Landslides in the Greater Pittsburgh Region, Pennsylvania

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1229

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By JOHN S. POMEROY

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Recognition of landslide areas on aerial photographs and a study of factors affecting slope stability in an urban to rural setting

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1982

DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

First printing 1982
Second printing 1984

**For sale by the Distribution Branch, U.S. Geological Survey,
604 South Pickett Street, Alexandria, VA 22304**

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LANDSLIDES IN THE GREATER PITTSBURGH REGION, PENNSYLVANIA

By John S. Pomeroy

"Every trip taken into the Appalachian Plateaus provides continuing education about the full scale and scope of mass movement of loose material. There is so much to learn from observing the signs of active slumping and mass wastage that one cannot but wonder why such phenomena are not better known and more widely publicized."

Byron N. Cooper (1969, p. 66)

ABSTRACT

The Greater Pittsburgh region, which is within the Appalachian Plateaus physiographic province and which is underlain mostly by nearly horizontal cyclothemic Pennsylvanian to Permian rocks, is in an area that has a high potential for landsliding; more than 3,000 recent and at least 12,000 older slides were recognized in Allegheny and Washington Counties alone.

Recent landslides in the region, generally less than 60 m in maximum extent, are commonly thin skinned; most are less than 3 m thick and are present in colluvial or residual silty clayey to clayey soil and weathered rock. Less common slides in bedrock are restricted largely to steep valley walls along major streams and tributary drainages. Slumps, earthflows, debris slides, and rockfalls are the most prevalent types of landslides. Transitional forms of the landslide types are abundant, and the classification of each form is often arbitrary, but most landslides resemble a slump at the head and an earthflow at the toe. Fill slumps are numerous within the more densely populated areas of the region. Soil creep, though not considered a landslide process, nevertheless contributes heavily to damage.

Natural factors that affect slope stability include parent material and soil characteristics, slope steepness and configuration, precipitation, presence of old landslides, and the oversteepening of slopes by stream erosion. Of particular significance to landsliding are deeply weathered slopes underlain by red mudstone and claystone in the Conemaugh Group, which is not only the most widespread stratigraphic unit but which also underlies the most populated area of the region. However, density of sliding is higher in terrain of the Dunkard Group of southern Washington County where the combination of steep slopes and soils derived from nonred claystone and mudstone is conducive to many failures. Underclay and other claystone in the Allegheny Group and glacial till (Illinoian) show fewer slope failures. Silty clayey to clayey landslide materials generally have a relatively high porosity, low permeability, and moderate to high plasticity index; they commonly slake, are illitic, and contain a smaller amount of expandable minerals.

Most site studies revealed that man has accelerated natural processes by overloading slopes, by excavating at the base of slopes, or by altering drainage conditions. Removal of vegetation, subsidence effects over mined-out areas, and vibrations caused by construction contribute locally to slope problems.

In the terrain that is highly susceptible to landslides in southern Washington County, most slides take place on north-facing slopes that have a 20 to 35 percent grade. The increased soil moisture of northwest- to east-facing slopes, together with generally steeper slope gradients, is conducive to a higher incidence of mass movement.

About 10 percent of all recent slides were related to strip mining and were generally due to the slumping and flowage of spoil banks. However, reclaimed (regraded) land failures were not uncommon.

An aerial photographic scale of 1:12,000 or larger is necessary for detailed landslide studies in urban areas such as Pittsburgh, but, even at that scale, many small slides cannot be discerned. Given two sets of photographs at the same scale, more features are discernible on the shorter focal-length photography. Direct scrutiny of stereoscopic pairs of aerial photographs enables the viewer to use various recognition elements in identifying mass movement.

INTRODUCTION

This report incorporates discussions related to mass-movement types, selected landslide localities, and recognition of mass-movement forms and potentially unstable slopes on aerial photographs. A study of shear zones and failure surfaces in colluvial slopes and their geotechnical properties, as well as a discussion of slope stability computations, is beyond the scope of the current investigation. Such studies have been made by Hamel (1978), Hamel and Flint (1969, 1972), D'Appolonia and others (1967), Deere and Patton (1971), and Ackenheil (1954).

PREVIOUS INVESTIGATIONS

Earlier landslide studies in the Greater Pittsburgh region were concentrated largely in Allegheny County, particularly Pittsburgh itself. Ackenheil (1954) defined the landslide types, discussed the causes, described methods of analysis, correction, and prevention, and presented some specific landslide examples in the Pittsburgh area.

Philbrick (1953, 1959, 1960) discussed engineering-geology problems, including landsliding. Engineering and slope-stability studies of the "Pittsburgh red beds" were conducted by Bonk (1964), Kapur (1960), and Winters (1972, 1973). Ackenheil and Associates (1968) prepared a mining and physiographic study of Allegheny County. Gray (1970) summarized the landsliding problem in the Pittsburgh area.

In one of the most thorough landslide-site investigations conducted in the Greater Pittsburgh region, Hamel (1970, p. 155-200), Hamel and Flint (1969, 1972), and Flint and Hamel (1971) studied the landsliding problems faced during the construction of I-79 north of the Ohio River in western Allegheny County. One of Pittsburgh's most famous slides (Brilliant Cut) was described by Hamel (1970, 1972). Kelley (1971a) stressed the role of structure in Pittsburgh's slope-stability problems and briefly examined one particular area (Kelley, 1971b). The interplay between geologic and man-produced factors in mass movement was described by Craft (1974a, b) and Heyman and Craft (1977). Landslides are briefly considered in a study of the Pine Creek watershed of northern Allegheny County (North Area Environmental Council, Land Use Committee, 1972).

In 1971, Advanced Management Systems (AMS), McLean, Va., contracted with the Federal Insurance Administration (Housing and Urban Development) to devise a preliminary methodology for landslide-risk analyses using Allegheny County (National Academy of Science, 1974). The study used existing published data on geology, soils, topography, and climate and required little or no field investigation. On the basis of this data, AMS created a three-division physiographic index and a four-division earth-materials index. Integration of these two indexes led to seven zones of landslide risk, which were then grouped into three categories that followed the terminology of the National Flood Insurance Program.

Many landslides were delineated by coal geologists in the Washington County 7½-minute quadrangle mapping program (Berryhill, 1964; Berryhill and Schweinfurth, 1964; Berryhill and Swanson, 1964; Swanson and Berryhill, 1964; Kent, 1967, 1972; Schweinfurth, 1967, 1976a, b; Roen and others, 1968; Kent and others, 1969; Berryhill and others, 1971; Roen, 1973). The main purpose of the geologic mapping was to show the stratigraphy and structure of the bedrock and to delineate coal horizons. Kent (1972) briefly described earthflows in his map text, although he did not delineate them on the map because of their prevalence and because they masked the bedrock stratigraphy. Washington County landslides were discussed in more detail by Berryhill and others (1971), Kent and others (1969), Pomeroy (in press), and Uhrin (1974).

Geologic maps are available for the entire area at a scale of 1:62,500 (Briggs, 1973; Wagner and others, 1975a). Geologic maps at a scale of 1:24,000 are available only for Washington County.

PRESENT INVESTIGATION AND METHODOLOGY

The current report is based on work performed between late 1973 and mid-1977.

1. The investigation dealing with Allegheny County, sponsored by the Appalachian Regional Commission, was part of the program initiated by the U.S. Geological Survey to prepare an environmental analysis of the Greater Pittsburgh region. An earth-disturbance inventory resulted in landslide-susceptibility maps of 7½-minute quadrangles prepared by Pomeroy (1974a–m) and Davies (1974a–l) that preceded more formal reports (Briggs and others, 1975; Pomeroy and Davies, 1975; Briggs, 1977; Pomeroy, 1977b).

The steps in the preparation of the Allegheny County maps were:

A. Integration of data on soils and geology, and other pertinent information from annotated U.S. Soil Conservation Service (1973) photographs. Information extracted from the old U.S. Geological Survey folios was adequate for indicating the approximate positions of major red-bed sequences in the Conemaugh Group even though the red-bed sequences had not been mapped separately. Graduate theses and unpublished data in the files of the Pennsylvania Geological Survey and the Allegheny Department of Planning and Development also were scrutinized.

B. Intensive study of 1973 aerial photographs for identification of old and recent landslides, fills, and rockfall areas.

C. Field reconnaissance involving road traverses by vehicle and a select number of short traverses on foot into the more critical areas.

D. Reexamination of aerial photographs.

E. Transfer of data to base maps. In addition to the transfer of quantitative data, susceptible areas were delineated on the basis of a qualitative judgment made from landslide incidence (past and present) and from the distribution of incompetent rocks and derivative unstable soils.

2. A reconnaissance inventory of landslides was begun in Beaver, Butler, and Washington Counties in late 1975, and new aerial photographs at a scale of 1:24,000 taken in early May 1975 and in December 1975 were incorporated. The area involved was approximately three times as large as Allegheny County and more varied in its geology and soils, although the techniques used were largely the same as those used during the Allegheny County investigation.

Published recent geologic maps of 11 of 16 quadrangles in Washington County were available. The time spent in field reconnaissance in Washington County was less than half the time spent in each Allegheny County quadrangle. A very high concentration of landslides in the southern part of Washington County contrasted sharply with a sparsity of landslides in northern Beaver and Butler Counties (Pomeroy, 1976a, b; 1977c–g, 1978b–d, 1979).

3. Reconnaissance in the two easternmost counties in the Greater Pittsburgh region was on a smaller scale. Armstrong and Westmoreland Counties were investigated in late 1976 as part of an inventory of several 1° × 2° quadrangles in the Appalachian region for landslide and features related to coal mining. Limited field checking followed interpretation of the 1:40,000-scale aerial photographs taken in late summer and early fall of 1974.

ACKNOWLEDGMENTS

Grateful acknowledgment is due the Pittsburgh office of the Pennsylvania Geological Survey and, in particular, Jesse Craft (formerly of that office) and J. P. Wilshusen of the Harrisburg office.

County planning commissions and U.S. Soil Conservation Service offices furnished available information. Discussions with Washington County Planning Commission members A. R. Glance and Kenneth Krupa were especially helpful. The author appreciates the assistance of William Morrison (formerly with the Allegheny Department of Planning, now with Pennsylvania Department of Community Affairs), W. R. Adams and Neil Dubrovsky (Allegheny Department of Public Works), Gerald Ferguson (Beaver County Planning Commission), J. L. Council (District Conservationist, U.S. Soil Conservation Service, Beaver), F. G. Ley (Executive Assistant, Beaver County Conservation District), and B. A. Breisch (District Conservationist, U.S. Soil Conservation Service, Butler).

Pennsylvania Department of Transportation personnel Neil Hawks (Indiana), William Luxner (Pittsburgh), and William Galanko (Uniontown) were helpful.

Special thanks are due Harry Ferguson (U.S. Army Corps of Engineers, Pittsburgh district), Norman Flint (University of Pittsburgh), Hugh Montgomery (Appalachian Regional Commission), and Peter Lessing (West Virginia Geological and Economic Survey).

Any statement of acknowledgment would be incomplete without mention of W. E. Davies, my colleague in the Allegheny County study, and R. P. Briggs (formerly with the U.S. Geological Survey, Carnegie), who coordinated the Greater Pittsburgh regional studies program.

GEOLOGY

The Greater Pittsburgh region as used in this report comprises Allegheny, Armstrong, Beaver, Butler, Washington, and Westmoreland Counties, an area of approximately 11,700 km^2; the city of Pittsburgh is at the approximate center of the area (fig. 1). The Greater Pittsburgh region is traversed by several major highway routes including the Pennsylvania Turnpike, I–70 and I–79, and U.S. 30 and 40. Two major rivers, the Allegheny and the Monongahela, merge to form the Ohio River at Pittsburgh.

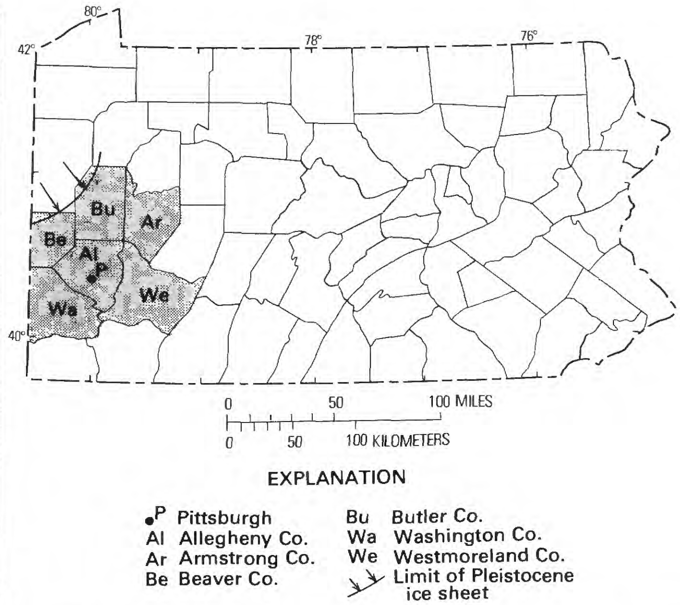


FIGURE 1.—Index map of Pennsylvania showing the counties of the Greater Pittsburgh region.

Most of the area is within the Allegheny Plateau section of the Appalachian Plateaus province. The extreme southeastern part of the area (Chestnut Ridge and Laurel Hill in Westmoreland County) is within the Allegheny Mountains section, and only a very small part in northwestern Butler and Beaver Counties is within the glaciated section that contains the Illinoian and Wisconsinan Stages of the Pleistocene. The region generally is an area of maturely dissected terrain of variable relief that, in most places, does not exceed 150 m. Valleys have been cut into a nearly flat to moderately dipping rock sequence by streams, which in preglacial times drained northward toward Lake Erie. During the later phase of the Pleistocene, ice damming of the lower courses forced the streams to alter their drainage and to flow generally southward and westward.

Bedrock units exposed in the Greater Pittsburgh region range in age from Mississippian to Permian and include the Pocono Sandstone, Mauch Chunk Shale, and the Pottsville, Allegheny, Conemaugh, Monongahela, and Dunkard Groups (figs. 2, 3). Landslide problems on slopes underlain by the oldest rock units are uncommon and are relatively minor on slopes underlain by the Pottsville Group. The most severe slope-stability problems are found on slopes underlain by the post-Pottsville cyclothemic units, especially in the Conemaugh and Dunkard Groups. The Conemaugh Group is not only the most widespread stratigraphic unit, but it also underlies the most populated area of the region.

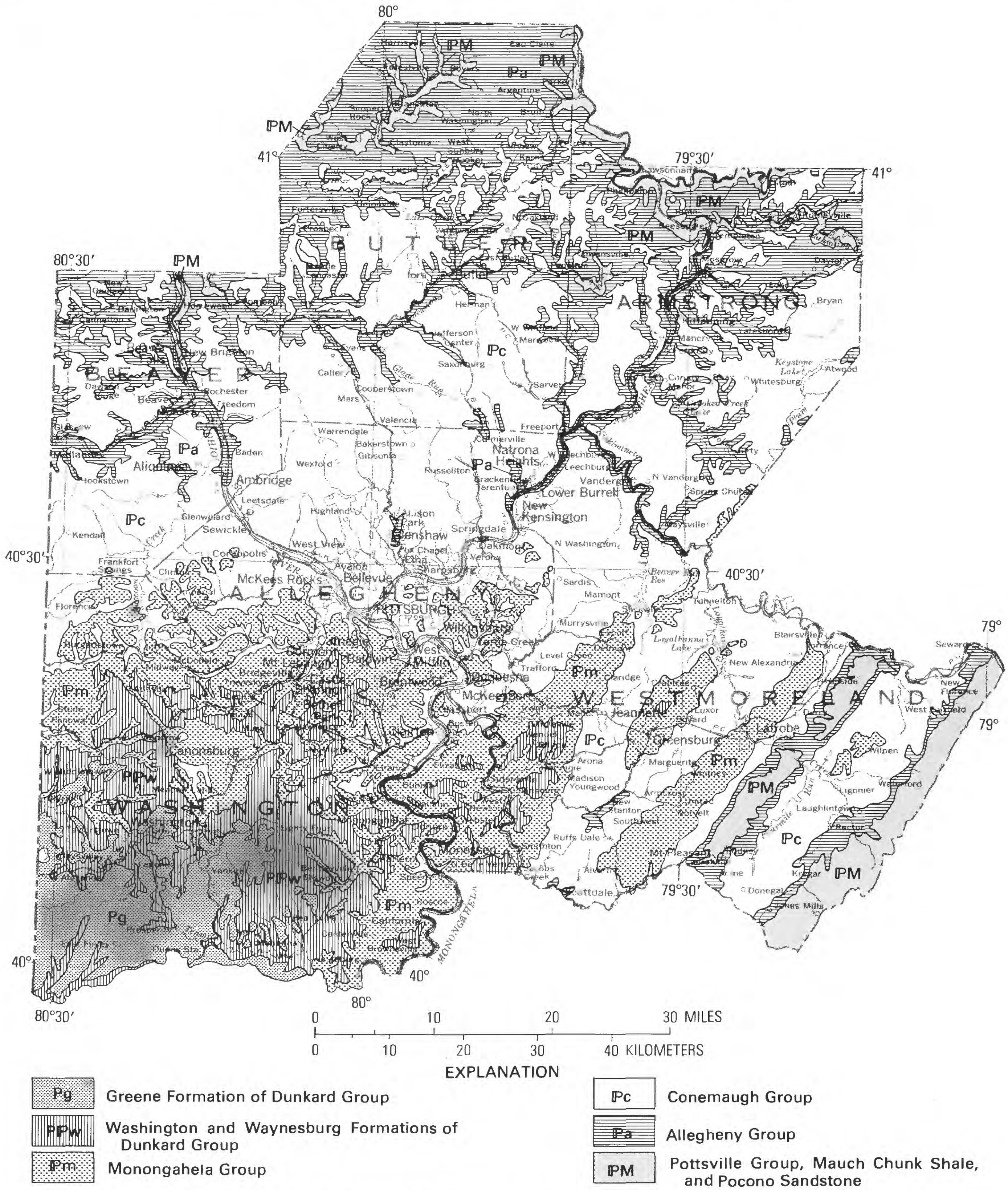
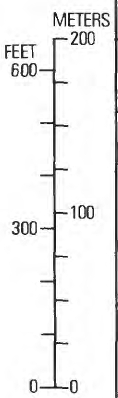


FIGURE 2.—Generalized geologic map of the Greater Pittsburgh region (from Gray and others, 1960).



SYSTEM	GROUP	FORMATION	APPROXIMATE THICKNESS, IN METERS	LITHOLOGY Shale ....Sh Mudstone ....Mu Claystone ....Cl Siltstone ....Sl Sandstone ....Ss Limestone ....Ls Coal C	KEY HORIZONS	RELATIVE SUSCEPTIBILITY OF DERIVATIVE SOILS TO LANDSLIDING
QUATERNARY	Alluvium, terrace, and glacial deposits		0–30	Unconsolidated clay to boulders		Nil to low in terrace and glaciofluvial deposits moderate to moderately high in silty clay till
PERMIAN	Dunkard	Greene	145	(Cyclic) Mu, Sl, Ss, Ls, Sh, Cl, C		Moderately high to severe
		Washington	60	(Cyclic) Ls, Mu, Sl, Ss, Sh, Cl, C	Washington coal	
PERMIAN AND PENNSYLVANIAN		Waynesburg	42	(Cyclic) Mu, Ss, Sl, Ls, Sh, Cl, C	Waynesburg coal	Moderate to high
PENNSYLVANIAN	Monongahela	Uniontown	30	(Cyclic) Mu, Sh, Ss, Sl, Ls, Cl, C		Low to moderately high
		Pittsburgh	91		Pittsburgh coal	
	Conemaugh	Casselman	190	(Cyclic) Sh, Mu, Sl, Ss, Cl, Ls, C		Low
					"Clarksburg red beds"	Moderately high to severe
					Morgantown sandstone	Low
					"red beds" Ames limestone member "Pittsburgh red beds"	Moderately high to severe
		Glenshaw			"red beds" "red beds"	Low to moderately high
					Upper Freeport coal	
	Allegheny	Freeport	85	(Cyclic) Ss, Sh, Mu, Sl, Cl, Ls, C		Moderate
		Kittanning				Low to moderate
		Clarion				
	Pottsville	Homewood	51	Ss, Sh, C		Low
		Mercer				
		Connoquenessing				
MISSISSIPPIAN		Mauch Chunk	60	Sh, Ss		Slight to low
		Pocono		Ss, Sh		

FIGURE 3.—Chart showing age, thickness, lithology, key horizons, and relative susceptibility to landsliding of geologic formations in the Dunkard, Monongahela, Conemaugh, Allegheny, and Pottsville Groups in the Greater Pittsburgh region.

Vertical repetition of the sandstone, siltstone, shale, limestone, mudstone, claystone, and coal units in a cyclic pattern is characteristic throughout the region. Within each cyclic sequence, most units commonly intertongue and grade laterally into other rock types. Coal beds and one thin but persistent limestone unit (Ames Limestone Member of Glenshaw Formation) serve as marker beds. During the Pennsylvanian and Permian, when the cyclothems were laid down, five distinct types of depositional environments—open-water, swamp, lake, stream, and delta types—existed in the region. These environments were west of an extensive alluvial plain that encompassed most of the State.

The rocks generally dip less than 1° in all but the southeastern part of the region. Several northeast-trending folds that have low structural relief dominate much of the area and include a major synclinal basin extending southwestward from Pittsburgh, the youngest rocks being exposed in Washington County. Pronounced anticlinal folds in the southeastern part of the region along Chestnut Ridge and Laurel Hill expose Mississippian rocks.

Considerable confusion exists in the literature on western Pennsylvania concerning the use of the terms "shale," "mudstone," and "claystone." For example, earlier geologists referred to massive poorly bedded to nonbedded argillaceous sedimentary rocks as "shale," and some recent investigators have used the words inconsistently (see "Glossary").

LANDSLIDE PROBLEM

Small-scale maps of the United States show southwestern Pennsylvania as an area of "major landslide severity" (Baker and Chieruzzi, p. 10, 1959), an area possessing a "high potential for landsliding" (Krohn and Slosson, p. 229, 1976), or one of "high susceptibility and high incidence" (Radbruch-Hall and others, 1976). The Indians recognized the instability of the slopes adjacent to the Monongahela River by giving the river its name, which translated means "river of the caving banks" (Scheffel, 1920). Most of the modern-day landsliding in the region has taken place since World War II and coincides with the introduction of large earth-moving equipment.

The small landslide is the persistent hazard throughout the Greater Pittsburgh region; only three landslides exceeding 100,000 m^3 in total area moved were listed by Ackenheil (1954, pls. 1-3) in Allegheny County during the 1940-54 period. Few individual small landslides are documented, and estimates of costs to individual landowners are unavailable.

The Allegheny Department of Planning and Development estimated that the yearly cost of damage from landsliding in that county from 1970 to 1974 was nearly $2 million (Briggs and others, 1975). Estimates of damage from landsliding in adjacent counties are lacking. Throughout the metropolitan Pittsburgh area, the small percentage of the area that can be considered valley flatlands has been developed to a large extent, and attention has been turned to slopes and ridgetops. In the more deeply incised terrain, ridge crests are commonly narrow, and few can accommodate extensive residential backyards. Manmade cuts and fills along slopes involve appreciable risks and require careful planning to avoid the threat of landsliding.

Road damage due to landslides is high (figs. 4*A*, *C*, *D*, 5*A*). Remedial action for some slide areas is commonly at a standstill owing to a lack of financial resources at the State, county, township, city, and borough levels. In Allegheny and Beaver Counties, the total cost for contractor and maintenance crews from 1971 to mid-1977 was almost $7 million (A. J. Gaeta, Pennsylvania Department of Transportation, written commun., 1977), and this amount is for State roads alone. Estimates of costs for utility service disruption (fig. 5*B*–*D*) are unavailable.

LANDSLIDE TYPES

The three principal types of landslide movement are falling, sliding, or flowing, or a combination (fig. 6*A*). Figure 6*A* shows the general form of many landslides and identifies the various component parts. Figure 7 illustrates the relation between slope angle and slope percent. Mass-movement phenomena from specific localities in the region are shown in figures 8–17.

Most landslides observed in the Greater Pittsburgh area took place in colluvial or residual clayey to clayey silt soil and weathered rock derived from mudstone, claystone, and some shale. Some slides other than rockfalls, however, do occur in bedrock. Rockfalls are very common along bedrock cliff faces, especially along highway cuts.

More than 95 percent of the recent landslides were less than 60 m in maximum extent. Slumps, earthflows, debris slides, flows, and avalanches are commonly thin skinned; most are less than 2.5 m thick. However, several slides have taken place in relatively thick (more than 15 m) colluvium along lower slopes and in relatively thick manmade fill deposits of both nonmining and mining-related origins. Massive fill failures are common in Allegheny County (fig. 10*B*, *D*; Pomeroy and Davies, 1975), but they also occur in other areas in the region (fig. 10*A*, *C*). Failures related to strip mining, including the slumping and flowage of spoil banks (fig. 9*A*, *B*), are minor in Allegheny County but are very common in Armstrong and Butler Counties and, locally, in Washington County. Also, slides take place both in areas where a mine's highwall has been cut into relatively

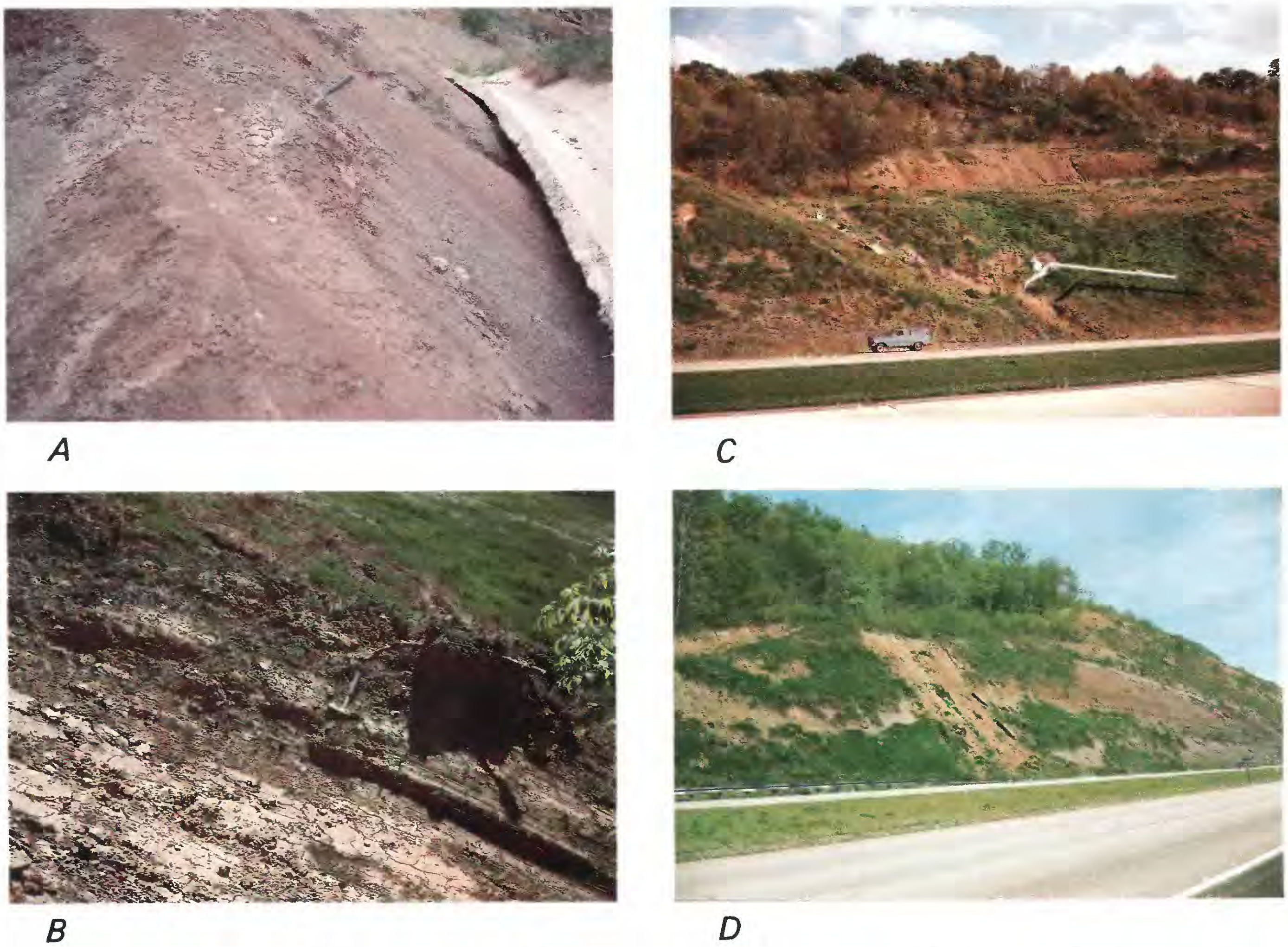


FIGURE 4.—Weathering of the red mudstone outcrop of the Conemaugh Group and mass movement of weathered rock and soils derived from "red beds" of the Conemaugh Group. *A*, Typical nonbedded red mudstone of "Pittsburgh red beds" along I–79 north of Ohio River, Allegheny County. Slaking has left drainage sluice unsupported. Small calcareous nodules are common within unit. *B*, Slickensided surface of sliding plane. Note grooves (striations). Slide involves weathered red mudstone from both Glenshaw and Casselman Formations. Off Wind Gap Road, west Pittsburgh. *C*, Slope failure in colluvium, "Pittsburgh red-beds" interval, I–79 north of Ohio River, Allegheny County. Note broken concrete drainage sluices. *D*, Debris slide along Pennsylvania Rte. 60 south of Aliquippa interchange, Beaver County. "Pittsburgh red beds" below Ames Limestone Member of Glenshaw Formation (thin gray bed at right side).

thick colluvium (in many such places, movement of the overlying material is a result) and in sections that have been reclaimed (regraded). Landslide problems in the Greater Pittsburgh area's strip-mine operations are similar to those in other areas of the Appalachian Plateau (Zook and Bednar, 1975).

The transitional forms of the various types of landslides are abundant, and the classification of each form is often arbitrary. Most landslides are composites of two or more types (fig. 6*A*), but usually a specific landslide is labeled for the dominant type present. Most of the landslides resemble a slump at the head and an earthflow at the toe (fig. 6*A*).

SOIL CREEP

Although not considered a landslide process (Varnes, 1958 p. 20), soil creep can contribute heavily to damage in an area (figs. 6*B*, *D*; 8*B*, *C*; 15*D*). Obvious ground breakage, in the form of scarps and transverse and radial cracks, is lacking in an area of creep; however, creep can accelerate into landsliding. Sags or bulges along the slope may result from the slightest release of stress and are subject to greater movements.

