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# RECENT GLACIAL HISTORY OF AN ALPINE AREA IN THE COLORADO FRONT RANGE, U.S.A.

## II. DATING THE GLACIAL DEPOSITS

*By* JAMES B. BENEDICT

(Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, U.S.A.)

ABSTRACT. Recent glacial deposits in the Indian Peaks area of the Colorado Front Range have been dated lichenometrically, using a growth curve developed locally for *Rhizocarpon geographicum*. Radiocarbon dates, where available, tend to support the lichen chronology. Three distinct intervals of glaciation, each consisting of several minor pulsations, have occurred in the area during the past 4 500 years. The earliest advance (Temple Lake Stade) is dated at 2500–700 B.C. A later advance (Arikaree Stade) began in about A.D. 100 and ended in A.D. 1000. The most recent advance (Gannett Peak Stade) is dated at A.D. 1650–1850. It remains to be seen whether the Arikaree Stade was purely a local development or whether glaciers were advancing elsewhere in the cordilleran region during this interval. Alluviation on the plains east of the Colorado Front Range seems to have occurred during the waning stages of mountain glaciation.

RÉSUMÉ. *Histoire glaciaire récente d'une zone alpine de Colorado Front Range, U.S.A. II. Datage des dépôts glaciaires.* Les dépôts glaciaires récents dans les Indian Peaks, Colorado Front Range, ont été datés à l'aide de lichens, en utilisant la courbe de croissance locale de *Rhizocarpon geographicum*. Les datages au radiocarbone, là où ils étaient disponibles, tendent à confirmer la chronologie obtenue par lichens. Trois intervalles distincts de glaciation, chacun comprenant plusieurs pulsations mineures, ont eu lieu dans cette zone pendant les dernières 4 500 années. L'avance la plus ancienne (Temple Lake Stade) est datée à 2500–700 années B.C. Une avance plus tardive (Arikaree Stade) débuta environ à 100 A.D. et se termina en 1000 ans A.D. L'avance la plus récente (Gannett Peak Stade) est datée à 1650–1850 ans de notre ère. Il reste à savoir si Arikaree Stade était purement un développement local ou si les glaciers étaient en crue autre part dans la région des Cordillières pendant cet intervalle. L'alluviation des plaines à l'est du Colorado Front Range semble avoir eu lieu durant les stades de disparition de la glaciation des montagnes.

ZUSAMMENFASSUNG. *Rezente Glazialgeschichte eines alpinen Gebietes in der Colorado Front Range, USA. II. Datierung der glazialen Ablagerungen.* Rezente glaziale Ablagerungen im Gebiet der Indian Peaks der Colorado Front Range werden nach der Flechtenmethode unter Benutzung einer lokal gültigen Wachstumskurve für *Rhizocarpon geographicum* (Landkartenflechte) datiert. Radiokarbon-Datierungen stützen—soweit verfügbar—die Flechten-Chronologie. Während der letzten 4500 Jahre traten in dem Gebiet 3 unterscheidbare Vereisungsperioden ein, von denen jede aus einigen kleineren Schwankungen bestand. Der früheste Vorstoss (Temple-Lake-Stadium) wurde auf 2500–700 v. Chr. datiert. Ein späterer Vorstoss (Arikaree-Stadium) begann etwa im Jahre 100 und endete im Jahre 1000 n. Chr. Der jüngste Vorstoss (Gannett-Peak-Stadium) fand 1650–1850 statt. Es bleibt zu untersuchen, ob das Arikaree-Stadium nur eine rein örtliche Erscheinung war oder ob auch anderwärts im Cordillerengebiet Gletscher während dieser Periode vorrückten. Aufschüttungen in den Ebenen östlich der Colorado Front Range scheinen während der Schlussphasen der Gebirgsvergletscherung erfolgt zu sein.

### INTRODUCTION

A Little Ice Age glacial chronology has been developed for the Indian Peaks area, an alpine area located about 70 km north-west of Denver, Colorado, at the crest of the Colorado Front Range. The chronology is based on a study of all major cirques lying east of the continental divide in the vicinity of North and South Arapaho, Arikaree, Navajo and Apache Peaks. Observations in other valleys suggest that the conclusions reached in the Indian Peaks area are valid for the Front Range as a whole.

The local environment is cold, dry and windy (Marr, 1961; Paddock, 1964). On Niwot Ridge, at 3 744 m elevation, the mean air temperature is $-3.3°$C and the average annual precipitation is 625 mm. Winter snowfall is immediately redistributed by prevailing westerly winds, which blow with an average velocity of 8.5 m/s. Gusts commonly exceed 50 m/s during the windy months of December, January, February and March.

