ray et al., 1983). These processes of frost heaving, frost-push, frost-pull, or convective activity force stones upward into domed polygonal centers. The stones then move laterally into depressions on the margins of the polygons. The stones that fill the bordering troughs produce sorted nets or stripes, depending upon angle of slope (Benedict, 1992). "Sorted polygons may be preserved because seasonal-flowing water permeates through the coarse network of polygonal boundaries without eroding the fine sediments from the polygon cores" (Bloom, 1998, p. 320).

The majority of research on patterned ground agrees that mean annual air temperatures of -6° to -8° Celsius are necessary for periglacial patterned ground to become well developed (Ritter et al., 2002). Although today, with the aid of aerial photography, patterned ground phenomena is often found at low latitudes and in warmer environments (Embleton and King, 1975). The reason for this is that much patterned ground is not actively forming. Instead it is relict patterned ground from past periglacial conditions that existed hundreds or even thousands of years ago. In 1982, Budel argued that fully 95 percent of the landforms of the midlatitude northern hemisphere are relicts from former periglacial conditions. This inactive or relict patterned ground can aid in environmental reconstructions and provide clues about past paleoclimates (Washburn, 1973).

Lichenometry

One chief indicator used to determine the age of relict patterned ground is lichen growth. Lichens often grow attached to a variety of substrates including soil, bark, mosses, and rock. Lichens are a combination of a fungus and an algae. The algae grows beneath the fungus for protection, and the fungus uses the algal cells for nourishment. The fungus-algae relationship is symbiotic since the algal cells reproduce faster than the fungus can destroy them. The body of the lichen is called the thallus (Corbridge and Weber, 1998). The lichen thallus grows outward on especially stable surfaces at a predictable rate. Lichens have a life expectancy ranging from a few years to thousands of years. With this long life expectancy and predictable growth rate scientists can use lichens to determine the age of stable periglacial landforms.

The dating of a surface using lichens is referred to as lichenometry. "The basic premise of lichenometry is that the diameter of the largest lichen thallus growing on a moraine, rock glacier, or other surface is proportional to the length of time that the surface has been exposed to colonization and growth" (Benedict, 1967, p. 818). In this study the lichen species *Rhizocarpon geographicum* was chosen for the lichenometry analysis. *Rhizocarpon geographicum* was selected because of its abundance at the study site, wide geographic distribution, ease of identification, and slow steady growth rate (Noller and Locke, 2000). Benedict noted that the *Rhizocarpon geographicum* can be used to date features over 3,000 years old, with the largest *Rhizocarpon* lichen dating back to nearly 6,000 years ago (Benedict, 1967).

The *Rhizocarpon geographicum* is a crutose lichen. A crutose lichen is closely appressed to its substrate and often appears "painted" onto a surface (Corbridge and Weber, 1998). Figures 3 and 4 are photographs of *Rhizocarpon geographicum*; it is bright yellow-green in color making it especially distinguishable from the other lichen varieties.

Lichenometry is based on a few primary assumptions: (1) the lichen growth starts on surfaces free of lichen thalli, (2) lichen colonization begins quickly after the surface stabilizes, and (3) the lichen growth rate is predictable over a long time period. The process of lichenometry is done by measuring lichens on a surface of a known age, constructing a growth rate curve, and comparing this growth rate to similar lichen-covered surfaces for relative dating. A growth curve is the mathematical relationship between the size of lichens and time. A lichen's growth rate can be influenced by many environmental factors including (1) rock type, (2) exposure to abrasion, (3) shading, (4) temperature, (5) moisture, (6) stability of substrate, and (7) length of growing season (Benedict, 1967). These factors can create variable growth rates in diverse environments

Figure 3. Close-up view of the *Rhizocarpon geographicum* lichen on red sandstone.

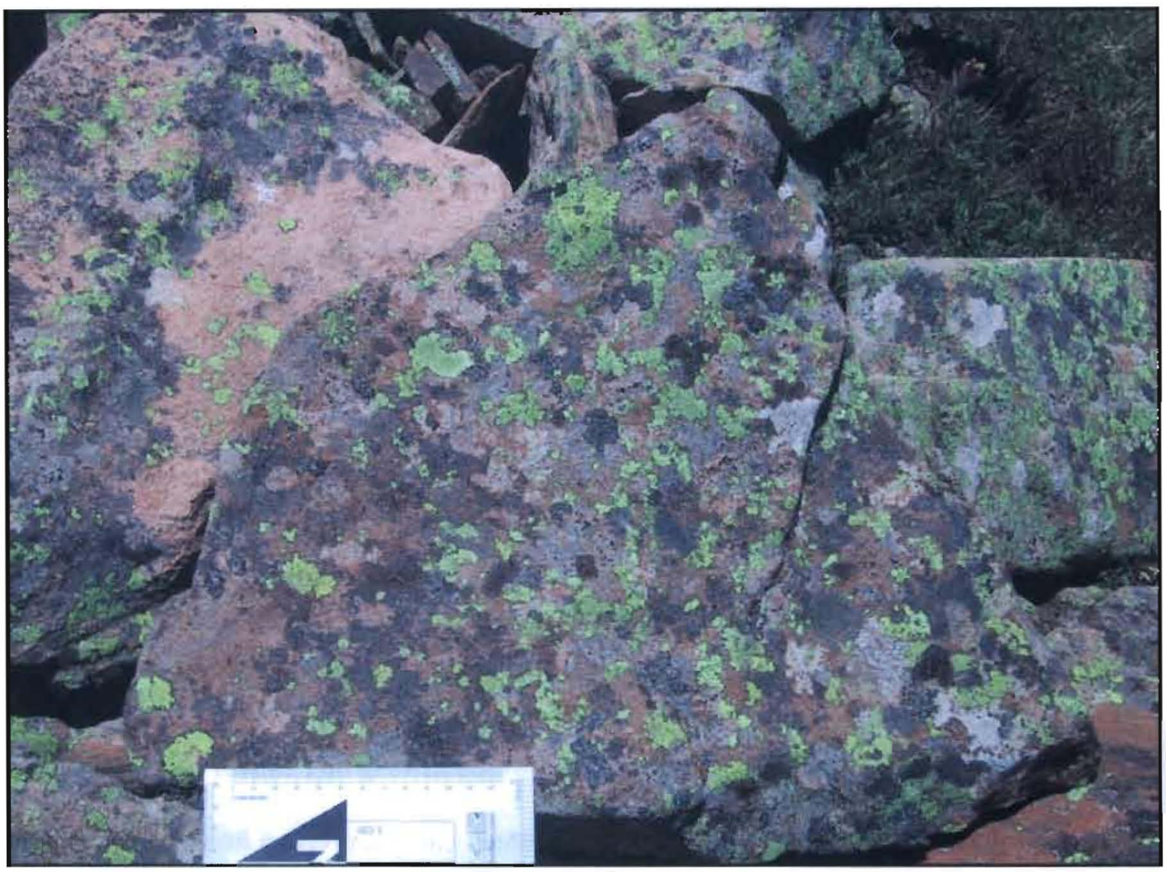


Figure 4. *Rhizocarpon geographicum* and other lichens covering sandstone rocks of Trinchera Peak.

and at different locations. In this study, lichen measurements on stones of the patterned ground in the Trinchera Peak vicinity were compared to a growth curve developed by Benedict for the Indian Peaks area in the Colorado Front Range.

Previous Work

Roland Beschel is a well known early pioneer of lichenometry. Methods and principles set forward by Beschel have been implemented with considerable success throughout various arctic and alpine regions (Carrara and Andrews, 1973). Lichenometry has been used with noticeable consistency by Beschel (1961), Benedict (1967, 1988), Birkeland (1973), Carrara and Andrews (1973), Lock, Andrews, and Webber (1979), Calkin and Ellis (1980), Innes (1984, 1985, 1986, 1988), McCarroll (1994), Bull and Brandon (1998), Tilton (2003), and numerous other authors.

In 1966, Benedict developed a lichen growth curve for the Indian Peaks Region in the Colorado Front Range,.70 kilometers northwest of Denver, Colorado (Fig. 5). Benedict's growth curve was composed using historically dated surfaces 3,125 to 4,047 meters above sea level. The growth curve was based on measurements of the lichen species *Rhizocarpon geographicum*. Benedict concluded through observations and experimentation that the species *Rhizocarpon geographicum* was most suitable for dating glacial and periglacial deposits within Colorado (Benedict, 1967).

Benedict used surfaces of known age to determine the lichens growth rate. "Measurements were made on 24 historically dated surfaces, ranging in age from 25 to 69 yr., and on three radiocarbon-dated surfaces, including (1) mudflow levees younger than 180 yr., (2) a rock wall built by prehistoric Indians about 970 yr. ago, and (3) ground

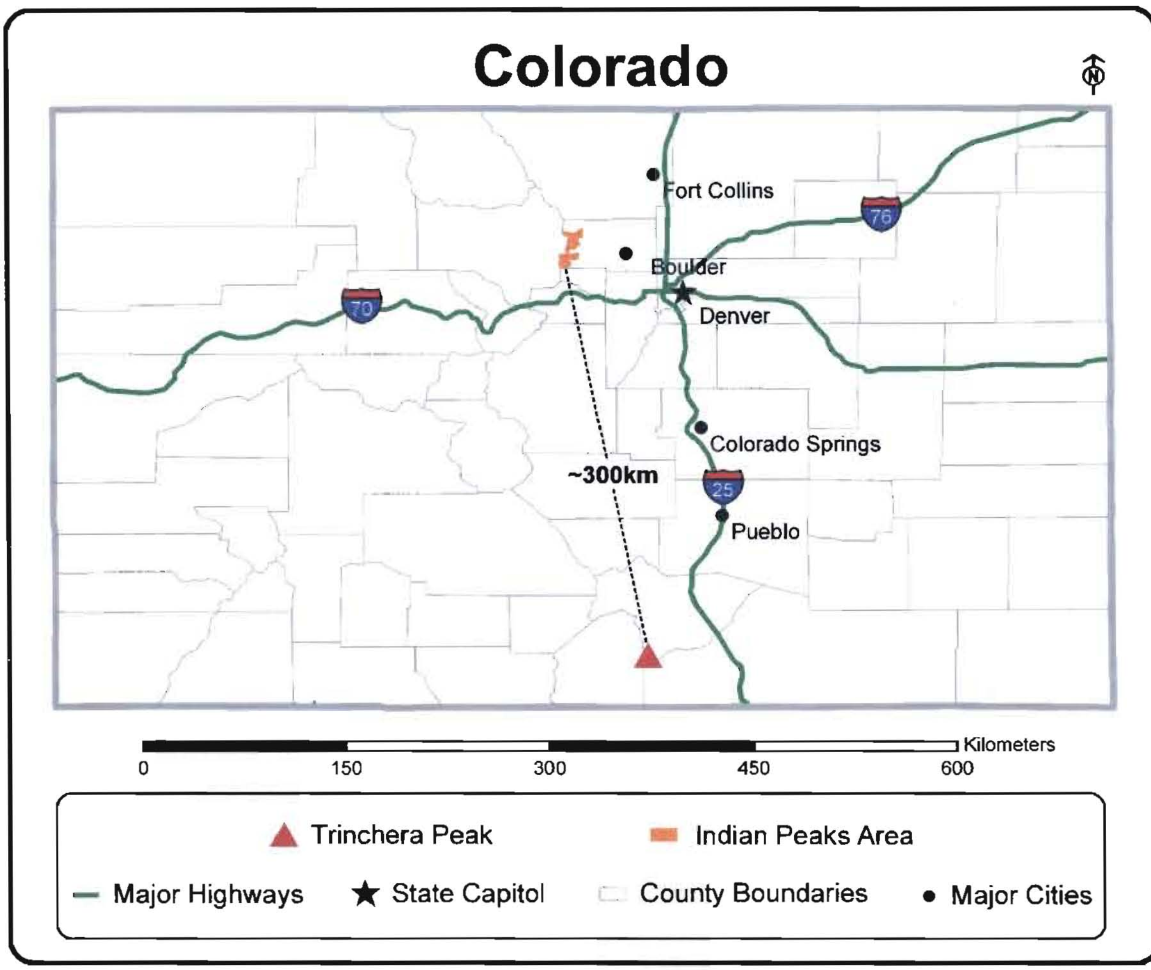


Figure 5. Location of Indian Peaks area relative to Trinchera Peak.

moraine deposited by a retreating valley glacier about 2,460 radiocarbon years ago" (Benedict, 1967 p. 817). Benedict concluded that the *Rhizocarpon geographicum* grows a rapid 14 millimeters for its first 100 years, and then growth slows to an average rate of 3.3 millimeters per 100 years (Benedict, 1967). Figure 6 shows Benedict's growth curve for lichens (*Rhizocarpon geographicum*) in the Indian Peaks region, Colorado Front Range.

In 2001, Joseph Tilton utilized the lichen growth curve developed by James Benedict to determine the approximate ages of specific periglacial features in the Trinchera Peak vicinity (Tilton, 2003). One periglacial feature Tilton attempted to date was the patterned ground on the summit of Trinchera Peak. He concluded that the stone polygons have a possible age range from 676 to 736 years. Lichen measurements of the patterned ground also indicated a bimodal distribution of lichen measurements. This could signify two distinct lichen populations separated by instability of the patterned ground due climatic fluctuations. Tilton noted that using Benedict's lichen growth curve may have created uncertainties in his results. The growth curve developed by Benedict was for an area over 300 kilometers away where rock type, exposure to abrasion, shading, temperature, moisture, stability of substrate, and length of growing season may differ. Tilton observed that in order to acquire a more accurate age of periglacial features, a complementary local lichen growth curve was necessary (Tilton, 2003).

A paleoclimatic study within the Sangre de Cristo Mountains of northern New Mexico indicated glacial activity from the late Pleistocene to late Holocene. Dating of sediment cores indicated a Pleistocene Pinedale glacial termination prior to 12,120 yr B.P., a Younger Dryas glaciation ~9,800 yr B.P., a mid Holocene warm interval,

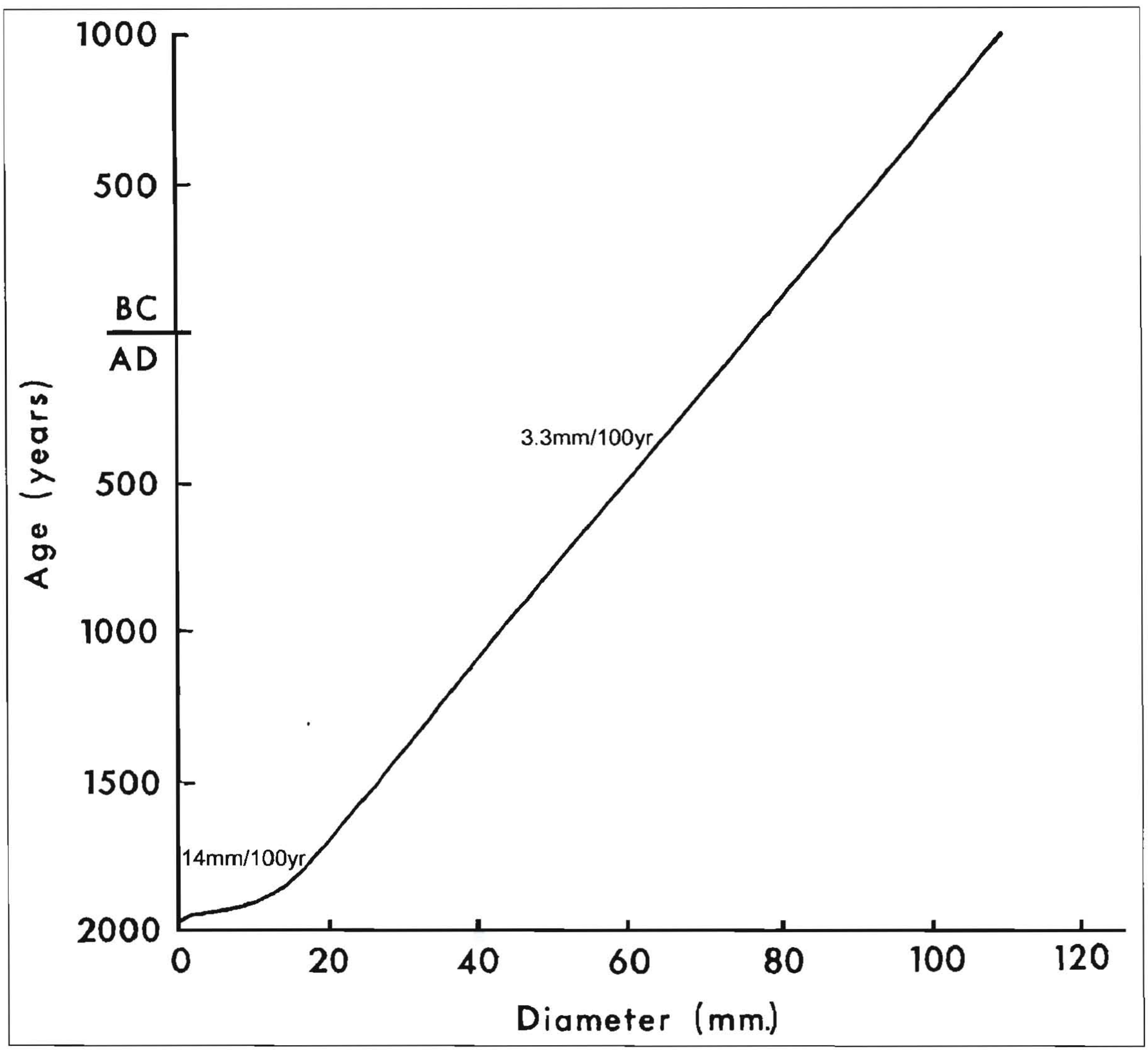


Figure 6. Benedict's (1967) growth curve for lichens (*Rhizocarpon geographicum*) in the Indian Peaks region, Colorado Front Range.

