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Patterned ground in the Culebra Range, southern Colorado

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Well-developed sorted stone polygons (patterned ground) and other periglacial phenomena are situated near the summit of Trinchera Peak and on the adjacent mountain ridge, Culebra Range, south-central Colorado. We investigated the age and origin of patterned ground with various methods of lichenometry, as well as aerial photography, soil sampling, and temperature logging. For lichenometry, the FALL (fixed area largest lichen) and percent-lichen-coverage methods were employed. Based on the largest lichens from two study sites, we estimate that lichen growth began in the mid-ninth century during the medieval climatic optimum; we conclude that stone polygons have been stable geomorphic features for at least the past millennium. Observations from soil and tree-rings support the notion of relative stability for patterned ground and lack of periglacial activity during this period. Recent mean annual air and ground temperatures at Trinchera Peak are in the range -4° to -6°C, which is not sufficiently cold to maintain periglacial processes. During the Little Ice Age (AD 1500-1900), cooler climate resulted in lichen snowkill events but was not cold enough to destroy all older lichens or reactivate periglacial processes of patterned ground.

Keywords: patterned ground, stone polygons, lichenometry, aerial photography, soil temperature, Little Ice Age, medieval climatic optimum, Trinchera Peak.

INTRODUCTION

The Culebra Range is part of the Sangre de Cristo Mountains, which form the Rocky Mountain front range in southernmost Colorado and northern New Mexico. The study area lies on the mountain crest at the headwaters of Cucharas Creek (Fig. 1). In the alpine zone, above ~12,000 feet (3700 m), strong frost action has produced various periglacial features, including rock glaciers, talus streams, and stone festoons and terraces on steeper slopes and valley sides. For example, Wallace and Lindsey (1996) mapped some small, inactive rock glaciers in the vicinity.

In the summer of 2000, one of us (VK) discovered well-developed patterned-ground phenomena near the summit of Trinchera Peak (site 1, Fig. 1). Two smaller zones with patterned ground were found subsequently on the mountain ridge to the north (sites 2 and 3). These sites are lower in elevation and smaller in size, and the patterned ground is less fully developed compared with site 1. The patterned ground consists of polygonal networks formed by loose stones in shallow trenches surrounding raised turf mounds (Fig. 2). Such periglacial features require deep seasonal ground freezing, if not permafrost, to form (Washburn 1973). Patterned ground in this geographic setting has not been previously described, mapped, or studied so far as we can determine. The goals of our investigation are to document the character of patterned ground and to determine its mode of origin, age, and history of development.

SITE CONDITIONS

The crest of the Culebra Range consists of the Sangre de Cristo Formation, a thick sequence of interbedded shale, siltstone, sandstone, and conglomerate of late Pennsylvanian and early Permian age. These strata are dominately arkosic in composition and red in color. However, the basal 200 m of the formation is gray, quartzose sandstone that stands in near-vertical position along the mountain ridge top (Wallace and Lindsey 1996). The patterned ground is developed in this resistant rock (Fig. 3).

The Culebra Range was glaciated repeatedly during the Pleistocene Epoch, most recently during the Pinedale stage, ~23,000 to 12,000 years ago (Richmond 1965, 1986; Armour, Fawcett and Geissman 2002). The zones of patterned ground are situated on the mountain ridge, well above the valleys in which glaciers existed. Since the end of the Pleistocene, several lesser cold-climate events have affected the Sangre de Cristo Mountains during the Holocene Epoch. These included minor glaciations and periglacial episodes, as well as a warm interval known as the Altithermal in the mid-Holocene (Table 1).

Modern climate of the Culebra Range is typical of alpine environments—long, cold winters and short, cool summers. The growing season is only 2-3 months long, depending mainly on snow-cover conditions. In southern Colorado, most snow falls in late winter and early spring: March-May. Snow

