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New Mexico Rock Glacier Inventory: Analysis of Geomorphology and Paleogeography

Bryan Kinworthy

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Bryan Kinworthy
Candidate

Geography and Environmental Studies
Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Chris S. Duvall, Geography and Environmental Studies, Chairperson

Christopher D. Lippitt, Geography and Environmental Studies

Caitlin L. Lippitt, Geography and Environmental Studies

NEW MEXICO ROCK GLACIER INVENTORY: ANALYSIS OF GEOMORPHOLOGY AND PALEOGEOGRAPHY

by

BRYAN KINWORTHY

B.S. GEOGRAPHY
MISSOURI STATE UNIVERSITY
2011

THESIS

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Dedication

To Mom.

Acknowledgements

As a Missourian, I had never heard of a rock glacier nor concerned myself with periglacial geomorphology until reading one sentence with the mysterious phrase, *rock glacier*, in Dr. Chris Duvall's physical geography lab manual. I have an enormous amount of gratitude towards the geographers at UNM for allowing me to ~~annoy~~ instruct students in the important topic of physical geography for two years. Dr. Chris Duvall has helped immensely in developing my ability to transform a passing curiosity into a thesis, and I offer my sincere appreciation. His patience, knowledge, and general appreciation for students is a guideline for my future.

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Obviously I became a geographer.

New Mexico Rock Glacier Inventory: Geomorphology and Paleogeography Analysis

By

Bryan Kinworthy

B.S. Geography, Missouri State University, 2011

M.S. Geography, University of New Mexico, 2015

Abstract

Rock glaciers are large masses of rock debris and interstitial ice that flow or have flowed downhill by permafrost creep. The formation and distribution of rock glaciers is restricted to climates conducive to permafrost development and lithology vulnerable to weathering for source rock. Subsurface ice is insulated from solar radiation, allowing rock glacier formation in lower latitudes and elevations than ice glaciers. Thus rock glaciers provide a useful geomorphic indicator of past and present climate change in regions absent of ice glaciers such as the U.S. Southwest. This study inventories 424 rock glaciers covering 18.36km^2 in the state of New Mexico, identifies environmental parameters that control their formation, and estimates dates for periods of periglacial activity.

New Mexico rock glaciers exist in a broad latitudinal range between 33°N in southern New Mexico to 37°N at the Colorado border. The distribution of rock glaciers is controlled predominantly by elevation, mean annual air temperature (MAAT), slope, and geology; precipitation and solar irradiance are also minor controls. Tertiary intrusive bedrock was found to create extremely dense distributions of rock glaciers. High elevation rock glaciers with extremely cold MAATs are more likely to be located outside areas shaded from solar irradiance, and may require increased ice temperature for internal deformation. A bimodal histogram of minimum elevation and MAAT suggests at least two pulses of periglacial activity. Rock glaciers that likely formed during the late to terminal Wisconsin (35 – 12kya) reach minimum elevations of ~2,400m, whereas those formed during the Neoglacial (4.9kya – 0.12kya) flow to ~3,450m. MAATs suggest some inventoried rock glaciers may still contain subsurface ice or remain active.

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Chapter 1: Introduction and Background

Rock glaciers are alpine landforms composed of rock debris and subsurface ice that flow slowly downslope through the process of permafrost creep. As a periglacial landform, rock glaciers occur in dry to semi-humid climates at elevations and latitudes where temperatures are supportive of permafrost conditions. The rock glacier structure can exist long after the periglacial climate has passed, making rock glaciers especially valuable for understanding regional paleogeography. Key challenges in utilizing rock glaciers as climate proxies exist in establishing environmental controls on their formation and establishing a universal definition that fits all rock glaciers.

Rock glacier studies have been challenged somewhat by the lack of a universal, unchanging definition used between disciplines and regions. Some argue that the term "rock glacier" should be left generic with no indication of genetic process landform (Vitek and Giardino 1987). Berthling (2011) argues that generic, morphology-based landform classifications are only useful for mapping, and not for scientific analysis, though it can be argued generic definitions are detrimental to mapping as well. Therefore, this study uses the Berthling genetic definition of rock glaciers as the "visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions." Only permafrost creep structures that move from the internal deformation of ice are considered rock glaciers in this thesis to eliminate any confusion with permafrost creep of solifluction. Ice glacier contributions to rock glacier formation must be classified as permafrost in accordance with this definition. A list of alpine landforms rock glaciers and their affiliated geomorphic processes are listed in Tables 1.1 and 1.2.

Table 1.1 Rock glaciers and similar landforms

Landforms	Expression	Process
Blockfield (felsenmeer)[*]	Extensive coverage of rocks and boulders, usually on a relatively flat surface	Frost-thaw weathering
Landslide[†]	Mass wasting deposit; divided into earthflow, debris flow, and rock slide by sediment size and moisture content	Mass wasting
Moraine	Lateral, terminal, and basal deposition of heterogeneous sediments from glacial sediment load	Glacial sediment movement
Rock glacier[‡]	Cumulative deformation and flow of rock and interstitial ice	Permafrost creep, glacial flow
Rock stream[§]	Blockfield deposit on a slope or in a valley where stones have collected due to mass movement	Frost wedging, mass wasting
Slump[†]	Rotational earthflow with scarp at the top and often hummocky or lobate deposit at the base	Mass wasting
Solifluction/gelifluction lobe[||]	Lobate structure of heterogeneous materials (soil and rock), often on very shallow slopes	Solifluction (frost creep, gelifluction)
Talus stream[§]	Lobate landslide deposit formed by slow mass wasting	Slow mass wasting, largely unknown

Sources: *French 1996, 41, 207; †Bloom 1998, 172-173; ‡Berthling 2011; §Barsch 1996, 202-207; ||French 1996, 151-155.

Table 1.2 Relevant geomorphic processes

Process	Definition
Frost creep[*]	Cyclical freeze-thaw action in water-saturated material causes slow, downhill movement due to expansion and contraction of water
Freeze-thaw weathering	Cyclical action whereby water within rocks expands and fractures the rock upon freezing.
Gelifluction[*]	Solifluction whereby an active layer of permafrost flows over and is lubricated by perennially frozen material
Glacial flow	Deformation and downhill movement of glacial ice upon reaching critical mass, aided by basal sliding
Permafrost creep[†]	Deformation and downhill movement of ice-saturated permafrost upon reaching critical mass
Solifluction[*]	Slow mass wasting from primarily frost creep with potential gelifluction

Sources: *French 1996, 151-155; †Haeberli et al. 2006

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Rock glaciers are classified using a variety of criteria including material source, activity, and morphology. Activity is classified as active for currently flowing structures, inactive for non-flowing structures that still contain ice, and relict for structures that maintain rock glacier morphology but are no longer flowing or contain ice. The presence of relict rock glaciers in environments presently unfavorable to their formation provides evidence of past climate changes (Barsch 1996, 252).

Material input classifications provide data about a rock glacier's formation. Ice input classifications for rock glaciers are defined as glacigenic and periglacial, though some controversy exists over definitions. Rock glaciers that contain buried glacial ice from a nearby or vanished ice glacier are said to be glacial or glacigenic rock glaciers. Periglacial rock glaciers contain only interstitial ice of permafrost with no glacial ice core. Rock input classifications are defined by the landform from which a rock glacier is generated and not the sediment input such as mass wasting. Talus rock glaciers are formed from talus accumulations that begin flowing due to a large subsurface ice mass. Debris rock glaciers are composed of glacial debris such as moraines and till (Barsch 1996, 11). Rock and ice input classifications are genetically related. A debris rock glacier is more likely than a talus rock glacier to form from glacial ice, and few cases exist in which a talus rock glacier contains non-permafrost ice.

This thesis presents the first complete inventory of rock glaciers throughout the state of New Mexico for utilization in research on periglaciation, periglacial geomorphology, and paleoclimate with potential uses in paleoecology and current climate change. The New Mexico rock glacier inventory was analyzed according to environmental factors such as elevation, climate, geology, and solar irradiance to

elucidate environmental parameters leading to rock glacier formation in the U.S. Southwest. Evidence is presented towards a new hypothesis on solar irradiance-based influence on ice rheology in rock glaciers at cold MAATs. Dates of rock glacier formation in New Mexico are compiled, including the first proposed rock glacier ages in the Sangre de Cristo Mountains, Jemez Mountains, and on South Mountain.

Three prominent methodologies are examined in this research. This thesis appears to be the first in utilizing freely available imagery in Google Earth software to identify and digitize rock glaciers. Solar irradiance modeling was used to explain the presence of rock glaciers on equatorward slopes. The established methodology of estimating paleotemperature from relict rock glacier elevation is evaluated and found lacking.

The primary goal of this research is to inventory all rock glaciers within the state of New Mexico, analyze environmental contributions to their formation, and propose dates of rock glacier formation in the region. The New Mexico rock glacier inventory is available for future research in several disciplines.

Chapter 2: Literature Review

Recognition and study of rock glaciers is younger than most other geomorphological studies, and it is similarly far less complete. Rock glaciers were first described by Stephen Capp's recognition of a "special agent of degradation" within periglacial environments of Alaska he termed "rock glaciers" (Capps, S 1910 pg 1-2). The majority of rock glacier studies stem from Wahrhaftig and Cox's 1959 publication also regarding Alaskan rock glaciers. While important research continues in Europe, very little recent progress has been made in understanding the rock glaciers of North America. This study fills a gap in understanding rock glacier formation and environmental forcing in the southwestern United States.

Four subjects of rock glacier literature have been reviewed to better shape the methodology used in this thesis. The first literature is a summary of rock glacier morphology, including internal structure and past debate, followed by rock glacier usage as an indicator of paleoclimate, as most rock glaciers in New Mexico formed during past climates. A review of environmental factors shaping rock glacier distribution is presented to identify expected patterns of distribution within the New Mexico rock glacier inventory. Finally, rock glacier research in the U.S. Southwest is reviewed in order to position this thesis within existing literature.

Rock Glacier Geomorphology

Rock glaciers are unique landforms with a distinctive combination of morphological characteristics. The most common visible expression of a rock glacier is an extremely large mass of very coarse rock debris with a wrinkled appearance of ridges and furrows spread over a sloped surface. The rock glacier “head” is its highest elevation where rock is input into the system from rock fall and mass wasting. A rock glacier head is often indistinguishable from surrounding rock debris. The lowest elevation of a rock glacier is the “toe.” A rock glacier toe consists of one to many large lobe-shaped structures, each with a steep slope greater than the angle of repose for the rock glacier material. The rock glacier toe is the current maximum extent to which the entire landform has flowed. Polymorphic rock glaciers contain two or more lobate structures due to changes in climate as well as ice and rock input throughout the life of the rock glacier (Frauenfelder and Kääb 2000). Each lobe within a polymorphic rock glacier represents a distinct flow regime with unique flow velocity, period of flow, and potentially different material input (Blagbrough 1999).

Numerous ridges usually form between the head and toe of a rock glacier. Transverse (latitudinal) ridges and furrows run perpendicular to the direction of rock glacier movement and appear to bend downslope towards the frontal lobe. Transverse ridges are produced from compression and tension within the rock glacier flow, and as such, they are usually parallel to the frontal lobe at the toe. Longitudinal ridges and furrows form down the length of a rock glacier, parallel to the direction of flow. The formation of longitudinal ridges and furrows usually occurs at the sides of a rock glacier due to flow velocity differences within the structure; flow velocity is greatest at the rock glacier center and lesser at the sides. The large transverse ridge that forms the toe lobe often curves around the toe to form longitudinal ridges on the rock glacier side (Barsch 1996, 18). An apparent distribution of depressions on the surface of a rock glacier such as furrows and isolated pits or craters can form as a result of subsurface ice melt. Subsurface ice supports rock debris on the rock glacier surface and, upon melting, leaves a depression where surficial material fills the void left by ice (Barsch 1996, 194).

Young rock glaciers that have not yet flowed far from a rock source are often termed “protalus lobes,” or “talus-foot rock glaciers.” These young rock glaciers are genetically identical to larger rock glaciers, but they are visibly distinct. A protalus lobe rock glacier appears as a lobe-shaped form, identical to the toe of larger rock glaciers, protruding from a talus accumulation. Ridges and furrows are often not yet developed in a protalus lobe rock glacier’s small size and young age (Barsch 1996, 223).

Protalus lobes are visibly nearly identical to a genetically different landform, the “protalus rampart.” Protalus ramparts are important because they are commonly confused with protalus lobes. A protalus rampart is a small ridge that forms a small distance from a talus source. The most common argument is that rock fall from a nearby slope travels over a perennial snowfield at the base of the slope and accumulates at the snowfield’s edge to form the rampart (Ballantyne and Kirkbride 2006). Hedding et al. (2010) recently confirmed that rock fall debris can travel over a snowfield to reach a rampart during field studies in Antarctica. Protalus lobes are rock glaciers formed from permafrost creep of talus deposits whereas protalus ramparts are “pronival,” or formed from and near to a large snowfield (Shakesby 1987, Hedding and Sumner 2013). Whalley and Azizi (2002) have provided detailed photographic evidence that displays the difference between protalus ramparts and lobes from hand-held, aerial, and satellite imagery. The distinction between rock glaciers and pronival rock accumulations such as protalus ramparts is difficult but extremely important, as some researchers have classified the two as the same landform and argued for only one process of formation (Barsch 1996, 224).

The internal structure of rock glaciers is a complex and controversial subject. The outermost portion of a rock glacier contains a layer of extremely coarse rock known as the "mantle." The mantle is thought to be composed of numerous mass wasting deposits from nearby slopes and a type of sediment sorting by rock glacier movement (Barsch 1996, 68-70). Prior debate between two prominent hypotheses concerning rock glacier sub-mantle structure shaped current understanding. Some such as Dietrich Barsch are strong believers in the periglacial hypothesis of rock glacier structure, in which beneath the rock glacier mantle is a chaotic distribution of frozen permafrost sediment highly saturated with interstitial ice in voids (Barsch 1987). The large amount of ice within the permafrost exceeds critical mass and deforms much like glacial ice. The deformation and movement of permafrost within rock glaciers causes their movement (Haeberli 1985).

Opposite the periglacial hypothesis of rock glacier formation is the glacigenic hypothesis. Potter, Jr.(1972) challenged the permafrost origin of rock glaciers when he discovered massive, glacigenic ice under a thin layer of detritus and determined the Galena Creek Rock Glacier to be ice-cored and a unique glacier, not a rock glacier. Barsch (1987) refuted Potter's glacigenic interpretation, arguing that the apparent massive ice was more likely a large sub-mantle ice lens identified in many rock glaciers. Potter, Jr. et al. (1998) returned to the rock glacier with ground penetrating radar and concluded that the Galena Creek Rock Glacier was indeed glacigenic, though the study was unable to determine the thickness of sub-mantle ice.

It is now generally accepted that rock glaciers may be sourced from glacial or periglacial ice. The Galena Creek Rock Glacier in particular is thought to have transitioned between rock glacier and ice glacier with changes in climate (Ackert 1998). A remnant glacial core was confirmed in the Foligno Rock Glacier of the Italian Alps through chemical and crystallographic analysis (Guglielmin et al. 2004), and ground penetrating radar (GPR) surveys identified another large body of ice in the Sachette Rock Glacier of the French Alps (Monnier et al. 2013). Rock glaciers have also been identified in regions with no known history of glaciation, necessitating a purely periglacial formation (Blagbrough 1994, 1999).

The existence of both glacigenic and periglacial rock glaciers are confirmed, and the decades-long debate is dead. Perhaps Haeberli best summarized the debate and its potentially harmful role in the history of rock glacier science.

> "Such semantic dispute about an artificial dichotomy involves believing, rather than knowing and understanding; it never provided any insight which would be considered remarkable or useful by a wider scientific community of permafrost and glacier specialists. Adequate treatment of permafrost and glaciers leads the way out of this scientific dead end and is, indeed, a far more interesting challenge." (Haeberli 2000, 290)

Paleoclimate and Dating Rock Glaciers

Relict rock glaciers offer an important opportunity for paleoclimate, though the research potential is relatively unexplored compared to glacier research. The presence of periglacial landforms such as rock glaciers indicates climate conditions conducive to subsurface ice accumulation, and the overall morphologic structure is preserved as climate conditions warm and ice melts. However, an accurate, repeatable method of utilizing rock glaciers for their paleoclimate potential has yet to be developed. A major challenge to applying rock glaciers to paleoclimate studies is accurately dating their formation and period of last flow.

The elevation of relict rock glaciers is an important indicator of paleoclimate conditions. Presently active rock glaciers usually form in locations with a mean annual air temperature (MAAT) of ≤-2°C (Barsch 1996, 250). The toe of a rock glacier is thought to usually extend to the elevation where MAATs reach ≥-2°C and permafrost creep ceases. Relict rock glaciers that formed during cooler climates have toe elevations lower than the present -2°C MAAT isotherm. The paleo-MAATs during rock glacier formation can be obtained by utilizing the elevation difference between relict rock glacier toe elevation and modern -2°C isotherm elevation multiplied by the normal adiabatic lapse rate. Examples of this type of study include Blagbrough's (1994) study of relict rock glaciers in New Mexico and Millar and Westfall's (2008) examination of rock glacier elevations in the Sierra Nevada Mountains of California. The rock glacier elevation method of determining paleoclimate temperatures does not account for other climate inputs into the rock glacier system such as precipitation (Barsch 1996, 250) and alpine microclimates that may reduce the elevation of the -2°C isotherm (Baroni, Carton, and Seppi 2004). Furthermore, paleotemperatures are of little use without accompanying dates.

Rock glaciers can be dated through several methods; a rock glacier's morphology changes as subsurface ice melts and erosion takes place. All slopes on a relict rock glacier become shallower through erosion, and the oldest rock glaciers express the shallowest slopes. Rocks fallen from the frontal slope create a field of boulders at the base of the rock glacier called a talus apron. The frontal lobe and large longitudinal ridges on the rock glacier's sides are the most prominent surface topography on a relict rock glacier, as ridges and furrows on a rock glacier's middle section become subdued due to subsurface ice melt (Barsch 1996, 194).

Vegetation growth on relict rock glaciers differs from their active or inactive counterparts. Vascular vegetation such as grasses and trees has sparse or no growth on active rock glaciers, as the constant movement offers no structural stability. Any growth of vascular vegetation on an active rock glacier takes place almost exclusively above the frontal slope where the rock glacier mantle is displaced and finer sediments are exposed (Burga et al. 2004). Inactive rock glaciers also host vascular vegetation above the frontal lobe, though the coverage is denser than on active rock glaciers. Decomposition of the rock glacier mantle in relict rock glaciers allows for vegetation growth throughout the structure, though vegetation continues to dominate on the frontal and side slopes (Barsch 1996, 194). Blagbrough (1999) was able to relative date relict rock glaciers in the Capitan Mountains by identifying different coverage densities of vascular plants on proximate rock glacier lobes, as lobes with the densest vegetation coverage are oldest.

Dendrogeomorphologic techniques can be utilized in locations where rock glaciers extend below treeline to impact tree growth. Rock glacier activity was successfully monitored by dating trees that were overcome by the rock glacier toe's advance in the Hilda (Bachrach et al. 2004) and Hilda Creek Rock Glaciers (Carter et al. 1999) of the Canadian Rocky Mountains.

Lichen growth also differs between rock glaciers of different ages. The most active sections of permafrost creep in a rock glacier show almost no lichen growth (Cannon and Gerdol 2003). As flow rates decrease and rocks become stable, lichen are amongst the first colonizers of surfaces exposed to the sun. The slow, consistent growth rates of the *Rhizocarpon* subspecies in particular allows for estimating the period of time the surface was exposed to the sun, or stopped moving in the case of a rock glacier (Refsnider and Brugger 2007). However, McCarthy (1999) argues that lichenometry in its current state is inadequate and not based on accepted biological principles. Most thalli live only 150 – 160 years, and original colonizers often die within decades. Thalli diameters are positively skewed by colonies within the first few generations of colonization (Osborn et al. 2015).

Several other rock glacier dating techniques were developed, though they are of less importance to this research in particular. The thickness of a rock's "weathering rind," or outermost layer that experiences weathering, is a well-known method of relative dating (Nichols and Butler 1996). The Schmidt hammer, originally a construction tool used to test the strength of concrete, measures rock hardness as a proxy estimate for time of exposure (Goudie 2006). Haeberli et al. (2003) successfully utilized radiocarbon dating on a rock glacier, though concede that little organic material is typically present. Optically stimulated luminescence (OSL) is the most recent dating technique used on rock glaciers. The amount of accumulated radiation remaining determines the time since a dosimeter such as quartz or feldspar was last exposed. OSL techniques have so far produced reasonable dates for age-constrained rock glaciers and may become the best dating technique possible for periglacial landforms (Fuchs et al. 2013).

Spatial Distribution of Rock Glaciers

Rock glaciers are now thought to exist in most of the world's major alpine regions. Inventorying rock glaciers is an important step in actualizing their potential usage as modern- and paleo-climate proxies. Rock glacier distribution is related to several environmental parameters, including but not limited to elevation, MAAT, precipitation, geology, and solar irradiance. The amount of control environmental parameters exhibit on rock glacier formation varies regionally, and ongoing research (including this thesis) continues to explore the underlying processes.

The elevation at which rock glaciers are present depends greatly on regional climate. Rock glaciers usually form in the belt of elevations beneath the elevation at which snow is common (snowline) but above the elevation isotherm of -2°C known as the periglacial belt. Rock fracturing is strongest in the periglacial belt due to temperatures conducive to freeze-thaw weathering and little snowfall to insulate bedrock from extreme temperatures. The periglacial belt's elevation is dependent on regional MAATs, but its size fluctuates with precipitation. The periglacial belt is largest in alpine areas with dry climates where the snowline is higher. Rock glaciers are most often located in dry, continental climates where the periglacial belt is largest (Barsch 1996, 36, 232-235).

Local geology is known to act as a control on rock glacier distribution, though the exact lithological contribution to rock glacier formation is not entirely understood. Data compiled from numerous studies in different regions suggests rock glaciers form primarily in igneous bedrock (in 65% of studies). Regions with metamorphic (23%) and sedimentary (13%) bedrock contain far fewer rock glaciers (Burger, Degenhardt Jr., and

Giardino 1999). However, the apparent igneous bias in rock glacier development is not conclusive evidence of geologic control, as a large proportion of mountain ranges globally are formed from igneous bedrock. Rock glacier lithology varies greatly even within regions: in the Italian Alps, 80% of rock glaciers are located in metamorphic bedrock, though several rock glaciers are composed of purely limestone (Guglielmin and Smiraglia 1998).

Geologic contribution to rock glacier formation appears to be a twofold process related to freeze-thaw weathering and bedrock jointing. Evin (1987) found that lithological variation in susceptibility to freeze thaw cycles drives talus production in a periglacial environment, a key contributor to the formation of talus rock glaciers. However, rock glaciers do not always form in geologic coverage most susceptible to freeze-thaw weathering. Rock glaciers are instead most often found in lithologies that weather into large, blocky detritus. Rocks that weather into fine material do not produce rock glaciers. Massive bedrock such as limestone, igneous, and metamorphic rock often develops strong jointing which produces the large, blocky detritus when fractured in freeze-thaw processes (Evin 1987). Morris (1981) was among the first to discover the link between bedrock jointing and rock glaciers in his topoclimatic survey of rock glaciers in the Sangre de Cristo Mountains of Colorado. However, even this theory of geologic control on rock glacier formation breaks down in the Argentinian Andes where rock glaciers are composed of much smaller surface debris than observed in Europe and North America (Barsch 1996, 68).

Slope diretion (aspect) also shows geologic control. Debris rock glaciers in the Italian Alps exist in locations with poleward aspects more often than talus rock glaciers, and protalus lobes had the least association with slope aspect. The authors attribute the difference in slope to topographic controls on talus production (Scotti et al. 2013). Another interpretation is that debris rock glaciers located in areas formerly occupied by ice glaciers inheriting the low solar radiation levels required for the ice glacier's existence.

Rock glaciers often form in locations poleward aspects shaded from shaded from exposure to solar radiation (Barsch 1996, 17). Morris (1981) helped pioneer the use of solar radiation rather than aspect in rock glacier studies. Johnson, Thackray, and Van Kirk (2007) utilized the Solar Analyst tool in ArcGIS software to analyze the effect of solar irradiance on rock glacier locations in Idaho. The Solar Analyst tool was used to convert a digital elevation model (DEM) using latitude and topography into potential direct solar irradiance data. The authors found that *direct* solar radiation is negatively correlated to rock glacier presence. Brenning and Trombotto (2006) used logistic regression on rock glaciers in the Argentinian Andes and discovered that while low elevation rock glaciers are high elevation rock glaciers are rock glaciers receive different levels of solar radiation according to elevation. The logistic regression model found low elevation rock glaciers primarily located in shaded areas, as expected, but high elevation rock glaciers were found to exist in locations exposed to higher solar radiation than the average at their elevation. There is no explanation yet as to why rock glaciers form under higher levels of radiation than average, as oppose to shaded areas, at higher elevation. It is possible that rock glaciers at high elevations do not require less solar radiation to maintain periglacial temperatures, and the excess radiation these rock glaciers receive is only an effect of their location at high elevations with less atmospheric attenuation.

However, this hypothesis does not explain why rock glaciers are located primarily in locations exposed to higher than average solar radiation at the same high elevation.

Rock Glacier Distribution and Dating in the U.S. Southwest

Mountain studies in the Southwestern United States have benefited from plentiful, detailed analyses of rock glaciers throughout the region. The Southwest is defined here as Utah, Arizona, Colorado, and New Mexico, as these states share a similar dry, continental climate well known to the region. Studies of active rock glaciers take place in Colorado where elevations are sufficiently high for extensive alpine permafrost. However, inactive and relict rock glaciers in other states provide an important source of paleoclimate data in the region. Figure 2.1 presents a map of mountain ranges where rock glacier studies have taken place in the region.

Rock Glacier Distribution in the U.S. Southwest

The distribution of rock glaciers throughout the Southwest is the subject of several studies. Rock glaciers in the San Juan Mountains of Colorado were inventoried in the 1970s. The active rock glaciers had an average toe elevation of 3,697m, and inactive rock glaciers were slightly lower at 3,516m. Orientation and shade from sunlight was found to be particularly important, as both active and inactive rock glaciers had an average aspect almost directly north (White 1979). Janke (2005) performed a similar inventory study of the Front Range in Colorado and found similar elevation and orientation results, though he concluded that glacial rock glaciers form at higher elevations than periglacial rock glaciers and are more likely to be shaded from sunlight. In the Mosquito Range of central Colorado rock glaciers have average elevations from 3,300 to 3,900m, though minimum elevations were not published (Vick 1981).

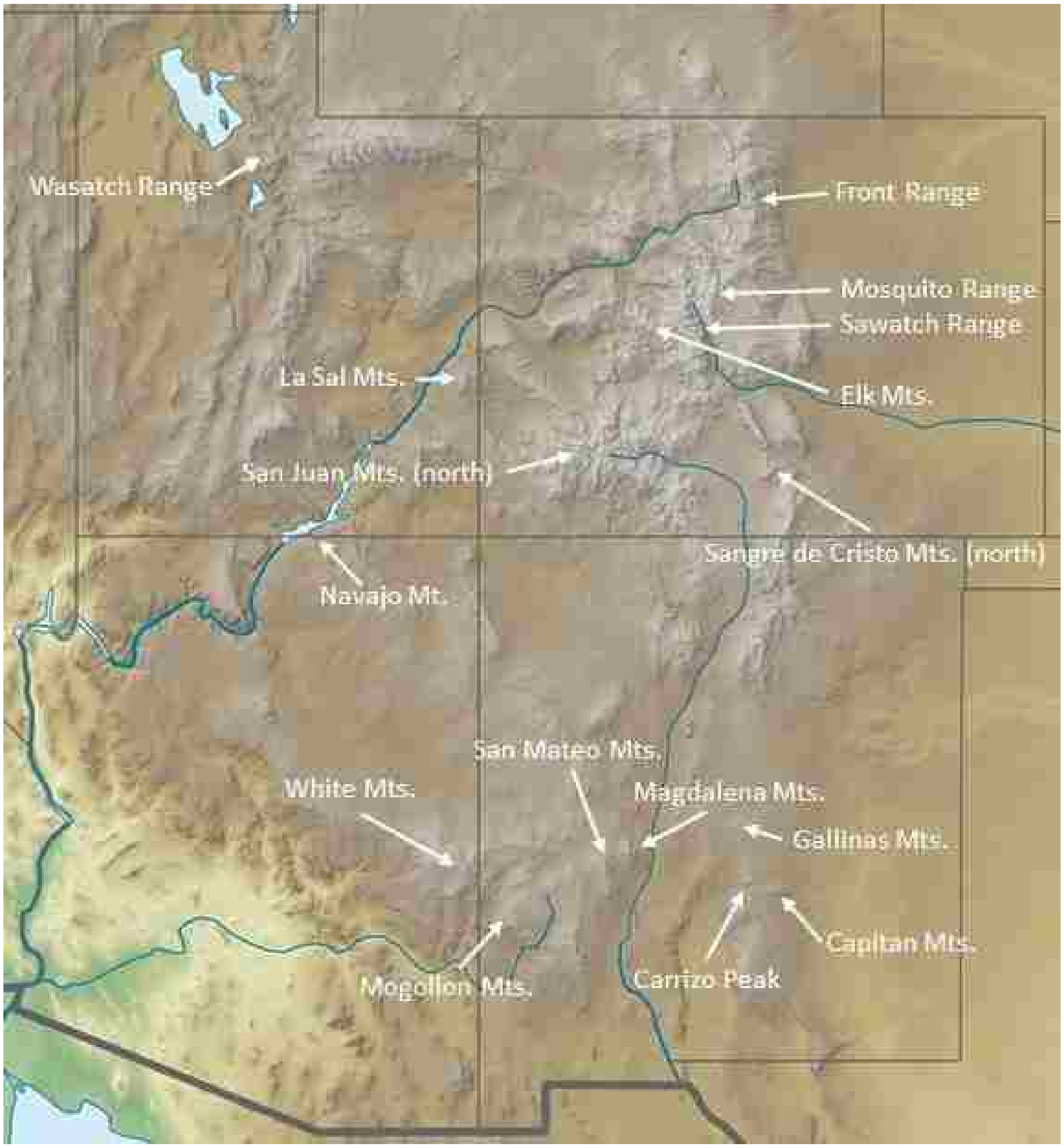


Figure 2.1 Map of previous rock glacier studies in the U. S. Southwest. Mountain ranges displayed are the site of glacier studies mentioned in this literature section. North is towards the top of the map. The Sangre de Cristo Mountains represented is the northern, Colorado segment, and not the southern segment studied in this thesis. *Source*: Adapted with permission from Karnstedt 2010

Colorado is the location of important attempts to statistically model rock glacier distribution using environmental factors. Morris (1981) was able to explain 72% of rock glaciers in the Colorado Sangre de Cristo Mountains using elevation, shading, and jointing in surrounding cirque walls that increase rock input. A more recent modeling effort in the San Juan Mountains of Colorado predicted rock glacier locations with 95% accuracy using elevation, slope, slope curvature, solar radiation, and various attributes from the area inputting rocks into rock glaciers (Brenning, Grasser, and Friend 2007).

Rock glaciers were previously mapped in the southern half of the New Mexico, and only relict rock glaciers have been identified as of yet. Inventories were taken in the Mogollon Mountains (Blagbrough 1994), San Mateo Mountains (Blagbrough and Farkas 1968), Magdalena Mountains (Blagbrough and Brown, III 1983), Gallinas Mountains (Blagbrough 2005), Carrizo Mountain (Blagbrough 1984), and Capitan Mountains (Blagbrough 1991, 1999). The inventoried rock glaciers display an east-west minimum elevation gradient. Rock glacier minimum elevations are lowest in the Capitan Mountains (2,430m) to the east and highest in the Mogollon Mountains (2,891m) to the west (Blagbrough 1994). The rock glacier elevations are far lower than the active and inactive rock glaciers in the nearby San Juan Mountains of Colorado where rock glaciers minimum elevation averages 3,626m (White 1979).

As latitude increases, average elevation of glaciers and rock glaciers is expected to decrease due to colder MAATs at higher latitude; the opposite is true in New Mexico and Colorado. Marker (1990) explained the inverse latitude-elevation relationship through differences in snowfall, whereby increased snowfall in Colorado and northern New Mexico insulates bedrock from strong diurnal temperature changes that induce freeze-thaw weathering. Areas of south-central New Mexico have enhanced freeze-thaw weathering due to less snowfall, as the periglacial belt extends to lower elevations (Marker 1990). Increased talus production from enhanced freeze-thaw weathering leads to stronger rock input into rock glaciers, aiding their formation. Similarly, rock glacier elevations are highest in western New Mexico where an increase in storm systems from the Pacific is thought to have enhanced winter precipitation during the Wisconsin glaciation (Blagbrough 1994). Rock glaciers in northern New Mexico were not considered by Blagbrough or Marker, and it is possible that rock glaciers in northern New Mexico and Colorado exist at high elevations because they formed during a different climate than rock glaciers elsewhere. A statewide rock glacier inventory with associated dates of formation are required to understand the inverse latitude-elevation relationship.

Rock glaciers in Utah were mapped in the Wasatch Range of north-central Utah, La Sal Mountains in the eastern part of the state, and Navajo Mountain to the south. Rock glaciers in the La Sal Mountains are either inactive or relict with minimum elevations from 2,200m (Nicholas and Garcia 1997) to 3,000m (Nicholas and Butler 1996). Rock glaciers in the Wasatch Range are strictly glacigenic, forming from high elevation cirques and extending to a minimum elevation of ~3,000m. Unlike the La Sal Mountains, several rock glaciers in the Wasatch Range around Mt. Timpanogos are considered active (Anderson and Anderson 1981). On Navajo Mountain, Blagbrough and Breed (1967) identified relict periglacial features they interpreted as protalus ramparts, though reinterpretation shows the structures to be rock glaciers extending to 2,600m (Gordon and Ballantyne 2006).

Arizona has the fewest high elevation areas and thus the fewest rock glaciers. Barsch and Updike (1971a, 1971b) identified relict rock glaciers in north-central Arizona on Kendrick Peak at an elevation of 2,385m. Relict rock glaciers are also located on Escudilla Mountain within the White Mountains of east-central Arizona. Rock glaciers on Escudilla Mountain flowed to an elevation of 2,935m, slightly higher than in the nearby Mogollon Mountains of New Mexico (Blagbrough 1994).

Rock Glacier Dating in the U.S. Southwest

Rock glaciers in the Southwest formed during a diversity of time periods in the Holocene and late Pleistocene. Relative dating performed on rock glaciers in the Southwest uses soil formation, weathering, and vegetation growth (Anderson and Anderson 1981, Birkeland 1973, Blagbrough 1994). Exact dates for rock glacier have not yet been established. Rock glacier ages are constrained somewhat by comparison with landforms such as glacial moraines (Blagbrough 1994) and pluvial lakes with well-constrained formation dates (Blagbrough 1999, 2005). Rock glaciers formed during different climate periods depending on regional climate and elevation.

Rock glaciers within Colorado were dated in the San Juan Mountains, Elk Mountains, and Sawatch Range. Birkeland (1973) studied the stratigraphy of rock glacier surface material on the flanks of Mt. Sopris in the Elk Mountains and estimated the rock glaciers of the region had been stable for ~30ky. Refsnider and Brugger (2007) used lichenometry to date rock glaciers in the Elk Mountains and nearby Sawatch Range and found the rock glaciers' surfaces stabilized during three different periods centered at 1,150; 2,070; and 3,080ya. Lichenometric studies of two rock glaciers in the San Juan Mountains produced ages of 850 and 1,150ya, though the authors found lichen not as useful a dating tool on rock glaciers as with other alpine landforms (Carrara and Andrews 1973). The similarity of age dates in studies using lichenometry may be suggestive of a period of increased snowfall that kills of lichen populations (snowkill) rather than rock glacier formation.