In 1938, the U.S. Soil Conservation Service began field studies in several areas in southeastern Ohio where earthflows were particularly abundant. Sharpe and Dosch (1942) demonstrated, on the basis of auger borings, that beds of coal, clay, and mudstone thin abruptly and bend downslope covering the lower beds, rather than extending horizontally to intersect the hill surface (fig. 6*D*). These impervious clay or mudstone layers, having been drawn out nearly parallel to the hillslope, interfere with the downward percolation of surface and

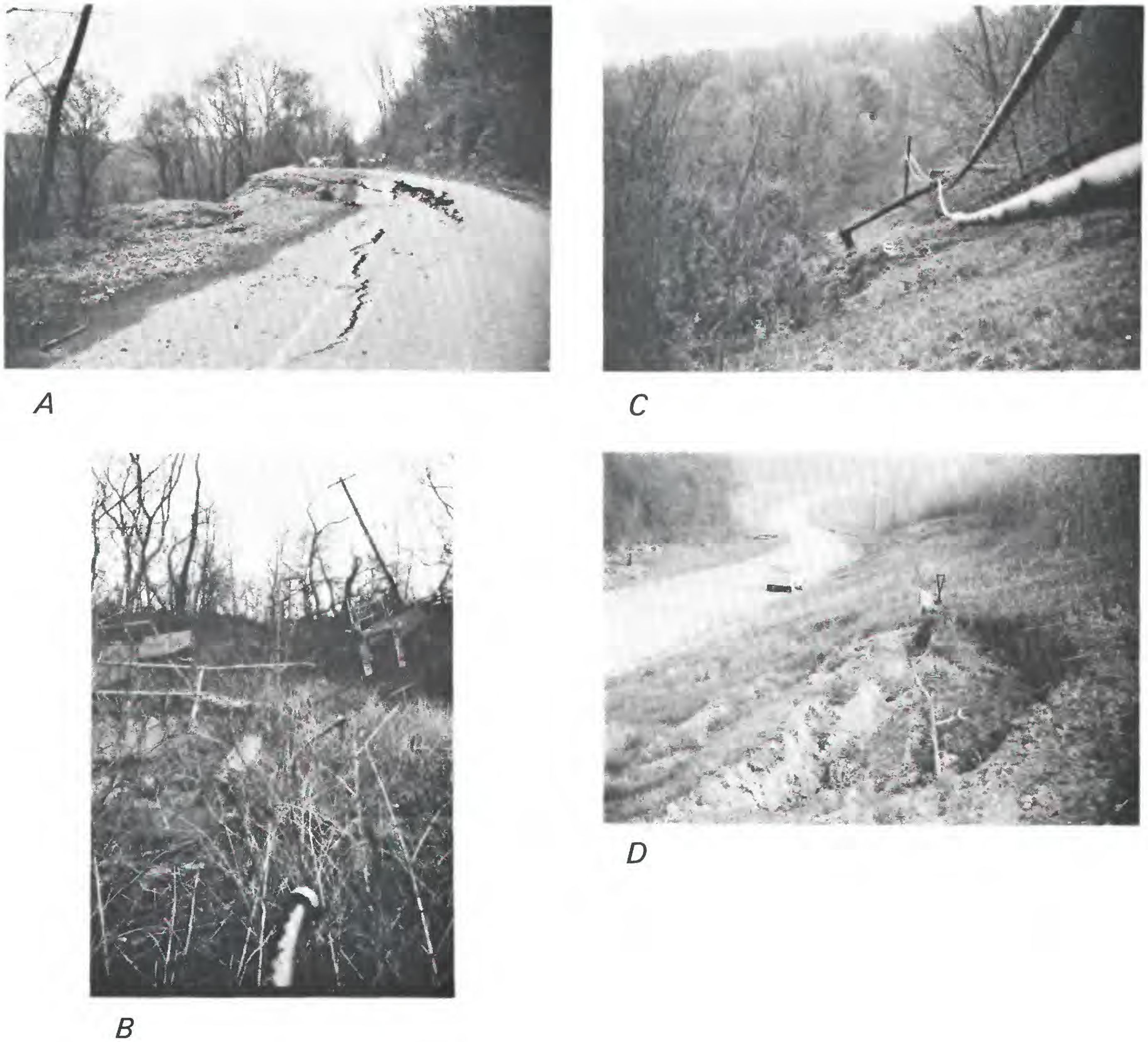


FIGURE 5.—Effects of mass movement on roads and utilities. Note that the stratigraphic unit cited underlies colluvial slope. *A*, Road failure above Raccoon Creek, Independence Township, Beaver County, Glenshaw Formation. *B*, Disrupted stairway and utility line; slide occurs below Sylvan Avenue, Greenfield area, Pittsburgh, Casselman Formation. *C*, Earthflow (e) has shifted telephone-pole alinement; above Buffalo Creek, Donegal Township, Washington County, Dunkard Group. *D*, Buried telephone cable (c) subjected to tensional forces within small slide activated by road-widening activity; Mt. Pleasant Township, Washington County, Monongahela Group.

ground water. After an intensive period of precipitation, the soil material overlying the clay is highly saturated; this saturation not only adds weight to the slope material but also increases the pore pressure and the shearing stress. At the same time, the cohesion and frictional resistance of the slope material to sliding is decreased. As a result, movement takes place during or after wet periods. Sharpe and Dosch (1942) concluded that the same general conditions favor both creep and earthflows and that the slow process of soil creep can precede localized and rapid earthflow.

Deformed trees commonly are cited as evidence of soil creep. However, curved tree trunks, downslope tilted tree trunks, and upslope trailing tree root systems are not always the results of soil creep. Parizek and Woodruff (1957, p. 64) argued against citing deformation as soil-creep evidence. More recently, Phipps (1974) contended that curvature and tilting of trunks are due to

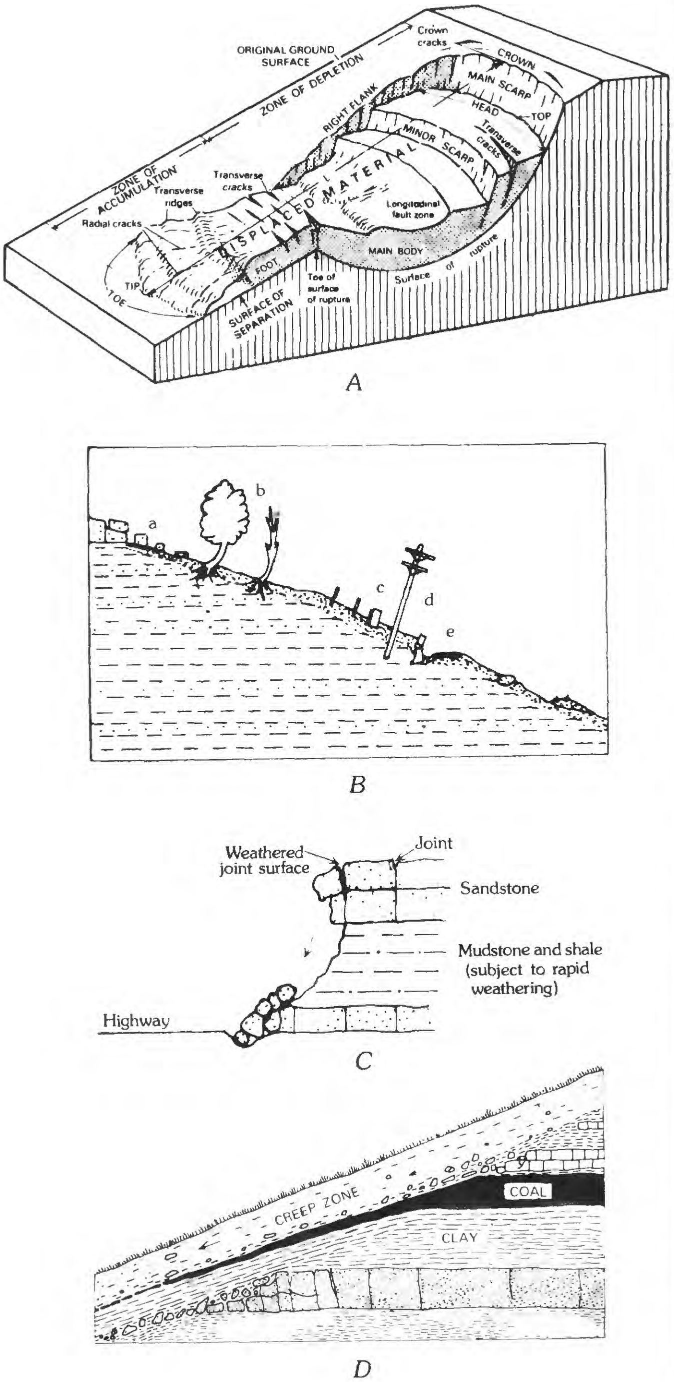


FIGURE 6—Diagrammatic representation of mass-movement phenomena. *A*, Slump-earthflow (from Varnes, 1978). *B*, Creep. Common evidence includes moved joint blocks of layered rock (a), trees with curved trunks concave upslope (b), displaced posts, poles, and monuments (c), broken or displaced retaining walls and foundations (d), roads and railroads moved out of alinement (e) (from Sharpe, 1938). *C*, Rockfall. *D*, Soil creep as a prelude to landsliding (modified from Sharpe and Dosch, 1942).

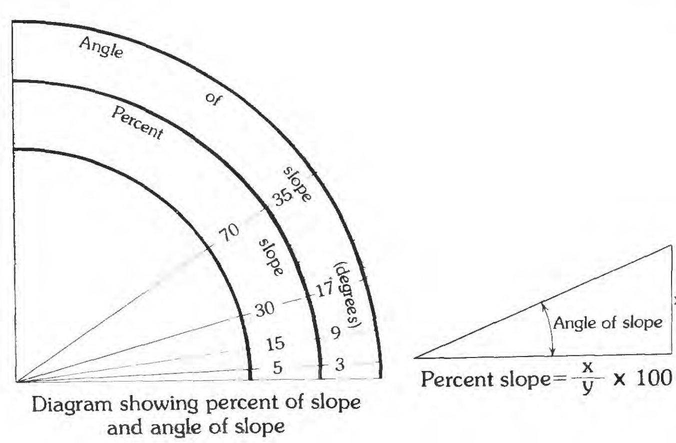


FIGURE 7.—Diagram showing percent slope and angle of slope (from Schmidt, 1972).

geotropic and phototropic responses to conditions unrelated to soil creep. The author has seen curved tree trunks on slopes where grade is considerably less than 15 to 25 percent; these curved tree trunks more likely are related to phototropic causes than to soil creep. Tree curvature as supporting evidence of slow mass movement is, undoubtedly, overemphasized. Other criteria such as the inclination of manmade structures, must be considered in evaluating the presence of soil creep.

"Cattle terraces" or "cowsteps," expressions of creep, are produced by animals' hooves cutting into the hillslope and producing scars on the uphill side of repeatedly used paths (figs. 8*D*, 11*D*). These features can be significant in the distribution of surface runoff to various parts of a slope and can influence the siting of slides.

SLUMPS AND EARTHFLOWS

An important type of mass movement in the Greater Pittsburgh region is slump in soil and weathered rock debris (fig. 9*D*) or fill (figs. 10*A*-*D*, 14*A*, *B*). A slump in fill material is a prevalent type of landslide, for example, in Allegheny County.

A slump consists of coherent or intact masses that move downslope by rotational slip on curved slip surfaces that underlie and penetrate the landslide deposit. Slump blocks tilt backward at their heads, and many bulge outward at their toes. The rupture surface is usually concave toward the slip block in horizontal section, and the rupture surface commonly shows curvature in the vertical cross section.

Most fill failures are slumps and are of two types—those within the fill material itself that are largely independent of the materials on which the fill was placed and those that result from emplacement of fill materials on steep unstable slopes where both fill and underlying slope material move.

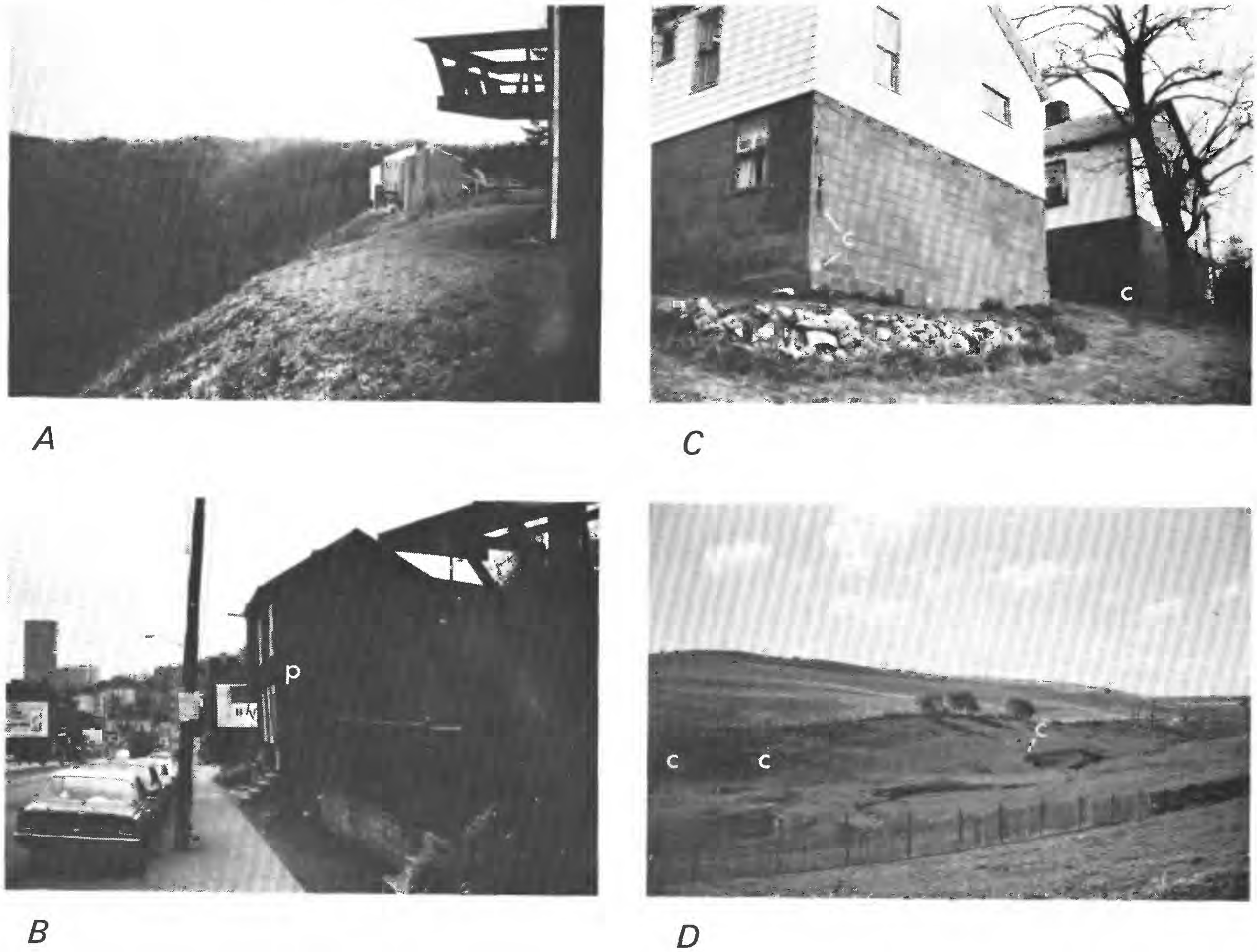


FIGURE 8.—Topographic limitations, creep effects, "cowsteps." Note that the stratigraphic unit cited in figures 8–17 underlies colluvial slope. *A*, Shallow backyard in new subdivision above Meeks Run, Moon Township, Allegheny County. Builder has wisely elected not to extend slope. Casselman Formation. *B*, Creep, causing out-of-plumb structure (p) at base of slope, Irvine Street, East Pittsburgh. Glenshaw Formation. *C*, Creep causing cracked corners (c) of foundations of two houses. Note tree possibly influenced by slow mass movement. Lincoln Hill, North Franklin Township, Washington County. Dunkard Group. *D*, "Cowsteps" (c), Chartiers Township, Washington County. Monongahela Group.

Earth (soil) and fill slumps outnumber rock slumps (fig. 9*C*) by at least 50 to 1. Because many of the rock slumps are larger than other slumps, they can be easily recognized, as they are at Bradys Bend (see fig. 9*C* and "Selected Landslide Localities") and Brilliant Cut (see "Selected Landslide Localities"). At Bradys Bend, bedrock forms the main scarp, and disrupted bedrock blocks litter the slope immediately in front of it. Slides at Fallen Timber Run (see "Selected Landslide Localities") and at I–79 in Allegheny and Butler Counties (see fig. 14*C*, *D* and "Selected Landslide Localities") involve bedrock to some extent. Rotational slumps of blocks of sandstone and limestone in the Monongahela River drainage system of eastern Washington County have been noted by Kent and others (1969, p. 29).

Earthflows (figs. 11; 15*A*, *B*; 16*C*, *D*) are as conspicuous in Washington County as slumps are in Allegheny County and consist of colluvial (or fill) materials that move downslope as a viscous fluid. An earthflow has a scarp at its head and bulges and tension cracks at the toe. It grades into a mudflow in which water content is greater.

Earthflows exist as crescent-shaped, rectangular, or oval bodies ranging in size from a few square meters to several acres, but they are commonly less than a quarter acre. Scarps of earthflows may heal within a few to 10 years, but the hummocky slopes show evidence of former slope movements for centuries. Sharpe (1938, p. 55) observed that many hills in eastern Ohio, West Virginia, and western Pennsylvania "are scarred by thousands of old earthflows and almost the entire surface of certain slopes show the typical scarps and hummocks of former movements."

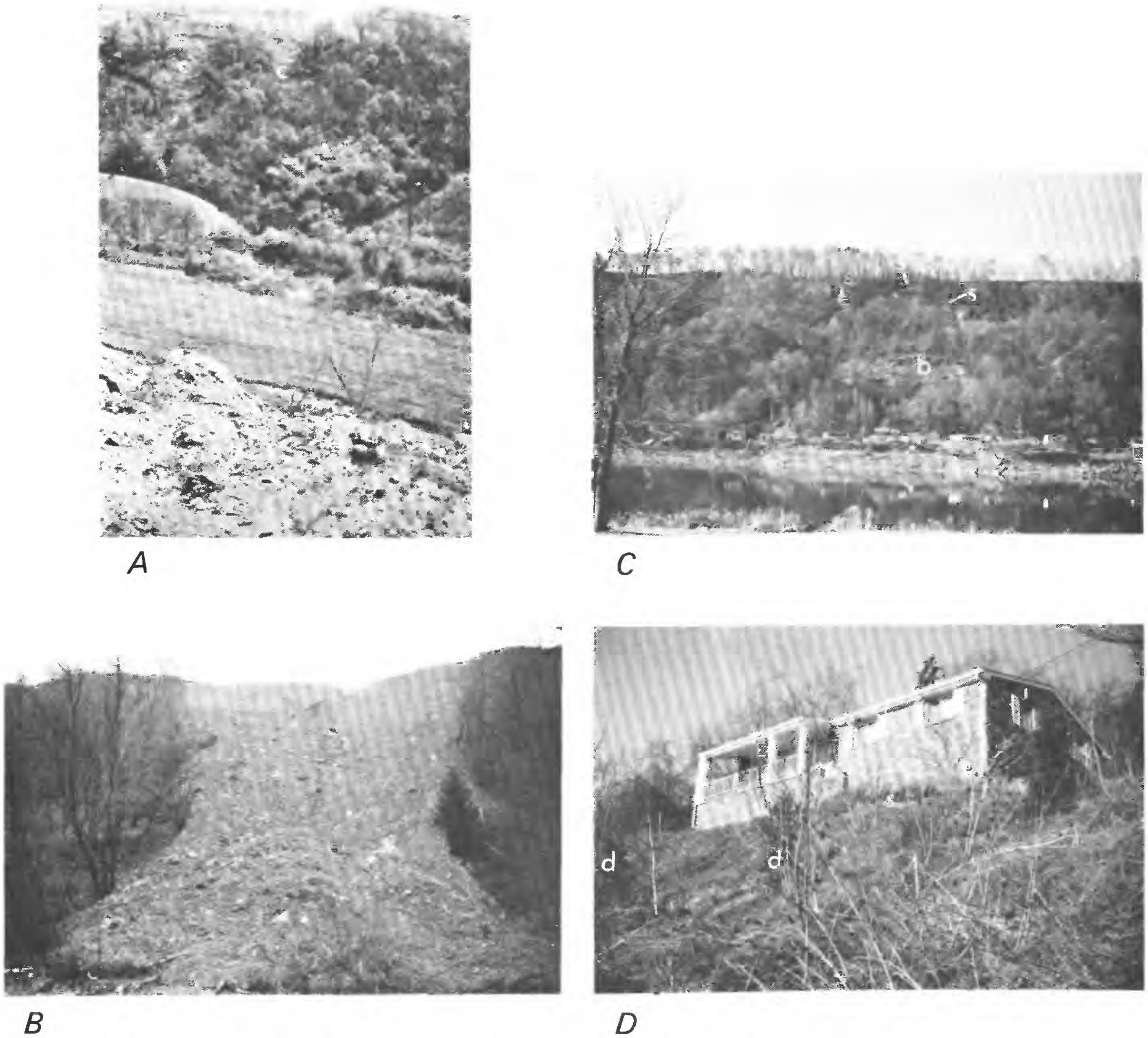


FIGURE 9.—Coal-waste slides, bedrock slump, soil slump. *A*, Coal-waste slides (c) in foreground and background, Jefferson Township, Washington County. Casselman Formation. *B*, Coal-waste flow, Hays Run, Rayburn Township, Armstrong County. Allegheny Group (Freeport coal zone). *C*, Rock slump at Bradys Bend, Armstrong County. Note arcuate head scarp (s) and dislocated rock blocks (b) downslope. Pottsville and Allegheny Groups. *D*, Soil slump. Front yard slumped along steep colluvial slope. Movement demolished a house at base of slope. Head scarp (s) lies between "dropped" foundation shrubbery (d) and house. Millvale, Allegheny County. Casselman Formation.

The present investigation confirms that many small earthflows can heal quickly; the sites of several small slides mapped by U.S. Geological Survey personnel in the mid-1960's were barely recognizable in early 1976. At the same time, the number of recent slides that have apparently taken place since the earlier mapping is astoundingly high.

Earthflows on reclaimed mined land were noted about 3 km southwest of Monongahela in eastern Washington County (Pomeroy, 1976b). Accelerated creep and tension cracks acting as an incipient stage to earthflow activity were observed on reclaimed land near Portersville in western Butler County. A photograph in Lessing and others (1976, p. 31) shows an earthflow, along a regraded strip-mining spoil bank, encroaching into backyards of newly constructed houses.

DEBRIS SLIDES, DEBRIS FLOWS, AND DEBRIS AVALANCHES

Debris slides (figs. 4*D*, 12*B*, *C*) consist of incoherent or broken masses of rock and other debris that move

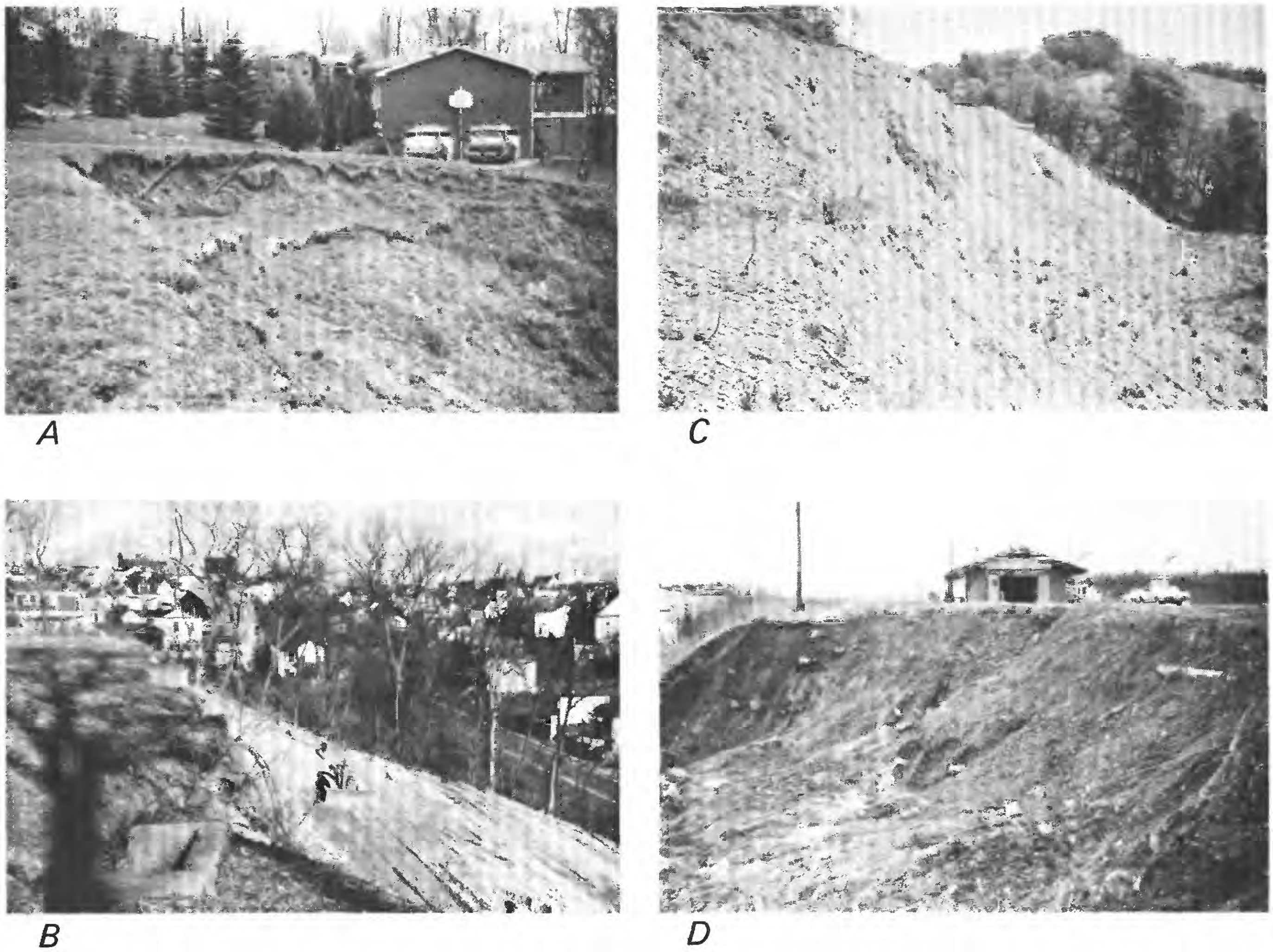


FIGURE 10.—Fill slumps. *A*, Slump in fill bridging old landslide deposit. Peters Township, Washington County. Dunkard Group. *B*, Head scarp at Woodruff Street playground fill slump. Area was being renovated in January 1974 when picture was taken. Aerial photographs taken in 1939 revealed a similar slump, but no evidence was shown on 1969 or on early 1973 aerial photographs. The fill had been emplaced at the head of a small tributary valley. Mt. Washington area, Pittsburgh. Casselman Formation. *C*, Complex fill-colluvial slump. Note benching (b) below steep primary head scarp. Greene Township, Beaver County. Allegheny Group. *D*, Fill slump adjacent to carwash station. Drainage over slope from extensive shopping-center asphalt surface. Problem was being compounded by discharge of water from carwash station. Kennedy Township, Allegheny County. Casselman Formation.

downslope by sliding on a surface that underlies the deposit. Many debris slides are shallower in vertical cross section than earthflows and slumps and may show backward rotation in the head area. The rupture surface is nearly parallel to the slope (planar), but near the top of the main scarp it steepens to intersect the land surface. Many debris slides involve a greater heterogeneity of earth material than do either earthflows or slumps and generally take place on steeper slopes. The material is not water saturated, but heavy rainfall usually will initiate movement. Debris slides are particularly frequent along highway and railroad cuts and in strip-mining areas.

Debris flows are more rapid downward movements of largely saturated earth material and vegetation. The rate of movement and the water content differentiate debris flows from debris slides. Debris flows commonly follow narrow preexisting drainage paths, and most result from heavy precipitation. Identification of older debris flows on aerial photographs is usually less certain than identification of other landslide types. Debris flows consist largely of coarse rock fragments, in contrast to mudflows, which consist predominantly of sandy to clayey material.

Debris avalanches (fig. 12*A*), like debris flows, result from heavy precipitation and are characterized by very rapid to extremely rapid movement of highly saturated material down long narrow paths. The earth material of a debris avalanche usually is more heterogeneous than that of debris flows. Most older debris-avalanche depos-

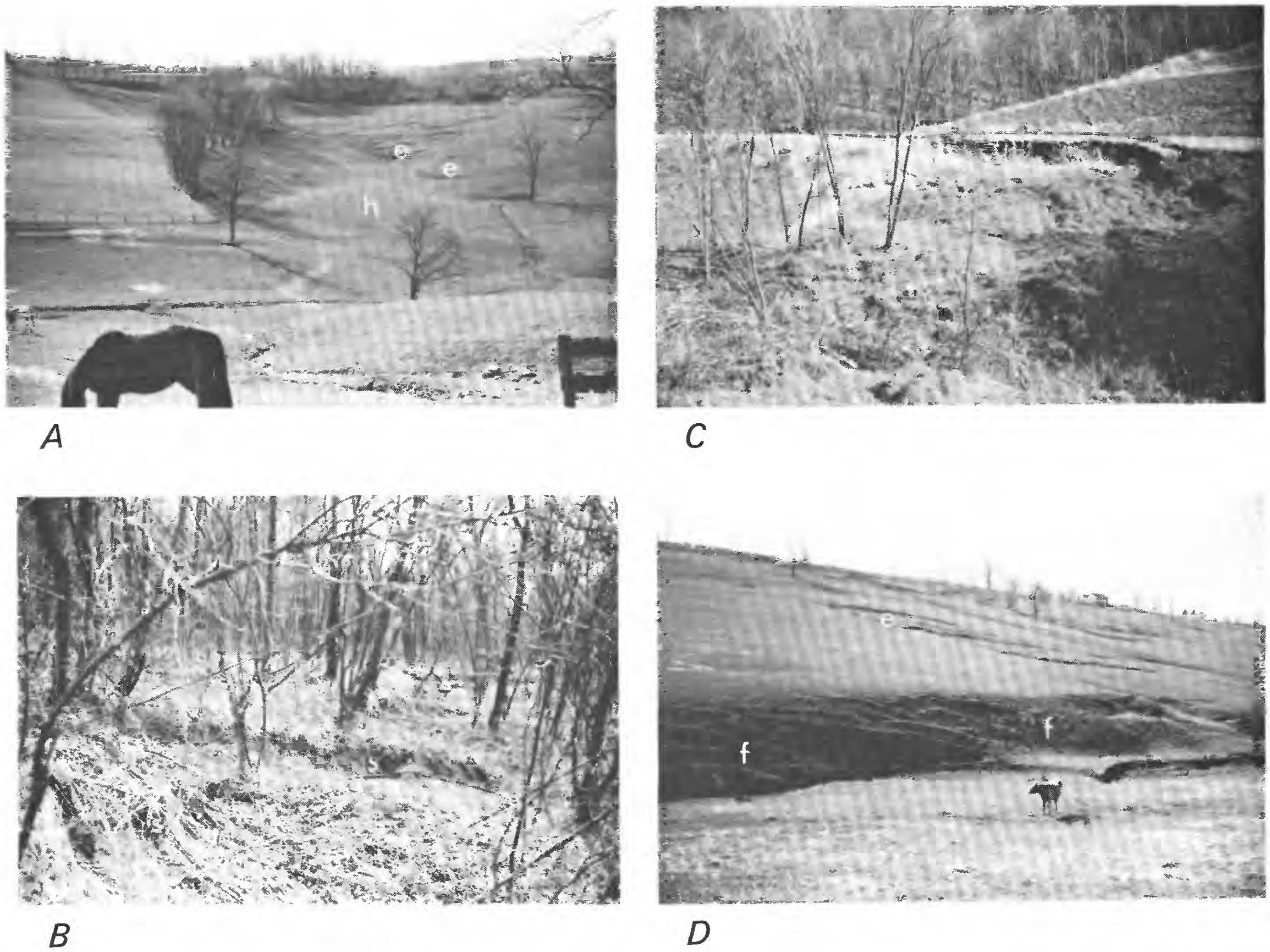


FIGURE 11.—Earthflows. *A*, Recent earthflows (e) within older landslide area (note concavity of slope). Hummock (h) in center is probable remnant of older slide. Somerset Township, Washington County. Dunkard Group. *B*, Sinuous head scarp (s) of flow along 15–20 percent slope in young woodland. Amwell Township, Washington County. Dunkard Group. *C*, Earthflow emanating from fill over "Pittsburgh red-beds" interval. Note outcrop along highway at right side of photograph. I–79, Kennedy Township. Allegheny County. Glenshaw Formation. *D*, Earthflow (e) on older landslide surface. Note toe of older landslide (f) and "cowsteps." South Strabane Township, Washington County. Dunkard Group.

its are more difficult to discern on aerial photographs but may be identified as small moundlike protuberances at the base of the slope.

Debris flows and avalanches are not as important in the Greater Pittsburgh region as in other sections of the Appalachian Plateaus, namely, selected areas in West Virginia (Lessing and others, 1976) and, particularly, the area surrounding Johnstown, Pa., affected by the devastating storm of July 19–20, 1977. Unlike these other areas, the Greater Pittsburgh region has been subjected to relatively few extremely heavy rains in historic times (Subitsky, 1975).

ROCKFALLS

Although deaths and injuries due to the common types of landslides are rare, some rockfalls have accounted for casualties in the past. The most serious event took place south of Aliquippa in 1942, when 115 m^3 of rock fell and crushed a bus; 22 passengers were killed, and 4 were injured (Ackenheil, 1954, p. 88–91).

