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SLOPES IN SOUTHWESTERN WISCONSIN, U.S.A., PERIGLACIAL OR TEMPERATE?

Abstract

Since 1960 near Madison studies have been carried on of mass movement rates and processes affecting slope angles and terracettes on Ordovician dolomite and Cambrian sandstone. Within fenced areas measurements of vertical, horizontal, and downslope components of movement are referred to bench marks cemented to bedrock and protected from the overlying soil and rubble by casings. Measurement techniques include taping between larger stones and use of point gages, dial indicators, linear-motion transducers, and SR-4 strain gages. Slope segments range from horizontal to almost 40 degrees. Annual downslope components of movement range generally from 2 to 20 mm. Consistant seasonal patterns of movement for different kinds of material are masked partly be erratic behavior of many particles. Active formation of terracettes is going on along with rapid displacement downslope of soil and small stones. Late winter movements from alternate freezing and thawing above seasonal frost are largest; late spring and early fall wetting and drying moves particles almost as much.

From mass movements alone, slopes are losing up to 100 cm of material per 1000 years. Rates many times faster are reported in nearby agricultural areas. Solution of carbonates is also rapid. The steeper slopes in southwestern Wisconsin are related to structurally controlled stream incision and migration in gently dipping cuestas of alternating sandstones and dolomites. Except for a thin silty alluvial fill related to deforestation and agricultural practices during the last century, local stream channels contain little rock waste. Periglacial climates existed at different times during the Pleistocene but are not considered to have produced any major slopes still identifiable. The present temperate climate acting through stream incision, ground water solution, and mass movements suffices to explain most features.

INTRODUCTION

Southwestern Wisconsin has long been almost synonymous with the "Driftless Area". There subaerial erosion has been going on since Mesozoic times. The present main topographic elements are thought to have been established in the Tertiary (Trowbridge, 1921) or as recently as mid-Pleistocene (Frye, 1963; Palm-

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quist, 1965). Submaturely dissected, cuesta-form topography is developed on sandstone and dolomite formations of early Paleozoic age (Martin, 1932). Whether one or more peneplains existed is debated (Thornbury, 1965, p. 245). However, recent workers, including the writer, deny that any unequivocal evidence for them still remains today because of rapid erosion since mid-Pleistocene (Thwaites, 1960; Palmquist, 1965).

During most of the erosional history of the "Driftless Area" continental temperate climates obtained. However, probably several times during that interval, and during at least the late Pleistocene, after the main topographic elements were established, periglacial climates affected the area for some thousands of years while continental ice stood nearby. Erosion was probably accelerated at those times. Abundant ice wedge casts (Black, 1965) and other periglacial features (Black, 1964; Smith, 1949 and 1962, p. 331) attest to the former presence of permafrost and frost climates. Did the periglacial processes modify the slopes sufficiently to permit them to be distinguished from slopes produced by processes operating during the temperate climates? If so, how much of the present topography of southwestern Wisconsin is inherited from the periglacial climates, or conversely, how much of the periglacial topography has been destroyed during the temperate climates of today?

These questions are explored in this paper by first discussing the present rates of denudation and the nature of the present-day slope processes. The nature of the slopes likely to be achieved by the different processes operating today is compared with those that might have originated under periglacial conditions. The conclusion is reached that slopes were modified markedly by the processes of periglacial climates in southwestern Wisconsin, but they were not sufficiently distinctive or were not permanent enough to permit us to differentiate them from slopes derived by present-day processes.

ACKNOWLEDGMENTS

This paper is an outgrowth of an attempt since 1960 to develop instruments and techniques for quantification of mass-movement rates and the effect of frost action on particulates on slopes developed on Ordovician dolomite and Cambrian sandstone near Madison, Wisconsin. The slope study was supported principally by funds supplied by the Wisconsin Alumni Research Foundation through the Research Committee of the Graduate School of the University of Wisconsin. The writer's field work in the Driftless Area was also supported by National Science Foundation Grant GP-2820 and by the Wisconsin State Highway Commission.

