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LANDSLIDES OF SOUTHEASTERN OHIO

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ABSTRACT

The Upper Pennsylvanian and Permian cyclothemic sedimentary rocks of the Ohio River valley are especially subject to downslope movements. Repairs of landslides on state highways in eastern Ohio alone cost over a million dollars annually. Eighty-seven slope failures were located within seven counties of southeastern Ohio; 50 of the larger of these movements were mapped in some detail. Earthflows and rotational slumps are the most common types of slope failures, the latter being the larger and constituting about 89 percent of the landslides mapped. Over 70 percent of the total number of slope movements occur within only one-sixth of the geologic column. Red shales predominate in the four most unstable intervals; the gray shales of the area seldom yield to sliding and the green shales vary greatly in strengths.

Almost all of the red shales and one-third of the green shales slake completely within three hours after immersion in water; many of the red shales deteriorate to an ooze within minutes. There is no apparent relationship between stability and the amounts of soluble salts in each type of shale. Differential thermal analyses and rehydration tests indicate that these shales are composed largely of illitic clay minerals which, in the red shales at least, are deficient in bonding by cations of potassium. Ferric ions, presumably connate, have prevented readsorption of potassium throughout time, thus permitting a thickening of the interlayer water with resultant weakening of bonding. When interlayer water is driven off, a faster and greater regain is noted in the more unstable shales, as compared with that in the relatively stable shales. When the unstable shales are replenished with potassium, they strengthen markedly, especially those samples from which much of the inhibiting iron oxides have previously been removed.

INTRODUCTION

Increasing costs of landslide repair in southeastern Ohio is a major problem, not only for highway engineers but also for building contractors and home owners faced with the necessity of utilizing the sloping surfaces so prevalent in the region. The average annual cost to Ohio alone for landslide correction on state highways is about $1,000,000 (written communication, J. W. Wilson, Chief Engineer, Ohio Department of Highways). Ladd (1935, p. 1093) has estimated that the four-state area covering the upper Ohio River valley spends more than $10,000,000 annually for slide repairs on all categories of roads, and, with increased costs and development of the region during the intervening years, this amount has certainly increased.

This paper summarizes the nature of the local downslope movements as to types and origins, discusses the stratigraphic intervals most susceptible to sliding, and examines some of the properties of the various types of rocks involved. Eighty-seven landslides were located from federal, state, and county agencies and from aerial photographs of Athens county. Fifty of the larger landslides were investigated or mapped in the field to determine the dimensions, volumes, magnitudes of displacement, patterns of ground cracks, and the slopes of the ground surfaces.

Forty-nine samples of shales were collected for laboratory analyses. Twenty-

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[1] Much of the material in this paper is condensed from Master of Science degree theses submitted by the junior authors and directed by the senior author.

[2] Manuscript received July 14, 1967.

three of the samples, obtained from 15 different slides, were from red shales known to be intimately involved in slope failures. Where the shale cropped out at the slide site, a couple of samples of it were taken at random elevations. A hand auger was used where the site was covered by debris and, where it was not possible to find the shale "intact", samplings from the largest slump block were taken. For purposes of comparison, 11 green shales and 15 gray shales were also sampled, although these comparative samples could not always be obtained from within the precise interval of slope movement.

LOCATION AND GEOLOGY OF THE AREA

The area selected for investigation includes Athens county and six neighboring counties in southeastern Ohio (fig. 1). The study area lies within the unglaciated portion of the Appalachian Plateau and is well drained and maturely dissected. The average relief is about 350 feet, but becomes somewhat greater along the bluffs of the Ohio River which borders the area on the south and east. Rugged terrain and thin, sandy soils inhibit farming, so that most of the land remains forested.

Pennsylvanian and Permian rock systems strike northeast-southwest across all of eastern Ohio and dip about 30 feet per mile to the southeast. The rock section is a cyclothemic succession of silty shales, sandstones, and coals, with some thin limestones, ironstones, and clays.

Thick massive nonmarine conglomerates and sandstones of Lower Pennsylvanian age, the Pottsville and Allegheny series, are exposed only along the western margin of the area and are the least important parts of the section from the standpoint of landslips. Next above is the Conemaugh series, which range in thickness from 355 feet to 545 feet and crops out across the center of the area in a belt 10 to 20 miles in width. Bedded marine shales and some thin marine limestones are present in the lower part of this series, whereas the upper part contains only nonmarine strata, including abundant red calcareous claystones. Coal and limestone seams of minable thicknesses are generally lacking. The Monongahela series, youngest of the Pennsylvanian system, averages about 270 feet in thickness within this area and contains more minable coals than does the underlying series. Red calcareous shales and nodular freshwater limestones are common throughout.

The Permian (Dunkard) system crops out in a belt 30 miles in width along the eastern border of Ohio and extends a somewhat greater distance eastward into West Virginia. Thin sandstones and shales with some freshwater limestones and a few coals occur to the north of Marietta, Ohio, whereas, to the south, thick massive sandstones, conglomerates, and red clays predominate, the "northern gray and southern red facies" of Cross and Schemel (1956). The lower series of the Dunkard, the Washington, is between 300 and 370 feet in thickness; the overlying Greene series is usually a mere capping on the higher hills and so does not play a role in this study.

In summary, it is the cyclothemic sedimentary rocks of the Conemaugh, Monongahela, and Washington series which are of most concern here. Specific intervals particularly susceptible to landslip will be discussed in a later section.

PREVIOUS INVESTIGATIONS

Published data relating specifically to the geologic aspects of landslides in southeastern Ohio are few. Most inclusive is the two-part report of Ladd (1927, 1928), though most of his examples are drawn from the folded-rock area of West Virginia. The first report concerns the characteristics and causes of local slides, whereas the second paper reviews the engineering problems involved and the methods of slide control which have been tried. Marshall (1953) presents a short outline of field investigative methods and engineering corrective practices as applied in eastern Ohio.