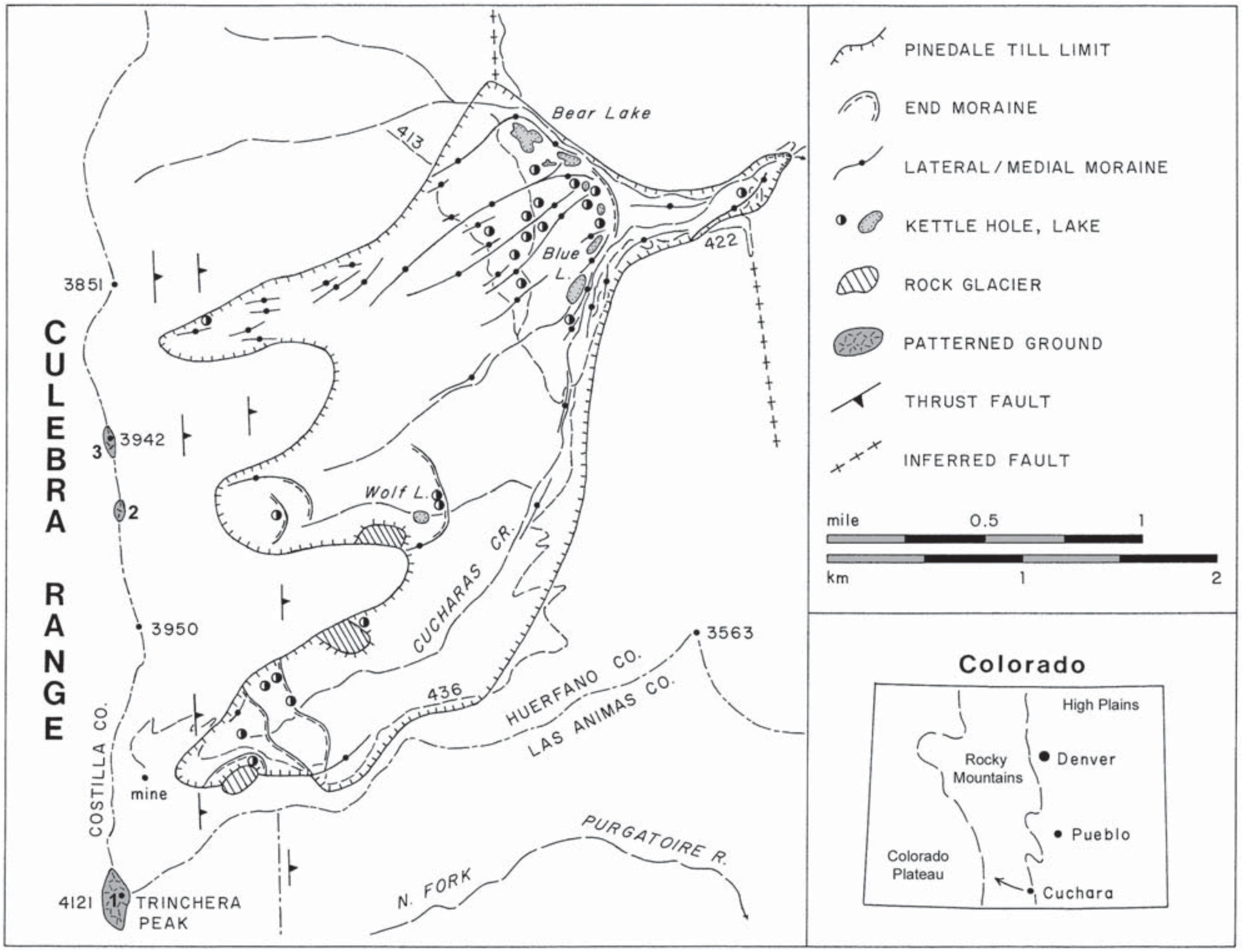


Figure 1. General location map for glacial and periglacial phenomena of the upper Cucharas Creek drainage basin in the Culebra Range, south-central Colorado. Three zones with patterned ground are situated on the mountain crest at Trinchera Peak and to the north (sites 1, 2, 3). These sites are located in the alpine zone, well above the valleys affected by glaciation (Pinedale till limit). A forest service road (436) provides jeep access to an old mine on the side of Trinchera Peak. Elevations given in meters.

Figure 2. Raised turf mound surrounded by stones in a shallow trench, which makes up a small polygon on Trinchera Peak (site 1). Turf area of polygon is ~2 m across.

Figure 3. Photograph looking southward along the Culebra Range crest from site 2 in the foreground to Trinchera Peak in the background. Trinchera Peak reaches a maximum elevation of 13,517 feet (4121 m).

Table 1. Composite stratigraphy of latest Pleistocene and Holocene glaciations and periglacial episodes in the southern Rocky Mountains, Colorado and northern New Mexico. Ages in years before present are based on various radiometric and relative dating methods. Compiled from Richmond (1986) and Armour, Fawcett and Geissman (2002).

Glaciation or Periglacial Episode	Age Range	Period
Grenadier, Temple Lake Ptarmigan, Triple Lakes	9000 to 10,000	Younger Dryas Earliest Holocene
Minimal glaciation or periglacial phenomena	8000 to 5000	Altithermal Early to mid-Holocene
Audubon Rock glaciers	2500 to 5000	Early Neoglacial Late Holocene
Arapaho, Gannett Peak Rock glaciers	120 to 400	Little Ice Age Late Neoglacial

patches may persist well into July, and frost can happen throughout the summer. Strong wind restricts vegetation to low-growing plants and small shrubs; lichens cover bare rock surfaces. Under these conditions the rate of lichen growth is extremely slow, as are the rates of soil development and other geomorphic processes.

METHODS OF INVESTIGATION

Primary methods of study include lichenometry, aerial photography, soil sampling, and temperature logging, along with general observations and descriptions of site conditions. Preliminary investigation of lichenometry at site 1 was undertaken by Tilton (2003), who measured relatively large lichens growing on stone polygons. Based on this unexpected discovery, we undertook further investigations of the situation. Sites 1 and 2 were selected for detailed field mapping and analysis, but only cursory observations were made at site 3. At sites 1 and 2, grid systems were established with 5-meter spacing. The sampling grid at site 1 measured 30 m by 40 m (Figs. 4 and 5), and the grid at site 2 was 20 m by 40 m.

Lichenometry — The chief indicator utilized to determine the age of relict patterned ground is lichenometry. *The basic premise of lichenometry is that the diameter of the largest lichen thallus ... 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 analysis (Fig. 6), because of its abundance at the study site, wide geographic distribution, ease of identification, and slow steady growth rate (Noller and Locke 2000). Lichenometry is based on a few basic assumptions:

- Growth starts on surfaces free of lichen thalli.
- Colonization begins quickly after the surface stabilizes.
- Growth rate is predictable over a long time period.

Lichen growth rate may be influenced by many environmental factors including rock type, exposure to abrasion, shading, temperature, moisture, stability of substrate, and length of growing season (Benedict 1967). These factors create variable growth rates in diverse environments. Lichenometry has been used with notable consistency in various alpine and Arctic environments by Beschel (1961), Benedict (1967, 1988), Birkeland (1973), Carrara and Andrews (1973), Locke,

Figure 4. Overview of the southern portion of study site 1. View toward the southwest from the summit of Trinchera Peak. Small orange flags mark the survey grid; asterisk (*) indicates location of soil sample site (see Fig. 11). Image taken August 2003.

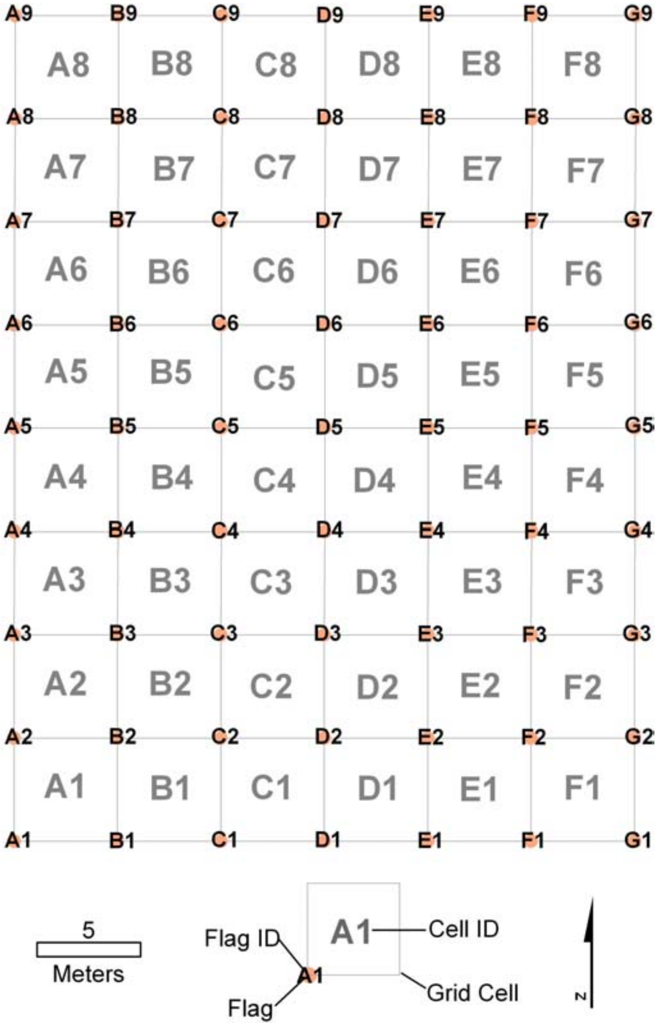


Figure 5. Schematic plan for the sampling grid at study site 1.