The writer is especially indebted to Thomas D. Hamilton who set up the initial field stations where movement rates were measured (Hamilton, 1963). Hamilton, Stig Johnsson, Ned K. Bleuer, and Albert F. Allong each in turn has carried on the bulk of the measurements in the study sites since 1963. Without their enthusiastic efforts individually throughout the years, the quantification of slope movements would not have been accomplished.

THE DRIFTLESS AREA

The Driftless Area of southwestern Wisconsin is surfaced principally by Ordovician dolomite of the Galena—Platteville and Prairie du Chien Formations and to a lesser extent with Ordovician sandstone of the St. Peter Formation and with Cambrian sandstone of the St. Croixan Group. Rocks of Silurian and Precambrian age are of negligible extent. The Ordovician dolomites are the principal cuesta formers (Martin, 1932). Locally other rocks are resistant ridge-formers (Thwaites, 1960). The Paleozoic formations are flat-lying — dipping very gently to the south and west.

The submaturely dissected upland has summit levels between 275 and 425 m. Roughly 10 percent exceeds 150 m in local relief (Trewartha and Smith, 1941). At a maximum, relief is 245 m. Average slope is commonly 10 to 20 percent, but this is misleading. Rounded divides and flat valleys are separated by steep slopes (Pls. 1 and 2). The uplands appear smooth to the eye, but an inspection of topographic maps belies that effect.

In the area dendritic drainage patterns everywhere and at all scales are influenced by bedrock structures such as folds, faults, and especially joints (Palmquist, 1965). "The gross drainage pattern reflects variations in the regional dip, and the locations of divides and topographic highs are controlled by slightly beveled structural highs." Palmquist (1965) also found that a state of dynamic equilibrium is indicated by conformance to the laws of drainage composition, a hypsometric integral below 0.60, a high index of drainage equilibrium, and a general similarity between drainage basins. Small departures are related to lithologic changes. By various approaches Palmquist (1965) concludes that present gross topography is probably mid-Pleistocene in age.

It seems clear that the slopes are controlled by sandstone and dolomite and have only some centimeters to a few decimeters generally of soil and rubble. Local disturbed patches of clayey residuum seem to have been inherited from Tertiary times. Loess some centimeters to six meters thick caps the uplands and commonly forms surfaces not parallel to the underlying bedrock configuration. Small stream valley bottoms contain many meters of silt derived in large part by slope wash since deforestation and farming began about 100 to 150 years ago. The silt is on top of a buried soil in more silt and colluvium with some chert and sandstone rubble. Most larger streams in their upper reaches locally scour to bedrock during floods (Palmquist, 1965).

PRESENT RATES OF DENUDATION

Quantitative measurements of rates of erosion in southwestern Wisconsin are few. Although specific examples of mass movements, gullying, and lateral planation by flooded streams can be cited, overall averages with time are difficult to obtain. Most publications contain remarks of qualitative nature specifying why local rates should be faster than regional rates. A regional rate of 5 cm per 1000 years has been obtained for the entire Mississippi River drainage basin (Judson and Ritter, 1964) of which 1.8 cm is by solution. A comparable rate of solution of carbonates from soils in Wisconsin is confirmed by radiocarbon dating of some drift sheets (Robinson, 1950). Much more rapid rate of erosion on steep slopes in southwestern Wisconsin has been measured by Hamilton (1963). Subsequent measurements show the same rate continues.

Hamilton (1963) started measurements in 1960 of the vertical, horizontal, and downslope components of movement of dolomite fragments from pebble-size to large blocks on surfaces from horizontal to 39° near Madison, Wisconsin. Two study sites still are fenced to maintain natural conditions (Pl. 3), and measurements continue. Grass-herb cover and some junipers are present. Measurement techniques include taping between 60 large stones in which aluminum plugs have been inserted; use of point gages, dial indicators, and linear-motion transducers for 17 smaller stones on which markers are cemented; and SR-4 strain gages in soil. Different techniques and instruments are used for evaluation of their capabilities. Accuracy and reliability of measurements vary considerably from one instrument or technique to another. Spot measurements and continuous recordings are employed. Continuous records of air and ground temperatures at different depths are also being obtained. The details cannot be presented here.