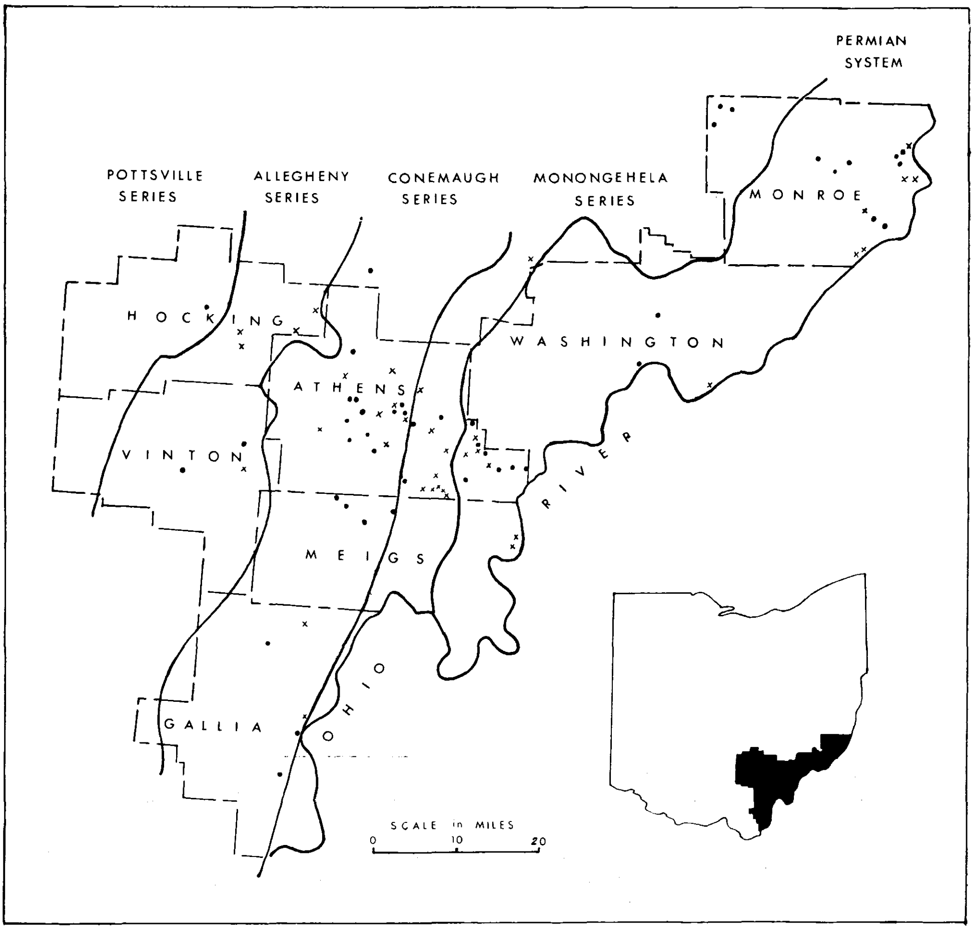


FIGURE 1. Sample location map. (•) denotes landslides mapped and studied in detail; (x) marks other, smaller landslides.

Subgrade soil conditions and highway drainage in relation to notable road failures in Ohio are examined by Eno (1928, 1934). Savage (1951) has published a few examples of slides in the northeastern part of the state. Webb and Collins (1967) discuss the geologic aspects of a large slide in Vinton county which, however, took place in lake silts and did not involve the ancient bedrock.

TYPES OF LOCAL DOWNSLOPE MOVEMENTS

Table 1 outlines a current classification of downslope movements; the types most common in southeastern Ohio are italicized and are defined below the chart. Undoubtedly most numerous of all perceptible movements are the earthflows, which occur within the detritus covering the lower parts of steep slopes, and the rock-falls so characteristic of areas of vertically jointed sandstones. Both of these movements are of small size and are restricted to the zone of weathered rock. Also, because the flows usually occur where man or natural agencies have excavated the toes of slopes, and because the resulting motion is about parallel to the original maximum slope, they are not necessarily indicative of a weakness

TABLE 1

Classification of downslope movements. (Modified after Sharpe, 1960).

Movements		Earth or Rock		
Kind	Rate	plus Ice	Dry or with some Ice or Water	plus Water
		Rock-glacier	Rock-creep	
Slow flow	Usually Imperceptible		Talus-creep	Solifluction
			Soil-creep	
	Slow			*Earthflow*
Rapid flow	to			Mudflow
	Rapid	Debris-avalanche		Debris-avalanche
	Medium		**Rotational slump* (mass intact)	
Slide	to		**Rotational slide* (mass jumbled)	
			Rock/debris-slide	
	Very Rapid		*Rock/debris-fall*	

*Slippage surfaces may or may not be bottomed upon a competent bed.
Types of movements italicized are those most prevalent in the study area.

within a particular stratum or type of bedrock. Therefore, no special effort was made to find and include these types of movements in this study.

Of the 50 largest landslides investigated or mapped, approximately 89 percent were classified as rotational landslides or slumps, the remainder being debris-slides and rock-falls. Two subtypes of rotational slumps have been recognized in this area. The first consists of those slumps in which the curvature of slippage is completed within "rock" having a rather homogeneous physical behavior. The material may be either a thick and uniform section of shales and siltstones or a thick talus piled against the lower part of the slope. In the latter case, either a flow or a rotational movement can occur. In the second subtype, the curve of failure has been deflected or bottomed upon a competent sandstone or limestone stratum. This subtype comprises about 11 percent of the landslides mapped for this report. In many cases the sliding mass of either subtype may be broken into several major blocks. Table 2 lists a few criteria for distinguishing actual rotational slides from earthflows. Many characteristics of the earthflows also apply to debris-slides.

