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Late Wisconsin climatic inferences from rock glaciers in south-central and west-central New Mexico and east-central Arizona

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Abstract

Inactive rock glaciers of late Wisconsin age occur at seven sites in south-central and west-central New Mexico and in east-central Arizona. They are at the base of steep talus in the heads of canyons and ravines and have surface features indicating they are ice-cemented (permafrost) forms that moved by the flow of interstitial ice.

The rock glaciers indicate zones of alpine permafrost with lower levels that rise from approximately 2,400 m in the east region to 2,950 m in the west. Within the zones the mean annual temperature was below freezing, and the climate was marked by much diurnal freezing and thawing resulting in the production of large volumes of talus in favorable terrain. The snow cover was thin and of short duration, which favored ground freezing and cryofraction.

The rock glaciers in the east region occur near the late Wisconsin 0°C air isotherm and imply that the mean annual temperature was depressed approximately 7 to 8°C during a periglacial episode in the late Wisconsin. A dry continental climate with a seasonal distribution of precipitation similar to that of the present probably prevailed, and timberline may have been depressed a minimum of 1,240 m. The rise in elevation of the rock glaciers from east to west across the region is attributed to greater snowfall in west-central New Mexico and east-central Arizona, which reduced the intensity and depth of ground freezing near the late Wisconsin 0°C air isotherm.

Introduction

Rock glaciers are periglacial mass-movement deposits that have been described in many alpine areas throughout the world. Wahrhaftig (1987) proposed that "rock glacier" be restricted to those formations of blocky debris, extending outward and downslope from talus cones or from glaciers or the terminal moraines of glaciers, that have moved in large part through the deformation of interstitial ice (ice-cemented rock glaciers) or clear ice (ice-cored rock glaciers) within them. He also emphasized that masses of blocky debris shown to have accumulated as landslides should be called a variety of landslide even though they have some morphologic characteristics of rock glaciers.

Ice-cemented rock glaciers are cemented by interstitial ice or contain large bodies of solid ice derived either from avalanche snow or refreezing of melt or spring water (Wahrhaftig and Cox, 1959), whereas ice-cored rock glaciers contain cores of massive glacial ice (Potter, 1972, p. 3027). Ice-cored rock glaciers are characterized by (1) saucer- or spoon-shaped depressions between the base of the cirque headwalls and the rock glacier heads, (2) longitudinal furrows along both sides, (3) central meandering furrows, and (4) conical or coalescing pits (White, 1976). Ice-cemented forms lack depressions at their heads and have continuous talus and avalanche slopes feeding onto their heads (Luckman and Crocket, 1978). They also are characterized by well-developed longitudinal and transverse ridges (White, 1976).

Rock glaciers are subdivided into lobate and tongue-shaped forms according to their over-all dimensions (Wahrhaftig and Cox, 1959; White, 1981). Lobate rock glaciers are formed mainly by unsorted talus, and their width is as great or greater than their length. They occur as single or multiple lobes at the base of talus along valley walls. Tongue-shaped rock glaciers are elongated masses of rock debris with a greater length than width. They originate in cirques or on valley floors near the valley head.

Climatic factors that favor the development of interstitial ice (permafrost) in rock glaciers are adequate precipitation for the formation of the ice and temperatures that are low enough for the maintenance and creep of the ice (Wahrhaftig and Cox, 1959). Active ice-cemented rock glaciers are good indicators of perennially frozen ground in alpine areas, and inactive forms suggest ancient permafrost (Péwé, 1983b). Permafrost can exist in alpine areas if the mean annual air temperature at ground level is 0 to −1°C, especially if snow cover is thin and of short duration (Péwé, 1983a). Most active rock glaciers occur above timber line (Wahrhaftig, 1987), and inactive forms may suggest approximations of former timberlines.

The lower limit of permafrost in maritime climates with abundant snow precipitation may approximate the equilibrium line of glaciers (Shumskii, 1964, p. 431). In comparison, the lower limit of permafrost in continental climates occurs far below the snow line, and the existence of glaciers is due mainly to low air temperatures. Corté (1987a) observed that rock-glacier activity in the ☞

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central Andes (latitude 33°S) is 1,300 m below the equilibrium line of glaciers on the continental side in Argentina whereas on the maritime side in Chile, they are 700 m below the equilibrium line. He ascribes this altitudinal variation to the difference in climate between the two regions. Greater snow precipitation on the west side of the Andes reduces the intensity and depth of freezing and raises the elevation of the lower limit of permafrost.