Topographic contrasts in the area are extreme, with high rugged summits rising above remnants of a gently rolling Tertiary or early Pleistocene erosion surface, which is itself deeply dissected by steep-walled glacial valleys. Modern glaciers in the area are small and they are nourished almost entirely by wind-drifted snow (Outcalt, 1965). Subtle differences in cirque orientation and topography, as well as in the size and roughness of the source area to windward, can cause major differences in winter snow accumulation. Rates of ablation are also largely controlled by local factors, and the condition of one glacier seldom reflects the conditions of others in its immediate vicinity.

Richmond (1960), Madole (unpublished) and others have summarized the Pleistocene glacial geology of the area. Although recent reports have mentioned the presence of Little Ice Age moraines in the high valleys, none has been concerned primarily with this period of renewed glacial activity that began in Front Range cirques about 4 500 years ago.

Efforts to date the Little Ice Age glacial sequence have been frustrated by a lack of suitable dating methods. The earliest photographs and written descriptions of the area were made in the 1890's. Although they document a general recession that began in the mid-nineteenth century and accelerated sharply after the beginning of the twentieth century (Waldrop, 1964), historic records give no important information about the ages of the glacial deposits. The trees that dot the older moraines below the timber line are young and ring counts give very inadequate minimum ages for the surfaces on which they grow. Recognizable ash layers have not yet been found in the deposits, and the apparent absence of organic material in association with the younger moraines has made radiocarbon dating impossible. As a result of these many difficulties, previous attempts to date the glacial sequence have been based on correlation with dated alluvial deposits on the plains to the east. The assumption involved—namely, that alluviation occurred during glacial maxima—should probably be examined more critically.

## Lichenometry

In the first part of this paper, the principles of lichenometry were outlined, the taxonomy and ecology of *Rhizocarpon geographicum* (L.) D.C. in the Indian Peaks area were discussed, and a growth curve for the species was developed (Benedict, 1967). This growth curve is reproduced in Figure 1.

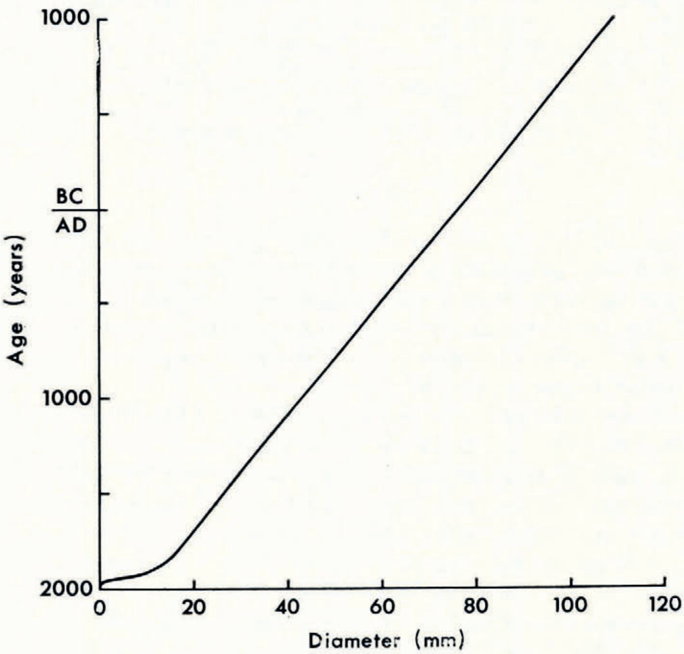


*Fig. 1. Growth curve for Rhizocarpon geographicum in the Indian Peaks area. Construction of the growth curve was described by Benedict (1967)*

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At best, lichenometry is imprecise. Small micro-environmental differences often distinguish the surfaces to be dated from those used in establishing lichen-growth rates, and departures from measured growth rates may be sizeable. In the present study an attempt has been made to minimize dating errors resulting from differences in environment (a) by determining growth rates in the immediate vicinity of the deposits to be dated, (b) by restricting all measurements to thalli growing on closely related rock types, chemically similar to granite, (c) by avoiding surfaces that are covered by late-lying snow banks, frequented by birds and animals, or irrigated by melt-water drainage during the growing season, (d) by sampling large areas that include rocks with a wide range of textures, slopes and exposures, and (e) by dealing with only the largest individual lichens, which have presumably grown under optimal local conditions. These precautions have helped in reducing the environment problem but they have not eliminated it entirely.