Neoglacial periglacial events at 4,900 yr B.P. and 3,600 yr B.P., and the Little Ice Age ~120 yr B.P (Armour et al., 2002). This climatic record may help in interpreting possible periods of patterned ground formation and activity at Trinchera Peak.

Chapter 2

Methods and Procedures

Field Methods

Extensive fieldwork was conducted from July 22nd thru August 8th 2003. A variety of field methods were used to determine a relative age range for the patterned ground of the Trinchera Peak vicinity. Key field methods included developing a sampling grid system, using a Global Positioning System (GPS) to survey the grid, pole aerial photography, measuring and photographing lichens, describing and sampling soil, and recording soil temperature data.

Developing a Grid Sampling System -- On the first visit to both Trinchera Peak and Site 2, the relict pattered ground was observed to determine the best location and coverage for developing a sampling grid. The grid was to be used for surveying, sampling lichens, drawing sketches, and pole aerial photo analysis. The grid developed on Trinchera Peak covered an area of 30 meters by 40 meters and was broken down into 5 meter by 5 meter cells (Fig. 7). The grid at Site 2 covered an area of 20 meters by 40 meters and was also divided into 5 meter by 5 meter cells (Fig. 8). The grids were created using a compass, flags, and a 100 meter tape. The compass was used to make sure the grids were oriented north-south and east-west. The flags were placed every 5 meters, which was measured off using the 100 meter tape. A black permanent marker was used to mark each flag with a specific ID. The ID of each flag also corresponded with an ID for each grid cell. Figures 7 and 8 illustrate the grids used at Trinchera Peak and Site 2.

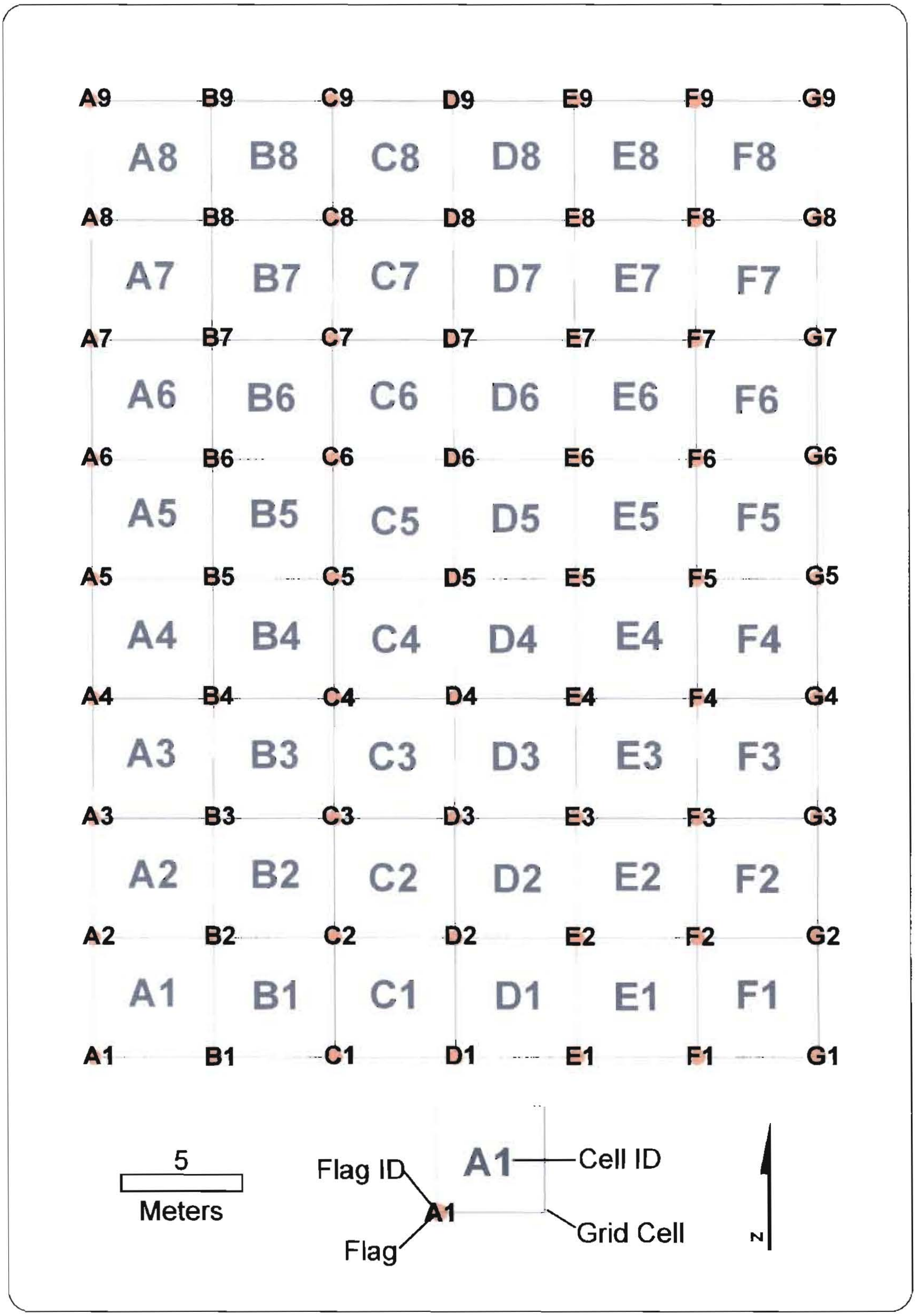


Figure 7. Sampling grid used at Trinchera Peak.

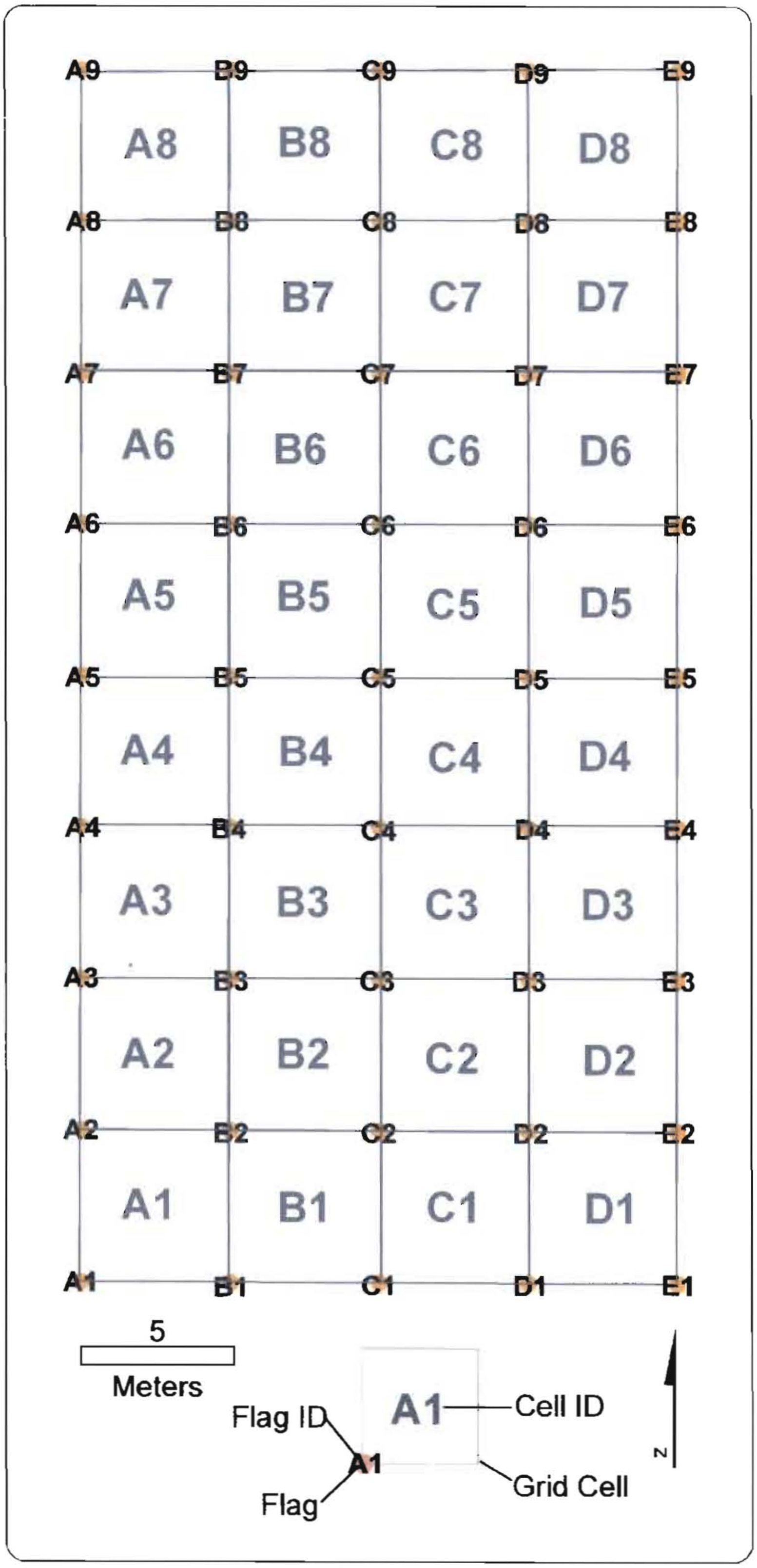


Figure 8. Sampling grid used at Site 2.

GPS and Surveying -- With the sampling grids in place, a Garmin Global Positioning System was used to survey the flag locations. Each flag location was recorded in latitude-longitude coordinates along with the flag ID. After using GPS to record flag locations, each flag was surveyed for elevation. A tripod with transit was erected at a slightly higher elevation just outside of the study grid. The ground elevation at the transit, the latitude and longitude of the transit, and height of the transit above ground were all recorded in a field book. Next, a stadia rod was placed near each flag and held upright while the transit operator recorded the flag IDs and rod reading for each flag. Figure 9 depicts the surveying setup at Site 2 with James Vopata operating the stadia rod.

Pole Aerial Photography -- Experimental pole aerial photography was used to obtain a bird's-eye-view of Trinchera Peak and Site 2. Efforts at pole aerial photography were undertaken using an 8-meter pole, c-clamp, and 35-mm film camera with remote control. The camera was clamped onto the one end of the pole and held up over a portion of the site (Fig. 10). Using the camera's remote control a picture was taken. The pole and camera system were then repositioned at numerous locations throughout the grid taking multiple photographs. Pole aerial photos were taken at both Trinchera Peak and Site 2.

Field Observations -- A general reconnaissance of the study areas was completed making observations and taking notes on surficial features of the patterned ground. General observations such as stone orientations, general topography, and signs of soil

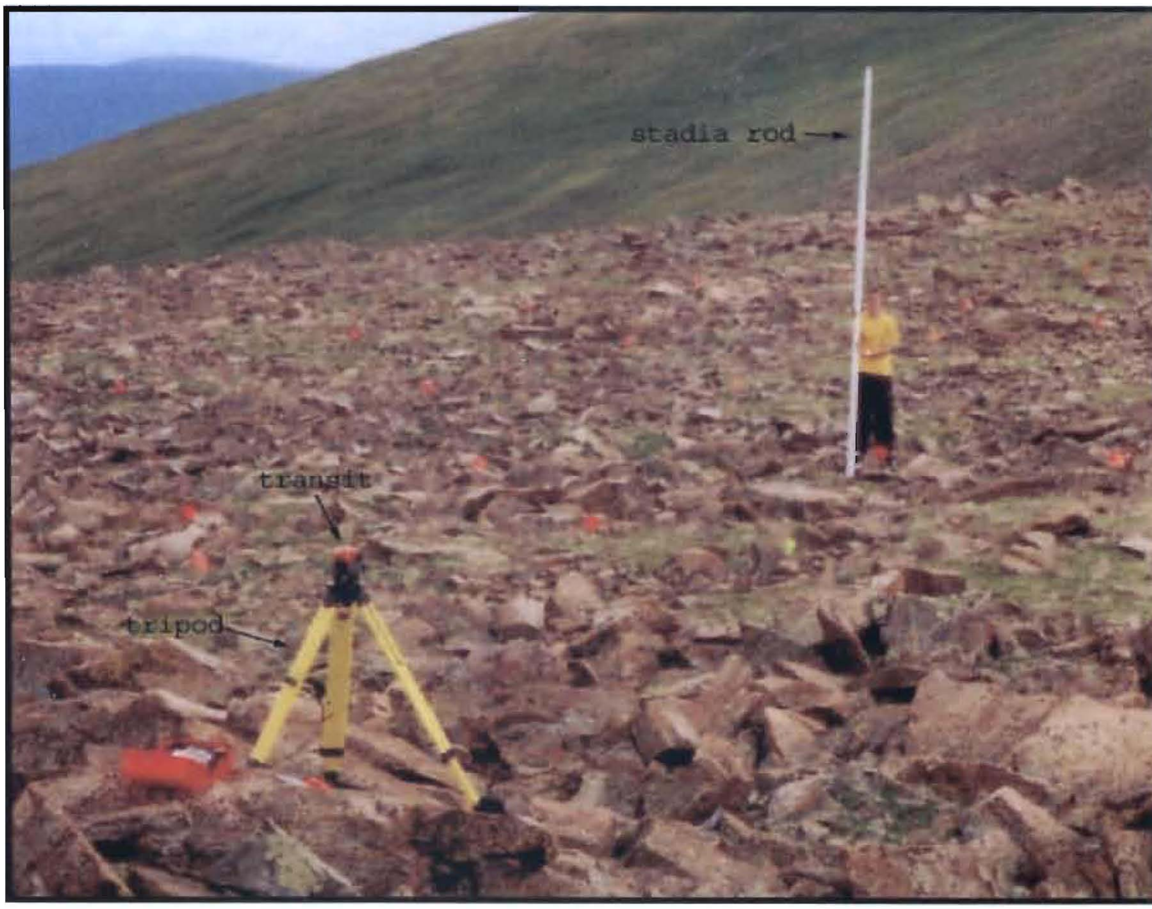


Figure 9. Surveying setup at Site 2 with James Vopata operating the stadia rod.

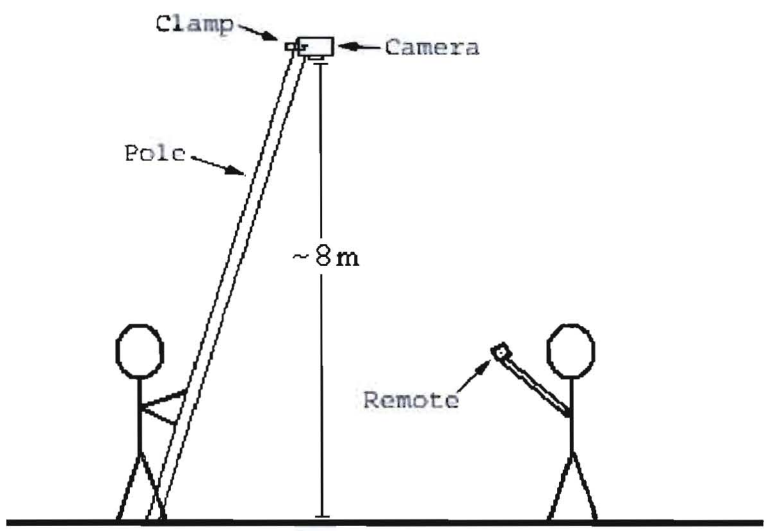


Figure 10. Illustration of pole and camera system for pole aerial photography (not to scale).

disturbance were recorded. In addition sketches were drawn of many of the grid cells. The sketches helped illustrate the spatial distribution of stones throughout the site.

Lichenometry -- Two separate methods of lichenometry were used to determine a minimum age of patterned ground formation. One method of lichenometry is based on the single largest lichen within a given area. This method is referred to as the FALL (Fixed Area Largest Lichen) method and was developed by Bull and Brandon (1998). The second method of lichenometry is based on the percent coverage of lichens on a stone surface. Methods for obtaining a digital analysis of lichen cover to determine percent lichen coverage were described by McCarthy and Zniewski (2001).