Corté (1987b) suggested several regional factors that promote the formation of rock glaciers. Among these are (1) diurnal freezing and thawing, which result in the generation of large volumes of debris, (2) a mean annual temperature below 0°C, (3) enough moisture in the ground to promote cryofraction and gelifluction, (4) moderate to low amounts of precipitation in the form of snow for the production of debris and some snow avalanches, and (5) reduced snow cover that favors ground freezing and cryofraction.

Late Wisconsin climate

The nature of the late Wisconsin climate in the southwest United States has been controversial mainly because of the difference between interpretations of the physical evidence and that of the fossil plant record. Models have ranged from climates with lower winter temperatures to climates with mild winters and cool summers, and from climates of decreased precipitation with maintenance of the present seasonal distribution to climates with greatly increased winter precipitation (Van Devender and Spaulding, 1979; Hawley, 1993). Many of these models were proposed to account for the water budgets of pluvial lakes or were based on the altitudinal distribution of cryogenic deposits that are assumed to indicate lower orographic snow lines and timberlines. Other models were inferred from fossil plant assemblages of packrat middens and from pollen records of pluvial lakes.

Galloway (1970) proposed a cold and dry model of late Wisconsin climate in the southwest United States utilizing undated solifluction deposits in the Sacramento Mountains of south-central New Mexico. He postulated a 1,300–1,400-m lowering of timberline resulting from a temperature decrease of 10 to 11°C for all seasons and a 10–20% reduction in precipitation. Brakenridge (1978) also presented evidence for a cold and dry late Wisconsin (full-glacial) climate in the American southwest. He inferred a 1,000-m depression of the orographic snowline, timberline, and cryogenic deposits and proposed a 7 to 8°C cooling in all seasons and no significant increase in annual precipitation.

Van Devender et al. (1984) and Van Devender (1990) made several inferences about the climate in the Sacramento Mountains in south-central New Mexico during the late Wisconsin (16,000 to 18,000 years B.P.) utilizing macroplant fossils from packrat middens. They suggested that summers were much colder than today with temperatures probably resembling present temperatures for late spring or early fall. Winters were not much colder than today, and most of the precipitation was in winter and spring with only modest amounts of summer rainfall. Van Devender and Spaulding (1979) and Spaulding et al. (1983), using similar data, advocated comparable models for an extensive region of the southwest United States.

Recent studies in New Mexico present evidence for variable climatic conditions during the late Wisconsin suggesting that all of the models noted above may be, at least, partially correct. Phillips et al. (1986) proposed a late Wisconsin climatic model for the San Juan Basin in northwest New Mexico utilizing the stable isotopic composition of ground water and noble gas paleothermometry. The period between 24,000 and 21,000 years B.P. was marked by mean annual temperatures 5 to 7°C cooler than present temperatures resulting in greater effective precipitation. A warming trend began approximately 19,000 years B.P. and coincided with low effective precipitation. This was terminated by a brief episode of moist conditions approximately 17,000 years B.P. The latest Wisconsin was characterized by a drier climate with precipitation no greater than that of the present.

Phillips et al. (1992) suggested a model of late Wisconsin paleohydrologic and paleoclimatic conditions for the San Agustin pluvial-lake basin in west-central New Mexico that is based primarily on ^{18}O variations in ostracod shells. The late Wisconsin full-glacial climate between 35,000 and 28,600 years B.P. was a dry and relatively cold period. An abrupt warming event occurred at 28,600 years B.P., and warm temperatures continued until 21,800 years B.P. interrupted by cold pulses of short duration. The late Wisconsin thermal minimum is defined by a cool and wet period between 21,800 and 20,600 years B.P. A rapid warming trend at 20,600 years B.P. marks the close of the late Wisconsin thermal minimum and was followed by a period of climatic instability characterized by rapid fluctuations in both temperature and precipitation.