Consistant seasonal patterns of movement are apparent, even though they are masked partly by erratic behavior of many stones on and in the soil. Heave, rotation, creep, and slump of individual stones may go on simultaneously in a small area, but distinct seasonal control of most stones is apparent — each moving like its neighbor. Active formation of terracettes is going on along with rapid displacement downslope of the soil and imbedded stones. Late winter movements of surface stones from alternate freezing and thawing above seasonal frost are largest, but late spring and early fall wetting and drying of the entire soil moves particles almost as much. Downslope movements of stones on the surface may be slightly greater than total soil movements but not of imbedded small stones and their adjacent soil. Failure of the SR-4 strain gages precludes detailed analysis of subsurface movements. However, changes in the configuration of the terracettes suggest slump and rotation accompany heave and creep movements.

The largest blocks present, 3 to 5 m across, are moving generally 1 to 3 mm per year on slopes between 4° and 12°, but movement of 2 to 10 mm per year on slopes of 18° to 30° was measured over a 3-year period. Most large blocks fall into the slower part of the range of movement, whereas blocks 1 to 3 m across are moving generally in the faster part of that range of movement. Their rate decreases as depth of burial increases. Smaller stones, a few centimeters to 1 to 2 decimeters, are moving faster still. In one fenced area with 25° slope Hamilton (1963) measured movements of 12 small stones parallel to slope of 3 to 15 mm per year. Subsequent rates of individual stones lie between 2 and 21 mm per year, and since 1960 average about 10 mm per year for all stones. Assuming movements are reduced to zero at the rock-soil interface (which is unlikely in the thin soil), total net displacement downslope of the soil averages about 5 mm per year. This is equivalent to a vertical lowering of the surface of about 2 mm per year or 200 cm per 1000 years. This rate represents the steeper stony slopes of southwestern Wisconsin, but they are common and characteristic.

The average slope of 10 to 20 percent (Trewartha and Smith, 1941, fig. 3) for much of southewestern Wisconsin calls for a much faster rate of erosion than the regional value but less than the 200 cm per 1000 years for 25° slopes. As rate of rock creep is directly proportional to the sine of the slope angle (Schumm, 1967), which is also proportional to the downslope component of gravity, average erosion rates of 20 to 100 cm per 1000 years can be expected in southwestern Wisconsin. The type of material and vegetation would likely be important factors which cannot be evaluated here. Unquestionably a continuous forest cover would retard the rate considerably.

The present rates of erosion in southwest Wisconsin, while high, are not unusual. Walker (1966) shows that hillslope erosion averaged 6 cm per 1000 years during the last 13,500 years in a closed bog system in central Iowa in which the maximum relief is only 5 m in horizontal distances of 250 m, and local maximum slopes are only 3°. In another closed bog system in which the maximum relief is only 11.6 m in horizontal distances of 500 m and local maximum slopes are only 5°, hillslope erosion averaged 16.8 cm per 1000 years. At those sites during the interval 3000 to 8000 years ago erosion rates were accelerated many times those of present rates, sufficient to remove all existing soils. Rates of erosion today in farm fields are 50 times as high as the average rates recorded by Walker.

Rapid alluviation of the central Wisconsin River Valley took place about 6000 years ago, coincident with the rapid erosion in Iowa. It may mean that erosion of the hillsides in Wisconsin, particularly southwestern Wisconsin where prairies advanced at that time, was also accelerated.

PRESENT SLOPE PROCESSES

Thwaites (1960, p. 29—30) has shown that present slopes in southwestern Wisconsin are in equilibrium, meaning that loose mantle is undergoing removal as fast as it is being formed, from the bases to the divides. Obviously material must be removed from the base of a slope as fast as it accumulates if the slope angle is not to be reduced with time. (The converse is also true). Very few such accumulations can be found at the bases of slopes in the Driftless Area. Valley fills several meters thick lie on buried soil surfaces that date back only 100 to 150 years when deforestation and farming began in the state. The rapid flood of material continues locally in some farmed areas. The slopes themselves, however, generally rise abruptly above relatively flat valleys. Amphitheater-like basins, similar in form to cirques and nivation hollows, characterize the heads of first-order streams whose courses across the basins are ill-defined. The steep head walls rise abruptly to the convex divides.