Most of the slides in this area are less than 400 feet wide and have upslope lengths of between 50 and 150 feet. In one instance the highwall of a coal strip mine was observed to have failed along a distance of some 1200 feet. Vertical displacements along the crown scarps are usually only a few feet, the maximum single drop measured being 22 feet. The depth to the base of the typical flow mass is only a few feet, whereas the larger rotational blocks may have a thickness of several tens of feet. In lieu of drilling or trenching equipment, the depths to the basal shear surfaces were estimated by observing fracture patterns, zones of crushed rock and water seeps, or by using the graphic slip-circle method.

TABLE 2

Field criteria distinguishing earthflows from landslides

Earthflows	Rotational Landslides
Mixed materials, few blocks. Few open cracks. Seldom comes to rest as high angle slope. Water seeps.	Predominantly of blocks which retain bedding and lithologic identity. Hummocky, high angle surface.
Crown scarps shallow and concave downslope.	Crown scarps open, deep, steep, and irregular. May end without curving downslope.
Squeeze ridges over the toe; lateral spreading but with few deep cracks.	Fan pattern of transverse cracks over the toe. Pressure bulges may occur beyond the toe.
Usually wider than long (in southeastern Ohio). Slip surface approximates original slope.	Width/length ratio variable. Blocks rotate so as to flatten or even reverse the original slope; the "sags" may retain water.
Trees are flattened or tilted downslope over entire length.	Trees near head of slide are tilted or lean upslope.

CAUSES OF LOCAL DOWNSLOPE MOVEMENTS

About two dozen different factors may contribute to downslope movements in general, but only those believed to be operative in southeastern Ohio are mentioned here. Some factors should be viewed as inherent, geologic *conditions*, several of which are always present, that make a slope susceptible to sliding, but do not of themselves initiate the failure. Conditions include: (1) steep slopes, (2) jointed rocks, (3) porous and finer rock textures, (4) soluble cements in clastic rocks, (5) clay seams or thick clay shales subject to lubrication by (6) appreciable subsoil water common to regions of adequate precipitation, and (7) dip of the beds with the slope of the land, a condition quite important throughout the Appalachian states but much less crucial in Ohio.

A second group of factors in the understanding of landslides are the *triggering actions*—mechanisms that finally initiate a slide at a particular place and time, even though similar detrimental geologic conditions may exist throughout the region. Triggering actions include: (1) vibrations, either natural earth tremors or man-made, such as blasting, (2) oversteepening of a slope by weathering, stream undercutting, or man, (3) weighting of an unstable slope by construction or by the sudden addition of water, and (4) increased pore-water pressures in rocks, especially where a water-bearing stratum is constricted or loses permeability. It is not always possible to decide whether a given factor will act or has acted as a condition or as a triggering action, but a review of all possible reasons for sliding at a specific locality will usually suggest the proper explanation.

A prime contributory factor or triggering action for flows and landslides is, as will be apparent below, shallow subsurface waters. Many rock-falls are initiated by the expansion of freezing water in fractures, but water also plays several other roles in earthflows and landslides. The annual precipitation for the Ohio River valley averages 40 inches per year and occurs during an average of 120 days. The greatest seasonal rainfall is from June through August, with over 11 inches, but spring months may also register heavy rainfall. At Athens the springs of 1963 and 1964 were unusually wet; in both years March alone had between eight and ten inches of rain, which is double the normal amount. To these rains must be added some of the meltwater from late winter snows. Thus the combination of rain plus meltwater makes the change from winter to spring the prime season for slope failures.

A relationship between rainfall and downslope movements is suggested by the fact that almost two-thirds of the larger slides in the area occurred on slopes facing south-southwest to southeast. Data are too sparse for a satisfactory explanation at this time, but such slopes do face the main southwesterly storm track and so may collect more water than do the more protected northerly slopes. Also, the regional dip of the rock strata in this area should direct the subsurface drainage of infiltration waters toward the east-southeast and out onto these slopes which are subject to the majority of the larger slides.

Water infiltrating into the soil passes on downward by means of pores or joint systems in sandstones and limestones until its progress is impeded by an impervious layer of shale or clay. Thus, abnormally high hydraulic head can build up within the overlying porous materials during periods of heavy rains. Similarly, if the excess water issues into an area of thick soil on a slope or behind a bank of fine colluvium, pore-water pressure tends to force the grains apart and may actually buoy up or "float" a moderate thickness of the superficial materials, thus reducing the shearing strength and triggering a slide or earthflow. The same result can occur on a slope where a porous sandstone underlies an impervious material at shallow depth. Were excessive underground waters unable to discharge laterally, perhaps because of decreased permeability or constriction of the sandstone, increasing water pressure might break through to the surface and initiate a small slide. It must be recognized, too, that the first open fissures at the head of the moving mass serve to conduct increasing amounts of runoff water down into the zone of failure.