In an area underlain by cyclic sedimentary rocks, the widely differing physical characteristics of the individual rock units are conducive to the abundance of rockfalls (fig. 12*D*). Rockfalls are produced by weathering and erosion that affect mudstone and shale more readily than sandstone, siltstone, and limestone and that cause unsupported ledges of these more resistant rocks to break away by falling. Fractures and bedding planes are instrumental in the control of rockfalls (fig. 6*C*). Where massive competent sandstone and less common limestone ledges that have widely spaced joints overlie weaker, thinner bedded, more closely spaced jointed

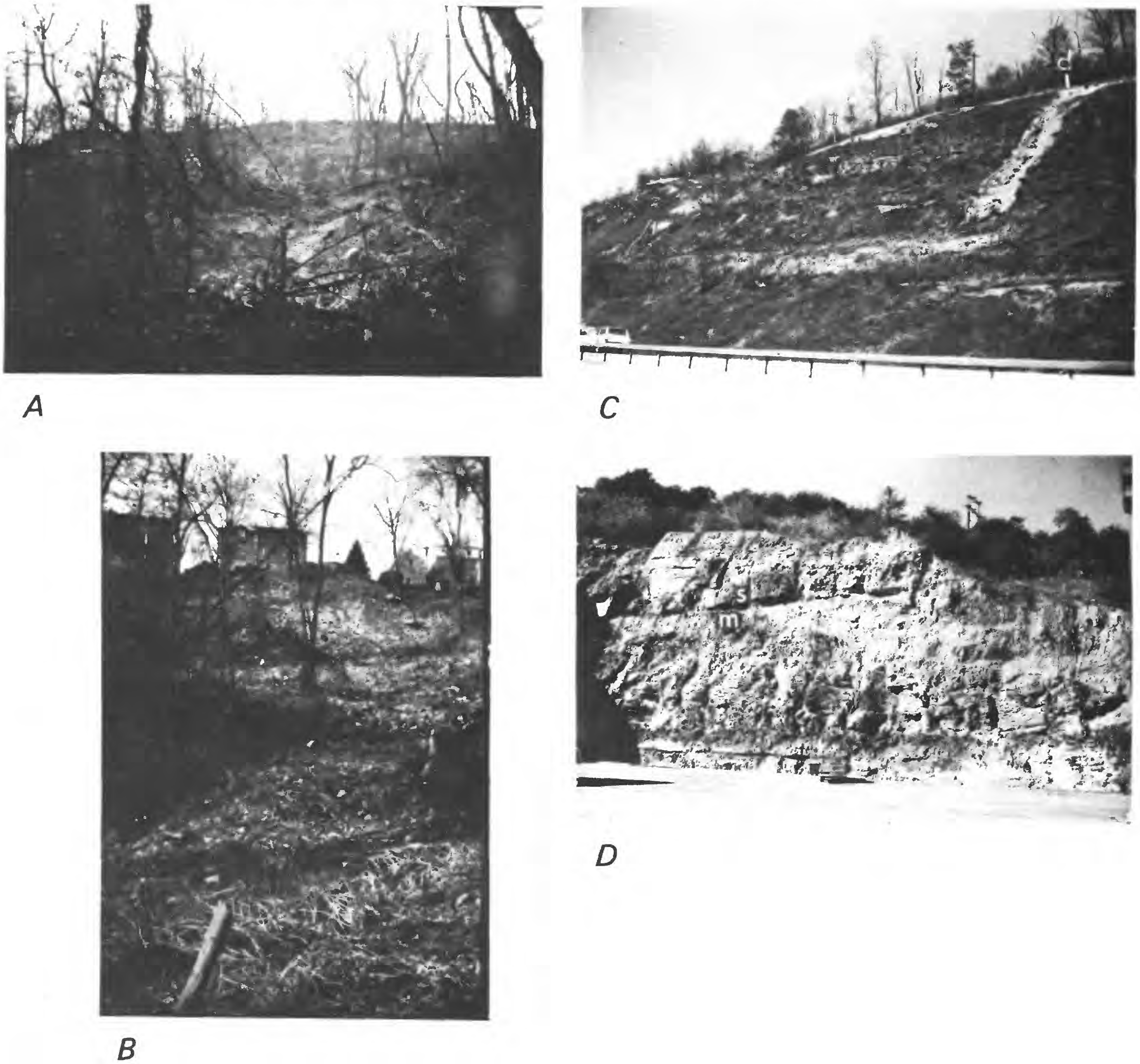


FIGURE 12.—Debris avalanche, debris slides, rockfall. *A*, Debris avalanche, probably caused by heavy precipitation. Above Connoquenessing Creek, Franklin Township, Beaver County. Allegheny Group. *B*, Fill failure behind house reactivated part of an older landslide deposit and caused this debris slide and flow. Harmony Township, Beaver County. Glenshaw and Casselman Formations. *C*, Debris slide (d), bluish-gray clay, exposed at head, served as slippage plane. Pennsylvania Rte. 18 near Rte. 60, Center Township, Beaver County. Glenshaw Formation. *D*, Rockfall hazard at parking lot next to toy store, McKnight Boulevard, Ross Township, Allegheny County. Casselman Formation. Note differential weathering of sandstone (s) and mudstone (m) and potential threat to cars and people.

shale and mudstone, cuts are especially prone to rapid undercutting. Rockfalls tend to be more prevalent during a rainy spring after a harsh winter or a winter characterized by many freeze-thaw cycles.

Rockfalls are particularly common in cut slopes along the Allegheny, Monongahela, and Ohio Rivers and tributary drainages. Elsewhere, many large rockfall areas are found along major highways, such as the Pennsylvania Turnpike in the eastern part of Allegheny County and I–79 in southern Allegheny County. Valley widening to accommodate extensive shopping complexes has caused problems throughout the area because of the many highwalls located next to buildings and parking lots (fig. 12*D*). Rockfalls can occur anywhere in the geologic section, and their potential for catastrophic damage cannot be overstated.

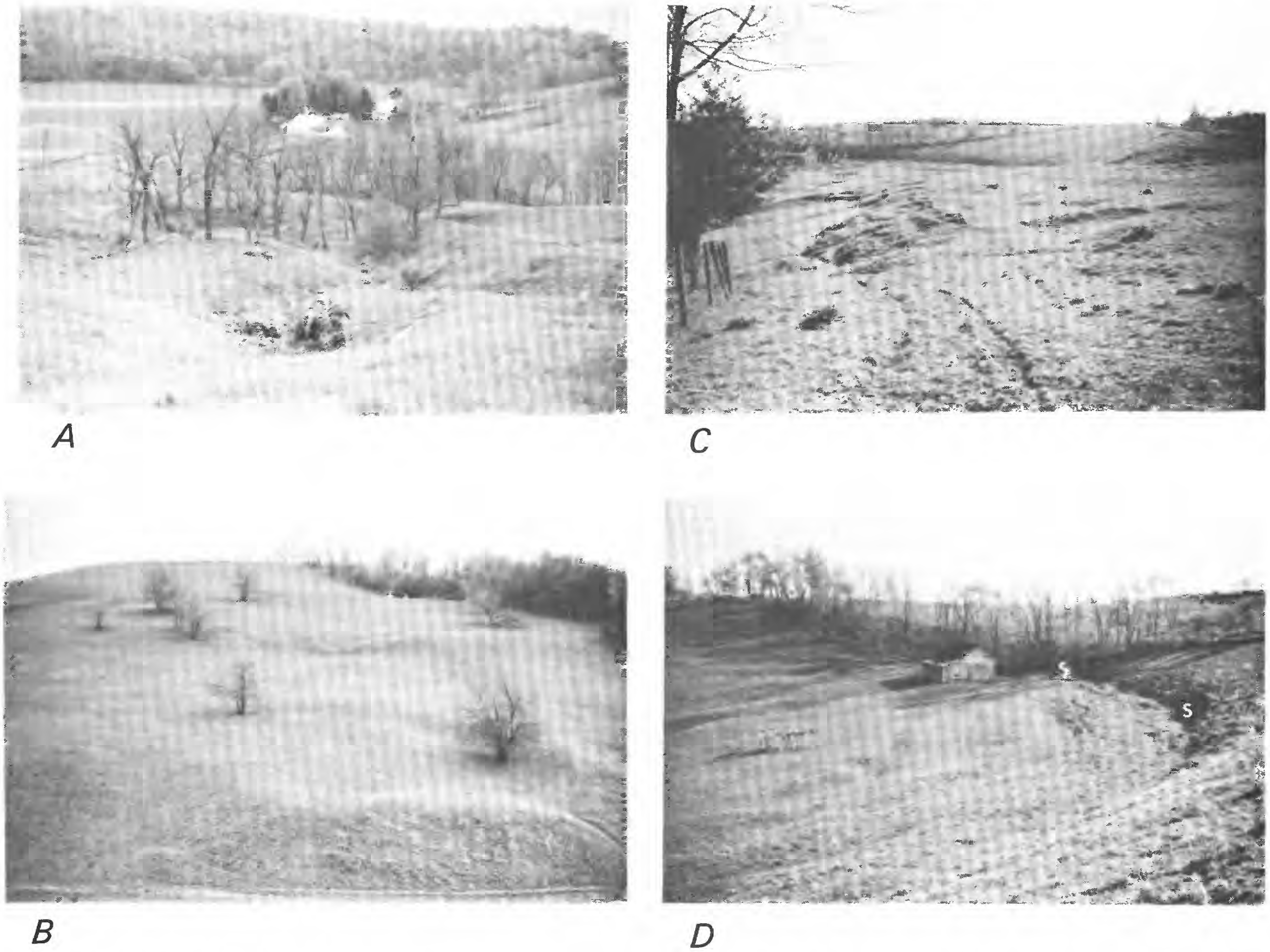


FIGURE 13.—Old landslides. *A*, Looking downslope to hummocky foot of old landslide. Buffalo Township, Washington County. Dunkard Group. *B*, Suggestion of scarp above two trees in foreground. Earth movement appears to have stabilized. Nottingham Township, Washington County. Monongahela Group. *C*, Partially reactivated toe of old slide. Donegal and East Finley Townships, Washington County. Dunkard Group. *D*, Well-preserved arcuate scarp (s) between foreground and barn. This photograph is of the head area of the slide shown in *C*.

On April 26, 1978, a rockfall took place along the Parkway East in downtown Pittsburgh; a car was damaged, the driver was injured, and three lanes were closed for a 24-hour period.

OTHER TYPES

Soil falls, although fairly common throughout the area, have escaped much attention largely because of their diminutive size. They are a hazard only in manmade excavations. A few can be seen along highway cuts and highwalls of strip mines.

Block glides are uncommon to rare. In block glides, the slip surface is planar and not curved as it is in slumps, and the moving mass may even slide out on the original surface (Varnes, 1958, p. 27). Ackenheil (1954, pl. 3) recognized only one slide that could be considered block glide. Mass movement along I-79 in Butler County (see "Selected Landslide Localities") might be related to block gliding, but the early removal of the affected rock material prevented verification.

GEOLOGIC AND OTHER FACTORS THAT AFFECT SLOPE STABILITY

The factors stated below are interrelated, and no sharp line of distinction exists for any particular situation. Most site studies revealed that natural processes have been accelerated by man. Nevertheless, a discussion of landslide susceptibility factors can best be made by separating natural from manmade factors. Natural factors include parent material and soil characteristics, slopes, precipitation, older landslide presence, and stream erosion.

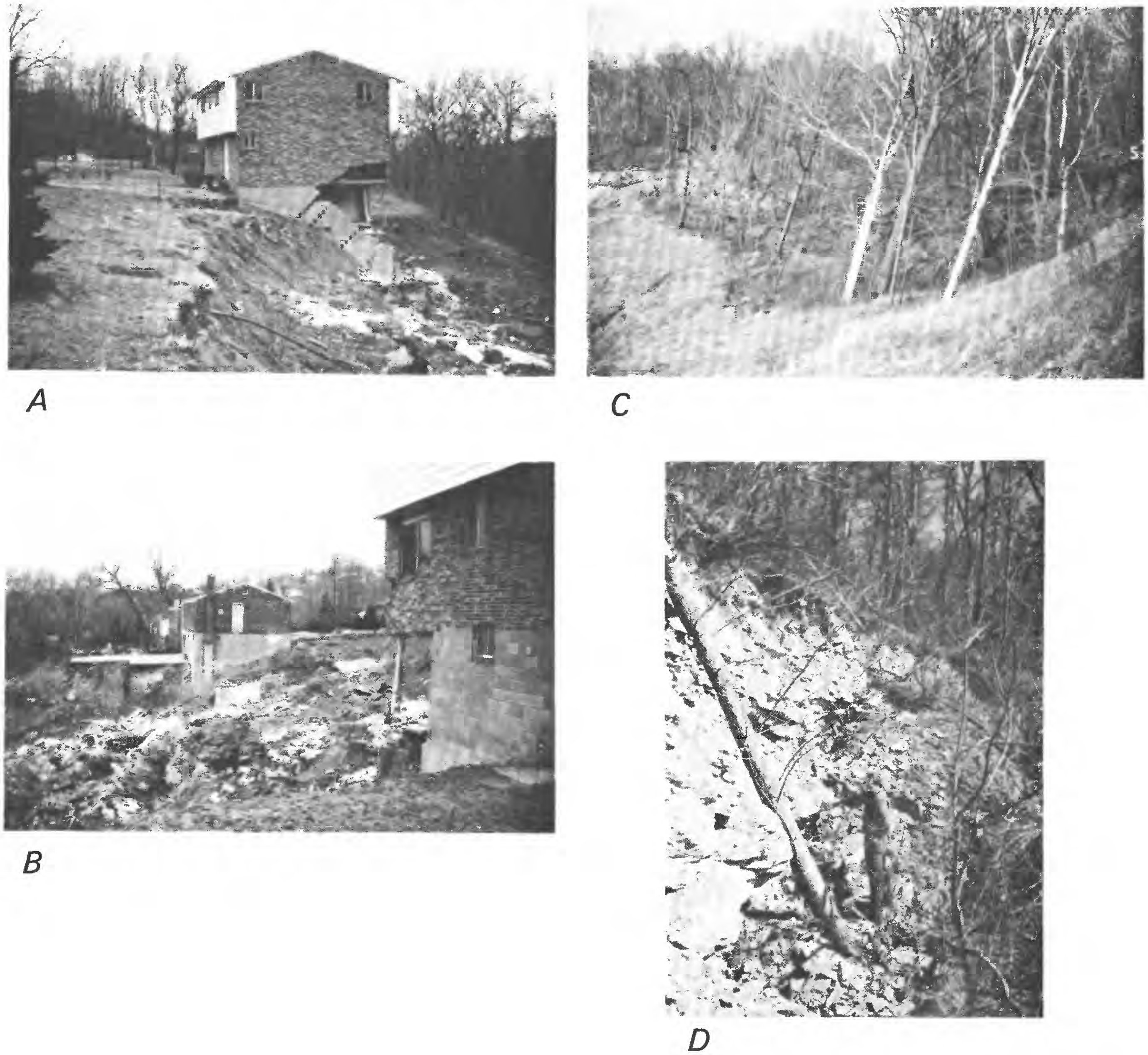


FIGURE 14.—Mass movements along Lawnwood Avenue, Pittsburgh, and along I–79, Allegheny County. *A*, *B*, Lawnwood Avenue, Pittsburgh. Monongahela Group (see pl. 8 and fig. 19, loc. 6). *A*, Head scarp (s). Two houses had been destroyed by sliding at time of investigation. House in background (built on fill) has since been razed. *B*, View across same slide. Note undermining of concrete slab in rear of house in background. *C*, *D*, I–79, Allegheny County. Glenshaw and Casselman Formations (see pl. 5 and fig. 19, loc. 10). *C*, Scarp (s) visible at both sides of photograph. Note rotational effect of movement (trees). *D*, Closeup of head scarp. Note bedrock (not colluvium).

NATURAL FACTORS

PARENT MATERIAL CHARACTERISTICS

Lithology.—Because the rocks of the Greater Pittsburgh area are cyclic and, hence, of diverse and heterogeneous character, slope stability problems are related largely to underlying incompetent rock types in the section (Pomeroy, 1977a, 1978a). Of particular significance to slumping and earth flowage are deeply weathered slopes underlain by:

1. Red mudstone, claystone, and shale, which are thickest and most consistent near the top of the Glenshaw Formation ("Pittsburgh red beds") but which also occur at other horizons lower in the Glenshaw and in the basal and upper middle parts ("Clarksburg red beds") of the Casselman Formation (fig. 3). The red

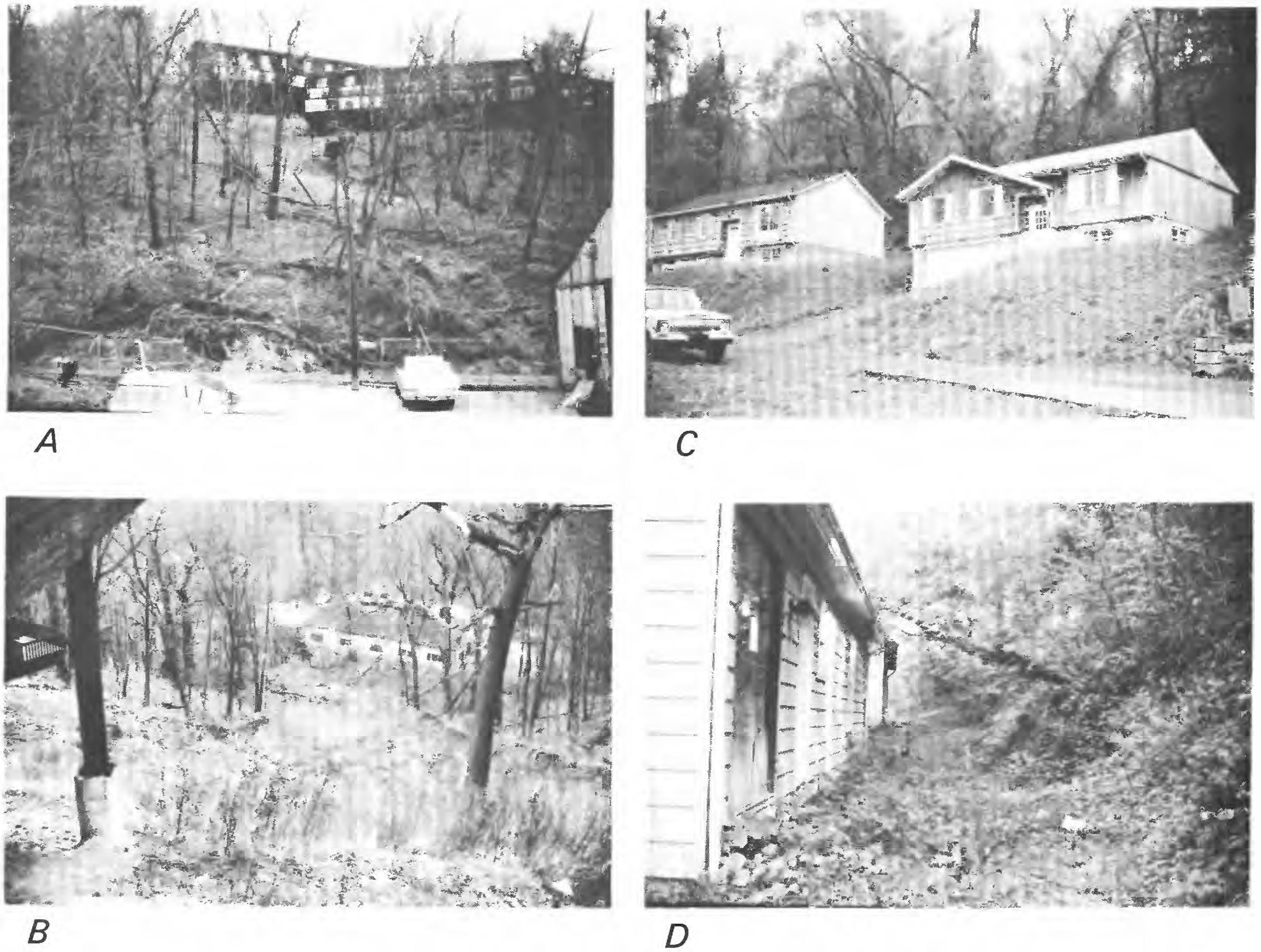


FIGURE 15.—Mass movements in the Kilbuck Drive-Marshall Road area, Pittsburgh, and in the Speers area, Washington County. *A*, *B*, Kilbuck Drive-Marshall Road area, Pittsburgh. Glenshaw and Casselman Formations (see fig. 19, loc. 8). *A*, Head of earthflow to left of top building. Obvious toe has encroached upon road. *B*, Above head of slide shown in *A*. Note lateral margins of earthflow and pellmell arrangement of trees at bottom. *C*, *D*, Speers area, Washington County. Monongahela Group. *C*, Colluvial slope subject to creep. Part of extensive old landslide. Note disarray of trees possibly due to cut bank behind houses. *D*, Cut bank behind house on left in *C*. Creep has accelerated over 1 year.

beds are of primary consideration, not only because they are widespread throughout the region but because the more densely populated areas (Allegheny County, northwestern Westmoreland County, southern Butler County, and southeastern Beaver County) are in this particular geologic environment.

2. Nonred mudstone and claystone, particularly in the Dunkard Group, in Washington County and southwestern Westmoreland County. Although these units are more limited in areal extent than are the "red beds" of the Conemaugh Group, the density of slides is greater throughout the nearly 250 m of section. Landslides can take place in profusion anywhere in the Dunkard terrain and are not limited to specific sequences, although the trend is toward an increased incidence higher in the section, which also is dominated by mudstone units. Lithologic maps in eastern and central Washington County show a close relation between earthflows and accumulations of weathered claystone and limestone (Kent, 1972; Kent and others, 1969, 4 pls.; Berryhill and others, 1971, pls. 1, 2). However, as observed by Berryhill and others (1971, p. 29), slides have taken place on thick units of mudstone that have a high clay content. Slides also start in the proximity of underclays (particularly the Upper Freeport coal zone) and in other nonred claystone, mudstone, and shale in the Pottsville, Allegheny, Conemaugh, and Monongahela Groups.

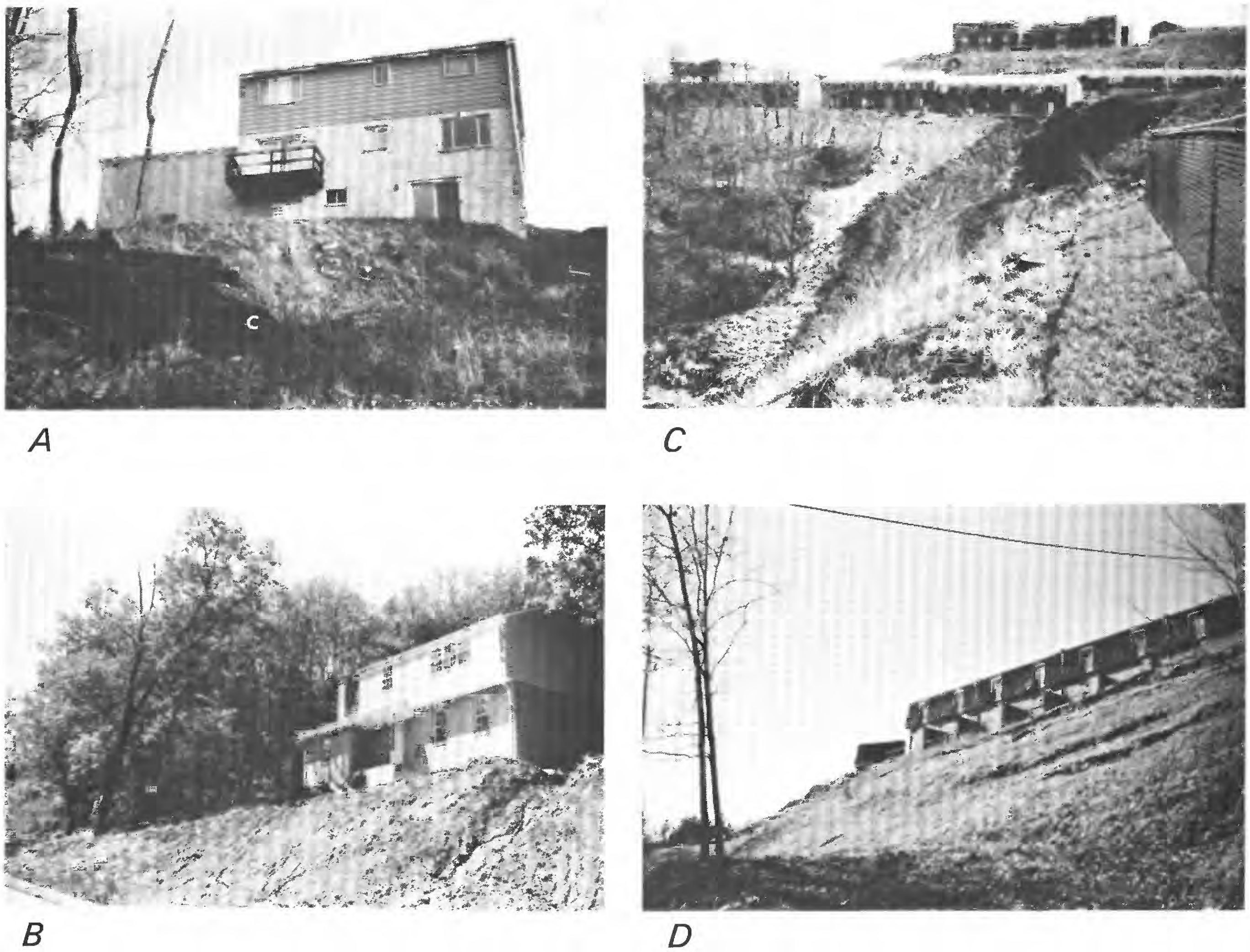


FIGURE 16.—Mass movements in the O'Hara Township area, Allegheny County; Elliot area, Pittsburgh; and Robinson Township area, Allegheny County. *A*, *B*, O'Hara Township area, Allegheny County. Casselman Formation (see pl. 8). *A*, Crib failure (c). Head scarp extends beyond right foundation corner. *B*, Inclined trees indicate soil movement along cut slope. *C*, Elliot area, Pittsburgh. Casselman Formation. Left side of earthflow (e) has not yet been regraded. *D*, Robinson Township, Allegheny County. Monongahela Group (see fig. 19, loc. 9). Small earthflows along oversteepened fill slope.

3. Glacial till (Illinoian) in the extreme northwestern corner of Butler County. Slumped material involves a relatively homogeneous bluish- to brownish-gray clay (Pomeroy, 1978c).

Although the rockfall hazard is not restricted to any particular stratigraphic unit, it is most pronounced where massive sandstone or limestone overlies weaker rock. Conspicuous sandstone and limestone beds are present in the Allegheny, Conemaugh, and Monongahela Groups.

Layering.—Rock types alternate and form layers that are commonly 2 cm to 3 m thick, but, in places, layers are thicker than 10 m, and lateral facies changes may be seen within short distances. Commonly, a thin layer of shale, mudstone, or claystone beneath a thick sandstone layer will indicate decomposition by weathering, resulting in a less firmly supported overlying sandstone. The sandstone is thus subject to rockfall in response to gravity. Alternation of incompetent lithologies with more competent overlying rock types causes stresses in the competent groups and creates a domino effect and consequent rock failure.

Thickness.—In his study of the "Pittsburgh red beds," Winters (1972) concluded that "arcuate scars and slump benches were largest and most abundant in the northwestern and southeastern parts, which coincide with the highest isopachs. The Allegheny County inventory (Pomeroy and Davies, 1975) confirmed the high concentration of landslides in the same areas (both north of the Ohio River and east of McKeesport). The same investigation (Pomeroy, 1974l, m) suggested cor-

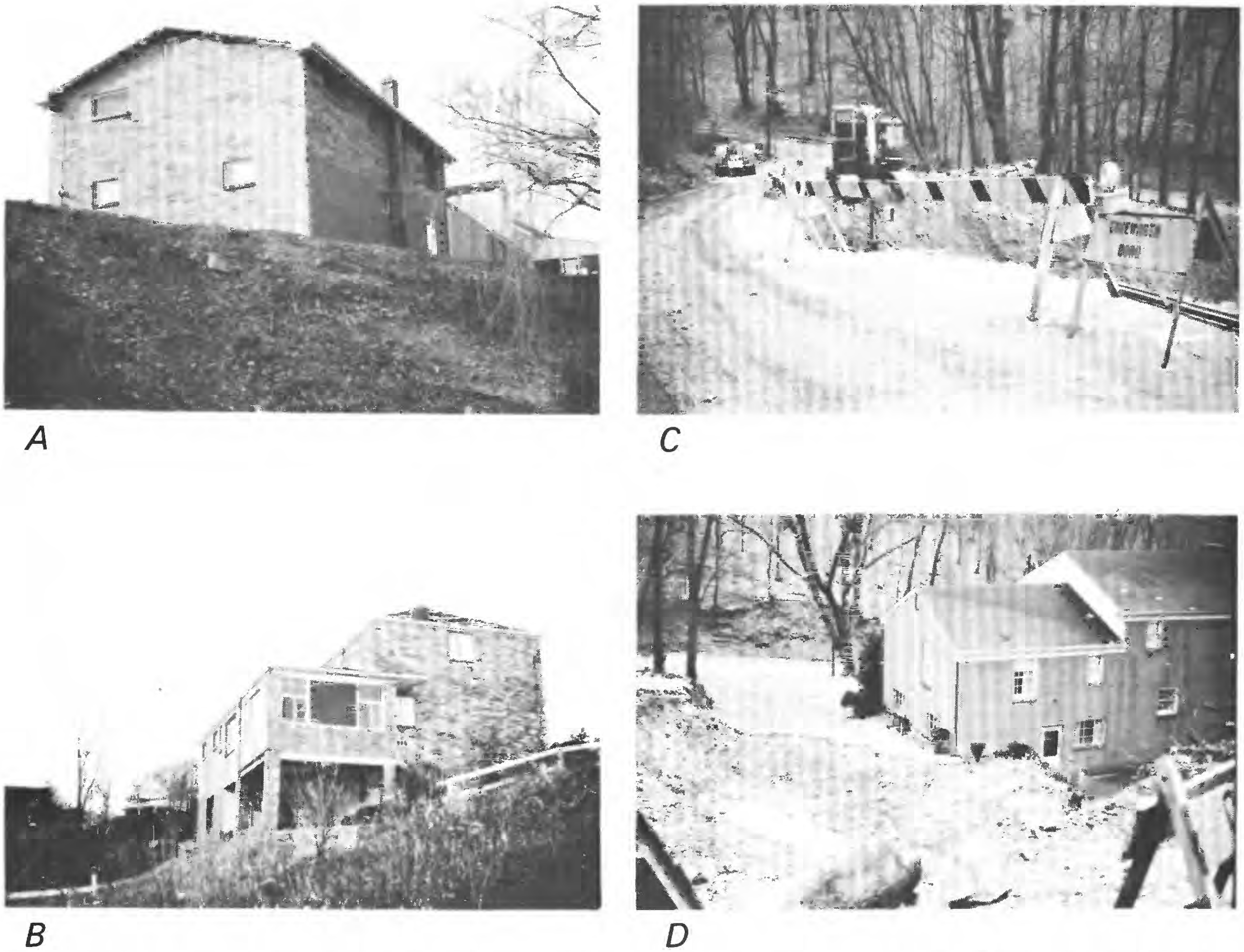


FIGURE 17.—Mass movements along Orchardview Drive and in Edgeworth, Allegheny County. *A, B,* Orchardview Drive, Scott Township, Allegheny County. Monongahela Group. *A,* View west from vacant lot formerly occupied by house destroyed by landslide. House in photograph shows partially rebuilt rear wall. (Compare house with unidentified photograph shown by the North Area Environmental Council, Land Use Committee (1972, p. 13).) *B,* House to east of vacant lot shows out-of-plumb brick porch column affected by soil movement. *C, D,* Edgeworth, Allegheny County. Glenshaw Formation. *C,* Head of slide. In November 1973, road was severely cracked; adjacent lower slope showed slanting trees. *D,* Foot of slide shown in *C.* Unstable earth material was removed before this January 1974 picture was taken. New fill (granular slag) emplaced afterward.

relation between the thickness of the "Clarksburg red beds" and the landsliding in the area north of the Allegheny River between O'Hara Township and Riverview Park. In the Washington County landslide reconnaissance, the thickest clay-rich mudstone units are inferred to be in the upper part of the Dunkard Group (Greene Formation), which is also the stratigraphic interval that has the highest landslide density.

Position of susceptible horizon on slope.—Winters (1972) indicated that the position of the "Pittsburgh red beds" on a slope influences the stability. The thesis that the lower the position of the susceptible horizon on a hillside, the greater the weight of overburden and the greater the volume of water available to the unit bears some credibility. In the northern part of Allegheny County and the southern part of Butler County, the "Pittsburgh red beds" crop out near the top of hills, and the landslide incidence is relatively minor. However, the gentleness of the slopes in this region is probably a deterrent factor in landsliding. Elsewhere in Allegheny County (Pomeroy and Davies, 1975) and in Beaver County (Pomeroy, 1977c, g) most landslides generally take place along the lower slopes. Furthermore, most of the slides related to the Upper Freeport coal underclay occur along the lower parts of slopes in Butler County. However, in the Dunkard terrain of Washington County, no clear pattern exists with respect to the position of landslides on a slope. In summary, this factor, may be significant in many areas because lower slopes are commonly colluvial and may represent old landslides.