Locally slopes on soft sandstone protected by dolomite or iron- or silica-cemented sandstone are especially steep. Undercutting seems apparent. Slopes on dolomite range from the steep edges of cuestas and of nearly horizontal beds to the gentle backslopes of the cuestas and horizontal bedding surfaces in isolated hills.

Based on the study sites near Madison and on observations in southwestern Wisconsin the coarser detritus is moving mostly by creep downslope. The creep mechanism involves freezing and thawing and wetting and drying of the finer portion of the soil — the former only slightly more important than the latter. Frost penetrates to bedrock on many steep slopes — 30 to 80 cm. Slope wash of the finer constituents is very important but has not been measured in Wisconsin except in farm fields. Wind action is only rarely and very locally considered to be important. During wet periods slump with rotation aids in producing small terracettes and hillside irregularities. Solifluction is not distinguished from creep. Cattle have been excluded by fences from two study areas, but are abundant on other slopes and aid materially in present-day accelerated erosion. Rodents of non-burrowing type visit the study sites occasionally without significant effect on movement, and are only locally important elsewhere.

During earlier drier times when prairies were widespread in southwestern Wisconsin, frequent fires destroyed the vegetal cover and unquestionably aided rapid erosion. Slope wash and mass movements under temperate climates would dominate.

THE PERIGLACIAL CYCLE IN SOUTHWESTERN WISCONSIN

The periglacial cycle (Peltier, 1950) has been described and illustrated for many decades, but disagreement still exists as to its explicit meaning (Dylik, 1964; Black, 1966; Bout, 1966; Cotet, 1966). More importantly, criteria for distinction of slopes produced in periglacial climates versus those in temperate climates are not entirely definitive (Hopkins and Wahrhaftig, 1961). Time and intensity become important in multiple processes, because one intense process, among others, operating for a short time often yields slopes different from those produced by a less intense process operating for a longer time. Dissimilar processes, or similar processes in different climates, may also yield similar slopes (Russell, 1964). Few slopes are produced by one process acting alone — most result from several processes acting together or alternately during different seasons of the year. Hence, no agreement now seems possible on the development and evolution of hillslopes (Schumm, 1966). In spite of these essentially insurmountable obstacles, an attempt is made here to deduce what kinds of slope modifications might have been generated in southwestern Wisconsin at times of periglacial climates.

First, it is necessary to establish the length and severity of the periglacial climates in southwestern Wisconsin during the Wisconsinan Stage — the last 75,000 years. The glacial record (Frye, Willman, and Black, 1965) shows ice in the vicinity and possibly over the area more than once from 75,000 to 28,000 radiocarbon years ago. Most if not all was covered by ice largely accumulating *in situ* and doing little work as recently as about 30,000 radiocarbon years ago. No glacial ice entered the area subsequently, but many meters of loess were deposited during the interval that followed up to the present day. Ice east and west of the area during the interval 22,000 to 12,500 radiocarbon years ago was accompanied for a time by periglacial climates. Most ice wedges seem to have been formed during that interval (Black, 1965). They reflect continuous permafrost conditions with annual mean air temperature of perhaps —5° C for 1000 to 3000 years. Less severe climates obtained during the rest of that glacial interval and also during a subsequent glacial interval 9000 to 11,000 radiocarbon years ago when ice was farther away (West, 1961). The climate of earlier glacial intervals is not recorded by specific indicators in southwestern Wisconsin, but is considered to have induced periglacial climates at times.

Assuming the major drainage lines were established prior to the Wisconsinan Stage, as seems likely (Palmquist, 1965), slope modification under periglacial processes would seem to be limited to a few intervals of some few thousands of years each. The last of importance seems to have been about 20,000 to 15,000 radiocarbon years ago.

What might the periglacial climates be expected to do? The undissected upland remnants would have been protected by thick loess from direct frost riving. Jagged frost-rived cliffs should have receded rapidly and developed talus-cones of angular fragments. Pinnacles or rock monuments should be left behind of the selectively cemented sandstone as the more easily removed material was carried away by accelerated erosion (Pl. 4). Block fields and boulder-strewn slopes would be common. Stream incision should be reduced as valleys became choked with debris from frost action and mass movements. Slope angles characteristically should become more gentle (Peltier, 1950). Time presumably would not permit the cycle to go beyond the youthful stage except in very local situations. Few of the isolated rock remnants and monuments, the frost-rived cliffs, and broad undissected uplands could be destroyed in the few thousands of years available.