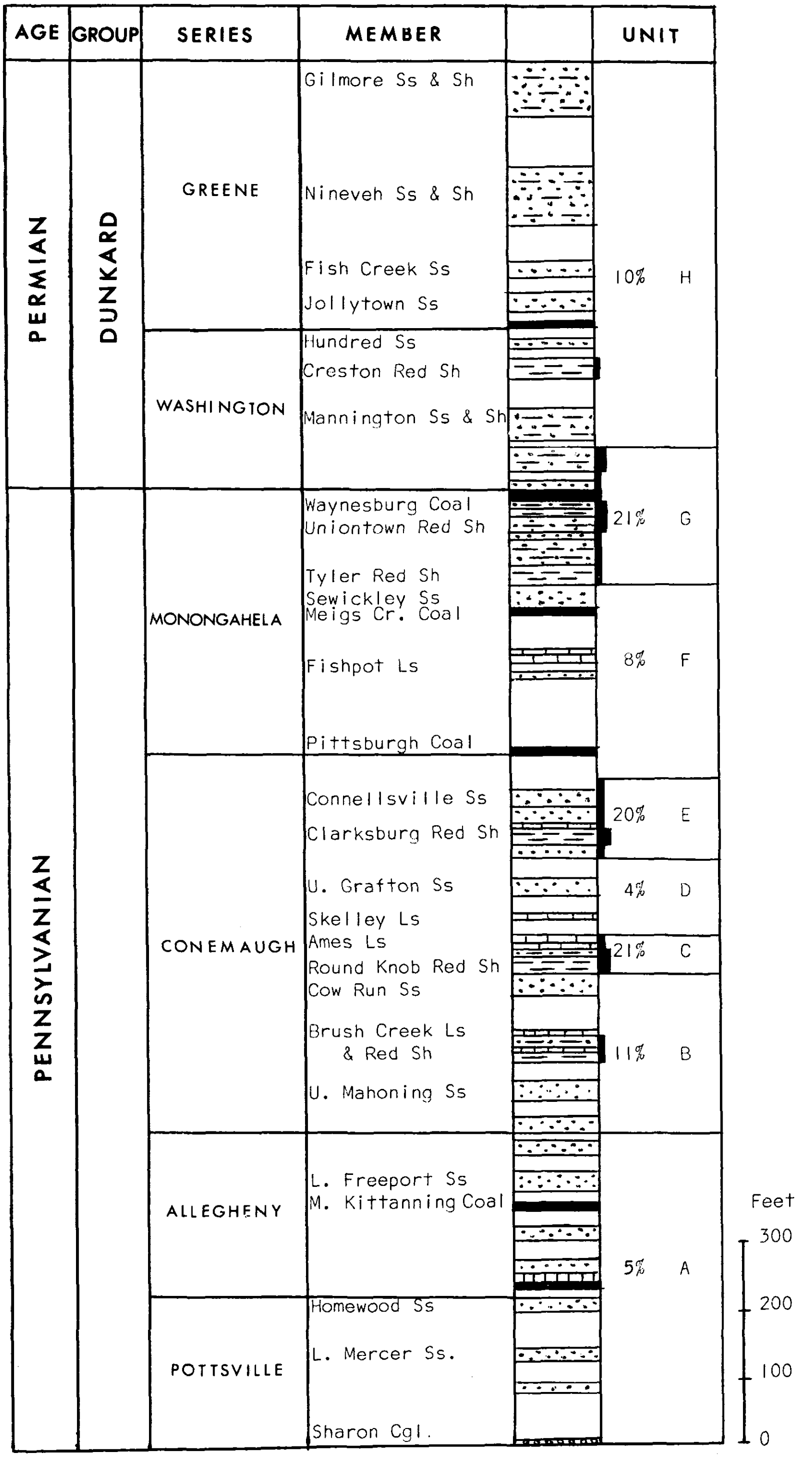
Shales and claystones present a more complex activation of slope movements. The shearing strength of shale is quite low, depending as it does upon the slight internal friction of microscopic platy grains and upon electrostatic bonding or cohesion between the particles. This cohesion is usually dependent upon a skin of adsorbed, oriented water molecules and sometimes also upon surface tension between the water and any air that may exist from time to time in the pores of the coarser phases of the sediment. However, excess water under pressure may reduce the cohesion, either by altering the molecular film of water or by destroying the surface tension as all air spaces become filled with water. Also, pore-water pressure in the silty phases of the rock may spread the grains apart so that internal friction is further diminished. Finally, certain clay minerals have the ability to absorb much water and swell, thus exerting an upward pressure that may reduce shear resistance within a claystone, and may conceivably reduce the stabilizing effect of the weight of thin overburden.

Frequencies of Slope Movements

About three-quarters of the landslides in southeastern Ohio occur within only one-fifth of the stratigraphic column: those parts characterized by the thickest red shales and claystones. The three rock intervals most subject to slope failures are designated units C, E, and G in the general rock column (fig. 2). These intervals are 55, 120, and 210 feet thick, respectively, and each accounts for 20

EXPLANATION FIGURE 2

FIGURE 2. Generalized stratigraphic column for eastern Ohio. At least 62 per cent of the area's landslides occur in the red shale intervals C, E and G which total only 385 feet in thickness. Blank portions of the column consist of thin siltstones, shales, clays and coals.


AGE
GROUP
SERIES
MEMBER
UNIT
PERMIAN
DUNKARD
GREENE
Gilmore Ss & Sh
Nineveh Ss & Sh
Fish Creek Ss
Jollytown Ss
WASHINGTON
Hundred Ss
Creston Red Sh
Mannington Ss & Sh
10% H
PENNSYLVANIAN
MONONGAHELA
Waynesburg Coal
Uniontown Red Sh
Tyler Red Sh
Sewickley Ss
Meigs Cr. Coal
Fishpot Ls
Pittsburgh Coal
21% G
8% F
CONEMAUGH
Connellsville Ss
Clarksburg Red Sh
U. Grafton Ss
Skelley Ls
Ames Ls
Round Knob Red Sh
Cow Run Ss
Brush Creek Ls
& Red Sh
U. Mahoning Ss
20% E
4% D
21% C
11% B
ALLEGHENY
L. Freeport Ss
M. Kittanning Coal
POTTSVILLE
Homewood Ss
L. Mercer Ss.
Sharon Cgl.
5% A
Feet
300
200
100
0

percent or more of the landslides in the area studied. Although not specifically noted in the rock column, the Brush Creek and Creston red shales each contribute five to ten percent of the local landslides.

