Photointerpretation of late Pleistocene-Holocene rock glaciers on Sacaton Mountain and Escudilla Mountain, Datil-Mogollon upland, west-central New Mexico and east-central Arizona

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PHOTOINTERPRETATION OF LATE PLEISTOCENE-HOLOCENE ROCK GLACIERS ON SACATON MOUNTAIN AND ESCUDILLA MOUNTAIN, DATIL-MOGOLLON UPLAND, WEST-CENTRAL NEW MEXICO AND EAST-CENTRAL ARIZONA

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Abstract—Rock glaciers on the flanks of Sacaton Mountain and Escudilla Mountain are below talus-mantled cliffs and slopes at an average elevation of about 2940-2980 m. They have surface features indicative of ice-cemented (permafrost) forms that moved by the flow of interstitial ice, and delineate ancient zones of alpine permafrost that probably existed in the late Wisconsinan and early Holocene. Within these zones the mean annual temperature was below freezing and snow cover was thin and of short duration. The rock glaciers probably formed during the late Wisconsinan under a periglacial climate characterized by much freezing and thawing, resulting in the generation of large volumes of talus. The rise in elevation of rock glacier occurrences from east to west across west-central New Mexico and east-central Arizona is attributed to greater snow fall in the Datil-Mogollon Upland, which reduced the depth and intensity of ground freezing near the late Wisconsinan 0°C air isotherm.

INTRODUCTION

Rock glaciers are periglacial mass movement deposits that commonly occur in alpine regions near the snow line. Potter (1972) defined a rock glacier as a tongue-like or lobate body composed of angular boulders that resembles a small glacier with ridges, furrows, and lobes on its surface and a steep front at the angle of repose. White (1981) distinguished two principal types of rock glaciers characterized by shape, topographic position and ratio of length to width. Tongue-shaped rock glaciers are elongated masses of rock debris that are longer than they are wide. They commonly occur in cirques or on valley floors. Lobate rock glaciers are broader than long and composed mainly of unsorted talus. They occur singly or in groups along valley walls and are usually extensions of talus.

Active rock glaciers occur either as an ice-cemented mass of debris that moved down slope due to the flow of interstitial ice (ice-cemented rock glacier) or as debris covering a small glacier that moved down slope due to the flow of glacial ice (ice-cored rock glacier) (Péwé, 1983a). Ice-cored rock glaciers are distinguished by saucer- or spoon-shaped depressions between the base of the cirque head wall and the rock glacier, longitudinal furrows along both sides, central meandering furrows, and conical or coalescing collapse pits (White, 1976). Ice-cemented rock glaciers lack depressions at their heads and have continuous talus and avalanche slopes feeding onto their heads (Luckman and Crockett, 1978). They are also defined by well-developed longitudinal and transverse ridges (White, 1976).

The formation of rock glaciers requires a periglacial climate that permits the dislodgement of blocks and slabs by intense freeze-thaw action and a mean annual temperature below 0°C that promotes the formation of permafrost (Corté 1987a). Active ice- cemented rock glaciers are good indicators of perennially frozen ground in alpine areas (Péwé, 1983b), and ancient forms imply the presence of former permafrost and a periglacial climate of sufficient intensity to permit ice to exist and deform under pressure (White, 1981). Permafrost can exist in alpine areas if the mean annual temperature at ground level is 0° to -1°C, especially when the snow cover is thin and of short duration (Péwé, 1983b). The lower limit of rock-glacier activity occurs in the zone of discontinuous permafrost and may be determined by mean annual air temperatures of 0° to -2°C (Barsch, 1978).

A comparison of the average elevation of rock glaciers at a specific locality to the elevation of the orographic snow line may suggest the regional climate (continental versus marine) under which the rock glaciers formed. Shumski (1964) pointed out that the equilibrium line of glaciers corresponds to the lower limit of permafrost in maritime climates with abundant snow precipitation. On the other hand, the lower limit of permafrost under a continental climate is far below the snow line and the preservation of glaciers is dependent mainly on low temperatures. Corté (1987b) noted that rock-glacier activity in the central Andes (latitude 33°S) is 1300 m below the equilibrium line of glaciers on the continental side in Argentina, whereas on the maritime side in Chile, rock-glacier activity is 700 m below the equilibrium line. He attributed this to the climatic differences between the two regions. Greater snow fall on the west side of the Andes reduces the intensity and depth of freezing and raises the elevation of the lower level of permafrost.

SACATON MOUNTAIN

Geographic and geologic setting

Sacaton Mountain, a prominent peak in the Mogollon Range, is located about 18 km southeast of Glenwood, New Mexico (Fig. 1). It is in the Gila Wilderness area (Gila National Forest) and is accessible by the Sacaton Mountain pack trail, which crosses the northern slope of the mountain (Fig. 2). The mountain has a summit elevation of 3249 m and is an isolated peak that extends about 600-760 m above the surrounding terrain. The upper slopes, above 2750 m, are less steep than the lower slopes and are dissected by canyons and gullies with maximum depths of about 200 m.