One minor source of error, unique to the present study, is a result of the types of dated surfaces that were used in establishing the Front Range growth curve. All but the oldest of these surfaces were initially stable and were available for lichen colonization as soon as they were exposed. Moraines and rock glaciers in the area, however, were ice-cored and unstable when first deposited. An interval of about 50 years seems to be required before *R. geographicum* can colonize the bouldery surface of an ice-cored moraine. Dates determined lichenometrically for ice-cored features will therefore be about 50 years too young.

## Techniques

In preparing the map shown in Figure 2, deposits were first sketched in the field on aerial photographs. Lichens were measured on almost all moraines, rock glaciers and pro-talus ramparts, as well as on selected talus slopes and bedrock surfaces. The maps were continually revised during 3 years of field work and lichen measurements were repeated in problem areas.

The surface of each feature to be dated was criss-crossed repeatedly, and the maximum diameters of all large *R. geographicum* thalli were measured and recorded. Measurements were made to the nearest millimeter. Only the five largest individuals were permanently recorded, with the single largest of these being used for dating. Exceptionally large thalli were viewed with suspicion, particularly near cirque headwalls, where it was possible for lichen-covered rocks to fall onto the surface from above. Elongate thalli, thalli growing in unusual micro-environments and complex thalli, suspected to consist of several smaller lichens growing together, were ignored.

Voucher specimens were collected at several sites and they were identified by Dr. Roger A. Anderson, University of Denver. Vouchers are on file at the University of Colorado Museum Herbarium.

## Glacial Chronology

A summary of lichen measurements made on 50 moraines in the Indian Peaks area is given in Figure 3. The data suggest three distinct stades of Little Ice Age glaciation, separated by two intervals in which moraines were not deposited. The youngest and oldest glacial advances are correlated with the Gannett Peak and Temple Lake Stades of Neoglaciation (Richmond, 1965), respectively. Correlation is based on the general appearance of the moraines, their positions in the cirques and the degree of soil-profile development at their crests. Glacial deposits of the intermediate advance have not been previously recognized in the area. Throughout this paper this advance will be referred to informally as the "Arikaree Stade", taking the name from a prominent pro-talus rampart overlooking Arikaree Glacier.

### *Gannett Peak Stade*

Moraines deposited during the Gannett Peak Stade are fresh and bouldery, and they lie