In an unpublished report, Price and Lilly (1936) noted the same relationship between frequency of sliding and the occurrence of red shales throughout West Virginia, particularly in the Clarksburg (Unit E) and the Pittsburgh (Unit C; the Round Knob beds of Ohio) red-bed members of the Conemaugh series. They state (p. 32):

> Out of 100 slips occuring in shale horizons, 55 are in red shale. Fifteen or more are in the Clarksburg "Reds", 8 or more in the Pittsburgh "Reds", and 32 in unidentified or various other red shales.
>
> These red shales were former muds which have consolidated by drying and compaction and generally represent structureless masses with little or no inherent strength. Fresh exposures in most unweathered shale of this type have shown the mass to be highly fractured in all directions, and to consist of innumerable small fragments with the fractured surfaces slickensided and polished.

Field Characteristics of the Red Shales

In general, the more stable rock intervals have a greater number of thick sandstones which, although they yield to rock-falls, are seldom involved in rotational slumps or earthflows. The red shales that occur within the more stable units are more silty, are fewer, and appear to be lenses and not as laterally extensive as those in the more active parts of the section. The term "red beds", as used in this paper, refers to the nature of the strata of some two dozen intervals, in most of which the shale or clay seams, though commonly red or purple in color, may also be mottled with yellow, gray, and green. Ferruginous and/or calcareous nodules are common, and the reddish shales often grade laterally and vertically into thin, irregular limestones.

Some differences between the types of failures of the major red shale intervals were noted in the field. *Unit C* (Round Knob red beds) usually displays either highly broken and jumbled rotational slides or actual earthflows. In both cases the various lithologies involved are quite intermixed. The ratio of failure per vertical foot of section is greater here than in other red-bed units. These shales are somewhat micaceous and laminated, locally almost fissile, more jointed, and contain extensive patterns of ancient dessication marks on most bedding surfaces. Individual clay-shale intervals are thicker than the other units, being as much as 24 feet in thickness at one locality. When wetted and weathered, these shales form a plastic mass over which even walking is very difficult.

In contrast, *Unit G* (Tyler-Uniontown red beds) and especially *Unit E* (Clarksburg red beds) usually yield rotational slumps which remain relatively intact. Thus, the surfaces of these slides are less hummocky. The larger slides do tend to break into separate blocks, but with neither thorough disruption of beds nor intermixing of various lithologies. Individual red shales of these two intervals appear to be thinner, more massive, less silty and micaceous, and less jointed than those of Unit C.

Laboratory Investigations of the Shales

Slaking Tests

The effects of water upon the various shales were tested by immersion of cut cubes of shales of equal size, which were then observed during a period of three and one-half days. The time at which initial breakdown appeared and the manner of deterioration were carefully noted. The samples were observed continuously during the first hour, at one-hour intervals during the next five hours, and at twelve-hour intervals thereafter. The results are given in table 3.

Twenty-three red-shale samples from undisturbed beds adjacent to 15 landslides within Units C, E, G, and H were tested; seven of these samples were tested a second time as a check and all behaved as they had at first. With three exceptions, the red-shale samples deteriorated completely; almost all slaked within one hour into chunks one to two mm in diameter, and two-thirds eventually became oozes covering the bottoms of the beakers. Three red shales became oozes within only ten minutes, and almost a dozen flaked badly on the bedding surfaces in the same span of time.

Eight samples of gray shales, under the same treatment, were essentially

TABLE 3

Slaking characteristics of shales involved in landslides and of nearby control samples

				Hours required for slaking													
	Sample	Rock Unit	Slaked Form	1	2	3	4	5	12	24	36	48	60	72	84	Not Slaked
Red Shales	A-4-1	C	Ch	X												
	A-4-2	C	Ch				X									
	A-5-1	C	Oo	X												
	A-5-2	C	Oo		X											
	A-7-1	C	Ch	X												
	G-3-1	C				f										X
	G-2-1	C	Oo	X												
	A-13-1	E	Oo	X												
	Mg-1-1	E	Ch	X												
	Mg-1-2	E	Ch	X												
	Mr-2-1	E	Oo	X												
	A-14-1	G	Oo	X												
	A-15-1	G														X
	A-15-2	G														X
	A-17-1	G	Oo	X												
	A-18-1	G	Oo	X												
	A-18-2	G	Oo	X												
	A-18-3	G	Oo	X												
	Mr-4-1	H	Ch								X					
	Mr-4-2	H	Oo	X												
	Mr-8-1	H	Oo	X												
	Mr-8-2	H	Oo	X												
	Mr-9-1	H	Oo	X												
Gray Shales	B-a															X
	B-b															X
	B-c					(Partial separation along laminae)										X
	B-d															X
	B-e															X
	B-f															X
	B-g															X
	B-h															X
Green Shales	G-a															X
	G-b		Ch		f											X
	G-c		Ch				X									
	G-d		Ch					X								
	G-e		Oo	X												
	G-f															X
	G-g															X
	G-h						f									X
	G-i		Ch			X										
	G-j		Ch			X										
	G-k															X

Symbol (f) denotes the time at which surfaces flaked but the sample did not deteriorate completely.

*Breakdown to chunk or granular form (Ch); to ooze (Oo).

uneffected; all maintained their original block form throughout, although perhaps one-half of these samples eventually showed very minor flaking. One sample had parted along the surficial laminae and softened slightly by the end of three and one-half days. Eleven green shales were also tested. These varied widely in behavior, some slaking within five hours, a few parting slightly, but most not deteriorating at all.