Figure 6. Photograph of *Rhizocarpon geographicum* (bright yellow-green) and other lichens on rock surfaces at Trinchera Peak. Compass is ~3 inches (7.5 cm) long. Image taken August 2003.

Andrews and Webber (1979), Calkin and Ellis (1980), Innes (1984, 1985, 1986, 1988), McCarroll (1994), Bull and Brandon (1998), and numerous other authors. In particular, Benedict (1967) developed a lichen growth curve for the Indian Peaks Region in the Colorado Front Range, approximately 300 km north of the study region. His growth curve was composed using historical and prehistorical surfaces in the elevation range ~3100 to ~4000 meters above sea level. He concluded that *Rhizocarpon geographicum* grows rapidly, 14 mm for its first century, and then growth slows to an average rate of 3.3 mm per 100 years (Fig. 7).

Two distinct methods of lichenometry were used to determine a minimum age of patterned-ground formation. One method is based on the single largest lichen within a given area. This approach is referred to as the FALL (Fixed Area Largest Lichen) method and was developed by Bull and Brandon (1998). The FALL method is based on the largest lichens within numerous sampling units. Each grid cell was examined to find the largest lichen on a vertical north-facing (shaded) surface and the largest lichen on a horizontal (sunny) surface. Neither study site showed obvious differences between rock orientation and lichen size; therefore, all lichen measurements were combined into a single dataset at each site for further statistical analysis. Both the median value of all lichens and the average of the five largest at each study site were used in the growth curve developed by Benedict (1967). The range of dates developed from the growth curve was then corrected for the length of colonization time necessary for lichens to become established. This colonization time was set at 50 years as indicated by Grove (1988).

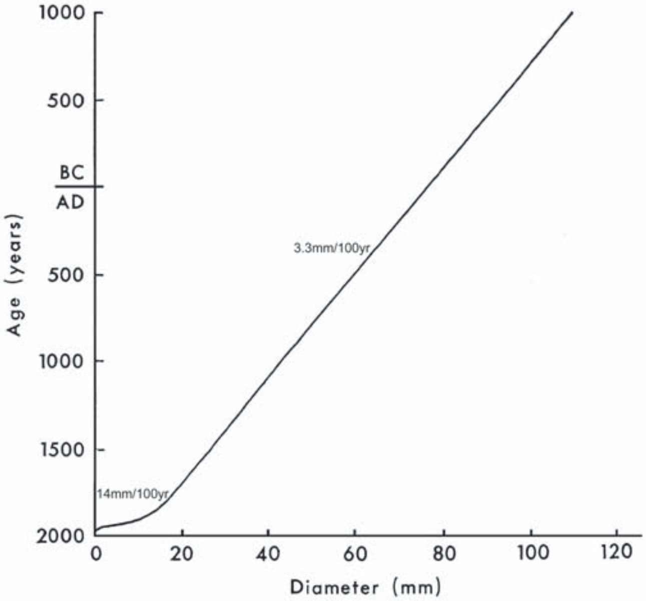


Figure 7. *Rhizocarpon geographicum* growth curve for the Indian Peaks vicinity near Boulder, Colorado. Based on Benedict (1967).

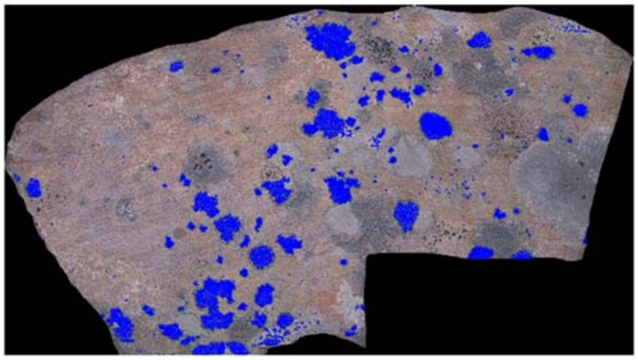
The second method of lichenometry is based on the percentage coverage of lichens on a stone surface (McCarthy and Zniewski 2001). This approach of lichenometry fieldwork consisted of taking digital photographs of the lichens in each of the grid cells. The photographs later were edited using both *Adobe Photoshop* and *Idrisi* software to determine percentage cover of *Rhizocarpon geographicum* (Fig. 8). No published quantitative relationship is available between surface age and percentage of lichen cover. Thus, the percent-coverage data give only relative ages of patterned-ground formation. The percent-coverage results were graphed by frequency and compared with the FALL results.

Aerial photography — Spatial distribution of patterned ground was documented with aerial photography. A 35-mm film camera was suspended from a boom 25 feet (8 m) tall (Fig. 9). Vertical photographs were acquired for all portions of the two study grids. Standard *Adobe Photoshop* techniques were utilized to enhance the visual appearance of images (Fig. 10). Individual pictures were stitched together using *D Joiner* software to create mosaics, which were imported into *ArcGIS* software and georegistered to fit the sample grid.

Soil observations — A soil pit was dug 60 cm (two feet) deep to bedrock on the side of a raised turf mound within a polygon in the southwestern portion of sample grid 1 in August of 2003 (Fig. 11). The soil profile was described in the field, and bulk samples were collected from the upper 10 cm (A organic horizon), the second 20-30 cm (Bw horizon), and the lower 30-60 cm (C horizon). Each soil sample color was distinguished using the Munsell soil color chart. Textural analysis was completed on each soil horizon following the methods of Black et al. (1965), and samples were sent to the Kansas State University Soil Testing Laboratory for organic matter analysis.

Climatic data — A temperature data logger was placed at the bottom of the soil pit in early August 2003, and the pit was filled and covered to restore the site to near-natural conditions. This data logger was recovered in late June 2004, and its temperature record was downloaded. The logger was placed again in the soil pit and covered for the period late August 2004 to early September 2005. The data logger recorded temperature each 6 hours throughout the two periods of operation.

Original stone surface with lichens



Photoshop edit

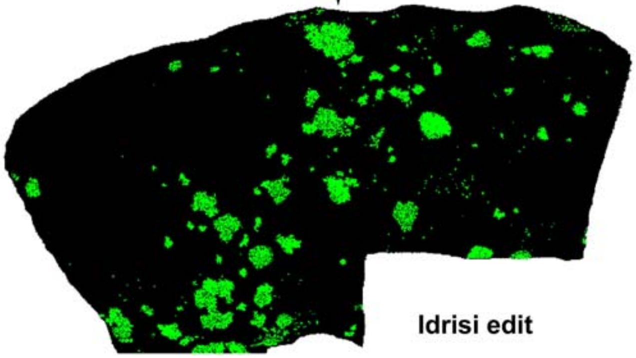


Figure 8. Example of image processing steps to derive percentage of *Rhizocarpon geographicum* cover on a rock surface.