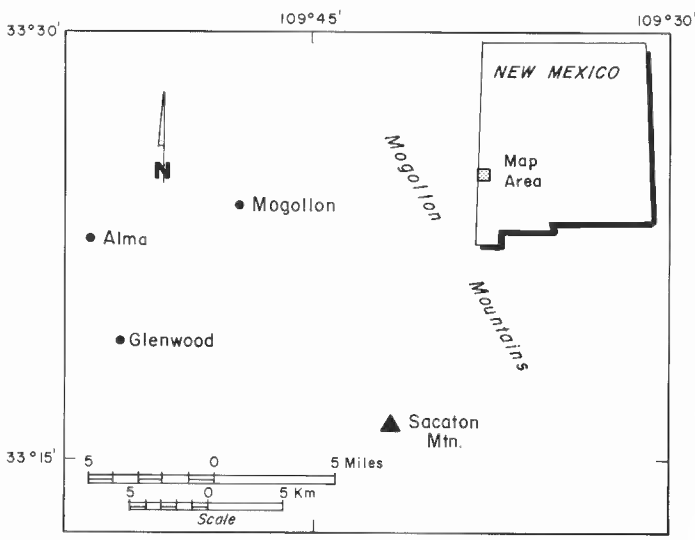

FIGURE 1. Location of Sacaton Mountain near Glenwood, New Mexico. Base map is U. S. Geological Survey topographic map, Clifton quadrangle, 1:250,000

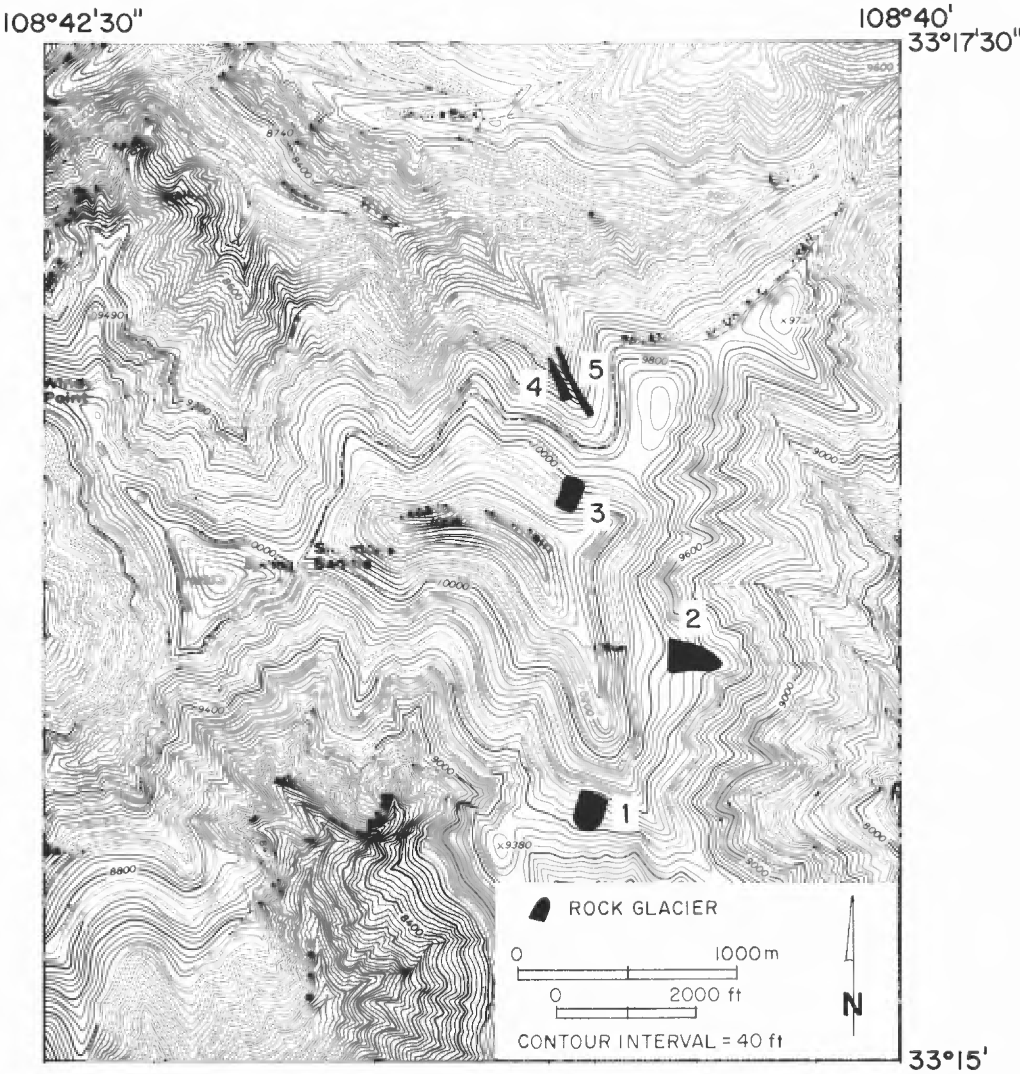

FIGURE 2. Topographic map showing the location of rock glaciers on Sacaton Mountain. Numbered localities indicate rock glaciers discussed in the text. Base map is the U. S. Geological Survey topographic map, Grouse Mountain, NM, 7.5 minute quadrangle.