New Mexico rock glaciers were interpreted as late Wisconsin in age, though exact dates are still unknown. More precise dates are available for rock glaciers in the Capitan and Gallinas Mountains, as these rock glaciers were compared with established dates in pluvial Lake Estancia. The formation of rock glaciers in New Mexico is unique in that it occurred in at least two distinct periods of periglacial climate. From 15 – 20kya, large rock glaciers formed in the Capitan Mountains while blockfields formed in the Gallinas Mountains. From 12 – 14kya, a second stage of rock glacier formation occurred in the Capitan Mountains, and the first rock glaciers formed in the Gallinas Mountains (Blagbrough 2005). The two pulses of periglacial activity in the Capitan Mountains each drove rock glacier formation in a different bedrock geology type, potentially due to differential rates of soil production in each lithology (Blagbrough 1999).

Rock glaciers of multiple ages exist in Utah. The Timpanogos Rock Glacier in the Wasatch Range is polymorphic; weathering rinds suggest the lower section formed during the early Neoglacial (4 – 5kya) while the upper section appears to still be active, having only formed in the last few hundred years (Anderson and Anderson 1981).

Nicholas and Butler (1996) have tentatively dated rock glaciers in the La Sal Mountains as early Neoglacial from a variety of relative dating techniques, though they have little confidence in the findings and suggest utilizing exact dating in the future.

Within Arizona, tentative dates are available only for rock glaciers on Escudilla Mountain. Blagbrough (1994) estimated that rock glaciers on Escudilla Mountain in Arizona and several ranges in New Mexico were active between 35 – 28.6kya and also potentially from 24 – 21kya. However, these dates were updated substantially for portions of New Mexico and may be inaccurate for Arizona as well (Blagbrough 2005).

Landforms Misidentified as Rock Glaciers

There are two important groups of studies in the Southwest that helped to differentiate rock glaciers from slow mass wasting landforms known as talus streams. Talus streams were misidentified as rock glaciers on Mount Mestas in the Sangre de Cristo Mountains of Colorado (Giardino, Shroder, Jr., and Lawson 1984) and Barney Top on the Table Cliffs of south-central Utah (Shroder, Jr.,1978). Dendrogeomorphological analysis was performed at both sites, and the structures termed "rock glaciers" were found to have been active on multiple occasions over the past millennium. Shroder Jr. and Giardino (1987) summarized both studies and demonstrated, among other aspects of their flow, that they are most active during times of abundant precipitation. Wahrhaftig (1987) added that the supposed active rock glaciers on Mt. Mestas were present at elevations well below the lowest known inactive rock glaciers in Colorado, and their location well below treeline suggests that extensive permafrost is unlikely in the area.

Flow activity during periods of high precipitation is indicative of landslides (Barsch 1996, 206). The two studies identified talus streams rather than rock glaciers, but the detailed descriptions and inventories of the landforms are of great importance for comparison with true rock glaciers.

Research Question and Justification

The study of rock glaciers offers enormous potential for understanding alpine geomorphology along with past and present climate. However, more than a century after the term rock glacier was coined, an abundance of periglacial creep structures in the Rocky Mountains and New Mexico have yet to be mapped or analyzed. New Mexico offers a unique physiography, with great diversity in climate and geology, which provides an opportunity to better understand environmental parameters that drive rock glacier formation. While Blagbrough explored rock glaciers in the southern portions of New Mexico, his work has not been revisited or compared with rock glaciers in other portions of New Mexico or the U.S. Southwest. The data Blagbrough published suggest a large number of rock glaciers in New Mexico in exceedingly warm locations with lower elevations than other rock glaciers in the region. Marker's (1990) snowfall-based explanation of the low elevation rock glaciers did not include variables such as geology, solar irradiance, or date of formation known to influence rock glacier distribution. To date, no research has considered rock glaciers in northern New Mexico. A complete inventory of New Mexico's rock glaciers is required to understand factors influencing their distribution.

This thesis seeks to answer to answer one primary question: “How do environmental factors affect rock glacier distribution and formation in New Mexico?” Answering the primary question requires interpreting the modern MAAT and elevation data of rock glaciers that formed in climates different from the present. A secondary research question is necessary for interpretation: “When did rock glaciers in New Mexico form?” Dating rock glaciers is necessary to understand answer the primary research question.

Chapter Three: Methodology

This study utilizes a two-step methodology in which rock glaciers are inventoried and then analyzed for environmental controls on their formation and clues towards regional paleoclimate. This thesis features two methodological differences from most rock glacier research. First, only free imagery in the publicly-available Google Earth software was used for rock glacier identification. Second, rock glacier identification techniques were developed and tested by viewing rock glaciers identified in existing literature. This study also avoids analyzing slope aspect as a proxy variable for solar irradiance and instead measures solar irradiance directly.

Study Sites

This thesis studies all rock glaciers within the state of New Mexico, though the presence of rock glaciers only in alpine regions necessitates splitting the region into numerous study sites best divided by mountain range. Rock glaciers were classified according to the mountain range in which they were located. Study sites comprise the full extent of United States Geological Survey (USGS) 7.5' quadrangles required to include all rock glaciers in the particular mountain range. To capture the full range of environmental conditions within each study site (alpine region), extra quadrangles were added to create a rectangle (Figure 3.1).

Rock glaciers were identified in the Animas, Capitan, Gallinas, Jemez, Magdalena, Manzano, Mogollon, Sacramento, San Mateo, and Sangre de Cristo Mountains along with Sierra Blanca and South Mountain. Rock glaciers on Carrizo Peak of the Sacramento Mountains were combined with rock glaciers in the Capitan Mountains as part of the same study site due to the similar climate, geology, and location of the two ranges (see Figure 3.2). The Sangre de Cristo Mountains were split into two study sites (north and south) due to the exceptional size and length of the range. The Animas Mountains, Manzano Mountains, and Sierra Blanca were found to contain one rock glacier each, and thus were removed from the larger sample due to insufficient numbers for analysis. A total of 424 of 427 identified rock glaciers in the 9 study sites presented in Table 3.1 and Figure 3.2.

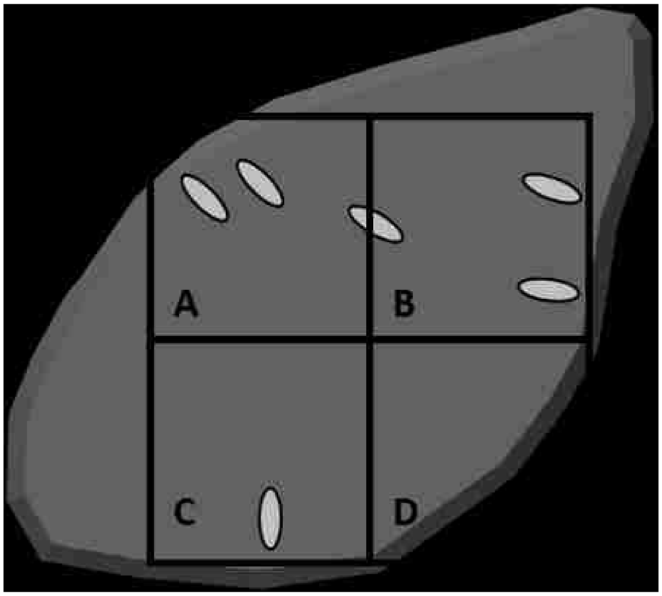


Figure 3.1 Defining study sites. Rock glaciers (light gray ovals) are present in an alpine area (dark gray oval) that covers multiple quadrangles (black squares). Rock glaciers are within quadrangle A, B, and C. The study site for the alpine region also includes quadrangle D to create a rectangle and capture a broader array of environmental conditions within the mountain range.

Table 3.1 Study site information.

Mountain Range	Lat (°N)	Long (°W)	Highest Peak	Highest Elevation (m)
Capitan Mts. (incl. Carrizo Peak)	33.6°	105.35°	Unnamed	3109m
Gallinas Mts.	33.24°	105.79°	Gallinas Peak	2632m
Jemez Mts.	35.9°	106.5°	Chicoma Mountain	3523m
Magdalena Mts.	34.99°	107.19°	South Baldy	3286m
Mogollon Mts.	33.37°	108.68°	Whitewater Baldy	3320m
San Mateo Mts.	33.75°	107.45°	West Blue Mountain	3150m
Sangre de Cristo Mts. (north)	36.7°	105.4°	Wheeler Peak	4013m
Sangre de Cristo Mts. (south)	36.0°	105.6°	Truchas Peak	3995m
South Mt.	35.184°	106.221°	South Mt.	2667m

Different levels of precision in coordinates reflect varying mountain range sizes.

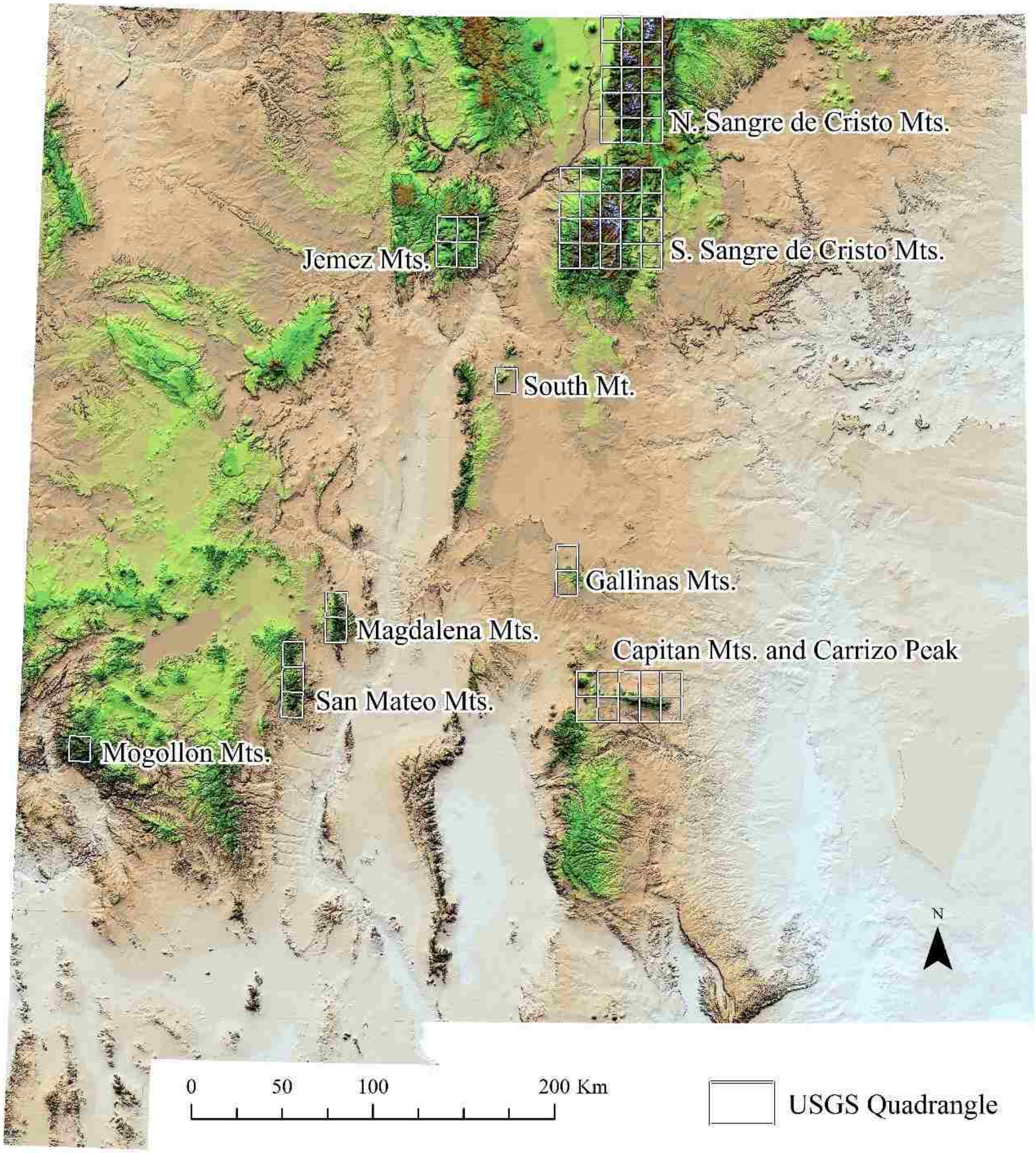


Figure 3.2 Map of study site locations. *Sources*: Earth Data Analysis Center shaded relief data 2007; United States Geological Survey (USGS) quadrangle grid 2013

Identifying Potential Rock Glaciers

Landforms were identified according to an adapted version of the Berthling (2011) genetic definition of rock glaciers as the geomorphic expression of permafrost creep. The definition was adapted in this study so that solifluction is not included; only permafrost creep structures developed from the internal deformation of ice are included in the New Mexico rock glacier inventory. Protalus lobes, formed by the internal deformation of ice, are included in this study. Protalus ramparts are considered pronival landforms and are not included. Block streams and talus streams are also not included, as no compelling evidence suggests these features are formed from permafrost creep (Barsch 1996, 202-207, 219). Landforms identified as potential rock glaciers in this thesis are henceforth termed rock glaciers.

An inventory of rock glaciers was collected through manual interpretation of aerial and satellite imagery. The Google Earth digital globe was chosen due to its rapid access to multiple images of the same site from different sensors, sensor angles, sun angle (time of day), and variation in groundcover such as snow. Google Earth imagery used in identification is sourced from a variety of providers, some of which are not listed in the software. Imagery utilized was available in Google Earth between July 2014 and March 2015. All alpine ridges and valleys within the state of New Mexico were examined for topographic indicators of rock glaciers. Topographic indicators were created from existing literature and by viewing rock glaciers studied in previous literature in Google Earth imagery. Structures identified as rock glaciers displayed a combination of the indicators listed below (in order of importance):

I. *Lobate structures.* Lobate structures are present at the base of a rock glacier and represent the furthest extent to which sediment has moved. Common names for lobate structures include nose, toe, and lobe. Rock glacier lobes were used to identify rock glaciers and differentiate them from solifluction, rock stream, and talus streams. Large lobate structures extending from talus deposits without longitudinal or transverse ridges were interpreted as protalus lobes.

II. *Steep frontal slope at lowest point of talus accumulation.* The frontal slope of the lobe at the lowest extent of a rock glacier is very steep, often beyond the angle of repose. An over-steepened frontal slope in a talus structure is indicative of permafrost creep. Side slopes may also exist with a similar form to the frontal slope, though their presence is not universal (Barsch 1996, 22).

III. *Longitudinal and transverse ridges and furrows*. Ridges and furrows were interpreted as evidence of rock glacier’s compression and extension stresses, variation in creep velocity, and variation in ice content.

IV. *Positive relief*. Rock glaciers display positive relief in that they “bulge” several meters from the surrounding terrain. Positive relief in rock glaciers differentiates them from rocky ground covers like blockfields. The front slope alone is often 5 to 10m above surrounding topography (Barsch 1996, 194).

V. *Vegetation located primarily on above the frontal lobe.* Rock glaciers often contain fine sediments conducive to vegetation growth only in areas where the mantle is exposed, usually above the frontal slope.

VI. *Subsidence morphology.* Furrows and pits indicate the melting of subsurface ice accumulation, thus differentiating periglacial landforms from rapid mass wasting.

VII. *No landslide or slump scars.* Large mass-wasting events often leave behind scars on the slope from which they originated. The scar is often an area with sparse vegetation, loose sediment, and a lighter tone due to limited exposure to weathering (see Figure 3.7). This particular identifier was carefully used, as rock glaciers often source rock from mass wasting events.

VIII. *Tonal change between frontal and side slopes and the greater body of talus.* Tonal change between the slope and upper surface of a talus accumulation was interpreted as a movement indicator. Rock glacier frontal and side slopes are often lighter in tone, as they have not been exposed and weathered for as long as the mantle structure.

IX. *Proximity to other rock glaciers.* The presence of a rock glacier indicates an environment conducive to its formation; the probability of a landform forming from permafrost creep is increased with proximity to areas where the processes are known to exist (Barsch 1996, 194).

Rock glacier morphological identifiers were created from viewing rock glaciers identified in previous research. An example of morphological indicators utilized in this research is apparent in the previously studied Muragl rock glacier of the Swiss Alps (Musil et al. 2006, Haeberli et al. 2006) and Upper Camp Bird rock glacier of the San Juan Mountains (Brenning and Trombotto 2006) in Figure 3.3, as well as rock glacier Murtèl in Figure 3.5 (Barsch 1977). Frontal lobes and transverse ridges appear in both structures, and the Muragl rock glacier also expresses longitudinal ridges. Both the Muragl and Upper Camp Bird Rock Glacier have positive relief over their surrounding topography. Structures identified as rock glaciers in the Capitan and Sangre de Cristo Mountains of New Mexico (Figure 3.4) present a similar set of frontal lobes, ridges, and furrows as seen in the Muragl and Upper Camp Bird rock glaciers. The Williams Lake Rock Glacier in Figure 3.4 has two directions of flow; the bottom segment encountered a lateral moraine and thus has no defined frontal slope. Vegetation growth is distributed primarily on the frontal slope and side slope of rock glaciers in the Capitan Mountains, where sediment is finest.

Morphological identifiers of protalus lobes are noticeable on a structure in Figure 3.5 previously identified as a protalus rampart by Barsch as a protalus rampart (1996, 221). While nearby rock glacier Murtèl has well-developed transverse and longitudinal ridges, the younger protalus lobe has little surface topography. Both structures display steep frontal slopes with lighter tones on the frontal slope than the greater body of rock. A protalus lobe located near Latir Peak in the Sangre de Cristo Mountains of New Mexico shows similar smooth surface topography and tonal changes between the frontal slope and broader structure.

Relict rock glaciers are in the Gallinas Mountains have greatly subdued surface topography and but display other rock glacier characteristics such as thermokarst pits (Figure 3.6). The potential rock glacier displayed are located near structures more confidently identified as rock glaciers; the depicted structures' location in an area known to have processes conducive to rock glacier formation provides additional evidence that they are indeed rock glaciers.

Landforms such as landslide deposits, moraines, and protalus ramparts are distinguishable from rock glaciers by their lack of transverse and longitudinal ridges, distinct frontal slopes, and continued positive relief throughout the landform. The landslide deposit in Figure 3.7 displays no defined frontal slope or surface topography, and an apparent scar from where material was sourced is located above the deposit. Glacial moraines in Figure 3.8 do not display positive relief throughout the structure's entirety. The top picture in Figure 3.8 depicts a terminal moraine (or potential protalus rampart) as a thin ridge, whereas the ground moraine in the bottom image is spread over a large area with patchy vegetation coverage not concentrated on a frontal lobe. Neither landform displays lobate structures or frontal slope.

Talus streams are landslide-like landforms depicted in Figure 3.9 represent the most significant challenge to rock glacier identification. Talus streams feature longitudinal and transverse ridges, flow downslope, present a rocky surface fabric like rock glaciers, and appear dissimilar to other landslide deposits. The talus streams identified on Barney Top, UT (Shroder, Jr. 1978) and Mount Mestas, CO (Giardino, Shroder, Jr., and Lawson 1984) were viewed in Google Earth imagery. These talus streams were found to lack a defined steep frontal slope, host vegetation distributed throughout the structure rather than on the frontal slope, display scars from apparent regolith detachment, and exist almost exclusively under high elevation ridges. In New Mexico, talus streams were identified near Jicarita Peak and Ash Mountain (north and south) in the Sangre de Cristo Mountains and ~10km west of Chama in the San Juan Mountains. All talus streams identified are located in sedimentary geology.

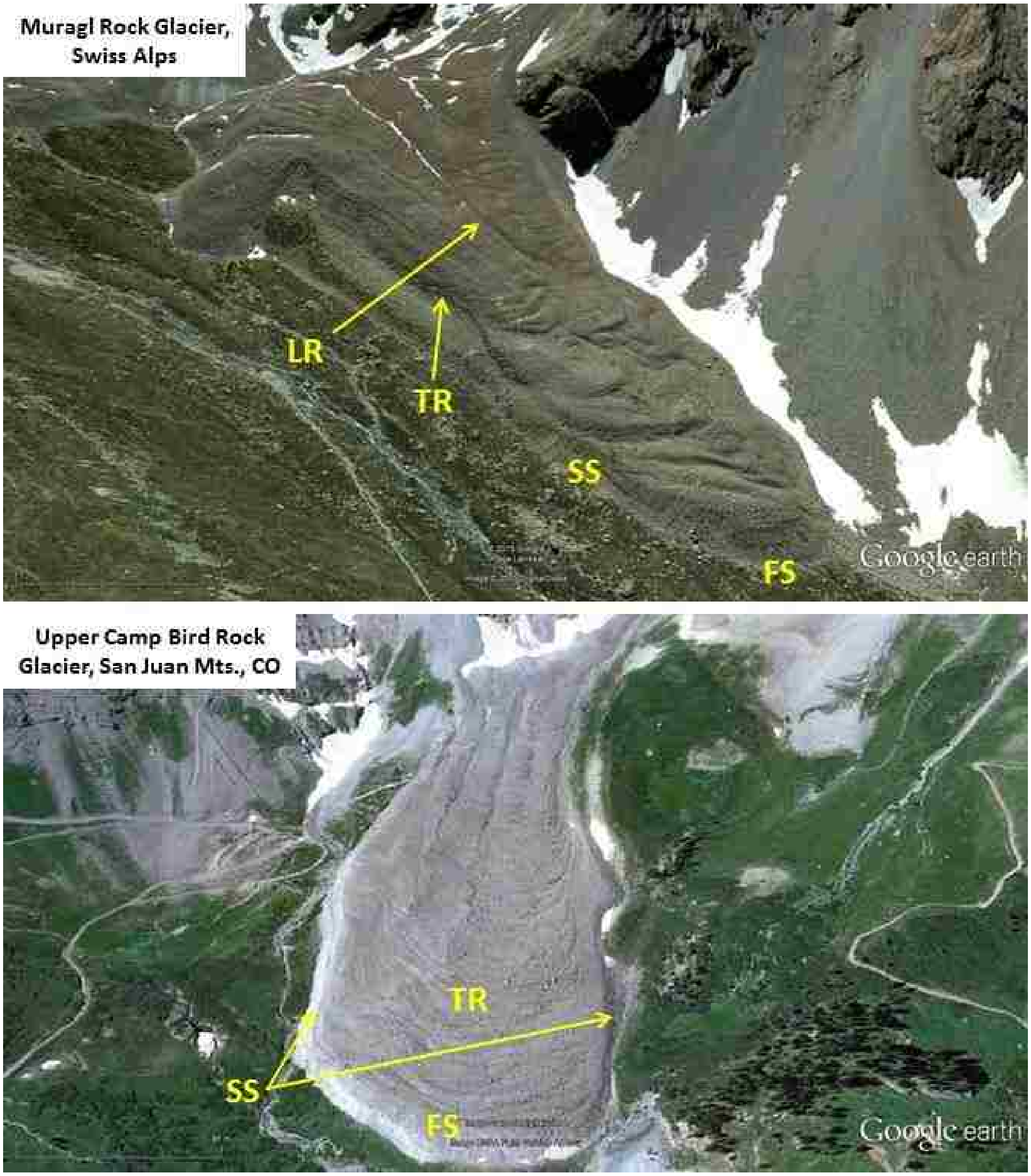


Figure 3.3. Features of the Muragl (top) and Upper Camp Bird (bottom) rock glaciers. LR – latitudinal ridge, TR – transverse ridge, FS – front slope, SS – side slope. *Source*: Google, Flotron/Perrinjaquet 2010 (top); Google, Digital Globe 2011 (bottom)

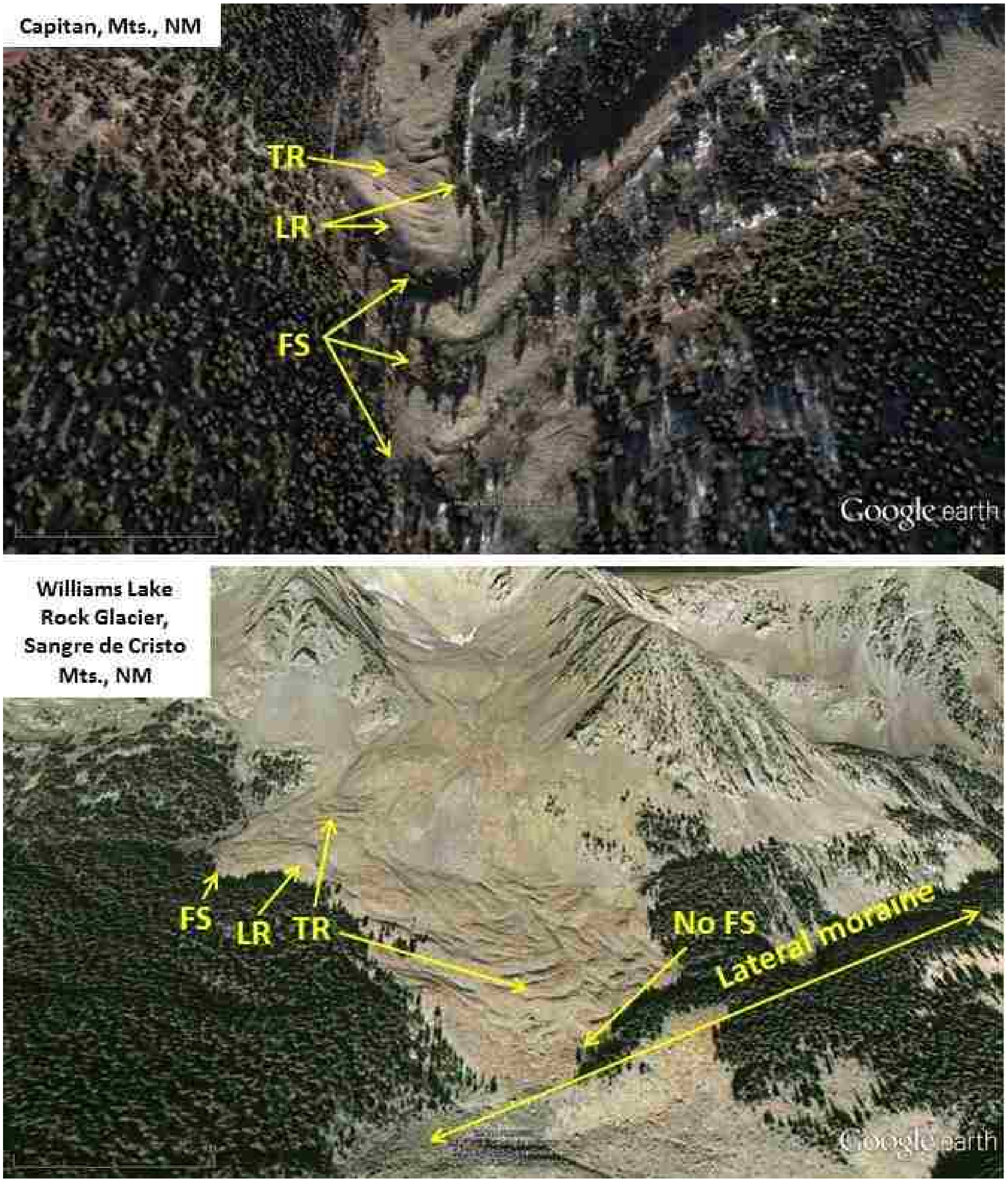


Figure 3.4 Rock glacier identifiers in the Capitan (top) and Sangre de Cristo Mountains (bottom). LR – latitudinal ridge, TR – transverse ridge, FS – front slope. *Source*: Google, Digital Globe 2003 (top); Google, National Agriculture Imagery Program (NAIP) 2005 (bottom)

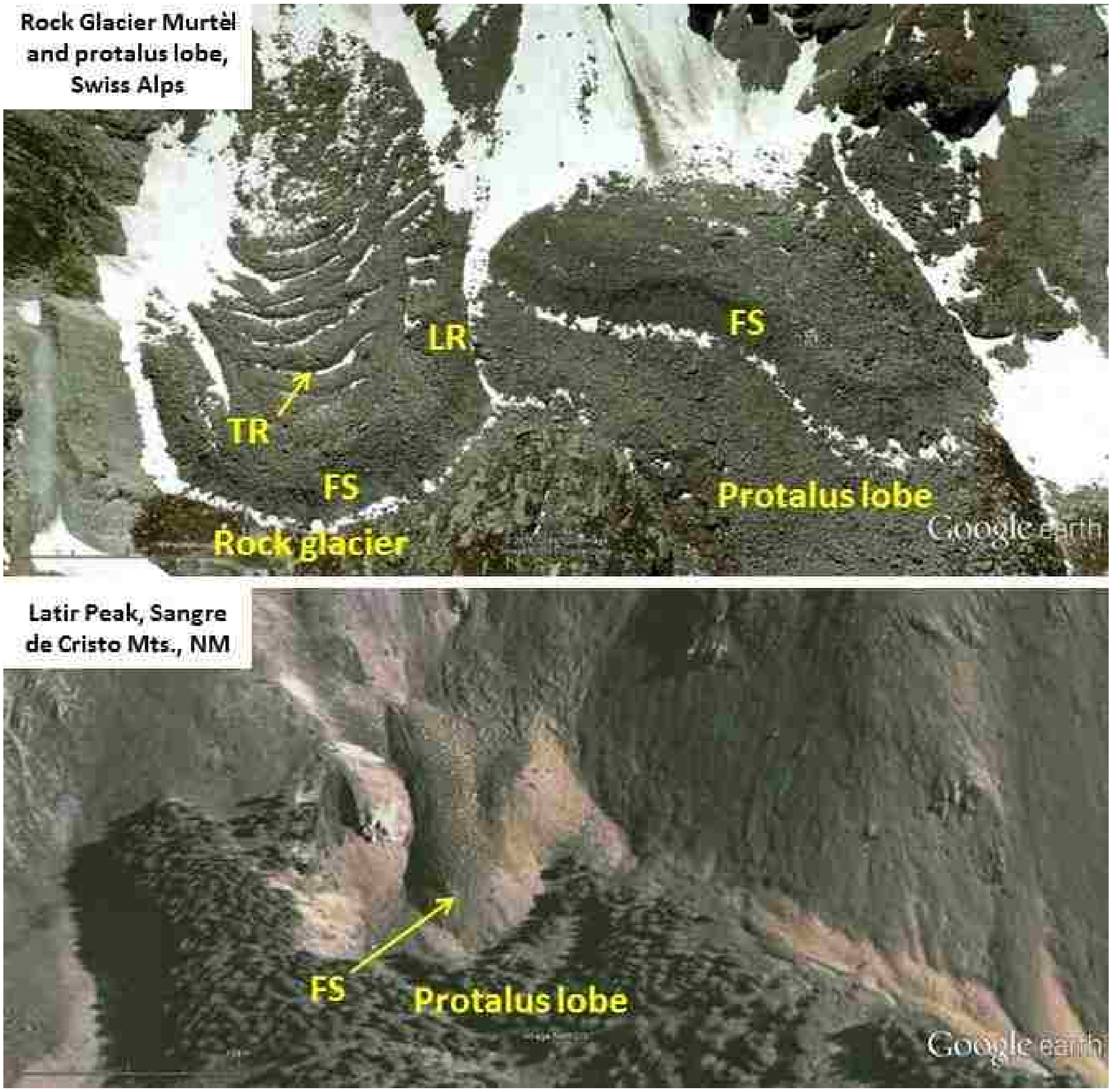


Figure 3.5 Rock Glacier Murtèl (top right) and protalus lobes (top left and bottom) in the Swiss Alps and Sangre de Cristo Mountains. LR – latitudinal ridge, TR – transverse ridge, FS – front slope. *Source*: Google, Flotron/Perrinjacquet 2010 (top). Google, NAIP 2005 (bottom)

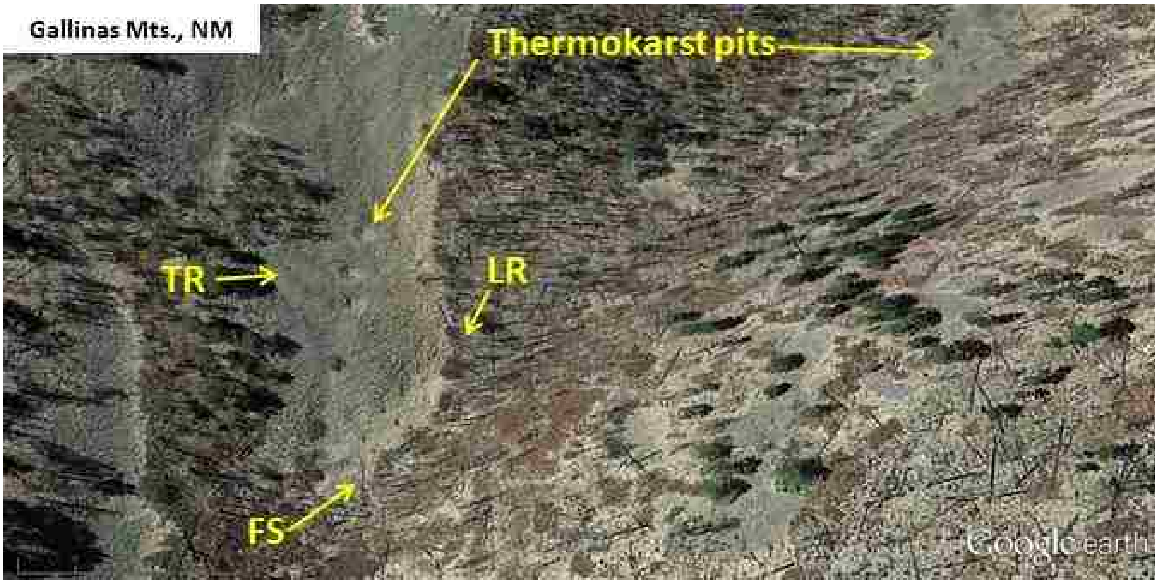


Figure 3.6 Thermokarst pits on rock glaciers in the Gallinas Mountains. LR – latitudinal ridge, TR – transverse ridge, FS – front slope. *Source*: Google, Digital Globe 2013

Figure 3.7 Landslide deposit in the Sangre de Cristo Mountains. *Source*: Google, NAIP 2011

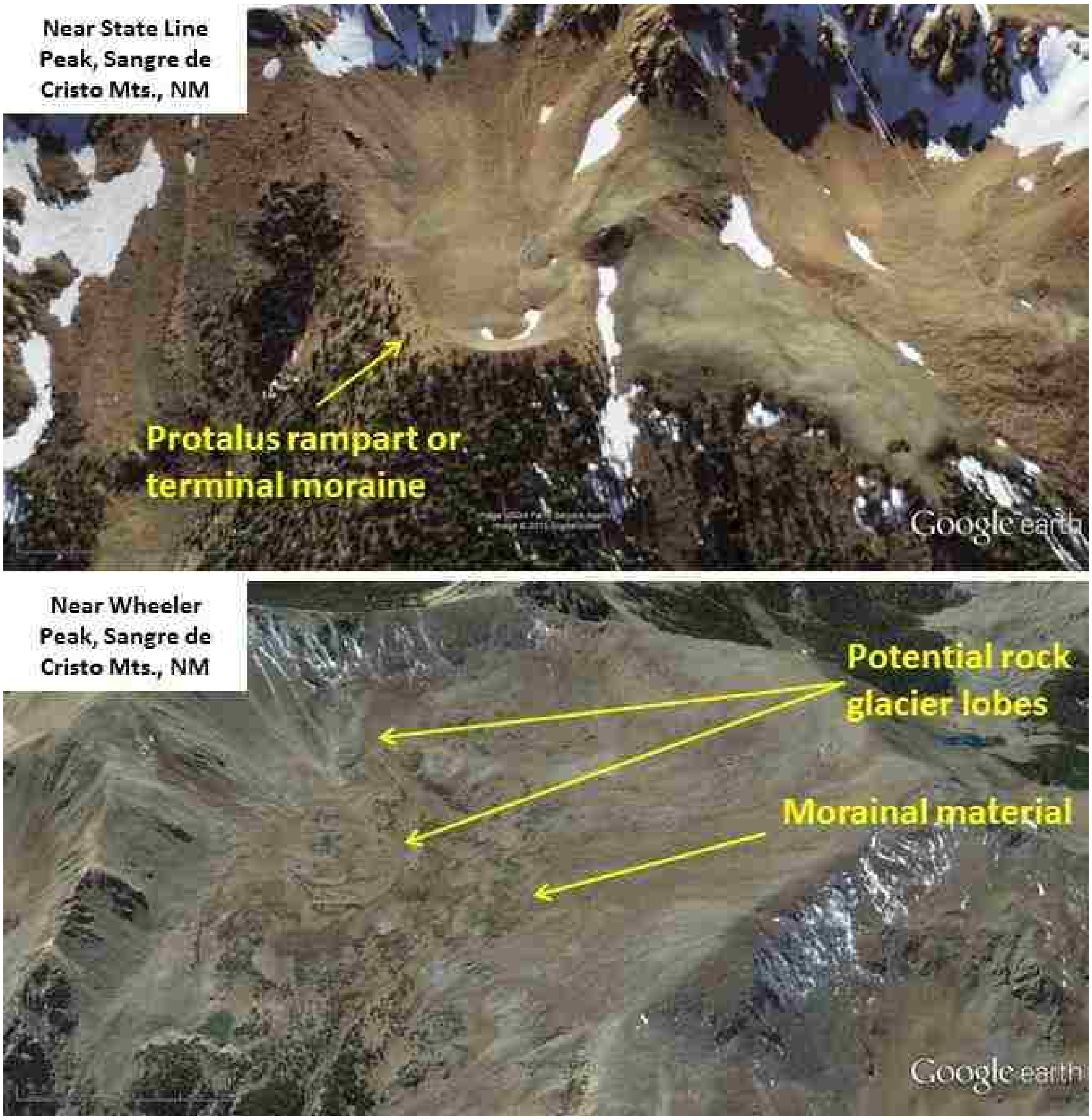


Figure 3.8 Moraines in the Sangre de Cristo Mountains. *Source*: Google, NAIP 2011; Google, Digital Globe 2013