Geographic, geologic, and modern climatic setting

Rock glaciers occur at seven alpine sites between 33°15′ and 34°15′ North latitude in south-central and west-central New Mexico and east-central Arizona (Fig. 1). The mountains have summit elevations between 2,638 and 3,316 m and rise 450 to 1,370 m above adjacent lowlands. Their slopes are cut by many steep-walled canyons with maximum depths of approximately 300 m. Numerous small canyons and ravines are tributary to the trunk canyons.

The rock glaciers in the east region are in the Sacramento section of the Basin and Range province and are formed mainly by fragments of intrusive rocks of mid-Tertiary age. They are north of the Sacramento Mountains, an extensive highland in south-central New Mexico. The rock glaciers in the central and west region are in the Datil–Mogollon section, a transitional zone between the Colorado Plateau and the Basin and Range province that forms a large highland in west-central New Mexico and east-central Arizona (Hawley, 1986). They are composed predominantly of debris derived from extrusive rocks of mid-Tertiary age.

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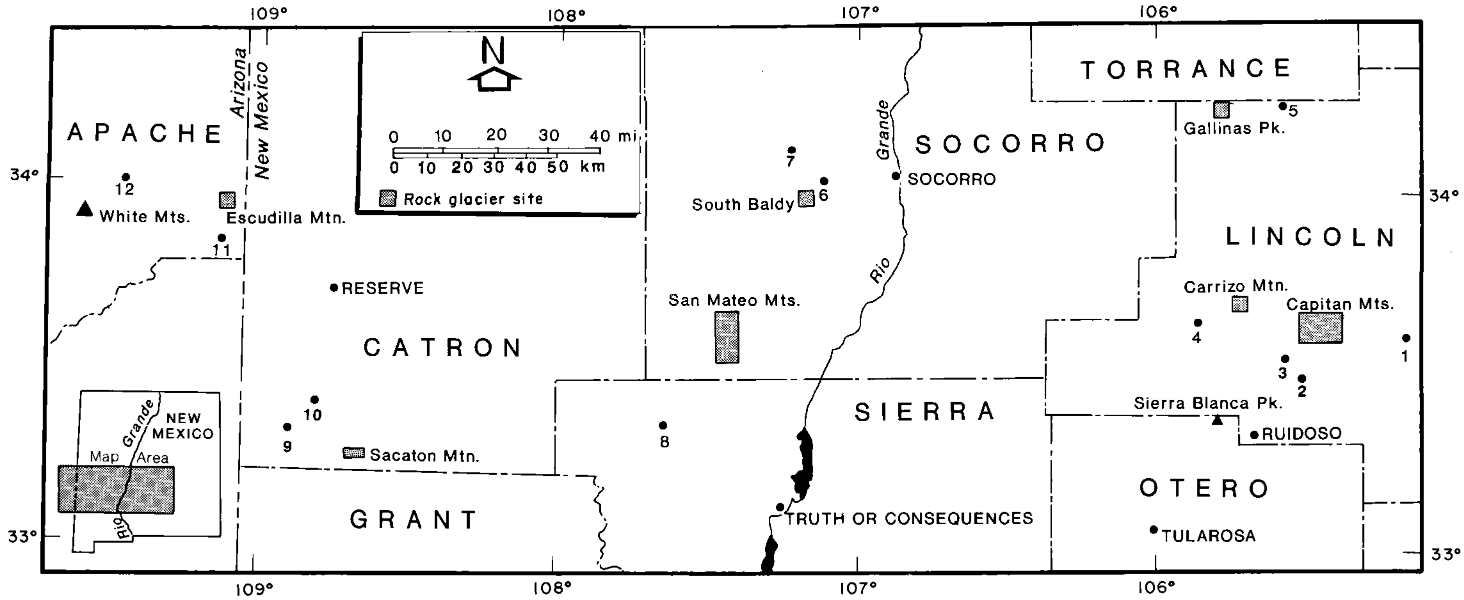

FIGURE 1—Rock-glacier sites in south-central and west-central New Mexico and in east-central Arizona. Numbered localities identify weather stations in Tables 2 and 3. Base maps are the U.S. Geological Survey's base maps of Arizona and New Mexico (scale 1:1,000,000).

TABLE 1—Comparative altitudinal and morphological data for the rock-glacier sites in south-central and west-central New Mexico and east-central Arizona.