The Mogollon Range is part of the Datil-Mogollon upland, which covers an extensive area of west-central New Mexico and east- central Arizona (Hawley, 1986). It includes several peaks above 3050 m and is eroded in lavas and tuffs of the Mogollon Plateau volcanic complex. The upper slopes of Sacaton Mountain, above 2600-2750 m, are formed by the Sacaton Mountain Quartz Latite, a porphyritic lava flow (Rhodes, 1970). On Sacaton Mountain this unit is a massive rock with blocky jointing. The Apache Springs Quartz Latite underlies the Sacaton Mountain Quartz Latite and forms the lower slopes of Sacaton Mountain. It is the major ash- flow tuff sheet in the Mogollon Range.

Talus sheets mantle extensive areas of the upper slopes of Sacaton Mountain. The debris is derived from the Sacaton Mountain Quartz Latite, a favorable source due to its massive outcrops and blocky jointing. Most deposits have smooth concave slopes; some have irregular or wavy surfaces that probably resulted from localized movement of the debris by solifluction or frost creep. Many of the talus sheets are devoid of vascular plants; on others, trees and shrubs project through the debris.

The town of Glenwood (elevation, 1441 m) is the closest weather station that maintains continuous long-term weather records. Thirty-six year normals for 1948-1983 indicate a mean annual temperature of 14.3°C (Kunkel, 1984). January is the coldest month (mean temperature, 4.9°C); July is the warmest (mean temperature 24.5°C). For the same period the average annual precipitation was 38 cm, with about 45% of the total occurring during the months of July, August and September.

Van Devender et al (1984) indicated a mean annual lapse rate in south-central New Mexico of 0.72°C/100 m. Utilizing this value, the following crude approximation of current temperature conditions were calculated for Sacaton Mountain: 5°C at about 2750 m, and 1°C for the crest (3249 m). Vertical precipitation gradients in the region suggest that the mean annual precipitation for the upper slopes and crest of Sacaton Peak may be about 75 cm. (Tuan et al, 1969). The cool temperatures and abundant precipitation result in a life zone characterized by spruce-fir on the upper slope and crest of the mountain.

Description

Five rock glaciers on Sacaton Mountain were identified on U. S. Forest Service aerial photographs (scale 1:15,840) and plotted on the U. S. Geological Survey topographic map of the area (Fig. 2). Their lengths and widths were determined and soil development and vascular plant cover were noted from the aerial photographs. The elevation of the fronts and heads, and their degree of slope were calculated from the topographic map.

Wahrhaftig and Cox (1959), in their studies in the Alaska Range, proposed a terminology of the gross features and surface relief of rock glaciers that is followed here with some modification. The front is the steep face that marks the down- valley end of the rock glacier. The sides are typically abrupt embankments that diminish in height up-valley, and the head is the place where the rock glacier terminates at the base of a cliff or steep slope. Lateral ridges are prominent embankments that border the sides.

Surface relief features include longitudinal, transverse and oblique ridges and furrows. Longitudinal ridges extend along the length of a rock glacier and parallel the apparent direction of flow. Transverse ridges and furrows are perpendicular to the apparent direction of movement and are generally convex down slope. Transverse ridges commonly die out against longitudinal or lateral ridges, or bend sharply to merge with them. Oblique ridges and furrows strike at about 45° to the apparent direction of movement.

The rock glaciers on Sacaton Mountain are below cliffs and in a ravine on the upper slopes. The elevation of the fronts average 2891 m and the heads 2987 m. They are tongue shaped, with lengths of 150 to 230 m and widths of 30 to 120 m. Heads terminate at talus which covers steep slopes or cliffs. Fronts are steep embankments with slopes of about 20° to 30°; the surfaces above the fronts slope valleyward at about 15°.

Rock glaciers 1, 2 and 3 are below talus-mantled cliffs on the south, east and north flanks of the mountain. Lateral ridges along their sides bend to form transverse ridges at the crest of the fronts. Surfaces above the fronts are hummocky due to many randomly oriented ridges and furrows. Rock glacier 2 is formed by two talus tongues with steep fronts (Fig. 3); the upper tongue appears to have overridden the head of the lower. Lateral ridges along the flanks of the upper tongue bend to form a transverse ridge at the crest of the front. A depressed area between the two lateral ridges extends from the base of the transverse ridge to the head.

Rock glaciers 4 and 5 are in a tributary ravine to Big Dry Creek on the north slope on the mountain (Fig. 4). The west flank of rock glacier 4 merges with talus on the west wall of the ravine and the east flank is delineated by an embankment that extends above the ravine floor. Many closely-spaced transverse ridges and furrows are on the front and the surface above the front. A small talus tongue with transverse ridges and furrows extends from the base of the front and may have been overridden by the front. The rock glacier appears to have developed from two talus lobes that accumulated along the west wall of the ravine. The lobes coalesced on the ravine floor and moved down slope as a single mass of debris.

The east flank of rock glacier 5 merges with talus on the east wall of the ravine and a well-defined lateral ridge along the west flank above the floor. Transverse ridges and furrows are on the front and many closely-spaced transverse and oblique ridges and furrows are on the surface above the front. A talus tongue extends from the base of the front and probably was overridden by the front.