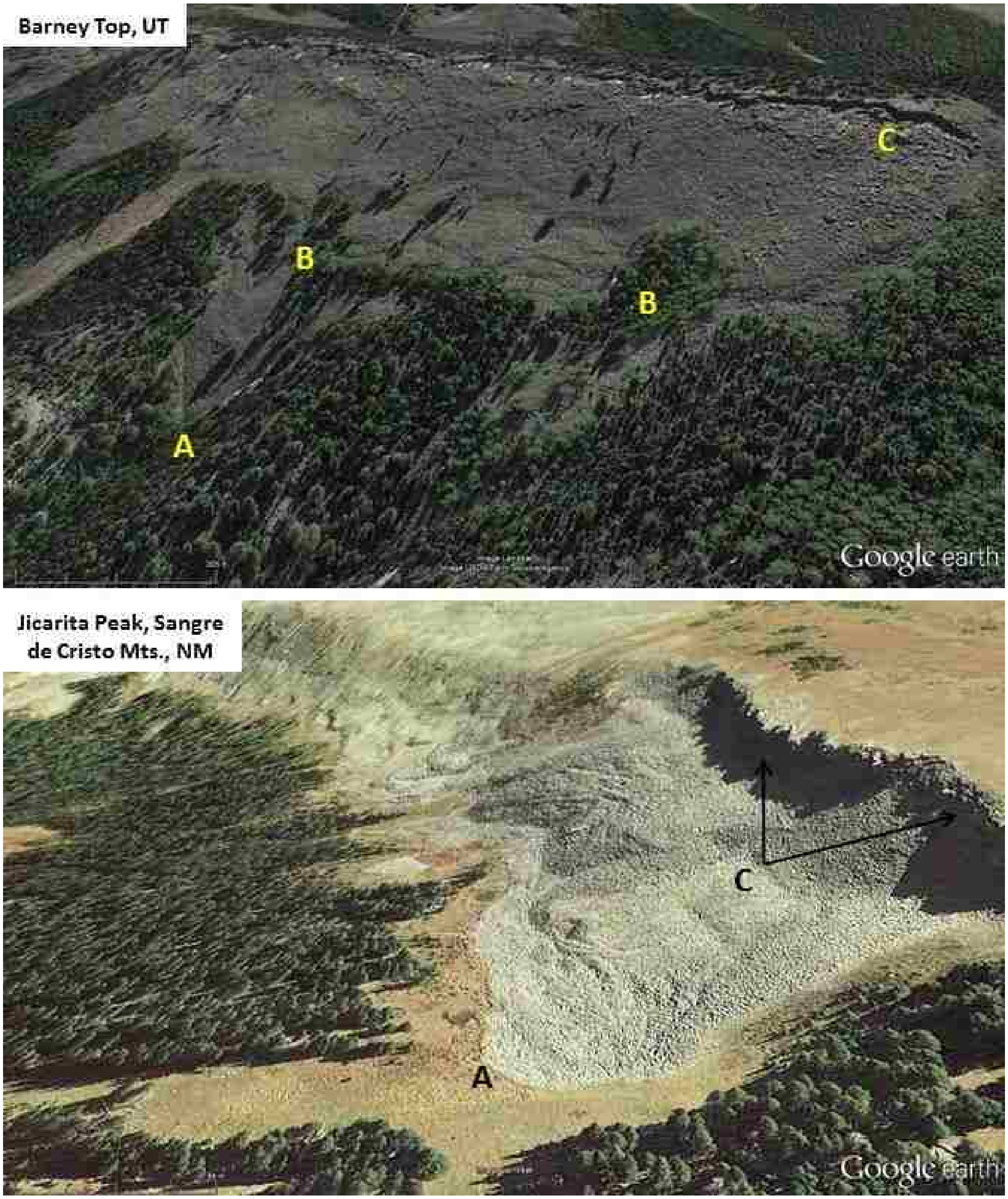


Figure 3.9 Talus streams on Barney Top, UT (top) and Sangre de Cristo Mountains, NM (bottom). A – no frontal slope, B – vegetation coverage dominantly outside a frontal slope structure, C – apparent regolith detachment source of material. *Source*: Google 2014 (top); Google, Digital Globe 2013 (bottom)

This study takes into account the findings of Jarman, Wilson, and Harrison (2013) in which image-based identification of rock glaciers in Britain was found lacking. All 28 landforms analyzed by the authors were analyzed using identification criteria presented in this thesis. Only 1 of 28 landforms was miscategorized, an accuracy rate of 96.4%. The miscategorized landform is located below large, isolated peaks on the Isle of Jura that are not similar to any landscape in New Mexico. The authors suggest protalus lobes are not rock glaciers, an interpretation not followed here. Image-based identification of rock glaciers using adequate imagery such as that often provided in Google Earth is not as error-prone as the dated material reviewed by Jarman, Wilson, and Harrison.

Rock Glacier Digitization

Rock glaciers were digitized through heads-up digitization by manually outlining their identified shape to create polygons in Google Earth. Rock glacier outlines were identifiable as the edge of rock debris and positive relief. The upper edge of the rock glacier head was identified as the location in which positive relief from surrounding talus is first noticeable. Polymorphic rock glaciers with multiple flow directions and lobes were incorporated into a single contiguous polygon. Rock glaciers that flow over, under, or in contact with other rock glaciers were also combined into a single contiguous polygon. An exact count of rock glaciers is not available, as methods for differentiating between polymorphic rock glaciers and several discrete rock glaciers do not yet exist. Examples of the digitization methods are presented in Figures 3.10 and 3.11.

Figure 3.10 Rock glacier digitization in the Sangre de Cristo Mountains. At least five rock glaciers are evident in the image to the left. Three of the five rock glaciers are in contact with each other and combined into one contiguous polygon in the image on the right (left most polygon). Source: Adapted from Google, NAIP 2013

Figure 3.11 Rock glacier digitization in the Capitan Mountains. At least 26 rock glaciers are visible in the top image. Many rock glaciers meet and flow over other rock glacier structures; thus only 21 polygons were created as seen in the bottom image. *Source*: Adapted from Google, NAIP 2012

The spatial accuracy of rock glacier digitization is dependent on the accuracy of Google Earth imagery registration. Rock glaciers were identified using several imagery sources within Google Earth, but digitization was performed using only imagery from the National Agriculture Imagery Program (NAIP). NAIP imagery is spatially accurate within six meters at maximum with a one meter spatial sampling distance (USDA Farm Service Agency 2014). Thus, rock glacier polygons digitized using NAIP imagery have a minimum spatial accuracy of seven meters. The digitized landforms believed to be rock glaciers are henceforth labeled rock glaciers.

Dating Estimation

Dates of rock glacier formation were estimated using a two-step method of relative age dating and comparing relative ages with established regional paleoclimate records. Rock glaciers were relative dated through vegetation and weathering characteristics. The youngest rock glaciers were identified by steep frontal slopes, pronounced surface topography of ridges and furrows, and no vegetation coverage except above the frontal slope. Oldest rock glaciers express shallow frontal slopes, subdued or no surface topography, and often dense, extensive vegetation coverage.

Relative dates of rock glacier formation were compared with established paleoclimate records of the region. The oldest rock glaciers according to relative dating were proposed to have formed in the late to terminal Wisconsin (35 – 12kya) according to Blagbrough (1994, 1999, 2005). Rock glaciers that are relatively younger than those dated by Blagbrough necessarily formed within the past 12kya. Rock glaciers that appear younger than Blagbrough's proposed ages occur exclusively within the Sangre de Cristo (north and south) and Jemez Mountains study sites. Younger rock glaciers were thus compared with a soil core paleoclimate record created by Armour, Fawcett, and Geissman (2002) for the Sangre de Cristo Mountains. Proposed dates of rock glacier formation were assigned to portions of the soil core paleoclimate record interpreted to represent periglacial or glacial conditions within the Sangre de Cristo Mountains.

GIS Data and Analysis

Rock glacier polygons were imported from Google Earth into ESRI ArcGIS software to extract elevation, climate, and geologic conditions at rock glacier locations. Data source and spatial resolution is displayed in Table 3.2. Climate data acquired for this study consists of mean annual air temperature (MAAT), mean annual minimum temperature, mean annual maximum temperature, and mean annual precipitation (MAP). Data acquired presents a 30-year average of annual climate measurements taken at multiple weather stations from 1981 to 2010 processed by the PRISM climate model (Daly et al. 2008) into a raster file with a pixel size of 800m. Data was accessed from the PRISM Climate Group at Oregon State University (PRISM Climate Group 2015).

Elevation data was acquired from the 2013 USGS National Elevation Dataset (NED) digital elevation models (DEMs) with a spatial sampling distance (SSD) of 1/9th arc second (~10m). The 2013 USGS NED 1/9th arc second dataset is built from the 1/3rd arc second dataset which has an average vertical accuracy of .81m, a standard deviation of 1.19m, and a maximum error of 10.71m. Slope calculated from the 1/3rd arc second 2013 USGS NED averages accuracy within .77° (USGS 2014-1008 2014).

Table 3.2 GIS Data Information.

Data	SSD (m)	Source
Elevation	~10	USGS NED
Geologic Coverage	~125*	USGS Geologic Map Data
Mean Annual Air Temperature (MAAT)	800	PRISM Climate Group
Mean Annual Maximum Air Temperature	800	PRISM Climate Group
Mean Annual Minimum Air Temperature	800	PRISM Climate Group
Mean Annual Precipitation (MAP)	800	PRISM Climate Group
Rock Glaciers	~7	Manual Digitization from NAIP
Slope	~10	USGS NED, ArcGIS
Solar Irradiance	~10	USGS NED, ArcGIS
Vegetation	1	FSA NAIP

*estimated SSD from calculation

Topographic slope and solar irradiance were calculated using the NED DEM in ArcGIS Spatial Analyst software and have a SSD of ~10m. Slope (*m*) is calculated in Spatial Analyst according to change in elevation (*z*) units over pixel distance (*x* and *y*) as presented in Equation 3.l. Solar irradiance models were set to calculate total solar irradiance (direct and diffuse insolation) for the summer solstice, equinoxes, and winter solstice using Equation 3.2. Default settings were used in the model for all study sites: day interval was set to 14 days, hour interval to .5 hours, calculation directions to 32 directions, azimuth divisions to eight sky sectors, and output was generated for total radiation. Climate factors such as cloud cover were not included in the model. Solar irradiance calculations are used as an estimate of relative differences between locations and do not attempt calculating exact solar irradiance at each site.

$$m = atan\sqrt{\left[\frac{\Delta y}{\Delta z}\right]^2 + \left[\frac{\Delta y}{\Delta z}\right]^2} * \frac{180}{\pi}$$

Equation 3.1 Formula for calculating slope from a DEM in ArcGIS. *Source*: ArcGIS Resource Center 2011b

$$Global_{tot} = [SolConst * \beta^{m(\theta)} * SunDur_{\theta\alpha} * SunGap_{\theta\alpha} * \cos(AngIn_{\theta\alpha})]$$

$$+[R_{gib} * P_{dif} * Dur * SkyGap_{\theta\alpha} * Weight_{\theta\alpha} * \cos(AngIn_{\theta\alpha})]$$

Equation 3.2 Formula for calculating solar irradiance at the surface in ArcGIS. Direct solar irradiance at a location is calculated using the amount of constant solar radiation at the top of the atmosphere ($SolConst_{\theta,\alpha}$), atmospheric transmissivity ($\beta_{\theta,\alpha}$), duration of sunlight ($SunDur_{\theta,\alpha}$), proportion of sky visible at the surface location ($SkyGap_{\theta,\alpha}$), and angle of incidence ($AngIn_{\theta,\alpha}$). Diffuse solar irradiance calculations also utilize normal global radiation without correction from angle of incidence (R_{gib}), proportion of radiation that is diffused (P_{dif}), time interval for analysis (*Dur*), and the proportion of diffuse radiation in a given section of the sky ($Weight_{\theta\alpha}$). Total solar irradiance ($Global_{tot}$) is the sum of direct and diffuse radiation. *Source*: ArcGIS Resource Center 2011b.

$$SpatialResolution = .5\frac{MapScaleDenominator}{1000}$$

Equation 3.3 Spatial resolution conversion formula. *Source*: adapted from Tobler 1988

Geologic coverage data was accessed from the USGS digital map of New Mexico. The geologic map was created from 1:250,000 scale maps, and it is intended to be displayed at a scale of 1:500,000 (USGS Mineral Resources 2004). According to Tobler (1988), spatial resolution of map scale can be compared with raster spatial resolution through the formula in Equation 3.3. Thus the geologic map data compiled at a scale of 1:250,000 has a spatial accuracy within ~125m.

Climate, geology, elevation, and solar irradiance parameters were extracted for each individual rock glacier. Temperature, precipitation, elevation, and solar irradiance data is in raster format and was processed for each individual study site. Temperature, precipitation, elevation, and solar irradiance values were averaged for each rock glacier. The average rock glacier values were then averaged for each study site to create a set of environmental characteristics at rock glacier locations for each study site. Average values for environmental parameters at rock glacier locations in each study site were then compared with the average conditions in the study site as a whole to determine if the particular environmental variable is different in rock glacier locations and may influence their formation.

Geologic coverage data was analyzed using all New Mexico rock glaciers and geologic coverages (no study sites). A study region of geologic coverages at or above elevations conducive to rock glacier formation was created and used for analysis. Elevations conducive to rock glacier formation is defined as any elevation at or above the lowest elevation at which a rock glacier is located in New Mexico (2,159m, Capitan Mountains). The percentage of rock glacier area contained with a particular geologic coverage was compared with that geologic coverage’s percentage of total ground area in the study region. Geologic coverages that contain a noticeably large amount of rock glacier area or contain a larger percentage of rock glacier coverage than study region coverage were interpreted as important to rock glacier formation.

Material inputs into rock glaciers were interpreted from the geologic coverage layer and rock glacier location. Rock glaciers located in high-elevation cirques of the Sangre de Cristo Mountains where post-Wisconsin glaciation is thought to have occurred (Armour, Fawcett, and Geissman 2002) were listed as having potentially glaciogenic ice input, while all other rock glaciers are listed as periglacial. Rock glaciers located within the glacial debris geologic coverage were interpreted as debris rock glaciers while all other rock glaciers were classified as talus rock glaciers. Proximate landforms were used to ascertain rock input source; rock glaciers extending from glacial moraines were interpreted as confirmation of debris rock glaciers while blockfields and talus accumulations above rock glaciers confirmed a talus input. No method for ascertaining ice input source was available, as ice is thought to have melted long ago in most cases.

Statistical testing was avoided as a dominant methodology due to the extremely large sample size and interrelated variables that corrupt test results. However, a bimodal distribution in MAAT and elevation was further examined using K-means clustering analysis. K-means clustering analysis identifies a preset number of cluster centers that lead to the least sum of squares variation within each of the clusters. Parameters were set to a convergence of .001 with a maximum of 50 iterations to identify cluster centers with maximum precision. Cluster centers were tested for independence with a one-way analysis of variance (ANOVA). A resulting ANOVA *F*-value becomes larger as the likelihood that the clusters are identical decreases. A resulting ANOVA *p*-value represents the probability of obtaining cluster data if the clusters are truly identical.

Chapter Four: Results

A total of 424 rock glaciers covering 18.36km^2 in nine study sites were digitized in this thesis. Rock glacier locations are available in Appendix C. The majority of rock glaciers are located within the Capitan and northern Sangre de Cristo Mountains study sites. Rock glacier elevations and MAATs are similar within study sites but vary greatly between regions. A bimodal frequency distribution is present within both elevation and MAAT. Each cluster within the bimodal frequency represents rock glaciers of a different climate period. Rock glaciers in southern New Mexico study sites are relative dated as younger than rock glaciers in the north. Rock glaciers within southern New Mexico formed during the late to terminal Wisconsin (35 – 12kya) while those in northern New Mexico are likely Neoglacial (4.9kya – 0.3kya) in age. Precipitation varies greatly between study site regions but is does not show a distinct frequency pattern. Geologic coverage is strongly related to rock glacier presence; >60% of rock glaciers are contained within one geologic unit (Tertiary intrusives), and >70% of rock glaciers are located within intrusive igneous geologic units. Abbreviations in Table 4.1 are used in charts and tables throughout the discussion and results section.

Table 4.1 Study site abbreviations.

Abbrev.	Study Site	Abbrev.	Study Site
Cap	Capitan Mountains	NSDC	Northern Sangre de Cristo Mountains
Gal	Gallinas Mountains	SanMat	San Mateo Mountains
Jem	Jemez Mountains	SoMt	South Mountain
Mag	Magdalena Mountains	SSDC	Southern Sangre de Cristo Mountains
Mog	Mogollon Mountains		

General Size and Distribution

The distribution and size of rock glaciers in New Mexico are strongly varied according to study site (Table 4.2). The Capitan and Northern Sangre de Cristo Mountains study sites account for the majority of rock glacier count and total rock glacier coverage (78% of rock glacier count, 88% of total area). Rock glaciers are largest in the Capitan (5.2ha), Magdalena (4.91ha), and northern Sangre de Cristo Mountains (4.66ha). Rock glaciers are largest in study sites with the most rock glaciers with the exception of the Magdalena Mountains study site.

Table 4.2 General rock glacier distribution data

Study Site	Rock Glaciers	Total Area (km^2)	% All RGs count	% Total Area	Avg RG Area (ha)
Cap	206	10.71	49%	58%	5.20
Gal	24	0.43	6%	2%	1.79
Jem	19	0.45	4%	2%	2.37
Mag	11	0.54	3%	3%	4.91
Mog	5	0.12	1%	1%	2.40
NSDC	116	5.40	27%	29%	4.66
SanMat	19	0.37	4%	2%	1.95
SoMt	14	0.16	3%	1%	1.14
SSDC	10	0.18	2%	1%	1.80

See Table 4.1 for study site abbreviations. RG – Rock Glacier.

Slope

All rock glaciers express variation in slope percentage, though average slope is very similar between rock glaciers and study sites (Table 4.3). Most study sites have average rock glacier slopes of ~24 – 27%. The northern and southern Sangre de Cristo Mountains study sites display lower average slope percentages at ~21%.

Table 4.3 Average rock glacier slope.

Study Site	Avg Slope (%)	Study Site	Avg Slope (%)
Cap	25.5±4.0	NSDC	20.5±5.1
Gal	24.4±2.7	SanMat	26.4±5.2
Jem	24.7±4.5	SoMt	27.1±3.6
Mag	24.9±3.8	SSDC	21.0±4.3
Mog	24.2±4.7		

Error percentages represent one standard deviation. See Table 4.1 for study site abbreviations.

Material Inputs

Rock glacier material inputs are divided primarily by study site as presented in Table 4.3. No known glaciation has occurred within the majority of study sites with the exception of the Sangre de Cristo Mountains. An absence of glaciation necessitates that the ice source for rock glaciers in most study sites is permafrost, and rock source must be talus with a lack of glacial debris to draw from. Rock glaciers in all study sites except the Sangre de Cristo Mountains evidently flowed from extensive blockfield deposits at high elevations (Figure 4.4)

Rock glaciers in the Sangre de Cristo Mountains evidently formed from multiple material sources. Several rock glaciers source material from glacial moraines, though other rock glaciers are talus-sourced at the base of talus slopes. Rock glaciers located in glacial cirques likely source glacial ice in combination with permafrost accumulations. However, talus rock glaciers source only permafrost and are strictly periglacial in origin. Examples of rock glaciers formed from each material input are provided in Figures 4.1 and 4.2.

Table 4.4 Rock glacier material inputs.

Ice Input*		Rock Input*	
Periglacial	Glaciogenic	Talus	Debris
Capitan	N. Sangre de Cristo	Capitan	N. Sangre de Cristo
Gallinas	S. Sangre de Cristo	Gallinas	S. Sangre de Cristo
Jemez		Jemez	
Magdalena		Magdalena	
Mogollon		Mogollon	
N. Sangre de Cristo		N. Sangre de Cristo	
San Mateo		San Mateo	
South Mt.		South Mt.	
S. Sangre de Cristo		S. Sangre de Cristo	

*Material input definitions are provided in the introduction section.

Figure 4.1 Glacigenic debris rock glacier in cirque beneath Venado Peak. This rock glacier formed from a glacial moraine in a cirque in the northern Sangre de Cristo Mountains. Its location in a cirque suggests it likely formed from glacial ice. *Source*: Google, NAIP 2011

Figure 4.2 Four blockfield-sourced, rock glaciers (white) in the Gallinas Mountains. The blockfield covers almost the entire image under patchy vegetation coverage. The rock glaciers are necessarily periglacial, as there is no evidence of glaciation in the region. *Source*: Google, [uncited] 2013

Environmental Conditions

Elevation

Rock glacier elevations vary considerably throughout New Mexico, though rock glaciers within individual alpine regions are similar. Throughout the state, minimum rock glacier elevation (glacier toe) is between 2,159 – 3,762m with a range of 1,513m. Maximum elevation (glacier head) is between 2,226 – 3,843m. Figure 4.3 displays rock glacier elevations and variation by study site. Vertical distance between the rock glacier head and toe averages 131m and varies greatly between study sites and individual rock glaciers (Figure 4.4). Figures 4.6 – 4.8 display maps of rock glacier elevations, supplemented by additional maps in Appendix B.

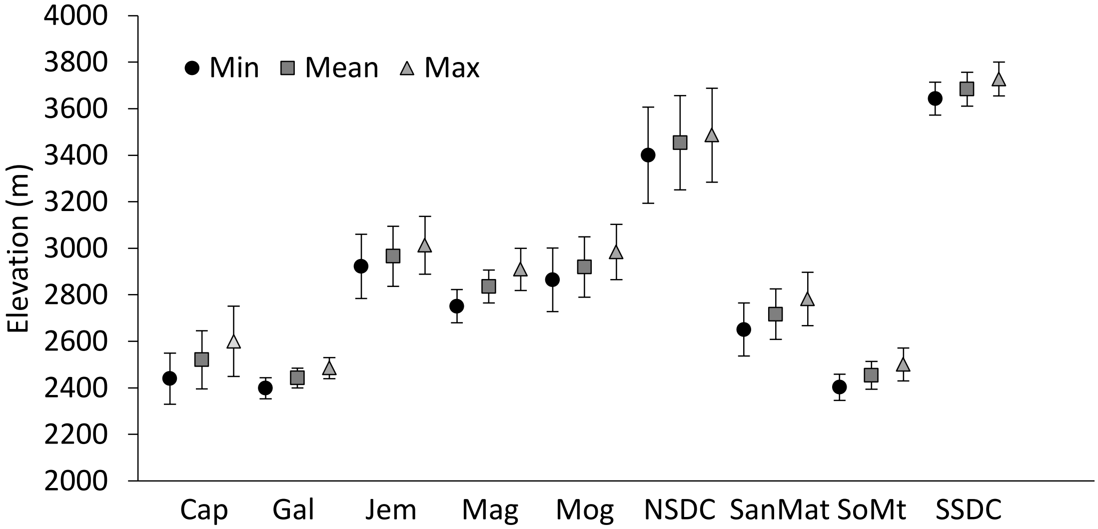


Figure 4.3 Average head, toe, and mean rock glacier elevation by study site. Whiskers represent one standard deviation. See Table 4.1 for study site abbreviations.

A histogram of minimum elevations at all rock glaciers displays a bimodal distribution (Figure 4.5). K-means clustering analysis identified the center of the distribution with lower values at 2,473m and 3,397m. An ANOVA test confirmed that the clusters are significantly different (F=3,885, p=2.88 x 10^{-192}).

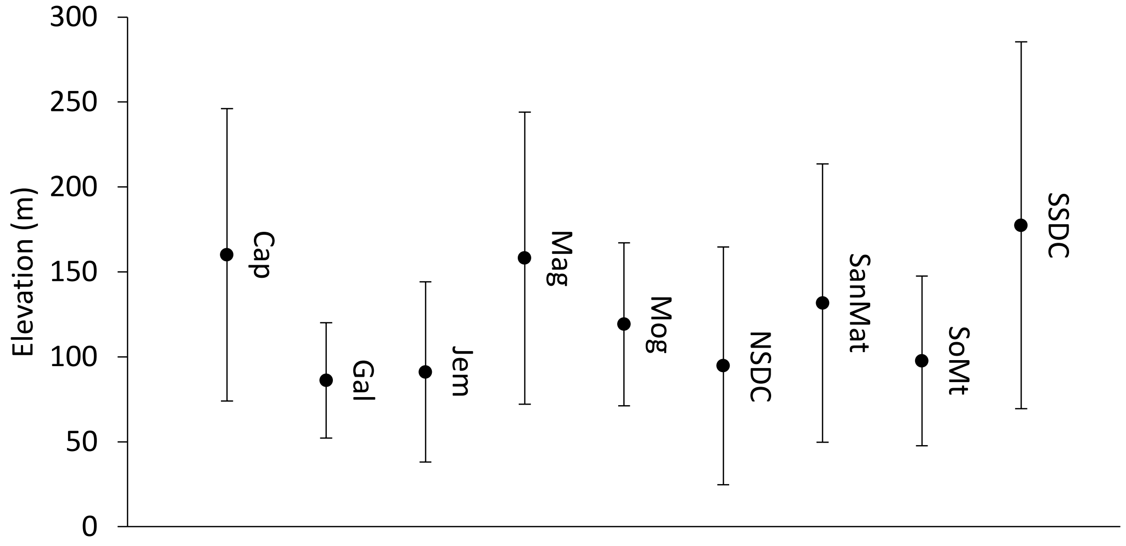


Figure 4.4 Average vertical distance (downslope drop) of rock glaciers by study site. Whiskers represent one standard deviation. See Table 4.1 for study site abbreviations.

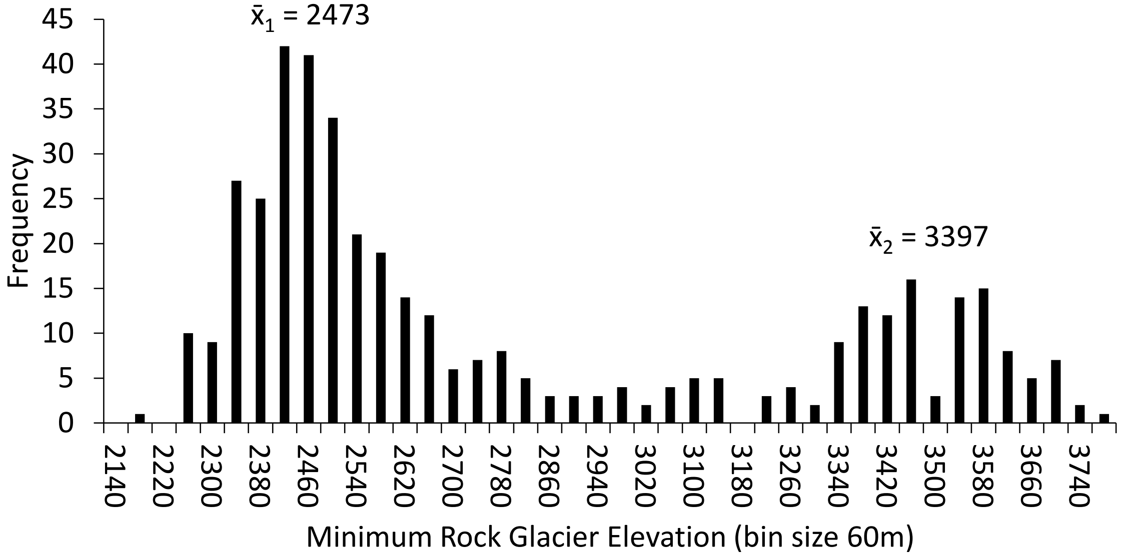
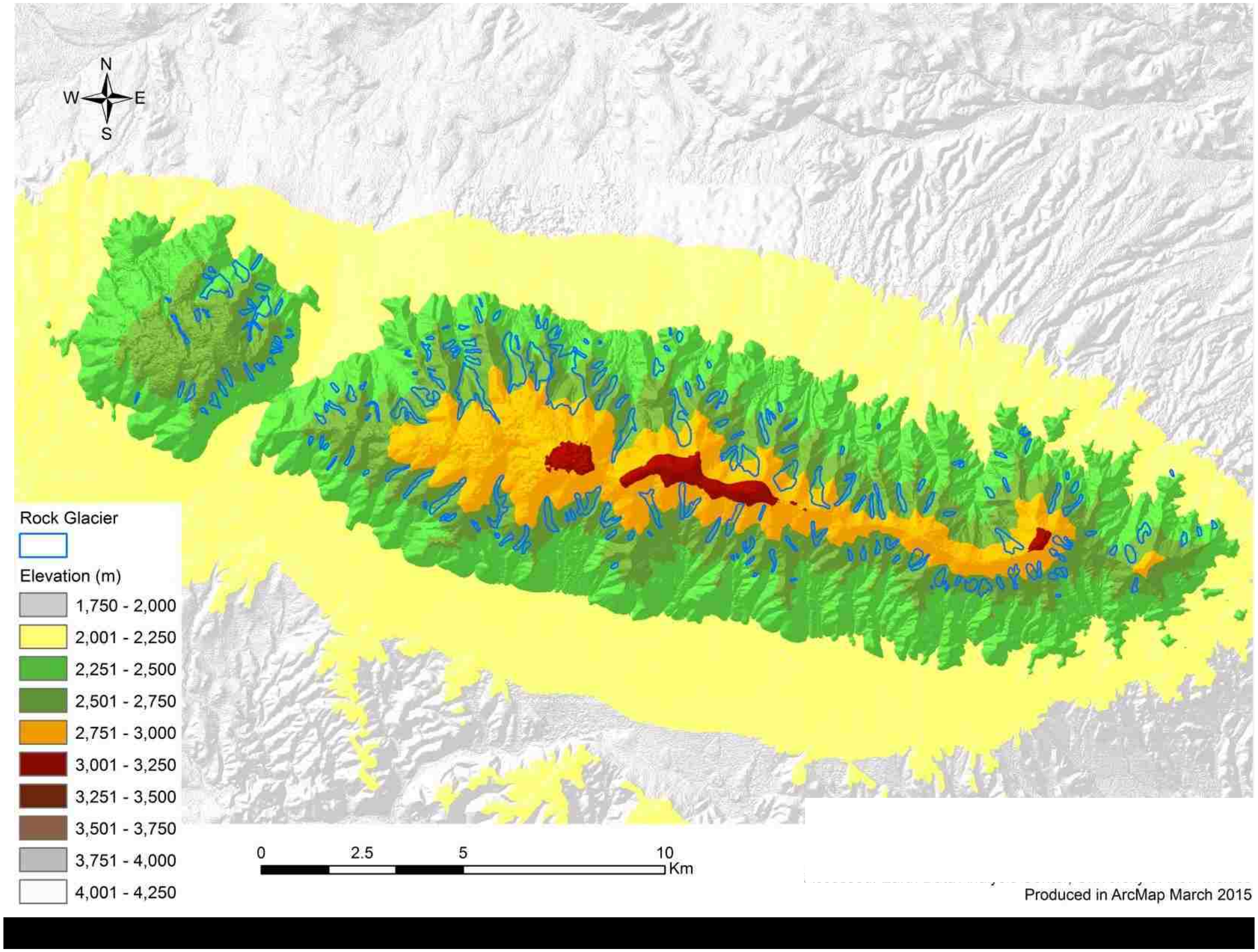
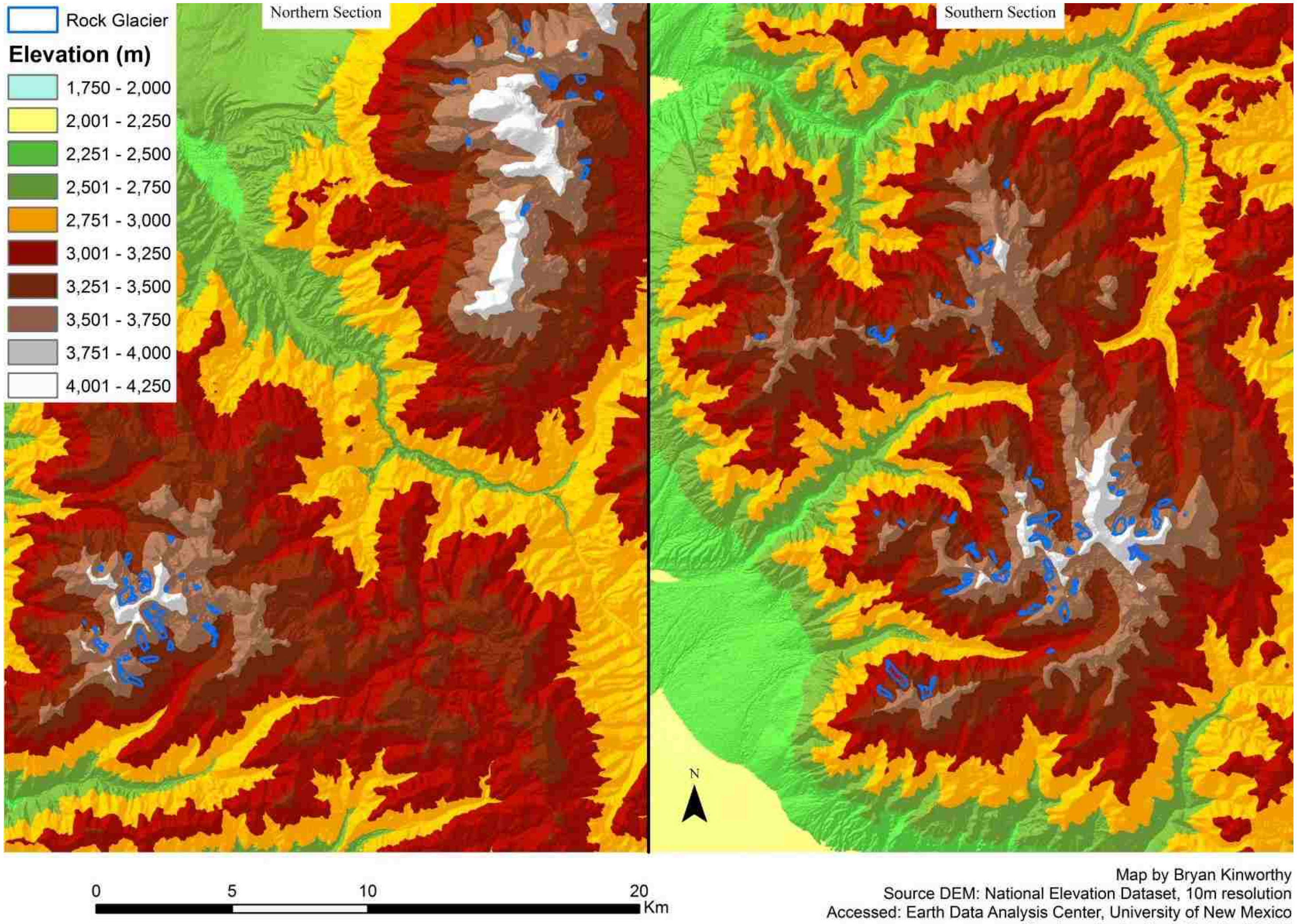


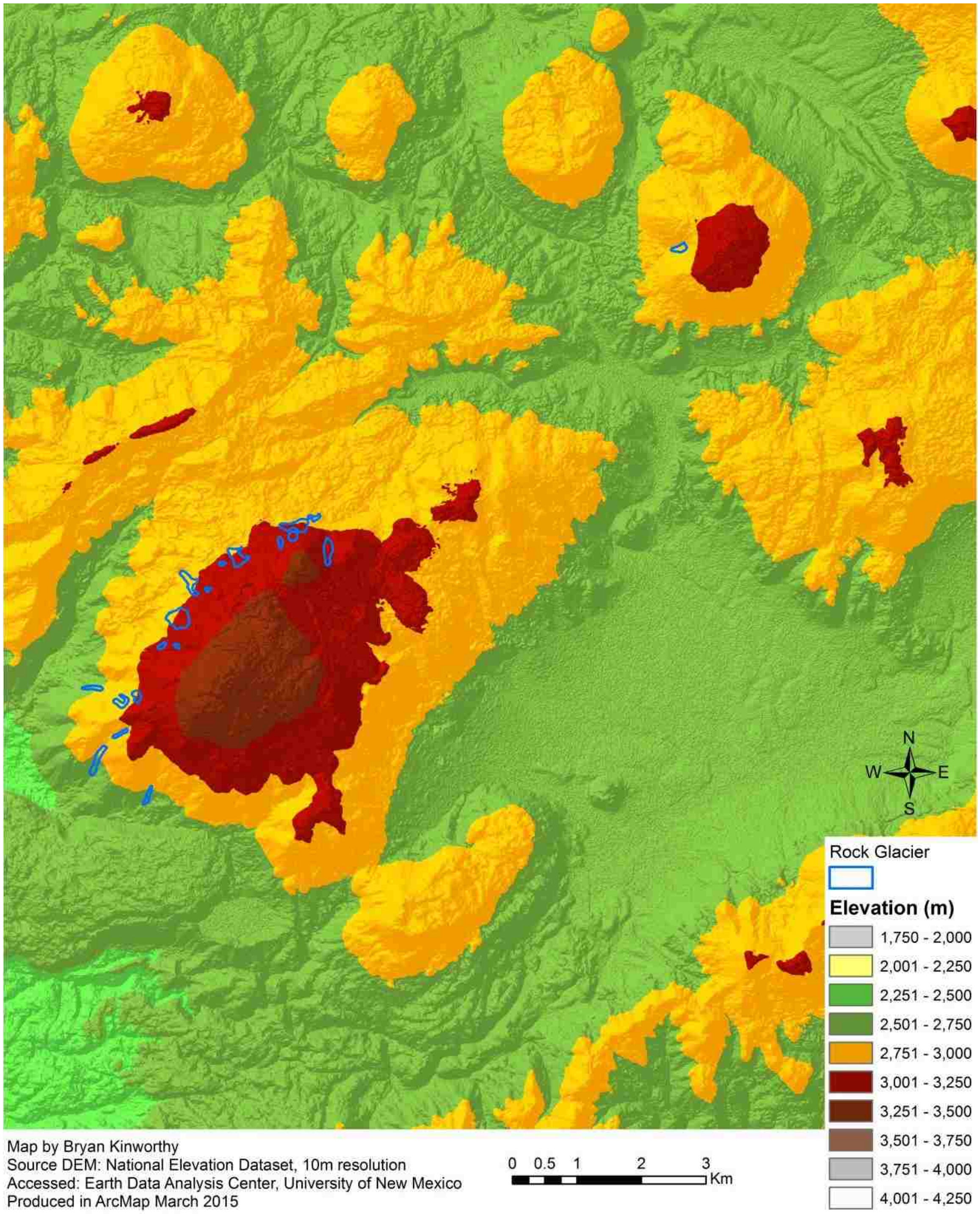
Figure 4.5 Histogram of minimum rock glacier elevations. K-means cluster centers are identified above each cluster.