FALL Method -- Lichenometry fieldwork was first completed using the FALL method set forth by Bull and Brandon (1998) and later used by Tilton (2003). The FALL method is based on the largest lichens within numerous sampling units. At Trinchera Peak and Site 2 the sampling units were the individual five-meter grid cells. Each grid cell was examined to find the largest lichen on a vertical north facing surface and the largest lichen on a horizontal surface. Bull and Brandon divided the vertical north facing lichens from the horizontal lichens because of growth rate differences due to sun exposure and moisture availability. A horizontal surface was defined as a surface with less than 30° of dip in any direction. A vertical surface was defined as having a dip of more than 60°. Other criteria for selecting suitable lichens for measurement included lichen length to width ratio, lichen health, and boarding lichens. Eligible lichens must have had a length to width ratio of less than 2:1. The lichen must have been alive and healthy with no signs of decay. Also, the lichen should have been isolated, not bordered by other lichens, which might impede its growth. Once a suitable lichen was found its long axis was measured with a flexible ruler. The lichen measurements were recorded to the nearest millimeter along with the corresponding grid cell and rock dip.

Percent Coverage Method -- The second phase of lichenometry fieldwork consisted of taking digital photographs of the lichens. Again, the individual grid cells were used as sampling units for this lichenometry technique. Within each grid cell, flat rock surfaces having the most coverage of active lichens (*Rhizocarpon geographicum*) were selected for photographing. One or two photographs were taken within each grid cell. The photos were taken at close range to include only the targeted flat rock surface within the image. Photography was done under even sunlight illumination and without shadows. A ruler was placed near each stone surface for scale. The photographs were later used in image processing to determine a percent cover of lichens (*Rhizocarpon geographicum*).

Subsurface Study -- Using a shovel and trowel a small trench was dug at Trinchera Peak to study the subsurface and soil development. The trench was dug within grid cell D4 of the Trinchera Peak site. The excavation included moving soil as well as various sizes of rocks. The trench was excavated to a depth of 60 centimeters. Many photographs were taken of the soil pit. Soil horizons were marked out and measured. Plastic bags were used to collect soil samples from each major horizon. A sketch of the soil pit was drawn and notes describing the soil exposed in the pit were recorded.

Recording Temperature Data -- A HOBO temperature data logger was placed in the bottom of the trench. The data logger was enclosed in a weather proof case along with mothballs used to detour curious wildlife. The temperature data logger had been previously activated with Boxcar computer software before fieldwork had begun. The data logger was set to record soil temperatures in both Celsius and Fahrenheit every six hours. The data logger was to remain intact for approximately one year collecting soil temperature data that could be beneficial in the study of patterned ground activity. After placing the temperature data logger the trench was refilled with soil and stones to its original condition.

Laboratory Methods

Returning from field work, laboratory work was completed to analyze data gathered in the field. GPS and surveying notes, pole aerial photography, lichen measurements, lichen photos, soil samples, and recorded temperature data were examined using various laboratory methods. The laboratory methods were applied to establish relative dates of the patterned ground activity.

Compiling a GIS Database -- The first data examined was the surveying information. This information would be used in building a GIS (Geographic Information Systems) database. The GIS database could give a better overview of the study sites including exact site locations and surface topography. The surface elevation at each flag was calculated from the surveying notes. The longitude-latitude GPS readings along with the surveyed elevations were entered into a Microsoft Excel spreadsheet and saved as a dbaseIV file (*.dbf). The GPS positions were not accurate due to the low quality GPS receiver, ionospheric conditions, and absence of ground truth. Errors in GPS were easily identified since the GPS positions did not reflect the arrangement of the surveyed grid. Many of the GPS points were offset by only 3-4 meters from their expected positions. The GPS points were corrected by altering the longitude-latitude values to fit the grid survey. The *.dbf file of longitude-latitude locations along with elevations was then imported into ArcGIS (Earth Systems Research Institute) software to build a GIS database. Using the U.S. Geological Survey Trinchera Peak Quadrangle Digital Raster Graphic as the background image the flag locations were displayed in ArcGIS. The elevation data associated with each flag was interpolated into a grid to create maps showing the general topography of Trinchera Peak and Site 2.

Mosaicking Aerial Imagery -- The aerial photographs taken at Site 2 and Trinchera Peak were scanned into digital images using a flatbed scanner. Using D-joiner (D Vision Works) software the individual digital images were mosaicked together. The images were mosaicked in order to create one complete image of each grid cell photographed. The mosaicked images were then cropped to include only the contents of the individual grid cells and saved as *.jpg images. The mosaicked aerial images were imported into ArcGIS and registered and rectified. The flags within the aerial images were used as reference points with the surveyed locations of the flags used as the control points. The resulting registered and rectified aerial photographs displayed a partial bird's-eye-view of the study sites that could be used in conjunction with other GIS layers.

FALL Method Lichenometry – Individual lichen (*Rhizocarpon geographicum*) measurements performed using the FALL method were entered into a Microsoft Excel spreadsheet. Microsoft Excel was used to analyze and graph the lichen measurements. Measurements recorded on horizontal faces were compared to those recorded on vertical faces. As illustrated in figure 11, neither study site showed obvious differences between rock orientation and lichen size. This may be contributed to similar light and moisture conditions for horizontal and vertical rock faces. Therefore, all lichen measurements were combined into one dataset including lichens of both horizontal and vertical faces.

Two methods were employed to determine the lichen length that would be used with Benedict's growth curve. One method set forth by Bull and Brandon (1998) was based on the average length of all lichens measured. However, for this particular study the median length of the lichens was used. The median lichen length was chosen because the distribution of lichen measurements was skewed. Thus, statistically a median value would be a more suitable measure of central tendency.

A second method was also utilized to determine the mean maximum lichen length. Benedict (1967), Innes (1988), and Lock et al. (1979) all concurred that only the five largest lichens recorded should be used in determining the age of a deposit. Therefore, the five largest lichens of Trinchera Peak and Site 2 were averaged and applied to Benedict's growth curve.

Both the median value of all lichens and the average of the five largest at each site were used in the growth curve developed by Benedict (1967). Benedict's growth curve of 14 millimeters the first 100 years and 3.3 millimeters for each following 100 years was employed to give a general range of dates for patterned ground stability. The range of

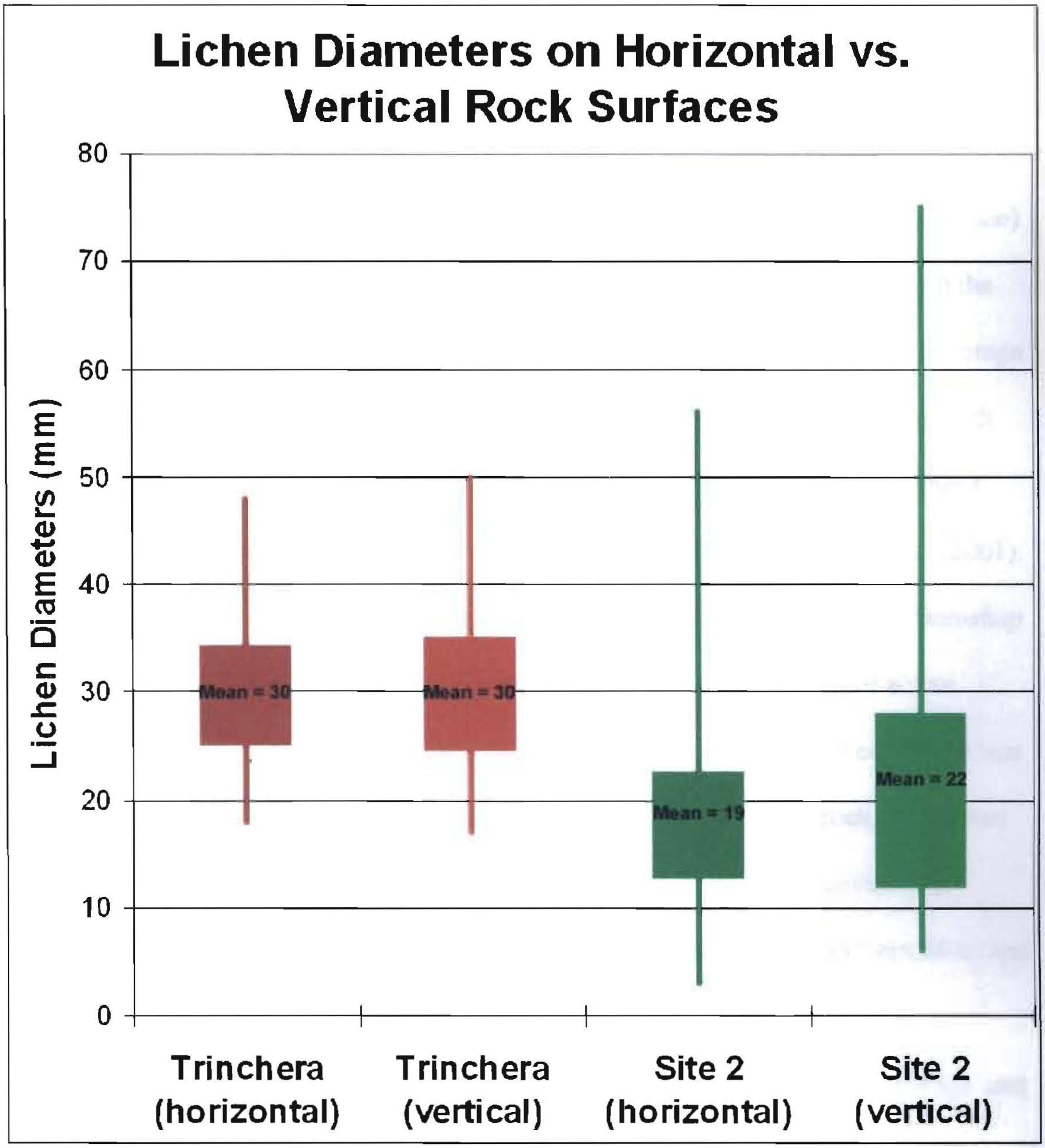


Figure 11. Lichen diameters on horizontal vs. vertical rock surfaces at Trinchera Peak and Site 2.

dates developed from the growth curve was then corrected for the length of colonization time necessary for lichens to develop. This colonization time was decided to be set at 50 years as indicated by Grove (1988).

Determining Percent Lichen Cover -- A second approach to lichenometry involved calculating the percent coverage of active lichens (*Rhizocarpon geographicum*) on flat stone surfaces. Photographs of rock surfaces were used in comparison with the FALL results to determine if a correlation existed between percentage of lichen coverage and the age of the exposed surface. Each individual photograph was edited using both *Adobe Photoshop* and *Idrisi* software to determine the percent cover of active lichens (Fig. 12). Methods for this approach were adapted from McCarthy and Zniewski (2001).

The initial stone images were first modified in *Adobe Photoshop* 6.0. *Photoshop* was used to remove the image background and select out only the individual active *Rhizocarpon* lichens. The individual lichens were then painted blue. The color blue was selected because it had the greatest color contrast from the background rock. *Idrisi* was then used to reclassify the image and calculate the percentage of lichen cover. The results of stone surface area versus lichen surface area were then exported from *Idrisi* and imported into Microsoft Excel to calculate the lichen percent coverage.

Currently, there is no published quantitative relationship between surface age and percentage of lichen cover. Thus, the percent cover data gives only relative ages of patterned ground formation. The percent cover results were graphed by frequency and compared with the FALL results.

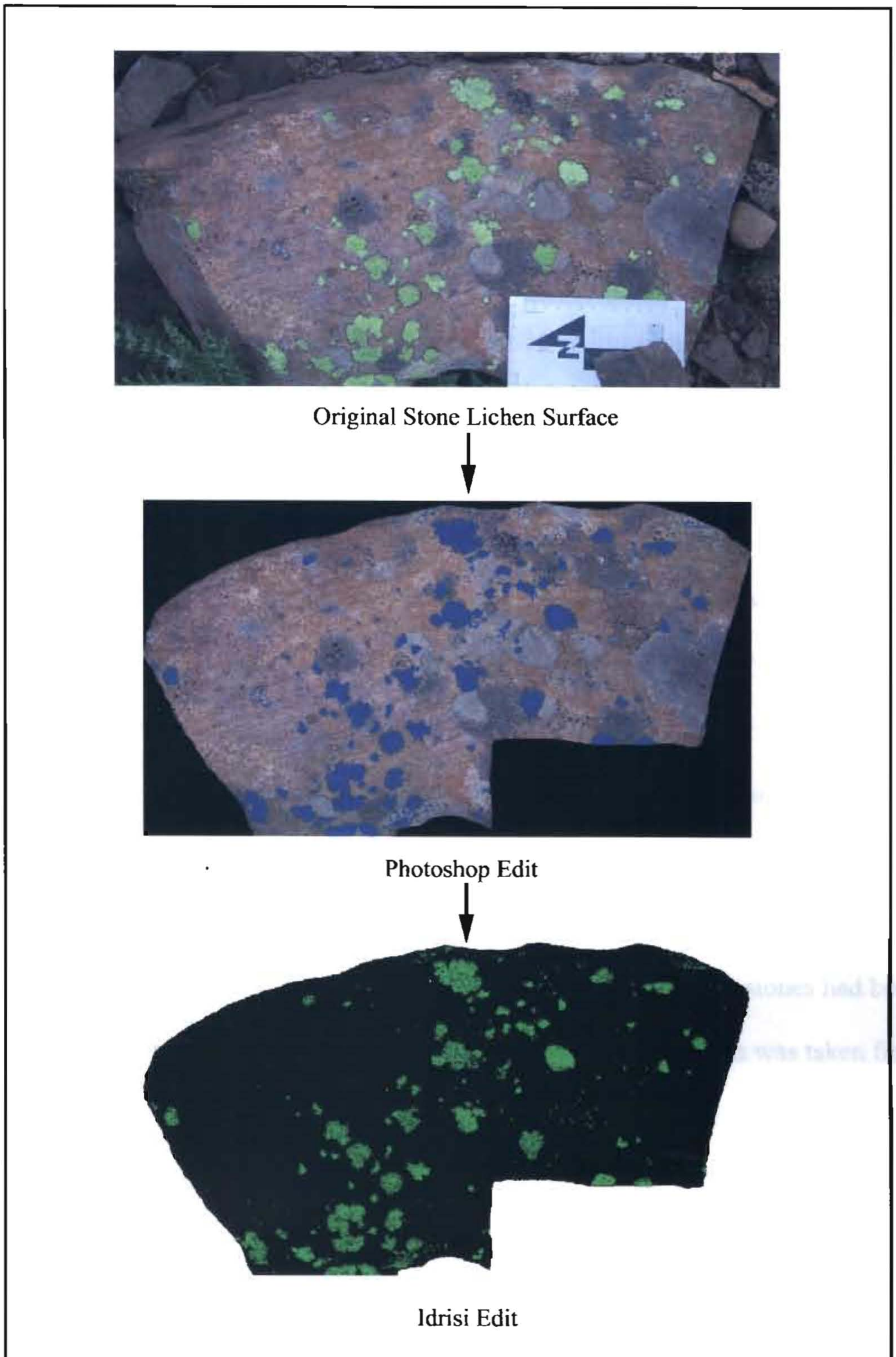


Figure 12. Example of photograph edited using *Adobe Photoshop* and *Idrisi* to determine percent lichen cover.

Analyzing Soil Samples – Lichenometric results from the study areas only provided an estimate of approximate age for patterned ground stability. In order to obtain an idea for the period of patterned ground activity a deeper look into the subsurface was necessary. The soil samples extracted from Trinchera Peak were analyzed by color, organic content, and texture. The soil samples include the upper 10 centimeters of soil described as the A (organic) horizon, the second 20-30 centimeters of soil described as the Bw horizon, and the lower 30-60 centimeters of soil just above bedrock described as the C horizon. Each soil sample color was first distinguished using the Munsell soil color chart. The chart was used in outside sunlight with both moist and dry soil samples to determine the most accurate soil color of each soil horizon. Soil samples were next sent to the Kansas State University Soil Testing Laboratory for organic matter analysis.

Textural analysis was also completed on each soil horizon. Prior to the texture analysis a 30% hydrogen peroxide solution was used to remove the organic matter. After the organic matter was removed from the soil samples, the textural analysis was completed to separate the clay, silt, sand, and gravel fractions of each soil horizon using hydrometer and sieving methods similar to (Black et al., 1956). Larger stones had been removed during fieldwork. The procedure used for the textural analysis was taken from Black et al. (1965). The percentages of clay, silt, sand, and gravel were calculated by entering the texture analysis results into an Excel spreadsheet provided by Dr. Sleezer.

Acquiring Temperature Data -- The temperature data logger was retrieved from Trinchera Peak on June 23, 2004, by Dr. Aber's Field Geology Class of 2004. The data logger was used with Boxcar software to export the temperature data into Microsoft

Excel. The temperature data were analyzed and graphed using the Excel software package.

Surface temperature data and snowfall data were acquired from the National Climatic Data Center website http://www.ncdc.noaa.gov/oa/ncdc.html. Surface temperature data were acquired for San Luis Colorado. San Luis is ~2440 meters above sea level and 28 kilometers southwest of Trinchera Peak. To calculate the approximate air temperature of Trinchera Peak, an average adiabatic lapse rate of 0.6° Celsius per 100 meters was applied to the San Luis temperature data. Thus, with an elevation difference of ~1,680 meters and a temperature change of 0.6° Celsius per 100 meters, temperatures of Trinchera Peak were estimated by subtracting ~10° Celsius from the surface temperatures recorded at San Luis. The calculated surface temperatures of Trinchera Peak were then compared with the soil temperature record. Additionally, the average annual temperature from 1981-2003 for Trinchera Peak was calculated and graphed to show recent climatic trends.