Joints.—Joints contribute to landslide susceptibility by providing planes of weakness along which rocks are prone to failure. In rockfalls, the tendency for failure would be far less if joints were not present. Whereas sandstone and limestone fractures are commonly open and well jointed (in outcrop), mudstone and shale joints are closely spaced, tight, and often difficult to distinguish but, nevertheless, represent planes of weakness. The nearly perpendicular relation of the most conspicuous joints to the bedding plane is an important factor in rock permeability. Kelley (1971a) emphasized the role of fractures (joints) in causing slope hazards. Gray (1970, p. 104) noted the sliding of large sandstone blocks along joint planes, during the construction of I-79.

Joints play a major role in slope failures along valley walls, especially along major streams. Their role in the formation of "block-rotation slumps" in eastern Washington County was suggested by Kent and others (1969, p. 28). Enlargement of joint openings appears to be related to slow stress release following the removal of support by stream erosion (Ferguson, 1967, 1974). The Brilliant Cut slide (pl. 7, fig. 1; "Selected Landslide Localities"), for example, is related to valley stress release, which resulted in the widening of the joints and allowed copious amounts of water from a spring thaw to pass downward to impermeable red clay (Ackenheil, 1954).

As downcutting of the valley progressed, beginning in the Pleistocene periglacial environment and continuing into modern times, rock and soil slumped from valley walls and slid along incompetent claystone, mudstone, or shale beds. The Bradys Bend slide (see fig. 9*C*; "Selected Landslide Localities") represents a reactivation of an older slide by a similar process. Valley stress-release joints are related to inferred basal failure surfaces of old deep-seated landslides in the I-79 area (Hamel, 1978, p. 10; "Selected Landslide Localities").

Attitude.—Rockfalls, in particular, are more likely to take place on an overdip slope. Overdip slopes can contribute to landsliding in two ways (Briggs, 1974; Kohl, 1976); jointing combined with the force of gravity is naturally more conducive to movement on these slopes, and, more critically, seeps and wet ground are common on overdip slopes (see "Glossary").

On the basis of a random sampling of 100 landslides in northern West Virginia, Lessing and others (1976, p. 39) questioned the importance of the overdip factor in slope stability in the Allegheny Plateau area. However, Hall (1974, p. 168) stated that more slides apparently take place in the dip direction along West Virginia highways.

In the Greater Pittsburgh region, except for southeastern Westmoreland County, rock layers in most areas dip at such small angles that these attitudes are best measured in meters per kilometer. At the site of the 1942 Aliquippa rockfall disaster (see "Rockfalls"), the rock layers dip toward the river at about 0.5°, but this observation, although recognized by Ackenheil (1954, p. 90), was not cited as a contributing cause. However, Craft (1974a) believed that even the slightest inclination establishes an inherent weakness in the rocks. Both Kohl (1976) and Briggs (1974) cited rockfall areas that relate to overdip slopes in Armstrong and Allegheny Counties, respectively.

The author regards overdip slopes as an important factor in many rockfall hazards throughout the region, but the role of overdip slopes in controlling the siting of earthflows and slumps needs further study. Certainly, the occurrence of seeps along slopes is controlled largely by the inclination of the underlying strata, and many examples can be cited where earthflows and slumps take place along these wet slopes. At one landslide locality on the east side of U.S. 119 north of Connellsville, an overdip slope on the west flank of the Chestnut Ridge anticline shows abundant seeps and transverse cracks in the colluvium. However, the existence of many reverse-dip slopes in Washington County together with many landslides is parodoxical. Clearly, other factors are active in affecting landslide susceptibility, and individual site studies are necessary to fully evaluate the cause of the failure.

SOIL COVER

Throughout the Greater Pittsburgh region, the rock strata are normally not well exposed because they are masked by a clay- and silt-rich residual and colluvial soil mantle. Colluvial-slope soils are relatively thin on upper slopes but increase in thickness to a maximum of about 30 m near the toes of slopes. High rates of weathering, soil formation, and mass wasting are the results of the periglacial climate (Philbrick, 1962; Rapp, 1967).

Soils weathered from red and nonred mudstone and claystone, in particular, are sensitive to mass movement (table 1). Although clayey to silty soils are friable and relatively low in weight per unit volume when dry, the wetting process causes the impermeable clayey soils to retain water and become heavier and more plastic.

PHYSICAL PROPERTIES OF ROCKS AND SOILS

Cyclic sedimentary rocks possess widely differing physical properties that affect their stability. Sandstone is at least five times as strong in compressive strength as indurated clay (claystone) and at least three times as strong in shearing strength as indurated clay (Philbrick, 1953). A sandstone from the Conemaugh Group has a bearing capacity that is more than four

TABLE 1.—*Soils susceptible to landsliding in the Greater Pittsburgh region*

[Soils listed are highly plastic and generally have a moderate or high shrink-swell potential. Landslides have been identified on all these soils]

Soil name	Stratigraphic interval	Lithology of parent material
Brooke	Monongahela-Dunkard	Limestone, calcareous shale, nonred mudstone.
Cavode	Allegheny-Conemaugh	Nonred shale, mudstone, and claystone.
Clarksburg-Guernsey	Monongahela-Dunkard	Variable colluvial material.
Culleoka	Conemaugh-Monongahela-Dunkard	Mostly nonred shale, siltstone, mudstone.
Ernest	Conemaugh (mostly)	Nonred shale and siltstone.
Gilpin-Upshur	Conemaugh	Largely red mudstone, claystone, and shale.
Gilpin-Vandergrift	Conemaugh	Largely red mudstone and shale.
Gilpin-Wharton	Allegheny-Conemaugh	Largely nonred shale, mudstone, and claystone.
Guernsey	Monongahela-Dunkard	Nonred shale, mudstone, limestone, claystone.
Guernsey-Culleoka	Conemaugh-Monongahela-Dunkard	Nonred shale, mudstone, claystone, siltstone, limestone.
Guernsey-Vandergrift	Conemaugh-Monongahela	Nonred and red mudstone and shale, limestone.
Library	Monongahela-Dunkard	Limestone, nonred mudstone and shale, claystone.
Tyler	Pleistocene	Silty-clay till.
Upshur	Conemaugh	Red mudstone, claystone, shale.
Vandergrift-Cavode	Conemaugh	Red and nonred mudstone, claystone, and shale.
Weikert-Culleoka	Conemaugh-Monongahela-Dunkard	Mostly nonred shale, siltstone, mudstone.
Wharton	Allegheny-Conemaugh	Nonred shale, mudstone, and claystone.

times greater than the "Pittsburgh red beds" (McGlade and others, 1972).

Slaking.—On the basis of the author's tests, many red and nonred claystones and mudstones in the region slake within an hour to a few hours after immersion in water. The samples included weathered red clay from the "Pittsburgh" and "Clarksburg red beds" of the Conemaugh Group, weathered gray clay from the Dunkard Group, and weathered red shale from the Conemaugh Group; only the weathered red shale failed to slake. Fisher and others (1968) performed slaking and other laboratory tests on equivalent rock units from southeastern Ohio.

Atterberg limits.—Atterberg limits have been determined for more than 40 samples taken from recent landslide deposits (table 2) and indicate that soils derived from the Dunkard have a slightly higher plasticity index than those from the Conemaugh. The expansivity of the sample is regarded as moderate where the plasticity index is 5 to 25 and high where the plasticity index is greater than 25. Plasticity index values for landslide material are higher than those for undisturbed samples.

Weathering and abrasion.—Kapur (1960), in his study of the weathering of the "Pittsburgh red beds" in Allegheny County, concluded that each cycle of freezing, thawing, drying, and saturation causes a loss in strength and a gain in moisture content; both of these effects are increased at a decreasing rate as cycling is continued. Bonk (1964), in a similar study, stated that the size of the weathered red-bed particles definitely decreases as the number of weathering cycles increases. The rate of weathering as measured at natural exposures by Bonk (1964) ranged from 2.5 to 15 cm per year.

TABLE 2.—*Physical properties of landslide material from the principal geologic units most susceptible to sliding in the Greater Pittsburgh region*

[Of the two units, the Dunkard Group material tends to have a slightly greater proportion of expandable minerals, higher plasticity index, and higher clay content]

Stratigraphic unit	Particle-size distribution[1] (percentage)			Plasticity index[2] (moderate 5-25; high >25)	Clay mineralogy[3] (x-ray diffraction)
	Sand	Silt	Clay		
"Red beds" of Conemaugh Group	26	47	27	18.2	Illite-kaolinite greater than vermiculite containing interlayered minerals.
"Nonred beds" of Dunkard Group	22	46	32	20.8	Illite, vermiculite, kaolinite, and interlayered minerals in decreasing order of abundance.

[1] Results are the average of analyses of 18 Conemaugh Group samples and 12 Dunkard Group samples. Analysts are K. S. Donovan, Monique Moore, and Brad Kauffman, supervised by S. F. Obermeier.

[2] Results are the average of analyses of 20 Conemaugh Group samples and 22 Dunkard Group samples. Analysts were K. S. Donovan, Monique Moore, and Brad Kauffman, supervised by S. F. Obermeier.

[3] Results are the average of analyses of two Conemaugh Group samples and three Dunkard Group samples. Analysts were Susan McNabb and Melodie Hess.

Younger Pennsylvanian and Permian nonred mudstone and claystone from Washington County were subjected to weathering and abrasion tests that demonstrated the effect of compactive forces and of repeated wetting and drying cycles upon the disaggregated samples (Berryhill and others, 1971). The results showed that the effect of a single compactive force (hammer test) is almost equivalent to four cycles of wetting and drying (p. 41-42).

Wind erosion, generally not recognized as an important erosional agent in southwestern Pennsylvania, was considered by El Ashmawi and Greenfield (1972) to be a significant factor in the weathering of vertical cut slopes in the Dunkard Group. If this is true, wind erosion is a factor in the occurrence of rockfalls.

Permeability and porosity.—Both properties are relevant to the landsliding process. Rocks and soils are most likely to be saturated by water in zones where permeable (sandy) materials overlie relatively impermeable (fine-grained) materials. Although limestone is fine grained and inherently impermeable, many limestone layers are permeable because of closely spaced joints.

The red clayey materials derived from the Conemaugh Group have a relatively high porosity (as much as 40 percent), but their relatively low permeability results in as little as 1 to 5 percent of the pore water draining by force of gravity (Subitsky, 1975). The chance of sliding is increased when excessive pore-water pressure in the clay decreases its shear strength.

The clay content of landslide debris derived mostly from Dunkard rocks is slightly higher than that from Conemaugh rocks (table 1) and is characterized by relatively high porosity and low permeability, similar to those of the red clayey materials of the Conemaugh Group. Berryhill and others (1971, p. 42) attributed the sliding to the capacity of the clayey material to absorb copious quantities of water that cannot easily pass through it.

Mineralogy.—X-ray diffraction analyses on three Dunkard Group samples revealed that the clay consists of illite, vermiculite, kaolinite, and interlayered minerals in decreasing order of abundance (table 2). The clay mineralogy is similar to that of soils derived from the Conemaugh Group, except that most of the Dunkard-derived soils have a slightly greater proportion of expandable minerals. Similar clay mineralogical data were obtained by Ciolkosz and others (1976). The moderate to high shrink-swell potential of most Dunkard- and certain Conemaugh-derived soils is due to both the relatively high clay percentage (table 1) and the moderately high expandable mineral content.

In a study of equivalent rock units from southeastern Ohio, Fisher (1973) and Fisher and others (1968, p. 79) indicated that the unstable red beds are illitic and have been degraded by the leaching of potassium ions. Fisher and others (1968, p. 79) concluded that "simultaneous deposition of ferric iron with degraded illitic clay prevented reabsorption of the bonding potassium ion in the depositional environment. The continued presence of iron has greatly inhibited the reconstitution of the clay throughout diagenesis and late geologic time." They indicated that degraded illites are similar to montmorillonite in the presence of water except that expandability is not as great.

SLOPE STEEPNESS AND CONFIGURATION

Steepness.—The steepest slopes are restricted to the major drainages as well as to the only prominent ridges (Chestnut Hill and Laurel Ridge) in the region. Landsliding is not a serious problem in the ridges owing to the largely competent nature of the rock. In most of Allegheny County, southeastern Beaver County, and northwestern Westmoreland County, slopes underlain by red mudstone are more apt to slide than are slopes of the same lithology in adjacent regions mainly because of the slope angle. In Allegheny County alone, slopes for which the angle is 25 percent or greater (fig. 7) occupy about one-fourth of the area. Soils derived from the "Pittsburgh red beds" in southern Butler County have a low incidence of sliding because of the more moderate slopes. In Washington County, slide incidence increases southward toward Greene County, in part because of steeper slopes.

Configuration.—The inventory revealed that most recent and older landslides took place on laterally as well as vertically concave slopes. Patton (1956) noted that recent earthflows were more common in coves or concave slopes than on other slope types. Both ground and surface water tend to concentrate in such areas; this concentration creates unstable surface conditions where clayey soils are present that have at least a moderate shrinkage-swell ratio. An absence of outcrop and a relatively thick accumulation of loose highly weathered material are characteristic of these concave areas. In addition to the term "cove," other appropriate names for these natural configurations are "bowls" or "amphitheaters," which have been recognized in neighboring West Virginia (Lessing and others, 1976). Amphitheater-shaped drainage basins and bowl-shaped depressions formed by large-scale mass movement have been noted in California (Nolan and others, 1976; Kelsey, 1978, p. 364). The origin of pseudocirques in Montana (Freeman, 1925) and that of an old concave slope scar in Wyoming (Bailey, 1971, p. 64) have been attributed to landsliding.

PRECIPITATION

Late winter and early spring rains in combination with the thawing of partially to completely frozen ground create unstable conditions along the slopes. Consequently, more slides take place at this time of the year because of the high water content of the soil mantle. However, heavy precipitation can be derived from waning stages of extratropical cyclonic storms entering the Ohio River basin as well as from storms resulting from continental weather movements (Subitsky, 1975). Rainfall from Hurricane Agnes ranged from slightly less than 5 cm in western Beaver County to as much as 20 cm in eastern Westmoreland County (Bailey and others, 1975, p. 46). At Pittsburgh, measurable precipitation from this storm amounted to slightly more than 10 cm (Subitsky, 1975). Heavy rainfall from continental weather movements occurs as cloudbursts. However, rainfall records for the Greater Pittsburgh area do not indicate any precipitation nearly as heavy as that which fell in the Johnstown area (outside the region to the east) on July 19-20, 1977.

During an intensive period of precipitation, clayey soil material eventually becomes highly saturated; saturation not only adds weight to the slope material but increases both the pore pressure and the shearing stress.[1] At the same time, the cohesion and frictional resistance of the slope material to sliding is decreased, and some form of mass movement results.

In the Appalachian Plateaus region, major deep-seated landslides commonly do not take place soon after heavy precipitation. According to W. E. Davies (oral commun., 1977), a 1- to 2-year lag between severe storms and the onset of large-scale slides is common in the area. A recently reactivated (April 1975) mammoth old landslide at McMechen, W. Va., south of Wheeling, has been attributed to above-normal rainfall recorded in 1974 and early 1975 (GAI Consultants, 1976; Gray and Gardner, 1977).

PRESENCE OF OLD LANDSLIDES

Many old (ancient) landslides (fig. 13) originated under climatic conditions that were wetter than those of modern times. Most of the old landslide deposits shown on the maps (Pomeroy and Davies, 1975; Pomeroy, 1976a, b, 1977b-g, 1978b, c) do not represent single events but are accumulations of coalesced deposits that have formed since Wisconsin Glaciation. Philbrick (1962) reported dates of 8,940 ± 350 years to 9,750 ± 200 years for ancient landslides in the upper Ohio Valley on the basis of carbon-14 dates of wood from slide planes at two dam sites. In many places, the resultant slope of an old landslide deposit has attained equilibrium, and, because of its now stable configuration, it will not be susceptible to further sliding. One can assume that, under the influence of the present drier climate, many of these deposits will remain stable unless extensively modified by man.

The foot and toe area of an old landslide deposit, like that of a recent slide, is hummocky; in some places, it is a benchlike deposit that is termed a "slump bench." The landslide deposit is generally less than 300 m from toe to valley head, and the width of many deposits is greater than the length. The valley form is semicircular (concave) rather than V-shaped in plan and cross section and rarely contains a well-defined water course. A veneer of heavy clay probably represents the surface of rupture on which landsliding has taken place, and even today it remains highly sensitive to overloading. The toe and foot areas are relatively stable, and many dwellings built on them decades ago have not been damaged. However, excavation at the toe can reactivate sliding.

Slumped bedrock has been observed in many ancient landslide areas, the dip of the layering bearing no relation to the regional structure. This suggests that bedrock was involved at least in the headward areas of the landslides.

Generally, the incidence of landslides in areas of recent and of older landslides shows a direct correlation, but man-related activities have altered this relation in wide areas. In areas of extensive strip mining (especially northern Armstrong County), many of the spoil-bank failures are associated with a comparatively sparse distribution of definite older landslides. Clearly, the sliding is related to the unconsolidated spoil-bank material rather than to any inherent weakness in the underlying slope lithology. In places, the high incidence of fill and natural-slope failures in metropolitan Allegheny County is difficult to relate with old landslides. Extensive slope modification since the 1940's in Allegheny County, resulting in the obliteration of geomorphic features, has made the identification of old landslides difficult. Nilsen and others (1976) discussed the same problem in mapping ancient landslide deposits in extensively urbanized areas in Alameda County, Calif.

One then has to study areas where manmade influences are at a minimum, as in rural southern Washington County, where a clear relation between high recent landslide incidence and older landslides is apparent. A similar correlation, on a smaller scale, exists in the rural setting of southern Beaver County.

[1] In reviewing this manuscript, R. H. Campbell (written commun., 1979) stated that the significance of the addition of the weight of increased soil moisture during a period of heavy precipitation involves a more complex relation than the statement implies. The addition of a uniform weight over the entire slope area does not change the ratio between the shearing stress and the normal stress in the slope. For the added weight on a slope to unbalance the ratio between the normal stress and the shearing stress, the weight must be distributed unevenly so that rotational stresses are developed. This geometric qualification is rarely stated explicitly and is not readily implicit in the words "overloading" or "added weight."

However, the added weight, even if uniformly distributed, does become an important factor when movement begins, because after cohesion and the frictional resistance of the normal forces have been overcome, then, indeed, the added weight causes increased shearing stress, which in turn tends to accelerate the heavy moving mass more rapidly than a lighter mass.

The inventory has shown that most recent slides clearly originate from reactivation of older landslides. Many slides that do not follow this relation have resulted from man's modification of less unstable natural slopes by road construction, subdivision and industrial development, or strip mining. In the Greater Pittsburgh area, more than 70 percent of the recent landslides are related to older landslides. Ancient landslide deposits also appear to be loci for renewed slope movement in the San Francisco Bay area (Nilsen and Turner, 1975; Nilsen and others, 1976).

OVERSTEEPENING OF SLOPES BY STREAM EROSION

Examples of slope oversteeping by stream erosion are widespread throughout the region but are most apparent along Raccoon Creek in Beaver County (Pomeroy, 1977g). Here, at the point of maximum curvature of the stream where the slope receives the greatest erosive force from the water, recent slides have taken place.

MANMADE FACTORS

OVERLOADING SLOPES

Ackenheil (1954, p. 37) stated that the most common cause of landsliding is the construction of a fill in which the slope is too steep for stability. This practice is common in the urbanized areas of the Greater Pittsburgh region where backyard-fill failures are common (figs. 10*D*, 14*A*, *B*, 16*A*). Many developers, realizing the problems brought about by the preponderance of unstable slopes, elect not to put in fill for backyards (fig. 8*A*). In addition to the backyard-fill problem, larger scale fill failures at multiple housing and commercial establishments (figs. 10*D*, 16*C*) and smaller fill slumps affecting roads (figs. 5*A*, 17*C*) and railroads are numerous.

Some of the slides involve the fill material only, but others are more complex and involve appreciable subjacent material as well. The most glaring and flagrant example of man's misuse of land is overextending a red-bed slope with red-bed fill taken from a nearby locality. Another practice, although occasionally less obvious, is to fill in the head of a tributary valley (fig. 10*A*). In several places, the heads of tributary valleys represent the head areas of ancient landslides. The slopes below might be unstable initially because of relatively thick accumulations of clayey colluvium lying below the additional weight at the top that surcharges the slope.

Improperly compacted spoil material from areas of surface coal mining can surcharge a slope and cause failure (fig. 9*A*, *B*). Quarry waste near the Sewickley, Pa., Water Works provided a surcharge load that contributed to a major earthflow (Ackenheil, 1954; pl. 3, fig. 1; "Selected Landslide Localities").

EXCAVATION AT THE BASE OF SLOPES

Excavation at the foot of the slope to make more flat land in the narrow valley areas is a popular practice. If the cut is in the toe of an unidentified old landslide deposit, slippage or accelerated creep (figs. 15*C*, *D*, 16*B*) might take place. Normally, where manmade modification is not present, the toe of an old landslide deposit is a restraining influence to any advance of uphill colluvium.

I-79 construction north of the Ohio River (figs. 14*C*, *D*, pl. 4; "Selected Landslide Localities") cut into several large old landslide deposits, and the effects have proved to be extremely costly. The widening of McKnight Boulevard (Pennsylvania Rte. 19) in a valley in north Pittsburgh (Pomeroy, 1974b) has led to increasing development of commercial establishments. Although no large individual landslides have taken place, extensive soil falls, small debris slides, and rockfalls (fig. 12*D*) must be constantly monitored.

ALTERATION OF DRAINAGE CONDITIONS

Ground- and surface-water changes originating upslope from houses built decades ago were a contributing factor in causing earth movements in the Russian Hill area of Pittsburgh (Kelley, 1971b).

In many places, highway and construction sites pose problems because they commonly necessitate both excavations and fills. Increased water discharge at the excavated face may increase rockfall potential, and ponding behind the fill material must be prevented because it leads to oversaturation of the material and possible subsequent slope failure.

Inadequate drainage systems have affected slopes lying below several multidwelling developments where runoff from downspouts has infiltrated underlying sensitive slopes (fig. 16*D*). Even where drainpipes have been installed, maintenance to insure the system's effectiveness may be lacking.

Water and sewer lines in established residential areas occasionally break under the influence of creep; such a break can result in the surcharging of the slope with additional moisture. Changes in drainage produced by strip mining are contributing causes in spoil-bank slides. Landsliding is common along slopes in areas immediately adjacent to abandoned secondary roads in part owing to a cessation of drainage maintenance.

VEGETATION REMOVAL

Vegetation loss can be due to natural causes such as disease and lightning-induced fire. More often than not, however, it is due to human activity—construction (highway, commercial, industrial, residential, pipeline), mining, logging, clearing for farmland or pasture, or man-produced fire.

Trees are conducive to slope stability through their ability to store water in their root systems. The effect of raindrops eroding the soil is reduced by any type of vegetative cover. The transpiration process naturally depends on vegetation; without it, water pressure builds up in the soil and, thus, stability is lessened.

Although fumes from several heavy industries have caused losses of vegetation, no major slides were found in the present inventory that could be directly attributed to such loss. However, several areas beneath powerlines were identified that contained slides (pl. 2, fig. 1; pl. 3, fig. 2).

VIBRATIONS

Several old slides along colluvial slopes recently have been reactivated along the Ohio River in the vicinity of Shippingport (Beaver County). Vibrations caused by foundation blasting for nuclear powerplants, combined with the increase in the movement of heavy construction equipment, might be largely responsible for the triggering of old slides. Pile driving in an area downstream from Shippingport and west of Midland has been cited by local residents as a cause of a major slide along Pennsylvania Rte. 68.

Accelerated creep and a relatively high density of landslides were found along the steep slopes bordering East Street, which is a major thoroughfare in north Pittsburgh. Vibration might be a contributing cause of the instability, but, without more documentation, its role can be only conjectured.

SUBSIDENCE

Any landsliding that is as much as several hundred feet above a mined-out horizon might be due, at least in part, to subsidence. Subsidence is probably a significant factor at the Greensburg and Baldwin Road locations (see "Selected Landslide Localities"). Emplacement of fill over a mined-out area could lead to a collapse of the underlying strata and induce movement of the overlying earth materials.

Differentiating the effects of subsidence and landsliding is occasionally difficult. Surface cracks are present along a narrow ridge south of Carnegie (Pomeroy, 1974g; Pomeroy and Davies, 1975; Briggs and others, 1975, p. 13). Although the cracks might be attributed to accelerated creep or to a slow-moving landslide (involving bedrock) at least in part induced by undermining, surface subsidence more likely is solely responsible for the cracking. The position of the mined-out Pittsburgh coal bed at this locality is less than 12 m below the crest of the ridge.

SELECTED LANDSLIDE LOCALITIES

Brief descriptions of 19 localities that are examples of landsliding phenomena in the Greater Pittsburgh region (figs. 18, 19) are given below. Several localities are represented on the stereoscopic models (fig. 20). The individual areas are represented on 1:24,000-scale inserts (fig. 19) so that the reader may more clearly visualize the problem.

BRADYS BEND, NORTHWESTERN ARMSTRONG COUNTY

The slide area at Bradys Bend (fig. 19, loc. 1), 0.7 km southwest of Pennsylvania Rte. 68 on west slope of Allegheny River, northwestern Armstrong County, is best viewed from East Brady at the right angle turn in Pennsylvania Rte. 68 (fig. 9*C*). The author's questioning of local residents at East Brady in 1978 failed to establish the date of movement, although it apparently took place before the mid-1940's. Summer residences along the river and at the foot of the slide clearly postdate the movement. The slope is underlain by the Allegheny and Pottsville Groups.

Strip mining is not a factor at this location, though it is a factor along the same slope nearly 1 km to the south. The landslide is best described as a bedrock slump whose head is approximately 60 m wide. Rapid movement probably took place downward and outward along a concave slip surface together with backward tilting parallel to the slope. Slumped bedrock inclined northwestward dominates the slope area. Probably owing to valley stress release, joint enlargement in competent sandstone and siltstone along the upper slope permitted water to penetrate downward to a claystone or underclay that acted as a slip surface. The lower colluvial slope is subject to severe erosion and oversteepening during high water that might have triggered the slide.

On the night of August 14–15, 1980, torrential rains fell in the East Brady-Brady's Bend area. The intensity of the storm (a reported 4 inches of rain fell within a 4-hour period) clearly exceeded the infiltration capability of the soil and resulted in heavy surface runoff, subsequent flooding, and landsliding. A 3-month (mid-May to mid-August) total precipitation tabulation shows that new record-high rainfalls were set at several communities in western Pennsylvania and indicates that the ground was already well saturated.

Two landslides originated within the older slide. A vacant mobile home was severely damaged by one slide. A car was swept into the river, and another car was damaged. Fortunately, no lives were lost because of landsliding. Eyewitness accounts established that the sliding took place during the storm.

GREENSBURG, WESTERN WESTMORELAND COUNTY

The fill bridging the head of a ravine on East Pittsburgh Street (north side), Greensburg, 0.2 km west of

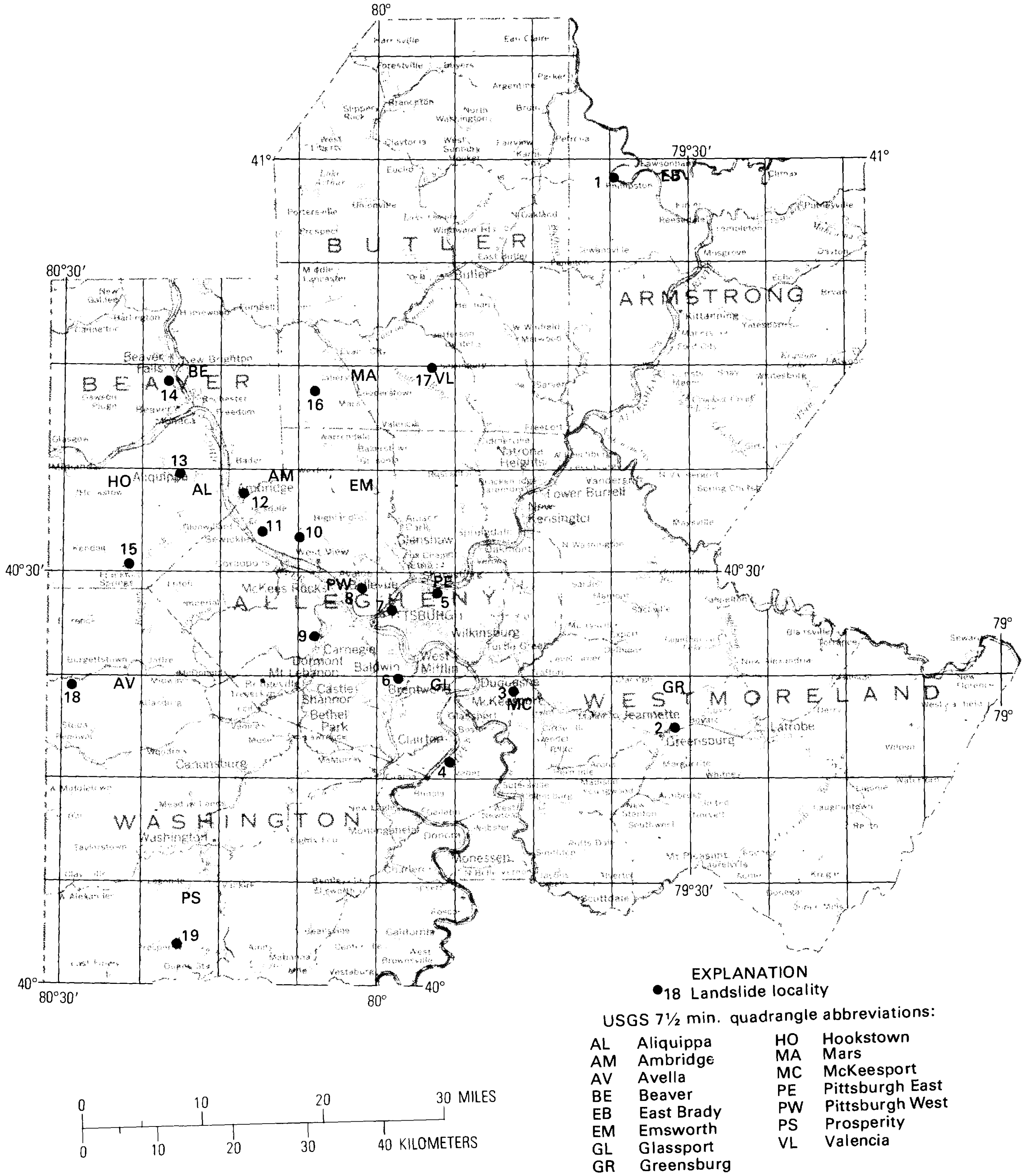


FIGURE 18.—Index map showing 19 selected landslide localities and U.S. Geological Survey 7½-min quadrangle locations and names.