REMNANTS OF THE PERIGLACIAL CYCLE

Ice-wedge casts (Black, 1965) are diagnostic indicators of former periglacial climates. However, everyone of the casts has been truncated by mass movements subsequent to cast filling so none of the original surfaces in which they formed remain today. Block fields, block streams, massive talus, and some isolated blocks (Smith, 1949; Black, 1964) which are not obviously moving now are considered to have formed during former periglacial climates. A number of the massive block fields, block streams, and massive talus accumulations show sufficient weathering, soil accumulation from loess, and evidence of long-term stabilization to be considered remnants of the original periglacial surfaces of deposition. They cover an exceedingly small percentage of the total surface.

Rock monuments and pinnacles of sandstone and rarely dolomite are numerous in southwestern Wisconsin (Pls. 2 and 4). Most are on spurs, edges of cliffs, or sharp ridges. Their origins and ages are conjectural. The writer believes that many originated during accelerated erosion during periglacial climates and as such represent periglacial remnants but little modified. Some large sandstone pinnacles probably existed prior to the last glaciation of the area about 30,000 years ago as indicated by boulder trains from them (Akers, 1964). However, some monuments are known to have originated during the last century by exhumation during the accelerated erosion accompanying farming. Stream incision accentuates some spurs, and present-day freeze and thaw and wetting and drying are sufficient to produce others in very few millenia. Although some of the more isolated and larger forms should date from former periglacial times or should pre-date the last glaciation that covered them, they too make up only a very small part of the total topography. Pinnacles of quartzite with but little modification are restricted to one area in the Baraboo Range and are thought to date from the last periglacial climate of 15,000 to 20,000 radiocarbon years ago but they may be older.

The loess-covered uplands are not the former periglacial surfaces as loess deposition has continued with no detectable break since about 29,000 radiocarbon years ago (Hogan and Beatty, 1963; Glenn, Jackson, Hole, and Lee, 1960). Some disturbed patches of residuum probably have been inherited from Tertiary times, and, if so, went through the periglacial cycle. They could be thought of as remnants of the periglacial surfaces even though they formed earlier. Asymmetry of small joint-controlled upland valleys in southwestern Wisconsin is reversed from what is found in permafrost areas (Judson and Andrews, 1955) so should not be periglacial. Many valleys are filled with several meters of organic material and colluvium derived larged from loess of which much has come in during the last century.

This leaves only the hillsides which cannot be remnants of the original periglacial surfaces if our measurements and observations of the rate of erosion are anywhere near correct. Between 3 and 15 m of material should have been stripped from the slopes under the temperate climates that followed the last strong periglacial times of 15,000 to 20,000 radiocarbon years ago if present rates of erosion are applicable. Walker (1966) found that erosion rates were many times greater during the interval 3000 to 8000 radiocarbon years ago when drier conditions obtained, and the same increase should have been apparent in southwestern Wisconsin. Thus, of the slopes only the more resistant sandstone monuments and surfaces of the resistant Baraboo Quartzite should have survived relatively unscathed.

If accumulations of loess, sand, and dolomite residuum were developed at the bases of slopes during the accelerated erosion of periglacial climates or the drier intervals of 3000 to 8000 radiocarbon years ago, they have subsequently been removed by water work. The cliffs in sandstone and dolomite are notoriously weak and friable today and could do no more than parallel the former periglacial cliffs.

CONCLUSIONS

Former times of periglacial climates are recognized in southwestern Wisconsin from ice-wedge casts particularly and also by block fields, block streams, talus, and some isolated moved blocks. Most pinnacles and rock monuments presumably date to the periglacial climates, but others are younger or older. Some patches of residuum probably date from Tertiary times and were, thus, periglacial surfaces now modified. Some quartzite surfaces with restricted outcrop date to the periglacial climates, but essentially all other surfaces, which make up the bulk of the topography, in southwestern Wisconsin are younger.