Produced in ArcMap March 2015



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap 10.1, April 2015



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure 4.8 Rock glacier elevations in the Jemez Mountains.

Climate Parameters

Rock glaciers in New Mexico experience strong variability in climate due to latitude, elevation, and orographic precipitation (Figure 4.9) MAP ranges from 456 – 1,258mm per year with no apparent pattern in frequency distribution (Figure 4.10). Average MAAT at rock glacier locations ranges from -0.76 to 11.39°C.

Rock glacier MAATs vary greatly between study sites averages as depicted in Figure 4.10. Study sites can be clustered into three main groups. Rock glaciers experience the warmest MAATs (~8°C) in the Capitan, Gallinas, Magdalena, San Mateo Mountains and South Mountain. Coolest MAATs exist in the at rock glaciers in the northern Sangre de Cristo Mountains (~2°C). Rock glaciers in the Jemez, Mogollon, and southern Sangre de Cristo Mountains have middle range MAATs (~5°C) that do not align with the other groups. The middle range group of rock glacier MAATs is too small in count to represent a distinct cluster in the frequency distribution. A bimodal frequency distribution in MAAT is presented in Figure 4.12. The bimodal distribution was separated into clusters centered at 1.6°C and 8.63°C through K-means clustering analysis. An ANOVA test confirmed the clusters to be significantly different (F=446, p=4.54 x 10^{-68}).

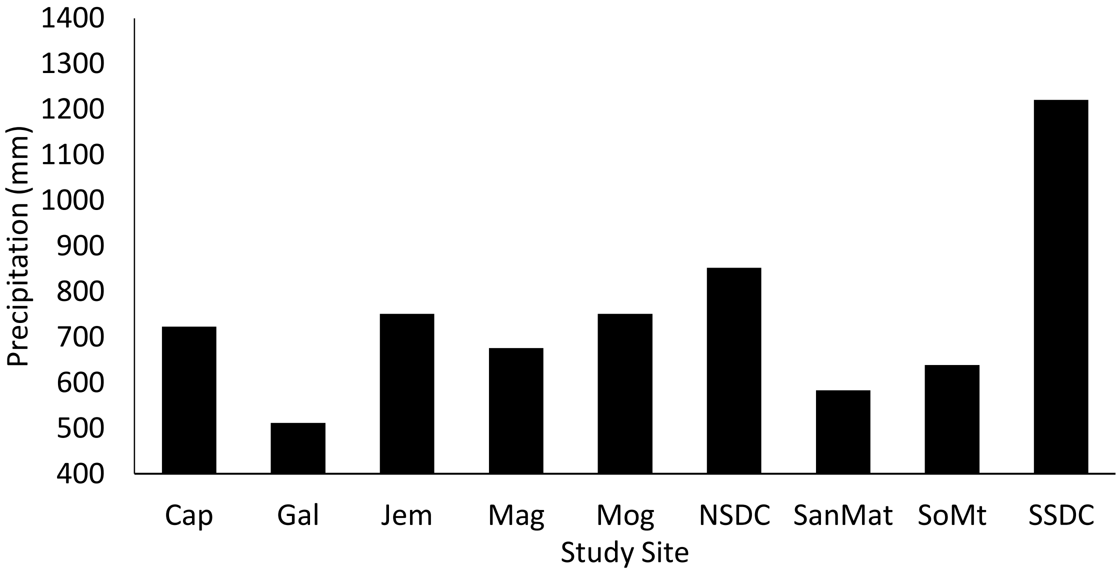


Figure 4.9 MAP at rock glacier locations by study site. See Table 4.1 for study site abbreviations.

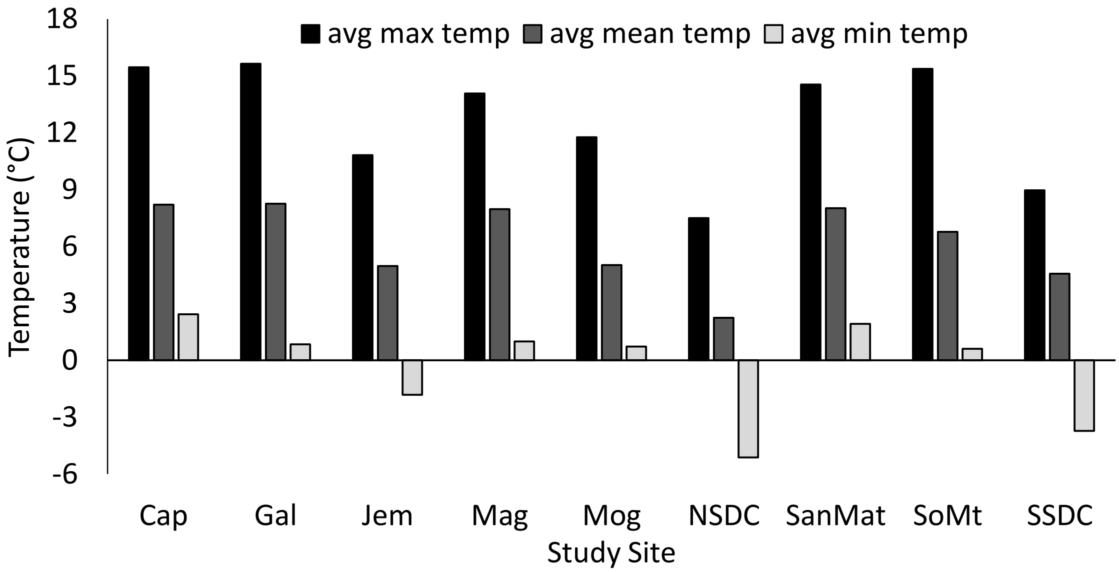


Figure 4.10 Average annual air temperatures at rock glacier locations by study site. See Table 4.1 for study site abbreviations.

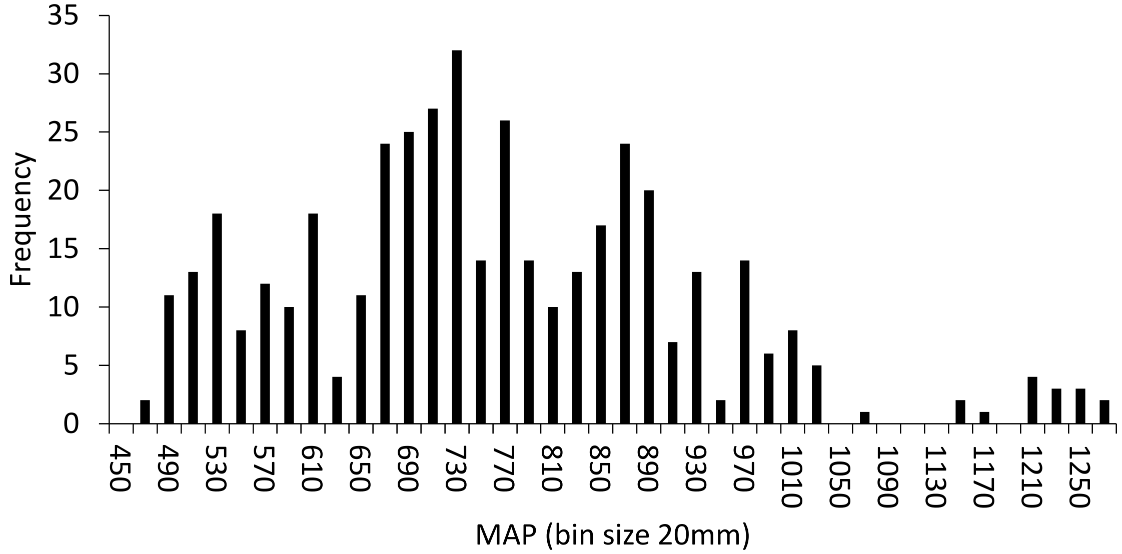


Figure 4.11 Histogram of rock glacier MAP. The distribution is nearly normal.

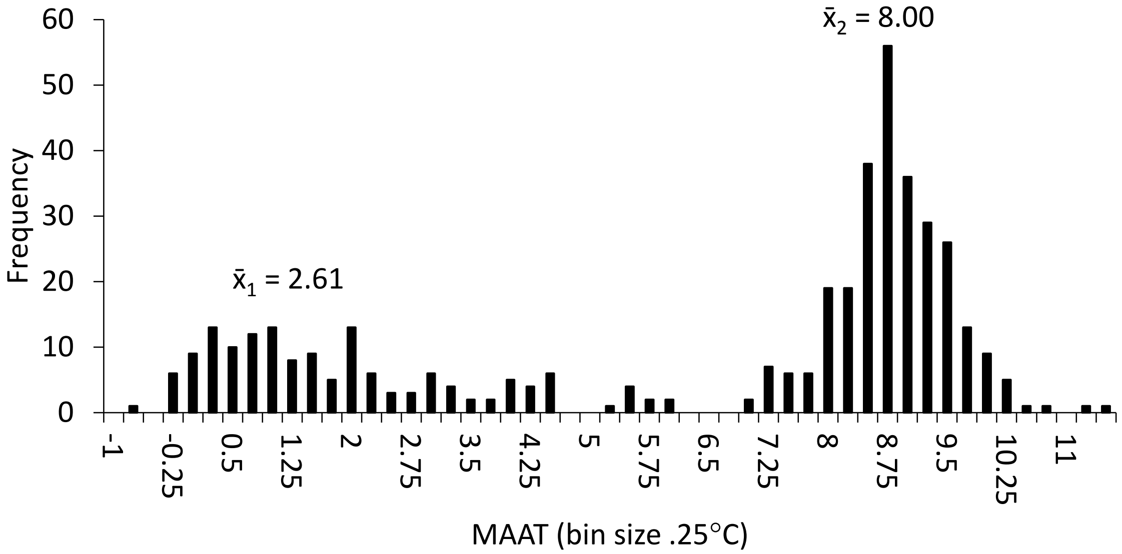


Figure 4.12 Histogram of rock glacier MAAT. K-means clustering means are displayed above each cluster.

Solar Irradiance

Data suggest that rock glaciers form primarily in areas shaded from solar irradiance as expected (Figure 4.16). On average, rock glaciers receive less irradiance than their host mountain range study site during all seasons, though there are several exceptions (Figures 4.13 – 4.15). Rock glaciers in the Jemez Mountains study site receive far greater solar irradiance than the study site average during all seasons except winter. The southern Sangre de Cristo Mountains receive greater irradiance at rock glacier locations than the study site average during all seasons. Rock glaciers in the Capitan and Mogollon Mountains study sites are on the other extreme, receiving far less irradiance than the study site average during most seasons.

The frequency distribution of solar irradiance values differs greatly with season; a seasonal bimodal distribution of solar irradiance frequency occurs during summer months. The bimodal distribution is still evident but subdued during equinox and completely obscured during winter solstice. Figures 4.17 – 4.19 depict the frequency distribution of solar irradiance received at rock glacier locations. Figures 4.20 – 4.22 display maps of solar irradiance; additional maps are available in Appendix B.

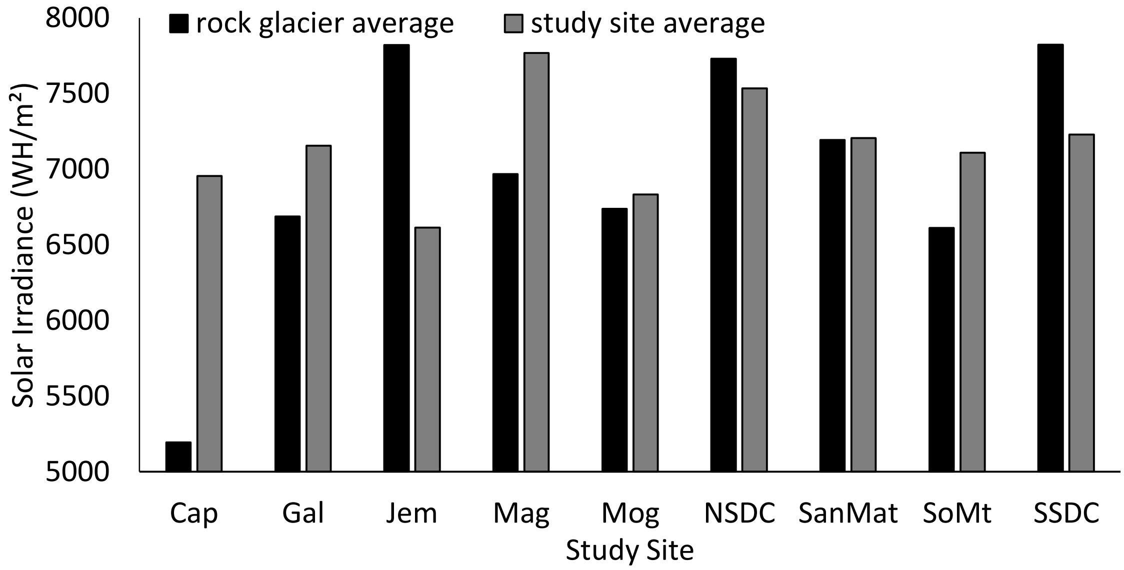


Figure 4.13 Solar irradiance at rock glaciers and study sites: summer solstice. See Table 4.1 for study site abbreviations.

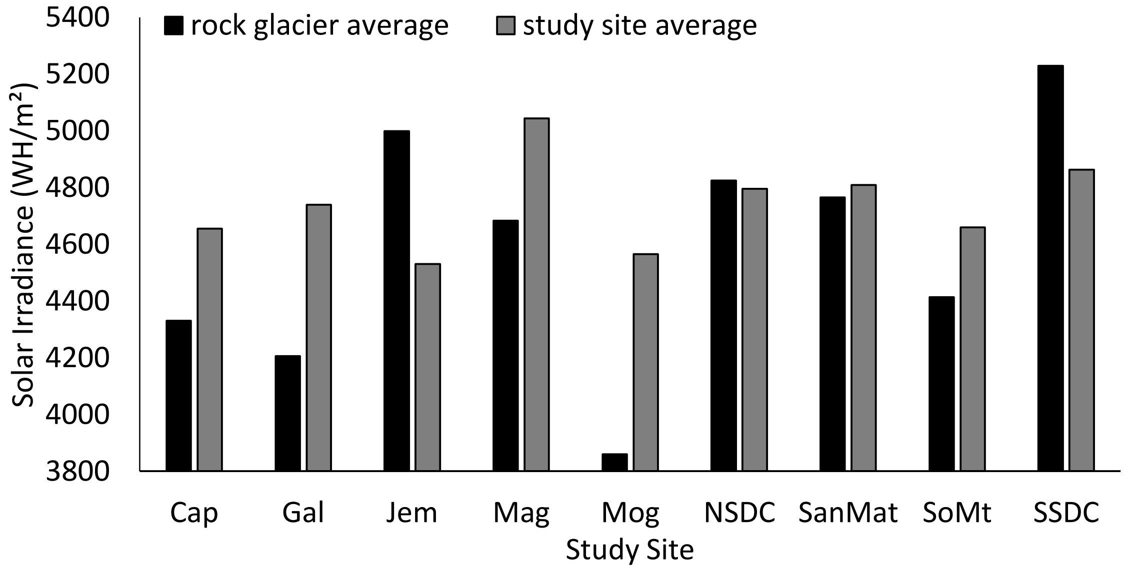


Figure 4.14 Solar irradiance at rock glaciers and study sites: equinoxes. See Table 4.1 for study site abbreviations.

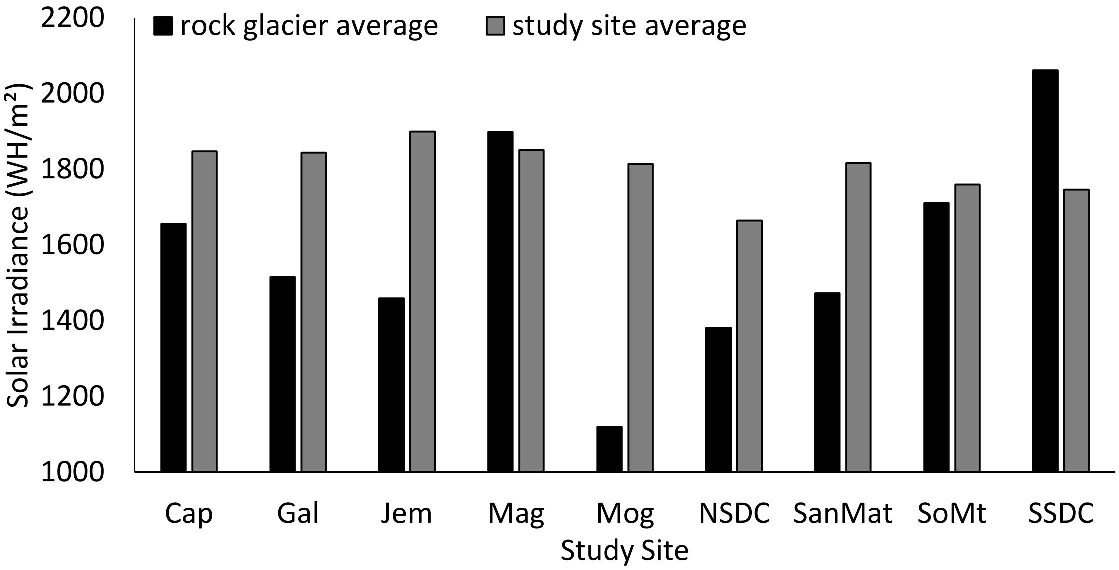


Figure 4.15 Solar irradiance at rock glaciers and study sites: winter solstice. See Table 4.1 for study site abbreviations.

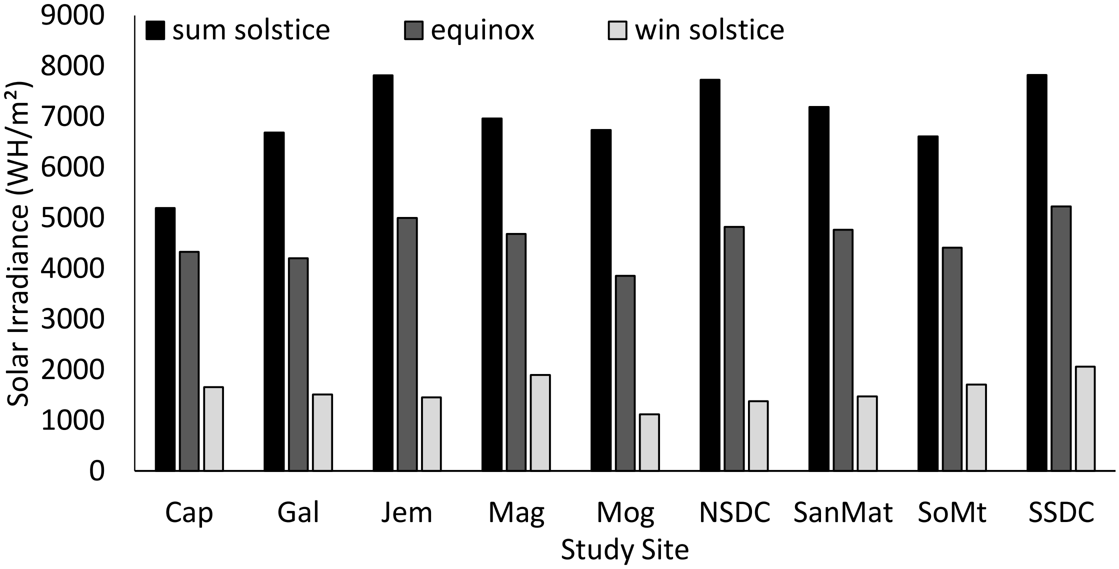


Figure 4.16. Solar irradiance at rock glaciers: all seasons. Rock glaciers are averaged by study site. See Table 4.1 for study site abbreviations.

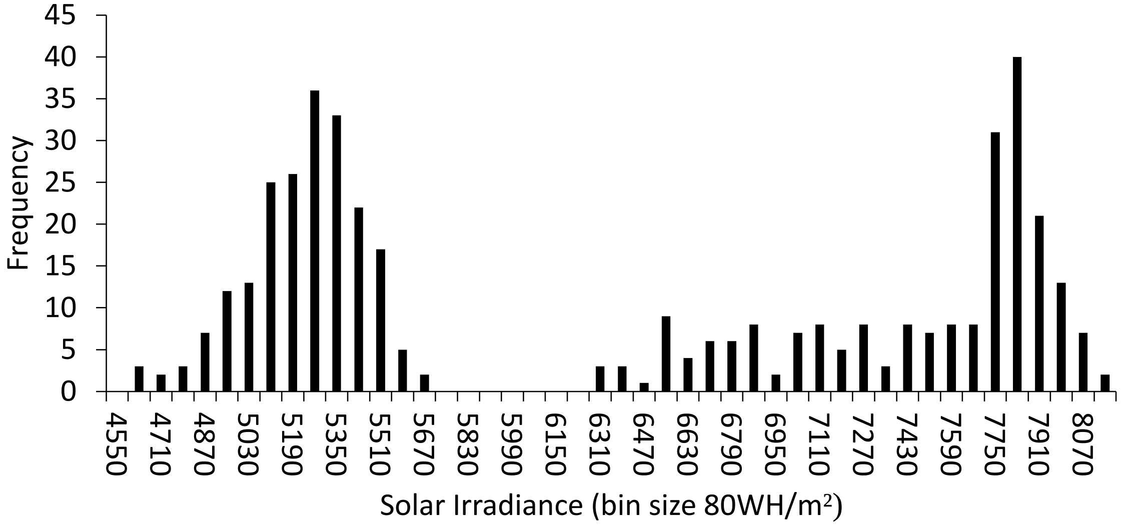


Figure 4.17 Histogram of solar irradiance: summer solstice.

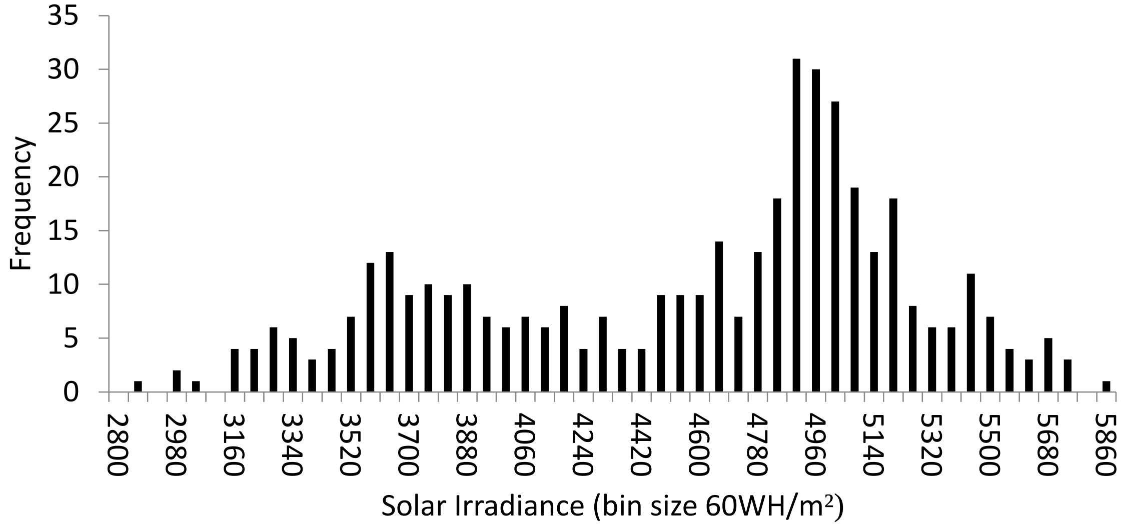


Figure 4.18 Histogram of solar irradiance: equinoxes.

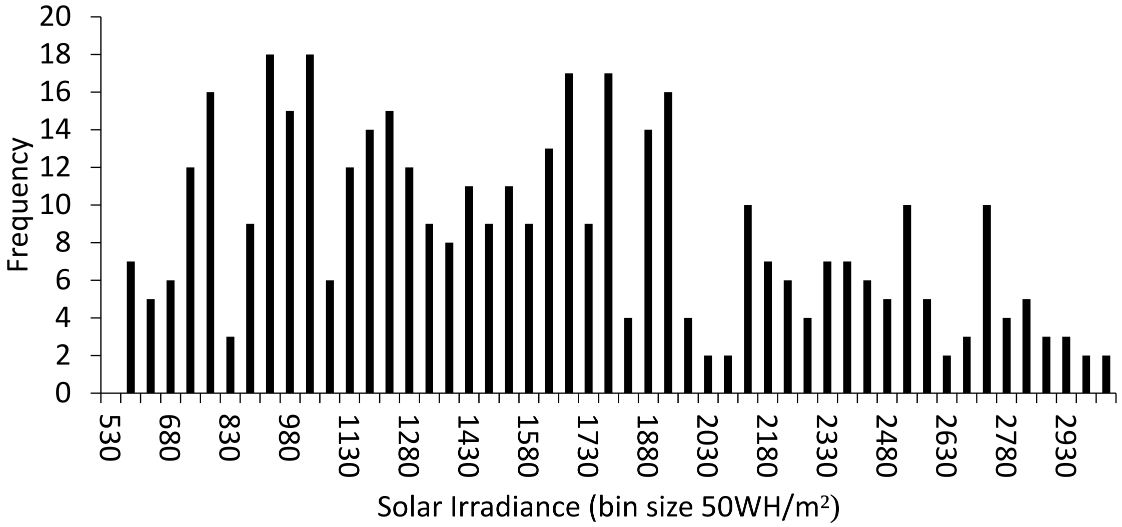
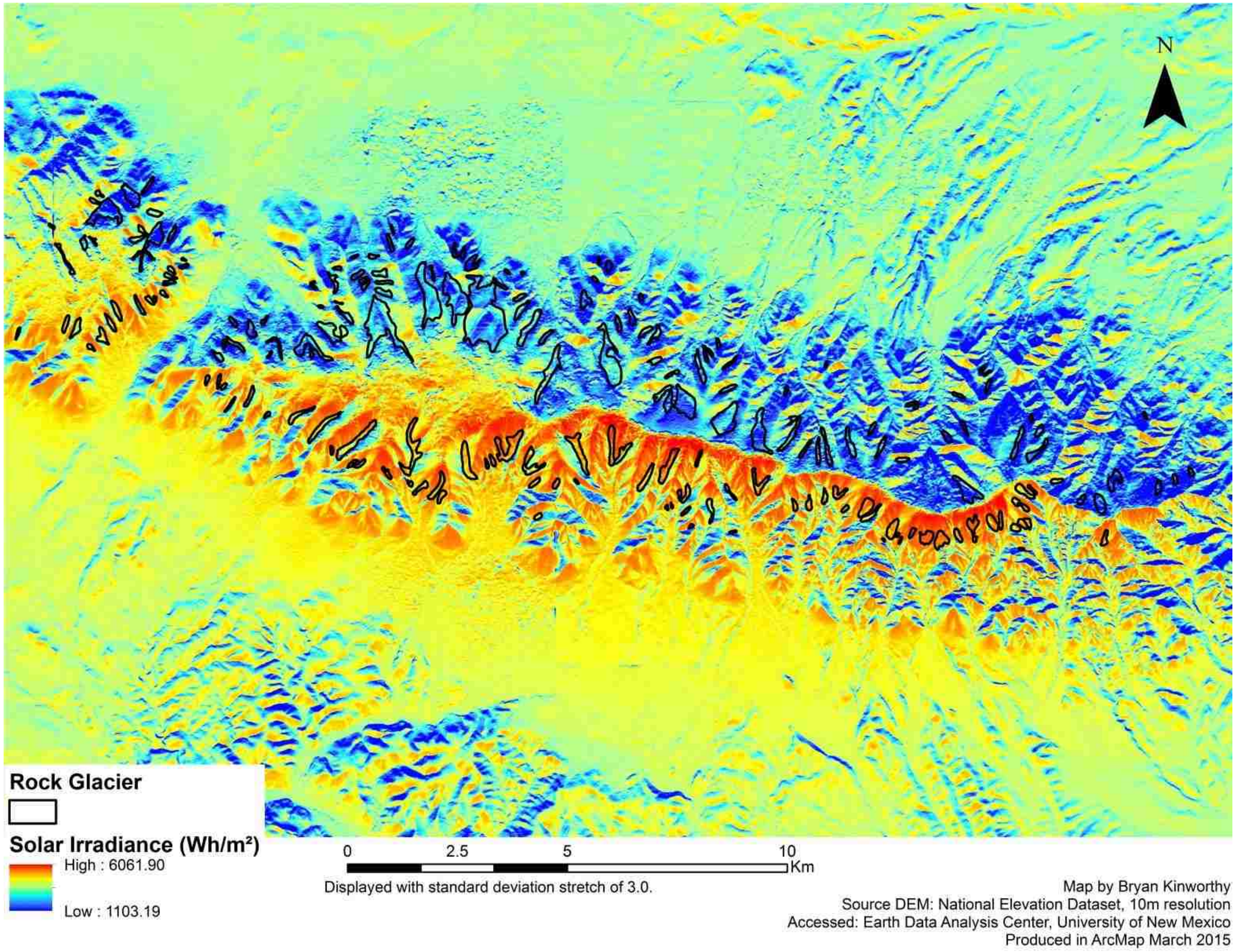
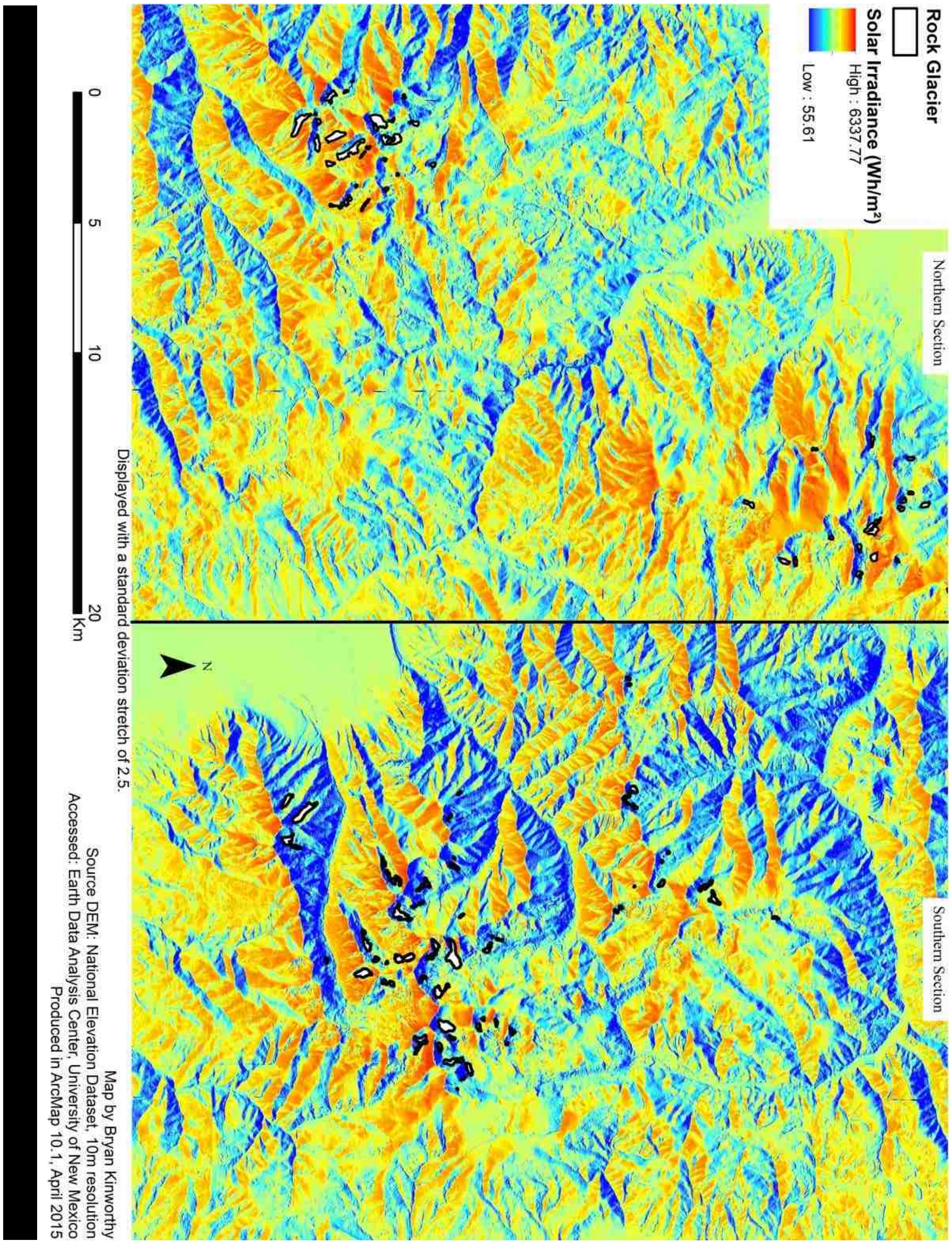


Figure 4.19 Histogram of solar irradiance: winter solstice.