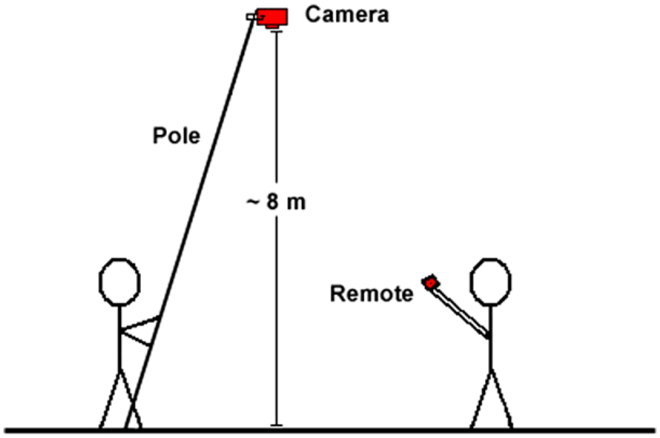


Figure 9. Cartoon showing arrangement for aerial photography using a pole to hold a camera vertically above the study site. Illustration is not to scale.

Figure 10. Single vertical photograph of stone polygon with turf center. Scale bar is 1 meter (3.3 feet) long.

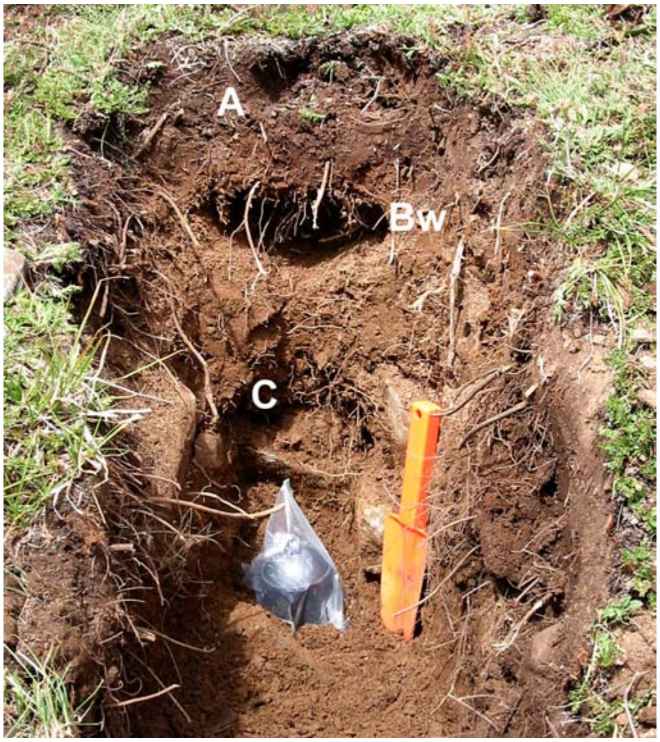


Figure 11. Soil sample pit showing soil horizons and the temperature logger at the bottom. The data logger is sealed in a plastic bag with moth balls to prevent moisture and animal damage. Digging trowel is approximately 25 cm (10 inches) long. For location see Fig. 4.

Surface temperature data and snowfall data were obtained from the National Climatic Data Center (NCDC 2004) for the nearest suitable weather stations. Surface temperature data were acquired for San Luis, Colorado at ~2440 m altitude and 28 km southwest of Trinchera Peak. To calculate the approximate air temperature of Trinchera Peak, an average adiabatic lapse rate of 0.6°C/100 m was applied to the San Luis temperature data, resulting in a correction of -10°C. The calculated surface temperature of Trinchera Peak was then compared with the soil temperature record. In addition, average annual temperatures from 1981-2003 for Trinchera Peak were calculated and graphed to show recent climatic trends. Snowfall data were acquired from Aguilar, Colorado at ~2600 m elevation and 50 km east of Trinchera Peak. These snowfall data were used to determine the dates and magnitudes of snowfall events in southern Colorado. The major snowfall events were then graphed against the soil temperature record at Trinchera Peak.

Results

Lichenometry — Sites 1 and 2 were examined to identify the largest lichens (*Rhizocarpon geographicum*) within each 5x5-meter grid cell according to the FALL method. (Figs. 12 and 13). The size-frequency graphs show a wide distribution of lichen measurements at both sites. However, a 75-mm lichen recorded at site 2 appeared anomalous and was disregarded for further lichenometry analysis. Most lichens observed at site 1 are between 20 and 35 mm in diameter, and median lichen diameter is 30 mm. The lichen diameters measured at site 2 are generally smaller than those recorded at Trinchera Peak. Most lichens at site 2 range from 10 to 25 mm in diameter, and median lichen diameter is 17 mm. Box plots of lichen diameters reveal clear statistical differences between the two sites (Fig. 14).

Despite the overall difference in lichen sizes between sites 1 and 2, the means of the five largest lichens at each site are statistically identical. The mean of the five largest lichens at

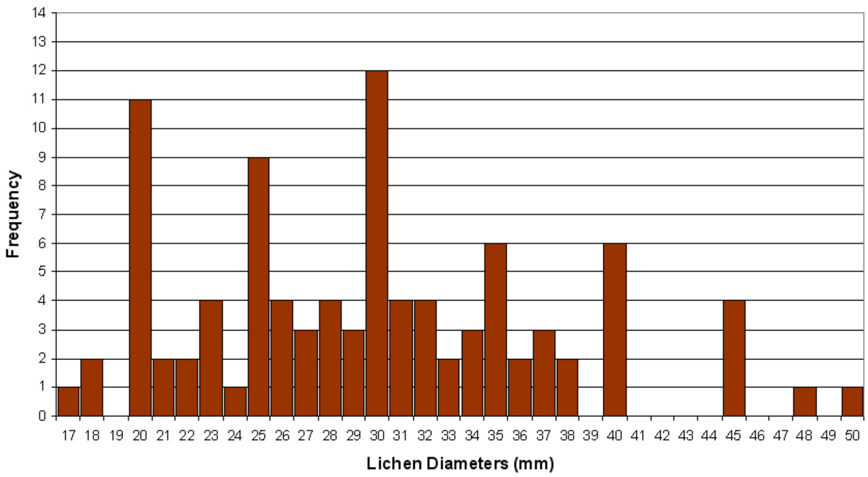


Figure 12. Site 1 largest lichen (*Rhizocarpon geographicum*) diameters per grid cell graphed by frequency of occurrence.