The surface debris of the rock glaciers appears to be stable and is composed of fragments derived from outcrops of the Sacaton Mountain Quartz Latite. Soil development is minimal and may be confined to isolated pockets filling voids between the debris. Vascular plants cover from 1 to 10% of the rock glacier surfaces.

ESCUDILLA MOUNTAIN
Geographic and geologic setting

Escudilla Mountain is located about 8 km north of Alpine in Apache County, Arizona (Fig. 5). It is in the Escudilla Wilderness area within the Apache National Forest and its summit is accessible by a pack trail that ascends the south flank. The summit has an elevation of about 3260 m and three prominent peaks extend above 3280 m. The flanks are formed by steep cliffs about 240-370 m high and are dissected by gullies and ravines with maximum depths of about 250 m.

Escudilla Mountain is capped by a sequence of Tertiary basalt flows with a maximum thickness of about 275 m (Wrucke, 1961). A friable Tertiary sandstone of eolian origin underlies the basalt and crops out around the flanks. Talus derived from the basalt forms extensive sheets on the mountain slopes below about 3050 m. Many sheets have smooth concave slopes and some have irregular or wavy surfaces due to localized movement of the debris.

There are no long-term weather records for Escudilla Mountain. However, the natural vegetation suggests a humid climate for the upper slopes and crest with a mean annual precipitation greater than 75 cm. Regional lapse rates and temperature records at Alpine (Sellers, 1974) give an approximation of current temperature conditions on Escudilla Mountain of 3°C at 2900 m and 1°C for the summit.

Field observations on Escudilla Mountain recorded periglacial deposits of Wisconsinan age that suggest more severe climate. Barsch and Updike (1971) noted inactive rock glaciers and considered them to be ice-cemented (permafrost) forms because they occur well below the Wisconsinan snow line. Péwé (1983a) observed periglacial talus and thought it indicated a more rigorous climate but not necessarily requiring permafrost.

Description

Twelve rock glaciers on Escudilla Mountain were observed on U. S. Forest Service aerial photographs (scale 1:15,840) and plotted on U. S. Geological Survey topographic maps (Fig. 6). The rock glaciers are below talus in ravines and gullies on the north, east and west sides of the mountain. The elevation of the fronts average 2935 m and the heads

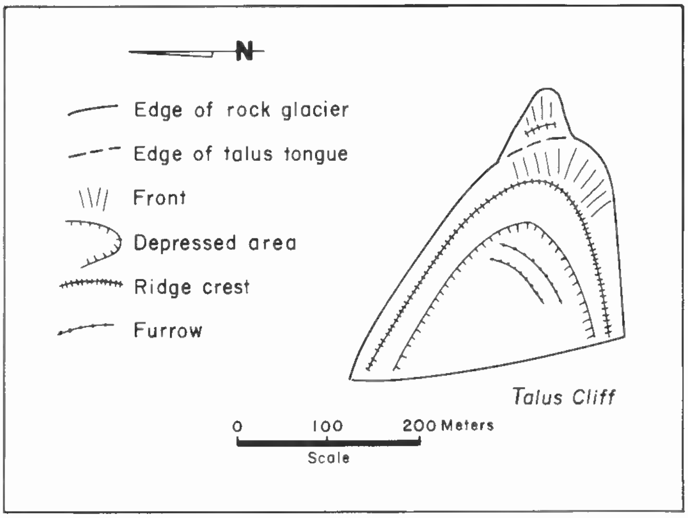

FIGURE 3. Sketch map of rock glacier 2 taken from U. S. Forest Service aerial photograph EDI-2-96. The rock glacier is below a talus-mantled cliff on the east side of Sacaton Mountain (Fig. 2).

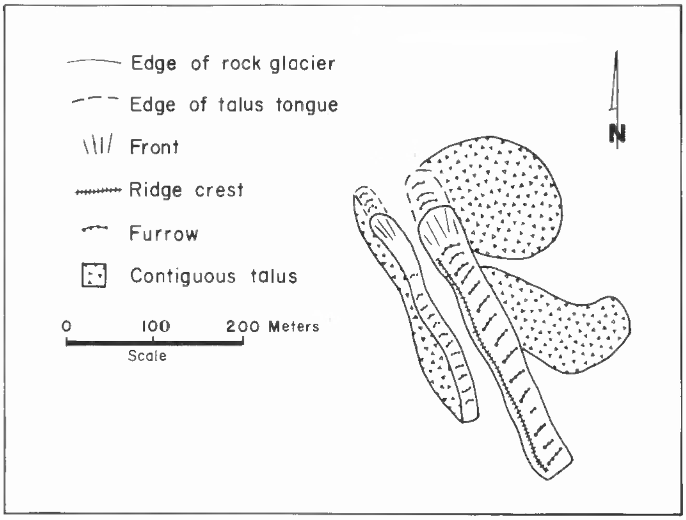

FIGURE 4. Sketch map of rock glaciers 4 and 5 taken from U. S. Forest Service aerial photograph EDI-295. The rock glaciers are in a ravine on the north side of Sacaton Mountain (Fig. 2).