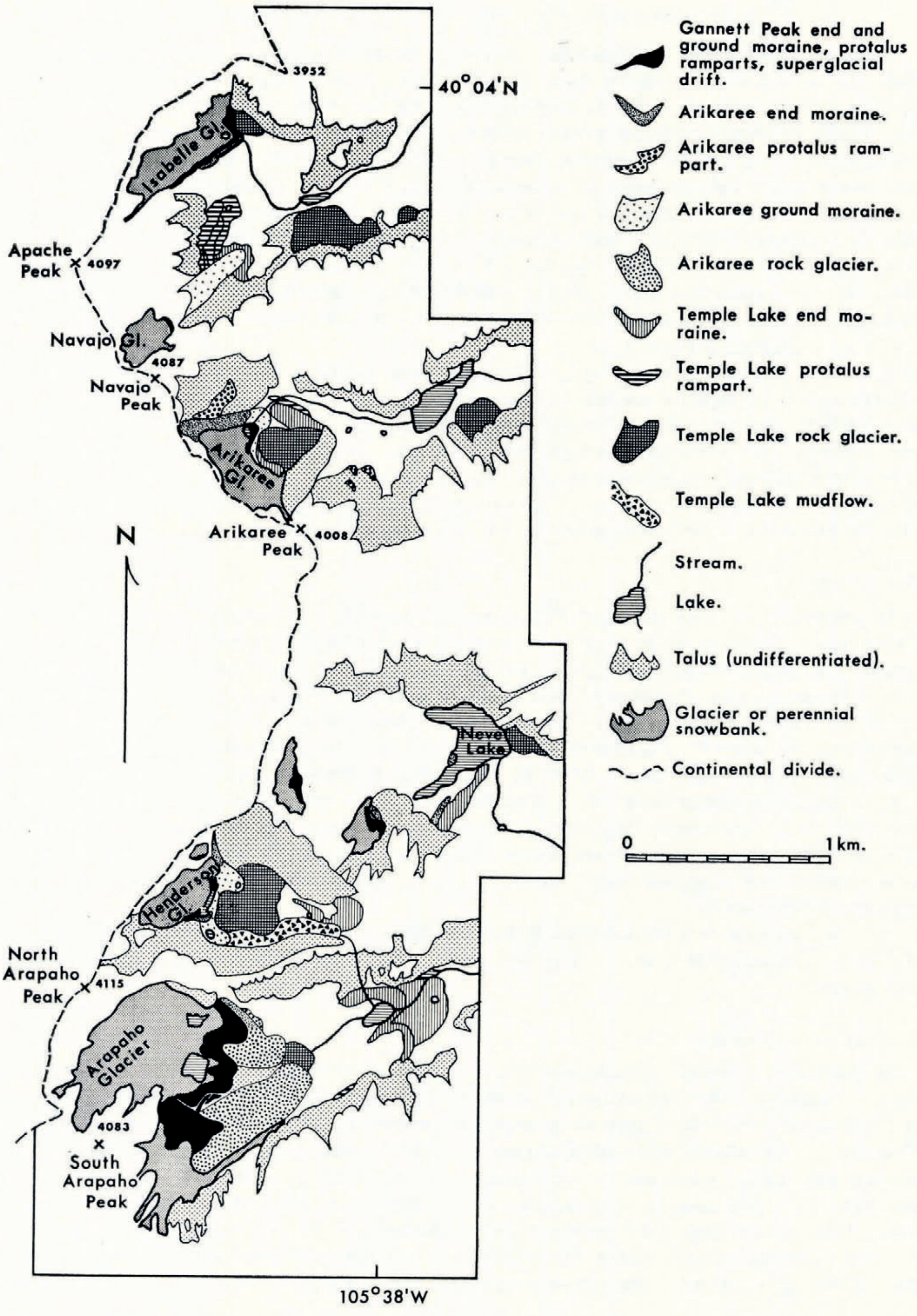


*Fig. 2. Map of Little Ice Age glacial and periglacial deposits east of the continental divide in the Indian Peaks area, Colorado Front Range. The ages of the deposits were determined lichenometrically*

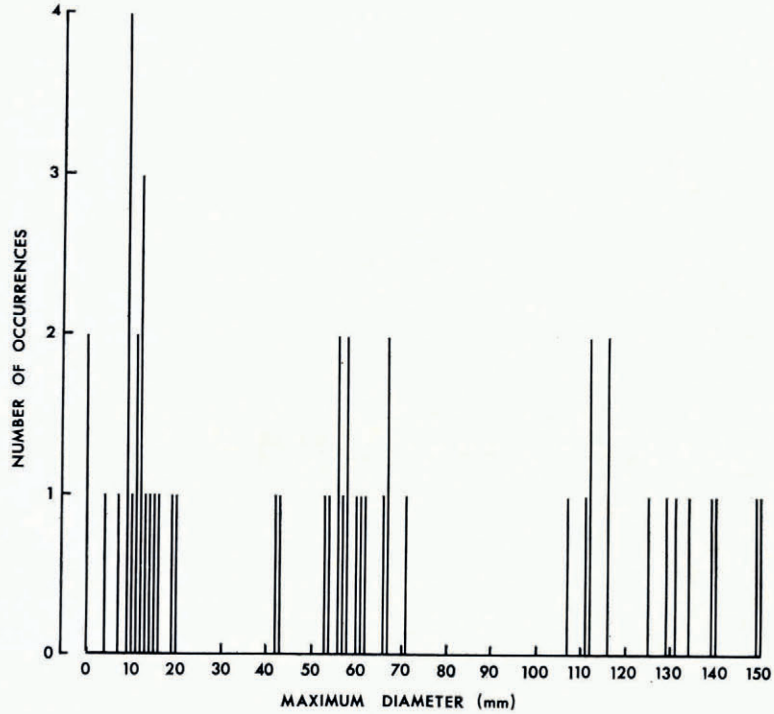


*Fig. 3. Maximum-diameter R. geographicum thalli measured on 50 moraines in the Indian Peaks area. The measurements fall into three broad size classes, suggesting three major periods of Little Ice Age glaciation*

within a few meters of the fronts of modern glaciers. Most of the moraines retain small lakes; shallow troughs crossing the crests of the moraines mark the locations of sub-surface outlet channels cut in the cores of glacial ice. Soil-profile development is restricted to a slight accumulation of surface organic matter in stable areas and to a downward migration of clay-sized particles into the 15–30 cm levels (personal communication from Bret Blosser). Areas of fine-textured soil support a sparse cover of mosses and pioneer herbs tolerant of instability. Lichen cover ranges from 0 to 5 per cent (Fig. 4), with *Umbilicaria virginis*, *Lecanora polytropa*, *Lecanora thomsonii*, *Lecidea atrobrunnea* and *Caloplaca elegans* being the most common species. Most rocks are lichen-free. *R. geographicum* thalli are rare and they grow either on very large coarse-textured boulders or at ground level, on small stones, in stable mossy areas. Maximum diameters of 20 mm suggest that *R. geographicum* began to colonize the oldest of these moraines in about A.D. 1700. Allowing 50 years for partial stabilization of the debris, a date of A.D. 1650 seems reasonable for deposition of the oldest moraines of this advance in the Front Range area. Historical records show that ice had already withdrawn from the innermost Gannett Peak moraines by the beginning of the twentieth century.