Rates of hillslope erosion today are so rapid that any reasonable extrapolation to the last significant periglacial climate in southwestern Wisconsin of 15,000 to 20,000 radiocarbon years ago would suggest 3 to 15 m of material have been removed from the slopes. These are slopes of friable sandstone and dolomite in which freezing and thawing and wetting and drying of fine particles in coarser rubble promote very rapid creep. Wetting and drying of material moves imbedded small stones almost as much as freezing and thawing. Small fragments are moved across most slopes as fast as they are being produced; large blocks are moving more slowly.

The slopes modified by the processes of periglacial climates at even more rapid rates than those of today in southwestern Wisconsin apparently were neither sufficiently distinctive nor permanent enough to permit us to differentiate them from slopes derived from present day processes which were also accelerated during drier times about 3000 to 8000 radiocarbon years ago. The present temperate climate acting through stream incision, mass movements, slope wash, and ground water solution suffices to explain most major and minor hillslopes in southwestern Wisconsin.

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DISCUSSION

Dr. Rapp: Professor Black reported that in his area of study in Wisconsin, the hill slopes have been more or less completely re-modelled by contemporary processes. There is not much left of fossil periglacial slope covers, etc. I made a little study in another locality in a similar latitude in the U.S.A., *viz.* in central Pennsylvania, south of the ice border (*cf.* publication in *L'évolution des versants*, Liège, 1967). I came to the opposite conclusion, that the hill slopes there have been stable during the Holocene and show many patterns of fossil periglacial character. Yet I think there is no contradiction in the conclusions drawn by professor Black from his area and my conclusions from Pennsylvania.

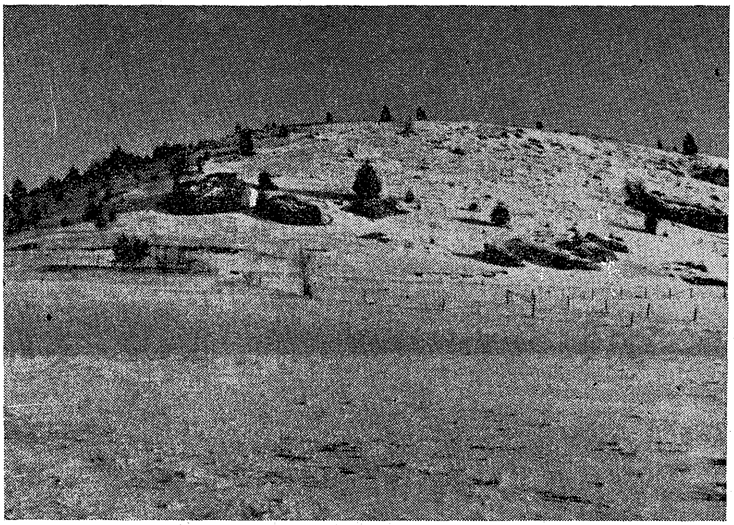
Climatic and structural conditions can explain the differences, I think. Hill slopes with rather fine-grained material in the continental climate of Wisconsin, not far from the prairie border, are probably very easily eroded under contemporary conditions particularly after deforestation.

On the other hand, hill slopes in the Pennsylvanian Appalachians, in coarser, quartzitic material and in a less continental climate are not much modified by contemporary slope processes.

Professor Black: Dr. Rapp's observations in central Pennsylvania are very appropriate and ones with which I am in agreement. Climate, vegetation and lithology play major roles in determining the intensity of hill slope processes. I wish to emphasize that the test site reported on in southwest Wisconsin provides optimum conditions for maximum movements. Therefore, the results of the quantitative measurements can not be applied over wide areas. They serve, however, to give an upper limit to the present rates. Practically all other areas should have less rapid slope movements.