Grain-Size Analyses and Mineral Content

In preparation for mineral identification of the coarser fraction of the shales, trial size analyses of nine red shales and three each of the green and gray shales were attempted using a Fisher-Dott (tube) separator. The red shales' analyses, when plotted, were more closely grouped and were somewhat finer than were those of either the gray or green shales tested. However, grain-size analyses of clays, dependent as they are upon settling velocities of the particles, are considerably influenced by the sizing technique used and the degree of dispersion obtained, and, where one suite of samples slakes exceptionally easily, sample preparations are difficult to control. Inasmuch as the finer median sizes of the red shales most probably reflected their tendency to slake, the tests were discontinued.

Samples used for microscopic mineral identification included the 15 shales disaggregated for size analysis, the coarse residues from the oozes of a dozen slaked shales, and a dozen thin sections. Fragments of additional shales were examined with a binocular microscope to obtain a rough appraisal of the silt (quartz) content.

The gray shales, which were relatively stable during the immersion tests, generally contained a notably greater percentage of quartz and muscovite than did either the green or red shales. A few of the gray shales should more properly have been classified as siltstones, and two of the four non-slaking green-shale samples also proved to have been siltstones. Thus, there appears to be a relationship between increasing amounts of quartz silt and improved stability of the rock. However, the precise reasons for this relationship are not certain because, in all the types of shales, the quartz grains are chiefly angular and the range of sizes is quite similar.

Hematite pellets (and aggregates) up to ten microns in diameter occur sporadically in many of the red and green shales. They may have derived from an unidentified ferrous mineral, a very little of which remains as green, mottled to translucent, pitted grains.

Many of the shales sampled were slightly calcareous, but, because the reaction to HCl was both mild and spotty, no attempt was made to extract the quantities of calcite present. A minor amount of the calcium carbonate was present in the form of sideritic stringers or threads.

Tests for pH and Electrolytes

While investigating the quick clays of Canada and Scandanavia, Kerr (1963, pp. 135–137) discovered that "electrolytes in a mass of clay tend to bind the particles together; consequently, as salt is leached out of the clay, it becomes thixotropic." The red shales of this report are generally considered to be of non-marine origin, and it is thus possible that they may be deficient in connate salts.

Further, work done by the Huber Corporation (1955, pp. 102–104) indicates that a clay slurry will give a pH value which varies according to the percent of clay concentration and the amount of settling that has occurred. These findings suggested to the writers that a wide range of pH and/or electrolyte values among the samples might point to a rapid means of detecting unstable shales—an "index of deflocculation" or breakdown. Such an index might relate to the slaking potentials, to ultimate particle sizes, and, thereby, possibly to the ion exchange capabilities of the clays. The many variables that could negate these relationships required rigidly controlled preparations of the samples, but, in spite of limited equipment and time available, it was decided to run trials on both techniques.

Thirty-nine samples of the three types of shales were tested for hydrogen-ion and for total-electrolyte concentrations, the latter component being measured by the conductances of the clay slurries. No systematic variance of the conductances or of the pH values between the stable and unstable shales could be ascertained. Neither was there any apparent correspondence between the conductances and pH readings in general. Although unsuccessful, the experiments are mentioned because they were a part of this study and because they may yet offer a rapid means of identifying unstable shales within the local rock column.

When the data are arranged according to stratigraphic position, however, each shale unit appears to have rather definite limits of conductance, which may have significance in stratigraphic correlation or environmental determinations. For example, all shales of Unit C have no measurable conductance, whereas the conductance of Unit G varies from zero to one millivolt, that of Unit H ranges from two to three and one-half millivolts, and that of Unit E varies from three and one-half to five and one-half millivolts. Inasmuch as the Pennsylvanian sedimentary rocks are cyclothemic and represent changes from marine or brackish to fresh-water environments, the several ranges of conductances may reflect certain chemical changes of the ancient waters which received the clays. The technique might be refined as a tool for rapid correlation or for tentative environmental determination on a local scale.

Differential Thermal Analyses

The results of DTA analyses indicate that these shales are mostly composed of an illitic clay. Curves of a few test samples of each type of shale are presented in figure 3. The characteristic curve of illite shows (a) a strong endothermic

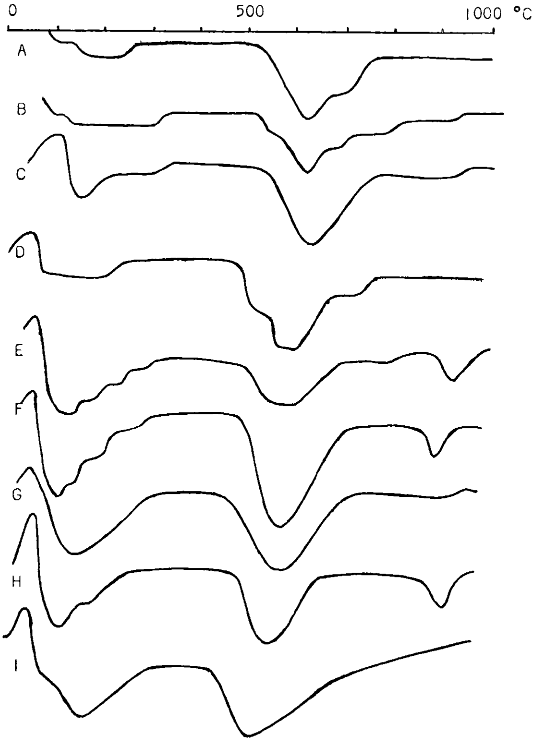


FIGURE 3. Representative differential-thermal-analysis curves of the gray shales (A–C), green shales (D–E), and red shales (F–I). Green shale D resisted slaking for six hours whereas green shale E collapsed within fifteen minutes.

reaction between zero and 250°C as interlayer water between the plates of unit lattices is driven off, (b) a second very strong endothermic peak between 475 and 550°C corresponding to the loss of hydroxyls from within the lattices, and (c) a slight reaction between 840 and 940°C. This last reaction is not always present and is usually much less intense than the first two. It is probably the result of breakdown or rearrangement of the lattice structure. Some of the test samples give evidence of being composed of interlayered clay minerals, as shown by a shelf or step in the second endothermic peak. These interlayered clays are probably mixtures of illite in larger percentages, stacked with smaller amounts of kaolin or, especially, montmorillonite, but final determination of compositions must await future X-ray study.