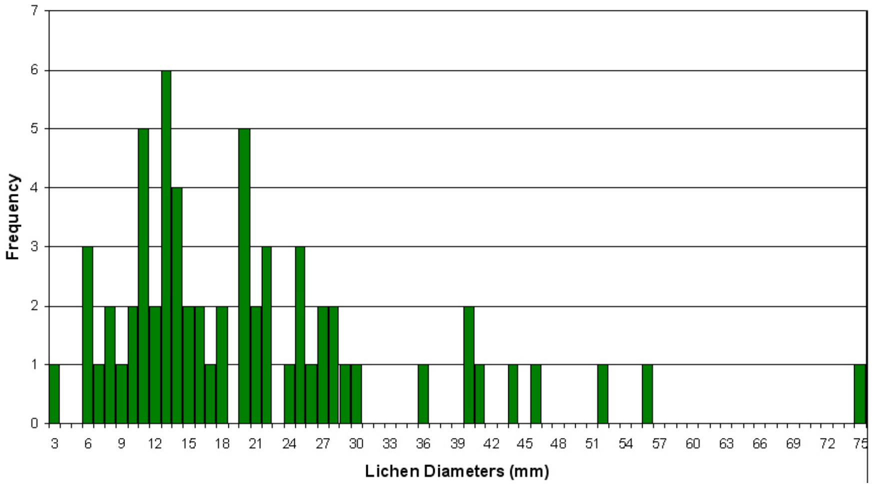


Figure 13. Site 2 largest lichen (*Rhizocarpon geographicum*) diameters per grid cell graphed by frequency of occurrence.

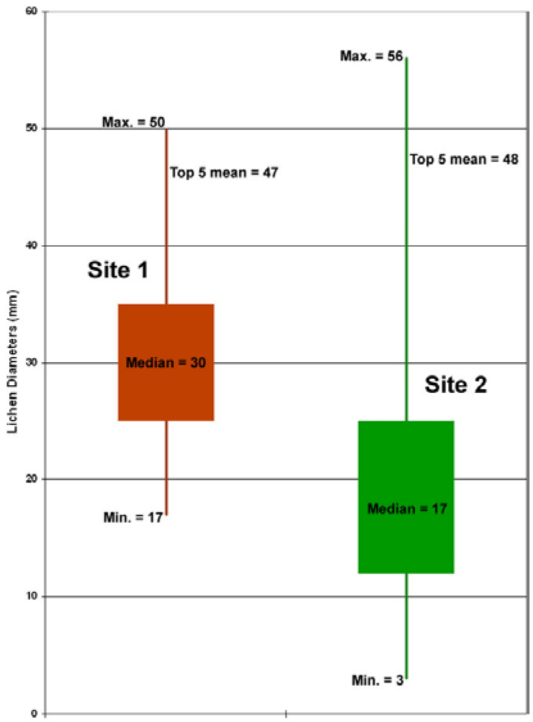


Figure 14 (left). Box-and-whisker plots of lichen measurements recorded at study sites 1 and 2. The box for each plot includes 50% of measurements for each site.

site 1 is 47 mm, and the mean of the five largest from site 2 is 48 mm. Both the median lichen sizes and the means of the five largest lichens were applied to Benedict's lichen growth curve. The two methods give quite different results for minimum ages of patterned-ground formation at sites 1 and 2 (Tables 2 and 3).

Results of the percent-coverage method indicate greater lichen cover on stones at site 1 compared with site 2 (Figs. 15 and 16). Site 1 coverage ranges from 3% to 27%; whereas, site 2 lichen coverage is only 1% to 17%. Box plots of percent-coverage data demonstrate significant separation in values for the two study sites (Fig. 17). Although percent-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. In this case, percent-coverage values confirm that lichen development is more advanced on site 1 compared with site 2.

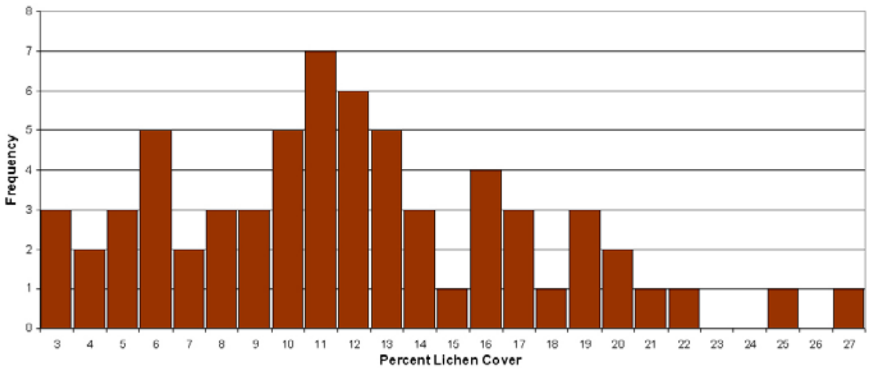


Figure 15. Site 1 percent coverage of active lichens (*Rhizocarpon geographicum*) per grid cell graphed by frequency of occurrence.

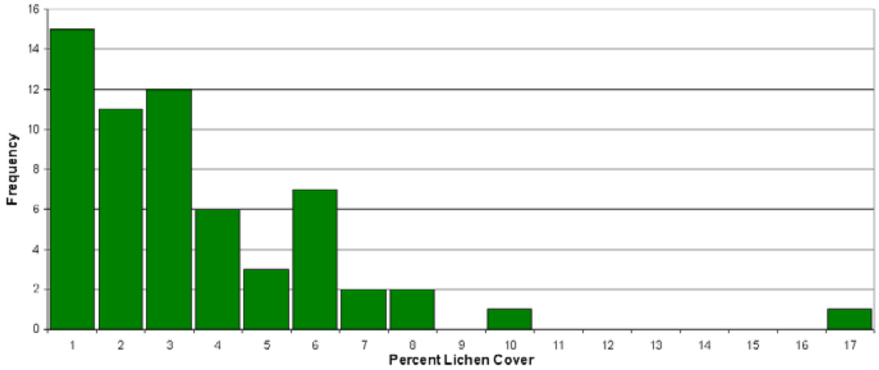


Figure 16. Site 2 percent coverage of active lichens (*Rhizocarpon geographicum*) per grid cell graphed by frequency of occurrence.

Aerial photography — Mosaics constructed from aerial photographs depict bird's-eye views of the study sites (Fig. 18). Such vertical images in combination with ground observations are the basis for the spatial description of patterned ground, which consists of a network of stone polygons with raised turf centers. Individual polygons are 3-5 m in diameter and typically have 4-6 sides, which may be linear in some cases or curved and somewhat irregular in others. The polygons are sorted; the margins of the polygons are composed of cobbles and small boulders, and the polygon centers consist of finer sediment and turf. The majority of polygon centers are domed with turf consisting of grasses, shrubs, mosses, and small forbs. Some polygon centers show evidence of frost boil or animal burrows, which appear as areas of bare soil within the polygonal centers. In general,

Table 2. Minimum age of patterned-ground formation calculated from the median of all lichen diameters at sites 1 and 2.