Site	Highest peak elevation (m)	Number of rock glaciers	Average elevation of fronts (m)	Average elevation of heads (m)	Average length (m)	Average width (m)
Capitan Mountains, Lincoln County, New Mexico	3018	76	2430	2538	347	74
Carrizo Mountain, Lincoln County, New Mexico	2928	14	2370	2447	186	62
Gallinas Peak, Lincoln County, New Mexico	2633	8	2413	2457	117	52
South Baldy, Socorro County, New Mexico	3288	6	2736	2842	244	74
San Mateo Mountains, Socorro County, New Mexico	3151	7	2702	2807	126	44
Sacaton Mountain, Catron County, New Mexico	3249	5	2891	2987	203	79
Escudilla Mountain Apache County, Arizona	3316	12	2935	3030	130	55

The climate is arid to humid and is controlled largely by altitude. Mean annual precipitation ranges from less than 25 cm along the Rio Grande and in the Tularosa Basin to more than 75 cm on mountain summits above 3,050 m. Uplands with extensive areas above 2,750 m often receive more than 50 cm of rainfall per year. Mean annual temperatures range from 15°C along the Rio Grande and in the Tularosa Basin to near freezing on mountain summits above 3,050 m.

Description

One hundred twenty-eight tongue-shaped rock glaciers in the region were identified on U.S. Forest Service aerial photographs and plotted on U.S. Geological Survey topographic maps (scale 1:24,000). Their lengths, widths, orientations, and the elevations of their fronts and heads were determined (Table 1), and the extent of vascular plant cover was noted. Aerial photographic interpretations of the rock glaciers on Sacaton Mountain and Escudilla Mountain were reported by Blagbrough (1994). Field studies were carried out in the Capitan Mountains (Blagbrough, 1991a), Carrizo Mountain (Blagbrough, 1984), Gallinas Peak (Blagbrough, unpublished data), South Baldy (Blagbrough and Brown, 1983), and the San Mateo Mountains (Blagbrough and Farkas, 1968; Blagbrough, 1986). At these sites, notations were made of size of the debris, soil and vegetation cover, slope and height of the fronts, and dimensions of the ridges and furrows.

The rock glaciers are at the base of talus at the heads of trunk canyons and in side canyons and ravines (Blagbrough, 1991b). They face in all directions of the compass but are most common on northwesterly, northerly, and northeasterly facing slopes. Their