Some of the DTA curves may be erroneously identified as montmorillinite, so, to make the first identification more certain, rehydration tests were run on 15 samples of all three types of shales. Grim (1953, pp. 229–238) has shown that illite has the ability to rapidly rehydrate after being heated to 600°C, whereas montmorillonite does not possess this property. After heating for three hours in an electric furnace, one portion of a sample was allowed to stand for 24 hours at room temperature and then a DTA was run. A significant regain of OH lattice water was apparent, but with little or no recovery of interlayer water (fig. 4).

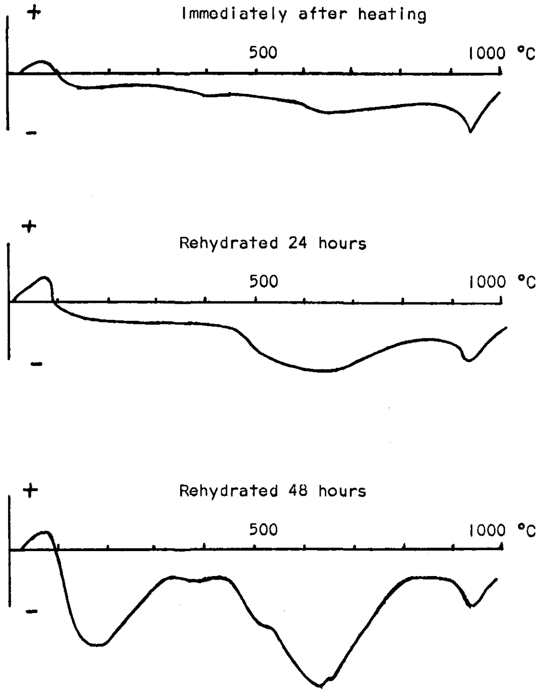


FIGURE 4. Representative DTA curves of a rehydrated red illitic shale, Sample A-4-2.

Another portion of the sample was cooled for 48 hours, when a second DTA analysis was run, producing a curve which showed a profound recovery of both OH lattice water and interlayer water; the curve is almost identical to that of a sample which was not preheated. There seems little doubt that most shales dealt with in this study are composed largely of illitic clay.

The rehydration tests indicated that the replenishment of water after the

48-hour period is much more complete in the red shales than in the gray shales. The DTA curves record a major difference between the two kinds of shales; the first endothermic reaction, resulting from the loss of interlayer water, is much more intense in the unstable red shales than in the gray shales. Thus, there must be a greater attracting force for water between the layers of the red shales. This reaction may, of course, be affected to some extent by major changes in atmospheric humidity and by the treatment of the samples prior to thermal analysis. To minimize this problem, all samples were carefully treated alike and 20 gray- and 10 green-shale samples were run as comparisons with over 60 red shales.

Some samples of the green shales showed a large amount of interlayer water, whereas others showed very little. Correlation between those green shales which slaked most readily and those which showed high interlayer water content was excellent.

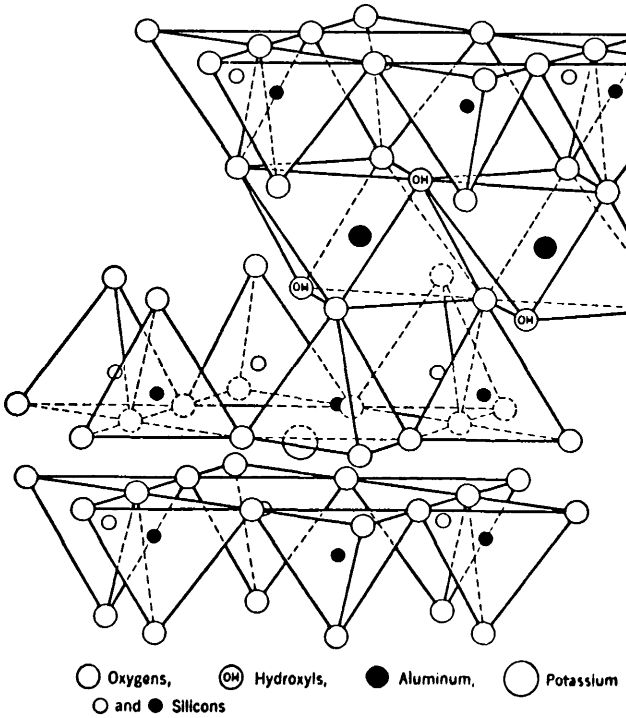


FIGURE 5. Diagrammatic sketch of the structure of illite. (After Grim, 1953).

Clay mineralogists describe the typical illite lattice as composed of two silica tetrahedral sheets with a central aluminum octahedral sheet (fig. 5). Each tetrahedron in the tetrahedral sheet contains one silica atom in the center of and equidistant from four oxygens, and each octahedron in the octahedral sheet consists of an aluminum atom in the center of and equidistant from four oxygens and two hydroxyls. The unit lattice has a silica tetrahedron layer on both top and bottom, from which perhaps one-sixth of the silicons can be replaced by aluminums, the resulting deficiency of charge usually being balanced by adsorption of potassium ions. The large size of the potassium ion permits a tight fit within the oxygen net or surface of the tetrahedral sheets, and so provides a firmer bond in the clay than do most other monovalent cations (Grim, 1953, p. 176). Thus, the tighter the bond, the less the acceptance of interlayer water. Further, the size of the potassium ion is such that it does not easily enter into and augment the net of water molecules, but tends to disrupt and inhibit the buildup of the water net. However, if the illite is degraded by the leaching of potassium ions, any surface charges existent will be partially balanced by interlayer water, and the bond of the clay is thereby weakened.