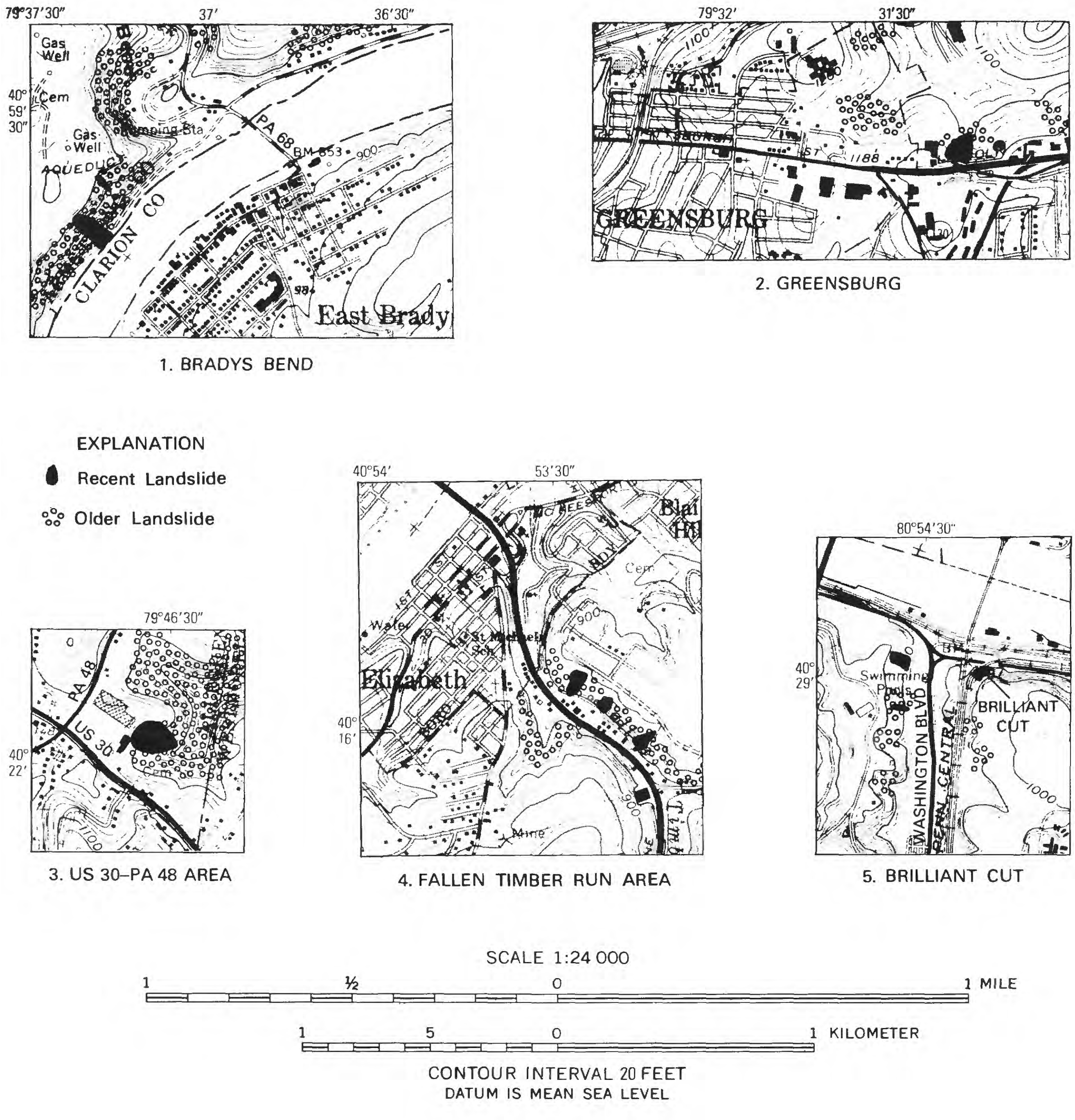


FIGURE 19.—Maps showing landslides at localities 1–19 shown in figure 18.

U.S. 30 intersection, western Westmoreland County (fig. 19, loc. 2), apparently has prompted light industrial-commercial development. Large-scale slumping has been recurring in part owing to the constant dumping of material at the edge of the man-modified land surface. A one-story office building presumably built on fill showed extensive interior and exterior cracking. Walls were being pulled away slowly from the footings in late

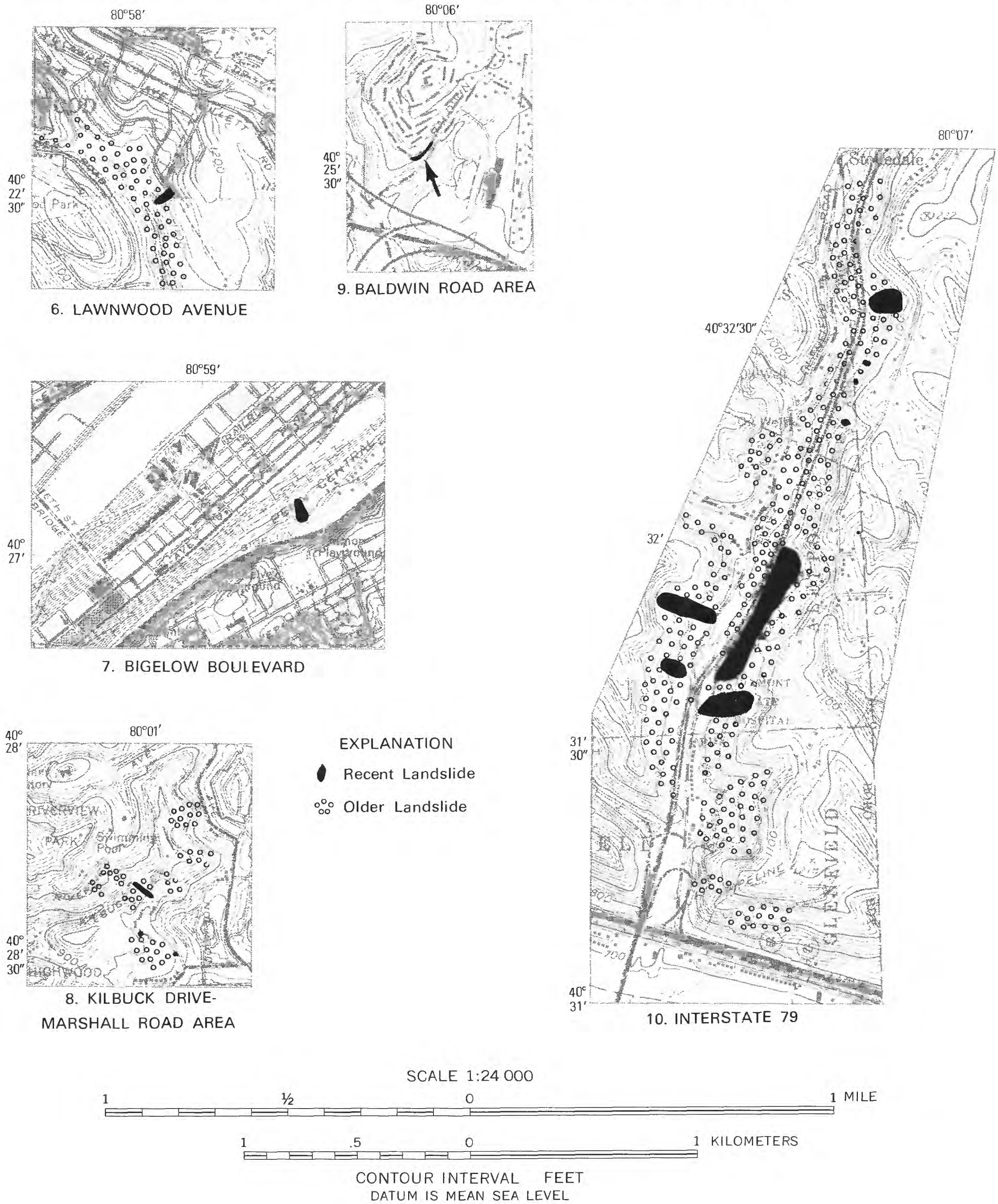


FIGURE 19.—Maps showing landslides at localities 1-19 shown in figure 18—Continued.

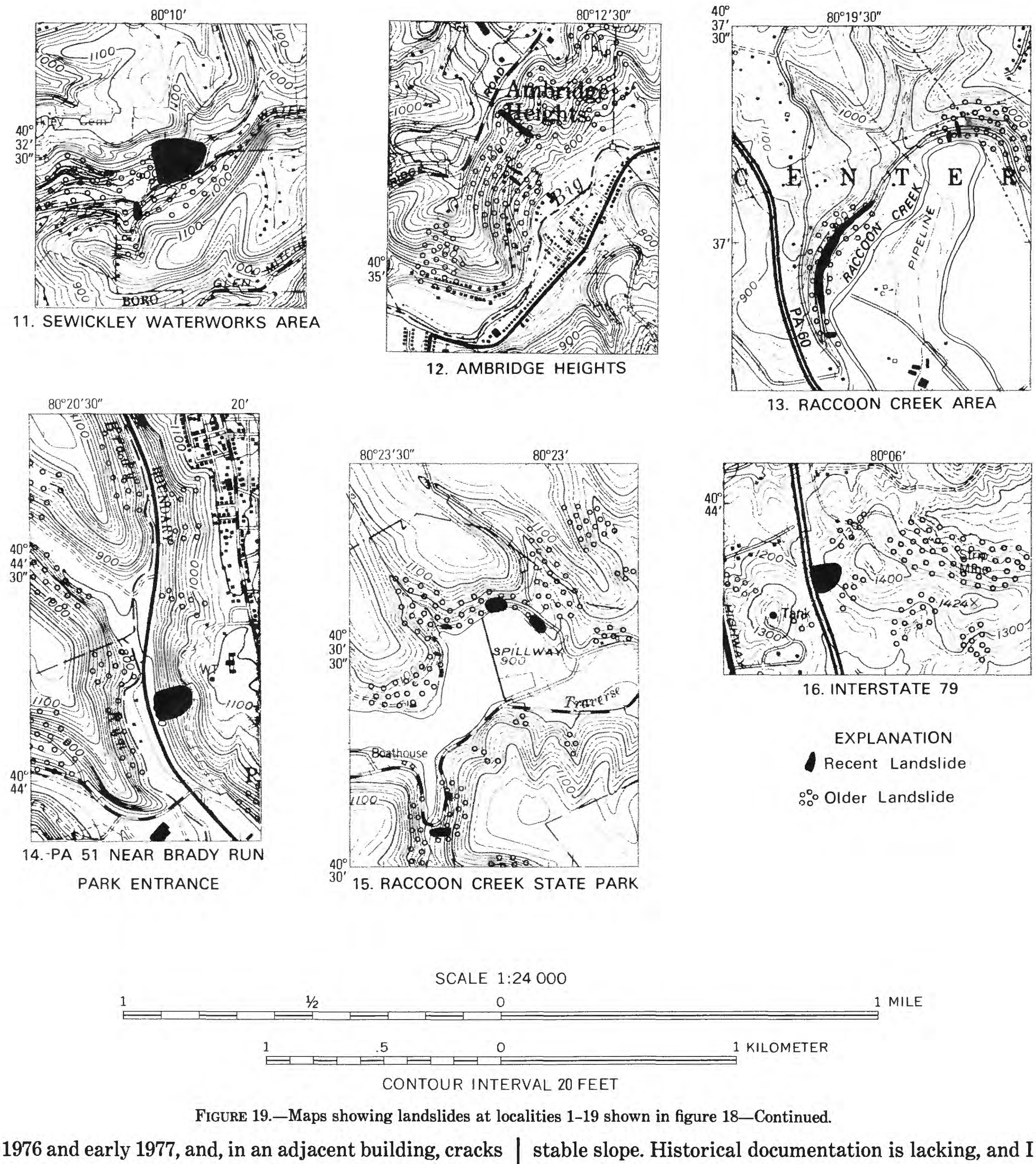


FIGURE 19.—Maps showing landslides at localities 1-19 shown in figure 18—Continued.

1976 and early 1977, and, in an adjacent building, cracks through the concrete block exterior wall could be seen. In early 1977, fresh cracks several meters behind the present scarp indicated continuous surcharging of the slope by fill dumping, which aggravated an already unstable slope. Historical documentation is lacking, and I do not know when slumping began.

Three major factors have to be considered. First, the slumping lies within an older landslide in colluvium underlain by the Monongahela Group. Second, maps

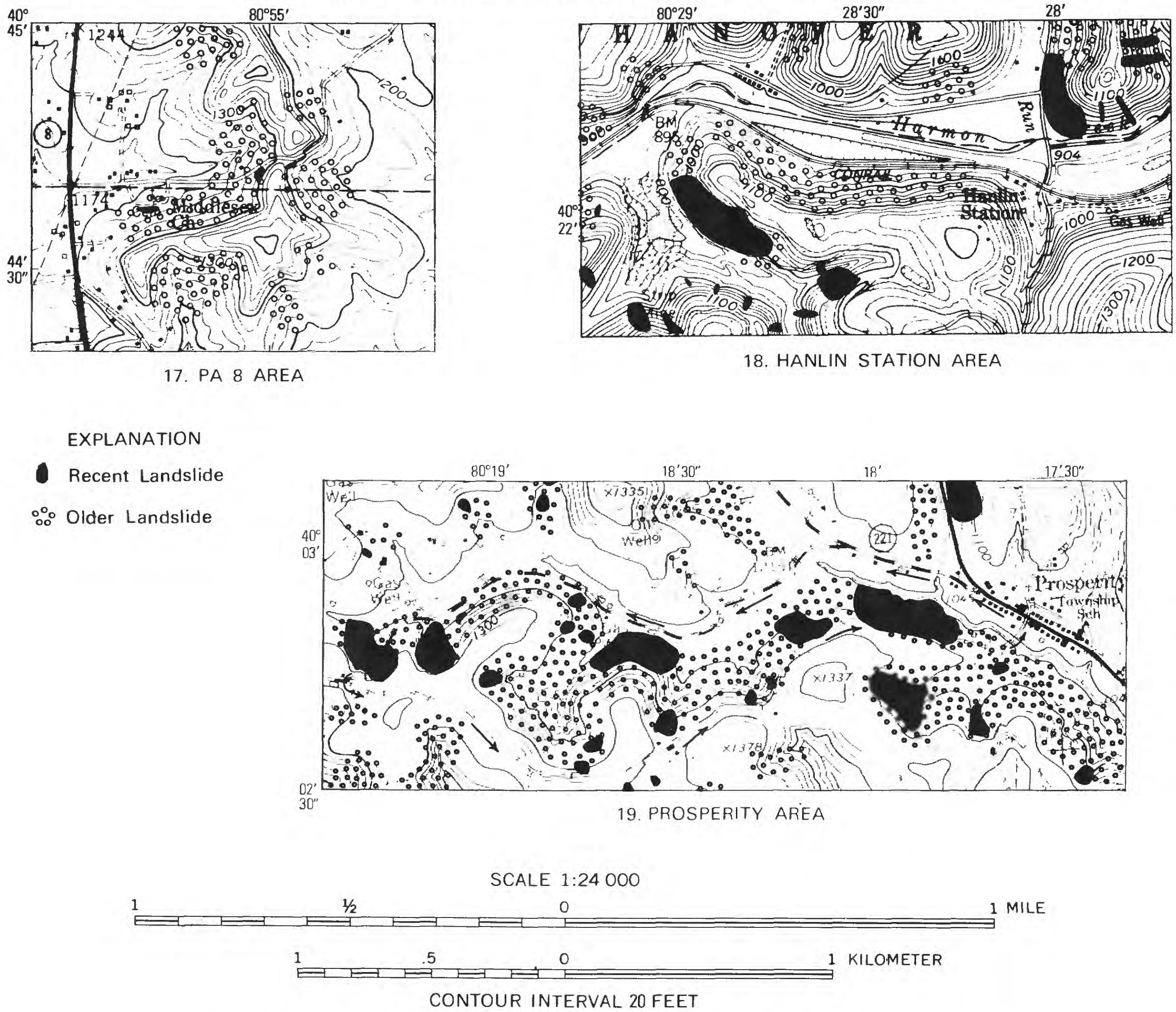


FIGURE 19.—Maps showing landslides at localities 1-19 shown in figure 18—Continued.

prepared by Bushnell (1975a, b) and Cortis and others (1975) indicated that the Pittsburgh coal, which lies roughly 45 to 60 m below the surface, has been mined in this area. Logically, loading earth material onto the original surface could cause collapse of the undermined strata, which would induce slope instability. Finally, apparently, the surface runoff is not controlled but is allowed to drain toward the main area of slumping.

U.S. 30–PENNSYLVANIA RTE. 48 AREA, EASTERN ALLEGHENY COUNTY

In the area of U.S. 30 and Pennsylvania Rte. 48 shopping-center parking lot on the northeast corner of the intersection, North Versailles Township, eastern Allegheny County (pl. 7, fig. 2; fig. 19, loc. 3; Davies, 1974h), an extensive slump took place shortly after the shopping center was built that carried away the eastern part of the parking lot, or more than 50,000 m^3 of fill. Montgomery (1975, p. 31) included an outstanding ground photograph of the slide taken soon after the slumping. Attempts to rebuild the parking area have resulted in renewed movement. In places, ponded water is present near the eastern edge of the landslide area. The base of the fill was emplaced on the generally incompetent red and nonred mudstone and shale section of the lower part of the Casselman Formation.

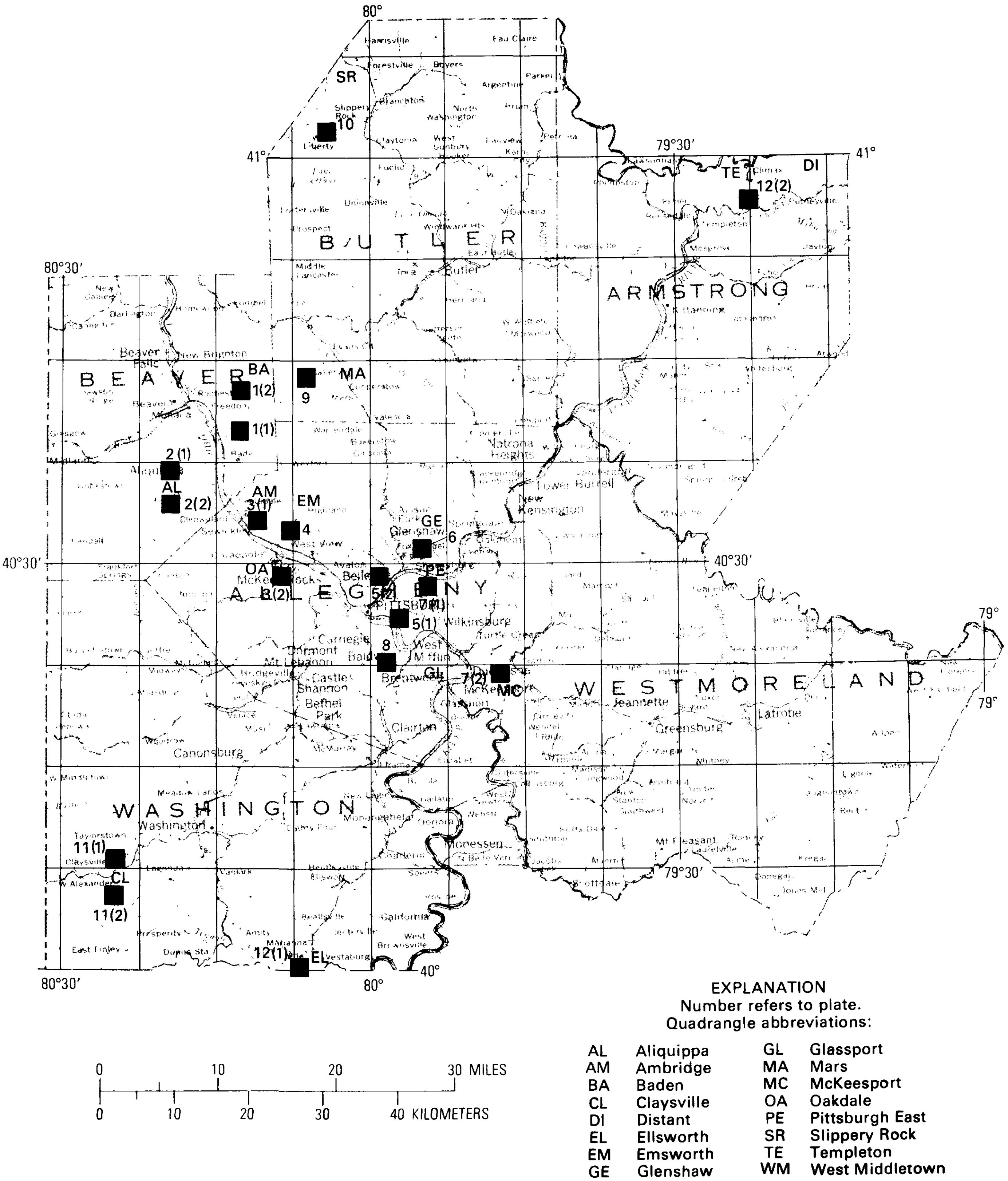


FIGURE 20.—Index map indicating locations of areas shown in plates 1–12.

FALLEN TIMBER RUN AREA, SOUTHEASTERN ALLEGHENY COUNTY

In the Fallen Timber Run area, Elizabeth Township, about 1.0 km southeast of the Monongahela River, southern Allegheny County (fig. 19, loc. 4), houses at the top of the slope on the northeast side of the valley may be in danger from a complex slope failure, according to Briggs and others (1975, p. 16). In mid-1974, no conspicuous structural damage to any house was apparent, but at least one house appeared to be moving because the owner had releveled appliances several times. Backyards constructed on fill have slumped, and escarpments and cracks in soil have resulted. Cracks as much as 3 m wide, 9 m deep, and several tens of meters long have opened in soil and rock on the slope between the houses and the valley. Earth material was encroaching on buildings in the valley, and, as of 1977, several governmental agencies were investigating this area. Studies included periodic use of precision surveying instruments to measure displacements. Because the nature and the extent of this landslide are not yet clearly known, the area is indicated as a prehistoric landslide on which recent landslides have been superimposed (Davies, 1974g; Pomeroy and Davies, 1975). The area is underlain by "red" and "nonred beds" of the Casselman Formation.

BRILLIANT CUT, PITTSBURGH

The slump at Brilliant Cut, Pittsburgh, about 0.7 km east of Highland Park Bridge, Allegheny County (fig. 19, loc. 5; pl. 7, fig. 1), which took place in 1941, can be attributed to the introduction of water through open joints. As a result, movement took place along a failure plane that had formed in mixed "red" and "nonred beds" in the upper part of the Glenshaw Formation. Like the Brady Bend landslide, it is an example of a slide in bedrock.

The slide is well documented by Ackenheil (1954) and Hamel (1970, p. 119; 1972). During the early 1930's, landslides took place after extensive lower slope excavation was made during the construction of a boulevard and the relocation of railroad tracks. A 0.3 m-wide fissure along the rest of the hill was filled with concrete grout, but, by 1940, the joint had reopened. During the spring of 1941, the slope moved with a backward and downward rotation; as a result, more than 80,000 m^3 of rock blocked the Pennsylvania Railroad tracks. Contributing causes were probably precipitation that was somewhat above normal and a sudden thaw during the previous week. The probable role of railroad-traffic vibrations, which might have led to continued opening of the joint after initial grouting, cannot be discounted. Valley stress release has created tension and has led to the formation of major joints. Correctional work resulting in benching and removal of rock waste has obscured all semblance of a former landslide area.

LAWNWOOD AVENUE, PITTSBURGH

A slide in fill at Lawnwood Avenue, Brentwood and Baldwin Boroughs, Pittsburgh, Allegheny County (pl. 8; figs. 14*A*, *B*; 19, loc. 6) has resulted in the destruction of three houses and damage to a fourth. The houses were built in the 1960's; footings were placed in fill, and backyards were built up by adding more fill. Backyards slumped shortly after the houses were completed. The backyards were built up again, but further movement took place. By June 1972, two houses were so damaged that they were abandoned, and subsequently the structures collapsed. The third house was evacuated in February 1974 when the backwall began to collapse. By early 1975, the entire structure had been razed to avoid possible accidents. The fourth house had no apparent structural damage and was still occupied in 1977. However, slumping in the side yard and part of the backyard had exposed part of the foundation and undermined the concrete slab parking area. Behind the house, the large trees that are inclined strongly downslope indicate creep. The Pittsburgh coal bed has been mined out less than 35 m below the head scarp of the slide, and mine drainage is evident at the foot of the slide. Lubrication from mine waters and an overdip slope situation may be factors (Craft, 1974a), even though the dip is less than 1°.

BIGELOW BOULEVARD, PITTSBURGH

Ackenheil (1954) gave a detailed account of the famous slide at Bigelow Boulevard, Pittsburgh, in line with 24th Street, southeast of the Allegheny River, Allegheny County (fig. 19, loc. 7). General G. W. Goethals (of Panama Canal fame), when asked what could be done to remedy that landslide, is reputed to have answered, "Let'er slide."

The boulevard was constructed in 1896, and fill was used at that time. Subsequent earth movements and further fill emplacements were made between 1896 and 1920. In 1920, filling the head of a ravine was started to eliminate a sharp curve. In late 1920, a landslide formed and encroached onto the Pennsylvania Railroad yard at rates as fast as 30 cm per hour. More than 150,000 m^3 of material was moved, and damage was $800,000. The "Pittsburgh red beds" of the Glenshaw Formation crop out at the railroad level, and the "Clarksburg" and underlying minor "red beds" of the Casselman Formation are exposed along the steep slope. Clearly, the ravine concentrated surface runoff over the inherently weak largely red-bed slope. Goethals' analysis (Ackenheil, 1954, p. 75) pointed out the saturated condition of the fill that was caused by the lack of proper drainage, in addition to overloading of the bank in the past. Ackenheil

(1954, p. 76) called it a debris flow on the basis of a lack of a definite slippage plane. The fill was clayey (despite considerable sandy shale, siltstone, and sandstone) and, when saturated, became very unstable.

KILBUCK DRIVE-MARSHALL ROAD AREA, PITTSBURGH

The head and the toe of a large earthflow in the vicinity of Kilbuck Drive and Marshall Road, Riverview Park area, Pittsburgh, Allegheny County (figs. 15*A*, *B*; 19, loc. 8) can be viewed from two locations. The toe of an active slide just opposite the maintenance office for Riverview Park has encroached on the road at various times since 1973 (fig. 15*A*). The "Pittsburgh red beds" underlie the lower half of the slope. A conspicuous rock exposure, about 100 m to the southwest along Kilbuck Drive, dips moderately toward the slope and suggests an old slump block because the regional dip is less than 1°. The exposure is inferred to have moved downslope during an earlier (prehistoric) mass movement.

The head of the landslide is immediately adjacent to the cantilevered apartment complex on the ridge above and can be viewed best from the north end of the apartment complex parking lot (fig. 15*B*). A sequence of "red" and "nonred bed" mudstones of the Casselman Formation underlies the upper slope. Steel bracing has been emplaced to safeguard the foundation wall of the upper apartment building, probably in response to interior wall cracking in the laundry utility space on ground level. At the east end of the lower apartment building, the outermost pier is out of plumb (1-2°), suggesting the influence of slope movement. Beneath the rear overhang at the southernmost building are small tension cracks at the headward edge of another landslide. Immediately north and south of the apartment complex in adjacent concave-shaped tributary valleys are larger older landslides that contain recently activated smaller slides.

BALDWIN ROAD AREA, WESTERN ALLEGHENY COUNTY

On the northwest side of Baldwin Road, Robinson Township, about 0.4 km north of Penn-Lincoln Parkway, "Parkway West," western Allegheny County (figs. 16*D*; 19, loc. 9), along the southeast side of the condominium complex, an oversteepened fill slope shows incipient slumping and small earthflows. Brick walls of some units of the complex are cracked, and minor slumping forced removal of back porches of several units. Downspout additions were emplaced to direct rain runoff, a possible factor in the landsliding, away from the foundations. A concrete retaining wall at another location in the complex showed failure in 1975 (Briggs and others, 1975, p. 13). The Pittsburgh coal bed is at slightly below the level of the lowest buildings of the complex, and the coal has been mined out. Many factors, including possible mine subsidence, unstable soil, poor surface drainage, incipient landsliding, and oversteepening of fill slopes in a highly modified landscape have caused costly maintenance problems.

INTERSTATE 79, WESTERN ALLEGHENY COUNTY

In 1968, construction of I-79 north of the Ohio River and Glenfield, western Allegheny County (pl. 4; figs. 14*C*, *D*; 19, loc. 10), resulted in excavation of the toe and reactivation of unrecognized colluvial older landslides derived largely from the "Pittsburgh red beds" of the Glenshaw Formation. Small sections of various parts of the slope above I-79 remain active today. Hamel and Flint (1969, 1972) and Hamel (1970, p. 155-200; 1978, p. 10) described and analyzed several landslides above the route. Significant summary statements of their investigations are:

1. Detailed mapping has demonstrated a close correlation between the weak claystone zone ("Pittsburgh red beds") and hillside benches.
2. Slumping during the I-79 construction took place at the site of these benches.
3. Evidence indicates that old slump masses (all colluvium) were reactivated by the construction.
4. Movements in the ancient slides reduced the shear strength along these failure surfaces to residual values.
5. Cut slopes in the colluvium (excavated at an inclination of 39°) were too steep for the combination of low shear strength and high ground-water levels existing on the slope.
6. Expandable-lattice clay minerals in shear-zone materials from interstate cuts appear to be a significant factor in the landsliding. They may form secondarily as a result of water seepage along ancient shear zones.
7. Deep-seated ancient landsliding may have involved a relation between bedding plane shear zones and valley stress-relief joints.

The slope on the east side of the highway from Glenfield to 2.5 km northward to the first bend in the road has been extensively modified (including benching) since the landsliding began. Vestiges of recent landslides are still apparent; renewed mass movement is in evidence. Retrogressive upslope movement in the form of large tension cracks is apparent in silty sandstone at several head scarps. One of the most conspicuous earthflows in the Greater Pittsburgh area is 0.2 km west of I-79 and about 1.5 km north of the Ohio River (Briggs and others, 1975, p. 7). Relocation of an alternate route that resulted in the excavation of the foot area of an older landslide may have triggered the earthflow.

SEWICKLEY WATERWORKS AREA, WESTERN ALLEGHENY COUNTY

Two landslides in the Sewickley Waterworks area, Nevin Avenue and Waterworks Road, Sewickley Borough, western Allegheny County (fig. 19, loc. 11; pl. 3, fig. 1), one in 1973 and a larger one in 1940 that was documented by Ackenheil (1954, p. 78), offer the opportunity to compare the characteristics (such as surface expression and vegetation) of a recent slide with those of an "older" recent slide. The base of the more recent landslide on the south wall of the valley near the westernmost impoundment is 30 m below the head scarp, which is in thin red mudstone colluvium at the edge of an upper road. Waterworks personnel reported that the slide took place during summer 1973 after heavy rains. Drainage on the upper road was investigated by the author in late 1973 and was found to be inadequate allowing infiltration of runoff into the slide area. An exposure of red mudstone ("Pittsburgh red beds" of the Glenshaw Formation) above the head scarp dips 15° to the southwest and represents slumped material from an ancient landslide deposit. Old landslide areas along both valley slides show hummocky lower slopes and typically thick colluvial deposits. The "Pittsburgh red beds" lie below the 1,000-foot contour where benching is present and are largely slumped and masked by colluvium.

The 1940 slide on the north side of the valley just upstream from the same impoundment measures approximately 230 m wide by 150 m long and is best described as a combination soil slump-earthflow. The toe crushed the sidewalls of a reservoir, severed pipelines, and laterally displaced Waterworks Road (Ackenheil, 1954, p. 78). Overloading of the "Pittsburgh red-beds" slope with sandstone-quarry waste was compounded by an unusually large amount of precipitation for that day, as well as for the previous week and month. The combined surcharging caused a slide that affected an estimated 250,000 m^3 of material. The slide clearly demonstrates the effects of unusually heavy rainfall combined with man's modification of an unstable slope.

The sandstone rubble covering the slope is extensive. In December 1973, I observed dense misty patches caused by warm-air exhalations into colder winter air and interpreted these patches to be a largely early-morning phenomenon that indicates the existence of extensive interconnecting cavities in the landslide mass. They are of environmental significance because heavy rains could saturate these permeable deposits resting on an impermeable clayey surface ("Pittsburgh red beds") and trigger further downslope movement.

AMBRIDGE HEIGHTS, SOUTHEASTERN BEAVER COUNTY

The entire slope area below Ridge Road, Ambridge Heights, Harmony Township, southeastern Beaver County (fig. 19, loc. 12), has been subject to extensive soil (colluvial) movements in the geologic past and has been sensitive to localized land-use changes in recent years. Note the well-defined concave slopes (fig. 19, loc. 12) south and southeast of Ridge Road.

Fill was emplaced for a backyard behind an established older house at the head of an old landslide. The placement of poorly compacted fill on an already inherently weak slope caused a debris slide that surcharged the lower slope underlain by the "Pittsburgh red beds" of the Glenshaw Formation (fig. 12*B*).

A larger older landslide deposit (roughly 0.3 by 0.3 km in area) is immediately adjacent to the southwest. Active slumping and accelerated soil creep have forced razing of two houses and threaten dwellings at the base of the slope.

Drainage appears to be a major factor. According to Jesse Craft (Pennsylvania Geological Survey, oral commun., 1975), a storm-drain control system along Ridge Road is needed to carry the water away from the hillside so that the surface runoff cannot freely flow over the unstable slope below. Geologic structure is possibly a factor because the area is along a synclinal axis plunging southward.