Site	Median size all lichens (mm)	Years for colonization	Years for first 14 mm growth	Years for remaining growth	Minimum age
1	30	50	100	484	AD 1369
2	17	50	100	90	AD 1763

Table 3. Minimum age of patterned-ground formation calculated from the mean of the five largest lichen diameters at sites 1 and 2.

Site	Mean 5 largest lichens (mm)	Years for colonization	Years for first 14 mm growth	Years for remaining growth	Minimum age
1	46.5	50	100	987	AD 866
2	47.8	50	100	1023	AD 830

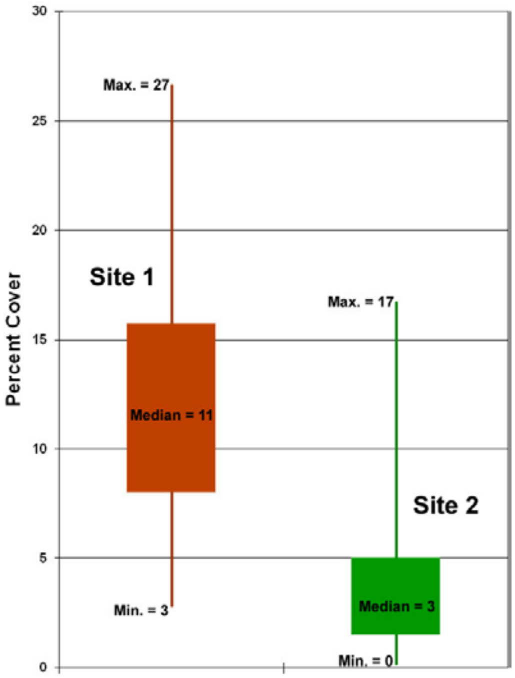


Figure 17. Box-and-whisker plots of percent lichen coverage obtained from sites 1 and 2. The box for each plot includes 50% of measurements for each site.

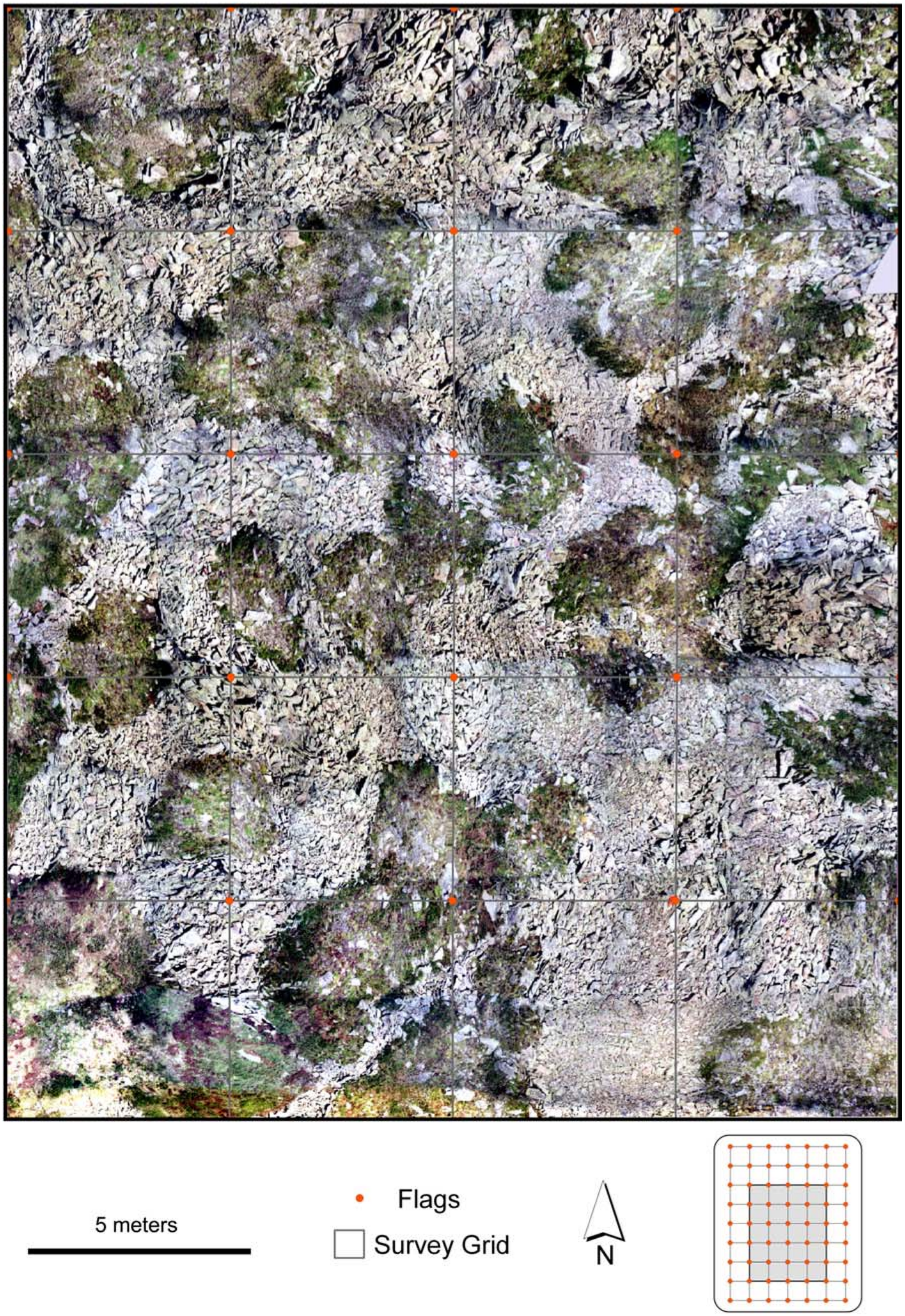


Figure 18. Airphoto mosaic of the central portion of study site 1 showing a network of stone polygons with raised turf centers.

Soil horizon	Depth	% clay	% silt	% sand	USDA texture	% organics	Munsell color (dry)	Munsell color (moist)
A	0-10 cm	17	19	64	sandy loam	6.5	10 YR 5/2	10 YR 2/2
Bw	20-30 cm	19	22	59	sandy loam	2.5	10 YR 6/3	10 YR 3/4
C	30-60 cm	30	21	49	sandy clay loam	1.2	10 YR 5/3	10 YR 3/4

Table 4. Soil characteristics in the sample pit, site 1, Trinchera Peak.

site 1 displays more distinct and better-defined polygonal structure than does site 2.