Grim (1958, p. 17) and White (1956, p. 1024) suggest that four or less oriented molecular layers of water can occur in a non-liquid state between the unit plates of illite, while the clay remains in a rigid, non-plastic state. Additional water induces less organized layers and the clay becomes more plastic and fluid until complete loss of cohesion and strength results. The water bond does not necessarily occur between every lattice unit; a series of lattice units may be bonded by potassium to form a crystal, and water bonds may hold several of these crystals together in a compound form. Thus, the volume and spacing of interlayer waters influence considerably the degree of stability of the shale.

Potassium Fixation Tests

Dion (1944, p. 411) and Wilklander (1950, p. 261) have shown that an abundance of ferric oxide in clays tends to reduce ion exchange of cations and to prevent potassium fixation. To test the role of potassium in the local unstable clays and shales, it was desirable to remove as much ferric oxide as possible and then to attempt to reconstitute potassium within some of the trial samples.

The reduction and solution of the iron oxides in the experimental samples of shales was accomplished by using nascent hydrogen, as described by Dion (1944, p. 413). A 400 ml beaker was one-third filled with aluminum foil folded at right angles to maintain maximum spacing, to which was added 100 ml of distilled water mixed with 10 g of sodium tartrate, followed by 2 g of powdered shale sample. This mixture was slowly boiled for an hour or until the red-brown coloration of the sample disappeared, thus indicating that reduction and solution of the iron oxide had taken place. For each shale, a second, control sample was boiled in distilled water for the same length of time in an attempt to cancel out any physical changes that may have been induced by the treatment. All samples were centrifuged and washed three times with distilled water.

Nine very unstable red shales were selected for testing. After removal of as much of the iron oxides as possible (none went to complete reduction), both the treated sample and an untreated control sample of the same shale were halved. The first half of each pair was soaked for one-half hour in a ten percent potassium hydroxide solution; the second half of each pair was again soaked in distilled water. All four specimens were mechanically agitated, allowed to stand for three hours, and then dried for 15 hours at 85°C. The four dried plugs now represented (1) a portion of the shale from which the iron oxides had been removed but which had not been treated with excess potassium, (2) a portion with iron oxides removed but then treated with an excess of potassium ions, (3) a portion containing the original iron oxides but untreated with potassium ions, and (4) a portion containing both the original iron oxides and the added potassium.

Each plug was then immersed in distilled water and observed for slaking, the results of which were very similar for each plug of the four-part suite of all nine red shales tested. All plugs which had not received excess potassium slaked immediately, whereas those to which potassium had been added showed only moderate signs of deterioration or none at all, even after 16 hours of immersion. This was true of both the plugs containing original iron oxides and the plugs from which much of the iron oxides had been removed, though the former showed somewhat greater effects of the immersion. Certainly, it appeared that the stability of the samples was appreciably enhanced by the addition of potassium, whether or not the iron oxides had been previously removed.

During the drying stage of the above procedure, it was noted that the plugs treated with potassium hydroxide shrank significantly more than those not so treated. These plugs were difficult to break with a stirring rod. This seemed as generally true for the samples still containing iron oxides as for the samples from which the iron oxides had been removed. To estimate the progressive effects of the addition of potassium, samples of four red shales were treated as described above, but with each portion of shale being subjected to successively longer periods of boiling than the preceding portion. Periods of boiling for the reduction of the iron oxides ran from two to five hours; the periods of drying and immersion in water were extended from two to four times the original periods. Although there was no means available for precise measurements, the portions of clay from which increasing amounts of iron oxides had been removed exhibited a toughness and an increasing stability commensurate with the assumed progressively efficient bonding by the potassium cations.

CONCLUSION

The unstable illitic red shales of southeastern Ohio have apparently been degraded by the leaching of interlayer potassium ions. Plants utilizing potassium may also have played a role in this removal (Bray and De Turk, 1939, pp. 101–106). Degraded illites behave very similarly to montmorillonites in the presence of moisture, with the exception that expandability is not nearly so great. The clays can remain in the degraded form throughout the weathering cycle, transportation, and continental deposition, but, if ultimately deposited under marine conditions, they should reabsorb potassium from the sea water and regain stable form (Weaver, 1958, p. 856, Keller, 1956, p. 2703).

The most obvious characteristic of the local shales, that makes them more or less unique among Paleozoic argillaceous rocks of the eastern United States, is their red color, which results from an abundance of ferric iron oxides. This suggests that simultaneous deposition of ferric iron with degraded illitic clay precluded 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 later geologic time. Thus, the degraded state of many of the local clays may offer the possibility, previously suggested, that determination of pH values and of the types and amounts of electrolytes present might, with further study, provide a rapid means of identifying both the more unstable shales and their broad depositional regimen.

It was not the intention of this paper to discuss techniques for the prevention or correction of landslides. However, in addition to obvious methods for preventing waters from percolating into unstable shales, some stability might be imparted by applications of potassium-bearing sprays or dusts over a period of time. Of course, the size of the area likely to be involved in failure and the costs are serious hurdles to this approach.

The present report is an initial effort to catalogue and to understand something of the slope movements in the Ohio River region. Future studies should include X-ray analyses of the composition of the troublesome shales and early recognition of unstable slopes and incipient landslips from aerial photographs.

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