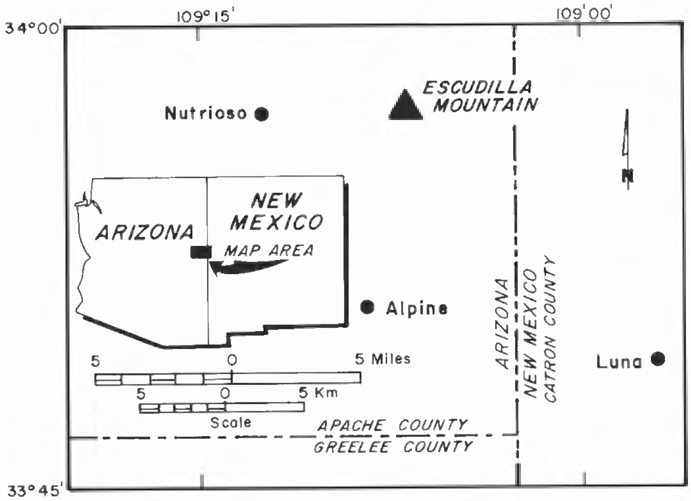

FIGURE 5. Location of Escudilla Mountain near Alpine, Arizona. Base map is U. S. Geological Survey topographic map, Clifton quadrangle, 1:250,000.

3030 m. They are tongue- shaped with average lengths of 130 m and widths of 55 m. Heads terminate at the base of talus sheets and fronts are steep embankments that slope at about 20 to 30°.

Most of these rock glaciers have lateral ridges along one or both sides that bend to form traverse ridges at the crests of the fronts. Transverse ridges and furrows occur on the fronts and the surfaces above the fronts. Some rock glaciers have depressed areas between the lateral ridges that extend from the crests of the fronts to the heads. Hummocky topography in the depressed areas is due to longitudinal, transverse and oblique ridges and furrows.

The debris on the surfaces of the rock glaciers appears to be stable and probably is composed predominately of fragments of basalt derived from the upper slopes of the mountain. Soil development is minimal and may be restricted to small pockets filling voids between the debris. Vascular plants cover from 0 to 10% of the rock glacier surfaces.

AGE

Glacial and periglacial deposits in the White Mountains in east-central Arizona provide a reference for estimating the age of the rock glaciers on Sacaton Mountain and Escudilla Mountain. Merrill and