Snowfall data were acquired for Aguilar, Colorado. Aguilar, Colorado is ~2600 meters above sea level and 50 kilometers east of Trinchera Peak. The snowfall data were used to determine the dates and magnitude of snowfall events in southern Colorado. The major snowfall events were then graphed against the soil temperature record at Trinchera Peak.

Chapter 3

Data and Results

Surveying and Observation Data

An overview of the study sites revealed patches of patterned ground activity within the stone felsenmeer block fields at Trinchera Peak and Site 2. The patterned ground was better formed at Trinchera Peak than at Site 2. An area of the patterned ground study site at Trinchera Peak is shown in figure 13 with Dr. Aber standing just beyond the soil trench. Figure 14 shows a portion of the Site 2 study area with Peter Vopata standing in the distance.

The surveying results indicated favorable slope conditions for polygonal patterned ground development. Figures 15 and 16 demonstrate the general topography of the sampling sites. The Trinchera Peak sampling area ranged in elevation from 4118.5 – 4122.5 m. The Site 2 sampling area ranged in elevation from 3903.5 – 3906 m. The polygonal patterned ground of both sites developed well on slopes of less than 10%. The gradual slopes of the study sites favored polygonal patterned ground development as opposed to patterned stripes or steps.

Sketches drawn at the study sites helped to develop a general overview of the patterned ground. The sketches were redrawn to produce maps depicting areas of stone versus areas of vegetation. Figures 17 and 18 illustrate the areas of stone and areas of vegetation at Trinchera Peak and Site 2. The patterned ground at Trinchera Peak displayed more distinct areas of grass versus stones. Site 2 appeared more as a stone block field with areas of scattered vegetation.

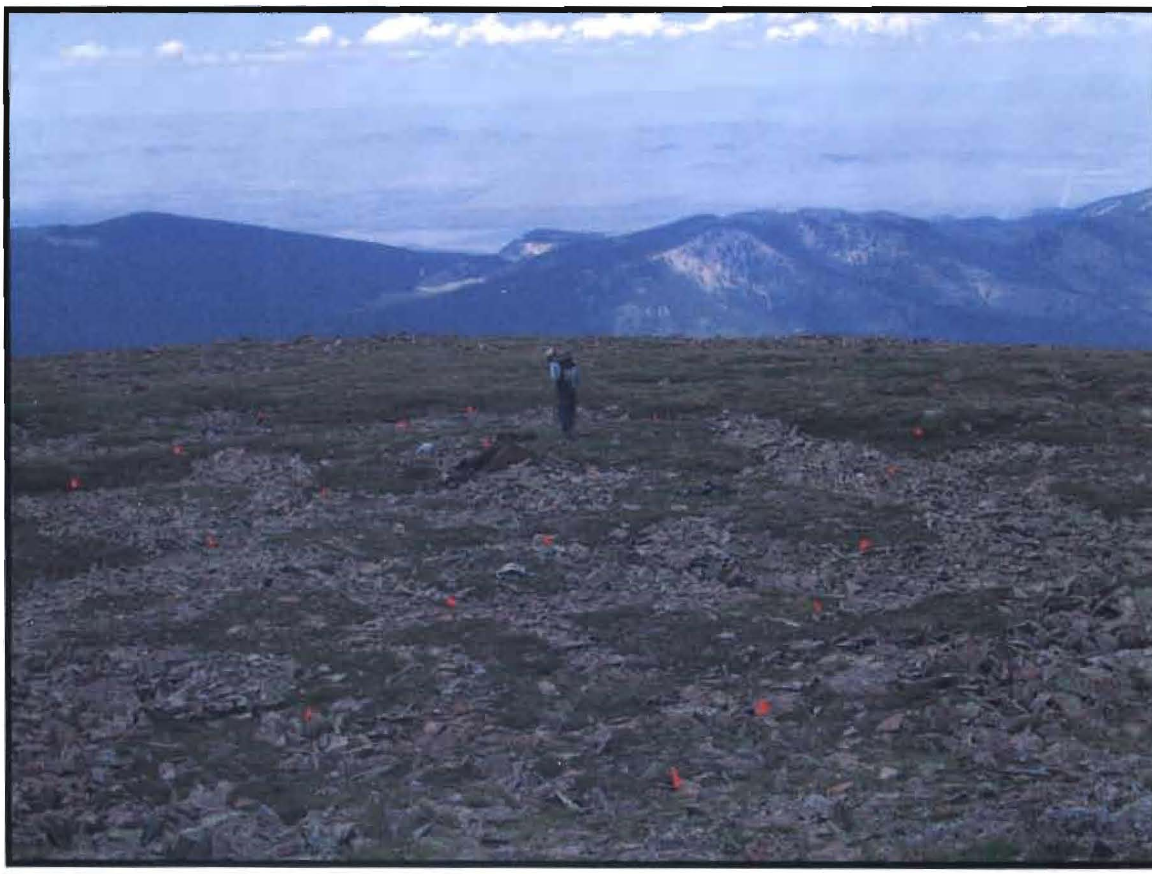


Figure 13. Photograph of Trinchera Peak study area with Dr. Aber standing beyond the soil trench.

Figure 14. Photograph of Site 2 study area with Peter Vopata standing in the distance.

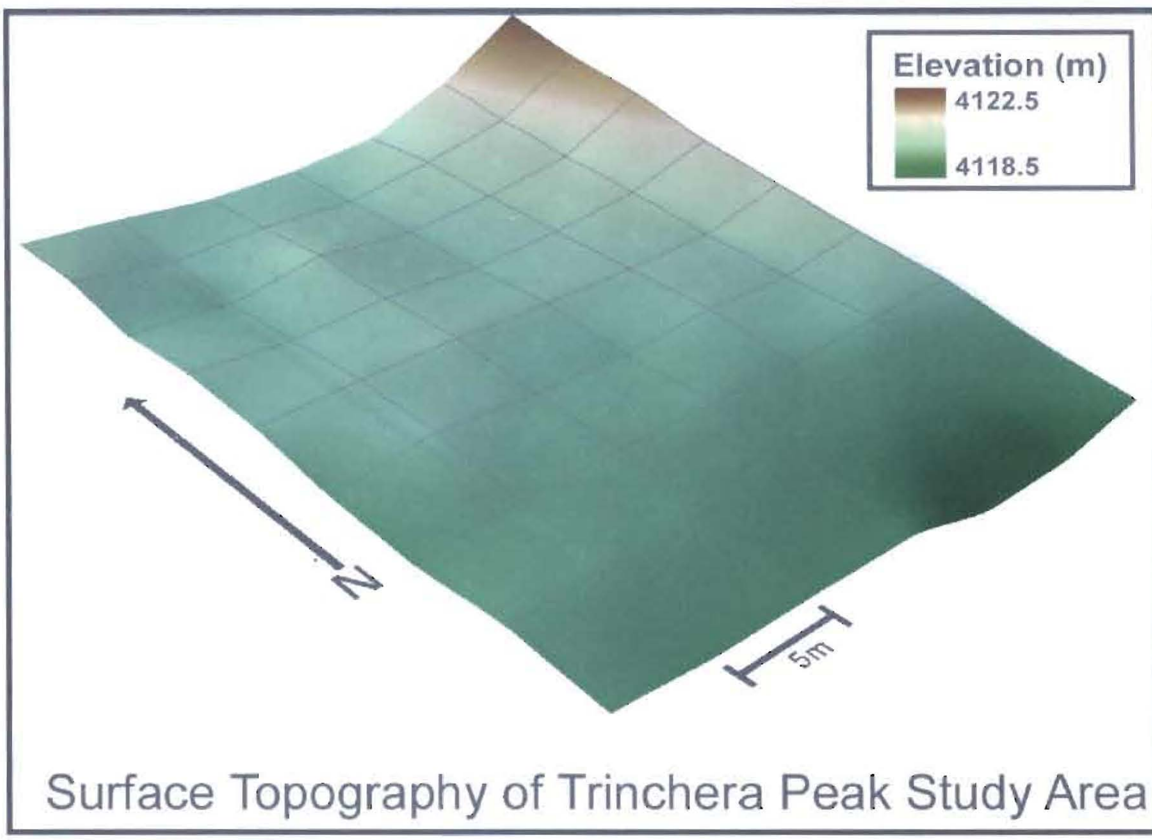


Figure 15. Image showing surface topography of Trinchera Peak study area.

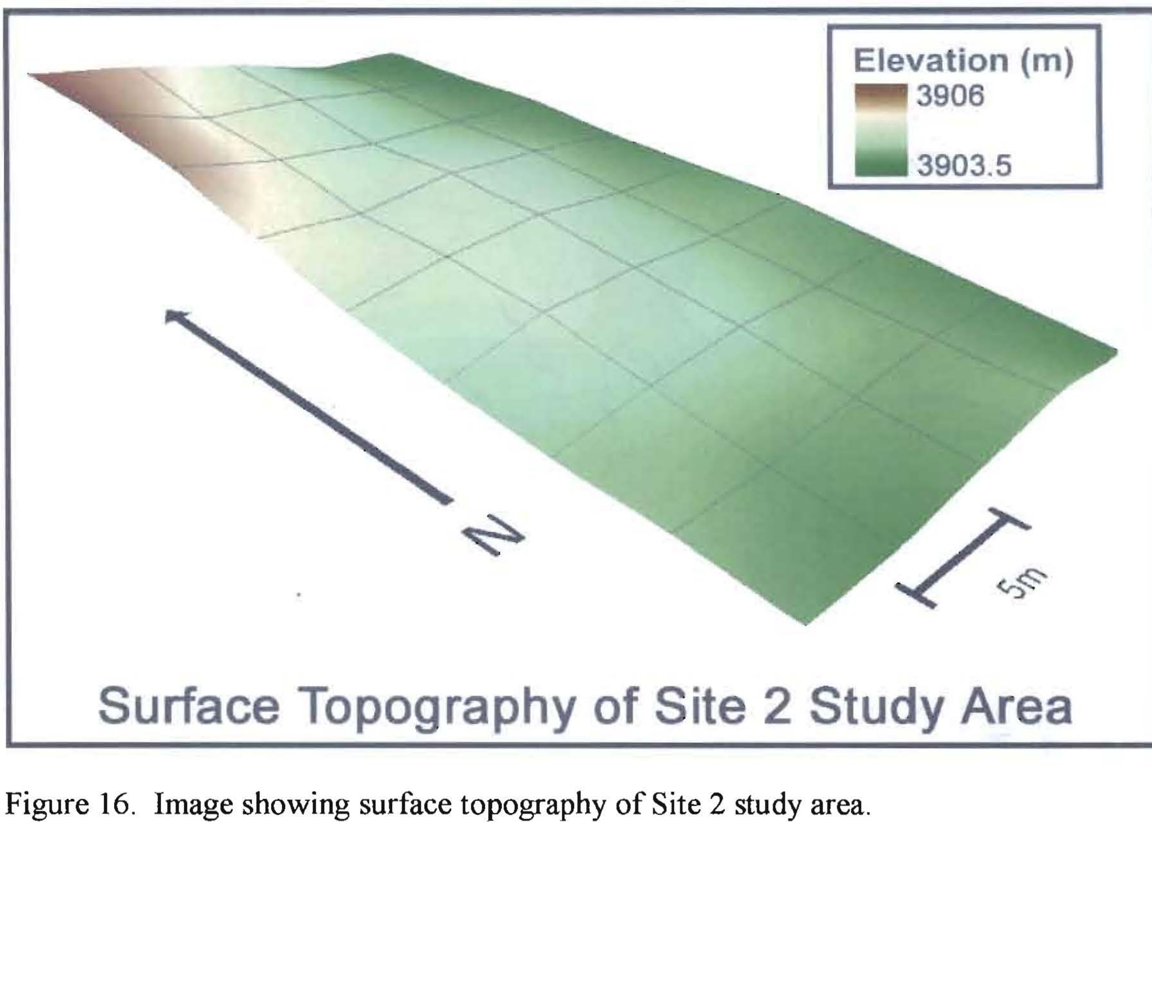


Figure 16. Image showing surface topography of Site 2 study area.

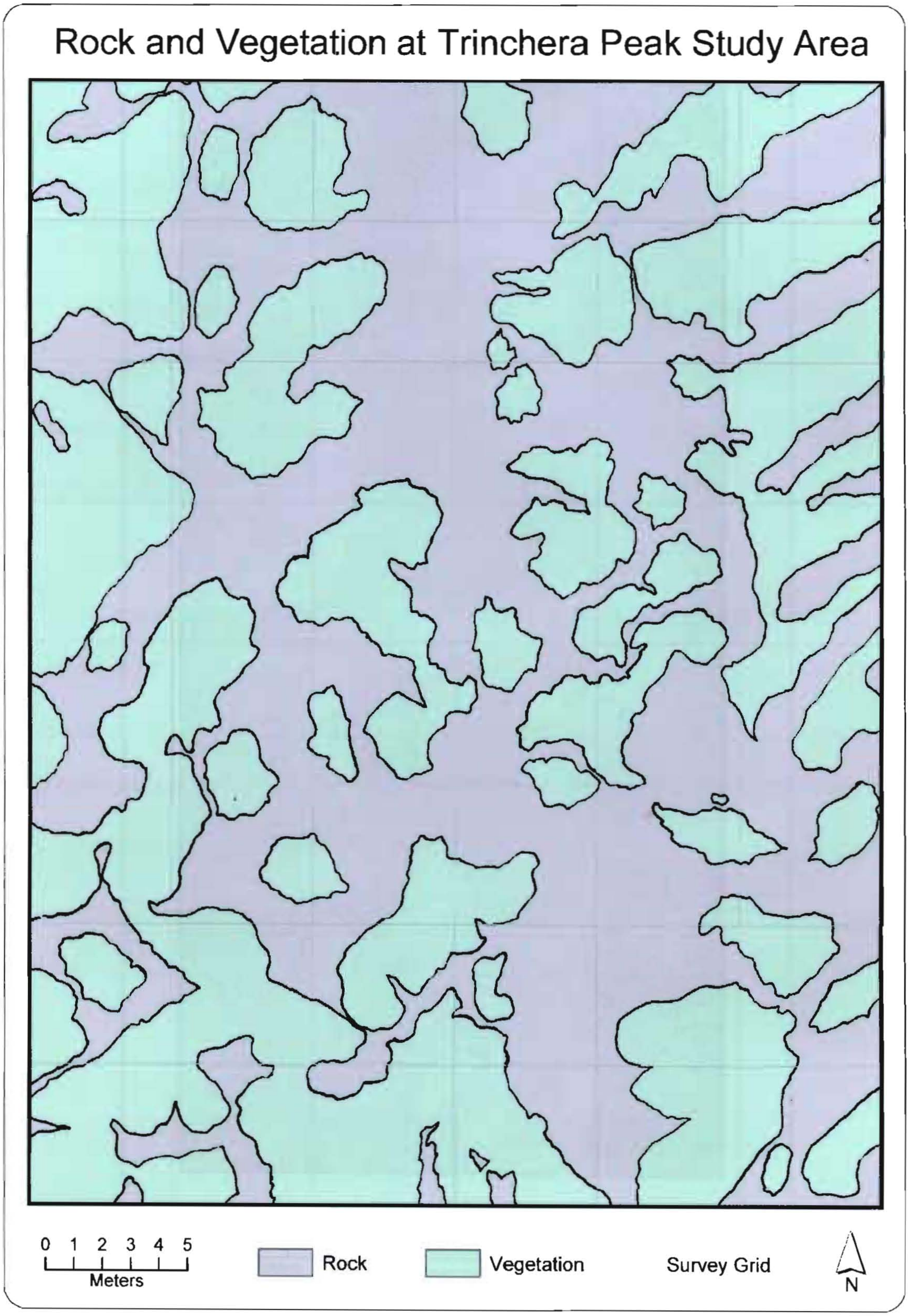


Figure 17. Sketch depicting rocky versus vegetative areas at Trinchera Peak study site.