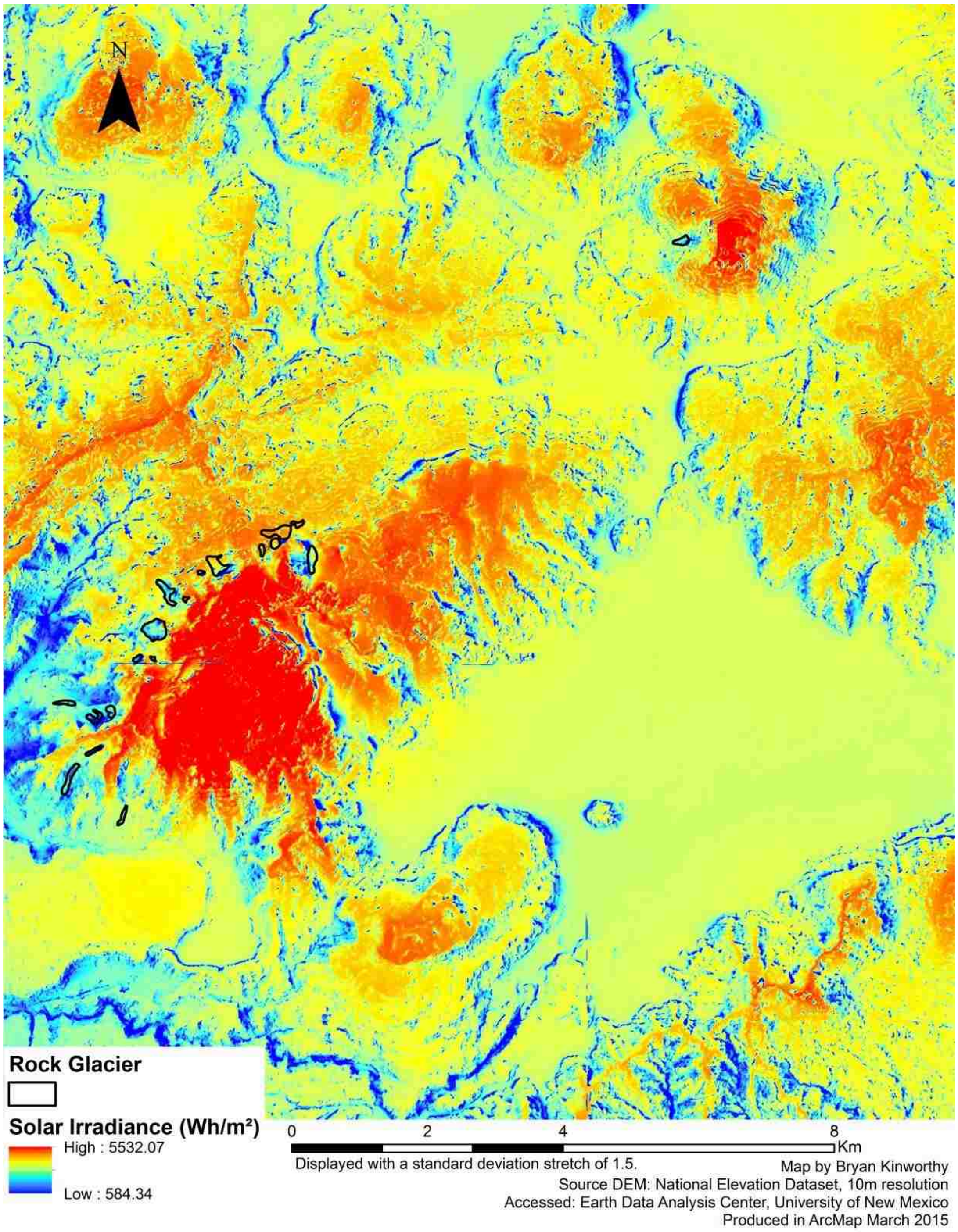
Displayed with standard deviation stretch of 3.0.

Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015



Displayed with a standard deviation stretch of 2.5.

Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap 10.1, April 2015



Displayed with a standard deviation stretch of 1.5.

Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure 4.22 Equinox solar irradiance in the Jemez Mountains.

Geology

The distribution of rock glaciers in New Mexico is related to bedrock lithology. There are 140 geologic units exposed to the surface at elevations conducive to rock glacier formation (>2,159m), but 9 geologic units contain ~96% of all rock glacier coverage (Figure 4.5). Geologic units that contain the highest percentage of rock glacier coverage do not contain a similarly large percentage of the study region area. Thus, it is evident that geologic units contained within rock glacier area influence rock glacier distribution.

Table 4.5 Geologic unit coverage in rock glaciers

Abbrev.	Geologic Unit	% RG Cover	% SR Cover	% Geologic Unit in RGs
Qbt	Bandelier Tuff	2.29%	1.12%	0.06%
Qd	Glacial Deposits	4.55%	0.06%	2.19%
Ti	Tertiary intrusives, undifferentiated	60.20%	0.87%	2.00%
Tual	Andesites and basaltic andesites	1.85%	1.17%	0.05%
Tui	Intermediate intrusive rocks	1.40%	0.41%	0.10%
Turf	Silicic or felsic pyroclastic flows	6.82%	2.28%	0.09%
Turp	Rholitic pyroclastics	5.09%	4.00%	0.04%
Xmo	Proterozoic metamorphics	3.75%	0.46%	0.23%
Xp	Proterozoic plutonics	9.98%	1.92%	0.15%
	Other (<1% rock glacier cover)	4.07%	0.41%	0.06%
Total	Above coverage types	100.00%	12.69%	4.97%

RG: rock glacier. SR: study region.

Intrusive igneous bedrock corresponds to Tertiary intrusives of the Capitan and Gallinas Mountains are important, as they combine for >60% of total rock glacier coverage and <1% of area in the study region. Figure 4.24 shows that rock glaciers are primarily located in igneous bedrock, potentially due to the occurrence of igneous lithologies in several mountain ranges. Tertiary intrusives and Quaternary glacial deposits contain the highest density of rock glaciers with >2% of each geologic unit's surface area contained in rock glaciers. The 4.56% of rock glaciers located in Quaternary glacial deposits also represent the percentage of rock glaciers formed form glacial debris within New Mexico.

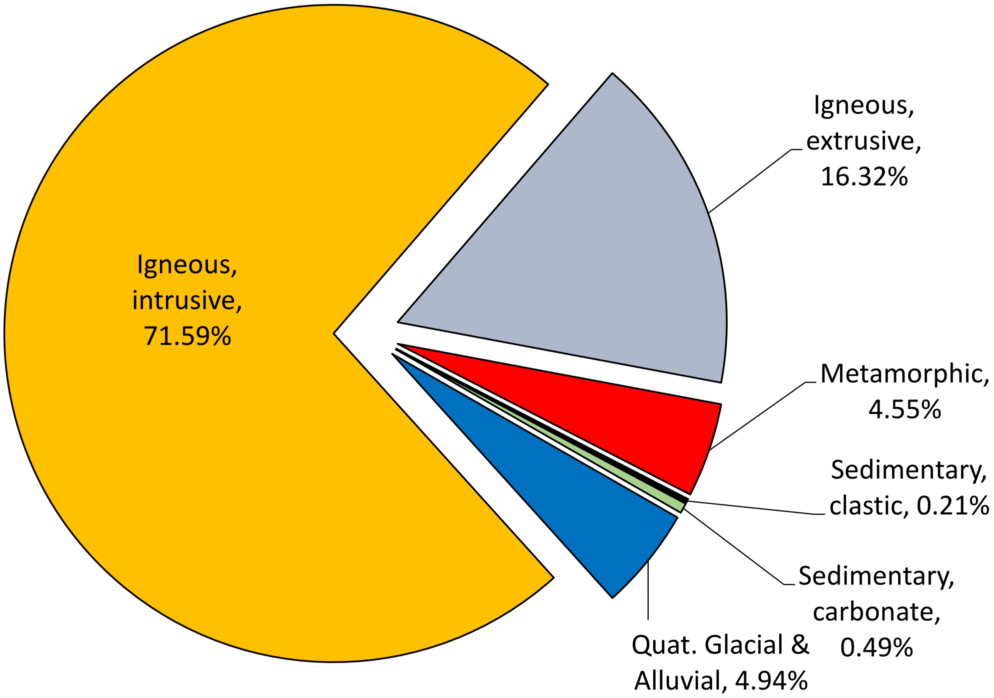


Figure 4.23 Percent geology type in rock glaciers.

Dating

Results from this thesis provide evidence of at least two periods of rock glacier formation in New Mexico. The bimodal frequency distribution present in elevation and MAAT data are suggest rock glaciers formed during two different climates. Rock glaciers within the Jemez and Sangre de Cristo Mountains (north and south) study sites occupy the high elevation, low MAAT clusters. If all rock glaciers formed during similar periglacial climates, the high elevations and low MAAT cluster of rock glaciers formed during a warmer period than the low elevation, high MAAT cluster.

Relative dating also suggests at least two periods of rock glacier formation with a probable middle period as depicted in Table 4.6. Rock glaciers in southern New Mexico study sites appear the oldest with extensive tree coverage and heavily subdued surface topography. Rock glaciers in the Sangre de Cristo Mountains (north and south) appear youngest with little to no tree growth located only above frontal and side slopes, despite their location below tree line in many locations. Frontal slopes on rock glaciers in the northern and southern Sangre de Cristo Mountains appear steep with sharp edges. Rock glaciers in the Jemez and some rock glaciers in the Sangre de Cristo Mountains (north and south) have limited tree growth located mostly above the frontal slopes, which are moderate to steep with some evidence of erosion. Some rock glaciers in the northern and southern Sangre de Cristo Mountains share the same, older appearance as rock glaciers in the Jemez Mountains and likely formed during the same climate period.

Table 4.6 Relative age of rock glaciers.

Relative Age	Study Site
Oldest	Capitan Gallinas Magdalena Mogollon San Mateo South Mountain
Middle Age	Jemez S. Sangre de Cristo N. Sangre de Cristo
Youngest	S. Sangre de Cristo N. Sangre de Cristo

Rock glaciers in southern New Mexico formed during the late to terminal Wisconsin according to Blagbrough's dating estimates (1994, 1999, 2005). The South Mountain study site is closest to the Gallinas and Capitan Mountains study sites in both geography and relative age dating. Thus South Mountain rock glaciers likely formed during the same period as the Capitan and Gallinas Mountains at 12 – 14kya as estimated by Blagbrough (1999, 2005). Rock glaciers likely formed in northern New Mexico during the Wisconsin period but were overridden by newer structures. The rock glaciers in northern New Mexico that are currently visible are relatively younger than any dated by Blagbrough. Alpine climates in northern New Mexico returned to periglacial temperatures in the Neoglacial which began ~4.9kya (Armour, Fawcett, and Geissman 2002). Rock glaciers in the Jemez Mountains, southern Sangre de Cristo Mountains, and some rock glaciers in the northern Sangre de Cristo Mountains likely formed during the Neoglacial period. However, several rock glaciers in the northern Sangre de Cristo are composed of glacial debris in high elevation cirques. Armour et al. also found that Neoglacial cirque glaciation began ~3.6kya in the Sangre de Cristo Mountains. Many rock glaciers within the Sangre de Cristo study sites must have formed after this neoglaciation or else would have been obliterated by glacial erosion. Rock glaciers may have extended from glacial cirques in a periglacial period 2.8kya and reactivated during the Little Ice Age only 120ya. Proposed dates of rock glacier formation are displayed in Table 4.7.

Table 4.7 Proposed dates of rock glacier formation.

Proposed Date	Cap	Gal	Jem	Mag	Mog	NSDC	SanMat	SoMt	SSDC
300ya - 3.6kya						X§			X§
3.6 - 5kya			X§			X§			X§
12-14kya	X*	X†						X§	
15-20kya	X*								
28.6-35kya				X‡	X‡		X‡		X‡

X: period of rock glacier formation. See Table 4.1 for study site abbreviations.
Sources: *Blagbrough 1999, †Blagbrough 2005, ‡Blagbrough 1994, § this thesis

Several large rock glaciers in the northern Sangre de Cristo Mountains may still contain ice. Average MAAT at rock glaciers in the northern Sangre de Cristo Mountains (2.25°C) are well within the range of discontinuous permafrost (French 1996, 20). Most rock glaciers throughout the northern Sangre de Cristo study site display very steep frontal slopes with lighter tone than the broader rock glacier mantle (as seen in Figure 4.24). Barsch (1996, 18) explains that a lighter tone in a frontal slope suggests less weathering than the rest of the rock glacier; areas with lighter tone are only recently exposed may have moved as recently as the Little Ice Age.

Figure 4.241 A rock glacier near Latir Peak that may contain ice. The frontal slope is very steep with a lighter tone than the rest of the rock glacier. *Source:* Google, [uncited] 2013

Chapter Five: Discussion

The inventory of rock glaciers in New Mexico provides new data for modeling rock glacier formation, establishing environmental controls on permafrost creep, and distribution comparison with other alpine regions. As part of an exploratory study, this discussion section identifies data patterns in the New Mexico rock glacier inventory and reconciles them with observed and hypothesized physical controls on rock glacier movement and formation.

Environmental Controls on Rock Glacier Distribution

The distribution of rock glaciers is governed by whether environmental controls in a location are conducive for rock glacier formation. Rock glacier distribution was analyzed against environmental parameters shown to influence rock glacier formation in other studies. Parameters include elevation, slope, temperature, precipitation, solar irradiance, and geology. The apparent level of control each environmental parameter displays on rock glacier formation in New Mexico is summarized in Table 5.1

Elevation and Temperature

The distribution of rock glaciers is strongly influenced by elevation and MAAT, though elevation is a proxy variable for temperature. Rock glaciers form in the periglacial elevation belt which is driven by mean annual temperatures. Thus elevation and mean annual temperature must be interpreted together. Results show that elevation is a stronger control on rock glacier formation than MAAT, though this is likely an artifact from the much higher spatial resolution of elevation data than temperature data. Average minimum elevations calculated in this study correspond closely to the same calculations recorded in previous studies, with the greatest difference being 50m in the San Mateo Mountains (Blagbrough 1994). Blagbrough estimated rock glacier elevation on topographic maps, whereas this study utilizes 10m resolution DEMs.

Rock glaciers are distributed in a small elevation belt within each study site, though the elevation of each belt varies within and between study sites (see Figure 4.5). The appearance of elevation belts within each study site suggests that rock glaciers are indeed forming at particular elevations due to MAAT. Rock glaciers at lowest elevations (Gallinas Mountains and South Mountain study sites) have the tightest distribution of elevations, likely due to a relatively small periglacial belt and small size of rock glaciers in these locations. The positive relationship between rock glacier size and elevation range can be seen in the Capitan, Magdalena, and northern Sangre de Cristo Mountains. The northern Sangre de Cristo Mountains have a much larger elevation range than other mountains, and this is interpreted as the combination of rock glaciers being larger and not as affected by temperature at high elevations.

Precipitation

Rock glaciers experience a very large range in MAP that is not clearly related to rock glacier distribution. Like temperature, precipitation is heavily influenced by elevation via orographic uplift. Rock glaciers experience precipitation levels between

512mm/yr in the Gallinas Mountains study site to 1,221mm/yr in the southern Sangre de Cristo Mountains. However, rock glaciers in study sites with the greatest number of rock glaciers and total rock glacier area, the Capitan Mountains and northern Sangre de Cristo Mountains, experience similar amounts of precipitation (723mm in the Capitan Mountains and 852mm in the northern Sangre de Cristo Mountains).

Precipitation may influence the distribution of rock glaciers within the northern and southern Sangre de Cristo Mountains. There are far more rock glaciers in the northern study site where MAP levels are lower than in the southern study site. In the northern Sangre de Cristo Mountains, total rock glacier area and precipitation levels are $5.4 km^2$ – 852mm/yr compared with $0.18 km^2$ – 1,221mm/yr in the southern Sangre de Cristo Mountains (Figures 4.2 and 4.9). These results suggest precipitation may cause a reduced number of rock glaciers in the southern Sangre de Cristo Mountains. There is no obvious relationship between precipitation and rock glacier distribution in study sites outside the Sangre de Cristo Mountains. Potential reasons for the poor detection of precipitation control on rock glaciers are the low spatial resolution of precipitation data and changes in precipitation rate since the time period when rock glaciers formed.

Marker (1990) concluded that precipitation drives the elevation of periglacial landforms such as rock glaciers through alterations to the regional snowline. Evidence provided in this thesis suggests that rock glacier elevations are driven primarily by MAATs during the climate in which the rock glaciers formed. Precipitation is a less important control on rock glacier distribution than temperature and geology, though it may control local rock glacier elevations.

Solar Irradiance

The relationship between the presence of rock glaciers and the amount of solar irradiance a location receives is unclear. On average, rock glacier locations receive less solar radiation than their host study site. However, numerous cases exist where rock glaciers receive greater solar irradiance than their host region. The number of regions with rock glacier radiation greater than the study site average is similar throughout all seasons (three in summer, three in spring and autumn, and two in winter). The Capitan Mountains study site has by far the greatest number of rock glaciers of all study sites; this is apparently associated with the rock glaciers' exposure to minimal solar radiation during all seasons. However, rock glaciers in the Mogollon Mountains, Gallinas Mountains, and on South Mountain are also exposed to less solar radiation than the study site average, but these sites do not contain nearly the number of rock glaciers as the Capitan Mountains.

The Jemez and northern Sangre de Cristo Mountains are particularly anomalous in that rock glaciers receive far greater solar radiation than the study site average during most of the year (Figures 4.13 – 4.16). In the Jemez Mountains, the anomaly may be explained by the especially smooth geomorphology of the region. Rock glaciers in the Jemez Mountains are located on large, smooth lava domes in the Valles Caldera. There is little to no shade from solar radiation on the flanks of these lava domes (see Figure 4.24), though there is still no explanation for how rock glaciers were able to form in spite of excess solar radiation. Rock glaciers in the southern Sangre de Cristo Mountains are located at very high elevations where MAATs may be cool enough to suppress the influence of solar irradiance on permafrost occurrence.

The relationship between rock glacier elevation and solar irradiance is no coincidence and may be important for rock glacier movement. Findings from this thesis echo Brenning and Trombotto's (2006) discovery that high elevation rock glaciers in the Andes Mountains occur more often in locations with greater solar irradiance. Rock glaciers are governed by the rheology of ice, whereby higher temperatures allow ice a higher capacity to flow downslope from internal deformation. According to previous research, rock glaciers appear to flow quicker during summer months when temperatures are higher (Barsch 1996, 145; Krainer and Mostler 2006) and as overall climate warms (Kääb, Fraunfelder, and Roer 2007). At high elevations where summer temperatures remain cold, increased solar irradiance during summer months may provide necessary heat for subsurface ice deformation.

This thesis detected a seasonal change in solar irradiance frequency distribution. During summer months, rock glaciers are clustered into two distinct groups of solar irradiance. At equinox, the clusters become subdued, and they diminish by the winter solstice. The latitudinal distribution of study sites is not enough to cause the observed distribution changes. Similar bimodal distributions exist in MAAT and elevation, though these two variables do not offer an explanation for the seasonal variation. This phenomenon does not appear to have been recognized in other rock glacier studies, and no scientifically defensible explanation for the phenomenon can be offered at this time.

Slope

The slope of rock glaciers is remarkably similar throughout all study sites (20.5% – 27.1%). The tightly grouped slope percentages throughout all study sites suggest rock glaciers require a specific slope for formation. Slope percentages are anomalously low in the Sangre de Cristo Mountains (20.5% – 21%). Several rock glaciers in the Sangre de Cristo Mountains appear to be glacigenic in origin (forming in cirques from ice glaciers). A greater amount of ice input may reduce the slope steepness necessary to cause internal deformation in the ice mass.

Geology

Geology is the strongest, most obvious control on rock glacier formation in New Mexico. Very few rock glaciers in New Mexico are formed from glacial debris; talus in the form of blockfields is the dominant form of rock input. With the exception of the Sangre de Cristo Mountains, New Mexico rock glaciers source rock exclusively from extensive blockfield deposits.

The Tertiary intrusive igneous geology (Ti) of the Capitan Mountains (including Carrizo Peak), Gallinas Mountains, and South Mountain is by far the most important rock glacier-forming lithology in New Mexico. Mountain ranges composed of Ti geology develop large blockfield deposits at high elevations, and these mountain ranges contain the largest, densest rock glacier distributions. More research is required to understand the physical processes behind the development of these large blockfield deposits. Blagbrough

(1999) attributed the expansive blockfields to the Ti unit's limited potential for soil formation that protects bedrock from freeze-thaw weathering.

Study sites in southwestern New Mexico form blockfields and rock glaciers from basaltic andesites in the Mogollon Mountains and rhyolitic pyroclastics in the San Mateo and Magdalena Mountains. The morphology of rock glaciers in these study sites is similar to that of Ti rock glaciers in central and southeastern portions of the state, but the density of rock glacier distributions is far less. In the Jemez Mountains, blockfields such as that in Figure 5.1 are developed from the Valles Rhyolite. Throughout all study sites, changes in geology produce changes in rock glacier distribution as seen in Figure 5.2.

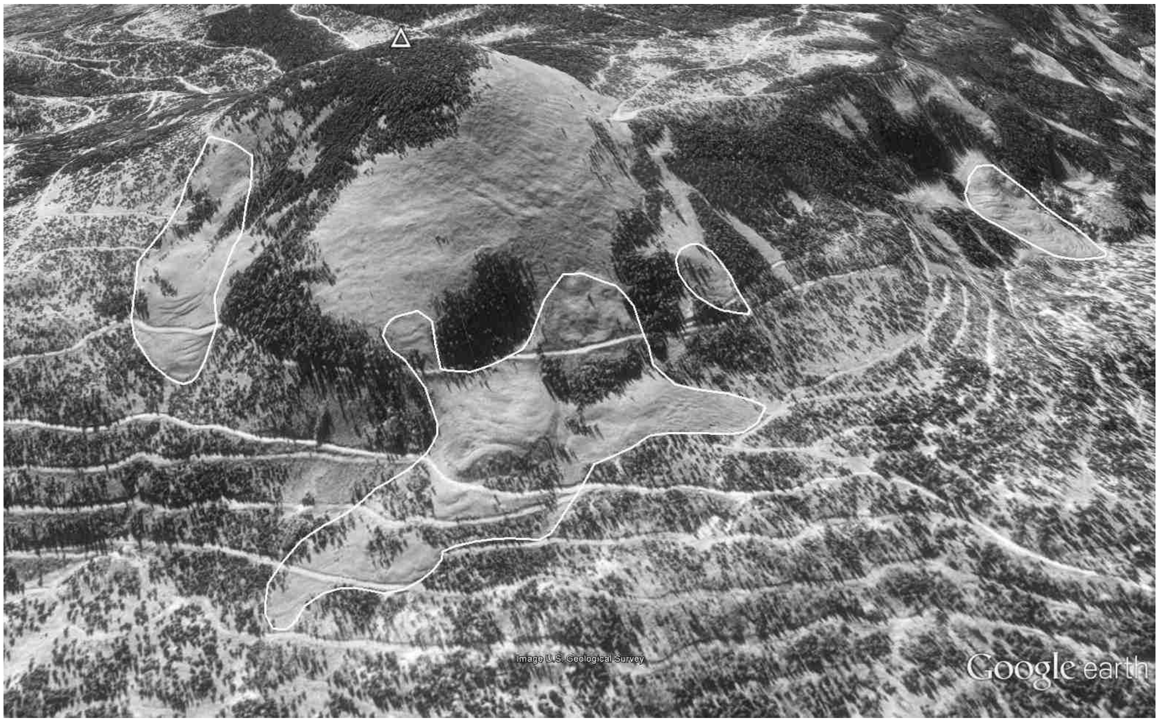


Figure 5.1 Rock glaciers on Redondita Peak (white triangle), Jemez Mountains. Numerous flow structures (white outlines) extend from blockfields on the peak's north and west slopes. Roads built through the rock glaciers would likely provide an excellent opportunity to study the rock glacier interior. *Source*: Google imagery, USGS 1996

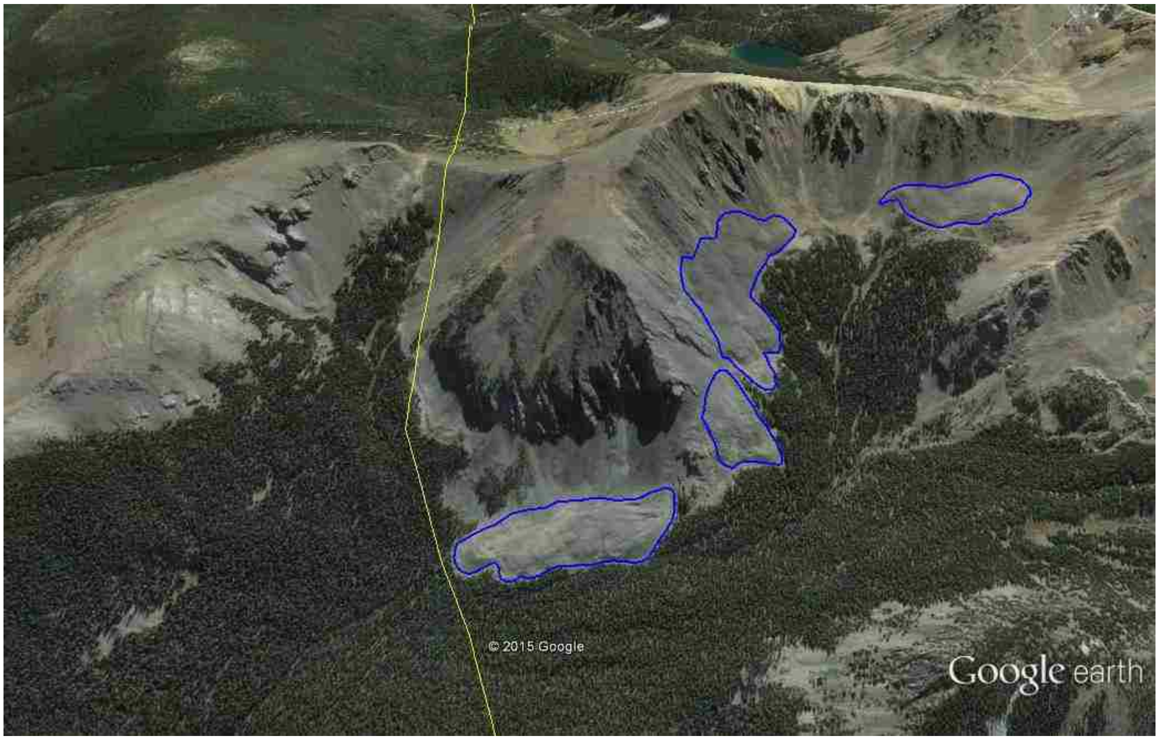


Figure 5.2 Rock glacier distribution divided by a fault. These two cirque valleys in the northern Sangre de Cristo Mountains share similar environmental conditions except for geology. Talus foot rock glaciers (blue polygons) form in Precambrian intrusive igneous rocks and Quaternary glacial debris on the right side of the fault (yellow line). Left of the fault, Pennsylvanian-age sedimentary rocks do not support rock glaciers. *Source*: adapted from Google, [uncited] 2013, annotations from USGS digital map of New Mexico 2015

Paleogeographic Implications

The paleogeographic implication of rock glacier presence does not appear to have been explored in any academic study. However, rock glaciers' relationship with environmental parameters such as climate and rock inputs allows for interesting insights into past environments. Rock glaciers and their blockfield sources provide evidence that alpine environments in New Mexico were very different only 12kya.

Rock glaciers in New Mexico are primarily sourced from blockfields that form in conditions with extensive freeze-thaw weathering. Soil and vegetation coverage inhibit freeze thaw weathering and prevent the formation of blockfields. Thus, New Mexico blockfields almost certainly formed above treeline. Rock glaciers that require MAAT of ≤-2°C extend to the lowest elevation of blockfields in most study sites; such cold MAATs provide additional evidence that both rock glaciers and block fields formed above treeline. Thus the treeline at the time of rock glacier formation was much lower than at present. Above rock glacier toe elevations, modern vegetation coverage appears less dense with different texture and tone in aerial images (Figures 5.10, 5.11). Not only was treeline lower at the time of rock glacier formation, but modern vegetation communities appear different where they interact with relict blockfields.

South Mountain depicts an example of vegetation interaction with blockfields whereby vegetation decreases in density and takes a lighter tone above ~2,300m (Figure 5.3). Vegetation on the nearby Sandia Mountains becomes denser and darker in tone at higher elevations due to increased precipitation. Thus the vegetation change on South Mountain is almost certainly from interaction with the relict blockfield. Given the ≤-2°C required for rock glacier formation and lack of vegetation required for blockfield formation, the distinct vegetation change at ~2,300m is likely the ancient treeline at the time of rock glacier formation.

If the ancient treeline was 2,300m, then the treeline can be extrapolated to the nearby Sandia Mountains. A treeline of 2,300m in the Sandia Mountains also indicates a very different geography for the area where present day Albuquerque exists. Figure 5.4 depicts the location of alpine tundra on the upper reaches of the Sandia Mountains, as it would have appeared from the Albuquerque area 12kya. The alpine forest belt was located at lower elevations reaching far into present day Albuquerque. If this is correct, the desert in which Albuquerque is located was largely forested 12kya.

This hypothesis towards the paleoenvironment in the Albuquerque area is deduced entirely by the presence of rock glaciers and their rock input source in a nearby mountain range. It is evident that rock glaciers present a powerful tool in reconstructing paleogeography that has not been utilized in previous research.

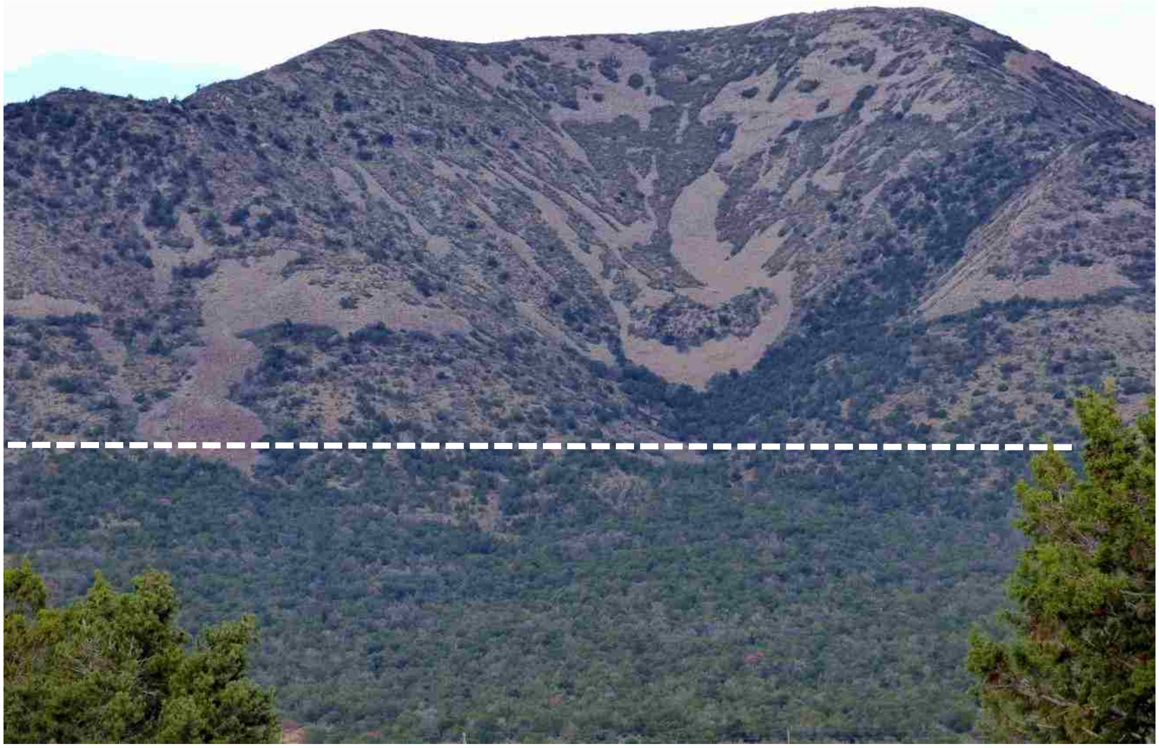


Table 5.3 Blockfield-influenced vegetation change on South Mountain. The dashed white line represents the textural and tonal change in vegetation coverage corresponding to ancient blockfields evident in the image. Note the relict rock glacier at center right in the image.

Figure 5.4 Sandia Mountains with paleo-treeline as of 12kya. Areas of the mountains in gray were alpine tundra. *Source:* Adapted from Google, [uncited] 2014

Insight on Methods

This thesis was successful in producing an expansive inventory of rock glaciers entirely from interpretation of aerial and satellite imagery. Interpretation of imagery in Google Earth software identified every rock glacier Blagbrough (1999) mapped in the Capitan Mountains and an additional 75 rock glaciers (polygons) never before identified. Furthermore, the methodology maintained a 94% accuracy rate identifying landforms previously misidentified as rock glaciers presented by Jarman, Wilson, and Harrison (2013). Freely available imagery of very high spatial and temporal resolution appears adequate for rock glacier identification. Complementary field studies are still necessary for rock glacier identification accuracy as well as more precise dating. Appendix A presents potential easy-to-access rock glacier study sites for future field work.

Solar irradiance modeling utilized in this thesis provides an insight into rock glacier formation that is not available by studying aspect alone. For example, South Mountain features prominent rock glaciers on south facing slopes that are difficult to explain through aspect analysis alone. Solar irradiance modeling in ArcGIS (Figure 5.7) indicates that rock glaciers are located in areas shaded from morning and evening sun by adjacent north-south trending ridges. However, this type of solar irradiance model is still unable to account for different in cloud cover.

Toe elevation of relict rock glaciers has long been used to calculate paleotemperatures using the adiabatic lapse rate (Blagbrough 1994, Millar and Westfall 2007). The rock glacier toe elevation is the assumed elevation where the paleoisotherm of ≤-2°C exists. By calculating the elevation between rock glacier toe elevation and the modern -2°C isotherm, the change in temperature between when rock glaciers formed and the present day is estimated.

This paleoisotherm-based methodology is not well supported by data in this research. Rock glacier toe elevations in this thesis have an average standard deviation range of 56 – 203 meters. A typical error range of two standard deviations presents a range of 112 – 414m. If an average environmental lapse rate of 7°C/1,000m is applied, the 112 – 414m margin of error is ±3°C. A calculated temperature depression of 7°C can only reasonably be reported as 4 – 10°C. Furthermore, there is no indication of whether the ±3°C margin of error accounts for variables known to influence toe elevation such as precipitation and solar irradiance.