As many as three morainal crests are locally present, although two crests are more common, and only a single moraine is present in many cirques. The most recent of the three Gannett Peak advances was generally the most extensive. A very prominent triple-crested moraine lies at the terminus of the modern Arapaho Glacier; a study of plant and soil development on this moraine led Blosser (personal communication) to conclude that the two inner crests had been deposited in rapid succession and that both were considerably younger than the outer-most crest.

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*Fig. 4. Representative Gannett Peak lichen cover. Most rocks are bare. Small thalli of Lecanora thomsonii* ($L_t$) *and Umbilicaria virginis* ($U_v$) *can be seen in the photograph. R. geographicum thalli are rare and reach maximum diameters of 20 mm on Gannett Peak surfaces. The knife is 17 cm long*

Small amounts of talus accumulated in the upper valleys and pro-talus ramparts were deposited in many of the cirques during Gannett Peak time. Rock glaciers on the floors of modern cirques received additional increments of ice and debris, but no new rock glaciers seem to have developed during this period. Patterned ground was locally active, as demonstrated by the poorly developed sorted polygons, 1.2–2.4 m in diameter, that occur along the crest of the innermost Gannett Peak moraine in Arapaho cirque.

*Arikaree Stade*

Associated with the youngest moraines, and in some cases partially buried beneath them, are deposits of an older stade of glaciation. From a distance, and on aerial photographs, these deposits are indistinguishable from moraines of Gannett Peak age. The moraines are fresh and bouldery, with sharp crests and steep unstable slopes. Many retain a deeply buried core of glacial ice. Melt-water drainage percolates through the moraines or flows across their crests through shallow channels. A thin, very dark grayish brown A horizon is the only evidence of soil-profile development on these deposits and it is limited to stable areas with fine-textured soil. Vascular plants are poorly represented. Lichen cover ranges from 10 to 40 per cent, with very large thalli of *Lecanora thomsonii* and *Lecidea atrobrunnea* (150–200 mm) being characteristic (Fig. 5). Many rocks are lichen-free. *R. geographicum* thalli reach maximum diameters of 42–71 mm. Allowing 50 years for partial stabilization of the debris, a date of A.D. 100 to A.D. 1000 seems reasonable for deposits of this stade.

The type locality for the Arikaree Stade is a large pro-talus rampart on the east flank of Navajo Peak, overlooking Arikaree Glacier. Alternating ridges of coarse- and fine-textured

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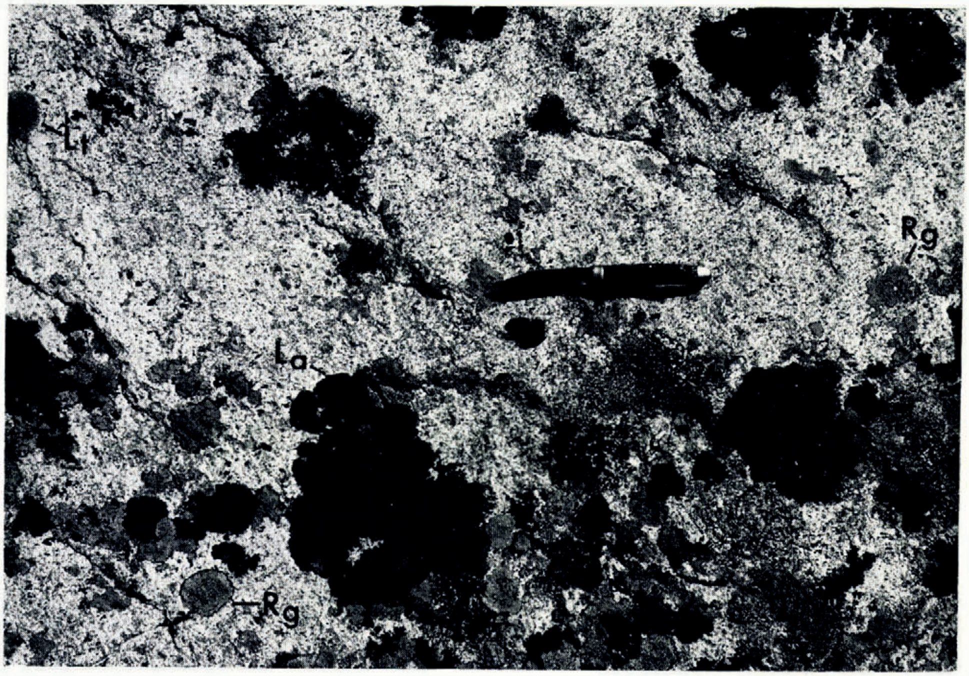