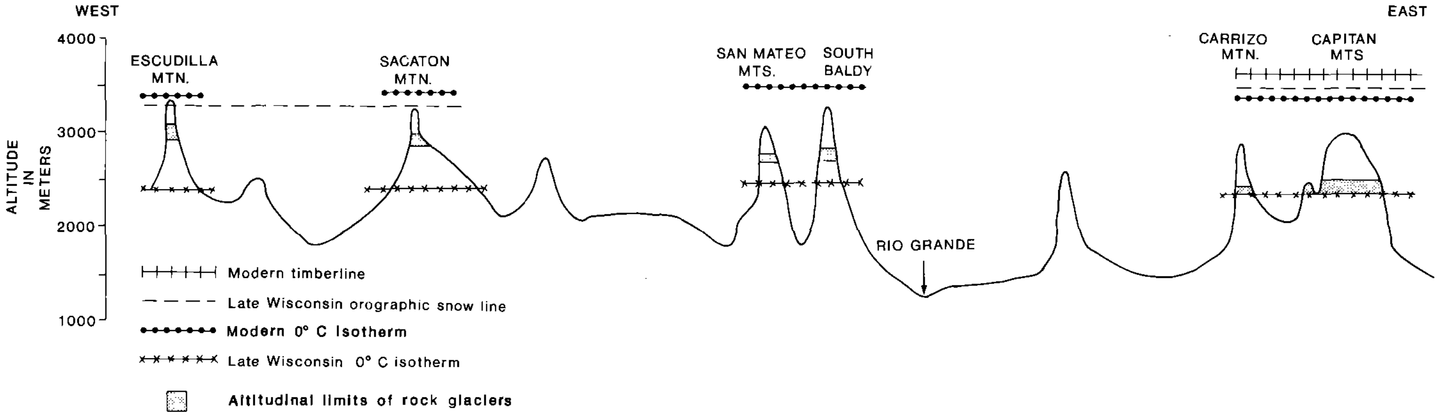

FIGURE 2—Generalized topographic profile across the region showing rock-glacier occurrences, the elevation of the modern and late Wisconsin 0°C air isotherm, and the late Wisconsin orographic snow line and timberline. Rock-glacier occurrences are determined by the average elevation of the fronts and heads at each site (Table 1). The elevation of the modern 0°C air isotherm is from Table 2. The late Wisconsin 0°C air isotherm is 1,000 m below the modern 0°C air isotherm (Péwé, 1983b). The elevation of the late Wisconsin orographic snow line in the east region is determined by the elevation of the cirque floor on Sierra Blanca Peak (Richmond, 1963) and in the west by the average elevation of the cirque floors in the White Mountains (Melton, 1961).

average elevation rises from east (2,440 m) to west (3,000 m) across the region (Fig. 2).

The rock glaciers have steep fronts that slope 20 to 30° and flanks that rise as steep embankments (Figs. 3 and 4). Heads merge with talus on the mountain slopes, and central areas slope downstream 5 to 15°. On many rock glaciers the flanks are delineated by lateral ridges that stand higher than central areas and often border depressed areas that extend from the crest of the fronts to the heads. Many lateral ridges bend to form transverse ridges at the crest of the fronts, and longitudinal and transverse ridges and furrows are common surface features on most rock glaciers (Fig. 5).

Multitongued rock glaciers occur on Carrizo Mountain (Blagbrough, 1984) and on San Mateo Peak in the San Mateo Mountains (Blagbrough, 1986). They are formed by two talus tongues, the upper having overridden the head of the lower. Multilobed tongue-shaped rock glaciers are in trunk canyons on the north and south sides of the Capitan Mountains (Blagbrough, 1991a). They are formed by two or more lobes of talus that moved onto the valley floors from the side-walls, and many have surface features indicating they developed from lobate rock glaciers that coalesced on the valley floors.

The rock glaciers are composed predominantly of angular to subangular blocks and slabby clasts of fine-grained igneous rock with average diameters between 60 and 90 cm. On most rock-glacier surfaces, the debris is a jumbled mass with no apparent orientation of the blocks and slabby clasts. The debris is stable, and all but freshly exposed or overturned rock surfaces are oxidized and contain a growth of lichen. Some fragments have undergone frost shattering while on the rock-glacier surface.

Soil and vascular plants cover 10 to 15% of the rock-glacier surfaces. The soil is dark brown and azonal with a maximum thickness of approximately 15 cm. It occurs as isolated pockets and is formed by decomposed organic material filling voids between the blocks and slabby clasts. Trees and shrubs grow in the soil and project through the debris on some rock glaciers.

Age

The glacial deposits in the Sangre de Cristo Mountains in north New Mexico, on Sierra Blanca Peak in south-central New Mexico, and in the White Mountains in east-central Arizona are used as reference for estimating the age of the rock glaciers in the region (Merrill and Péwé, 1972, 1977; Richmond, 1963, 1986). In utilizing the glacial record, it is necessary to note the lack of firm age control for the glacial deposits and to point out that climatic conditions that favored formation of glaciers may differ greatly from periglacial conditions that promoted generation of the rock glaciers.

Moraines of Illinoian age have broad crests, smooth slopes, and broadly scattered surface boulders. They bear a mature soil approximately 90 cm thick with a well-developed B horizon. Moraines of early Wisconsin age are moderately subdued but commonly sharply crested. Their soils are zonal with thicknesses of 25 to 30 cm. Moraines of late Wisconsin age have irregular form, abundant surface boulders, and an immature soil 20 to 25 cm thick. Moraines of Holocene age are blocky and have sharp constructional relief. They bear a thin azonal soil where fine material is exposed at the surface.

Soils on the rock glaciers examined in the field suggest that they are equivalent in age to the Holocene moraines because both deposits have shallow azonal soils that developed on sediment between boulders. However, this method of correlation may not be reliable because of altitudinal differences that influenced the local climate. At the present time the rock glaciers (2,400 to 3,000 m) exist under a semiarid to subhumid climate, whereas the Holocene moraines (3,600 m) are under a humid climate. Such variations must have existed in the past and would have had a significant influence on soil development, intensifying the process at higher elevations because of greater precipitation.