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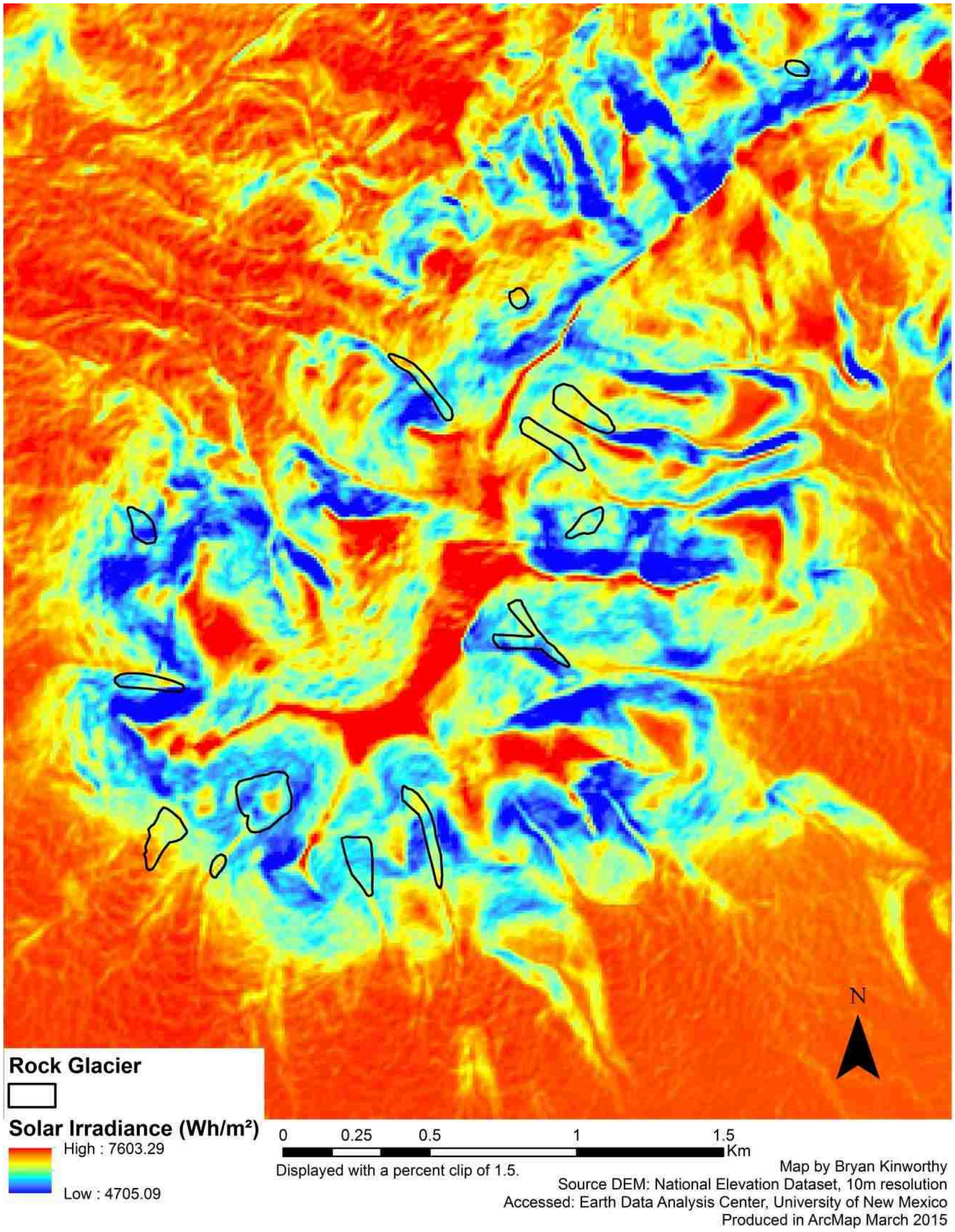


Displayed with a percent clip of 1.5.

Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure 5.5 Low solar irradiance at south-facing slopes on South Mountain. This figure displays South Mountain during the summer solstice. The top of the mountain is represented by very high solar irradiance values at left center.

Chapter 6: Conclusion

This thesis provides new data on ancient and recent periglaciation in New Mexico for rock glacier studies and other disciplines. The rock glacier inventory created in this research contains rock glaciers of all types in various climates and geologic coverages now accessible for future study. This is the second known rock glacier inventory that provides evidence of ice rheology as a geomorphic control in rock glaciers at very cold MAATs. Statistically analyzing the rock glacier locations in the inventory could provide one of the most in-depth analyses of rock glacier distribution available in current research.

Most of the inventoried rock glaciers are relict landforms that provide information on ancient periglaciation. Relict rock glaciers' locations and elevations can be utilized to model paleoclimate, landscape evolution, periglacial geomorphology, and even ecology of alpine regions during the late to terminal Wisconsin. Several inventoried rock glaciers display indicators of containing subsurface ice that may be monitored to understand modern alpine climate change in the region.

The methodologies explored in this thesis provide information on current techniques for rock glacier identification and usage in paleoclimate analysis. Freely available imagery with high spatial resolution such as that within Google Earth software appears extremely useful for research requiring imagery-based object identification. The prevalent methodology of estimating paleotemperature from rock glacier elevation is not supported by data in this thesis due to large error margins and the inability to control for environmental factors that influence rock glacier elevation.

Key Findings

Permafrost creep structures in New Mexico are located only in areas elevation, MAAT, slope, and geology are conducive to their formation. Rock glaciers experience large variation in precipitation and solar irradiance that suggests these variables are not as influential to their formation. Differing precipitation levels in the Sangre de Cristo Mountains may partially drive rock glacier distribution. Rock glaciers at high elevations may require greater amounts of solar radiation to aid in the warming and internal deformation of subsurface ice. Seasonal variation in solar irradiance was identified but remains unexplained.

This thesis identified a bimodal distribution in elevation and MAAT that was interpreted as a climate signal from two periods of periglacial activity. Rock glaciers in southern New Mexico likely formed in the late to terminal Wisconsin (35 – 12kya), as estimated by Blagbrough (1994, 2005). South Mountain rock glaciers probably formed at the same time as rock glaciers in the Capitan and Gallinas Mountains around 12 – 14kya. Rock glaciers in northern New Mexico are likely of Neoglacial age (4.9kya – 0.12kya). Several rock glaciers in the Sangre de Cristo Mountains of New Mexico likely contain ice, and a few may be active.

Study Limitations

Unavoidable limitations exist within the methodology, interpretation, and need for further study (see Future Research section). Within the methodology, the possibility for error exists in identification, digitization, and data analysis. In the identification process, there is potential error in misidentifying landforms as rock glaciers and rock glaciers as different landforms. An attempt to reduce any identification error was made by comparing potential rock glaciers in New Mexico to rock glaciers identified in previous studies. Any error in misidentification likely strays towards underrepresenting the number of rock glaciers in the state. In the digitization process, any error is likely at the head of rock glaciers due to difficulty in determining the exact location where talus slopes transition to rock glaciers with some imagery.

Data analysis uses several GIS datasets, each with an individual level of error (Table 3.2). The spatial accuracy is known for all GIS data used with the exception of the USGS geology layer. Spatial accuracy of rock glacier polygons is within ~7m given parameters of the NAIP data used. The majority of error in raster data sets is within the PRISM climate information, as the extremely coarse resolution (800m SSD) is incapable of detecting topographic microclimates or individual variation within most rock glaciers. The USGS coverage layer is a vector layer with a minimum spatial accuracy of ~125m pixels, and any inaccuracies in geologic field mapping are present in the layer. Geologic coverage analysis does not consider that rock glaciers transport rock from high to low elevations. A rock glacier located on a particular geologic unit may source rock from a different geologic unit at higher elevations.

DEM raster datasets were mosaicked to represent each study site. Mosaicking was set to average any instance where two images contain values for the same location. Some error was noticed where small slivers of area (tens of meters) were not covered by any image. Areas not covered by a raster dataset had minimum values. Rock glaciers located in an area with no raster data incorporated these minimum values into calculations of regional average. The mosaicking errors pertain exclusively to elevation, slope, and irradiance data. Sample size is extremely high for all study sites, and any error from missing data is very slight if at all noticeable.

The climate and solar irradiance data used in this thesis was collected under present conditions. Rock glaciers form over hundreds or thousands of years, and several rock glaciers in New Mexico are thought to have formed in the late Pleistocene and early Holocene. Sun angle and climate were certainly different in the past.

Interpretations in this thesis are limited by methodology and a strong regional focus. Additional field work is required to better understand vegetation coverage and constrain rock glacier dates. Remote sensing techniques such as utilizing Google Earth only provide limited ability to detect lichen growth. Rock size is also not visible in a large number of rock glaciers within central and southern New Mexico due to imagery resolution. Field mapping a sample of rock glaciers in all study sites is necessary to better constrain dating and understand vegetation and sediment distribution.

The proposed dates presented in this thesis are based on probability, not laboratory testing as preferred. For example, it is highly likely that some rock glaciers in the northern Sangre de Cristo Mountains developed during the Neoglacial period, though radiocarbon dating or optically stimulated luminescence would further confirm this conclusion (see Future Research section). Again, field study is required to collect samples for dating.

This thesis focuses exclusively on rock glaciers in the U.S. state of New Mexico, an arid to semi-arid environment with isolated alpine areas. The observations and conclusions drawn from rock glaciers in New Mexico do not necessarily apply to rock glaciers in different geographies – which is exactly the goal. Regional focus is a strength, not a weakness; the regional traits of rock glaciers provide valuable information on the regional environment to be compared with other areas. Instead, future research would benefit from continuing regional studies and compiling regional rock glacier inventories into a global rock glacier inventory to analyze differences between regions.

Future Research

Rock glaciers in New Mexico provide information useful to numerous disciplines, though this section is specific to rock glacier studies. The New Mexico rock glacier inventory is available for future statistical analysis that might elucidate further environmental controls on rock glacier formation in the region. Quantitative measurements can then be compared with rock glacier study sites in other parts of the world.

Dating and landscape evolution research requires additional field study. The environmental parameters that created such dense distributions of rock glaciers such as that in the Capitan Mountains are largely unexplored. Blagbrough (1999) suggested that the Tertiary intrusives underlying the mountain range do not lead to strong soil production, thus bare bedrock is fully exposed to freeze-thaw processes. However, this hypothesis was never tested in subsequent literature. Laboratory freeze-thaw tests of lithology within the Capitan Mountains and other regions are needed to fully understand the extent of freeze-thaw processes involvement in blockfield formation.

Landscape evolution within the Capitan Mountains and other mountain ranges with blockfield-sourced rock glaciers needs more thorough examination. There is little understanding of how blockfields and rock glaciers interact, why blockfields in some regions form rock glaciers and not in others. Better constrained dating, perhaps OSL, is required to better constrain the ages of blockfield deposits and the multiple layers of rock glaciers extending from the deposits.

Climate parameters require further examination with higher spatial resolution data than is utilized in thesis. North-south trending valleys within all study sites likely harbor microclimates shaded from morning and afternoon sun that were not detected in this thesis. The role of microclimates in rock glacier formation should be examined in future studies through the use of small, temporary temperature air thermometers placed on rock glacier surfaces and surrounding areas.

A different set of research opportunities exists in the northern Sangre de Cristo Mountains, where MAATs allow for the presence of subsurface ice. GPR techniques are likely to discover ice in at least one of the several rock glaciers in the region with ice-conducive MAATs. Should ice be discovered, the potential exists to monitor its change due to climate warming and help determine the extent of modern permafrost loss. The direct observation of a rock glacier obtaining ice by freezing rainfall and snowmelt would likely be a first, as there does not appear to be any direct evidence of ice input in rock glacier literature. At the same time, measuring the isotopic fractionation of O^{16} to O^{18} would be recorded for climate analysis at the time when the rock glacier was active.

Appendix A: Easy Access Rock Glaciers in New Mexico

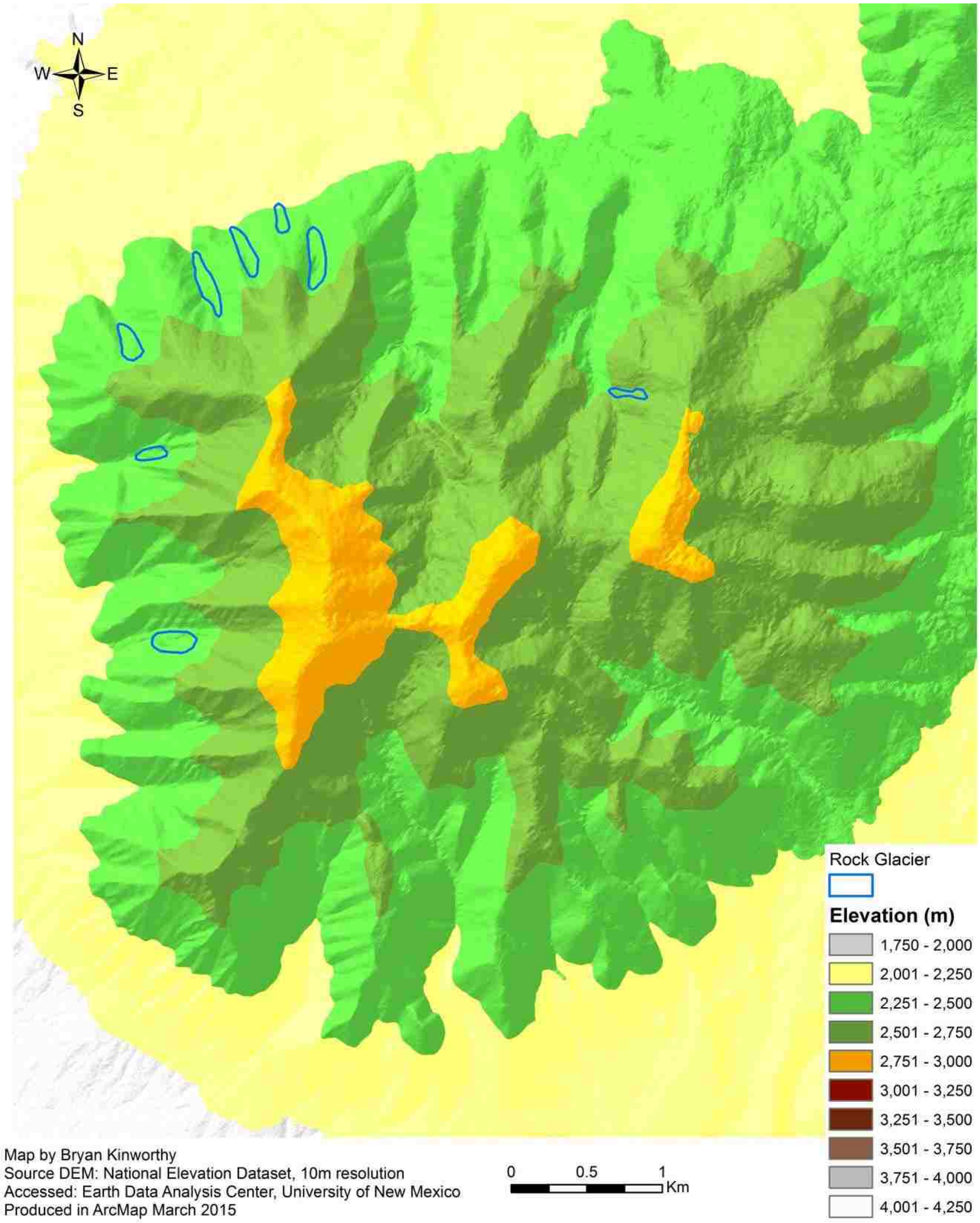
Should future field studies or visits to rock glaciers in New Mexico be desired, there are several rock glaciers of different ages accessible by vehicle or short hike. Summer or spring visits are likely to be the most successful, as most rock glacier locations in New Mexico are snow-covered during winter and early spring. By far the most accessible rock glacier for viewing rests on the southeastern face of South Mountain near Edgewood, New Mexico. This is a small rock glacier relative to others in the state, but it is easily visible from I-40. Closer views can be achieved by taking small roads north of the interstate.

No mountain range in New Mexico, or perhaps North America, is more densely populated with rock glaciers than the Capitan Mountains. Roads run parallel to north and south facing slopes of the mountains, allowing easy viewing of the large rock glaciers. A rough trail (4WD required) up the mountains is accessible from C001, and the tops of numerous rock glaciers are accessible via a short hike from the trail.

Near Taos, a large is accessible via a two-mile hike from Taos Ski Valley to Williams Lake. This is the youngest easily accessible rock glacier in the state, and it flows .75 miles from a cirque at the base of Lake Horn Peak to Williams Lake. Lower portions of the rock glacier show soil development, but ice may remain in the upper portions. Camping is available at the base of the rock glacier.

Well-developed protalus lobes can be viewed in the Magdalena Mountains via a short trip from Socorro. Highway 60 heading west from Socorro meets Water Canyon Road on the opposite side of the Socorro Mountains. Water Canyon Road travels via a rough trail (4WD recommended) to the top of South Baldy where the Magdalena Ridge Observatory is located. Upon reaching treeline, protalus lobes are visible at the base of talus slopes in a valley visible from the left side of the road. The trailhead to Timber Peak provides an excellent view of the landforms in the valley. Larger rock glaciers are located on the opposite (western) side of South Baldy and are likely easy to access from the Magdalena Ridge Observatory should the facility be open.

Appendix B: Solar Irradiance and Elevation Maps



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B2 Rock glacier elevations on Carrizo Mountain.

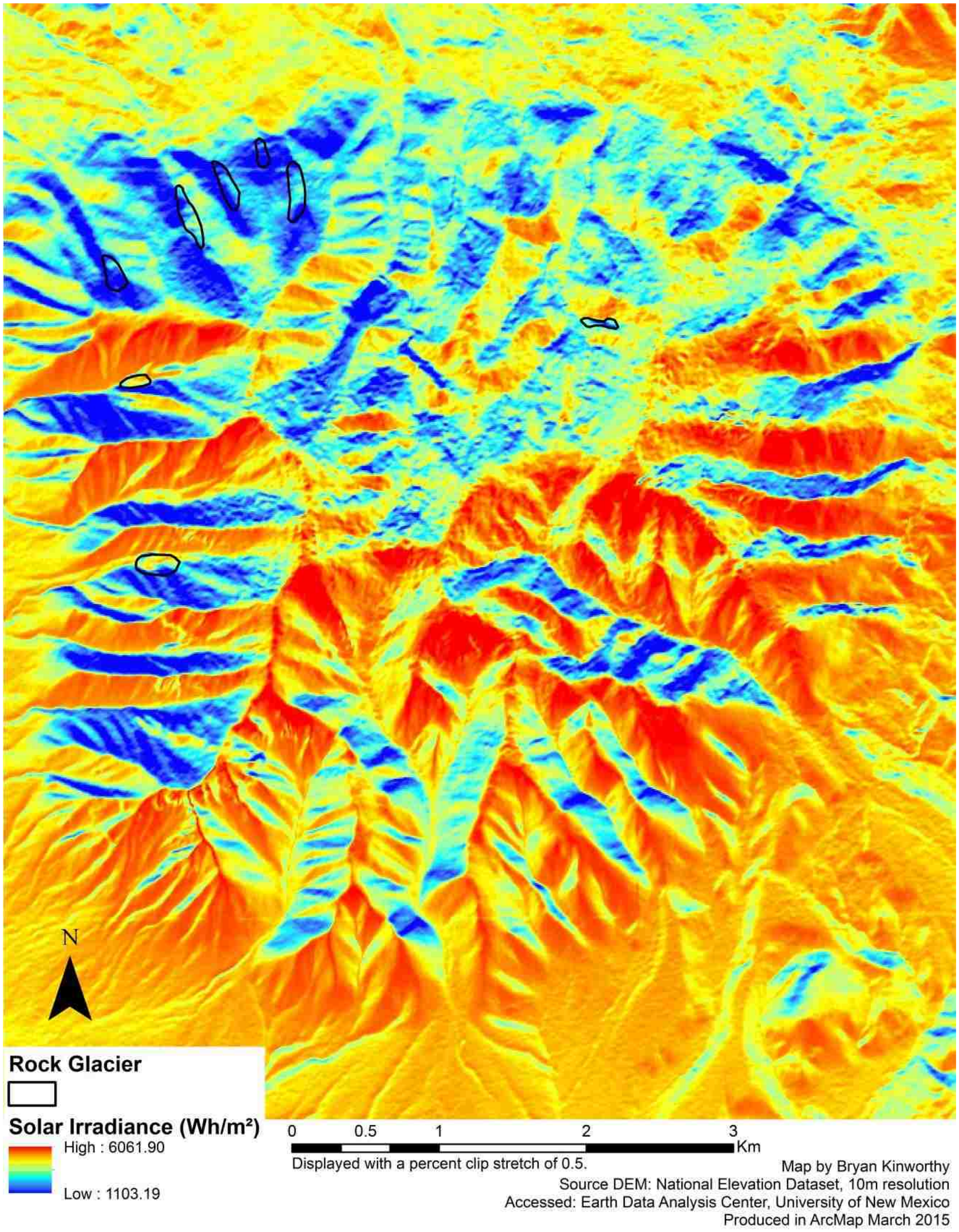
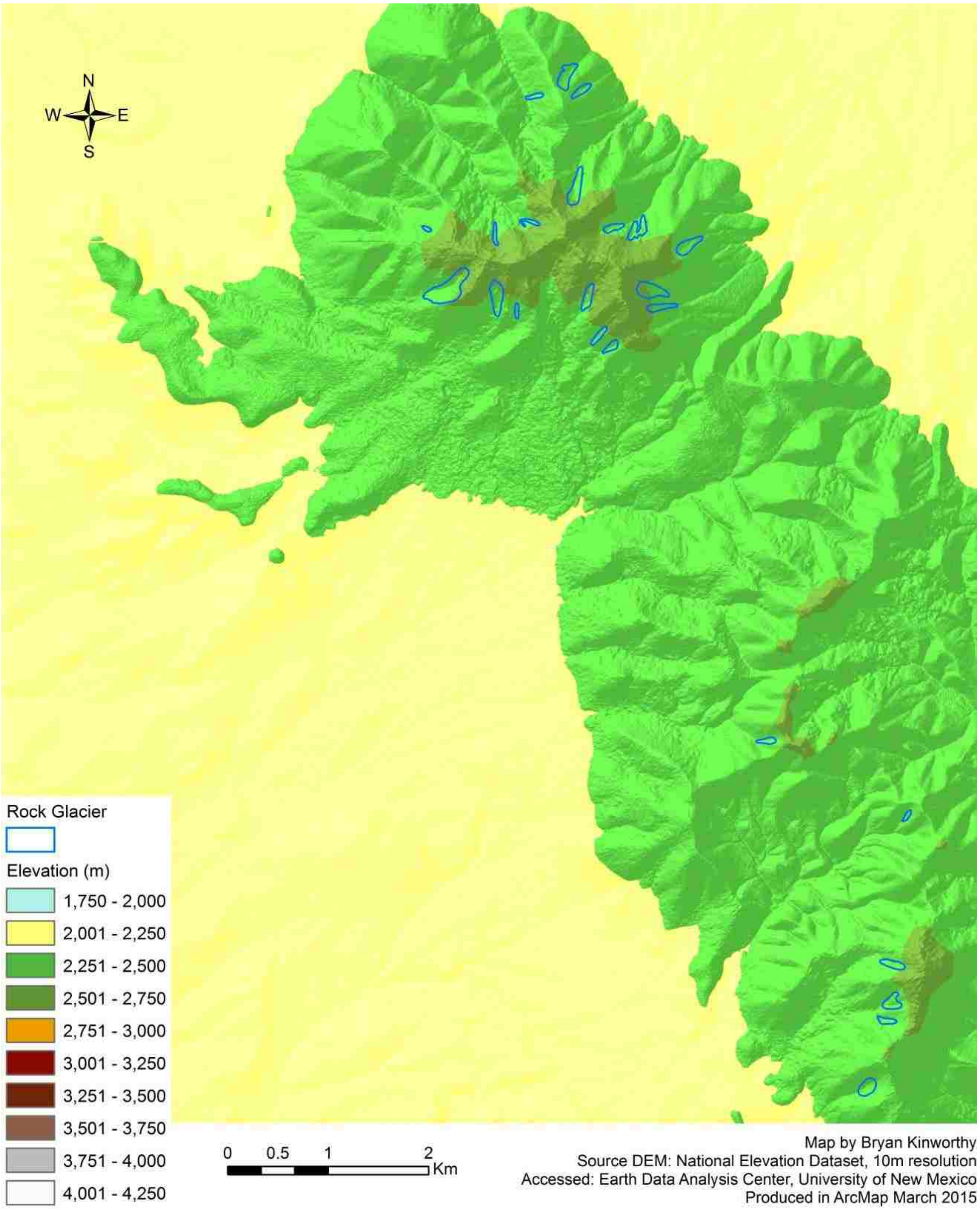


Figure B2 Equinox solar irradiance on Carrizo Mountain.



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B3 Rock glacier elevations in the Gallinas Mountains.

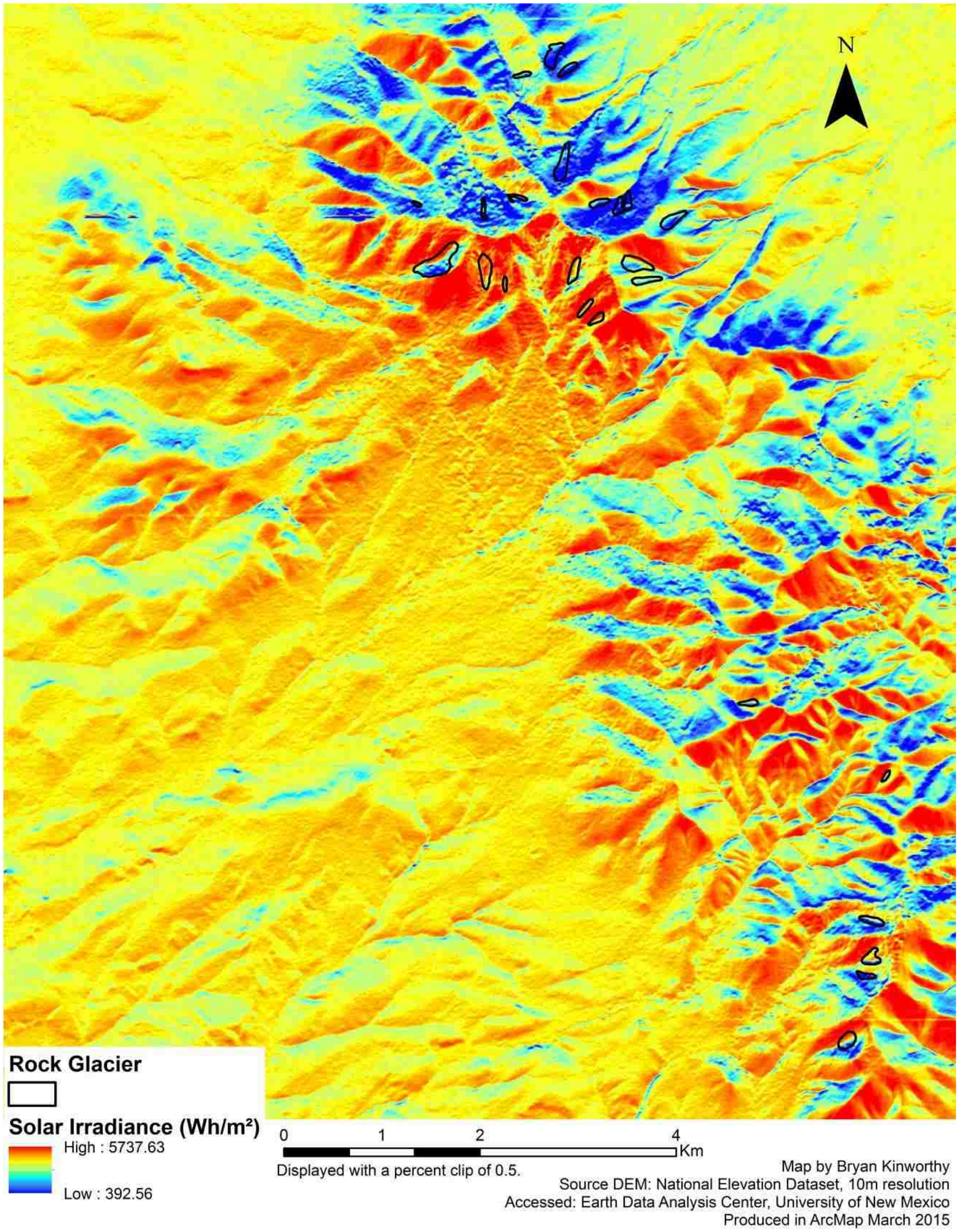
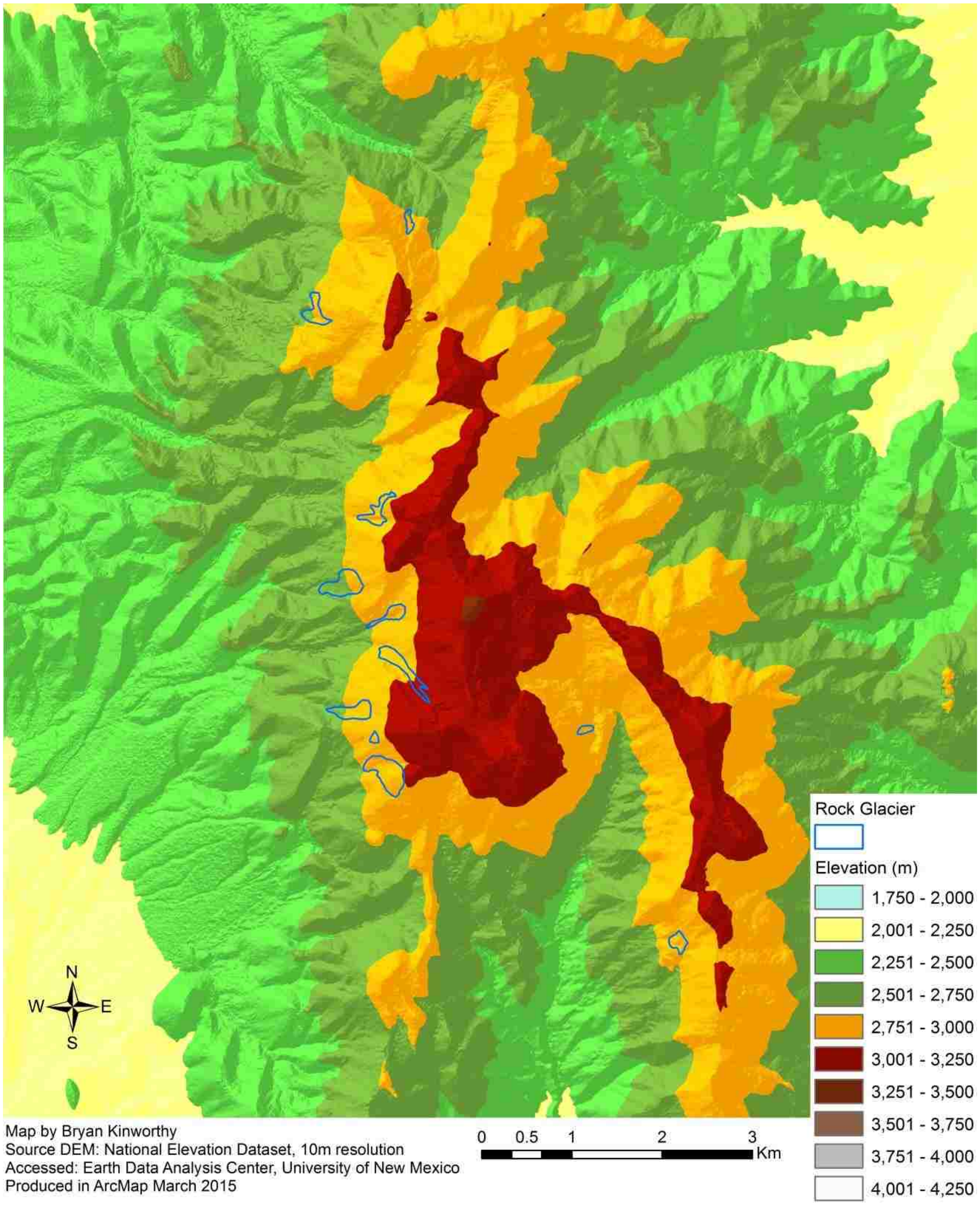
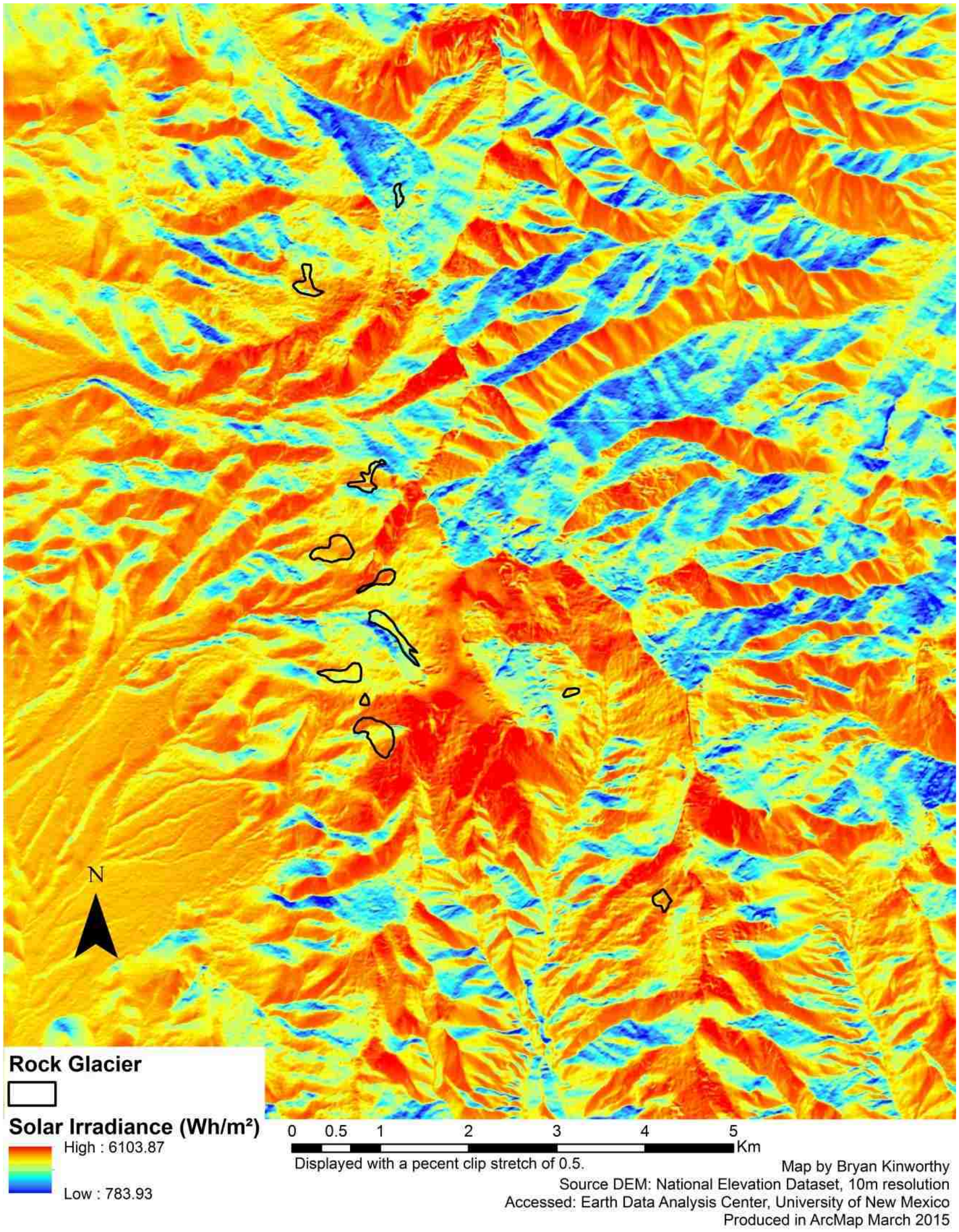


Figure B4 Solar irradiance in the Gallinas Mountains.



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B5 Rock glacier elevations in the Magdalena Mountains.