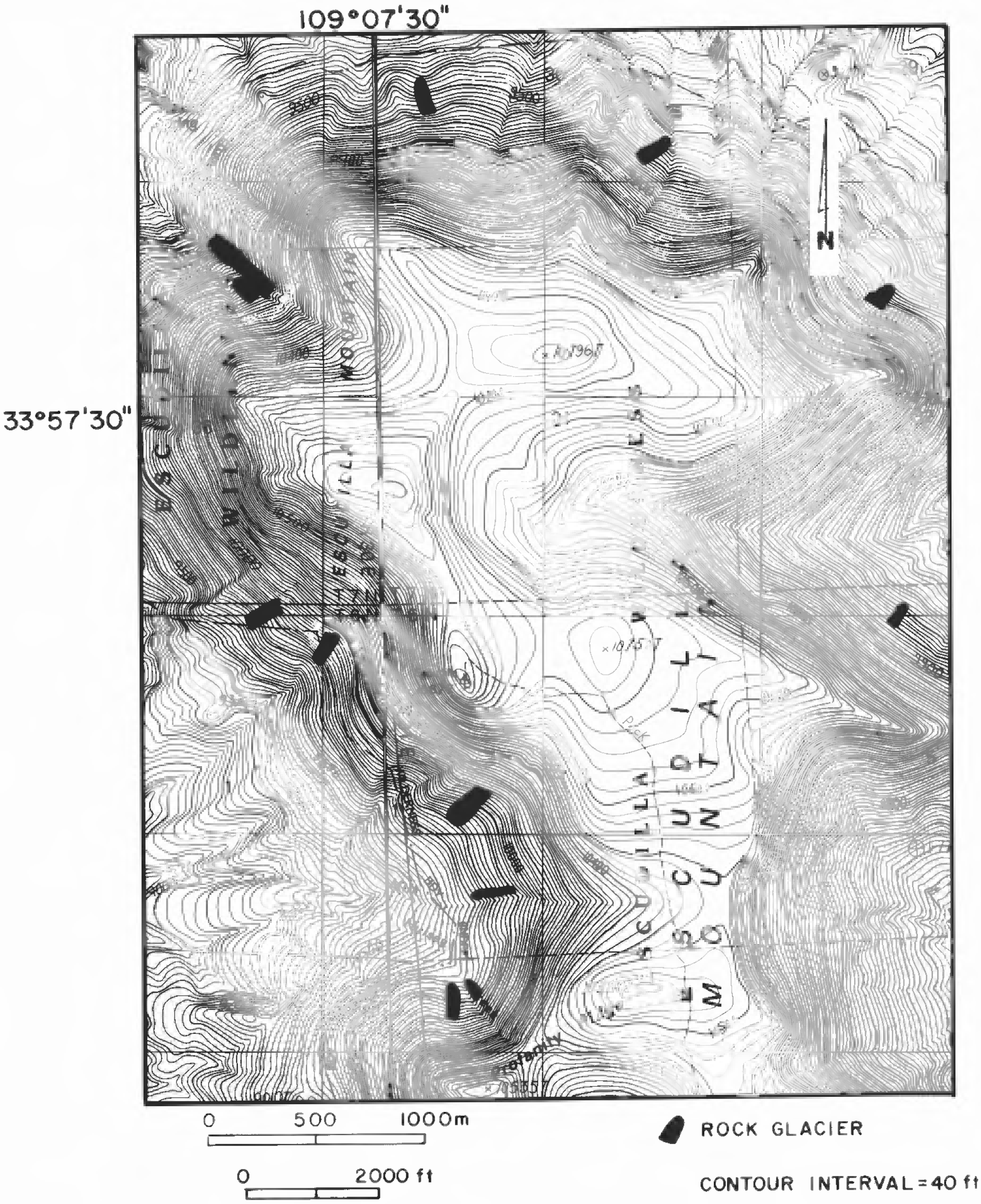

FIGURE 6. Topographic map showing the location of rock glaciers on Escudilla Mountain. Base maps are the U. S. Geological Survey topographic maps of the Escudilla Mountain, Arizona and New Mexico and the Nutrioso, Arizona, 7.5 minute quadrangles.

Péwé (1972, 1977) mapped moraines of pre-Wisconsinan, Wisconsinan and Holocene age in cirques and alpine valleys on Baldy Peak and Mount Ord. Moraines of the Purcell Glaciation of pre-Wisconsinan age are weathered to a depth of more than 50 cm and the surface boulders have deep weathering pits. The deposits are highly subdued and have a moderate to well-developed soil. Moraines of the Smith Cienega Glaciation (early Wisconsinan) bear a zonal soil 25-30 cm thick. Moraines of the Baldy Peak Glaciation (late Wisconsinan) are sharp crested and have a shallow azonal soil about 20 cm thick developed on their surfaces.

A moraine, protalus ramparts and periglacial talus are included in the Mount Ord Glaciation. The moraine is in a cirque on the northeast side of Mount Ord at about 3350 m. Its original surface is well-preserved and boulders on the surface are fresh. The moraine is forested and has a weak azonal soil about 12 cm thick developed on sediment between the boulders. Merrill and Péwé (1972) assigned the Mount Ord deposits an early Holocene or Neoglacial age. Richmond (1986) suggested that the Mount Ord moraine may be latest Wisconsinan in age because of its forest cover, a characteristic not reported on Holocene moraines elsewhere in the Rocky Mountain region.

In considering the age of rock glaciers it is important to be aware that the climate in which they formed may differ greatly from that in 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 creep of interstitial ice can take place in a climate with a mean annual temperature of 0° to -2°C of either 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 on Sacaton Mountain and Escudilla Mountain may have been active when the Mount Ord deposits were forming in the White Mountains because both have pronounced constructional relief. This suggests rock-glacier movement either during the late Wisconsinan or the Holocene. The sharply defined ridges and furrows, the restricted growth of vascular plants, and the scarcity of soil on the rock glaciers imply movement during the Holocene because well-preserved periglacial deposits in the southern Rocky Mountains generally are assigned a Holocene age (Richmond, 1986).

Recent studies in the Sacramento Mountains in south-central New Mexico (Van Devender et al, 1984, Van Devender, 1990) and in the San Agustin Plains in western New Mexico (Markgraf et al, 1984) indicate moderate cooling during the early Holocene and very little cooling during the middle and late Holocene. The early Holocene cooling may have resulted in the creep of interstitial ice in the rock glaciers on Sacaton Mountain and Escudilla Mountain and the accumulation of periglacial talus and protalus ramparts in the White Mountains. The late Wisconsinan glacial record in the White Mountains and an evaluation of the late Wisconsinan water balance of Lake San Agustin (Phillips et al., 1992) indicate a climate of sufficient intensity and duration to have favored the generation of rock glaciers on Sacaton Mountain and the Escudilla Mountain.

CLIMATE

The rock glaciers on Sacaton and Escudilla Mountains are permafrost forms because they have continuous talus extending onto their heads and well-defined longitudinal and transverse ridges and furrows on their surfaces. They indicate zones of alpine permafrost of probable late Wisconsinan and early Holocene age with a lower limit of about 2800 m on the north side of Sacaton Mountain. Within these zones the mean annual temperature was below freezing and the snow cover was thin and of short duration. During the late Wisconsinan, extended periods of diurnal freezing and thawing generated large volumes of talus which were mobilized into rock glaciers.

The altitudinal relationships between the rock glaciers on Sacaton Mountain and the modern and late Wisconsinan 0°C air isotherm, and the late Wisconsinan orographic snow line are shown in Fig. 7. The modern 0°C air isotherm is calculated at 3427 m using the lapse rate established by Van Devender et al., (1984) in south-central New Mexico, and climatic data from the weather station at Glenwood, New Mexico. The late Wisconsinan 0°C air isotherm is 1000 m below the modern 0°C air isotherm (Péwé, 1983, p. 175). The late Wisconsinan orographic snow line at 3260 m is based upon the average elevation of the cirque floors in the White Mountains in east-central Arizona (Melton, 1961).