In addition, the rock glaciers are composed of coarse talus with voids between the debris so that some time lag was required in the acquisition of the fines that are necessary for soil-building processes. The Holocene moraines probably had fines exposed at the time of deposition that provided an immediate basis for soil-building processes. Because the rock glaciers have existed under a more-arid climate than the Holocene moraines, and because they lacked fines at the time of deposition, they are thought to have formed during a periglacial episode in the late Wisconsin when temperatures were lower than those of the present.

In considering the age of rock glaciers it is important to be aware that the climate under which they formed may differ greatly from that under which they may have moved a little. Rock glaciers require a periglacial climate of sufficient intensity and duration to generate talus and to mobilize the talus into rock glaciers, whereas the preservation of interstitial ice can take place under a climate with a mean annual temperature of 0° to −1°C that may be either of long or short duration. Soil and vascular plants on rock glaciers probably date from the termination of the last episode of significant movement and do not necessarily indicate the age of formation.

The rock glaciers in the region may have formed during the cold and dry episode between 35,000 and 28,600 years B.P. recorded in the paleoclimatic model of pluvial-lake San Agustin (Phillips et al., 1992). Subsequent movement could have taken place during the late Wisconsin thermal minimum (24,000 to 21,000 years B.P.) noted in the climatic records for the San Juan Basin

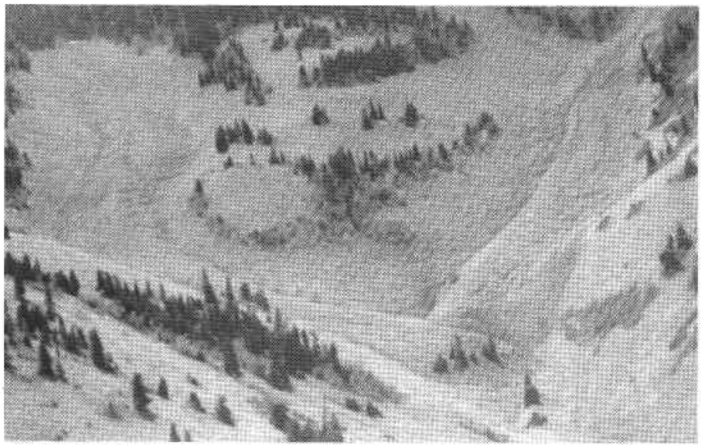

FIGURE 3—Low-angle aerial photograph of the two large rock glaciers in the east and west branches of Corral Canyon on the north side of the Capitan Mountains. The view is to the south and shows the steep fronts and flanks and the longitudinal and transverse ridges and furrows. The scarcity of soil and vegetation on the rock glaciers suggests movement near the close of the late Wisconsin.

and pluvial-lake San Agustin (Phillips et al., 1986, 1992). Rock-glacier creep during a periglacial episode near the close of the late Wisconsin would account for the sharp constructional relief and restrictive development of soil on the rock glaciers.

Paleoclimatic inferences

The rock glaciers in the region are thought to have moved by the flow of interstitial ice (permafrost) because they have continuous talus extending onto their heads and well-defined longitudinal and transverse ridges and furrows. In addition, they occur from 170 to 1,100 m below the late Wisconsin orographic snow line eliminating the possibility of movement caused by glacial ice (Fig. 2).

Present-day precipitation in the San Mateo Mountains is sufficient for the formation of interstitial ice (Blagbrough, 1986; Blagbrough and Farkas, 1968), and climatic data for the Capitan Mountains indicate that mean temperatures for the winter months of December, January, and February would favor the preservation of interstitial ice at the present time (Blagbrough, 1991b). These observations imply that lower summer temperatures in the region were essential for the maintenance and creep of the ice.

The altitudinal distribution of the rock glaciers indicates zones of alpine permafrost with lower limits at approximately 2,400 m in the east region, 2,750 m in the center, and 2,950 m in the west. Within the zones the mean annual temperature was below freezing and the snow cover was thin and of short duration. Prolonged periods of diurnal freezing and thawing resulted in intense freeze-thaw action that generated large volumes of talus in favorable terrain.