Soil conditions — Results of soil analyses are presented in Table 4. Upon digging the soil pit, numerous large pebbles and cobbles were encountered; these are not included in the size analysis. Root systems extend to approximately 30 cm (one-foot) depth. The soil is generally friable and non-cohesive. Ice or permafrost was not encountered while digging. A schematic section through a polygon boundary is presented, based on surface observations and features encountered in the soil pit (Fig. 19).

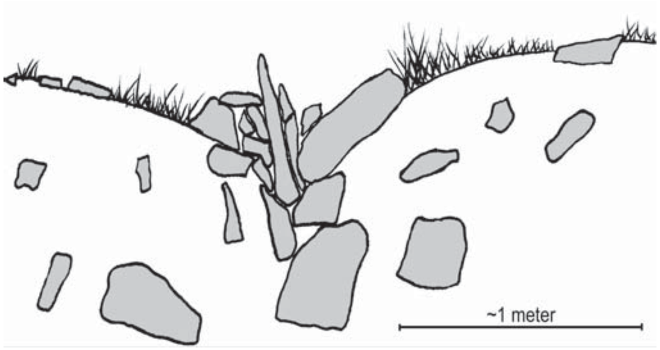


Figure 19. Schematic section across the boundary between two polygons. Larger stones (shaded) are concentrated in the shallow trough between raised turf centers of polygons. Notice how stones in the boundary zone are steeply tilted into near vertical positions.

The A horizon is 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. The Bw horizon is marked by a sharp contrast in soil color; it is dark yellowish brown. Roots continue into this soil horizon but are much less dense. The organic content of this layer is significantly less. The C horizon appears faintly lighter in color than the Bw horizon above it. The C horizon contains no noticeable roots or organic material. Stone sizes increase in this lowermost horizon, which impeded our ability to dig deeper.

Climatic data — Soil temperature in 2003 declined below the freezing point in late October and remained below freezing until the data logger was retrieved in late June 2004 (Fig. 20). Minimum soil temperature reached -10°C in late February. Heavy snowfall in April resulted in stable ground temperature of -5°C until mid-May, after which temperature began to rise gradually. Snow patches were still present at study site 1 when the data logger was recovered (Fig. 21).

The soil temperature record for August 2004 to September 2005 is similar (Fig. 22). Ground temperature dropped below the freezing point at the beginning of October 2004 and reached a minimum of -8°C in early February. Heavy snowfall resulted in stable ground temperature of -6 to -5°C from late

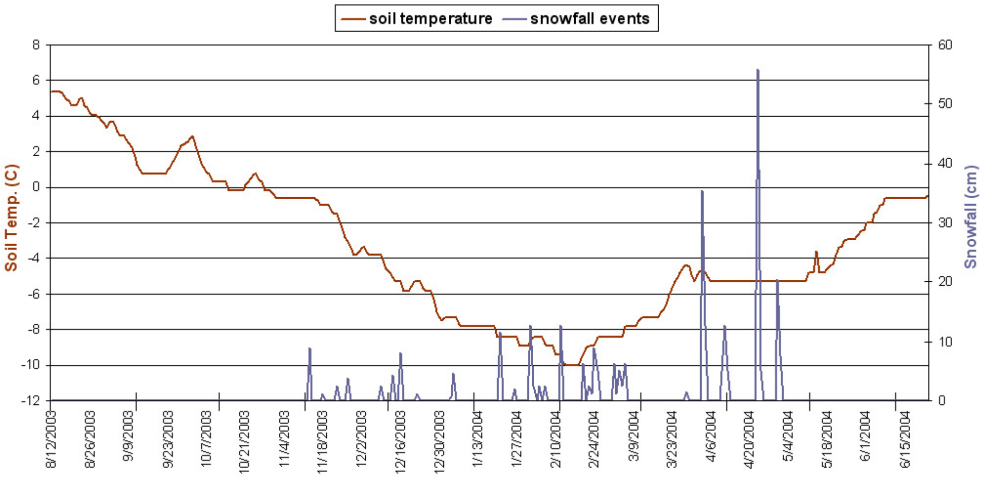


Figure 20. Soil temperature and major snowfall events at Trinchera Peak for the period August 2003 to June 2004. Snowfall data based on Aguilar, Colorado.

Figure 21. Snow patch covering part of study site 1 on Trinchera Peak in late June 2004. View toward southwest.

February until late May 2005; ground temperature remained below freezing until early July. Highest temperature of +4 to 5°C was reached in early August, and then fell to +3 to 4°C by early September. Due to thick snow cover, it was impossible to reach the study site during our initial field visit in late June 2005, and the data logger was not recovered until early September.

On this basis, it seems that soil at 60 cm (two-foot) depth is frozen for roughly nine months, October through June, and thaws only during the summer months of July, August and September. As projected from the temperature record at San Luis, average annual air temperature at Trinchera Peak from 1981 to 1995 was approximately -6°C. More recently, average annual air temperature has warmed to about -4°C. The latter figure approximates average annual soil temperature measured at study site 1 for the period 2003-2005.

DISCUSSION AND INTERPRETATION

Lichenometry — Colonization and growth of lichens on stones of patterned ground presumably represents a period of warm climate, when periglacial processes were reduced and the stones became stable in their present positions. Median lichen diameters give minimum ages for patterned ground about AD 1370 for site 1 and around AD 1760 for site 2. These dates are highly suspect as suitable periods when patterned ground became stablized. Beginning in the 1300s, global climatic cooling culminated with the Little Ice Age (LIA), which lasted from the late 1500s to early 1900s (Grove 1988). During this interval, periglacial processes and activity of patterned ground would be expected to increase, not decrease. Another major discrepancy in this method is the nearly four-century difference in dates for sites 1 and 2. Thus, we question the validity of using median lichen diameters as the basis for determining ages of patterned ground at Trinchera Peak.

Using the means of five largest lichens from each study site gives minimum ages of patterned-ground formation for both study sites in the mid-ninth century. The medieval climatic optimum (AD 850-1200) was underway during this time period (Reyes et al. 2006). The ninth and tenth centuries were at least as mild, perhaps even slightly warmer, compared with the 20th century (Grove 1988). This warm period probably would not support patterned-ground activity, but would be favorable for stable soil conditions and the initiation of lichen growth.

The variability of median lichen diameters between sites 1 and 2 may be a function of snowkill. Patches of snow persisting throughout the summer inhibit lichen photosynthesis and respiration (Innes 1988). As a result, lichens may die and spall from their substrates. Benedict (1993) noted that lichen diameters of 15-21 mm are credible candidates for Little Ice Age snowkill. Numerous snowkill episodes may have taken place during the Little Ice Age, particularly at site 2, which is located in a topographic saddle where thicker snow tends to accumulate. The reduced percentage of lichen cover at site 2, compared with site 1, supports this interpretation. However, substantial activity of patterned ground during the Little Ice Age likely would have killed all pre-existing lichens, in which case lichen diameters would not exceed 14-15 mm.