The rock glaciers are about 290 m below the orographic snow line, which eliminates the possibility of movement due to glacial ice. They are about 500 m above the late Wisconsinan 0°C air isotherm, suggesting a climate of sufficient intensity to favor the formation of rock glaciers. The average elevation of the rock glacier fronts suggests that the early Holocene 0°C air isotherm was lowered a minimum of about 535 m. Utilizing this value and the lapse rate of Van Devender et al (1984) a mean annual temperature depression of about 4°C may be implied for the early Holocene.

The altitudinal ranges of the rock glaciers on Sacaton Mountain and Escudilla Mountain may be compared to the rock-glacier occurrences on South Baldy in the Magdalena Mountains (Blagbrough and Brown, 1983) and in the San Mateo Mountains (Blagbrough and Farkas, 1968) (Figs. 8, 9). The rise in altitude of the rock glaciers from east to west may be due to more abundant snow fall in the Datil-Mogollon Highland during the late Wisconsinan. A greater percentage of the total mean annual precipitation occurs during the winter months of December, January and February at weather stations in the Datil-Mogollon Highland than at those in the vicinity of the Magdalena Mountains and the San Mateo Mountains (Table 1).

These differences can be attributed to the location of the Datil-Mogollon Highland nearer to the Pacific Ocean, which is the principal source of winter moisture in the southwestern United States, and to orographic influences. The Datil-Mogollon Highland covers an extensive area in west-central New Mexico and east-central Arizona and has an important orographic control over the middle latitude Pacific-type winter storms moving from the southwest. This setting results in a mean annual precipitation of more than 100 cm in the White Mountains, the greatest in Arizona (Merrill and Péwé, 1972). The San Mateo Mountains and Mount Baldy are located on the leeward side of the Datil-Mogollon Highland which results in reduced winter precipitation.

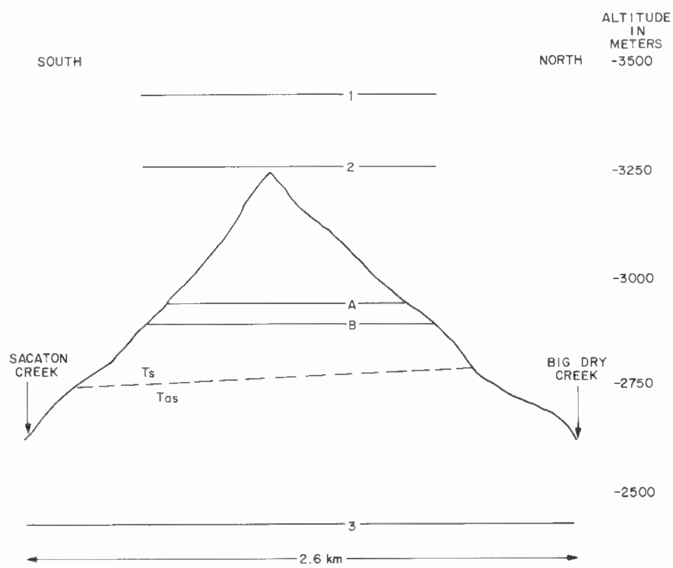

FIGURE 7. Diagrammatic cross section of Sacaton Mountain showing vertical distribution of glacial and periglacial features and the late Wisconsinan and modern 0°C air isotherm. 1, modern 0°C air isotherm; 2, late Wisconsinan orographic snow line; 3, late Wisconsinan 0°C air isotherm. A, average elevation of rock glacier heads; B, average elevation of rock glacier fronts. Tas, Apache Springs Quartz Latite; Ts, Sacaton Mountain Quartz Latite.