*Fig. 5. Representative Arikaree lichen cover. R. geographicum thalli* ($R_g$) *reach maximum diameters of 42–71 mm on moraines of Arikaree age. Very large thalli of Lecanora thomsonii* ($L_t$) *and Lecidea atrobrunnea* ($L_a$) *are conspicuous. The lichen cover on Arikaree surfaces ranges from 10 to 40 per cent*

material, orientated down-slope, give the pro-talus rampart a fluted appearance on aerial photographs. Some of the ridges are composed entirely of cobbles and others of boulders. The troughs between the ridges are choked with large boulders and it is on these relatively stable surfaces that *R. geographicum* thalli reach their maximum diameters (57 mm). The slope below the pro-talus rampart is covered with talus of Temple Lake age; the slope above is blanketed entirely by Arikaree talus.

The largest and most prominent rock glaciers in the Indian Peaks area were deposited on the floors of modern cirques during the Arikaree advance. Several of these features are currently being studied by Dr. Sidney E. White, The Ohio State University. Rock glaciers in Arapaho cirque consist of at least two, and possibly three, superimposed lobes of Arikaree age. The youngest lobes retain a core of glacial ice at depths of 2.0 to 2.5 m. The apparent three-fold sequence found in rock glaciers of Arikaree age is duplicated in sequences of pro-talus ramparts in the area and it seems likely that three minor advances occurred during Arikaree time.

The earliest Arikaree advance, which may have reached its maximum in about A.D. 250, was the most extensive. In Navajo cirque, it deposited a long and narrow tongue of ground moraine extending from near the front of the modern glacier to a point about 0.5 km down-valley. The ground moraine is fluted, with low ridges of cobbles and small boulders trailing off down-valley for distances of 5–20 m in the lee of larger rocks. Ice of this advance seems to have had very little erosive power. At its terminus in Navajo cirque, the ice tongue over-ran a Temple Lake terminal moraine. Sorted polygons on the moraine were not destroyed or modified by burial beneath Arikaree ice, suggesting that the glacier may have advanced over perennially frozen ground. Cobbles and boulders of Arikaree still lie scattered in the borders of the polygons, and, in the polygon centers, they rest on a thin A horizon developed during the interval between Temple Lake and Arikaree time.

A second Arikaree advance probably reached its maximum extent in about A.D. 550. Moraines and pro-talus ramparts were deposited during this sub-stade, and additional debris and ice were added to rock glaciers formed during the first Arikaree advance.

A third Arikaree advance attained its maximum in about A.D. 950. Additional material was added to the depressions at the rear of large rock glaciers on the floors of modern cirques. A few pro-talus ramparts were deposited in the area during this sub-stade. Evidence for the third advance is limited to a few cirques. Lichen dates on bedrock immediately down-valley from Gannett Peak moraines show that Arikaree ice had retreated into the cirques and probably had disappeared completely by A.D. 1050.

### *Temple Lake Stade*

Moraines deposited during the Temple Lake Stade are topographically subdued. They lie at distances of 0.1–1.3 km down-valley from the fronts of modern glaciers. Boulders are numerous and angular, and they show a much higher degree of pitting and weathering than boulders in deposits of the younger advances. The moraines are blanketed with tundra vegetation and many bear a scrub cover of krummholz spruce and fir. An A horizon, 10–25 cm thick, is present where the soil is fine-textured. Well-developed sorted polygons, 1–5 m in diameter, occur on many of the moraines. Terminal moraines commonly retain small lakes, which drain through shallow channels cut across their crests. In bouldery areas, the lichen cover ranges from 80 to 95 per cent (Fig. 6). *Lecanora thomsonii* and *Lecidea atrobrunnea* are no