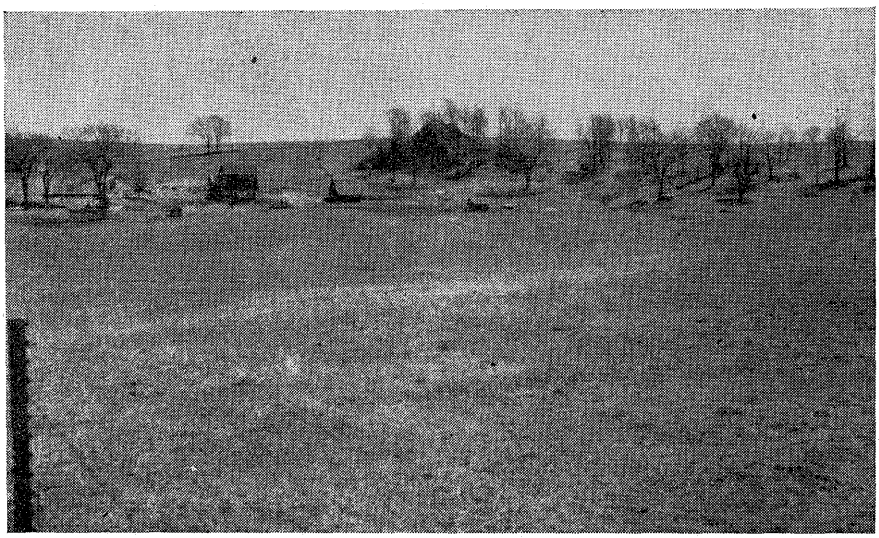
Professor Galon: After yours and other American investigators there is, in Wisconsin, a driftless area, of course non covered by the ice sheet during the last glaciation. Now arises the question whether the slopes in the driftless area show another shape than in the driftcovered area. Maybe the difference of slope evolution in driftless and driftcovered areas gives a contribution to the problem of climatic conditions and the origin of the slopes in Wisconsin.

Professor Black: We can demonstrate that the driftless area of southwest Wisconsin has been glaciated, but not as recently as the rest of the state. Hence, slopes differ in lithology, structure and time.



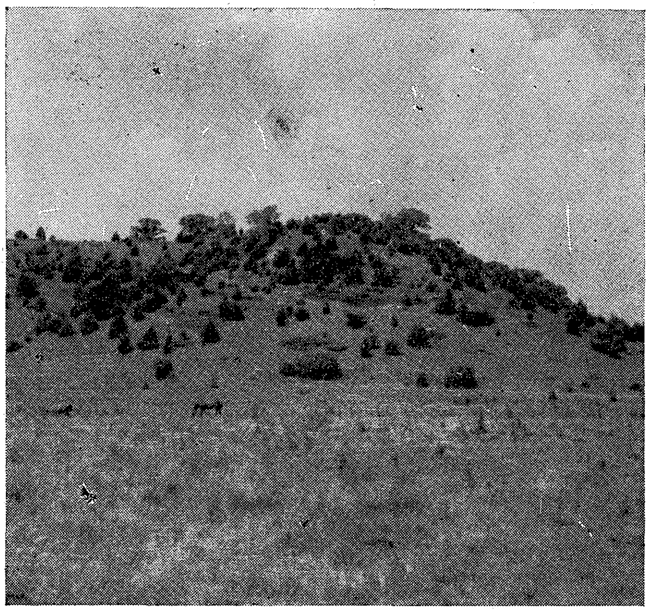
Pl. 1. Rounded summit and flat valley separated by steep slope in southwestern Wisconsin

Large blocks of Prairie du Chien dolomite (Ordovician) litter the slope. View southwestward in the NE corner Sec. 8, T 7 N, R 7 E; 2,5 km southwest of Cross Plains, Dane County



Pl. 2. Rounded upland and monument of St. Peter sandstone (Ordovician) with loess covered slopes in foreground developed on Prairie du Chien dolomite

View northwestward in the NW 1/4, NW 1/4, Sec. 23, T 11 N, R 3 W; 6 km northeast of Soldiers Grove, Crawford County



Pl. 3. Slope-study site 30 km west of Madison

The upland is capped with basal Prairie du Chien dolomite (Ordovician) which is on upper Cambrian sandstone. View northward in the SE 1/4, SW 1/4, Sec. 25, T 8 N, R 6 E; 1.5 km east of Black Earth, Dane County

Pl. 4. Pinnacle of St. Peter sandstone (Ordovician) produced presumably by periglacial processes since the last glaciation of the area about 30,000 radiocarbon years ago

View westward in the SE 1/4, SW 1/4, Sec. 29, T 5 N, R 5 E; 0.5 km east of Hollandale, Iowa County