RACCOON CREEK AREA, SOUTHERN BEAVER COUNTY

Slumping in the Raccoon Creek area, east of Pennsylvania Rte. 60, Center Township, southern Beaver County (fig. 19, loc. 13; pl. 2, fig. 1), has been taking place recently on a colluvial slope along a 0.6-km stretch of abandoned road. Also, debris slides are numerous above the sharp bend in the creek near the transmission line northeast of the slumped areas. Several areas in Beaver and Butler Counties that are susceptible to landslides are along slopes underlain by the uppermost units of the Allegheny Group, and, in this area, the sliding plane is probably closely related to the Upper Freeport coal underclay. Red beds are not present anywhere in the section.

PENNSYLVANIA RTE. 51, NORTHERN BEAVER COUNTY

Near Pennsylvania Rte. 51 on the east slope 0.3 km north of Brady Run Park entrance, Patterson Township, northern Beaver County, is one of the largest recent landslide areas (approximately 200 m long by 120 m wide) in the county (Pomeroy, 1978d). The head of the slide area is at the abandoned road along the upper part of the slope. Slippage possibly has taken place in a weathered underclay or claystone horizon in the Allegheny Group, and, again, as at the Raccoon Creek area, red beds do not make up the clayey to silty colluvium. This part of the Brady Run area is one of the sections that is more highly susceptible to landsliding in northern Beaver County owing to several extensive colluvial slope areas.

RACCOON CREEK STATE PARK, SOUTHERN BEAVER COUNTY

In Raccoon Creek State Park, Hanover Township, southern Beaver County (fig. 19, loc. 15), the hummocky lower parts of the slopes throughout the park area are underlain by the "Pittsburgh red beds" of the Glenshaw Formation. Recent slides and vestiges of "older" recent slides, most common along 25-35 percent slopes, are conspicuous along the road rimming the north side of the dam area. Well-defined old slides are present along Traverse and Little Service Creeks west and northwest of the dam area.

INTERSTATE 79, SOUTHWESTERN BUTLER COUNTY

Near I-79, Cranberry Township, 6 km north of the Allegheny County boundary, southwestern Butler County (fig. 19, loc. 16), a relatively fresh arcuate-shaped landform on the east side of the highway spanning approximately 140 m at its maximum width is clearly discernible on the aerial photographs (pl. 9). A rock-cut bench between the highway and the cirquelike feature suggested a massive slope failure during or shortly after construction of I-79. Neil Hawks (Pennsylvania Department of Transportation, Indiana, Pa., oral commun., 1977) later confirmed that failure of the slope took place during highway construction in the summer of 1968. Field inspection indicated a complete renovation of the slope area, and substantial removal of red soil and rock from the "Pittsburgh red-beds" sequence of the Glenshaw Formation. In this massive slide, more than 500,000 m^3 of rock and colluvium were moved; the slide is exceptional because of its immense size and because the head of the movement extended into bedrock. Preconstruction aerial photographs reveal that the recent slide area is part of an old landslide.

PENNSYLVANIA RTE. 8 AREA, SOUTHERN BUTLER COUNTY

In an area east of Pennsylvania Rte. 8, Penn and Middlesex Townships, 2.3 km north of Glade Mills, southern Butler County (fig. 19, loc. 17), minor mass movement has been taking place in the vicinity of a new mobile-home community north of the east-trending road just inside the Penn Township border. As of early 1977, soil slips were evident at the east end of the development itself. Larger slides have taken place above the Middlesex church parking lot and along the road east of the church on both sides of the drainage divide. Red clayey soils derived from the "Pittsburgh red beds" of the Glenshaw Formation are highly susceptible to sliding and dominate the slopes of this hilly area where ancient landslides are part of the landscape. As development in southern Butler County continues, houses, no doubt, will be built on hilly areas that afford scenic vistas. Proper engineering and judicious control of land use in these sensitive areas can check the threat of soil movement on slopes.

HANLIN STATION AREA, NORTHWESTERN WASHINGTON COUNTY

Two areas of extensive mass movement are present immediately northeast of the settlement in the Hanlin Station area, Hanover Township, northwestern Washington County (figs. 9*A*; 19, loc. 18), and 1 km to the west. The Pittsburgh coal has been stripped from both areas where it was present close to the hilltops (1,100-foot contour shown on map, fig. 19). The landslides take place along largely colluvial slopes underlain by red mudstone of the Casselman Formation or along the coal spoil banks themselves and their regraded areas. The practice of surcharging the slopes with mine waste compounds the ingrained weakness of the weathered slope material, which makes it sensitive to hastily constructed access roads.

PROSPERITY AREA, SOUTHWESTERN WASHINGTON COUNTY

Earthflows dominate the slopes in the Prosperity area, Morris Township, southwestern Washington County (fig. 19, loc. 19), and the slopes of the south-central part of the county. A suggested 9-km road traverse from Prosperity affords an excellent view of recent and older earthflows where one can evaluate various landslide factors, such as slope grade, orientation or aspect, morphology, topographic form, and relative size. Although most slides take place in concave-shaped areas, a few are found on noses of slopes (convex) where a minimum of colluvium would be expected. The Greene Formation underlies the slopes except for the lowermost slopes in the immediate vicinity of Prosperity. The average slope on which sliding has taken place is roughly 20-35 percent.

LANDSLIDE STATISTICS

Statistical data on the characteristics of landslides are useful in determining landslide-risk assessments. The various factors that are considered are the slope (grade and orientation), morphology and topographic setting, size, strip-mining-related slides, underlying stratigraphic unit, and recent and older slides (figs. 21, 22), all of which were used by Lessing and others (1976).

SLOPE

A study of slope characteristics of recent landslides was made for selected quadrangles in the region. More than 75 percent of the landslides took place on slopes that have 20-35 percent grade; slides were less common on slopes of less than 20 percent grade, and rare on those of less than 15 percent (fig. 7). Earthflows seldom take place on slopes where grade exceeds 35 percent, but

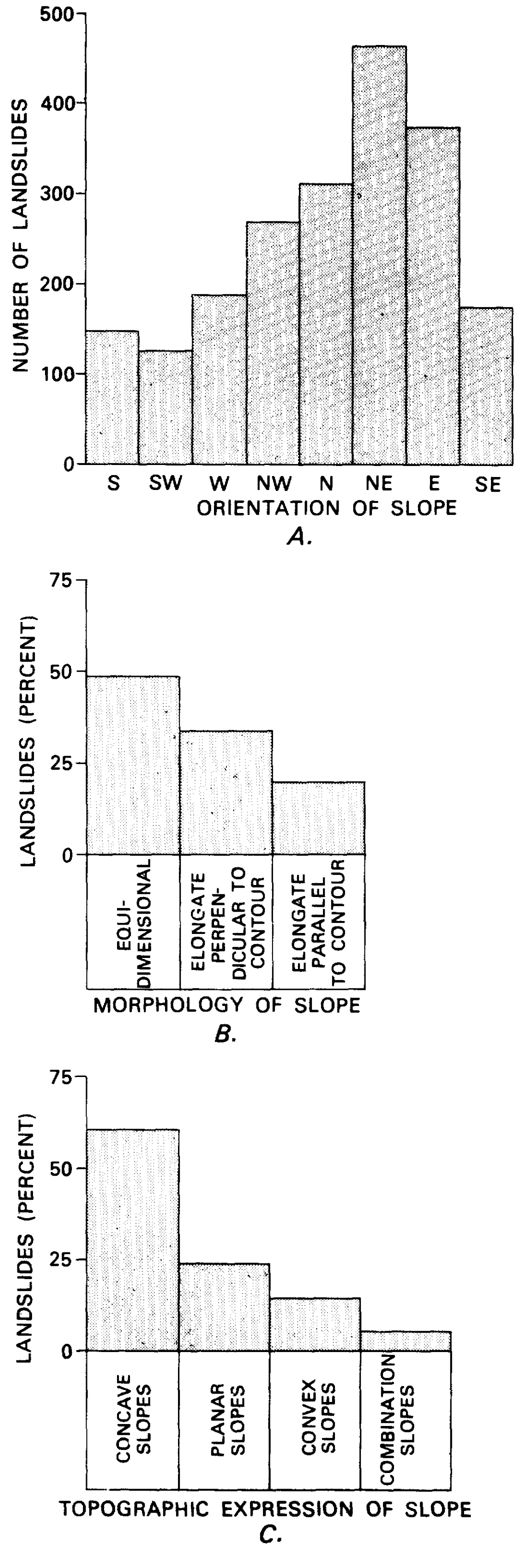


FIGURE 21.—Statistical data comparing orientation, morphology, and topographic expression of slopes in areas of Washington County where recent landslides have taken place. *A*, Distribution of 2,032 recent landslides by orientation of slope. *B*, Percentage of 1,350 recent landslides classed by morphology and *C*, topographic expression of slope.

debris slides along highway cuts and deeply incised drainages are common on slopes where grade exceeds 50 percent. Approximately 90 percent of the slides in the Pittsburgh West quadrangle (Pomeroy, 1977b; U.S. Geological Survey, 1975) took place on slopes where grade was more than 25 percent, and about 10 percent on slopes where grade was 15–25 percent.

Because of the high density of landslides in much of Washington County, the orientation of recent and older slides was sampled from selected areas in five quadrangles. The study showed that approximately 33 percent of the slides took place on northeast- and east-facing slopes. A more comprehensive inventory of more than 2,000 recent slides in Washington County revealed that a larger percentage (41 percent) took place on slopes facing these two directions and that 69 percent of the slides took place on northeast-, east-, north-, and northwest-facing slopes (fig. 21*A*). North-facing slopes receive less exposure to the sun, and, after a rain, soils there remain wet longer than soils on south-facing slopes. East-facing slopes, of course, receive insolation in the early morning, but the drying effect on these soils is small because of the lower temperatures at that time of the day; this explains, at least in part, the high incidence of slides on east-facing slopes. Snow cover, obviously, lingers longest on slopes facing northwest, north, northeast, and east.

Beaty (1956) stated that a careful examination of the literature failed to reveal any information regarding the relation of landslide occurrence to slope orientation. In the past 20 years, this situation has improved just slightly. The direction of movement is not cited in most landslide reports possibly, in part, because of a lack of an obvious trend shown in the few landslides that may be present in any given area. Recently, inventory studies of landslides in Italy (Carrara and Merenda, 1976) and Czechoslovakia (Pašek, 1975) cited the orientation factor.

Lessing and others (1976) mentioned that no preferred orientation of slopes was obvious in 100 landslides in West Virginia. However, a close examination of their orientation graph (p. 37) shows that the slopes having the most landslides are those facing northeast, east, and northwest.

Van Buskirk (1977) stated that north-facing slopes are more apt to be less stable than are south-facing slopes in the glaciated region of northeastern Ohio. Beaty (1956) determined that 70 percent of the slightly more than 100 slides he examined in an area east of San Francisco Bay were on northwest, north, northeast, or east slopes—a result practically identical with that of the Washington County inventory despite Beaty's smaller sampling. Harden (1976) found that most landslides near Aspen, Colo., are on east-facing slopes of north-trending valleys and on north-facing slopes of

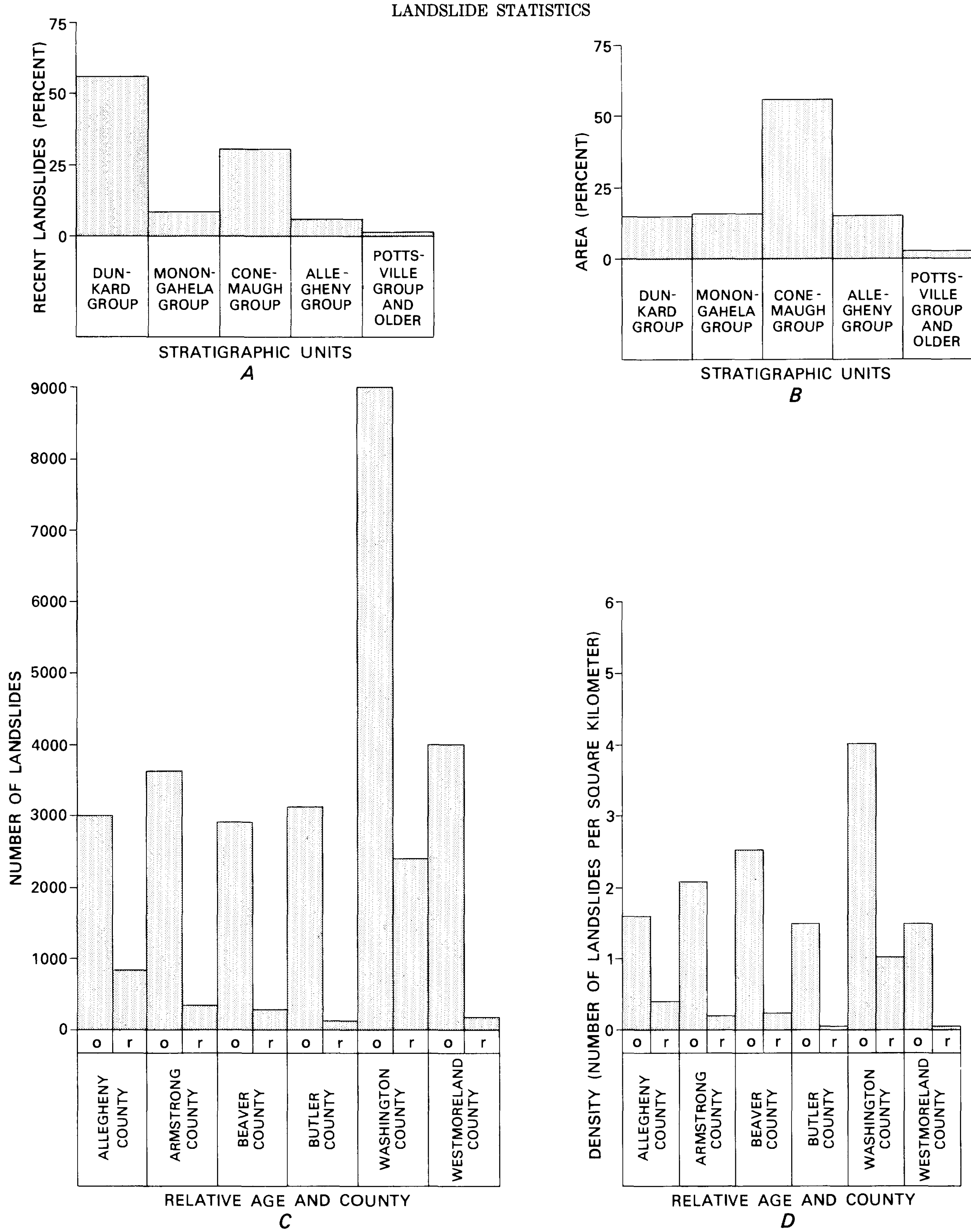


FIGURE 22.—Statistical data related to stratigraphic units and relative age and density of landslides, excluding strip-mine spoil-bank slides, in the Greater Pittsburgh region. (Caution must be applied because of the smaller scale reconnaissance in Westmoreland and Armstrong Counties (see "Present investigations and methodology").) *A*, Distribution of landslides by stratigraphic units. *B*, Areal distribution of stratigraphic units. *C*, Distribution of number of landslides by relative age (o, older; r, recent) and by county. *D*, Areal density of older and recent landslides by county.

east-trending valleys and concluded that the abundance of slides on these slopes and the sparsity of slides on southwest-facing slopes are related to soil-moisture regimes of the respective slopes. Colton and Holligan (1977) reported that south-facing slopes are more stable than equally steep north-facing slopes because the higher rate of evaporation causes the south-facing slopes to be drier.

Slope gradients are generally steeper along north-facing slopes in many areas within the Greater Pittsburgh region. This characteristic, coupled with the increased soil moisture of north-facing slopes, contributes to a less stable environment.

MORPHOLOGY AND TOPOGRAPHIC SETTING

Sampling of 1,350 recent slides from five quadrangles in Washington County formed the basis for this study (fig. 21*B*, *C*). In summary, nearly 50 percent of the landslides were approximately equidimensional, about 33 percent were elongated perpendicular to the contour, and nearly 20 percent were elongated parallel to the contour. Approximately 60 percent of the slides from the sampled area were on concave slopes, less than 25 percent on roughly planar slopes, about 12 percent on convex surfaces, and less than 5 percent on a combination of planar, concave, and convex slopes. Lessing and others (1976, p. 36) found that 69 percent of the slides that they sampled were along concave slopes. Waltz (1971) discussed the significance of concave and convex slopes in relation to landsliding in the San Francisco Bay area and concluded that landslides are less common where the slope is relatively convex, both downslope and across slope.

SIZE

The average recent landslide in the region is too small to be seen on 1:24,000-scale aerial photographs. Furthermore, most recent landslides seen along the road are too small to be shown on 1:24,000-scale maps.

Ackenheil (1954, pl. 1) recorded the volumes of materials involved in 79 recent landslides in Allegheny County. Although they ranged from 1 to nearly 300,000 m^3 and averaged about 14,000 m^3, roughly 70 percent were less than 765 m^3. Most landslides in the Greater Pittsburgh region were less than 200 m^3 in volume. Landslides commonly range from a few meters to 30 m in width, and the horizontal distance from the main scarp to the landslide toe is commonly less than 60 m.

Old slide areas as wide as several kilometers are present throughout the Greater Pittsburgh area. (Pomeroy, 1977e, 1978b; Pomeroy and Davies, 1975). However, because most of these designated older landslides do not represent single events but are accumulations of landslide deposits originating in the Pleistocene and continuing into historic time, the size of individual ancient landslides is extremely variable and is difficult to determine for statistical purposes.

STRIP-MINING-RELATED SLIDES

Most slides related to strip mining are those along spoil banks, and, less commonly, along reclaimed (regraded) land. Less than 2 percent are related to soil falls or debris slides cascading over the highwall, generally on a concave slope. Not included in this category are strip-mine access-road slides.

Armstrong County has the greatest percentage of slides related to strip mining (68 percent); next highest is Butler County (41 percent). Less than 10 percent of the landslides in the other four counties are due to mining activities. Overall, 10 percent of all recent slides in the Greater Pittsburgh region are related to strip mining.

STRATIGRAPHIC UNIT

The greatest number of landslides (56 percent) are on slopes underlain by the Dunkard Group (fig. 22*A*), even though this stratigraphic unit crops out in less than 15 percent of the Greater Pittsburgh region (mostly Washington County) (fig. 2). Soils derived from the Greene Formation show the highest density of recent landslides (2.4/km^2), as contrasted with soils derived from the Waynesburg and Washington Formations, which show a lower density (1.0/km^2). The two main factors involved are the higher percentage of clay-rich mudstone in the Greene Formation and steeper slope angles.

Approximately 30 percent of landslides take place along slopes underlain by the Conemaugh Group (fig. 22*A*), which is the immediate underlying unit for more than 50 percent of the region (fig. 22*B*). Although the Conemaugh is the dominant stratigraphic unit in Armstrong and Butler Counties, less than half the slides that are not related to coal mining take place on its slopes there. In these two counties, the moderate upper slopes are underlain generally by the Conemaugh Group, in contrast to the steeper lower slopes, which are underlain generally by the Allegheny Group. Despite the widespread occurrence of the Conemaugh Group throughout the Greater Pittsburgh region, only on slopes underlain by the red-bed sequences do significant problems exist (Allegheny, southeastern Beaver, and northwestern Westmoreland Counties).

RECENT AND OLDER SLIDES

Figure 22*C* shows that Washington County had the greatest number of recent landslides and that Allegheny County had the next highest. However, the ubiquitous earthflows of Washington County take place largely in a rural setting and cause less damage than landslides in highly urbanized Allegheny County. Density of recent landslides (per square kilometer) is also highest in Washington County; density is second highest in Allegheny County (fig. 22*D*). Butler and Westmoreland Counties have the lowest number of recent slides (incidence) as well as the lowest landslide density (fig. 22*C*, *D*). Although western Westmoreland County has many slides, most of the county, the largest in the Greater Pittsburgh region, has relatively few slides. On aerial photographs, both Westmoreland and Butler Counties also show the lowest density of old landslides (fig. 22*D*). The number of older landslides in Allegheny County seems relatively small (fig. 22*C*), but most of the central area of the county has undergone such extensive land-surface modification, as a part of the long-term urbanization, that landslides are difficult to recognize on aerial photographs.

The occurrence of recent and older landslides, slope characteristics, and the presence of unstable soils are elements that have been used in the preparation of a map showing relative susceptibility to landsliding (fig. 23). An incidence map (fig. 24) shows only locations of recent landslides. Rockfalls are not shown on either map.

OTHER CHARACTERISTICS

Approximately 12 percent of the interpreted old landslide deposits in five Washington County quadrangles have become reactivated to some extent. Renewed sliding is usually restricted to a small section of the old deposit. In areas outside the five sampled Washington County quadrangles, the recurrence rate is less than 3 percent.

The distance between landslide deposits varies throughout the region. In the same Washington County quadrangles, 98 percent of the slides (old and recent) are within 300 m of another slide. Conversely, in an area of considerably lower landslide density, such as in the Butler 7½-minute quadrangle, slightly less than two-thirds of the slides are within 300 m of another slide.

RECOGNITION OF LANDSLIDE AREAS ON AERIAL PHOTOGRAPHS

LITERATURE

Ta Liang (1952) prepared a comprehensive study of the use of aerial photographs in the interpretation of landslides in widely scattered geographical locations mostly within the United States. He included a few stereoscopic pairs that illustrate slope-stability problems in western Pennsylvania. Subsequent papers by Liang and Belcher (1958) and Belcher and others (1960) discussed landform interpretation of aerial photographic studies of landslide areas. Mollard (1952) included aerial photographs in his doctoral dissertation concerning landslides in the Bearpaw Shale of Saskatchewan. Massive landslide detection on small-scale aerial photographs in British Columbia was described by Dishaw (1967).

Watson (1971) used aerial photographs in formulating a hypothesis regarding mass movements on natural slopes in southern England. Norman and others (1975) analyzed the best photographic conditions for detecting landslides in England.

The use of aerial photographs in New Guinea to estimate the frequency of landsliding and the volumes and types of landslides, as well as their contribution to denudation, has been documented by Simonett and others (1970).

McKean (1977) successfully used the color-density slicer in detecting soil moisture and vegetation density changes along suspected unstable slopes in the Pierre Shale of north-central Colorado.

The advantages inherent in the application of both large- and small-scale color and color infrared photography in the detection of slope-failure forms are stated by Poole (1969).

The hypothesis that future debris slides are most likely to take place at the site of past slides was confirmed by the analysis of aerial photographs from an area in southern California (Kojan and others, 1972).

Systematic photointerpretative observations complemented by field studies were applied to the study and mapping of landslides triggered by an earthquake in Italy (Govi, 1977).

Comprehensive manuals on aerial photographic interpretation as related to geology by Ray (1960) and von Bandat (1962) include examples of landslide terrain. A significant contribution was made by Mollard (1976), who devoted one chapter of his terrain analysis of Canada to 66 stereopairs showing colluvial landforms, landslides, and a wide variety of related slope-instability features. Denny and others (1968) and Warren and others (1969) cited landslide examples from selected aerial photographs. Rib and Liang (1978) discussed remote-sensing techniques for landslide detection.

That the subject is a timely one was evident in the August 5, 1978, landslide workshop following the Second Circum-Pacific Energy and Mineral Resources Conference held at Honolulu, Hawaii. Instruction on recognition of landslides on aerial photographs and topographic maps (as well as the preparation of regional landslide inventories and landslide-susceptibility maps) was given at this workshop.

RECOGNITION CRITERIA

Liang (1952) and Liang and Belcher (1958) established several elements by which landslides could be recognized on aerial photographs. In the present investigation, these criteria were applied, and additional elements were formulated. Relatively young or recent

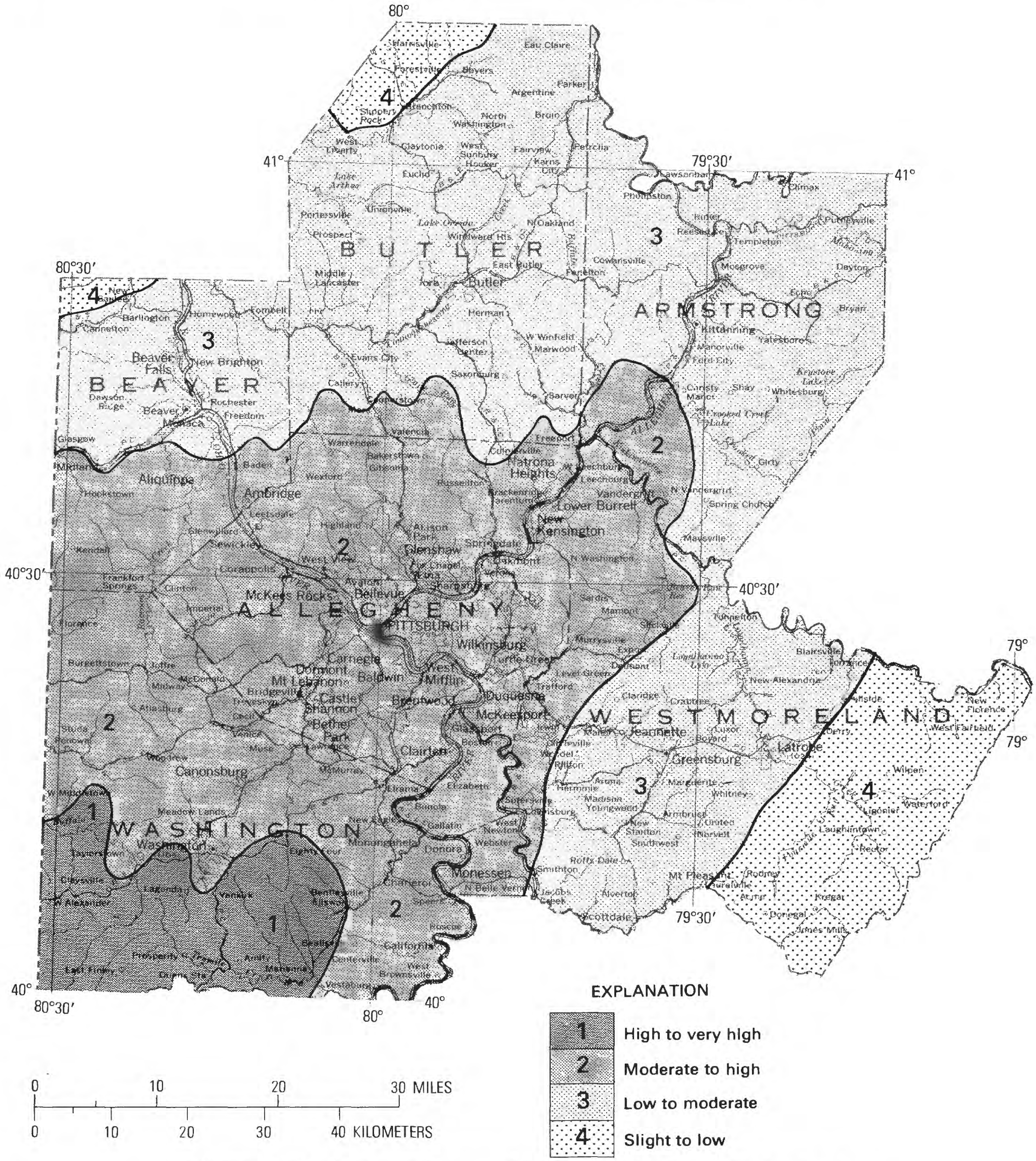


FIGURE 23.—Map showing relative susceptibility to landsliding, Greater Pittsburgh region.

landslides can be recognized by the following features:

1. Presence of an overall light-colored scar. Vegetation may not yet have grown over recent slides.
2. A sharp break (often arcuate) represented by the head scarp. Additional scarps below the head scarp may appear as steplike features on the aerial photographs.
3. Photographic tonal distinction between the landslide and the adjacent slope. Different tones may be due to vegetational differences and moisture, but care

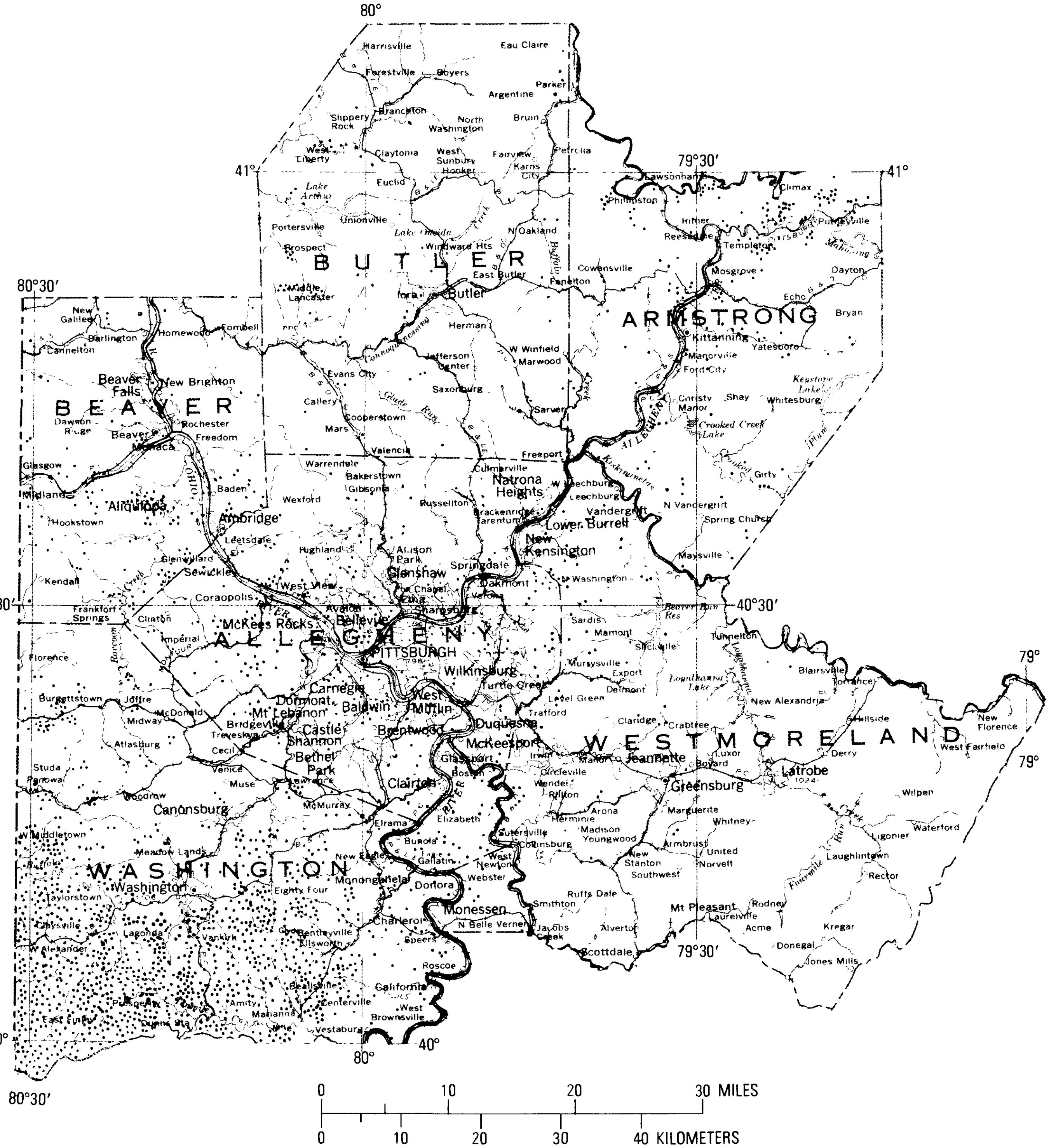


FIGURE 24.—Generalized map showing incidence of recent landslides, Greater Pittsburgh region. Each dot represents one landslide event.

must be exercised here. Although photographic tone in many unstable areas is lighter than in adjacent more stable areas because trees and shrubs are smaller, it might be darker owing to seepage zones.

4. Hummocky topography below the head scarp. This feature is a major recognition element because the hummocky surface is not likely to be extensively modified unless altered by man or subjected to catastrophic flooding.
5. Small ponded areas in the lower part of the landslide (pl. 2, fig. 2). Although in some places, wet ground may be due to water-line breakage, most poorly drained areas on landslide surfaces are due to impermeable clayey to silty earth material.