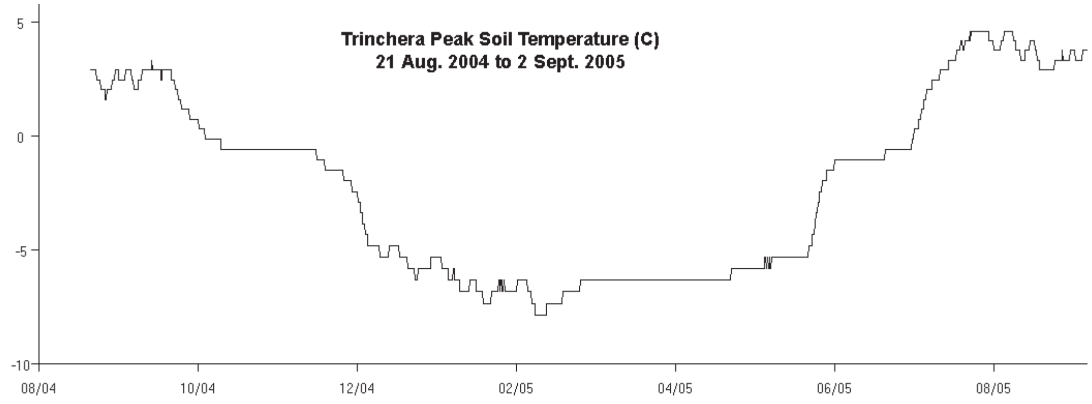


Figure 22. Record of soil temperature at Trinchera Peak for the period August 2004 until September 2005.

The assumed lichen colonization date of ~AD 850 could be attributed to prior extensive snowkill periods which eliminated all previous *Rhizocarpon geographicum*. For example, Benedict (1993) found that snowkill during the Audubon glaciation destroyed all crustose lichens in more than 90% of areas studied in the Colorado Front Range. This was a time of increased periglacial processes, as demonstrated by numerous active rock glaciers during the early Neoglacial period (Table 1). Furthermore, Reyes et al. (2006) recently documented widespread glacier advances in the Pacific coastal regions of Alaska and Canada during the interval AD 200-700. On this basis, we believe snowkill and active periglacial processes prevented lichen survival prior to the ninth century. Patterned ground in vicinity of Trinchera Peak apparently has been stable for at least the past 1100 years, since the medieval climatic optimum when the largest lichens became established.

Origin of patterned ground — Periglacial stone polygons at Trinchera Peak are complex phenomena. The exact mechanisms which initiated patterned-ground development are still unclear. The sorted stone polygons may have resulted from upward mass displacement of plugs of fine sediment in response to density imbalances in the soil caused by deep frost action (Benedict 1992).

Trinchera Peak displays well-developed patterned ground with surprisingly thick soil, which has relatively high organic and clay contents. Morphology resembles classic sorted stone polygons described in high-latitude permafrost environments in Alaska, Canada, Svalbard, and many other localities (Washburn 1956, 1973; Embleton and King 1975; Kessler and Werner 2003). This suggests patterned ground at Trinchera Peak is a mature product representing a long time span of formation. In all likelihood, patterned ground developed during the Pleistocene and was active during the last major cold phase, which ended with the Younger Dryas glaciation about 10,000 years ago (see Table 1). During Pleistocene glaciations, permafrost conditions undoubtedly existed in the Culebra Range.

During the subsequent Altithermal interval, global climate warmed to levels that equalled or surpassed modern climate; certainly the western United States experienced this climatic optimum (Viau et al. 2002). At Trinchera Peak, soil horizons presumably developed and organic matter began to accumulate during this warm phase, although no lichens or other direct evidences survive from this period. Soil stability and lichen growth were interrupted by the Neoglaciation, an interval of globally cooler climate of the past few millennia, which impacted western North America (Polyak et al. 2001; Reyes et al. 2006). Reactivitation of patterned ground and snowkill of lichens may have occurred during this phase lasting until the medieval climatic optimum, when patterned ground stabilized and lichens began to grow again.

Climatic conditions — According to Ritter, Kochel and Miller (2002), mean annual air temperature of -7° to -8°C or lower is necessary for patterned ground to develop under periglacial conditions. Neither air temperature nor ground temperature at Trinchera Peak is cold enough nowadays for active periglacial processes to take place. A decline in mean annual temperature of 3-4°C would be necessary to reach the point at which periglacial processes might become active for stone polygons. During the Little Ice Age, global mean surface temperature was on the order of 1-2°C cooler compared with the 20th century (Grove 1988). LIA climate at Trinchera Peak apparently was cold enough to produce snowkill events, but not so cold as to reactivate patterned-ground processes or to kill all older lichens dating from the medieval climatic optimum. This suggests that LIA temperature at Trinchera Peak remained at or above the mean annual range of -7° to -8°C.

Veatch (2000) examined the dendroclimatic record based on spruce (*Pseudotsuga menziesii*) growing at timberline (~3600 m altitude) nearby on the northeastern flank of Trinchera Peak. These trees are up to four centuries old and are proxies for local temperature conditions. Growth rates were depressed during the Little Ice Age by low summer temperature and short growing season; the transition to modern growing conditions took place in the 1890s. The fact that trees now growing at timberline survived during the Little Ice Age suggests that local impact of cooler climate during the LIA was insufficient to alter vegetation substantially in the vicinity. This dendroclimatic record corroborates our interpretation of LIA climatic impact on lichens growing close by on the mountain top.

CONCLUSIONS

Multiple methods of lichenometry were applied to determine the age of sorted stone polygons at two sites in close proximity to each other at Trinchera Peak in the Culebra Range, south-central Colorado. The approach using means of the five largest lichens from each study site provided internally consistent results dating to the mid-ninth century AD during the medieval climatic optimum. We conclude that patterned ground has been stable for at least the past millennium. Other methods of lichenometry produced more variable and younger results that we interpret as consequences of snowkill events during the Little Ice Age (AD 1500 to 1900).

Late-20th- and early-21st-century mean annual air and ground temperatures at Trinchera Peak are in the -4° to -6°C range. This temperature is not cold enough to support active periglacial processes for stone polygons nowadays. During the Little Ice Age, mean annual temperature declined approximately 1-2°C in the Culebra Range, comparable to global climatic cooling, but this was insufficient to reactivate periglacial processes or to kill all old lichens dating from the medieval climatic optimum. Ancillary evidence from dendroclimatology bolsters this interpretation. As this study demonstrates, a single method or line of evidence may prove misleading; therefore, multiple approaches should be utilized when attempting to decipher paleoclimatic and geomorphic events in the alpine environment of the southern Rocky Mountains.

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