The modern mean annual temperature at the average elevation of the rock glacier fronts and the modern 0°C air isotherm are computed for the rock-glacier sites in Table 2 using a lapse rate of 0.72°C/100 m, established by Van Devender et al. (1984) in south-central New Mexico, and climatic data from the nearest weather stations maintaining long-term weather records. The late Wisconsin 0°C air isotherm is 1,000 m below the modern 0°C air isotherm (Péwé, 1983b, p. 175). The lower limit of rock-glacier activity in the east region closely approximates the late Wisconsin 0°C air isotherm, whereas in the west region the lower limit of rock-glacier activity is approximately 460 to 590 m above the 0°C air isotherm (Fig. 2).

The modern mean annual temperature at the average elevation of the rock-glacier fronts in the east region is 7.2 to 7.9°C, which implies that the mean annual temperature was depressed a minimum of approximately 7 to 8°C in south-central New Mexico during one or more periglacial episodes of the late Wisconsin.

FIGURE 4—Low-angle aerial photograph of the large rock glacier in the east branch of Ferris Canyon on the north side of the Capitan Mountains. The view is to the southeast. The rock glacier has a steep front and flanks, with lateral ridges along the flanks that bend to form a transverse ridge at the crest of the front. Two smaller rock glaciers in the foreground extend from the west wall of the canyon onto the floor.

FIGURE 5—Low-angle aerial photograph of the rock glacier in the west branch of Ferris Canyon on the north side of the Capitan Mountains. View is to the south. The rock glacier has a steep front approximately 75 m high, lateral ridges along the flanks, and longitudinal and transverse ridges and furrows on the surface.

This amount of lowering may approximate the actual depression because the lower limit of rock-glacier activity nearly coincides with the late Wisconsin 0°C air isotherm. The inferred reduction in the mean annual temperature conforms to that proposed by Brakenridge (1978), is less severe than that advocated by Galloway (1970), and is marginally higher than that inferred by Phillips et al. (1986). ☞

TABLE 2—Mean annual temperatures at the average elevation of the rock-glacier fronts and the elevation of the modern and late Wisconsin 0°C air isotherm at the rock-glacier sites in south-central and west-central New Mexico and east-central Arizona. Weather stations are in Fig. 1. Climatic data is from Gabin and Lesperance (1977), Kunkel (1984), and Sellers and Hill (1974).

Site	Average elevation rock-glacier fronts (m)	Weather station	Map locality	Elevation weather station (m)	Years of record	Mean annual temp. (°C)	Mean annual temp. rock-glacier fronts (°C)	Elevation modern 0°C air isotherm (m)
Capitan Mountains	2430	Fort Stanton	2	1826	74	11.1	7.3	3437
Carrizo Mountain	2370	Carrizozo	4	1658	58	12.3	7.2	3360
Gallinas Peak	2413	Corona	5	2026	47	10.7	7.9	3512
South Baldy	2736	Magdalena	7	1994	36	11.1	5.8	3536
San Mateo Mountains	2702	Winston	8	1890	35	11.4	6.7	3473
Sacaton Mountain	2891	Glenwood	9	1441	36	14.3	3.7	3427
Escudilla Mountain	2935	Alpine	11	2454	27	6.4	2.9	3343

The modern timberline occurs at an elevation of approximately 3,640 m just north of Sierra Blanca Peak in the Sacramento Mountains (Dyer and Moir, 1977) approximately 1,240 m above the lower limit of rock-glacier activity in south-central New Mexico. This suggests that timberline was lowered a minimum of 1,240 m in the locality during the late Wisconsin. This amount of depression is somewhat less than that proposed by Galloway (1970), is substantially greater than that inferred by Brakenridge (1978), and is far in excess of the vegetation lowering recorded in the packrat midden records of the northern Chihuahuan Desert (Van Devender, 1990).

The lower limit of rock-glacier activity in the east region is approximately 1,100 m below the late Wisconsin orographic snow line on Sierra Blanca Peak (Fig. 2). In comparison, most active rock glaciers occur near the orographic snow line, many in cirques (Flint, 1971, p. 273). This is demonstrated by the lower limit of active rock glaciers in the Swiss Alps approximately 400 m below the present snow line (Barsch, 1969a, 1969b) and by the same limit in the Alaska Range approximately 120–360 m below the present snow line (Wahrhaftig and Cox, 1959). These occurrences appear to indicate a significant difference between the Late Wisconsin periglacial climate in south-central New Mexico and the present periglacial climate in mountain ranges at higher latitudes.