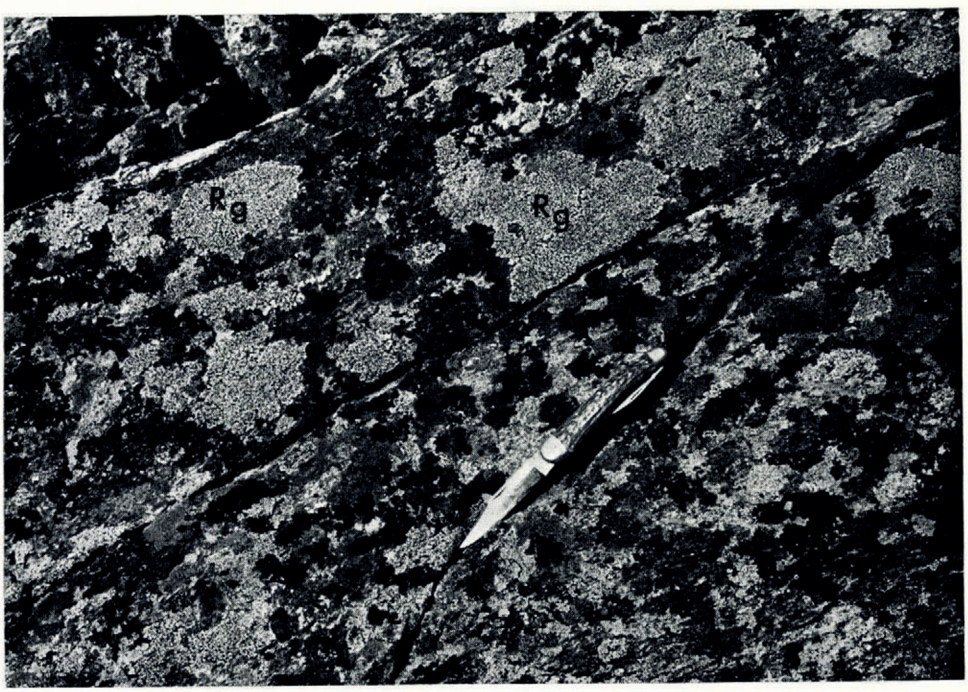


*Fig. 6. Representative Temple Lake lichen cover. Bouldery areas on Temple Lake moraines support an almost complete (80–95 per cent) cover of lichens. R. geographicum* ($R_g$) *is the dominant species. The large complex Rhizocarpon thallus growing above the knife consists of four or five smaller individuals. R. geographicum thalli reach maximum diameters of 107–150 mm on moraines of Temple Lake age*

longer dominant and large *R. geographicum* thalli are conspicuous. *Alectoria pubescens*, *Acarospora chlorophana*, *Lecanora caesiocinerea*, *Lecidea armeniaca*, *Rinodina oreina* and *Sporastatia testudinea* contribute to the almost complete lichen cover on these deposits.

Most rock glaciers at the bases of steep valley walls were deposited during Temple Lake time, although some may be as old as late Wisconsin. Many are too old to be dated with lichens, which can be used with confidence only for dating deposits younger than about 3 000 years. Rock glaciers of glacial origin (Outcalt and Benedict, 1965) were deposited on valley floors during the Temple Lake Stade; because they have lost their cores of glacial ice, many now resemble moraines.

At least two, and perhaps as many as four, periods of expanded snow cover occurred during the Temple Lake Stade. A series of four pro-talus ramparts, all apparently of Temple Lake age, lies at the base of Apache Peak, between Navajo and Isabelle cirques. The outermost ridge merges with a Temple Lake terminal moraine; the three innermost ridges are truncated at their southern ends by fluted ground moraine of Arikaree age. Arikaree talus fills the depression at the rear of the pro-talus ramparts.

Lichen measurements (Fig. 3) indicate that the youngest Temple Lake moraines in the area were deposited in about 900 B.C. Radiocarbon dates of 410±120 and 610±100 B.C. (I-2424 and I-2469) give a minimum age for the disappearance of late Temple Lake ice from the floor of the valley draining the present Arapaho Glacier (Benedict, 1967), and a radiocarbon date of 520±110 B.C. (I-1792) dates the beginning of A-horizon development on a nearby slope that was covered with perennial snow during Temple Lake time (Benedict, 1966). An age of about 700 B.C. therefore seems reasonable for the shift from glacial to non-glacial conditions that brought the Temple Lake Stade of Little Ice Age glaciation to a close.

*R. geographicum* can be used only for dating deposits younger than 3 000 years. In the absence of local radiocarbon control, a beginning date for the Temple Lake advance has been inferred from radiocarbon age determinations made in areas outside the Indian Peaks area. In pollen profiles from the San Juan Mountains, 315 km to the south-west, Maher (unpublished) found evidence for a sharp drop in temperature shortly after 2990±200 B.C. (LJ-539; Hubbs and others, 1963). Dates of 2220±100 B.C. (WIS-70; Bender and others, 1966) and 2400±400 B.C. (M-952; Pennak, 1963) apply to the beginning of organic-matter accumulation in low-elevation bogs, and probably reflect increasing moisture in the foothills area. These three dates suggest that Temple Lake glaciation began in the Colorado Rocky Mountains about 4 500 years ago, or in approximately 2500 B.C.