6. Lack of a well-defined drainage network anywhere on the surface of a landslide. The disturbed mass may show a haphazard drainage pattern, or the pattern may be concealed beneath the mass and reappear lower on a slope as seepage.
7. Tilted trees where the photo scale is larger than 1:12,000. At the head area, trees commonly lean back toward the slope, but, at the foot end, they may lean downhill. Disoriented trees leaning at appreciable angles and lacking preferred orientation might be seen throughout the slide mass. However, many trees on slopes tend to bend outward somewhat as they seek sunlight (phototropic response).
8. Appearance of manmade features. Roads may show a darker or lighter tonal pattern than adjacent sections because failure of the underlying slope has necessitated repatching of the repaved surface (pls. 2, fig. 1; 4, fig. 2). An abruptly terminated road along a slope may indicate a landslide. Some playgrounds and parking lots, commonly built on fill in urban areas, have been overextended along a planar slope or have been emplaced in heads of tributary valleys; the resulting failure is indicated by an abrupt head scarp (fig. 10*B*).
9. Anomalous constrictions in or rerouting of drainages. These are caused by earth movement damming the stream and diverting its course (pl. 12), especially along stream courses that make a sharp 90° turn instead of curving into the bank.

Older slides are less apparent on aerial photographs, but the recognition criteria are similar to some factors expressed above.

1. Hummocky ground surface, representing colluvial material from previous episodes of sliding, is clearly discernible in some places, but in others it may be difficult to recognize.
2. Slump benches, indicative of extensive ancient landsliding, are commonly identifiable (pls. 3, fig. 1; 5, fig. 2).
3. An abruptly terminated lower slope, as much as several meters in relief and representing the front of an old slide, is apparent in some places (figs. 11*D*; 13*B*, *C*).
4. A suggestion of the head scarp may be present (fig. 13*B*, *D*).
5. Well-defined surface drainage on older slides may or may not be the same as that on adjacent slopes.
6. In forested areas, tonal differences between the landslide and the more stable neighboring slope areas may be so gradational that differentiation is not possible. However, in several places, many dead or dying trees associated with a profusion of a junglelike growth of vines and brush reflect both poor drainage conditions and constant but slow soil movement (creep). Many such areas show lighter tones on aerial photographs than do surrounding environs and may be indicative of old landslide areas (pl. 1, fig. 2).
7. Bowl- or amphitheater-shaped upper slope areas, discussed earlier in the report (see "Slope Steepness and Configuration"), may have been formed by landslide processes. Because most landslides take place along concave slopes (see "Selected Landslide Localities"), recognition of these slopes is critical.

SUGGESTIONS RELATED TO AERIAL PHOTOGRAPHY AND LESSONS LEARNED

Photo scale, focal length of camera lens, optimum time for photography, and film type are factors that need clarification.

A photo scale of 1:12,000 or larger is necessary for detailed landslide studies in urban areas such as Pittsburgh. Recent landslides are generally small, and most cannot be identified on smaller scale 1:24,000 aerial photographs. However, the 1:24,000-scale photographs were generally adequate for delineating the more significant larger slides in the less urbanized counties surrounding Allegheny County and Pittsburgh.

Even at a 1:12,000 scale, many landslides in Allegheny County were apparent only during the field investigation and had not been discerned on the photographs because they were too small and lacked distinguishing characteristics. Generally, an experienced photointerpreter can identify landslides as small as 12 m in maximum extent on 1:12,000-scale photographs where a $\times$ 2 to $\times$ 4 magnifying stereoscope is used.

Some considerations regarding low-altitude aerial photography have to be weighed. The additional cost of larger scale photographs (if available) has to be seriously considered. For example, complete coverage in one Allegheny County quadrangle would require 27 photographs at 1:24,000 but 84 photographs at 1:12,000, resulting in greater cost and a considerable increase in interpretation time. Furthermore, the limited area covered in each photograph might cause the interpreter to lose perspective in comparing an affected area with adjacent parts of the slope. A smaller factor is the greater amount of space needed to store the photographs.

The determining factor, of course, is the purpose of the study—is it to be a regional or a one- or two-quadrangle study? Lessing and others (1976) found that vertical photographs at scales 1:20,000 to 1:30,000 were satisfactory for their landslide investigations in West Virginia.

The focal length of the camera lens is significant. Vertical exaggeration, which enables the interpreter to detect surface features that have a minimum of relief, is improved by the use of a shorter focal-length lens. Norman and others (1975) showed the advantage of a shorter focal-length lens on feature detectability at various scales. Note in plates 6 and 8 how the vertical exaggeration on the 1969 photographs (camera focal length of 305 mm) is less obvious than that of the later photographs (camera focal length of 152 mm) and how interpretation is affected.

Late winter-early spring (when no snow cover exists) or late fall is the best time for aerial photography because of the absence of tree foliage. Late-fall photography has its advantages and limitations. Significantly, north-facing slopes along deeply incised drainages are commonly in shadow, as seen in the early December 1975 photographs. However, north-facing slopes along moderately sloping upland surfaces clearly show earthflows of low relief owing to the low sun angle (pl. 11).

Norman and others (1975) indicated that the best technical photographs for detecting landslides are infrared color transparencies. Areas of high soil moisture should be detectable by dark tones on infrared color photographs. Unfortunately, experimentation with different types of film was not a part of the current project. The cost of color film, which is higher than that of black-and-white film, must be considered.

Observations made from the landslide inventory are:

1. The author considers the maps resulting from the investigations to be a conservative interpretation. More detailed mapping would reveal a considerably higher number of both recent and older landslides on the basis of selected foot traverses in several areas. Subtle expressions of older slumping in a relatively young forest were discovered at several levels along a few roughly planar slopes in Washington County where neither the topographic map nor the 1:24,000-scale photographs could be expected to reveal the details. Interpretations made from photographs of several forested slopes have wrongly indicated that slopes were devoid of old landslides. Therefore, further ground investigation in more areas of the Greater Pittsburgh region would result in the identification of additional ancient landslides, as well as small recent slides.
2. The available aerial photographs must be studied several times during the investigation. Interpreters have often found significant information as late as at final map compilation.
3. If other recent fall or spring aerial photographs exist for the area of interest, a few stereo pairs should be purchased to determine whether the cost of a complete set is justified.

STEREOSCOPIC PAIR ANALYSIS

Stereoscopic pairs have been used by Liang (1952), Liang and Belcher (1958), Dishaw (1967), Mollard (1976), and Burroughs and others (1976) in their discussion of landslides. In any study of vertical aerial photographs, the most clearly written explanation regarding recognition elements is no substitute for direct scrutiny of stereoscopic pairs. Mollard (1976, p. 1) pointed out that this "is particularly true when dealing with subtle distinguishing details of size, shape, and slope of relief forms, tonal, and drainage patterns, vegetation and land use. In landforms recognition, a description of such distinguishing characteristics is similar to the word description of a person without a photograph—it seldom permits recognition when the person is part of a large population."

The stereoscopic pairs shown in this paper (fig. 20) were selected from nearly 2,000 photographs used for the landslide mapping of the six counties in the Greater Pittsburgh area.

Emphasis in the following suite of stereoscopic pairs is on direct observation of subjects identified by letter symbols discussed on pages opposite those of the plates. Subtle features pertaining to landslide susceptibility have to be recognized and understood by geologists and engineers working in the area. I hope that a larger audience, including planners, teachers, and students, and Federal, State, and local officials, will be motivated to take a closer look at these examples.

GLOSSARY

Some of these definitions were taken, with little or no modification, from Gary and others (1972).

Atterberg limits.—Water-content boundaries between the semiliquid and plastic states (known as liquid limit) and between the plastic and semisolid states (known as plastic limit).

Claystone.—Indurated clay having the texture and composition of shale but lacking its fine lamination or fissility; a massive mudstone in which the clay predominates over silt. Most claystone is thin and seldom exceeds a few meters in thickness and includes underclay beneath a coal bed.

Colluvium.—Heterogeneous and incoherent mass of soil material or rock fragments deposited chiefly by mass wasting; usually most pronounced at the base of a steep slope but also higher up on the slope.

Mudstone.—Indurated mud having the texture and composition of shale but lacking its fine lamination or fissility; a blocky or massive fine-grained sedimentary rock in which the proportions of clay and silt are approximately the same; or a general term that should be used only where the amounts of clay and silt are not known or cannot be precisely identified. Mudstone is not as fine grained as claystone, is more abundant in the stratigraphic section, and has greater maximum thickness.

Overdip slope.—Land surface sloping in approximately the same direction as, but more steeply than, the dip of the rock layers that crop out on that surface.

Plasticity index.—Water-content range of a soil at which it is plastic, defined numerically as the liquid limit minus the plastic limit.

Shale.—Fine-grained indurated detrital sedimentary rock formed by the consolidation of clay, silt, or mud and characterized by finely stratified structure and (or) fissility that is approximately parallel to the bedding.

Shrink-swell potential.—Estimate of the soil's tendency to swell when wet and then shrink when drying. Plastic clays generally have a moderate to high shrink-swell potential.

Slaking.—Process by which a dried clayey earth material immersed in water disintegrates into a soft wet mass. Because of the unequal expansion of the soil as the water penetrates the mass, soil particles are flaked off. As water enters the air-filled pockets, the air is trapped, and air pressure builds up. The pocket eventually explodes, and the soil disintegrates.

Soil.—Material from rock weathered in place (residuum), as well as weathered material that has been moved downward and has accumulated along the slope.

Soil creep.—Gradual imperceptible downslope movement of soil in response to gravity.

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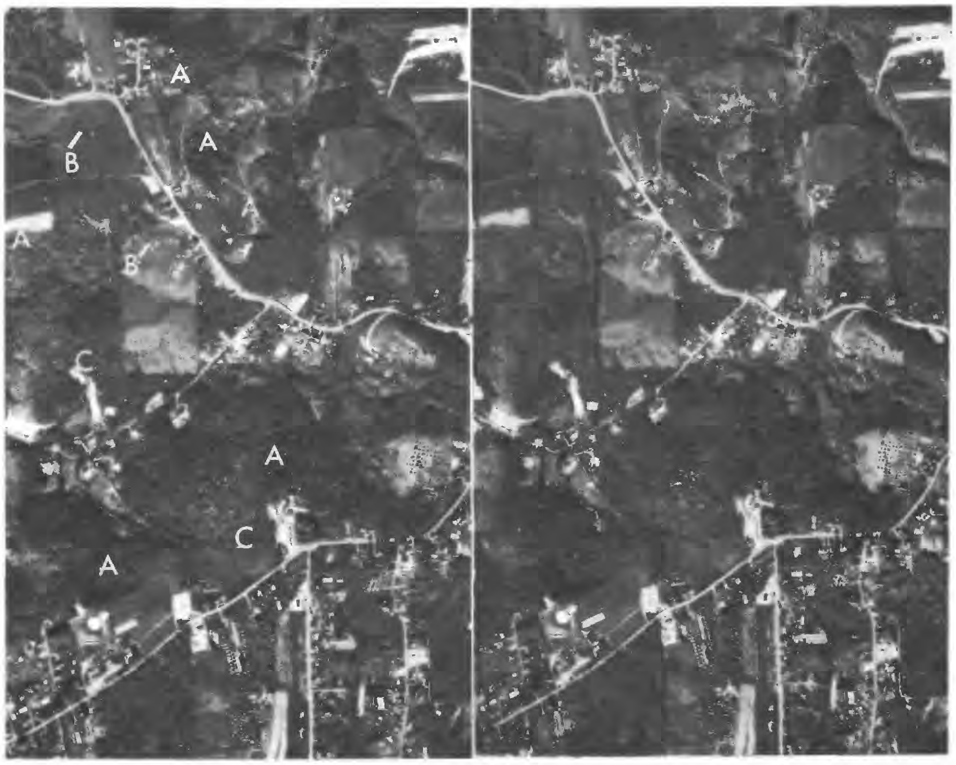
PLATES 1–12

Stereoscopic pairs of aerial photographs showing mass movement phenomena in selected areas (see fig. 20, index map).

PLATE 1

FIGURE 1. Conspicuous old landslides (A) are most readily identifiable north of major road on west side of model. These spooned-shaped areas are apparent even in the forested areas. Recent earthflows are present at B. Head scarp shows as a light-colored scar on the westernmost slide. Probable old landslides occupy C areas.
Geology: Largely Glenshaw Formation, "Pittsburgh red beds."
Location: Economy Township, southwest Baden 7½-minute quadrangle, Beaver County
Aerial photography: May 11, 1975 GS-VDWD, 1-97, 98, scale 1:24,000.

2. Old landslides are better defined at Big Knob (prominent hill in center of photograph). At A, conspicuous concave slopes or coves are apparent that have hummocky surfaces along lower slope on east and northeast sides of hill. Note relatively sparse tree growth on east and northeast sides of Big Knob. Vines, brush, and fallen trees in these colluvial areas indicate creep. Small unmappable reactivated patches of red soil at B. Note similarity of topography to that of a glaciated terrain (cirques, aretes).
Geology: Glenshaw Formation, "Pittsburgh red beds"; Casselman Formation.
Location: Big Knob, Sewickly Township, northwest Baden 7½-minute quadrangle, Beaver County.
Aerial photography: May 11, 1975, GS-VDWD, 1-100, 101, scale 1:24,000.



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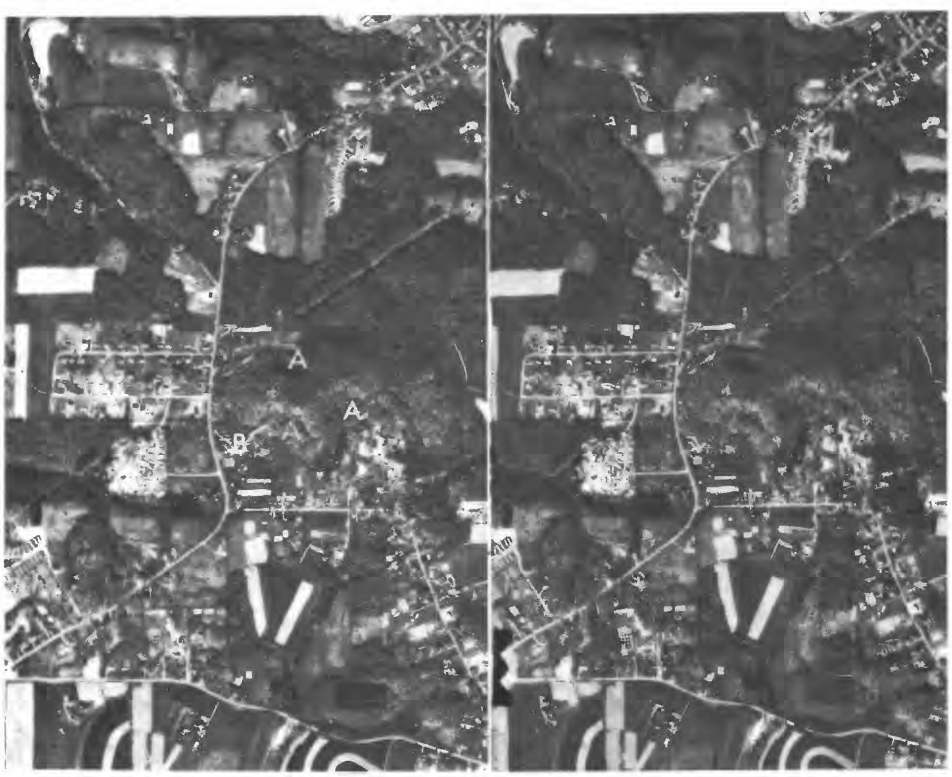

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PLATE 2

FIGURE 1. New highway necessitating cut and fill operations in area of small tributary valleys, recent sliding shown at cove A. Highway patches below cove indicate former fill failure. Wide colluvial slope B is suggestive of old landslide. Recent fill failure is apparent at C. Road above D is closed because of active slumping along lower colluvial slope. Unstable lower slope E, inherently weak because of stream erosion and cutting, has been subjected to recent sliding above and below road (note light-toned areas). Lack of significant vegetative cover at transmission line above E contributes to instability of colluvium. Entire slope area is part of old landslide deposit (F). Note toe (G) of an old slide (pre-highway) whose head is at H.

Geology: Glenshaw Formation mostly, lowermost slopes in Allegheny Group.

Location: Raccoon Creek-Pennsylvania Rte. 60 area, Center Township, west of Aliquippa, northern Aliquippa 7½-minute quadrangle, Beaver County.

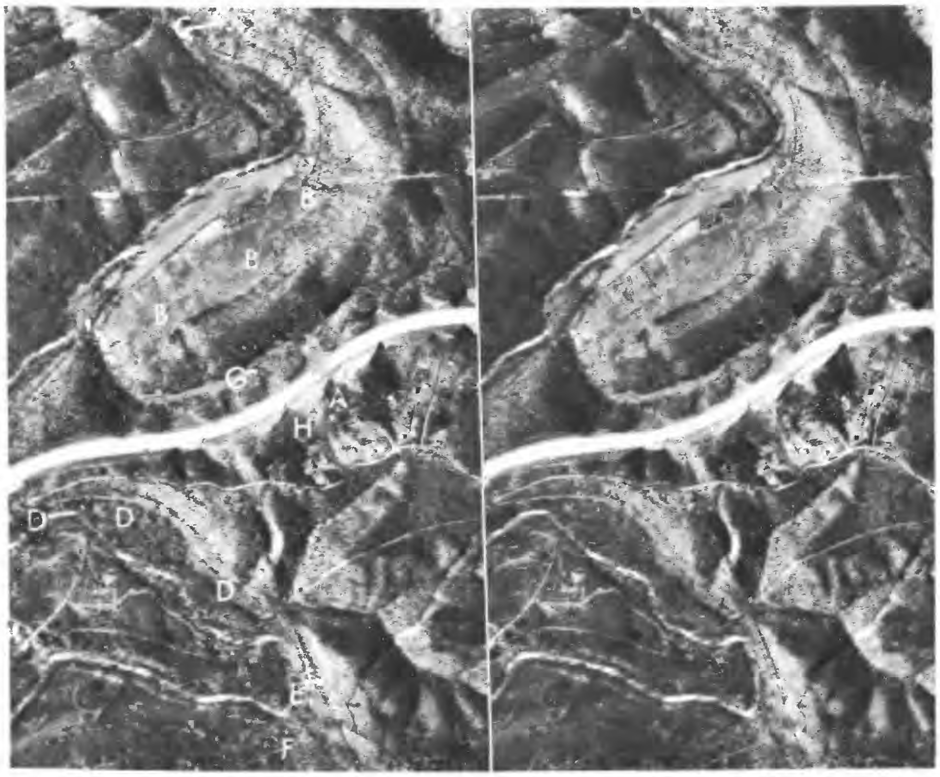
Aerial photography: December 5, 1975, GS-VDWD, 3-82, 83, scale 1:24,000.

FIGURE 2. Complex old landslide (A) is better viewed when illustration is rotated 180°. Several recent road shoulder failures (B) are above creek, older landslides (C) higher on slope. D is suggestive of a frontal lobe of an old landslide. Slope E shows slump features (small narrow terraces, ponded areas) below road. Ponded areas are difficult to discern on photos.

Geology: Glenshaw Formation mostly, upper slopes in Casselman Formation.

Location: Raccoon Creek-Independence area, Independence Township, Aliquippa 7½-minute quadrangle, Beaver County

Aerial photography: December 5, 1975, GS-VDWD, 3-79, 80, scale 1:24,000.



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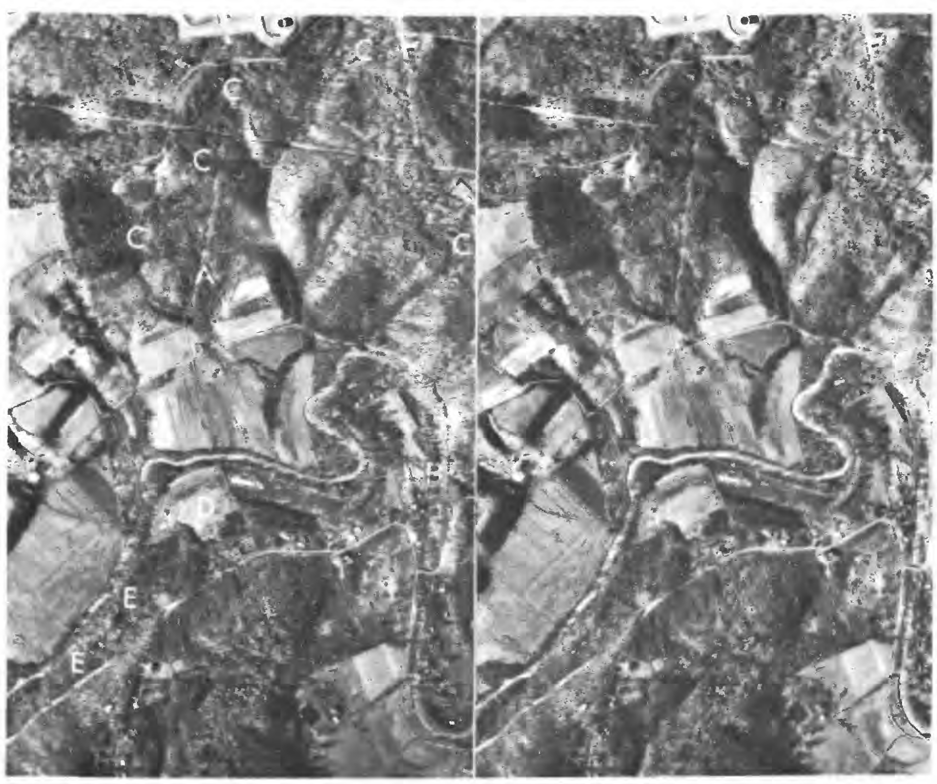

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PLATE 3

FIGURE 1. Arcuate scarp of 1940 landslide (Ackenheil, 1954) is evident at A. Slide extended to creek. B indicates site of former sandstone quarry operation. Mid-1973 slide (C) in part caused by inadequate drainage from access road upslope. Road was partly blocked at D until late 1973. Dwellings along slope E show effects of creep (out-of-plumb structures, broken concrete surfaces, etc.). F is the site of a fill failure. Slump benches at G are indicative of old landslides.

Geology: Glenshaw and Casselman Formations.

Location: East of Sewickley, Sewickley Heights and Aleppo Townships, southeast Ambridge 7½-minute quadrangle, Allegheny County.

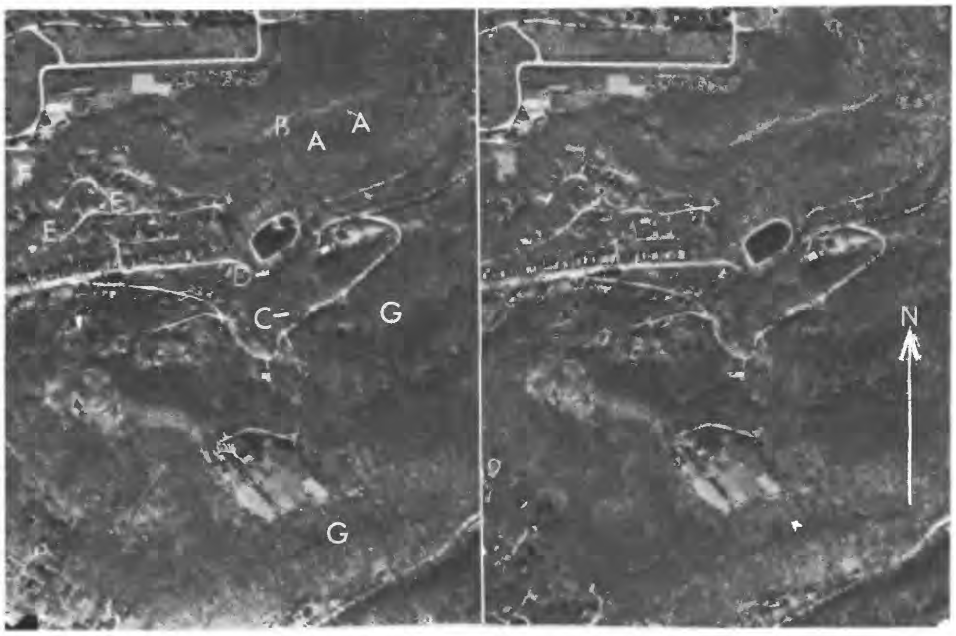
Aerial photography: April 14, 1973, GS–VDGY 1–327, 328, scale 1:12,000

2. Hummocky material (A) is indicative of ancient landslides. Large arcuate-shaped old landslide (B) and other old landslides (C) lie above valley floor. Heads of recent fill failures (D) are found at road level. Slide E appears to originate at transmission line.

Geology: Glenshaw and Casselman Formations.

Location: Montour Run area, Robinson Township, northeast Oldale 7½-minute quadrangle, Allegheny County.

Aerial photography: April 14, 1973, GS–VDGY 2–105, 106, scale 1:12,000.



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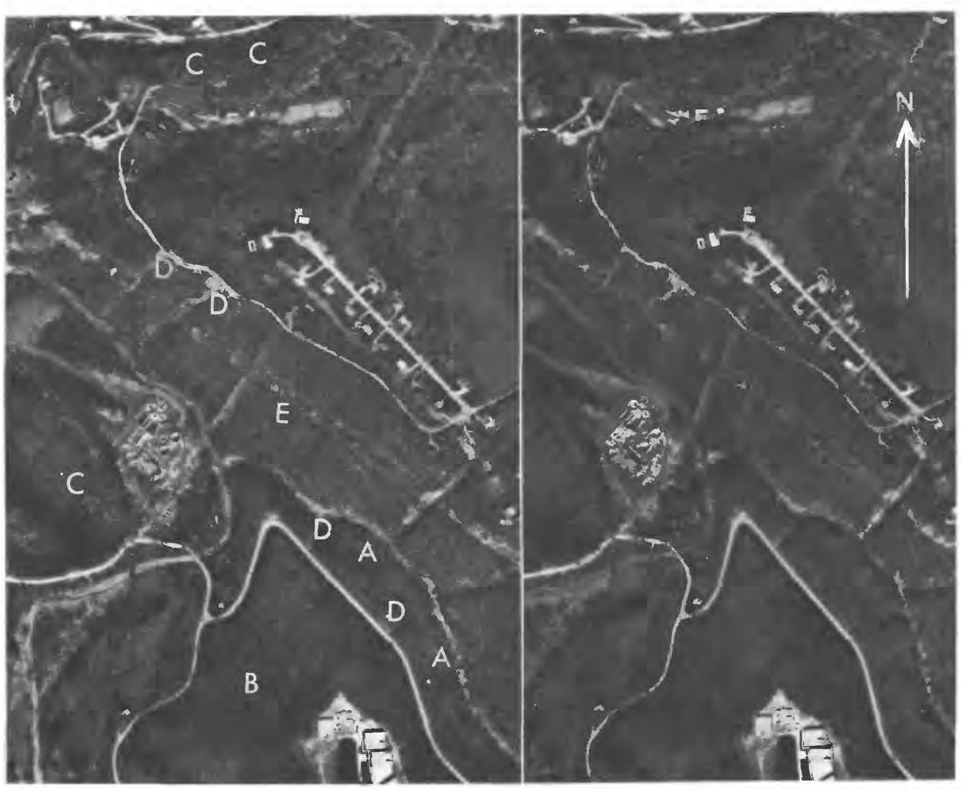

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PLATE 4

FIGURE 1. Tributary valley (A) has been filled from highway excavation. Note head scarp (B) of a recent failure and slide C stemming from fill. Area D also has been filled in. Note slide E above manmade bench and slides F below bench. Area G is an old landslide; within it is recent slide H whose head scarp is in bedrock (fig. 14*C*, *D*).

2. Extensive old landslide I bears several areas of renewed activity. White rectangular objects at J (fig. 4*C*) are concrete drainage sluices that have been separated and carried downslope. Is scarp K natural, or has it been formed by earth-moving equipment? Conspicuous head scarp of recent slides is present at L. Slides at M are old. Note road-surface tone at N where slide has caused road to be reconstructed.

Geology: Glenshaw and Casselman Formations, "Pittsburgh red beds."

Location: I–79, Ohio and Aleppo Townships, southwest Emsworth and southeast Ambridge 7½-minute quadrangles, Allegheny County.

Aerial photography: April 14, 1973, GS–VDGY 1–323, 324, 356, 357, scale 1:12,000.

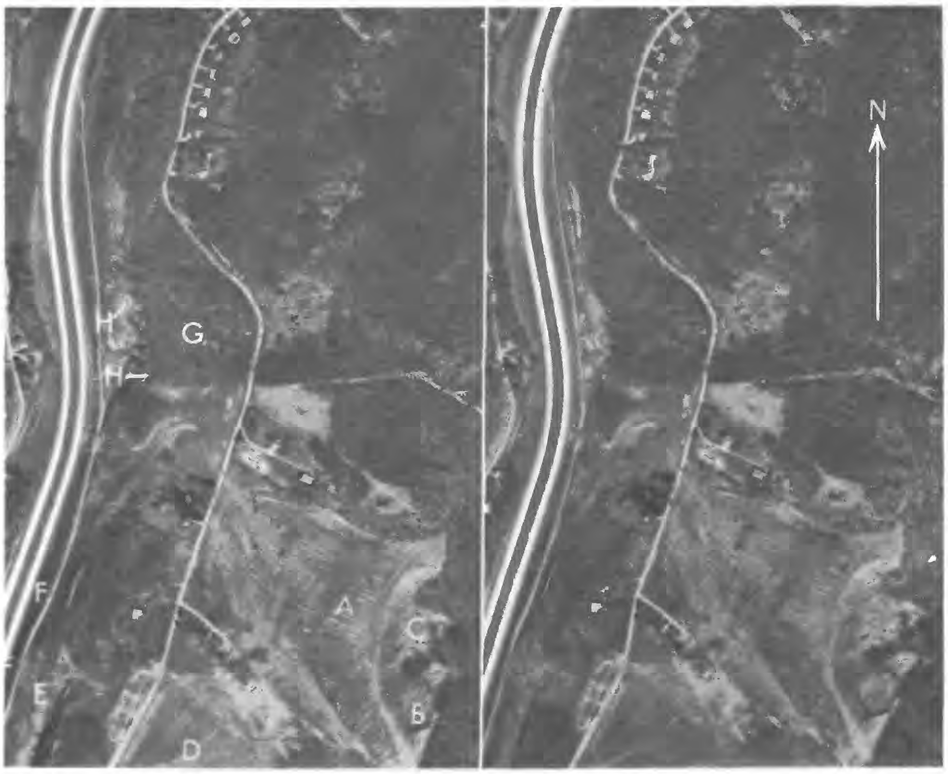

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PLATE 5

FIGURE 1. Recent landslides at A are fill failures. Note sinuous scarp (B) and toe (C) of large recent fill slump approximately 130 m long and 120 m wide at foot. Slide took place in March 1971. Fill had extended upland area, which was the site of a nursery. Failure also took place immediately to the north along the same slope. D indicates site of an older slide (note the hummocky lower slope). E points to rockfall areas above expressway.

Geology: Casselman Formation with exception of lowermost slope shown here.

Location: Opposite Schenley Park, Pittsburgh, Pittsburgh East 7½-minute quadrangle, Allegheny County.

Aerial photography: April 14, 1973, GS-VDGY 2-338, 339, scale 1:12,000.

2. Large hummocky area (A) is lower part of old landslide upon which two houses have been built. Shed behind one house stands on unmodified part of slide. Recent slumping took place behind backyard (B). Other more subtly exposed old landslides are indicated at C. Older landslide (D) shows slope concavity ("scooped out" appearance) and unevenness of surface. Outer slope of subdivision E is derived largely from fill from adjacent cut-slope operation. Failures took place after fill emplacement. Recent sliding (F) along west side of ridge road originates from fill. Areas G suggest slump benches indicative of ancient landsliding.

Geology: Mostly Casselman Formation, " red beds."

Location: Mt. Troy Road area, west of Millvale, Reserve Township, northwest Pittsburgh East 7½-minute quadrangle, Allegheny County.

Aerial photography: April 14, 1973, GS-VDGY, 2-166, 167, scale 1:12,000.