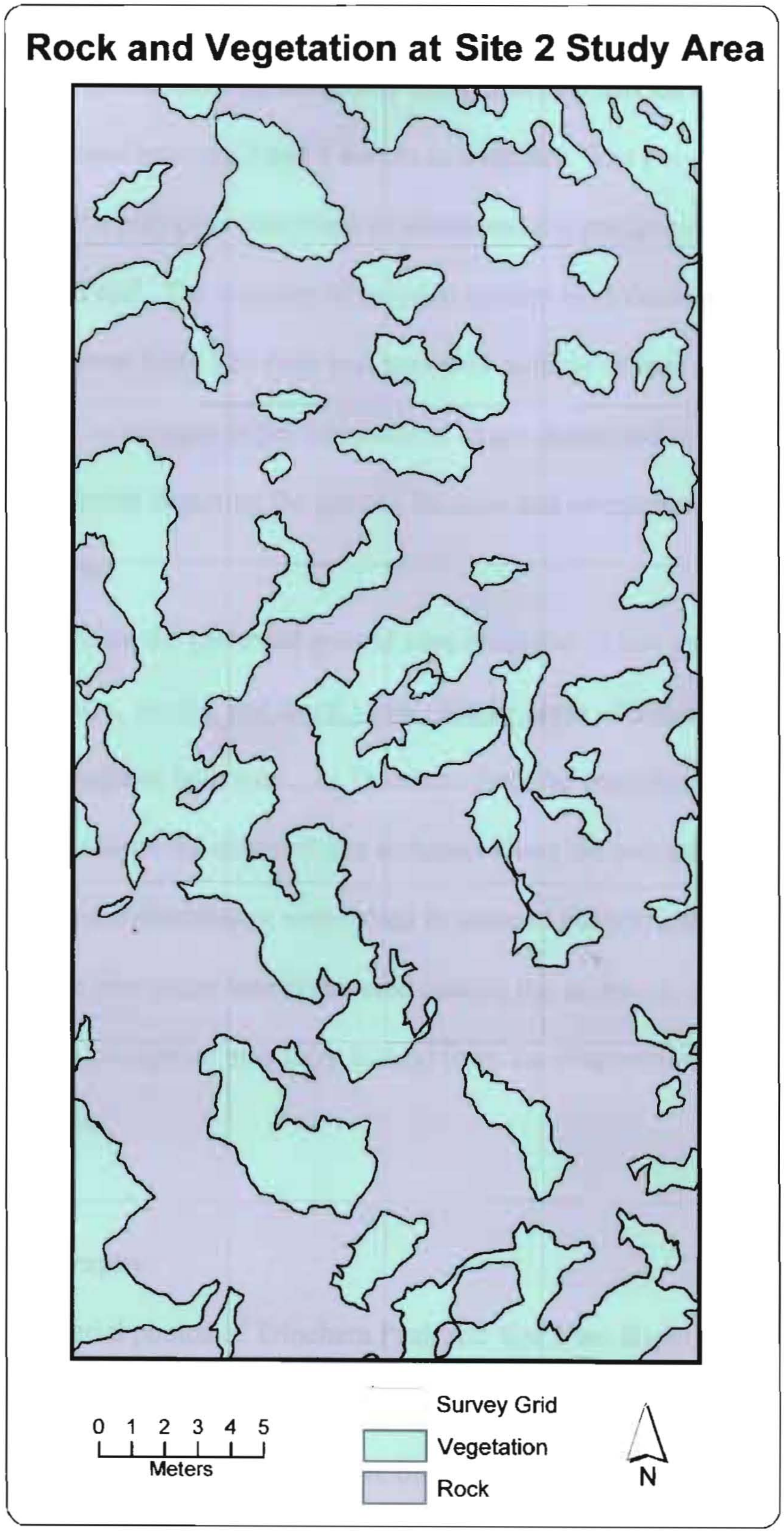


Figure 18. Sketch depicting rocky versus vegetative areas at Site 2 study site.

The patterned ground at Trinchera Peak appeared as a classic example of periglacial patterned ground activity created by cyclic freezing and thawing. The most distinct polygons ranged between 3 and 5 meters in diameter. The polygons were sorted with the margins of the polygons composed of stones and the polygon centers consisting of finer sediment and turf. The majority of polygon centers were domed and some showed evidence of frost boil. The frost boil appeared as areas of bare soil within the polygonal centers. The polygon edges consisted of larger stones and boulders. Figure 19 is a cross-sectional sketch depicting the general location and orientation of stones along the polygon boundaries.

Vegetation within the patterned ground sites consisted of low growing cushion plants including grasses, shrubs, and small forbs. Patchy areas of dense vegetation and shrubs appeared throughout both sites. At Trinchera Peak the majority of the dense vegetation tended to follow the edges of fine sediment along the polygon boundaries. Animal burrows and soil disturbance were noted in some of the polygon centers. Also, an unidentified white precipitate was discovered coating the underside of stones at Trinchera Peak. The precipitate may have formed from the evaporation of mineralized groundwater at the site.

Pole Aerial Photography

Mosaicked aerial photos of Trinchera Peak and Site 2 are displayed in Figures 20 and 21. Additional higher resolution aerial photos taken at Trinchera Peak are shown in Figures 22, 23, and 24. The aerial photos give birds-eye-views of the patterned ground development.

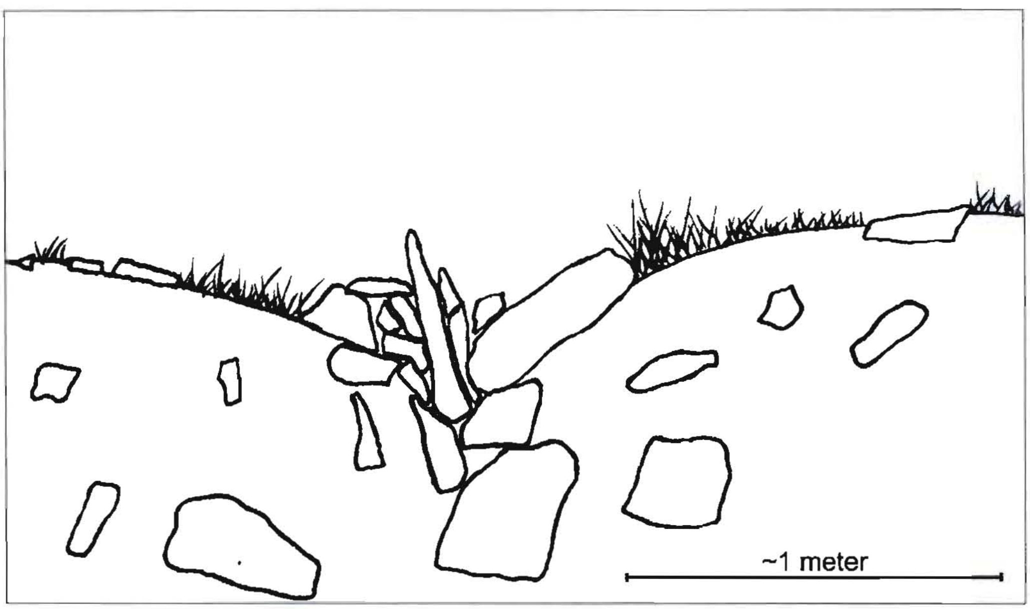


Figure 19. Inferred cross-section illustration depicting general location and orientation of stones along polygon boundaries.

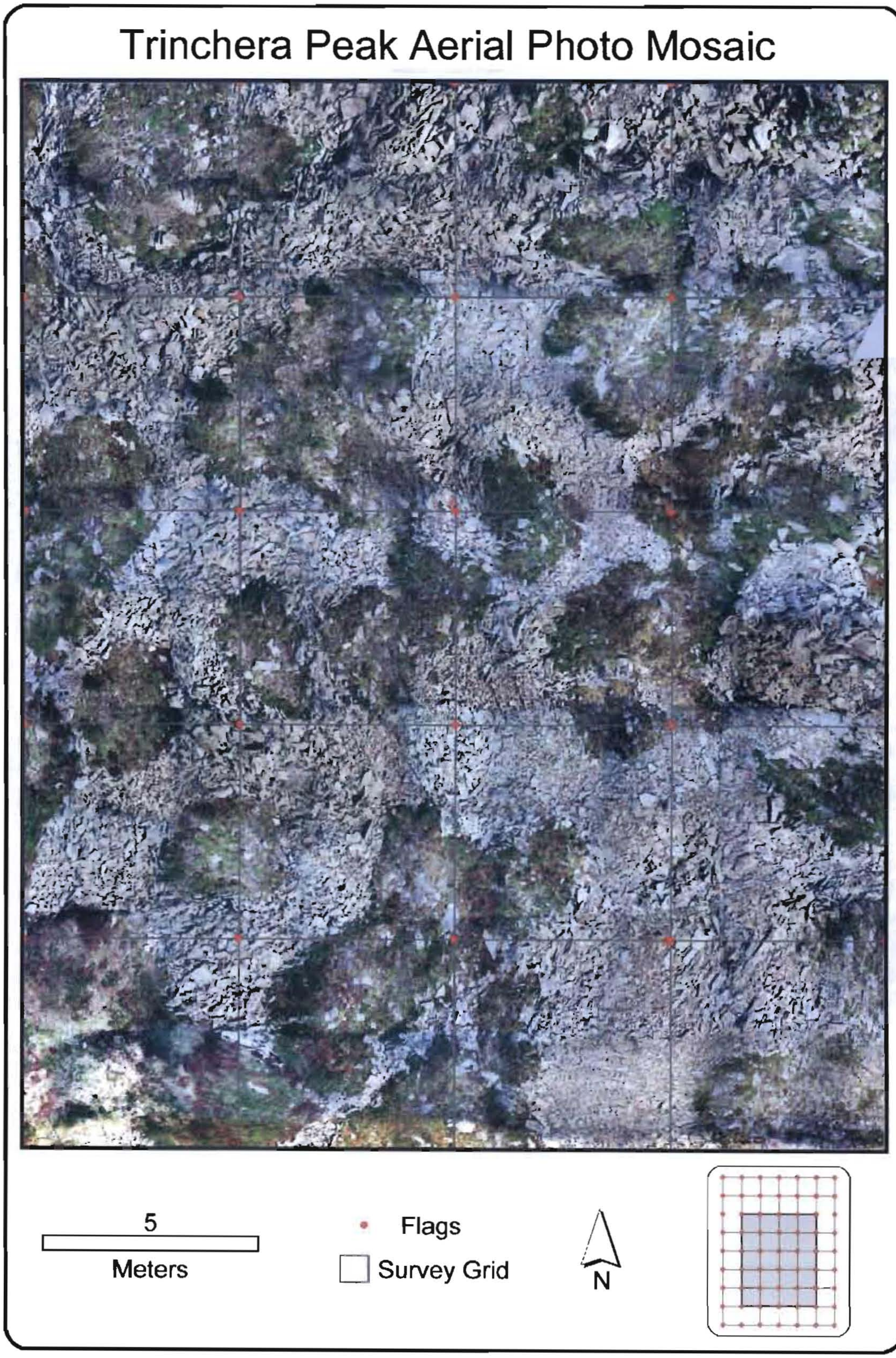


Figure 20. Aerial photo mosaic of Trinchera Peak study area.

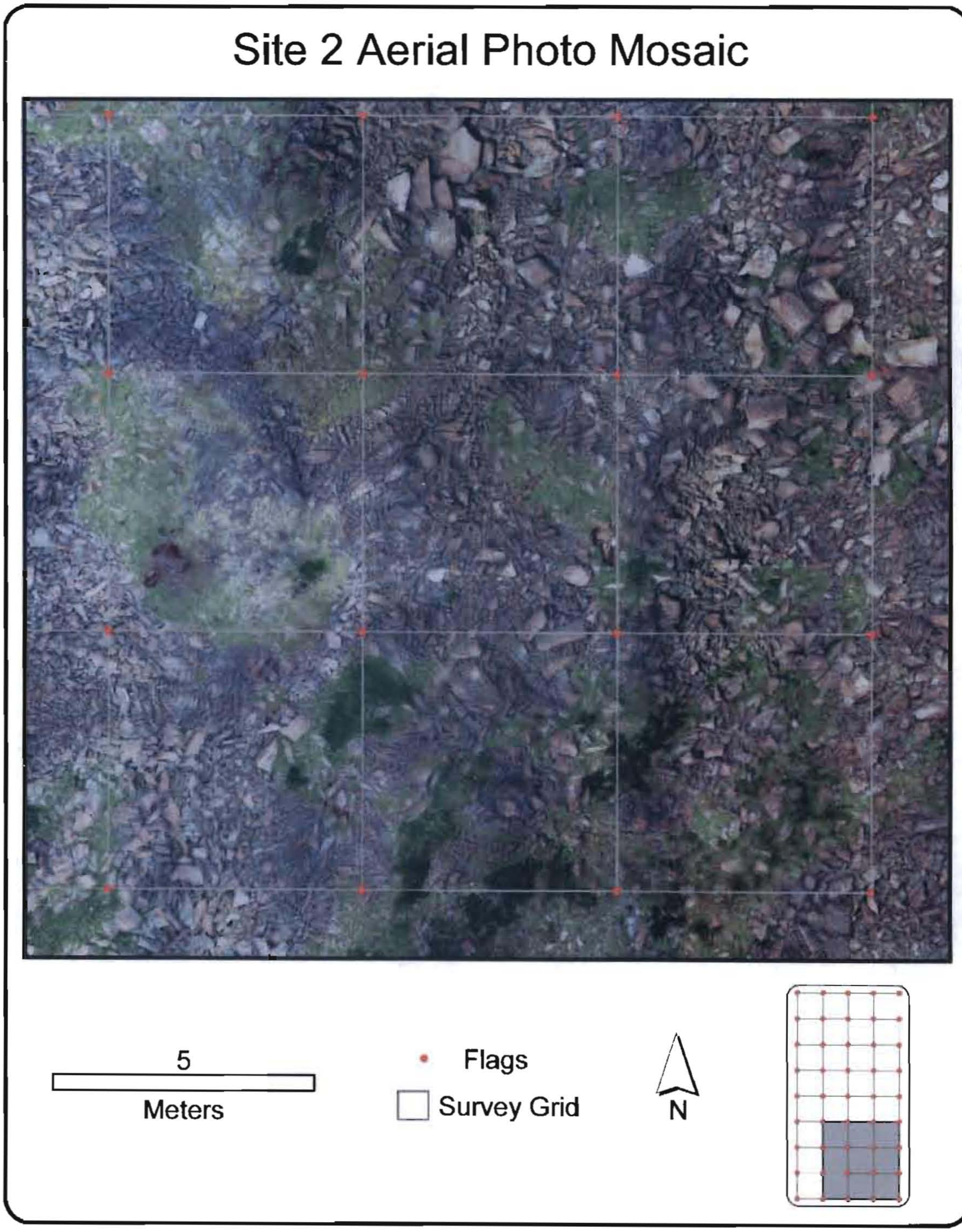
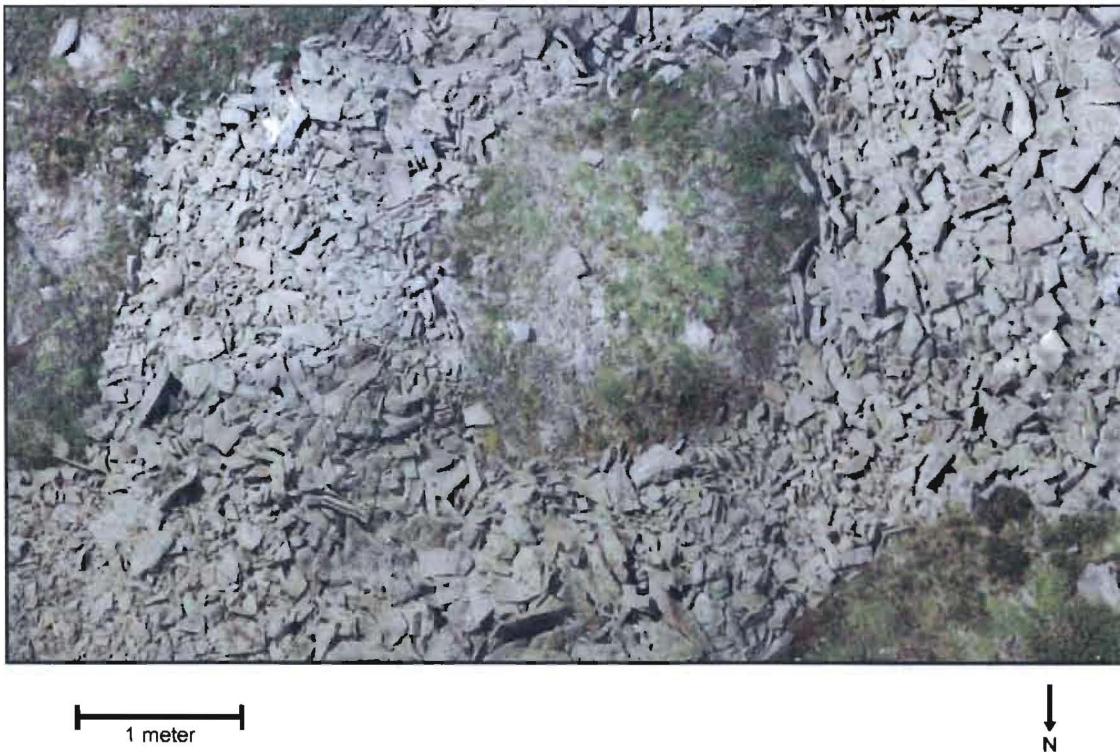


Figure 21. Aerial photo mosaic of Site 2 study area.



Figures 22 and 23. Aerial photos of patterned ground at Trinchera Peak.