Barsch and Updike (1971) suggested that such variations in altitude may be due to the more intense radiation and the greater aridity in the southwest United States. They noted that both factors have a greater impact on glaciers than on rock glaciers because the interstitial ice is protected from direct radiation and sublimation by the blocky mantle of debris.

Aridity in the southwest United States is also important in determining the lower limit of rock glaciers because it restricts snow fall. Marker (1990) noted that periglacial forms tend to appear at lower elevations in the isolated mountains of south New Mexico than in the Sangre de Cristo Mountains in north New Mexico and in the Front Range in Colorado. She attributed this to the aridity in south New Mexico that reduces winter snow cover and lowers the timberline exposing lower altitudes to periglacial processes. Such conditions could have been enhanced during the late Wisconsin resulting in permafrost and intense frost action occurring at lower altitudes in the isolated mountains in the south than in the larger mountain masses farther north.

The observations noted above suggest that the rock glaciers in the east region formed under a cold and dry continental climate that resulted in a thin snow cover of short duration. This favored the formation of permafrost and intense freeze-thaw action near the 0°C air isotherm and resulted in a lower limit of rock-glacier activity approximately 1,100 m below the orographic snow line. The mean annual precipitation and the seasonal distribution of precipitation may have approximated that of the present with a summer maximum because increased precipitation during the winter months would have resulted in a more permanent snow cover that restricted periglacial processes.

The rise in altitude of the rock glaciers from east to west across the region may be due to more-abundant snow fall in the west region during the late Wisconsin. Table 3 demonstrates that a greater percentage of the total mean annual precipitation occurs during the winter months of December, January, and February at weather stations in west-central New Mexico and east-central Arizona than at those in south-central New Mexico. This can be attributed to the location of the west region nearer to the Pacific Ocean, which is the principal source of winter moisture in the southwest United States.

Middle-latitude Pacific-type winter storms probably were intensified and displaced southward during the late Wisconsin (Spaulding et al., 1983). This would have enhanced winter precipitation in the west region and may be responsible for the lower altitude of the orographic snow line in the White Mountains (3,260 m) as compared to that on Sierra Blanca Peak (3,400 m). Greater snow precipitation on Sacaton Mountain and Escudilla Mountain apparently reduced the intensity and depth of ground freezing near the 0°C air isotherm and raised the lower level of permafrost approximately 570 m above the 0°C air isotherm.

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TABLE 3—Mean annual precipitation and winter precipitation (December, January, and February) at selected weather stations in south-central and west-central New Mexico and east-central Arizona. Weather stations are in Fig. 1. Climatic data is from Gabin and Lesperance (1977), Kunkel (1984), and Sellers and Hill (1974).

Station	Location	Map locality	Elevation (m)	Years of record	Precipitation (cm)		
					Mean annual	Winter	Percentage in winter
Arabella	Lincoln County, New Mexico	1	1634	17	52.51	5.23	10.0
Fort Stanton	Lincoln County, New Mexico	2	1896	43	35.51	4.56	12.8
Capitan	Lincoln County, New Mexico	3	1971	42	39.60	5.03	12.7
Carrizozo	Lincoln County, New Mexico	4	1658	53	33.87	5.36	15.8
Corona	Lincoln County, New Mexico	5	2026	46	38.48	5.49	14.3
Kelly Ranch	Socorro County, New Mexico	6	2043	39	36.10	4.41	12.2
Magdalena	Socorro County, New Mexico	7	1994	53	28.82	3.59	12.5
Winston	Sierra County, New Mexico	8	1890	35	31.48	3.08	9.8
Glenwood	Catron County, New Mexico	9	1441	36	37.95	9.21	24.3
Mogollon B	Catron County, New Mexico	10	2012	13	46.92	11.18	23.8
Alpine	Apache County, Arizona	11	2451	30	49.56	10.33	20.8
Greer	Apache County, Arizona	12	2591	20	61.54	16.54	26.9

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