## Conclusions

Several of the time boundaries proposed here are more reliable than others. The lichen dates suggested for the Gannett Peak Stade and for the conclusion of both the Arikaree and Temple Lake advances appear to be satisfactory; all are supported by independent lines of evidence. The beginning date for the Temple Lake Stade is less secure and it may need to be revised as local radiocarbon dates become available. The proposed date of A.D. 100 for the beginning of the Arikaree Stade is an approximation, for there are no control points on the lichen-growth curve between 460 B.C. and A.D. 970. If *R. geographicum* grew at an accelerated rate during the latter part of this interval, when conditions were presumably moister than during the preceding interstadial, the date given here for the onset of the Arikaree glaciation may be several hundred years too old. All of the dates, including those determined lichenometrically, will eventually need to be corrected for the effects of long-term variations in the atmospheric $^{14}C$ inventory.

Despite uncertainties about the placement of time boundaries, it is clear that the traditional sub-division of Little Ice Age deposits in Front Range cirques into an early (Temple Lake) advance and a later (Gannett Peak) advance is unsatisfactory. Deposits of an intermediate advance (the Arikaree Stade) are present in almost every cirque. It is only because of their superficial resemblance to Gannett Peak moraines that they have gone unrecognized.

A recent summary of the Little Ice Age glacial history of western North America suggests that glaciers in the Cordilleran region were generally retracted during the Arikaree interval. Dated moraines equivalent in age to the Arikaree Stade are restricted to Alaskan coastal glaciers and their regional significance is not yet known (Porter and Denton, 1967). It remains to be seen whether the Arikaree advance was purely a Front Range phenomenon, or whether, in other areas, the deposits of this stade have simply not been recognized because of their similarity to deposits of Gannett Peak age. The latter seems to have been the case in the Sierra Nevada of California, where Robert R. Curry (personal communication) has recently outlined a three-fold Little Ice Age sequence that is similar in its broader aspects to the chronology developed in the Front Range. Curry has suggested that a major interval of expanded snow cover occurred in the Sierra Nevada during the period A.D. 760–1160.

An alluvial chronology for the High Plains east of the Colorado Rocky Mountains is shown in Figure 7. The sequence is based on a recent summary by Scott (1965), with time boundaries adjusted slightly in order to reflect radiocarbon dates that have recently become available. Comparison between the alluvial and glacial chronologies suggests that the post-Piney Creek alluvium in the Denver area was deposited during the waning stages of the Arikaree glaciation, and that the Piney Creek alluvium was deposited late in the Temple Lake Stade. This lends support to Scott's (1963) conclusion that alluviation occurred on the High Plains during the late stages of mountain glaciation, as climatic conditions became warmer and drier.

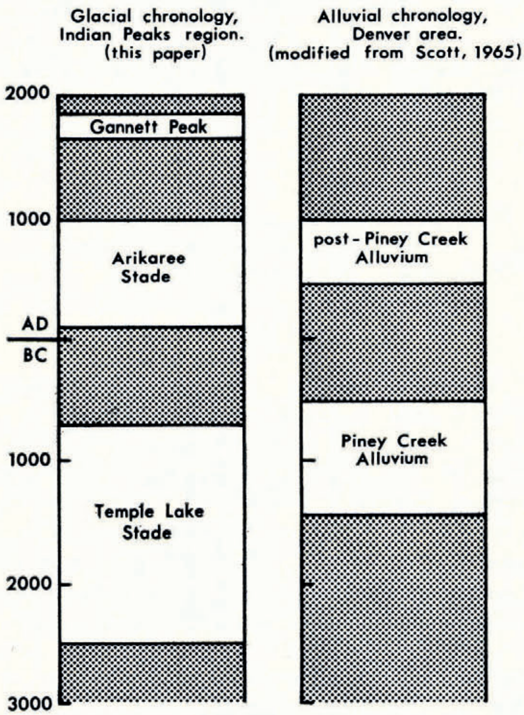


*Fig. 7. Comparison of the Front Range glacial sequence with an alluvial chronology for the High Plains east of the Colorado and Wyoming Rocky Mountains. If the lichen dates are correct, alluviation occurred during the waning stages of alpine glaciation rather than during glacial maxima*

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