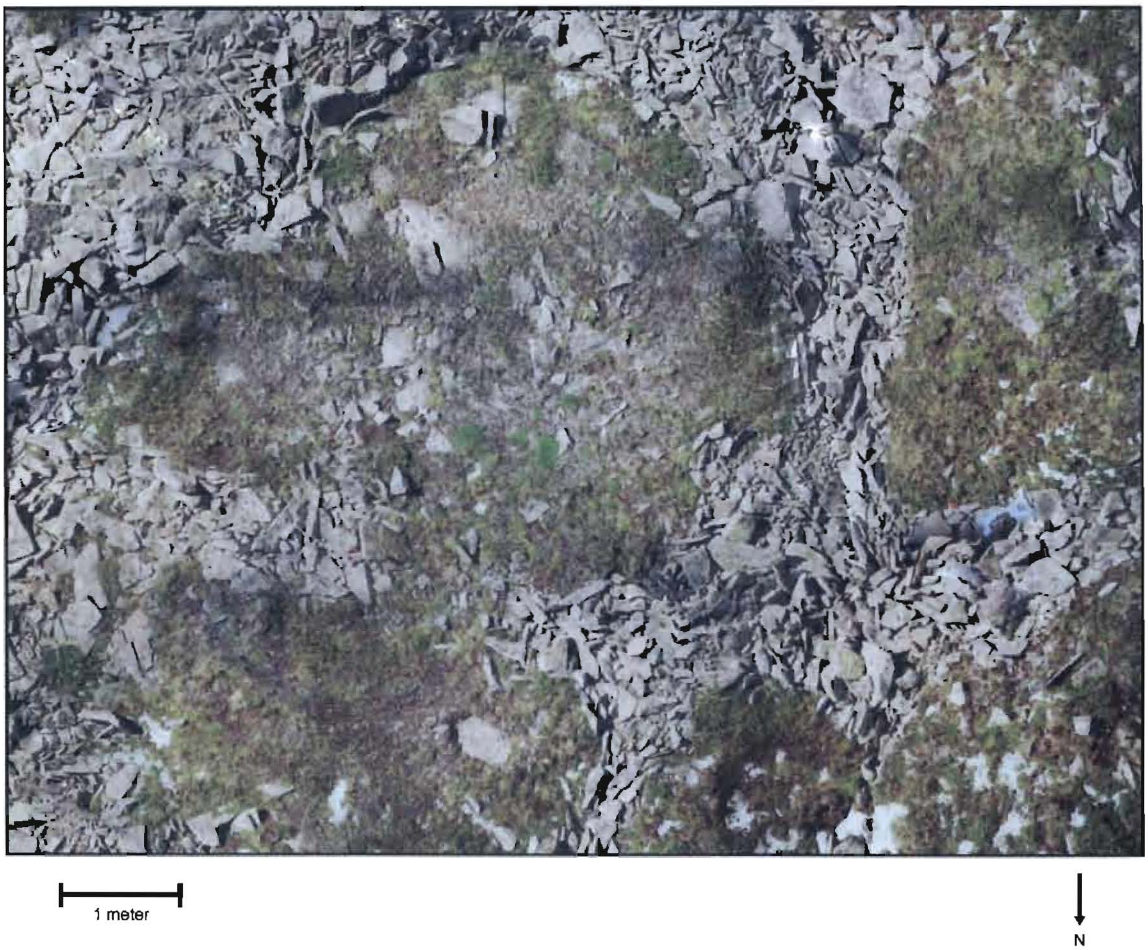


Figure 24. Aerial photograph of patterned ground at Trinchera Peak.

Lichenometry

FALL Method -- The Trinchera Peak and Site 2 study areas were examined to identify the largest lichens (*Rhizocarpon geographicum*) within each 5 meter by 5 meter grid cell. The lichen measurements are summarized as size-frequency graphs (Figs. 25 and 26). The size-frequency graphs show a wide distribution of lichen measurements at both Trinchera Peak and Site 2. A 75-millimeter lichen recorded at Site 2 appeared to be anomalous and was disregarded in lichenometry analysis.

Figure 27 shows a box and whisker plot of lichen measurements recorded at Trinchera Peak and Site 2. The majority of lichens observed at Trinchera Peak were between 25 and 35 millimeters in diameter. The median lichen diameter for Trinchera Peak was 30 millimeters. The lichen diameters measured at Site 2 were generally smaller than those recorded at Trinchera Peak. The Site 2 lichens ranged from 25 to 12 millimeters in diameter. The median lichen diameter for Site 2 was 17 millimeters.

Despite the overall difference in lichen sizes between Trinchera Peak and Site 2, the means of the five largest lichens at each site were remarkably similar. The mean of the five largest lichens at Trinchera Peak was 47 millimeters and the mean of the five largest of Site 2 was 48 millimeters. This close correlation between the largest lichens at both sites may indicate a similar date for the minimum age of patterned ground formation at both sites.

Both the median lichen size and the mean of the five largest lichens were applied to Benedict's lichen growth curve. Table 1 shows the minimum age of patterned ground formation calculated from the median lichen diameters. Table 2 shows the minimum age of patterned ground formation calculated from the mean of the five largest lichens. Both

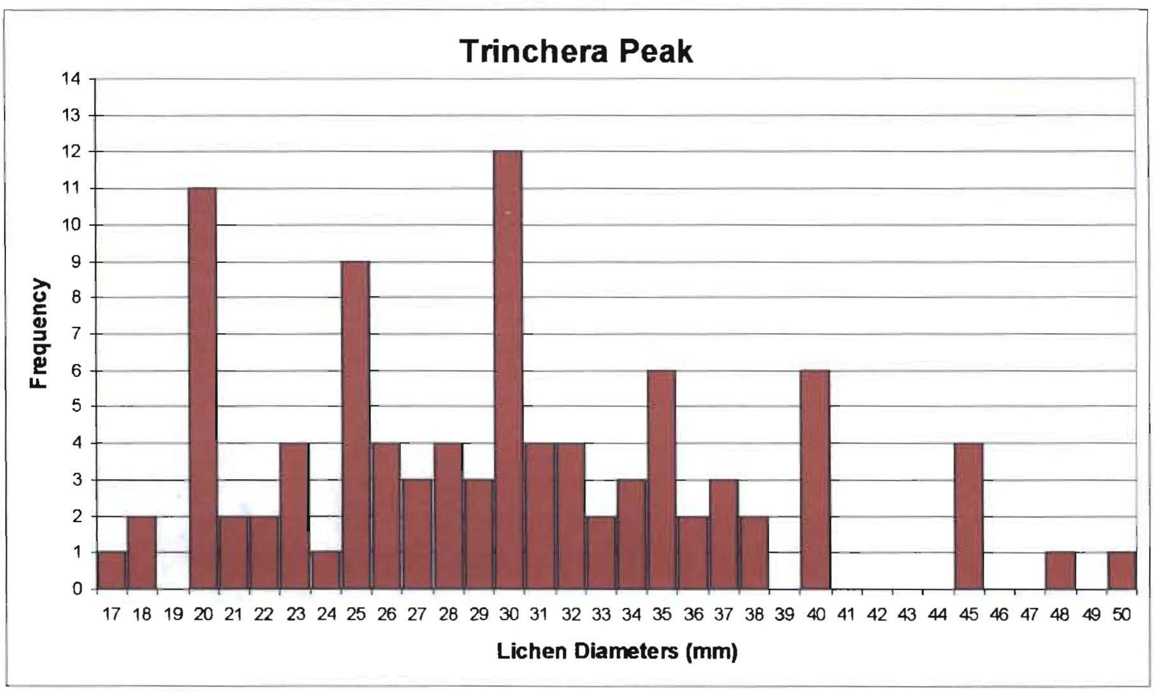


Figure 25. Trinchera Peak measured lichen diameters graphed by frequency.

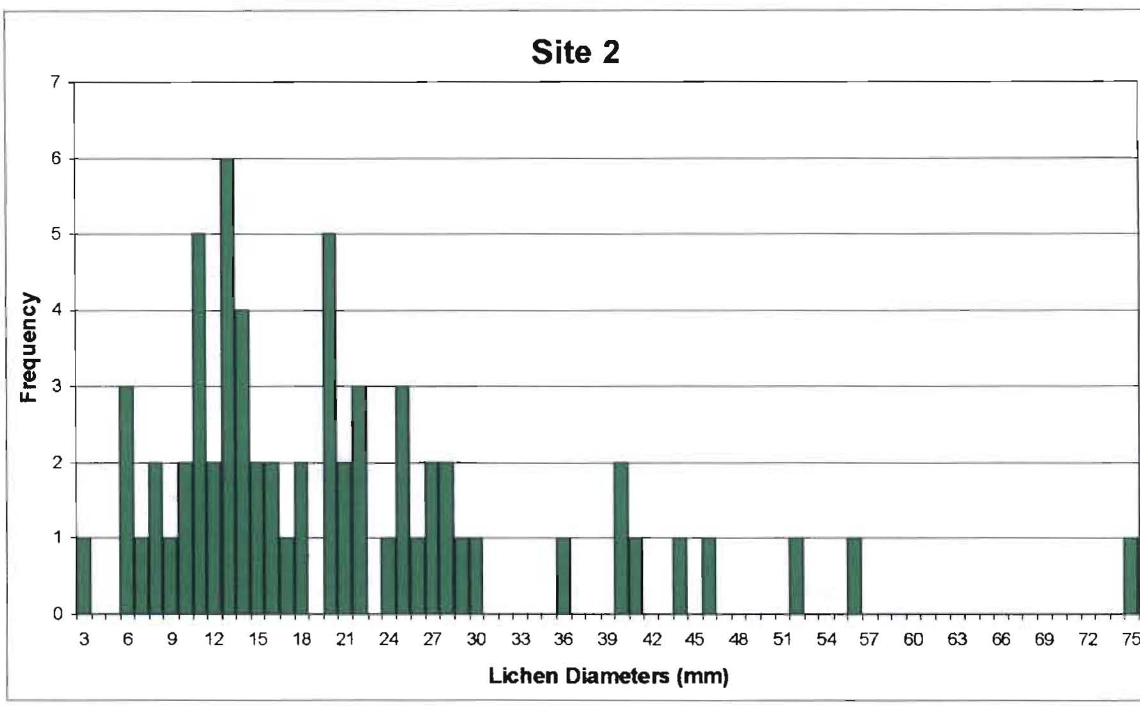


Figure 26. Site 2 measured lichen diameters graphed by frequency.

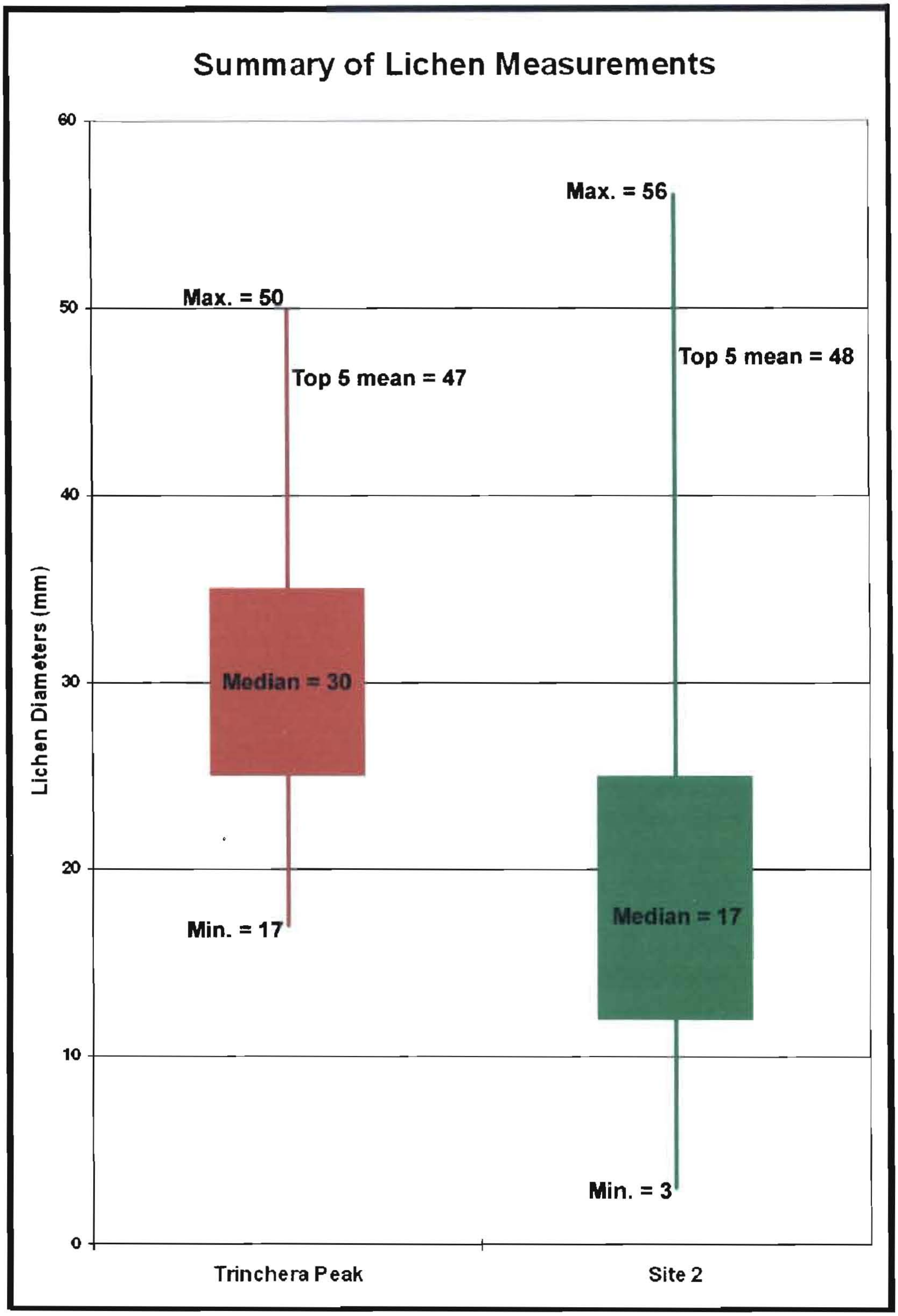


Figure 27. Box-and-whisker plot of lichen measurements recorded at Trinchera Peak and Site 2.

	Median size of all lichens (mm)	Years for lichen colonization	Years for first 14mm of growth	Years for remaining lichen growth	Average Minimum age of patterned ground formation
Trinchera Peak	30	50	100	485	AD 1369
Site 2	17	50	100	91	AD 1763

Table 1. Minimum age of patterned ground formation calculated from the median of all lichen diameters.

	Mean five largest lichens (mm)	Years for lichen colonization	Years for first 14mm of growth	Years for remaining lichen growth	Average Minimum age of patterned ground formation
Trinchera Peak	46.6	50	100	988	AD 866
Site 2	47.8	50	100	1024	AD 830

Table 2. Minimum age of patterned ground formation calculated from the mean of the five largest lichen diameters.

methods of lichenometry give different results for a minimum age of patterned ground formation.

Percent Coverage Method -- Figures 28 and 29 are the results of the percent cover of active lichens (*Rhizocarpon geographicum*) on stone surfaces. Figure 28 shows the percentage of rock covered by active lichens graphed by frequency at Trinchera Peak. Stones photographed at Trinchera Peak ranged from 3% – 27% lichen cover. The Site 2 percent lichen cover versus frequency graph (Fig. 29) illustrates much less lichen coverage was observed there. At Site 2, percent lichen cover ranged from 1% to 17% with the majority of stones having less than 6% lichen coverage.

Figure 30 summarizes the variation in percent lichen cover. This box-and-whisker plot illustrates the differences in lichen coverage at Trinchera Peak and Site 2. The median percent lichen coverage for Trinchera Peak was 11%, while the median percent lichen coverage of site 2 was only 3%. Although the percent lichen coverage results cannot be used to calculate actual dates, they do indicate different lengths of time for lichen growth or rates of lichen colonization and growth.

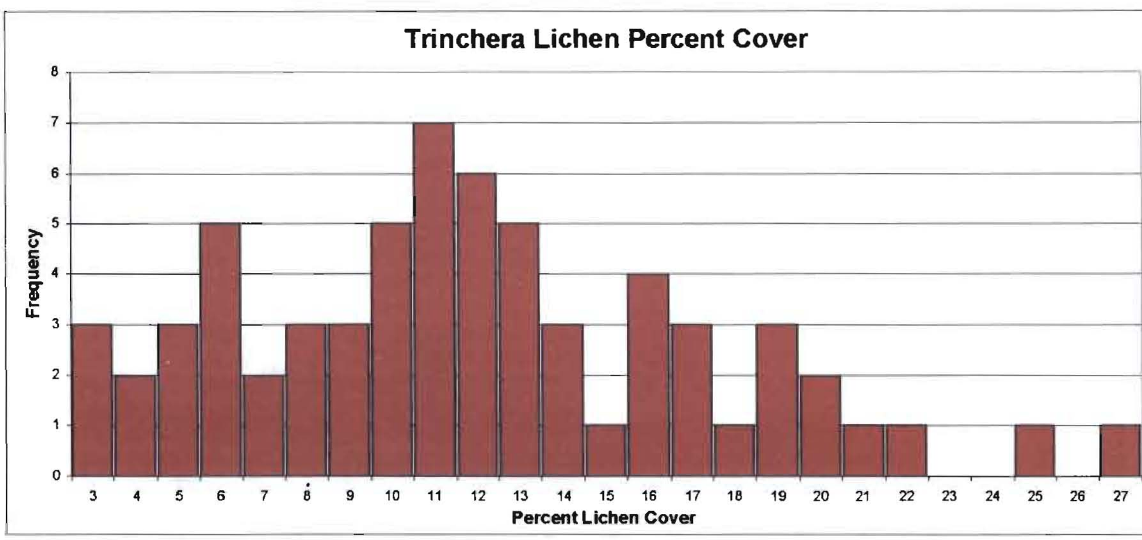


Figure 28. Percent cover of active lichens (*Rhizocarpon geographicum*) at Trinchera Peak.