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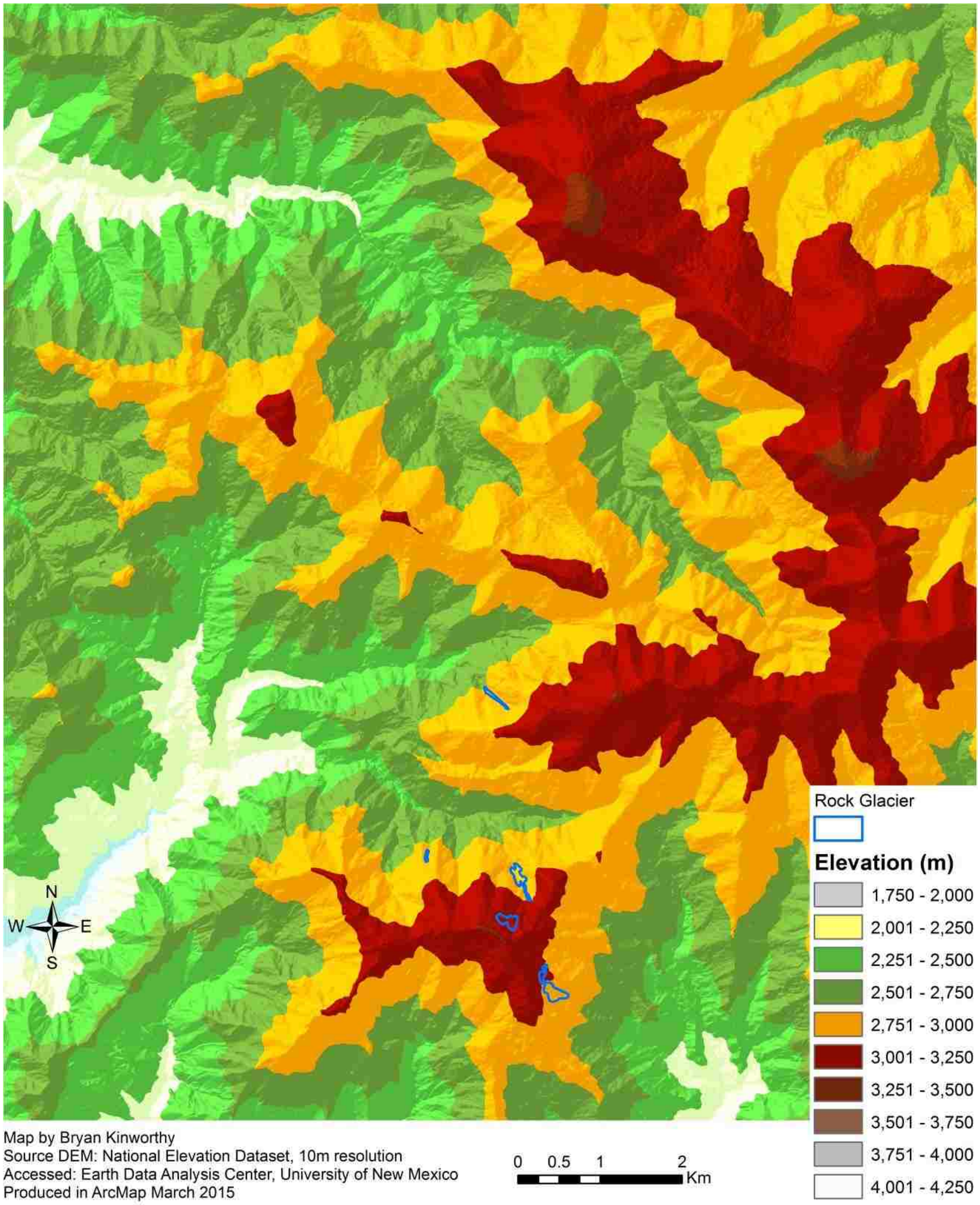
Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B6 Solar irradiance in the Magdalena Mountains.



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B7 Rock glacier elevations in the Mogollon Mountains.

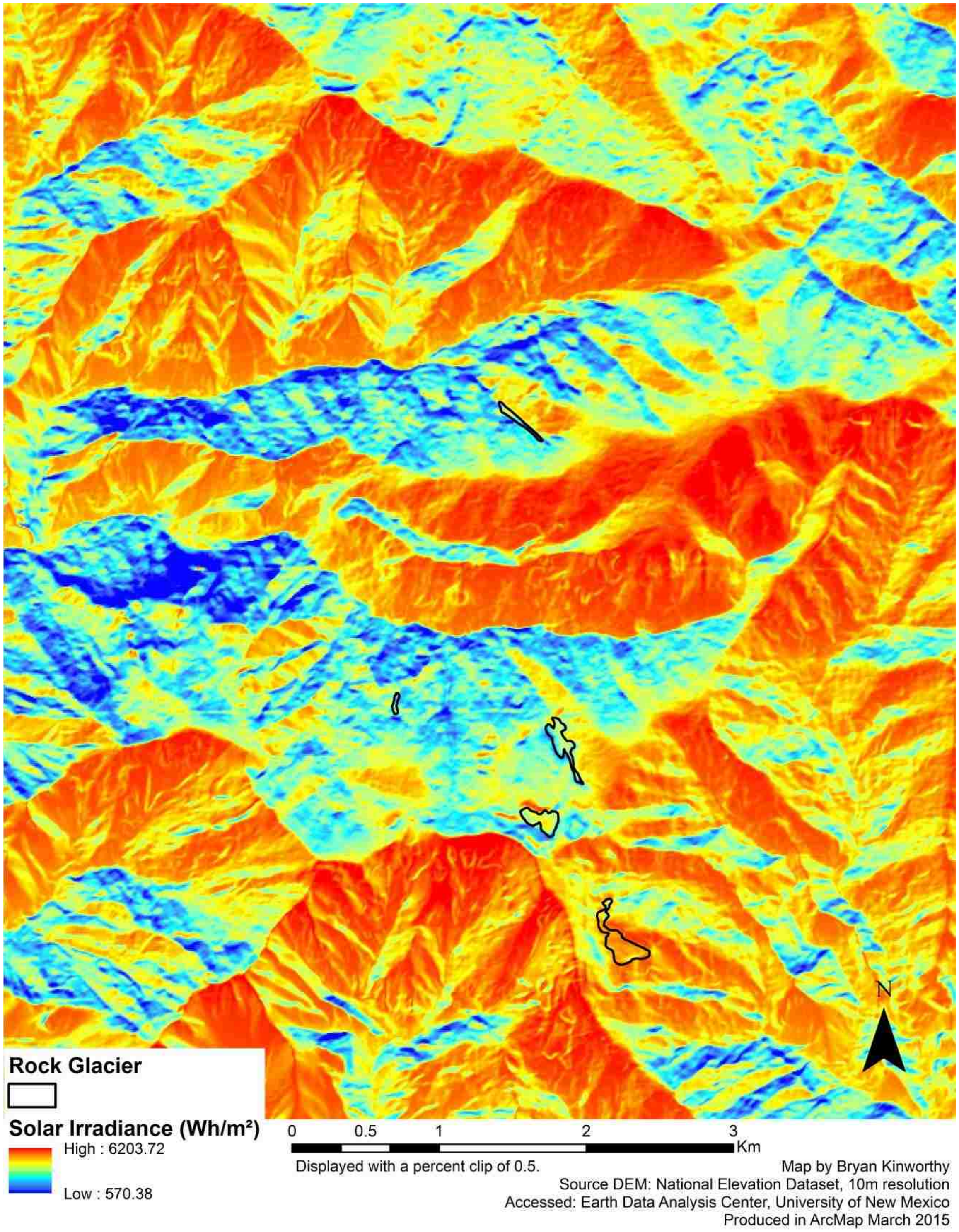
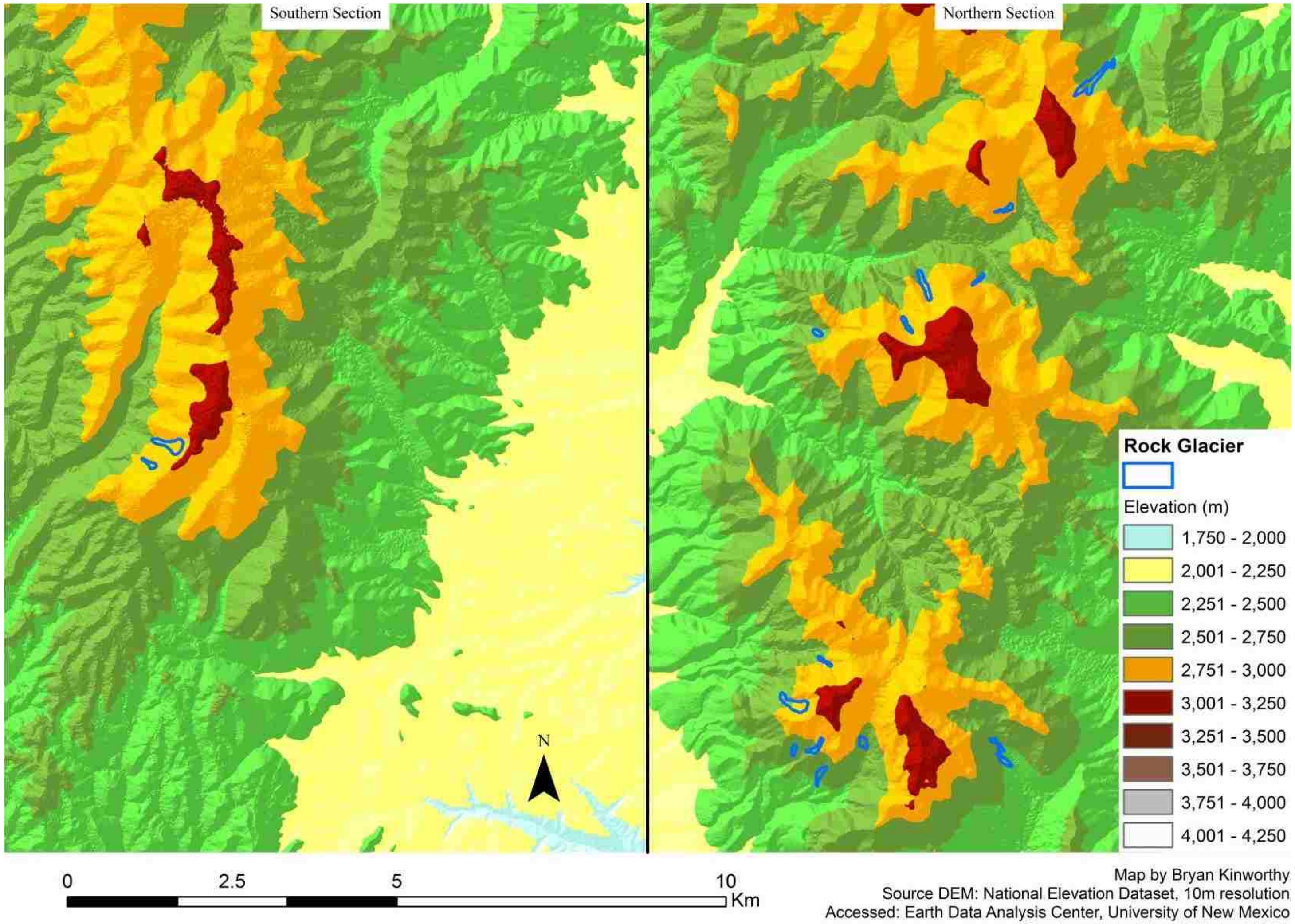
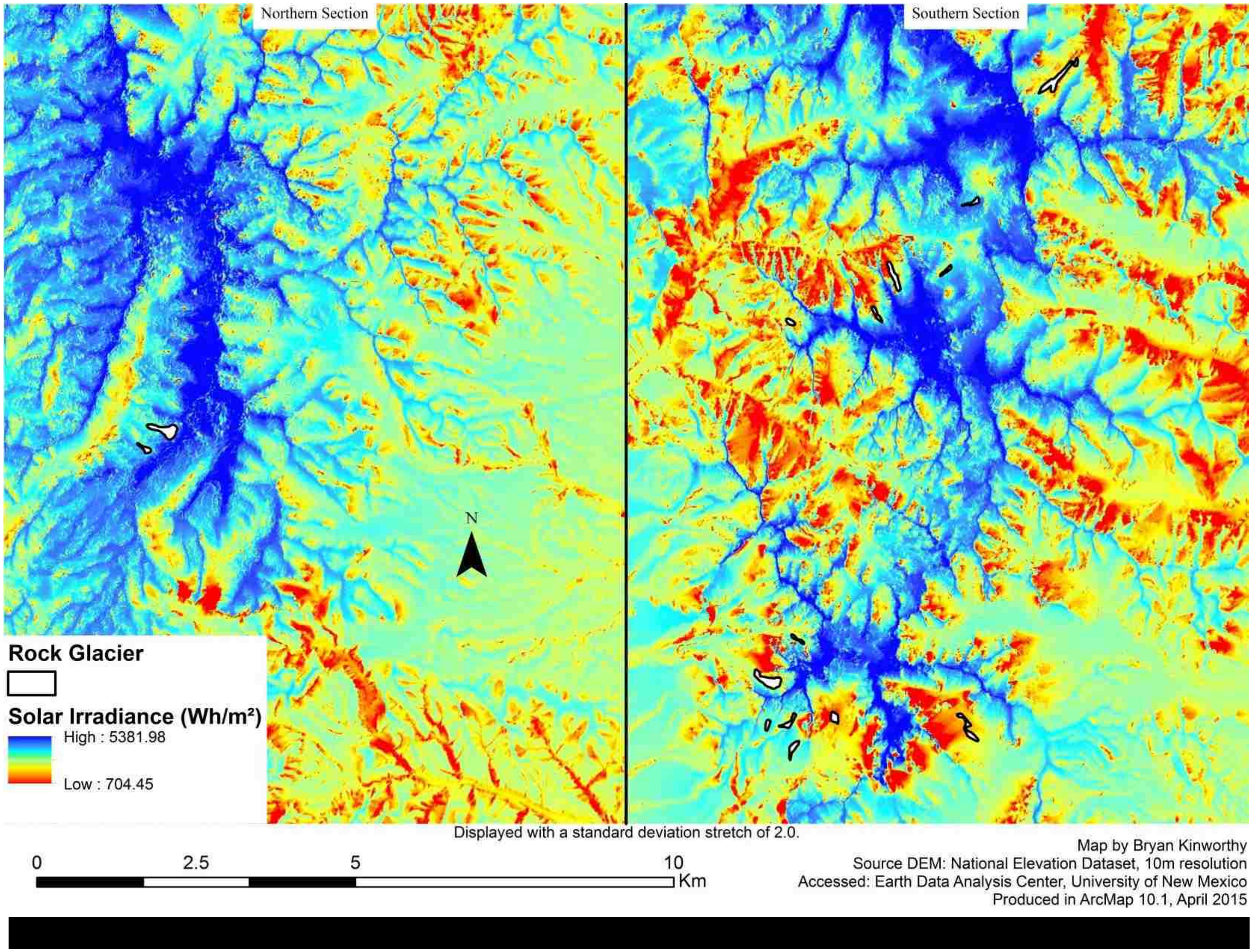


Figure B8 Equinox solar irradiance in the Mogollon Mountains.

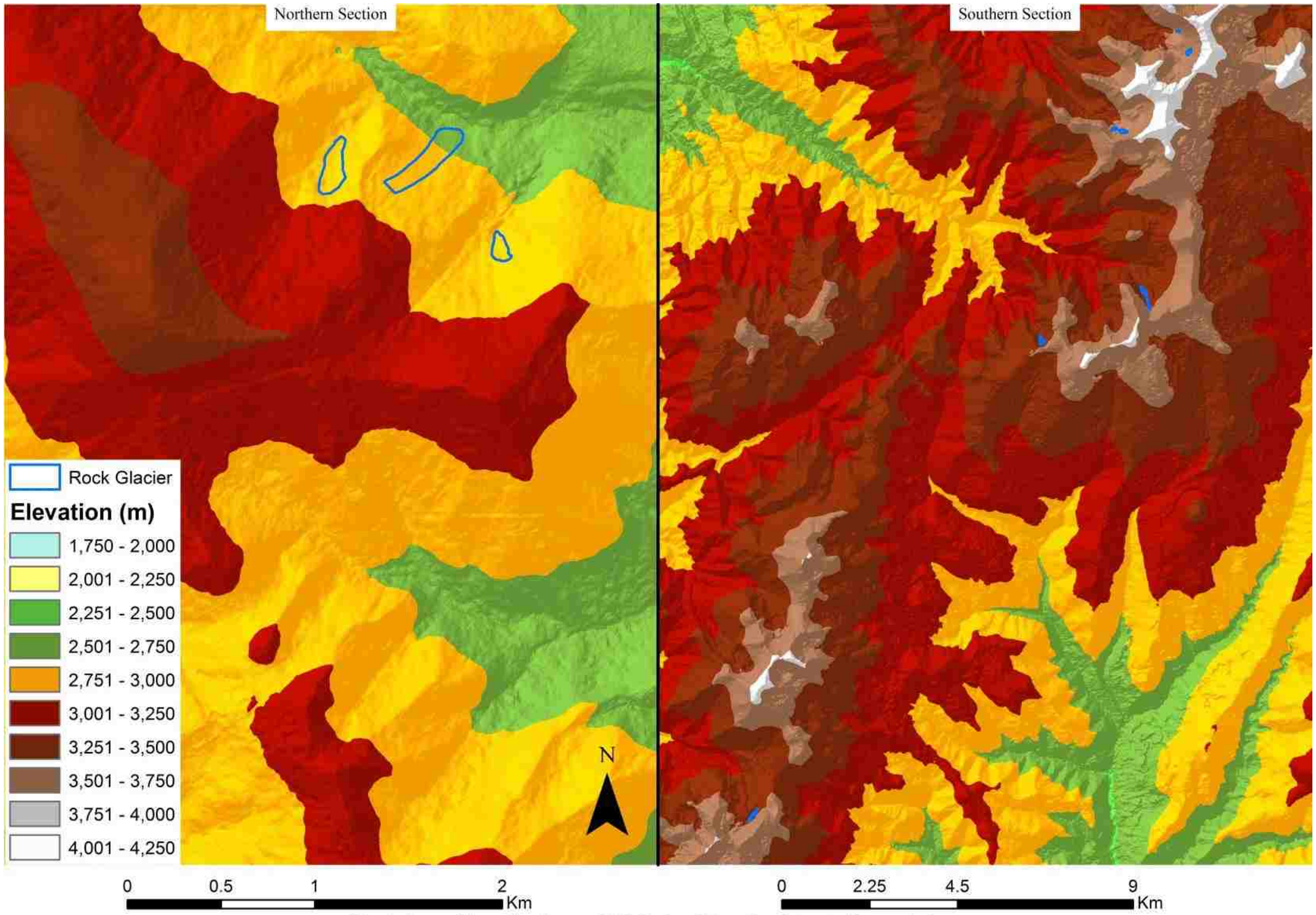


Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap 10.1, April 2015



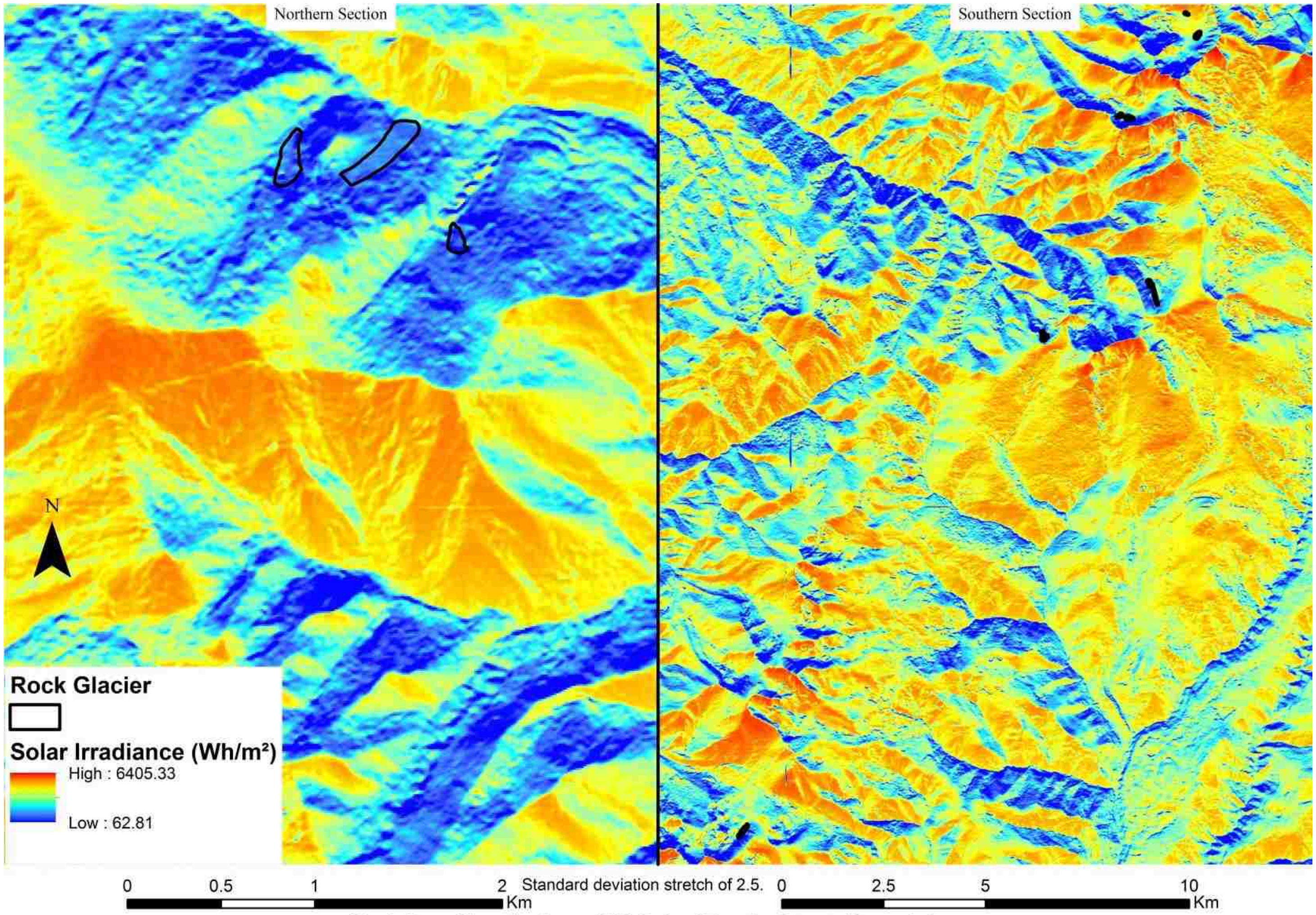
Displayed with a standard deviation stretch of 2.0.

Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap 10.1, April 2015

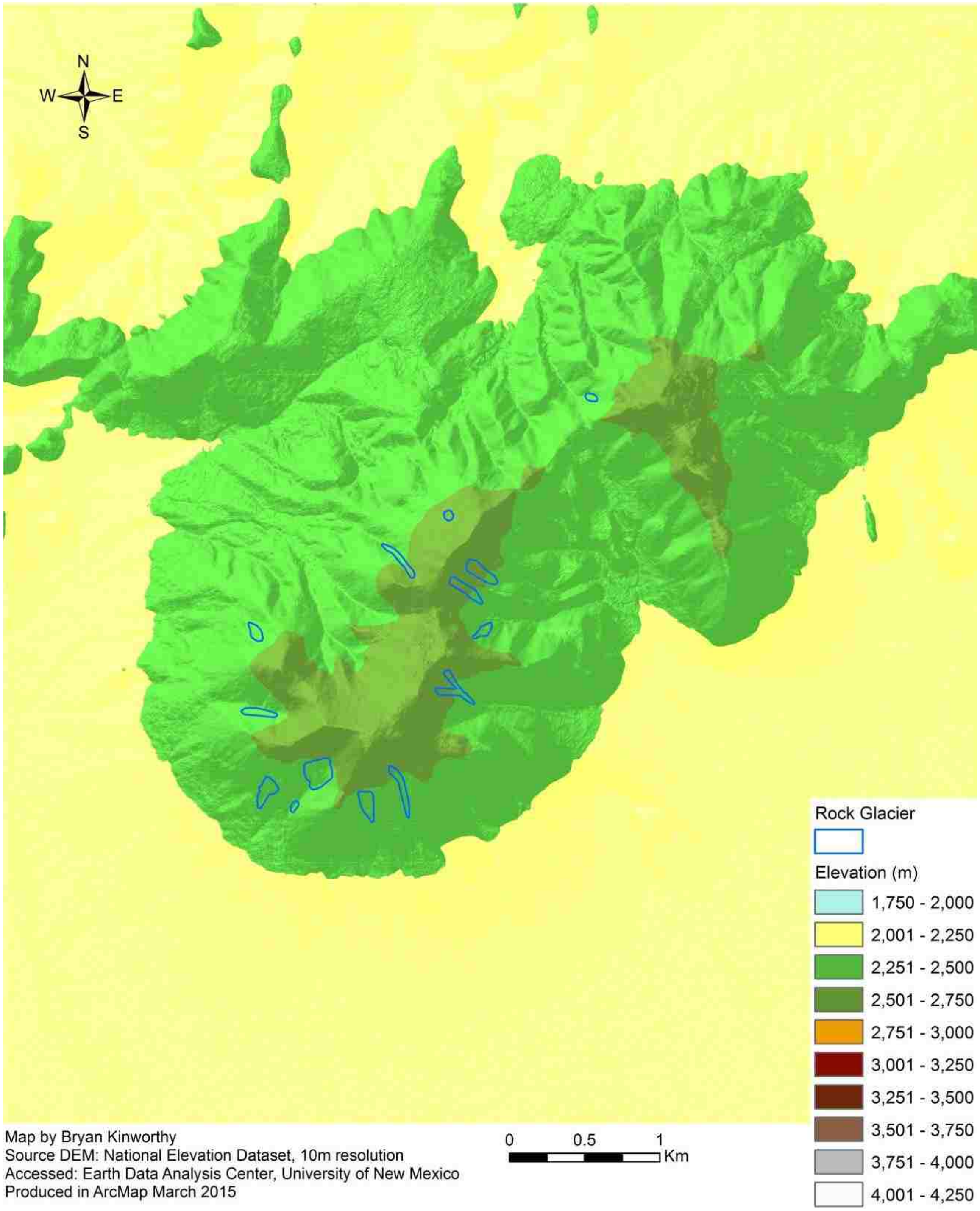


Map by Bryan Kinworthy. Source DEM: National Elevation Dataset, 10m resolution.
Accessed: Earth Data Analysis Center, University of New Mexico. Produced in ArcMap March 2015

[redacted]



Map by Bryan Kinworthy. Source DEM: National Elevation Dataset, 10m resolution.
Accessed: Earth Data Analysis Center, University of New Mexico. Produced in ArcMap March 2015



Map by Bryan Kinworthy
Source DEM: National Elevation Dataset, 10m resolution
Accessed: Earth Data Analysis Center, University of New Mexico
Produced in ArcMap March 2015

Figure B13 Rock glacier elevations on South Mountain.

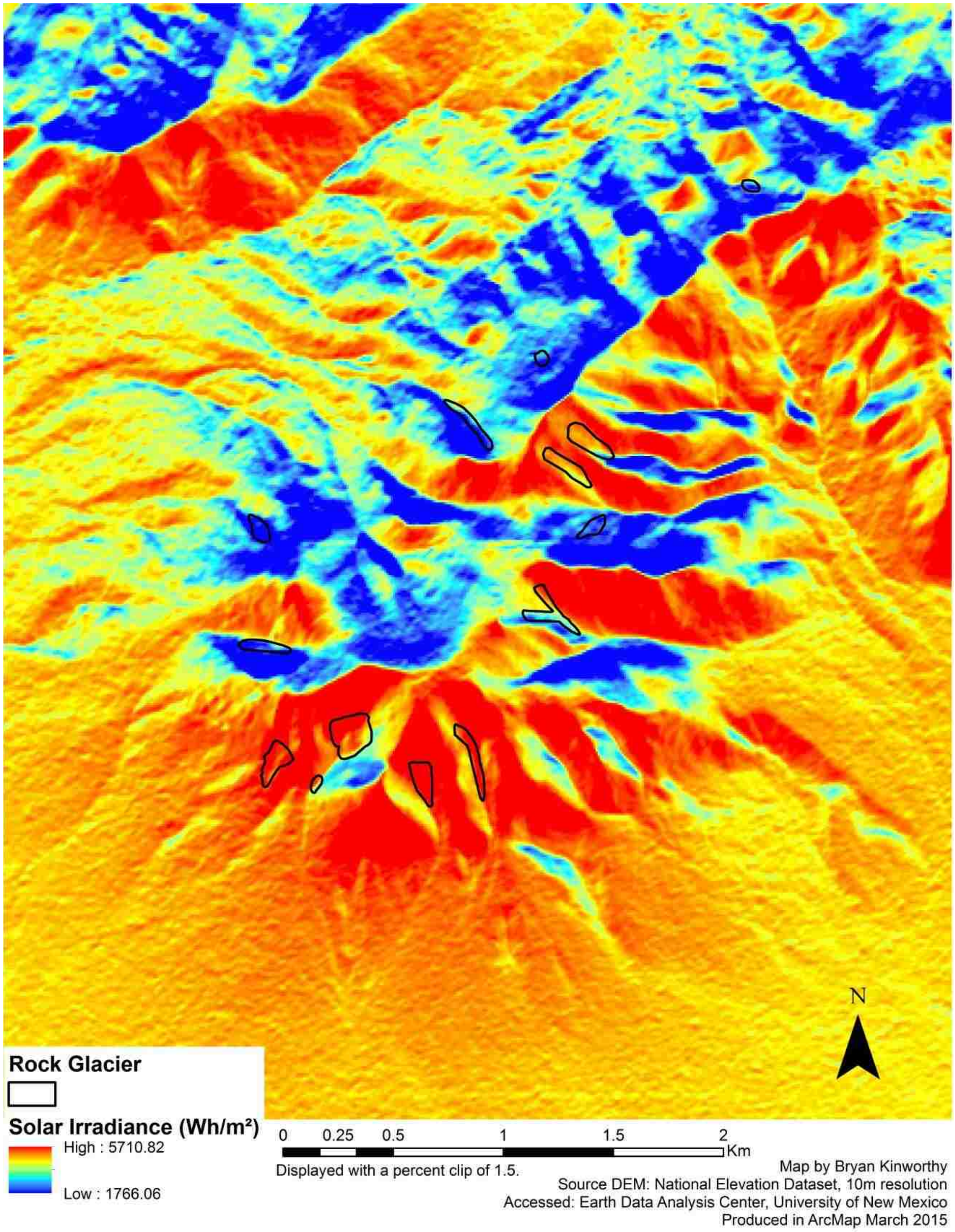


Figure B14 Equinox solar irradiance on South Mountain.

Appendix C: New Mexico Rock Glacier Locations

Table C1 Rock Glacier locations

Mountain Range	Latitude	Longitude	Mountain Range	Latitude	Longitude
Animas Mts.	31.5676	-108.7914	Capitan Mts.	33.5990	-105.3146
Capitan Mts.	33.6218	-105.3783	Capitan Mts.	33.6083	-105.3440
Capitan Mts.	33.6368	-105.3965	Capitan Mts.	33.6085	-105.3481
Capitan Mts.	33.5931	-105.2239	Capitan Mts.	33.6224	-105.3513
Capitan Mts.	33.5839	-105.2613	Capitan Mts.	33.6104	-105.3498
Capitan Mts.	33.5909	-105.2589	Capitan Mts.	33.6308	-105.4180
Capitan Mts.	33.5926	-105.2530	Capitan Mts.	33.6301	-105.3549
Capitan Mts.	33.5872	-105.2607	Capitan Mts.	33.6273	-105.3844
Capitan Mts.	33.5883	-105.2629	Capitan Mts.	33.6363	-105.3629
Capitan Mts.	33.6028	-105.2572	Capitan Mts.	33.6146	-105.3774
Capitan Mts.	33.5880	-105.2423	Capitan Mts.	33.6258	-105.3572
Capitan Mts.	33.5905	-105.2610	Capitan Mts.	33.6169	-105.3625
Capitan Mts.	33.5914	-105.2280	Capitan Mts.	33.6337	-105.3662
Capitan Mts.	33.6121	-105.2698	Capitan Mts.	33.6294	-105.3687
Capitan Mts.	33.5929	-105.2388	Capitan Mts.	33.6237	-105.3823
Capitan Mts.	33.5985	-105.2580	Capitan Mts.	33.6299	-105.3847
Capitan Mts.	33.5887	-105.2468	Capitan Mts.	33.6324	-105.4225
Capitan Mts.	33.6230	-105.3539	Capitan Mts.	33.6350	-105.3840
Capitan Mts.	33.6016	-105.2798	Capitan Mts.	33.6352	-105.3878
Capitan Mts.	33.6036	-105.2756	Capitan Mts.	33.6326	-105.3895
Capitan Mts.	33.6147	-105.2701	Capitan Mts.	33.6261	-105.3934
Capitan Mts.	33.6055	-105.2591	Capitan Mts.	33.6299	-105.4005
Capitan Mts.	33.6003	-105.2626	Capitan Mts.	33.6329	-105.4179
Capitan Mts.	33.6101	-105.2771	Capitan Mts.	33.6301	-105.4070
Capitan Mts.	33.6155	-105.2712	Capitan Mts.	33.6410	-105.4165
Capitan Mts.	33.5969	-105.2908	Capitan Mts.	33.6409	-105.4117
Capitan Mts.	33.5996	-105.2960	Capitan Mts.	33.6180	-105.4459
Capitan Mts.	33.6001	-105.3035	Capitan Mts.	33.6350	-105.4061
Capitan Mts.	33.6082	-105.2881	Capitan Mts.	33.6343	-105.4245
Capitan Mts.	33.5984	-105.3114	Capitan Mts.	33.6382	-105.4207
Capitan Mts.	33.6144	-105.3472	Capitan Mts.	33.6348	-105.4188
Capitan Mts.	33.6033	-105.2982	Capitan Mts.	33.6358	-105.4294
Capitan Mts.	33.5991	-105.3093	Capitan Mts.	33.6260	-105.4272
Capitan Mts.	33.6164	-105.3096	Capitan Mts.	33.6330	-105.4302
Capitan Mts.	33.6246	-105.3604	Capitan Mts.	33.6382	-105.4252
Capitan Mts.	33.6155	-105.3404	Capitan Mts.	33.6334	-105.4231

Table C1 Rock glacier locations.

Mountain Range	Latitude	Longitude	Mountain Range	Latitude	Longitude
Capitan Mts.	33.6287	-105.4290	Capitan Mts.	33.6413	-105.4748
Capitan Mts.	33.6240	-105.4186	Capitan Mts.	33.6361	-105.4671
Capitan Mts.	33.6210	-105.4457	Capitan Mts.	33.6469	-105.4744
Capitan Mts.	33.6195	-105.4436	Capitan Mts.	33.6222	-105.5076
Capitan Mts.	33.6194	-105.4361	Capitan Mts.	33.6526	-105.4759
Capitan Mts.	33.6228	-105.4313	Capitan Mts.	33.6383	-105.4755
Capitan Mts.	33.6249	-105.4473	Capitan Mts.	33.6433	-105.4773
Capitan Mts.	33.6230	-105.4505	Capitan Mts.	33.6125	-105.4583
Capitan Mts.	33.6201	-105.4571	Capitan Mts.	33.6493	-105.4890
Capitan Mts.	33.6176	-105.4585	Capitan Mts.	33.5896	-105.3453
Capitan Mts.	33.6247	-105.4548	Capitan Mts.	33.6114	-105.4572
Capitan Mts.	33.6201	-105.4543	Capitan Mts.	33.6077	-105.4555
Capitan Mts.	33.6411	-105.4892	Capitan Mts.	33.6056	-105.4388
Capitan Mts.	33.6407	-105.4916	Capitan Mts.	33.6113	-105.3336
Capitan Mts.	33.6441	-105.4994	Capitan Mts.	33.6128	-105.4612
Capitan Mts.	33.6438	-105.4160	Capitan Mts.	33.5910	-105.4046
Capitan Mts.	33.6061	-105.2313	Capitan Mts.	33.6093	-105.4508
Capitan Mts.	33.6018	-105.3181	Capitan Mts.	33.6057	-105.4465
Capitan Mts.	33.6051	-105.3176	Capitan Mts.	33.6033	-105.4329
Capitan Mts.	33.6373	-105.4960	Capitan Mts.	33.6003	-105.4249
Capitan Mts.	33.6294	-105.4740	Capitan Mts.	33.5985	-105.4306
Capitan Mts.	33.6426	-105.4700	Capitan Mts.	33.5987	-105.4110
Capitan Mts.	33.6505	-105.4800	Capitan Mts.	33.5917	-105.4113
Capitan Mts.	33.6508	-105.4879	Capitan Mts.	33.5957	-105.4245
Capitan Mts.	33.6243	-105.4849	Capitan Mts.	33.5939	-105.4171
Capitan Mts.	33.6471	-105.4862	Capitan Mts.	33.5909	-105.4087
Capitan Mts.	33.6216	-105.4869	Capitan Mts.	33.5892	-105.4037
Capitan Mts.	33.6194	-105.4898	Capitan Mts.	33.5964	-105.3912
Capitan Mts.	33.6279	-105.4779	Capitan Mts.	33.5961	-105.3975
Capitan Mts.	33.6290	-105.4754	Capitan Mts.	33.5959	-105.3818
Capitan Mts.	33.6269	-105.4834	Capitan Mts.	33.5993	-105.3872
Capitan Mts.	33.6304	-105.4720	Capitan Mts.	33.5957	-105.3926
Capitan Mts.	33.6416	-105.4787	Capitan Mts.	33.5898	-105.3436
Capitan Mts.	33.6327	-105.4707	Capitan Mts.	33.5984	-105.3701
Capitan Mts.	33.6353	-105.4701	Capitan Mts.	33.5954	-105.3483
Capitan Mts.	33.6340	-105.4705	Capitan Mts.	33.5999	-105.3620

Table C1 Rock glacier locations continued.