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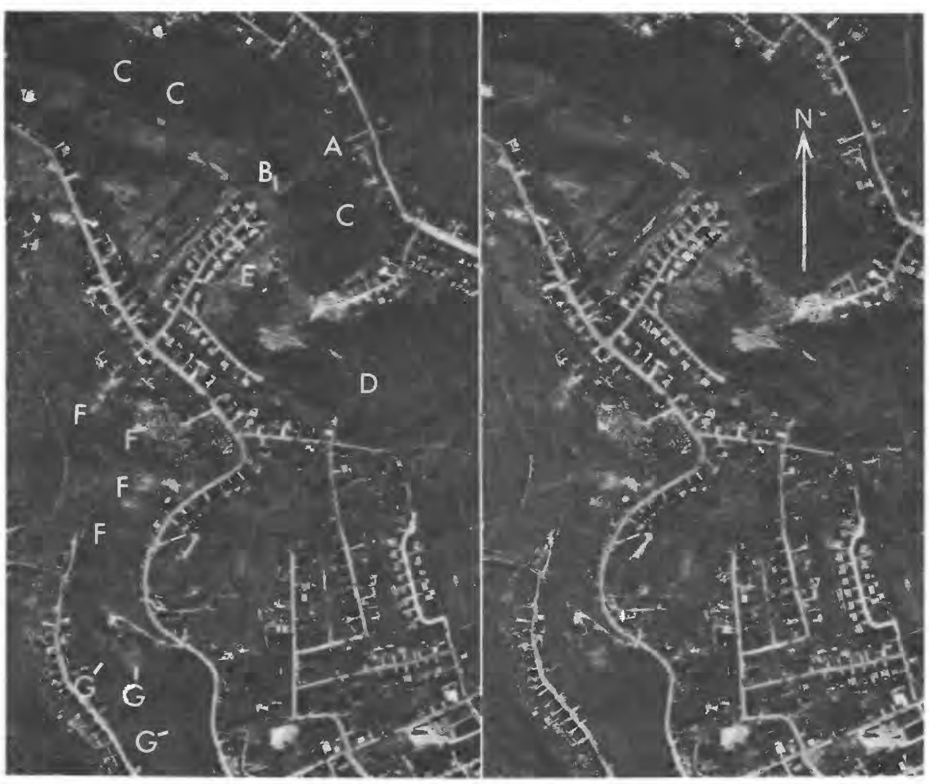

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PLATE 6

FIGURE 1. Predevelopment rural setting. Interpreted old landslides at A, B, and C (note the concave slopes).

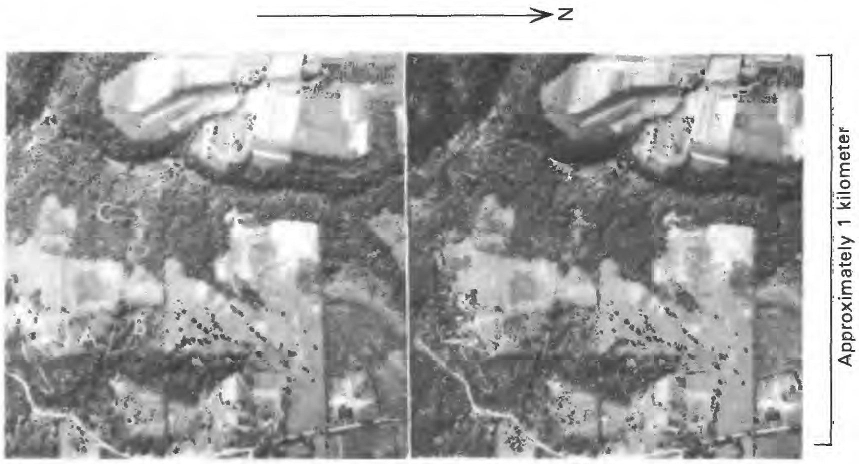
2. First stage of development. Old landslide at A has been surcharged with fill. Old landslide shown at B is now occupied by road and housing (necessitating fill) and has lost its identity. Note fill behind house within old landslide C. Ballfield fill has been emplaced and slumping has taken place (D). Long focal length of camera lens is responsible for subdued vertical exaggeration.

3. Later stage of development. Note reactivation of old landslide A. As of 1976, the frontal lobe extended nearly to the backyard of house at E. Backyard fill has slid at F (fig. 16*A*), which is at edge of old landslide C. Note ballfield-fill failure at D as in figure 2 of plate 6. Slope cutting at G has caused minor slumping. Scarp in backyard lawn at H is barely discernible. Rock exposure (I) is slump block remnant of old landslide material. J is an old landslide area (fig. 16*B*).

Geology: Casselman Formation, "red beds."

Location: O'Hara Township, southeast Glenshaw 7½-minute quadrangle, Allegheny County.

Aerial photography: Figure 1, September 25, 1938, APS 11-67, 68, scale 1:20,000.
Figure 2, March 4, 1969, GS-VBZB-12, 6-40, 41, scale 1:16,000.
Figure 3, April 14, 1973, GS-VDGY, 2-52, 53, scale 1:12,000.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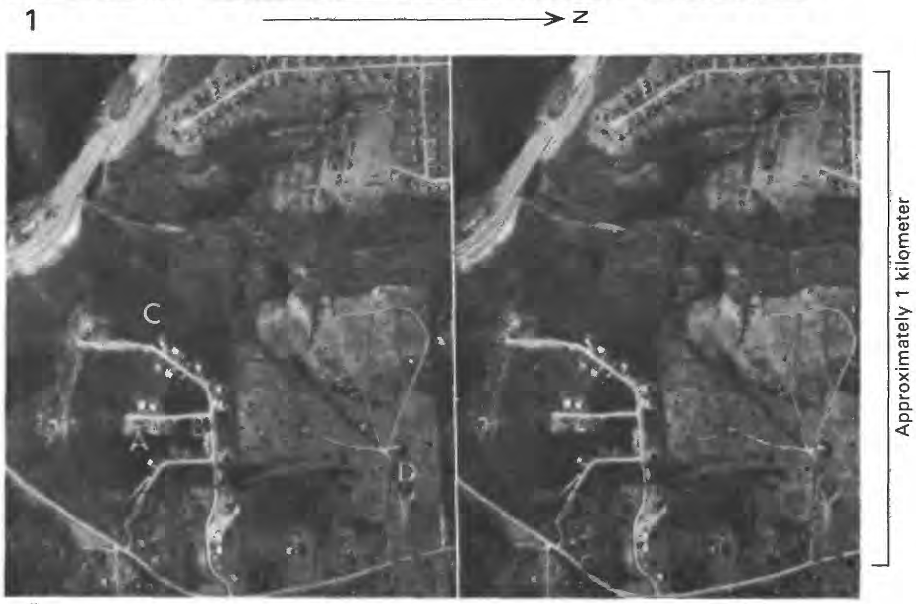
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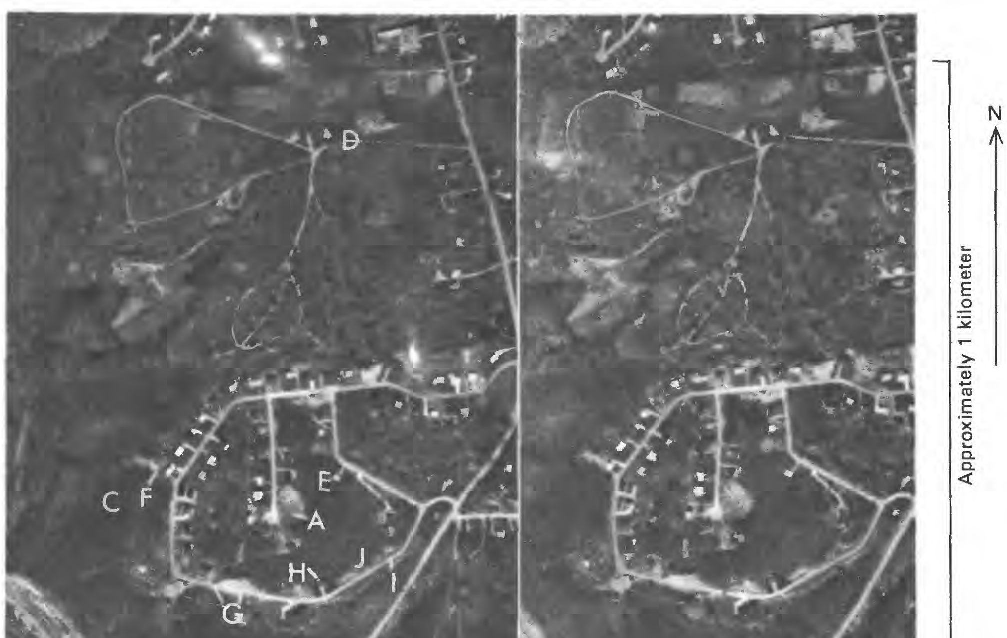
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PLATE 7

FIGURE 1. Brilliant Cut landslide shown at A (partly in shadow) took place in 1941 (fig. 18 and 19, loc. 5). Rockfalls are indicated at B, and recent debris sliding, at C. Extension of the upland surface with fill has been the contributing cause of the landslide at E. Two older landslides (D) show the characteristic bowl-shaped upper slope (east of valley floor) and the hummocky lower slope (west of valley floor). Obvious slide at F, which took place in spring 1948, caused the loss of a fill-founded ballfield (Ackenheil, 1954, pl. 1). Small debris slides are found along upland rim at G.

Geology: Mostly Casselman Formation, lowermost slopes in Glenshaw Formation.

Location: Washington Boulevard, near Allegheny River Boulevard, Pittsburgh, northeast Pittsburgh 7½-minute quadrangle, Allegheny County.

Aerial photography: April 14, 1973, GS-VDGY, 2-160, 161, scale 1:12,000.

2. Massive fill slump (A). Note the well-preserved northeast corner of parking lot as compared with the irregular east edge that represents the head of the slump. Slope B (including the recent landslide) is an undifferentiated old landslide surface (Davies, 1974h).

Geology: Casselman Formation.

Location: U.S. 30 and Pennsylvania Rte. 48 intersection, North Versailles Township, northeast McKeesport 7½-minute quadrangle, Allegheny County.

Aerial photography: April 14, 1973, GS-VDGY, 2-458, 459, scale 1:12,000.

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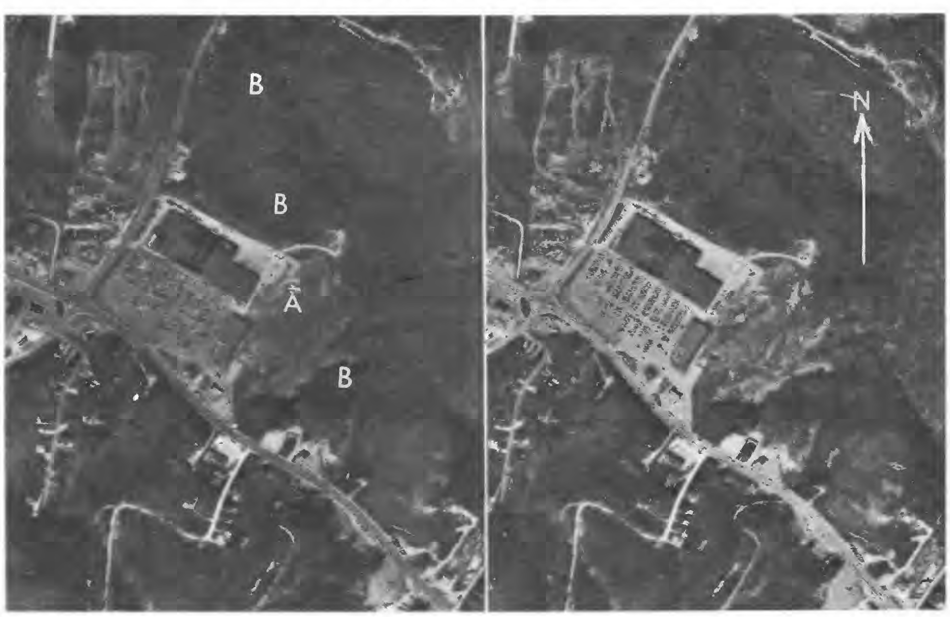

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PLATE 8

FIGURE 1. Hummocky parts of slopes at A and B suggest old landslide topography. Area shown at C is strongly indicative of definite old landslide. Few recent slides are present.

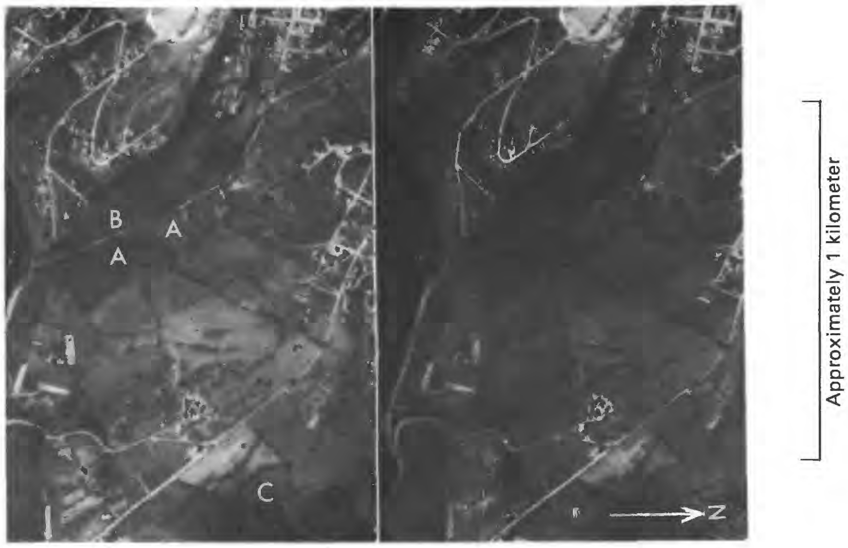
2. Sliding has taken place at E, an area that has been developed over a 30-year period. Old landslide shown at C has been reactivated by surcharging east side, resulting in extensive slump. Note fill at D and the two houses shown at end of leader.

3. Houses shown in figure 2 at D have been destroyed by sliding (E). Note arcuate head scarp (F). Concrete slab behind house (G) has been undermined (fig 14B). Field inspection revealed that house (H) had been founded on fill. In early 1975, this house was razed because of progressive deterioration of structure (fig. 14A). This recent sliding was along a slope where, in the past, mass movement probably took place.

Geology: Mostly Monongahela Group.

Location: Lawnwood Avenue, Baldwin-Brentwood Boroughs, Pittsburgh, southwest Pittsburgh East and northwest Glassport 7½-minute quadrangles, Allegheny County.

Aerial photography: Figure 1, October 25, 1938, APS 24-22, 23, scale 1:20,000.
Figure 2, March 4, 1969, GS-VBZB-12, 6-92, 93, scale 1:16,000.
Figure 3, April 14, 1973, GS-VDGY, 2-472, 473, scale 1:12,000.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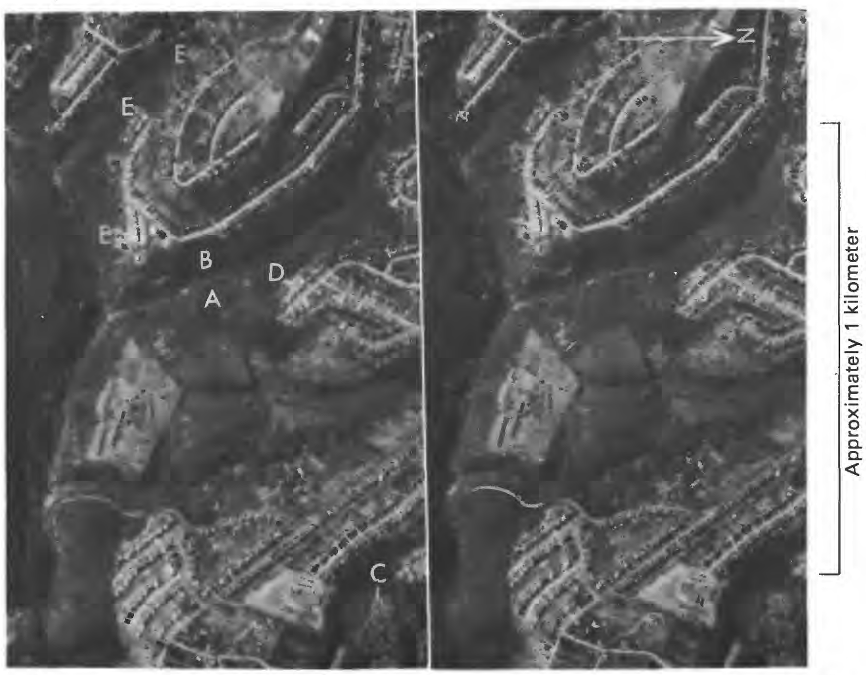
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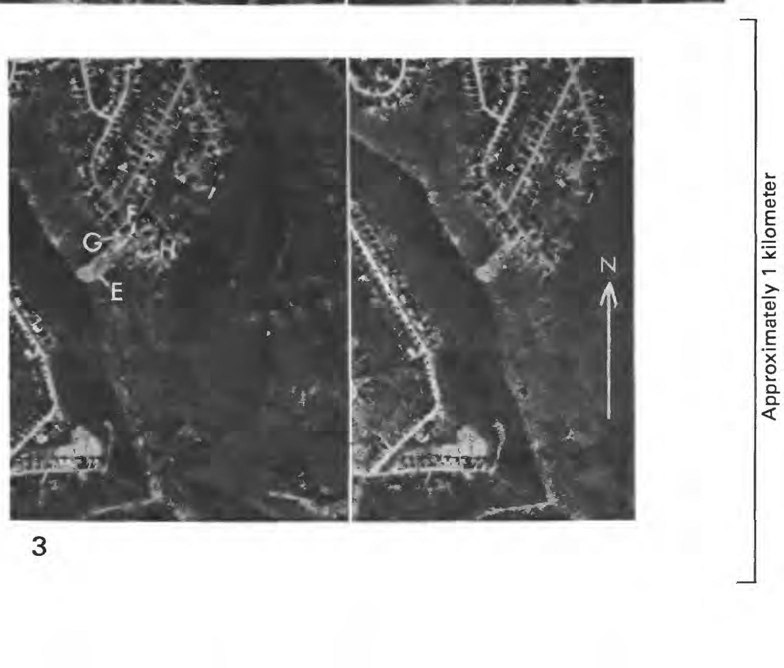
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PLATE 9

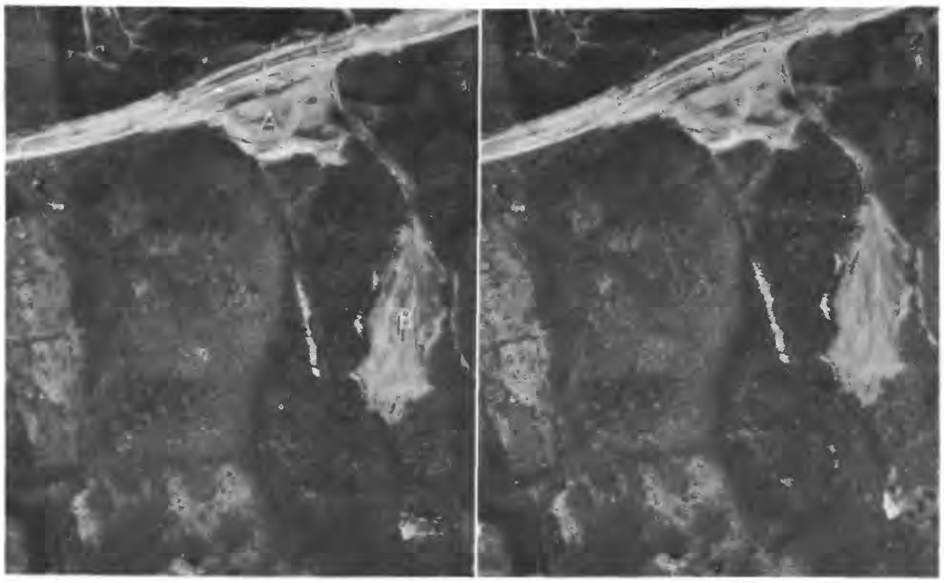
FIGURE 1. Extensive slide shown at A took place the summer before this photograph was taken. Note realinement of northbound construction traffic owing to frontal movement of 1968 landslide. Bedrock was moved at head of slide. Landslide material was deposited in valley at B.

2. Greater vertical exaggeration and sharper tonal contrast have improved interpretation. Note artificially cut bench above road (C) and arcuate-shaped headwall (scarp) (A). Old landslides (D) are more conspicuous on this stereoscopic pair because of the shorter focal length of camera lens. Area of 1968 slide has been successfully stabilized.

Geology: Glenshaw and Casselman Formations, "red beds."

Location: Interstate 79, Cranberry Township, northwest Mars 7½-minute quadrangle, Butler County.

Aerial photography: Figure 1, March 5, 1969, GS-VBZB-12, 8-171, 172, scale 1:16,000. Figure 2, March 11, 1975, GS-VDWD, 1-134, 135, scale 1:24,000.



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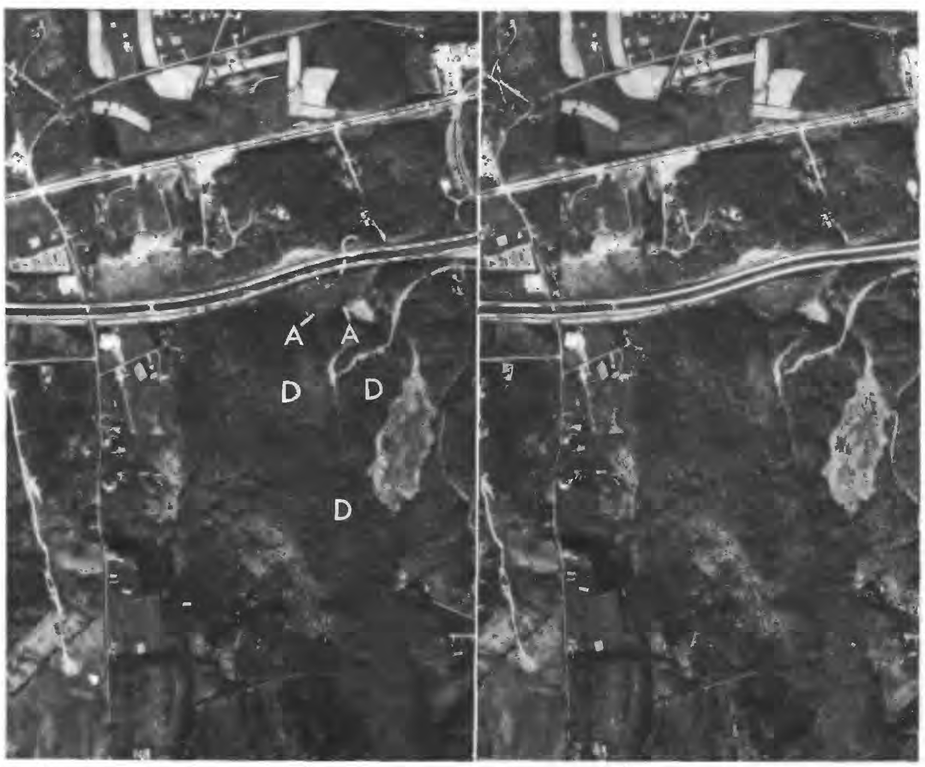

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PLATE 10

FIGURE 1. Active slumping (A) along roadcut. Note head scarp (thin light-toned arcuate line) on west bank in glacial till. Older slump has been reactivated in part (B). Slope concavity suggests probable old sliding (C). Wide zone of old sliding at D is above abandoned meander. Definite old slide at E formed by undercutting of river bank. Old sliding is inferred at F.

Geology: Glacial silty clay till (Illinoian).

Location: Slippery Rock Creek area, Slippery Rock and Brady Townships, southern Slippery Rock 7½-minute quadrangle, Butler County.

Aerial photography: May 11, 1975, GS–VDWD, 1-162 to 164, scale 1:24,000.

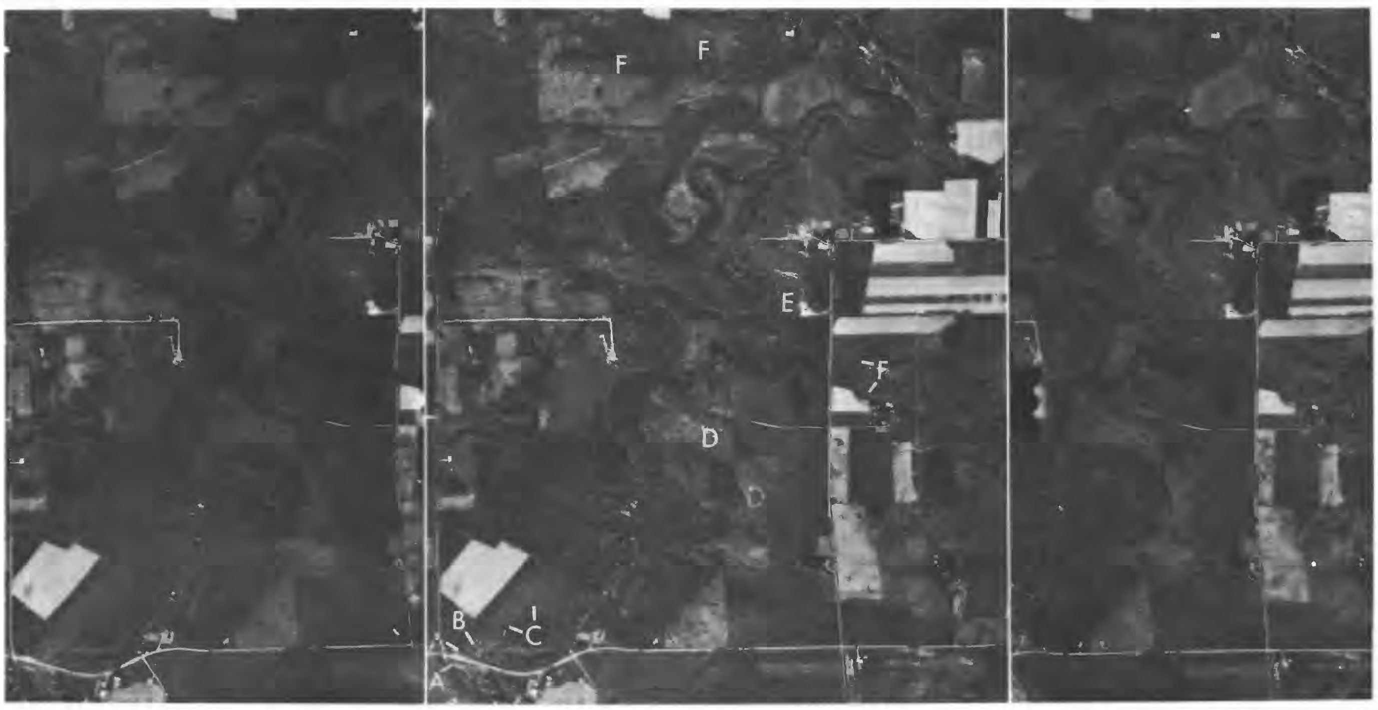

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PLATE 11

FIGURE 1. Old landslides (A) contain small recent slides. Old landslide B shows extensive reactivation. Note recent sliding on northwest-facing convex slope (C). Inferred old landslides indicated at D. Note gullying at lower end of slides (A and D).

Geology: Washington and Greene Formations.

Location: North of Claysville, Donegal and Buffalo Townships, southeast West Middletown 7½-minute quadrangle, Washington County.

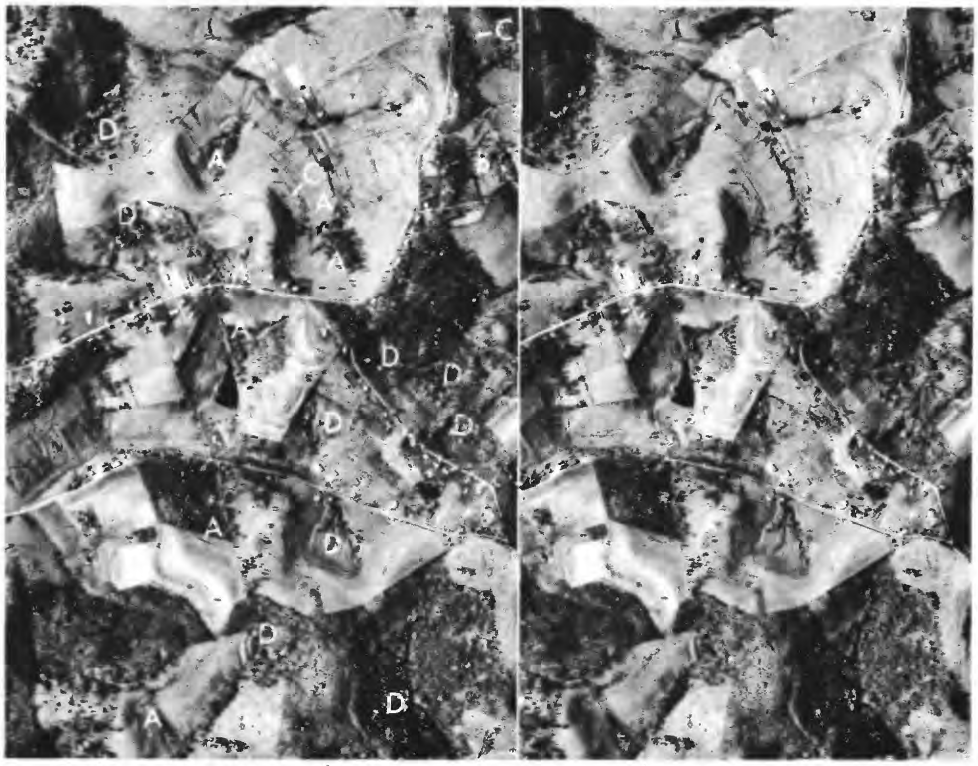
Aerial photography: December 5, 1975, 3–152, 153, scale 1:24,000.

2. Large complex landslide (A) shows head scarp at B (fig. 13*C*, *D*). Coalescence of two or more earthflows at C. Low relief landslides at D are easier to discern on north-facing slopes than on south-facing slopes because of sun angle. Photographs taken about the time of winter solstice. Some slopes (E) show several overlapping recently healed earthflows.

Geology: Mostly Greene Formation.

Location: South of Claysville, Donegal and East Finley Townships, northeast Claysville 7½-minute quadrangle, Washington County.

Aerial photography: December 5, 1975, GS–VDWD, 3–154, 155, scale 1:24,000.



1

Approximately 1 kilometer

N

2

PLATE 12

FIGURE 1. Discernible scarps and frontal lobes are conspicuous on several recent earthflows (A). Large 0.3-km-wide old landslide (B) obviously predates dwellings. Stream diversion reflected by road on opposite bank. Old landslides shown at C.

Geology: Washington and Greene Formations.

Location: Southwest of Marianna, West Bethlehem Township, southwest Ellsworth 7½-minute and northwest Mather 7½-minute quadrangles, Washington County.

Aerial photography: December 5, 1975, GS-VDWD, 2-148, 149, scale 1:24,000.

2. Surface mining slides are discernible largely on small-scale photographs. At A, shallow spoil-bank sliding has constricted river channel slightly. East of highway are conspicuous spoil-bank slides (B) and an older landslide (C). West of highway are more spoil-bank slides (D).

Geology: Pottsville, Allegheny, and Conemaugh Groups.

Location: Mahoning Creek area south of Distant, Mahoning Township, northwest Distant and northeast Templeton 7½-minute quadrangles, Armstrong County.

Aerial photography: September 24, 1974, USDA-ASCS, 374-5, 6, scale 1:40,000.

1

Approximately 1 kilometer

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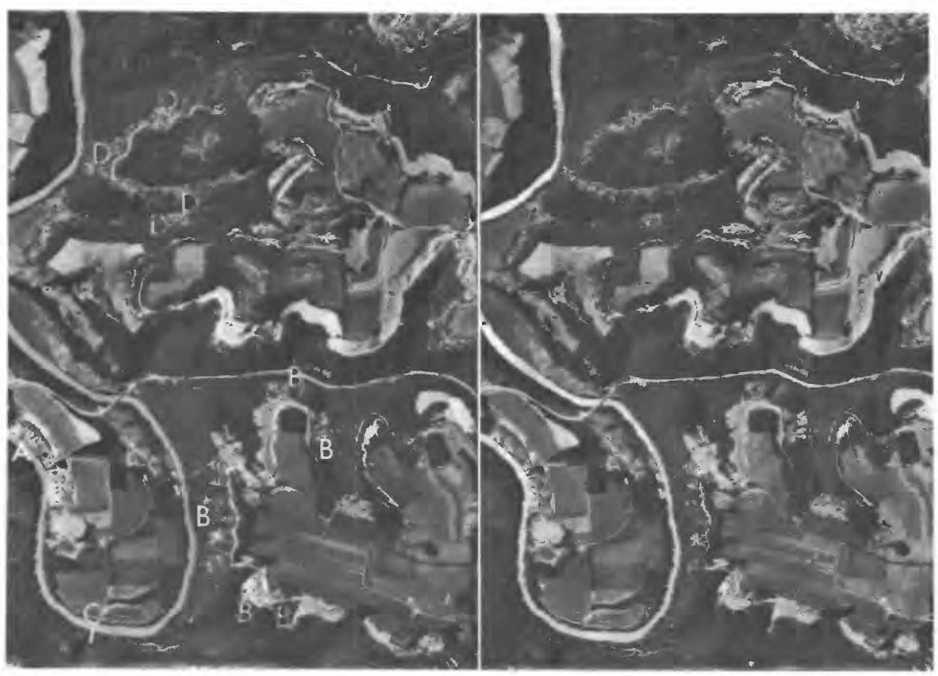

2

Approximately 1 kilometer

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