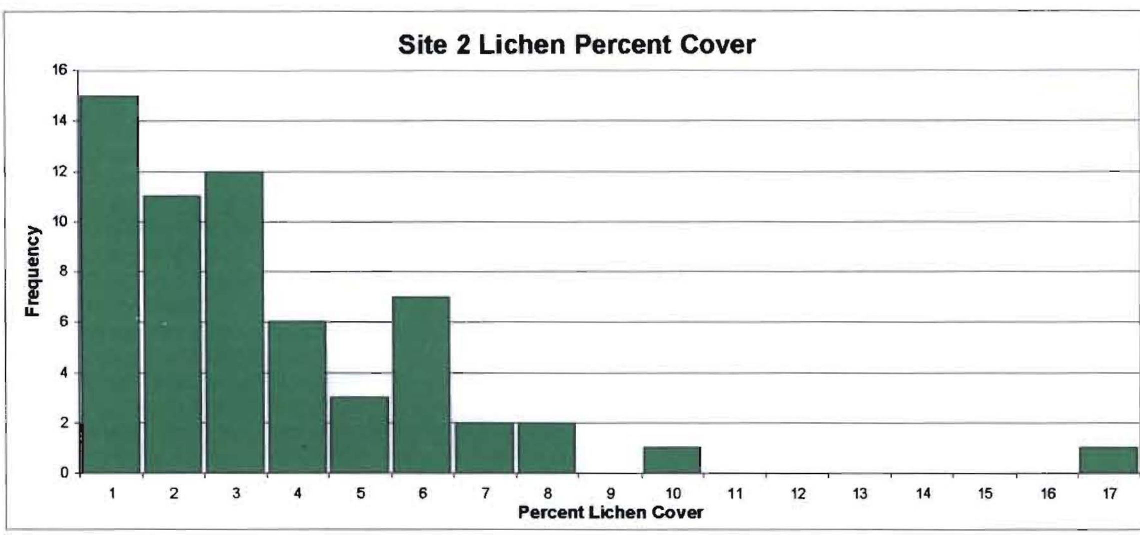


Figure 29. Percent cover of active lichens (*Rhizocarpon geographicum*) at Site 2.

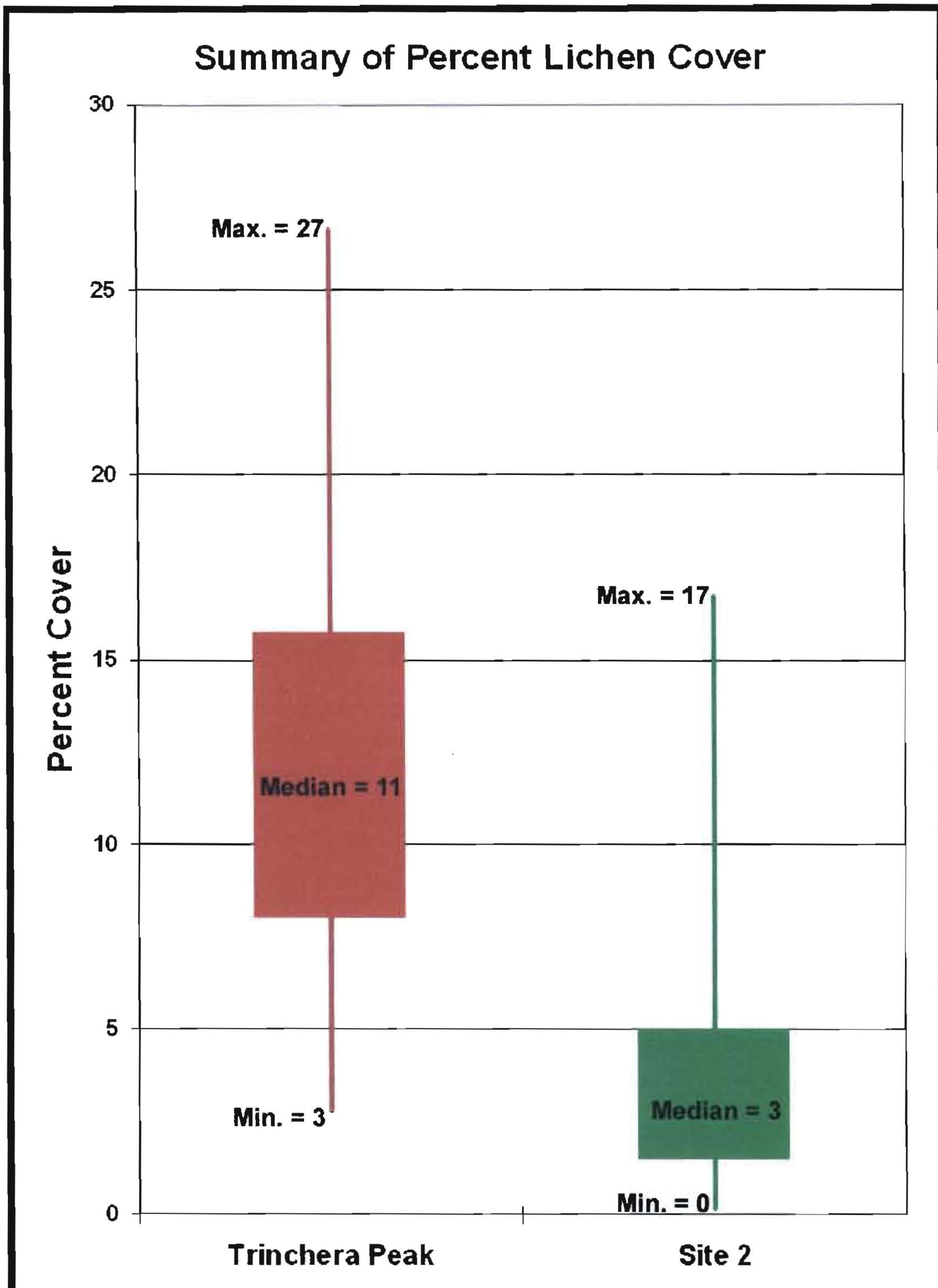


Figure 30. Box-and-whisker plot of percent lichen coverage obtained from Trinchera Peak and Site 2.

Subsurface Data

Figure 31 shows the soil trench dug at Trinchera Peak for soil description and sampling. The soil trench was dug to a depth of 60 centimeters before reaching solid rock. Numerous pebble to boulder sized rocks were encountered while digging. Root systems extended to approximately 30 centimeters. The soil was generally friable and non-cohesive. Ice and permafrost were not encountered while digging.

The trench was used to study a typical soil profile at Trinchera Peak. The soil profile was divided into three major horizons A, Bw, and C. The A-horizon consisted of the uppermost 10 centimeters of soil. An additional organic horizon may have existed in the top few centimeters of soil but was not differentiated in the field. The A-horizon was distinguished by its prominent dark brown color and humus-rich content. This soil horizon is best described as a light-weight mossy soil containing fine sand and silt particles bound by fine roots.

Below the A-horizon was the Bw-horizon. The Bw-horizon ranged from 10-30 centimeters in depth. This soil horizon was marked by a sharp contrast in soil color. The Bw-horizon was dark yellowish brown in color. Roots continued into this soil horizon but were much less dense. The organic content of this layer was significantly less. The Bw-horizon also included several stones.

The lowest horizon reached was the C-horizon. This horizon was marked from 30-60 centimeters in depth. The C-horizon appeared faintly lighter in color than the Bw-horizon above it. The C-horizon contained no noticeable roots or organic material. Stone sizes increased in this lowermost horizon, eventually impeding the ability to dig deeper.

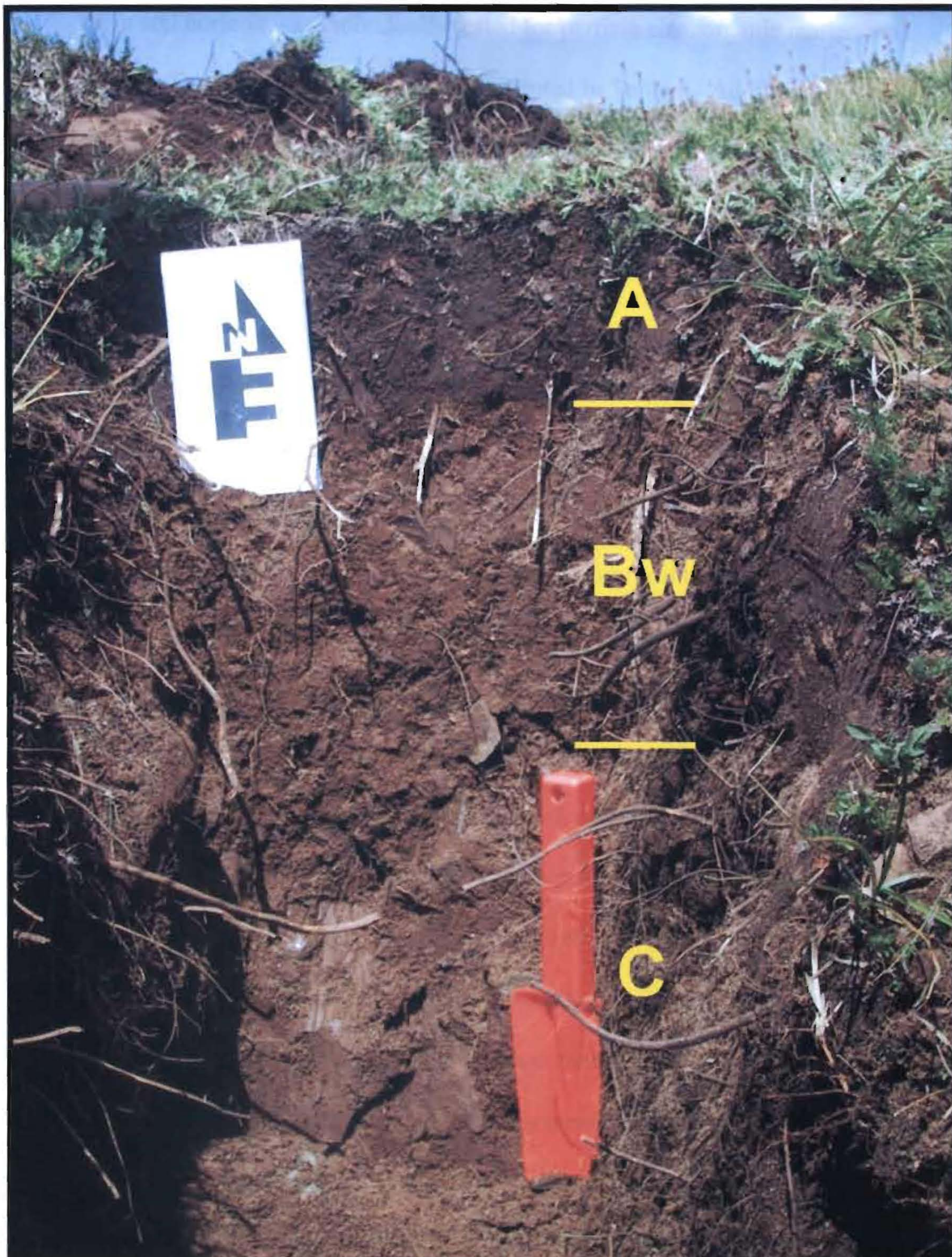


Figure 31. Soil trench at Trinchera Peak.

Each soil horizon was individually tested for particle size, organic matter, and Munsell color. The results of these tests are presented in Table 3. Additionally, the percentages of clay, silt, and sand for each horizon were graphed to demonstrate particle size changes with depth (Fig. 32).

Temperature Data

Figure 33 shows the soil temperature readings at Trinchera Peak plotted against the estimated air temperatures. The soil temperature readings taken at a depth of 60 centimeters show little variation throughout the year unlike the calculated air temperatures, which tended to fluctuate greatly. The steady soil temperatures are due to the insulation provided by soil and snow cover. The uppermost organic horizon and turf may act as good insulators keeping the deeper soil from experiencing frequent cycles of freezing and thawing. Snow cover also acts as an insulator keeping the soil at a constant temperature. This is demonstrated in figure 34, which compares major snowfall events of Trinchera Peak to soil temperature. Following large snowfall events the soil temperatures remain steady often for days or even weeks at a time.

A graph depicting estimated average annual air temperatures at Trinchera Peak from 1981-2003 is shown in figure 35. The average annual temperature from 1981 to 1995 was approximately -6°C. From about 1995 to present the average annual air temperature of Trinchera Peak increased to about -4°C with a continuing warming trend. Low annual temperatures from the mid-80s and early 90s may signify near reactivation of the patterned ground.

Soil Horizon	Depth	% clay	% silt	% sand	USDA Texture	% Organic Matter	Munsell Color (dry)	Munsell Color (moist)
A	0-10 cm	17	19	64	sandy loam	6.5	10YR 5/2	10YR 2/2
Bw	10-30 cm	19	22	59	sandy loam	2.5	10YR 6/3	10YR 3/4
C	30-60 cm	30	21	49	sandy clay loam	1.2	10YR 5/3	10YR 3/4

Table 3. Results of soil testing and analysis on Trinchera Peak soil samples.

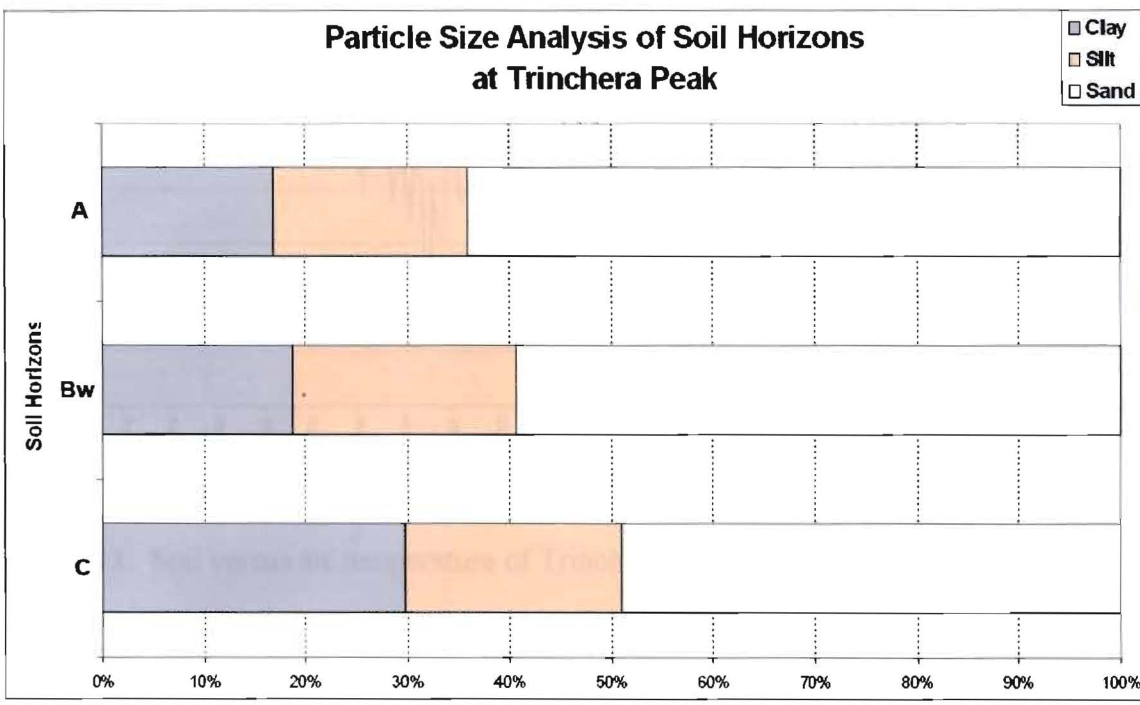


Figure 32. Percent clay, silt, and sand of Trinchera Peak soil horizons.