Mountain Range	Latitude	Longitude	Mountain Range	Latitude	Longitude
Capitan Mts.	33.5867	-105.3377	Capitan Mts.	33.5815	-105.2919
Capitan Mts.	33.6166	-105.3331	Capitan Mts.	33.5804	-105.2912
Capitan Mts.	33.5981	-105.3593	Capitan Mts.	33.5810	-105.2848
Capitan Mts.	33.5873	-105.3472	Capitan Mts.	33.5805	-105.2813
Capitan Mts.	33.5870	-105.3484	Capitan Mts.	33.5814	-105.2771
Capitan Mts.	33.5971	-105.3407	Capitan Mts.	33.5833	-105.2734
Capitan Mts.	33.6050	-105.3341	Capitan Mts.	33.5842	-105.2680
Capitan Mts.	33.5862	-105.3438	Capitan Mts.	33.5830	-105.2630
Capitan Mts.	33.5831	-105.3425	Capitan Mts.	33.5787	-105.2615
Capitan Mts.	33.6110	-105.3193	Capitan Mts.	33.5840	-105.2599
Capitan Mts.	33.6021	-105.3258	Capitan Mts.	33.5808	-105.2411
Capitan Mts.	33.6206	-105.3359	Capitan Mts.	33.5805	-105.2953
Capitan Mts.	33.6186	-105.3387	Capitan Mts.	33.5906	-105.2747
Capitan Mts.	33.6279	-105.4334	Capitan Mts.	33.6374	-105.3653
Capitan Mts.	33.5928	-105.3536	Capitan Mts.	33.6389	-105.3986
Capitan Mts.	33.5850	-105.3800	Capitan Mts.	33.6392	-105.4006
Capitan Mts.	33.5919	-105.3809	Capitan Mts.	33.6228	-105.4278
Capitan Mts.	33.5902	-105.3330	Capitan Mts.	33.6233	-105.4933
Capitan Mts.	33.5820	-105.3323	Capitan Mts.	33.6241	-105.4959
Capitan Mts.	33.5945	-105.2200	Carrizo Mt.	33.7014	-105.7410
Capitan Mts.	33.5918	-105.3756	Carrizo Mt.	33.7135	-105.7344
Capitan Mts.	33.5922	-105.3706	Carrizo Mt.	33.7155	-105.7319
Capitan Mts.	33.6374	-105.4671	Carrizo Mt.	33.7116	-105.7372
Capitan Mts.	33.6171	-105.3514	Carrizo Mt.	33.7052	-105.7070
Capitan Mts.	33.6320	-105.4353	Carrizo Mt.	33.7132	-105.7294
Capitan Mts.	33.6328	-105.4354	Carrizo Mt.	33.6902	-105.7393
Capitan Mts.	33.5921	-105.3259	Carrizo Mt.	33.7080	-105.7427
Capitan Mts.	33.5875	-105.3171	Gallinas Mts.	34.2509	-105.7867
Capitan Mts.	33.5877	-105.3136	Gallinas Mts.	34.2495	-105.7813
Capitan Mts.	33.5892	-105.3098	Gallinas Mts.	34.2454	-105.7853
Capitan Mts.	33.5901	-105.3065	Gallinas Mts.	34.2439	-105.7842
Capitan Mts.	33.5868	-105.3047	Gallinas Mts.	34.2510	-105.7894
Capitan Mts.	33.5855	-105.2986	Gallinas Mts.	34.2545	-105.7935
Capitan Mts.	33.5871	-105.2996	Gallinas Mts.	34.2633	-105.7929
Capitan Mts.	33.5826	-105.2932	Gallinas Mts.	34.2646	-105.7946
Capitan Mts.	33.5820	-105.2883	Gallinas Mts.	34.2628	-105.7980

Table C1 Rock glacier locations continued.

Mountain Range	Latitude	Longitude	Mountain Range	Latitude	Longitude
Gallinas Mts.	34.2515	-105.7984	Magdalena Mts.	33.9804	-107.2021
Gallinas Mts.	34.2508	-105.8095	Magdalena Mts.	33.9848	-107.1963
Gallinas Mts.	34.2454	-105.8072	Magdalena Mts.	33.9580	-107.1626
Gallinas Mts.	34.2448	-105.8019	Magdalena Mts.	33.9901	-107.1978
Gallinas Mts.	34.2435	-105.7997	Magdalena Mts.	34.0295	-107.1967
Gallinas Mts.	34.2448	-105.7921	Magdalena Mts.	33.9777	-107.1995
Gallinas Mts.	34.2413	-105.7908	Magdalena Mts.	33.9790	-107.1743
Gallinas Mts.	34.2404	-105.7895	Magdalena Mts.	34.0004	-107.1998
Gallinas Mts.	34.2503	-105.8021	Magdalena Mts.	34.0202	-107.2077
Gallinas Mts.	34.1851	-105.7585	Mogollon Mts.	33.2659	-108.6784
Gallinas Mts.	34.1741	-105.7612	Mogollon Mts.	33.2779	-108.6831
Gallinas Mts.	34.1817	-105.7586	Mogollon Mts.	33.2976	-108.6872
Gallinas Mts.	34.1801	-105.7592	Mogollon Mts.	33.2799	-108.6953
Gallinas Mts.	34.1985	-105.7571	Mogollon Mts.	33.2731	-108.6844
Gallinas Mts.	34.2051	-105.7723	NSDC Mts.	36.8000	-105.4623
Jemez Mts.	35.8873	-106.5604	NSDC Mts.	36.4459	-105.0279
Jemez Mts.	35.8586	-106.5839	NSDC Mts.	36.6283	-105.4815
Jemez Mts.	35.8624	-106.5800	NSDC Mts.	36.6442	-105.4616
Jemez Mts.	35.8537	-106.5751	NSDC Mts.	36.6655	-105.4536
Jemez Mts.	35.8668	-106.5799	NSDC Mts.	36.7994	-105.4751
Jemez Mts.	35.8837	-106.5685	NSDC Mts.	36.4439	-105.0353
Jemez Mts.	35.8748	-106.5705	NSDC Mts.	36.4447	-105.0334
Jemez Mts.	35.8883	-106.5448	NSDC Mts.	36.9641	-105.3087
Jemez Mts.	35.9314	-106.4852	NSDC Mts.	36.9691	-105.3159
Jemez Mts.	35.8687	-106.5847	NSDC Mts.	36.9869	-105.3272
Jemez Mts.	35.8786	-106.5703	NSDC Mts.	36.9694	-105.3185
Jemez Mts.	35.8747	-106.5731	NSDC Mts.	36.9676	-105.3173
Jemez Mts.	35.8676	-106.5773	NSDC Mts.	36.9693	-105.3046
Jemez Mts.	35.8827	-106.5654	NSDC Mts.	36.9421	-105.3025
Jemez Mts.	35.8863	-106.5630	NSDC Mts.	36.8162	-105.4730
Jemez Mts.	35.8930	-106.5472	NSDC Mts.	36.9704	-105.3200
Jemez Mts.	35.8918	-106.5504	NSDC Mts.	36.9640	-105.2972
Jemez Mts.	35.8894	-106.5530	NSDC Mts.	36.9794	-105.3290
Jemez Mts.	35.8903	-106.5509	NSDC Mts.	36.9545	-105.3128
Magdalena Mts.	33.9930	-107.2037	NSDC Mts.	36.9786	-105.3256
Magdalena Mts.	33.9742	-107.1979	NSDC Mts.	36.9261	-105.3274

Note: NSDC – northern Sangre de Cristo.

Table C1 Rock glacier locations continued.

Mountain Range	Latitude	Longitude	Mountain Range	Latitude	Longitude
NSDC Mts.	36.7814	-105.4552	NSDC Mts.	36.5534	-105.3912
NSDC Mts.	36.7823	-105.4850	NSDC Mts.	36.5568	-105.3918
NSDC Mts.	36.9820	-105.3323	NSDC Mts.	36.5598	-105.3881
NSDC Mts.	36.6164	-105.5010	NSDC Mts.	36.5496	-105.3974
NSDC Mts.	36.8061	-105.5022	NSDC Mts.	36.5230	-105.4289
NSDC Mts.	36.8033	-105.4838	NSDC Mts.	36.4997	-105.4830
NSDC Mts.	36.7972	-105.4916	NSDC Mts.	36.5274	-105.4349
NSDC Mts.	36.7860	-105.4566	NSDC Mts.	36.5304	-105.4252
NSDC Mts.	36.7896	-105.4637	NSDC Mts.	36.5423	-105.4652
NSDC Mts.	36.7761	-105.4818	NSDC Mts.	36.5312	-105.4335
NSDC Mts.	36.7995	-105.4837	NSDC Mts.	36.5371	-105.4355
NSDC Mts.	36.7765	-105.4912	NSDC Mts.	36.5329	-105.4246
NSDC Mts.	36.7962	-105.4888	NSDC Mts.	36.5350	-105.4690
NSDC Mts.	36.7806	-105.5019	NSDC Mts.	36.5560	-105.5064
NSDC Mts.	36.8020	-105.4919	NSDC Mts.	36.5323	-105.4700
NSDC Mts.	36.7927	-105.4556	NSDC Mts.	36.5103	-105.4345
NSDC Mts.	36.6261	-105.4681	NSDC Mts.	36.5298	-105.4764
NSDC Mts.	36.7876	-105.4789	NSDC Mts.	36.4964	-105.5029
NSDC Mts.	36.8040	-105.4686	NSDC Mts.	36.5021	-105.4978
NSDC Mts.	36.5741	-105.4054	NSDC Mts.	36.5542	-105.4787
NSDC Mts.	36.8097	-105.4908	NSDC Mts.	36.5529	-105.4965
NSDC Mts.	36.7805	-105.4732	NSDC Mts.	36.5520	-105.4949
NSDC Mts.	36.7699	-105.4903	NSDC Mts.	36.5545	-105.4752
NSDC Mts.	36.7937	-105.4802	NSDC Mts.	36.5532	-105.4749
NSDC Mts.	36.5728	-105.3989	NSDC Mts.	36.5542	-105.4366
NSDC Mts.	36.5429	-105.4590	NSDC Mts.	36.5446	-105.4676
NSDC Mts.	36.6420	-105.4676	NSDC Mts.	36.5406	-105.4577
NSDC Mts.	36.5751	-105.4037	NSDC Mts.	36.5466	-105.4365
NSDC Mts.	36.6105	-105.4560	NSDC Mts.	36.5358	-105.4543
NSDC Mts.	36.5691	-105.4080	NSDC Mts.	36.5695	-105.4438
NSDC Mts.	36.6152	-105.5067	NSDC Mts.	36.5480	-105.4410
NSDC Mts.	36.4966	-105.4858	NSDC Mts.	36.5676	-105.4451
NSDC Mts.	36.5630	-105.4061	NSDC Mts.	36.5661	-105.4399
NSDC Mts.	36.5645	-105.4096	NSDC Mts.	36.5710	-105.4435
NSDC Mts.	36.5239	-105.4423	NSDC Mts.	36.5435	-105.4269
NSDC Mts.	36.5537	-105.4014	NSDC Mts.	36.5489	-105.4209

Note: NSDC – northern Sangre de Cristo.

Table C1 Rock glacier locations continued.

Mountain Range	Latitude	Longitude
NSDC Mts.	36.5519	-105.4232
NSDC Mts.	36.9952	-105.2903
NSDC Mts.	36.6395	-105.4657
NSDC Mts.	36.9685	-105.3550
NSDC Mts.	36.5517	-105.4063
NSDC Mts.	36.5430	-105.3994
NSDC Mts.	36.7755	-105.4946
NSDC Mts.	36.5579	-105.3840
NSDC Mts.	36.9819	-105.3472
NSDC Mts.	36.9486	-105.3510
NSDC Mts.	36.7918	-105.4772
NSDC Mts.	36.9775	-105.3031
NSDC Mts.	36.9382	-105.3027
NSDC Mts.	36.7860	-105.5043
NSDC Mts.	36.7882	-105.5087
NSDC Mts.	36.6261	-105.4775
NSDC Mts.	36.6120	-105.4577
NSDC Mts.	36.5557	-105.3795
NSDC Mts.	36.5569	-105.4538
NSDC Mts.	36.6145	-105.5535
NSDC Mts.	36.6167	-105.4668
NSDC Mts.	36.6142	-105.5562
San Mateo Mts.	33.7940	-107.4684
San Mateo Mts.	33.7913	-107.4717
San Mateo Mts.	33.6184	-107.4360
San Mateo Mts.	33.6467	-107.4096
San Mateo Mts.	33.5544	-107.4556
San Mateo Mts.	33.6194	-107.4272
San Mateo Mts.	33.6129	-107.4388
San Mateo Mts.	33.6493	-107.4060
San Mateo Mts.	33.6735	-107.4424
San Mateo Mts.	33.6291	-107.4229
San Mateo Mts.	33.5606	-107.4556
San Mateo Mts.	33.5548	-107.4520
San Mateo Mts.	33.5511	-107.4512
San Mateo Mts.	33.5545	-107.4217
San Mateo Mts.	33.6115	-107.4534
San Mateo Mts.	33.6769	-107.4336
San Mateo Mts.	33.5666	-107.4509
San Mateo Mts.	33.6794	-107.4380
San Mateo Mts.	33.5556	-107.4443
Sierra Blanca	33.4021	-105.8251
South Mt.	35.1819	-106.2241
South Mt.	35.1974	-106.2148
South Mt.	35.1799	-106.2258
South Mt.	35.1870	-106.2143
South Mt.	35.1903	-106.2288
South Mt.	35.1947	-106.2183
South Mt.	35.1808	-106.2279
South Mt.	35.1940	-106.2124
South Mt.	35.1905	-106.2121
South Mt.	35.2046	-106.2045
South Mt.	35.1930	-106.2135
South Mt.	35.1855	-106.2285
South Mt.	35.1801	-106.2205
South Mt.	35.1810	-106.2180
SSDC Mts.	35.9611	-105.6573
SSDC Mts.	35.9231	-105.6507
SSDC Mts.	35.9125	-105.6800
SSDC Mts.	36.2386	-105.2732
SSDC Mts.	36.2429	-105.2776
SSDC Mts.	36.2424	-105.2832
SSDC Mts.	35.8021	-105.7609
SSDC Mts.	35.9795	-105.6388
SSDC Mts.	35.9844	-105.6419
SSDC Mts.	35.9616	-105.6598

Note: NSDC – northern Sangre de Cristo; SSDC – southern Sangre de Cristo.

Appendix D: Elevation, Climate and Solar Irradiance Data

Table D1 Average rock glacier elevation by study site (m).

Study Site	Min	SD	Mean	SD	Med	SD	Max	SD	Rng	SD
Cap	2440	110	2521	125	2522	125	2600	151	160	86
Gal	2399	45	2442	42	2442	43	2485	45	86	34
Jem	2922	138	2966	129	2966	130	3013	124	91	53
Mag	2751	71	2836	71	2838	69	2909	90	158	86
Mog	2865	137	2919	130	2917	132	2984	119	119	48
NSDC	3400	207	3454	203	3437	204	3486	202	95	70
SanMat	2650	114	2717	109	2717	110	2782	115	132	82
SoMt	2403	56	2453	60	2454	60	2500	71	98	50
SSDC	3643	71	3684	73	3686	74	3728	73	177	108

Min: minimum, SD: standard deviation, Med: median, Max: maximum, Rng: Range. See Table 4.1 for study site abbreviations.

Table D2 Average rock glacier temperatures by study site (°C).

Study Site	Maximum MAAT			MAAT			Minimum MAAT		
	Mean	SD	Rng	Mean	SD	Rng	Mean	SD	Rng
Cap	15.45	0.21	0.57	8.22	0.13	0.33	2.43	0.13	0.34
Gal	15.63	0.05	0.10	8.26	0.02	0.04	0.84	0.04	0.10
Jem	10.83	0.20	0.49	4.98	0.16	0.39	-1.82	0.14	0.33
Mag	14.08	0.39	0.89	7.98	0.28	0.64	1.00	0.36	0.82
Mog	11.77	0.44	1.08	5.03	0.43	0.92	0.72	0.40	1.04
NSDC	7.50	0.19	0.47	2.25	0.20	0.51	-5.12	0.19	0.46
SanMat	14.55	0.27	0.68	8.02	0.22	0.52	1.93	0.27	0.69
SoMt	15.38	0.09	0.19	6.78	0.01	0.03	0.62	0.05	0.11
SSDC	8.97	0.14	0.36	4.57	0.36	0.97	-3.72	0.12	0.28

SD: standard deviation, Rng: range. See Table 4.1 for study site abbreviations.

Table D3 Average rock glacier MAP by study site.

Study Site	Mean	SD	Rng
Cap	723	9	25
Gal	512	1	2
Jem	751	6	14
Mag	676	9	21
Mog	752	16	35
NSDC	852	6	16
SanMat	584	4	12
SoMt	639	0	1
SSDC	1221	2	6

SD: standard deviation, Rng: range. See Table 4.1 for study site abbreviations.

Table D4 Average rock glacier solar irradiance by study site (Wh/m^2)

	Summer Solstice		Equinox		Winter Solstice	
Study Site	Rock Glacier	Study Site	Rock Glacier	Study Site	Rock Glacier	Study Site
Cap	5195	6956	4330	4656	1656	1847
Gal	6687	7155	4206	4739	1515	1843
Jem	7821	6614	4999	4531	1459	1899
Mag	6968	7769	4683	5044	1899	1850
Mog	6738	6834	3860	4565	1119	1814
NSDC	7731	7536	4825	4795	1381	1664
SanMat	7193	7206	4766	4809	1472	1816
SoMt	6611	7109	4414	4660	1711	1759
SSDC	7824	7230	5230	4863	2061	1746

See Table 4.1 for abbreviations.

References

Ackert, Jr., R. 1998. “A Rock Glacier/Debris-covered System at Galena Creek, Absaroka Mountains, Wyoming.” *Geografiska Annaler: Series A, Physical Geography* 80(3-4): 267-276.

Anderson, L., and D. Anderson. 1981. “Weathering Rinds on Quartzarenite Clasts as a Relative-Age Indicator and the Glacial Chronology of Mount Timpanogos, Wasatch Range, Utah.” *Arctic and Alpine Research* 13(1): 25-31.

ArcGIS Resource Center. 2011a. “How Slope Works.” Last modified June 19. http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_Slope_works/009z000000vz000000/.

ArcGIS Resource Center. 2011b. “How Solar Radiation is Calculated.” Last modified June 19. http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_solar_radiation_is_calculated/009z000000tm000000/.

Armour, J., Fawcett, P., and J. Geissman. 2002. “15 k.y. Paleoclimatic and Glacial Record from Northern New Mexico.” *Geology* 30(8): 723-726.

Average Annual Snowfall [map]. 2009. NWS: Climatology, Snow Climatology Maps. Aug 20. http://www.srh.noaa.gov/images/abq/prep/winter/snowanavg.jpg

Bachrach, T., Jakobsen, K., Kinney, J., Nishimura, P., Reyes, A., Laroque, C., and D. Smith. 2004. “Dendrogeomorphological Assessment of Movement at Hilda Creek Rock Glacier, Banff National Park, Canadian Rocky Mountains.” *Geografiska Annaler: Series A, Physical Geography* 86(1): 1-9.

Ballantyne, C., and M. Kirkbridge. 1986. “The Characteristics and Significance of some Lateglacial Protalus Ramparts in Upland Britain.” *Earth Surface Processes and Landforms* 11(6): 659-671.

Baroni, C., Carton, A., and R. Seppi. 2004. “Distribution and Behaviour of Rock Glaciers in the Adamello-Presenalla Massiff (Italian Alps).” *Permafrost and Periglacial Processes* 15(3): 243-259.

Barsch, D. 1996. *Rockglaciers: Indicators of Present and Former Geoecology in high Mountain Environments*. Berlin: Springer.

———. 1987. “The Problem of the Ice-cored Rock Glacier.” In *Rock Glaciers*, edited by J.R. Giardino, J.F. Shroder, Jr., and J.D Vitek, 45-53. Boston: Allen & Unwin.

———. 1977. “Ein Permafrostprofil aus Grabünden, Schweizer Alpen.” *Zeitschrift für Geomorphologie NF* 21(1): 79-86.

Barsch, D. and R. Updike. 1971a. “Late Pleistocene Periglacial Geomorphology (Rock Glaciers and Blockfields) at Kendrick Peak, Northern Arizona.” *Arizona Geological Society Digest* 9: 225-243.

——— 1971b. “Periglaziale Formung am Kendrick Peak in Nord-Arizona während der letzten Kaltzeit.” *Geographica Helvetica* 26: 99-114.

Berthling, I. 2011. “Beyond Confusion: Rock Glaciers as Cryo-conditioned Landforms.” *Geomorphology* 131(3-4): 98-106.

Birkeland, P. 1973. “Use of Relative Age-Dating Methods in a Statigraphic Study of Rock Glacier Deposits, Mt. Sopris, Colorado.” *Arctic and Alpine Research* 5(4): 401-416.

Blagbrough, J. 2005. “Periglacial Mass Movement Deposits of Late Wisconsin age, Gallinas Mountains, Lincoln County, central New Mexico.” *New Mexico Geology* 27(2): 31-39.

———. 1999 “Rock glaciers of two ages in the Capitan Mountains, Lincoln County, south-central New Mexico.” *New Mexico Geology* 21(3): 57-65.

———. 1994. “Late Wisconsin Climatic Inferences from Rock Glaciers in south-central and west-central New Mexico and east-central Arizona.” *New Mexico Geology* 16(4): 65-71.

———. 1991. “Late Pleistocene Rock Glaciers in the Western Part of the Capitan Mountains, New Mexico: Description, Age, and Climatic Significance.” In *New Mexico Geological Society Fall Field Conference - 42 Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico,* edited by J. M. Barker, B. S. Kues, G. S. Austin, and S. G. Lucas, 333-338. NMGS.

———. 1984. “Fossil Rock Glaciers on Carrizo Mountain, Lincoln County, New Mexico.” *New Mexico Geology* 6: 65-68.

Blagbrough, J. W. and W. Breed. 1967. “Protalus Ramparts on Navajo Mountain, Southern Utah.” *American Journal of Science* 265(9): 759-772.

Blagbrough, J. and H. G. Brown, III. 1983. “Rock Glaciers on the West Slope of South Baldy, Magdalena Mountains, Socorro County, New Mexico.” In *New Mexico Geological Society Guidebook - 34: Socorro Region II,* edited by C. E. Chapin and J. F. Callender, 299-302. NMGS.

Blagbrough, J. and S. Farkas. 1968. “Rock glaciers in the San Mateo Mountains, south-central New Mexico.” *American Journal of Science* 266(9): 812-823.

Bloom, A. 2004. *Geomorphology: A Systematic Analysis of Late Cenozoic Landforms.* Longland: Waveland Press.

Brenning, A., Grasser, M., and D. Friend. 2007. “Statistical Estimation and Generalized Additive Modeling of Rock Glacier Distribution in the San Juan Mountains, Colorado, United States.” *Journal of Geophysical Research: Earth Surface* 112: F02S15.

Brenning, A., and D. Trombotto. 2006. “Logistic Regression Modeling of Rock Glacier and Glacier Distribution: Topographic and Climatic Controls in the Semi-Arid Andes.” *Geomorphology* 81(1-2): 141-154.

Burger, K., Degenhardt, Jr., J., and J. Giardino. 1999. “Engineering Geomorphology of Rock Glaciers.” *Geomorphology* 31(1-4): 93-132.

Cannone, N., and R. Gerdol. 2003. “Vegetation as an Ecological Indicator of Surface Instability in Rock Glaciers.” *Arctic, Antarctic, and Alpine Research* 35(3): 384-390.

Capps, Jr., S. 1910. “Rock Glaciers in Alaska.” *Journal of Geology* 18: 359-375.

Carrara, P. and J. Andrews. 1973. “Problems and Application of Lichenometry to Geomorphic Studies, San Juan Mountains, Colorado.” *Arctic and Alpine Research* 5(4): 373-384.

Carter, R., LeRoy, S., Nelson, T., Laroque, C., and D. Smith. 1999. “Dendroglaciological Investigations at Hilda Creek Rock Glacier, Banff National Park, Canadian Rocky Mountains.” *Géographie Physique et Quaternaire* 53(3): 365-371.

Daly, C., Halbleib, M., Smith, J., Gibson, W., Doggett, M., Taylor, G., Curtis, J., and P. Pasteris. 2008. “Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States.” *International Journal of Climatology* 28(15): 2031-2064.

Evin, M. 1987. “Lithological and Fracturing Control of Rock Glaciers in the Southwestern Alps of France and Italy.” In *Rock Glaciers*, J. R. Giardino, J. F. Shroder, and J. D. Vitek.edited, 86-106. Boston: Allen & Unwin.

Giardino, J., Shroder, Jr., J., and M. Lawson. 1984. “Tree-Ring Analysis of Movement of a Rock Glacier Complex on Mount Mestas, Colorado, U.S.A.” *Arctic and Alpine Research* 16(3): 299-309.

Giardino, J., and J. Vitek. 1987. “Rock Glaciers: A Review of the Knowledge Base” In *Rock Glaciers*, edited by J. Giardino, J. Shroder, Jr., and J. Vitek, 1-26. Boston: Allen & Unwin.

Gordon, L. and C. Ballantyne. 2006. “’Protalus Ramparts’ on Navajo Mountain, Utah, USA: Reinterpretation as Blockslope-sourced Rock Glaciers.” *Permafrost and Periglacial Processes* 17(2): 179-187.

Goudie, A. 2006. “The Schmidt Hammer in Geomorphological Research.” *Progress in Physical Geography* 30(6): 703-718.

Guglielmin, M., Camusso, M., Polesello, S., and S. Valsecchi. 2004. “An Old Relict Glacier Body Preserved in Permafrost Environment: The Foscagno Rock Glacier Ice Core (Upper Valtellina, Italian Central Alps).” *Arctic, Antarctic, and Alpine Research* 36(1): 108-116.

Guglielmin, M., and C. Smiraglia. 1998. “The Rock Glacier Inventory of the Italian Alps.” Paper presented at *Permafrost - Seventh International Conference (Proceedings), Yellowknife, NWT, June 23-27*.

Frauenfelder, R. and A. Kääb. 2000. “Towards a Palaeoclimatic Model of Rock-glacier Formation in the Swiss Alps.” *Annals of Glaciology* 31: 281-286.

French, H. 1996. *The Periglacial Environment*. Essex: Longman.

Fuchs, M., Böhlert, R., Krbetschek, M. Preusser, F., and M. Egli. 2013. “Exploring the Potential for Luminescence Methods for Dating Alpine Rock Glaciers.” *Quaternary Geochronology* 18(Dec): 17-33.

Haeberli, W. 2000. “Modern Research Perspectives Relating to Permafrost Creep and Rock Glaciers: A Discussion.” *Permafrost and Periglacial Processes* 11(4): 290-293.

———. 1985. “Creep of Mountain Permafrost: Internal Structure and Flow of Alpine Rock Glaciers. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie. 77:142.

Haeberli, W., Brandova, D., Burga, C., Egli, M., Frauenfelder, R., Kääb, A., Maisch, M., Mauz, B., and R. Dickau. 2003. “Methods for Absolute and Relative Dating of Rock-Glacier Surfaces in Alpine Permafrost.” In *Permafrost* edited by Phillips, Springman, and Arenson, 343-348. Lisse: Swets & Zeitlinger.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S., and D. Mühll. 2006. “Permafrost Creep and Rock Glacier Dynamics. *Permafrost and Periglacial Processes* 17(3): 189-214.

Hedding, D., Meiklejohn, K., Le Roux, J., Loubser, M., and J. Davis. 2011. “Some Observations of the Formation of an Active Pronival Rampart at Grunehogna Peaks, Western Dronning Maud Land, Antarctica.” *Permafrost and Periglacial Processes* 21(4): 355-361.

Hedding, D., and P. Sumner. 2013. “Diagnostic Criteria of Pronival Ramparts: Site, Morphological and Sedimentological Characteristics.” *Geografiska Annaler, Series A: Physical Geography* 95(4): 315-322.

Janke, J. 2005. “Photogrammetric Analysis of Front Range Rock Glacier Flow Rates.” *Geografiska Annaler: Series A, Physical Geography* 87(4): 515-526.

Janke, J. 2007. “Colorado Front Range Rock Glaciers: Distribution and Topographic Characteristics.” *Arctic, Antarctic, and Alpine Research* 39(1): 74-83.

Jarman, D., Wilson, P., and S. Harrison. 2013. “Are there any Relict Rock Glaciers in the British Mountains?” *Journal of Quaternary Science* 28(2): 131-143.

Johnson, B., Thackray, G., and R. Van Kirk. 2007. “The Effects of Topography, Latitude, and Lithology on Rock Glacier Distribution in the Lemhi Range, central Idaho, USA.” *Geomorphology* 91(1-2): 38-50.

Kääb, A., Frauenfelder, R., and I. Roer. 2006. “On the Response of Rockglacier Creep to Surface Temperature Increase.” *Global and Planetary Change* 56(1-2): 172-187.

Karnstedt, A. 2010. “USA Region West Relief Map [map].” Wikimedia Commons. April 25. https://upload.wikimedia.org/wikipedia/commons/0/06/USA_Region_West_relief_location_map.jpg.

Krainer, K., and W. Mostler. 2006. “Flow Velocities of Active Rock Glaciers in the Austrian Alps.” *Geografiska Annaler: Series A, Physical Geography* 88(4): 267-280.

Marker, M. 1990. “Minimum Altitudes for Former Periglacial Landforms Adjacent to Longitude 106°W in Colorado and New Mexico, USA, Between Latitudes 33°N and 40°N.” *Arctic and Alpine Research* 22(4): 366-374.

McCarthy, D. 1999. “A Biological Basis for Lichenometry?” *Journal of Biogeography* 26(2): 379-386.

Millar, C. and R. Westfall. 2008. “Rock Glaciers and Related Periglacial Landforms in the Sierra Nevada, CA, USA; Inventory, Distribution and Climatic Relationships.” *Quaternary International* 188(1): 90-104.

Monnier, S., Camerlynck, C., Rejiba, F., Kinnard, C., and Galibert, P. 2013. “Evidencing a Large Body of Ice in a Rock Glacier, Vanoise Massif, Northern French Alps.” *Geografiska Annaler: Series A, Physical Geography* 95(2): 109-123.

Morris, S. 1981. “Topoclimatic factors and the Development of Rock Glacier Facies, Sangre de Cristo Mountains, southern Colorado.” *Arctic and Alpine Research* 13(3): 329-338.

Musil, M. Maurer, H., Hollinger, K., and A. Green. 2005. “Internal Structure of an Alpine Rock Glacier based on Crosshole Georadar Traveltimes and Amplitudes.” *Geophysical Prospecting* 54(3): 273-285.

Nicholas, J. and D. Butler. 1996. “Application of Relative-Age Dating Techniques on Rock Glaciers of the La Sal Mountains, Utah: An Interpretation of Holocene Paleoclimates.” *Geografiska Annaler: Series A, Physical Geography* 78(1): 1-18.

Nicholas, J., and J. Garcia. 1997. “Origin of Fossil Rock Glaciers, La Sal Mountains, Utah.” *Physical Geography* 18(2): 160-175.

Osborn, G., McCarthy, D., LaBrie, A., and R. Burke. 2015. “Lichenometric Dating: Science or Pseudo-science?” *Quaternary Research* 83(1): 1-12.

Potter, Jr., N. 1972. “Ice-Cored Rock Glacier, Galena Creek, Northern Absaroka Mountains Wyoming.” *Geological Society of America Bulletin* 83(10): 3025-3058.

Potter, Jr., N., Steig, E., Clark, D., Speece, M., Clark, G., and A. Updike. 2004. “Galena Creek Rock Glacier Revisited – New Observations on an Old Controversy.” *Geografiska Annaler: Series A, Physical Geography* 80(3-4): 251-265.

PRISM Climate Group. 2015. “30-Year Normals.” Last modified June 19. http://www.prism.oregonstate.edu/normals/.

Refsnider, K. and K. Brugger. 2007. “Rock Glaciers in Central Colorado, U.S.A., as Indicators of Holocene Climate Change.” *Arctic, Antarctic, and Alpine Research* 39(1): 127-136.

Scotti, R., Brardinoni, F., Alberti, S., Frattini, P., and G. Crosta. 2013. “A Regional Inventory of Rock Glaciers and Protalus Ramparts in the Central Italian Alps.” *Geomorphology* 186: 136-149.

Shakesby, R. A. 1997. “Pronival (protalus) Ramparts: A Review of Forms, Processes, Diagnostic Criteria, and Palaeoenvironmental Implications.” *Progress in Physical Geography* 21(3): 394-418.

Shakesby, R. A., Dawson, A. G., and J. A. Matthews. 1987 “Rock Glaciers, Protalus Ramparts and Related Phenomena, Rondane, Norway: A Continuum of Large-scale Talus-derived Landforms.” *Boreas* 16(3): 305-317.

Shroder, Jr., J. 1978. “Dendrogeomorphological Analysis of Mass Movement on Table Cliffs Plateau, Utah.” *Quaternary Research* 9(2): 168-185.

Shroder, Jr., J. and Giardino, K. 1987. “Analysis of Rock Glaciers in Utah and Colorado, USA, using Dendrogeomorphological Techniques.” In *Rock Glaciers* edited by J. R. Giardino, J. F. Shroder, Jr., and J. D. Vitek, 151-159. Boston: Allen & Unwin.

Tobler, W. 1988. “Resolution, Resampling, and All That.” In *Building Data Bases for Global Science* edited by H. Mounsey and R . Tomlinson, 129-137. London: Taylor and Francis.

USDA Farm Service Agency. 2014. “NAIP Imagery.” Last modified June 10. http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai.

U.S. Department of the Interior. U.S. Geological Survey. *Accuracy Assessment of the U.S. Geological Survey National Elevation Dataset, and Comparison with Other Large-Area Elevation Datasets – SRTM and ASTER*, by D. Gesch, M. Oimoen, and G. Evans. Open-file report, 2014-1008, U.S. Geological Survey. Reston, Virginia, 2014. http://pubs.usgs.gov/of/2014/1008/pdf/ofr2014-1008.pdf.

USGS Mineral Resources. 2004. “Preliminary Integrated Geologic Map Databases for the United State Central States: Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas, Missouri, Arkansas, and Louisiana, - The State of New Mexico.” Last modified Oct 2004. http://mrdata.usgs.gov/geology/state/metadata/nm.faq.html#quality.

Vick, S. 1981. “Morphology and the role of Landsliding in Formation of some Rock Glaciers in the Mosquito Range, Colorado. *Geological Society of America Bulletin* 92(2): 75-84.

Wahrhaftig, C. 1987. “Foreword.” In *Rock Glaciers*, edited by J. Giardino, J. Shroder, Jr., and J. Vitek, [1-7]. Boston: Allen & Unwin.

Wahrhaftig, C. and A. Cox. 1959. Rock Glaciers in the Alaska Range. *Geological Society of America Bulletin* 70(4): 383-346.

Whalley, W. B. and F. Azizi. 2003. “Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars.” *Journal of Geophysics: Planets* 108:E4.

White, P. 1979. “Rock Glacier Morphometry, San Juan Mountains, Colorado.” *Geological Society of America Bulletin* 90(6): 924-295.