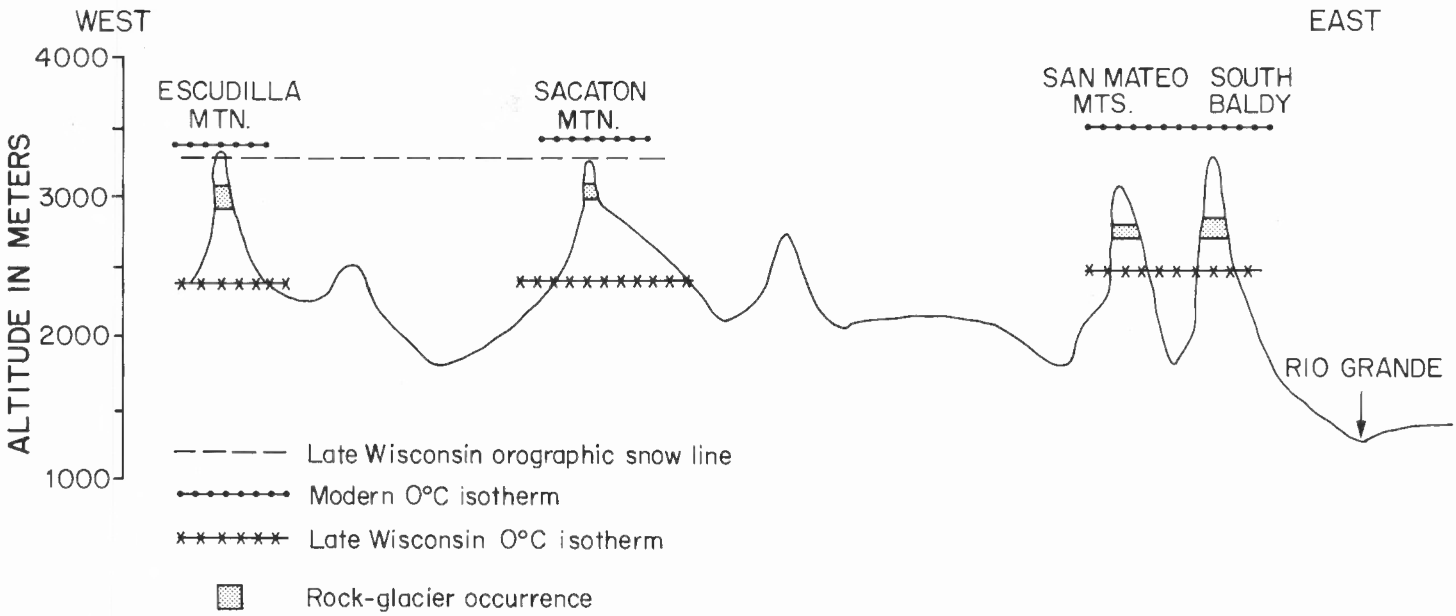

FIGURE 8. Generalized topographic profile across west-central New Mexico and east-central Arizona showing rock-glacier occurrences, the elevation of the modern and Late Wisconsin 0°C air isotherm, and the late Wisconsinan orographic snow line. Rock-glacier occurrences are determined by the average elevation of the fronts and heads at each site. The elevation of the modern 0°C air isotherm at each locality was calculated from lapse rates. The late Wisconsinan 0°C air isotherm is 1000 m below the modern 0°C air isotherm (Péwé, 1983a). The elevation of the late Wisconsinan orographic snow line is determined by the average elevation of the cirque floors in the White Mountains (Melton, 1961). The location of the rock- glacier sites are shown in Fig. 9.

The middle latitude Pacific-type winter storms probably were intensified and displaced southward during the late Wisconsinan (Spaulding et al., 1983), which would have enhanced winter precipitation in the Datil-Mogollon Highland. Greater snow fall on Sacaton Mountain and Escudilla Mountain apparently reduced the intensity and depth of ground freezing near the 0°C air isotherm and raised the elevation of the lower limit of permafrost to a higher elevation than in the San Mateo and Magdalena Mountains.

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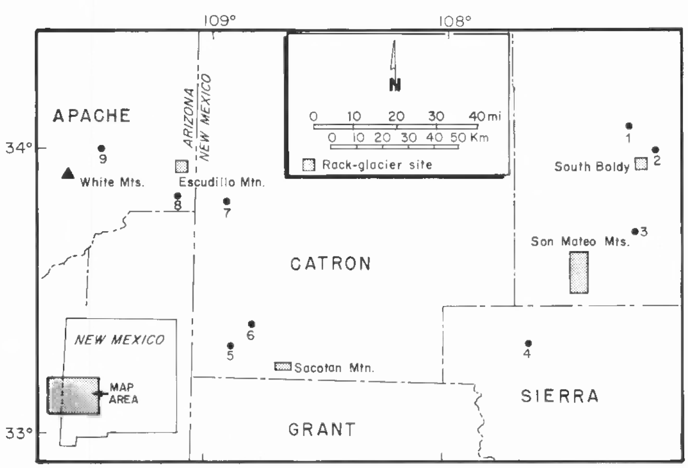

FIGURE 9. Location of rock-glacier sites in west-central New Mexico and east-central Arizona. Numbered localities identify weather stations in Table 1. Base maps are the U. S. Geological Survey's base maps of Arizona and New Mexico (scale 1:1,000,000).

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TABLE 1. Mean annual precipitation and winter precipitation (December, January and February) at selected weather stations in west-central New Mexico and east-central Arizona. The locations of the weather stations are shown in Fig. 9. Climatic data is from Gabin and Lesperance (1977), Kunkel (1984), and Sellers and Hill (1974).

Station	Location	Map Locality	Elevation m	Years of Record	Mean Annual cm	Winter cm	Percent Winter Precipitation
Magdalena	Socorro County, New Mexico	1	1994	53	28.82	3.59	12.5
Kelly Ranch	Socorro County, New Mexico	2	2043	39	36.10	4.41	12.2
Rienhardt Ranch	Socorro County, New Mexico	3	1662	33	23.31	2.26	9.7
Winston	Sierra County, New Mexico	4	1890	35	31.48	3.08	10.0
Glenwood	Catron County, New Mexico	5	1441	36	37.95	9.21	24.3
Mogollon B	Catron County, New Mexico	6	2012	13	46.92	11.18	23.8
Luna	Catron County, New Mexico	7	2149	53	38.46	7.12	18.5
Alpine	Apache County, Arizona	8	2451	30	49.56	10.33	20.8
Greer	Apache County, Arizona	9	2591	20	61.54	16.54	26.8

Receding thunderstorm and pine trees in Gila National Forest southeast of Pelona Mountain, New Mexico. View is N30°E. Camera station is alongside Highway 163 in NW ¼ sec. 17, T8S, R11W. Wayne Lambert photograph No. 93L88. August 15, 1993, approximately 6:23 p.m. MDT.