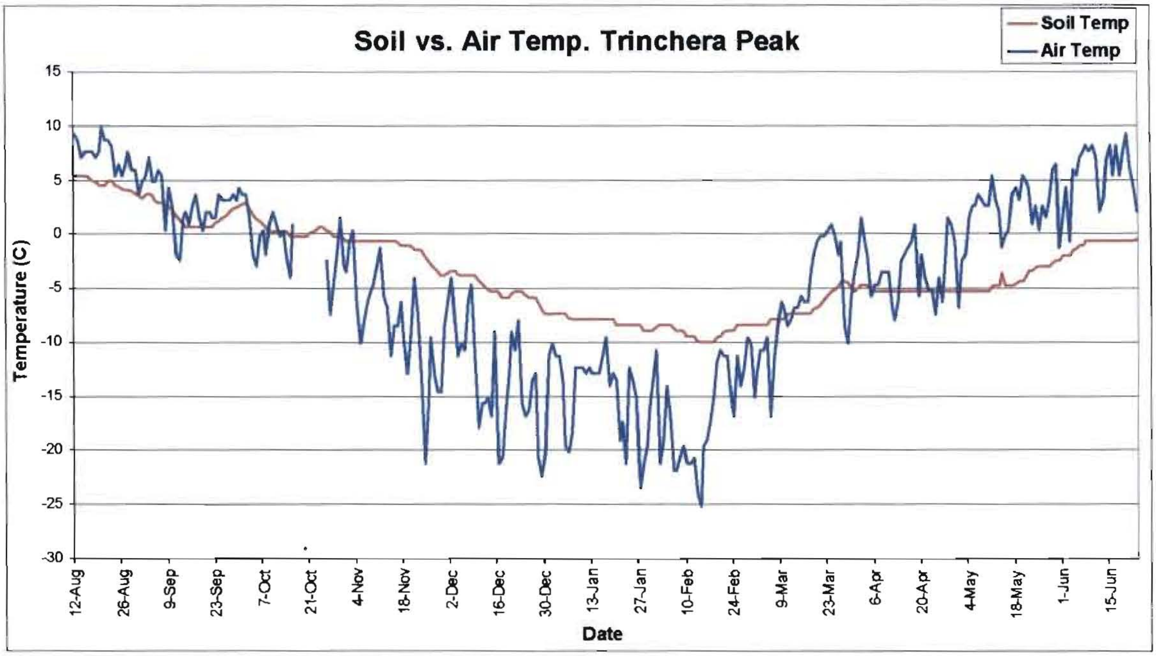


Figure 33. Soil versus air temperature of Trinchera Peak.

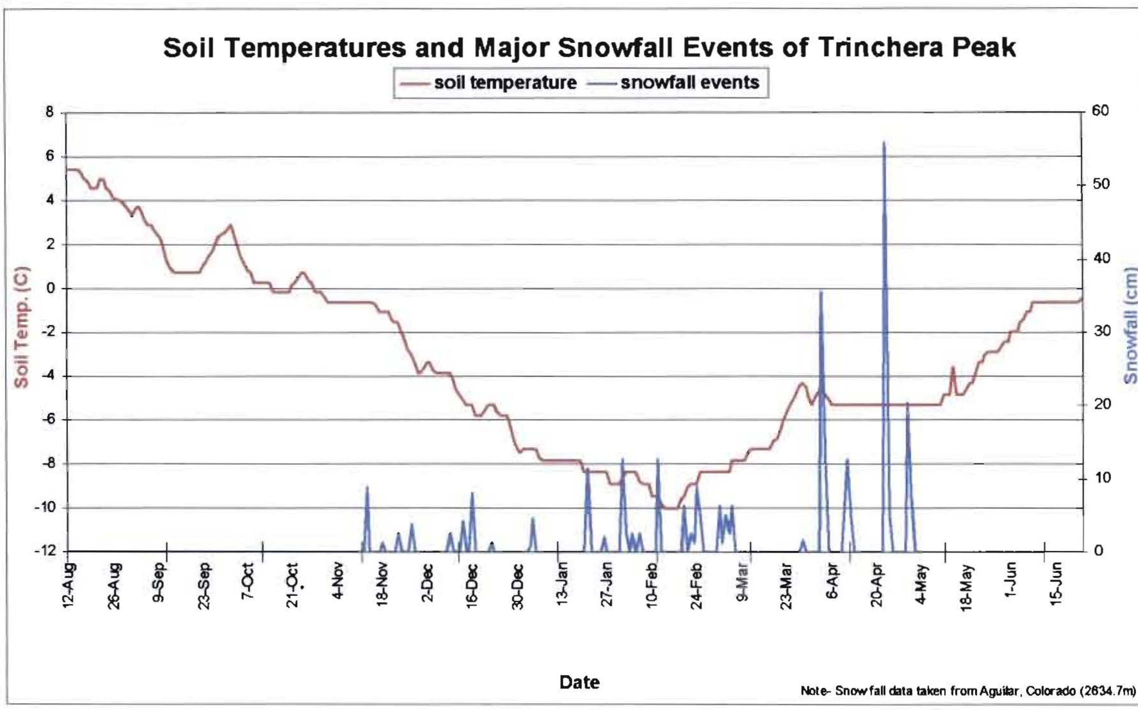


Figure 34. Soil temperature and major snowfall events of Trinchera Peak.

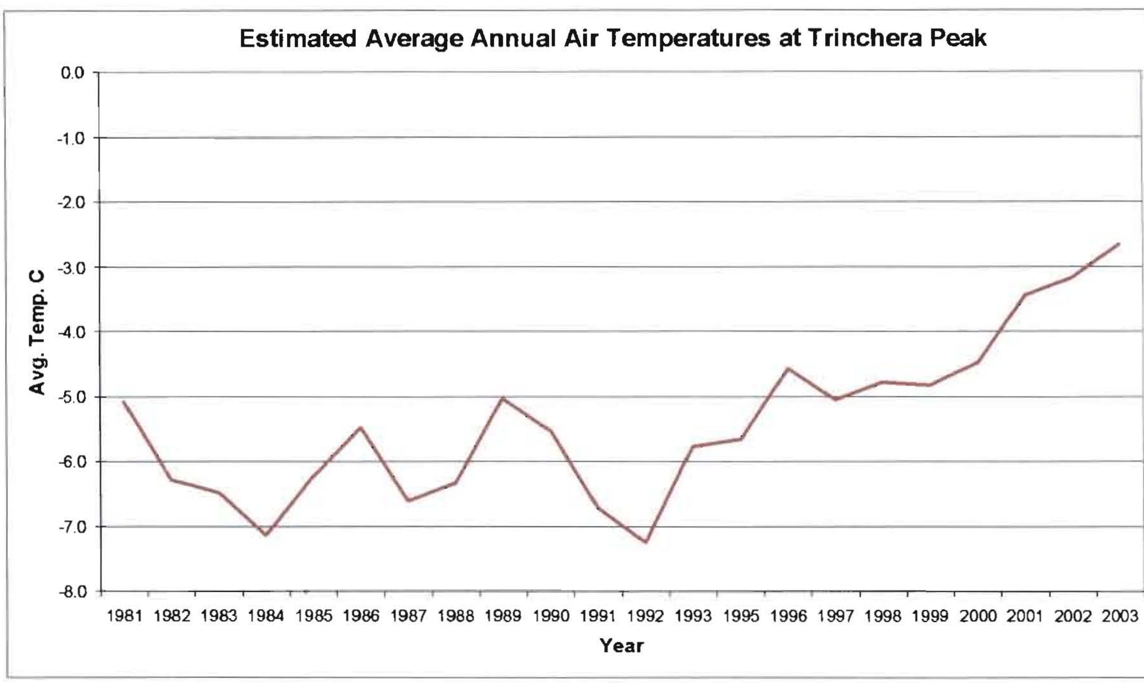


Figure 35. Average annual air temperatures at Trinchera Peak 1981-2003.

Chapter 4

Interpretations & Discussion

Lichenometry Results

The median lichen diameters calculated at Trinchera Peak and Site 2 gave minimum ages of patterned ground activity to be ~ AD 1350 for Trinchera Peak and ~ AD 1750 for Site 2. These dates are highly suspect. If around ~1350 the world's climate was cooling into the Little Ice Age as the Medieval Warm Period ended (Grove, 1988), this time period would not be a good candidate for the ending of patterned ground activity. During the 17th century both sites were likely to have been experiencing the effects of the Little Ice Age. However, if the patterned ground sites were greatly active during the Little Ice Age, one would expect lichen colonization to occur at the end of the Little Ice Age (1900s) rather than the middle of the Little Ice Age (1700s). Additionally substantial patterned ground activity during the Little Ice Age would likely kill all pre-existing lichens, thus lichen diameters should not have exceeded 14 millimeters. Another major discrepancy in this dating method is the variability in dates obtained using the median lichen diameter. It is unlikely that the patterned ground activity at Site 2 would end nearly 400 years after that at Trinchera Peak. This evidence leads to the conclusion that dates obtained from median lichen diameters are misleading.

Using the five largest lichens of both study sites a minimum age of patterned ground formation was calculated to ~AD 850. The Medieval climatic optimum was taking place during this time period. Therefore, the warm period from AD 800-900 would probably not support patterned ground activity. However, this period would be favorable for the initiation of lichen growth.

As stated previously, the percent cover results cannot provide actual dates for interpretation. Instead percent cover is based on the assumption that the mean percent lichen cover increases with time (Innes, 1985). The percent lichen cover at Trinchera Peak was greater than the percent cover at Site 2. This may lead to the assertion that patterned ground of Site 2 was active more recently than patterned ground of Trinchera Peak. This statement is probably untrue since Trinchera Peak is located at a high altitude where climatic conditions are more extreme. Therefore, there must be an additional explanation for the younger lichen community at Site 2.

Snowkill

Snowkill may help explain the unusual lichenometry results at Site 2 and Trinchera Peak. Snowkill is the extermination of active lichens by persistent snow cover. Patches of snow persevering throughout the summer months will inhibit lichen photosynthesis and respiration (Innes, 1988). As a result lichens may die and spall from their substrates.

Minor patches of snow cover may have created small-scale snowkill episodes at both sites. Figure 36 shows a late-lying snow patch at the Trinchera Peak study site on June 23, 2004. The variability in lichen diameters may indicate numerous periods of snowkill primarily during the Little Ice Age. In 1993 Benedict noted that lichen diameters of 15-21 millimeters are credible candidates for Little Ice Age snowkill. Therefore, the majority of lichen diameters at Site 2 could be a function of

Figure 36. Snow patch at Trinchera Peak study site June 23, 2004. Photo by Dr. James Aber.

snowkill events during the Little Ice Age. Trinchera peak could also have been affected by Little Ice Age snowkills but to a lesser degree. The percent lichen cover data also supports the more recent and greater snowkill activity of Site 2.

The maximum lichen colonization date of ~ AD 850 could be attributed to an extensive snowkill period which wiped out all previous lichens (*Rhizocarpon geographicum*). Benedict (1993) found that lichen snowkill during the Audubon (400 BC to AD 1050) destroyed all crutose lichens in more than 90% of areas studied. This extensive snowkill was caused by extreme winters and reduced snow drifting, thus creating thick blankets of persistent snow cover. These Audubon snowkill events differ from snowkills of the Little Ice Age wherein snowkill activity was more restricted to narrow bands and late-lying snow patches. He concluded that the recolonization of lichen free areas began in AD 210, 375, 570, 700, 1025, and 1255 (Benedict, 1993). It is possible that a snowkill episode of ~ AD 700 contributed to the maximum lichen diameters of ~50 millimeters.

Recent snowkill activity appeared to be more pronounced at Site 2 than at Trinchera Peak. This may be attributed to the site locations and direction of prevailing winds. The Trinchera Peak site rests near the summit on the western side of the mountain. Site 2 rests on the eastern edge of the mountains ridge. Therefore the prevailing winds from the west would tend to blow the Trinchera Peak patterned ground free of snow while the more sheltered Site 2 would accumulate snow cover more readily. This may also help explain why the patterned ground of Trinchera Peak is more pronounced than that of Site 2. The absence of snow allows for a greater fluctuation in soil temperatures, thus an increase in freeze-thaw cycles favoring patterned ground activity.

Errors in Lichenometry

The lichenometry results may be considered erroneous due to inaccuracy in the growth curve. The lichen growth curve developed by Benedict (1967) was created for the Indian Peaks Region of Colorado. The Indian Peaks region is more than 300 kilometers north of Trinchera Peak where substrate, climate, moisture, and growing season differ. These variables all affect the growth rate of *Rhizocarpon geographicum*. In order to establish more accurate dates using lichenometry one would need to create a local lichen growth curve for the Trinchera Peak area (Tilton, 2003).

Evidence of Patterned Ground Activity

Besides lichens other features noted at Trinchera Peak can be used to determine relative ages of patterned ground formation and activity. Many characteristics of the patterned ground observed at Trinchera Peak are similar to features reported by Benedict (1992). Benedict studied patterned ground phenomena of Niwot Ridge in the Colorado Front Range. Comparing Benedict's results to those at Trinchera Peak one may conclude that patterned ground at Trinchera Peak likely formed during the same period as the patterned ground of Niwot Ridge.

The surface topography of Trinchera Peak strongly supported polygonal patterned ground development. Trinchera peak illustrated a textbook example of sorted patterned ground containing irregular patches of fine sediment domes within a network of large stone-filled troughs. The fine sediment centers were generally convex and borders depressed, however some raised boarders did occur infrequently. The patterned ground of Site 2 was less developed and less prominent. Site 2 appears to have some polygonal structure although the activity which created the patterns was probably short lived and has been dormant for a substantial time. The patterned ground at Trinchera Peak and Site 2 is no longer actively forming. This may be noted by the active lichen cover and abundance of vegetation within the study areas.

Data gathered at Trinchera Peak indicates that the patterned ground phenomena may have originated during the Pleistocene, possibly during the Pinedale glacial phase prior to 12,120 yr B.P. Benedict (1992) wrote, "Many ridges and summits were unglaciated during the Pleistocene and were exposed for long periods to climatic conditions more rigorous than those of the present." This statement along with field observations led Benedict to the conclusion that patterned ground in the Colorado Front Range had initially developed during the Pleistocene. Complimentary field observations made at Trinchera Peak also suggest patterned ground activation during the Pleistocene.

The soil profile of the patterned ground of Trinchera Peak indicates a substantial time for soil activity and formation. As one may expect, weathering of bedrock at Trinchera Peak is primarily accomplished by frost processes. Therefore, the breakdown of larger particles into silt and clay sized sediment would have taken considerable time. Additionally, the formation of distinct soil horizons could have taken over tens of thousands of years in an environment such as that of Trinchera Peak (Buol et al., 1997).

Large lichens predating the Little Ice Age indicate long term existence of the Trinchera Peak patterned ground. Many lichens appeared to have survived the effects of the Little Ice Age. Since patterned ground may have been only briefly reactivated during the Little Ice Age, this would imply that an exceedingly extreme and extensive cold climatic periods occurring before ~ AD 850 would be likely candidates for the most recent episodes of patterned ground development during the late Holocene Neoglaciation. The Younger Dryas glaciation ~9,800 yr B.P. and Neoglacial periglacial events at 4,900 yr B.P. and 3,600 yr B.P., are strong candidates for periods of patterned ground reactivation (Armour et al., 2002).

The most recent period of increased patterned ground activity was probably the "Little Ice Age" (~ AD 1300–1900). It appears that few lichens had survived the effects of the Little Ice Age. Frost boils observed at Trinchera Peak indicate partial patterned ground reactivation during the Little Ice Age (Benedict, 1992). Additionally, it is possible that discontinuous permafrost existed on Trinchera Peak during this time. Tilton's (2003) lichenometry results at Trinchera Peak also signify possible periods of patterned ground reactivation during the Holocene. His bimodal distribution of lichen sizes may indicate a cold climatic period when patterned ground activity inhibited lichen colonization.

Since the Little Ice Age, the trend has been toward revegetation of the patterned ground. As the vegetation returns it often starts along the stone borders and continues to move inward toward the polygon centers (Benedict, 1992). Current temperature records indicate a relatively warm climate which has halted patterned ground activity. The soil temperature data indicated annual cycles of freezing and thawing activity but average annual temperatures were too warm for modern patterned ground development. The current mean annual air temperature of Trinchera Peak is only ~ -4°C and a reoccurring annual temperature of -7 to -8°C is often required for patterned ground activity (Ritter et al., 2002).

Chapter 5

Conclusions

The periglacial patterned ground activity at Trinchera Peak is a complex phenomenon. The exact mechanisms which initiated patterned ground development are still unclear. The patterns may have resulted from upward mass displacement of plugs of fine earth in response to density imbalances in the soil caused by frost action (Benedict, 1992). The patterned ground at Trinchera Peak is remarkably similar to other patterned ground sites described by Washburn (1956, 1973), Embleton and King (1975), Benedict (1992), and other authors.

The lack of dating options and datable material made this study particularly challenging. Lichenometry results were found to provide tentative dates and climatic indications. Lichen ages may suggest episodes of snowkill rather than periods of patterned ground activity. Lichen dates obtained may be erroneous due to differences in substrate, climate, moisture, and length of the growing season between the Indian Peaks Region of Colorado, where growth curves were originally developed, and Trinchera Peak. Despite these setbacks, using observations and data acquired from Trinchera Peak in conjunction with other patterned ground studies one may speculate about the approximate ages of patterned ground formation and activity.

Advanced soil development, large lichens, and the relatively mild climate of the Holocene indicate the polygonal patterned ground may have developed initially as far back as the Pleistocene prior to 12,120 yr B.P. Variability in lichen sizes, frost boil, and current revegetation at Trinchera Peak indicate periods of patterned ground activity as well as episodes of snowkill during the Holocene. Patterned ground activity may have occurred during the Neoglaciation (prior to AD 850) and then been partly reactivated during the Little Ice Age (~ AD 1300-1900). The recent climatic warming trend has lead to revegetation and stability of Trinchera Peak patterned ground.

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