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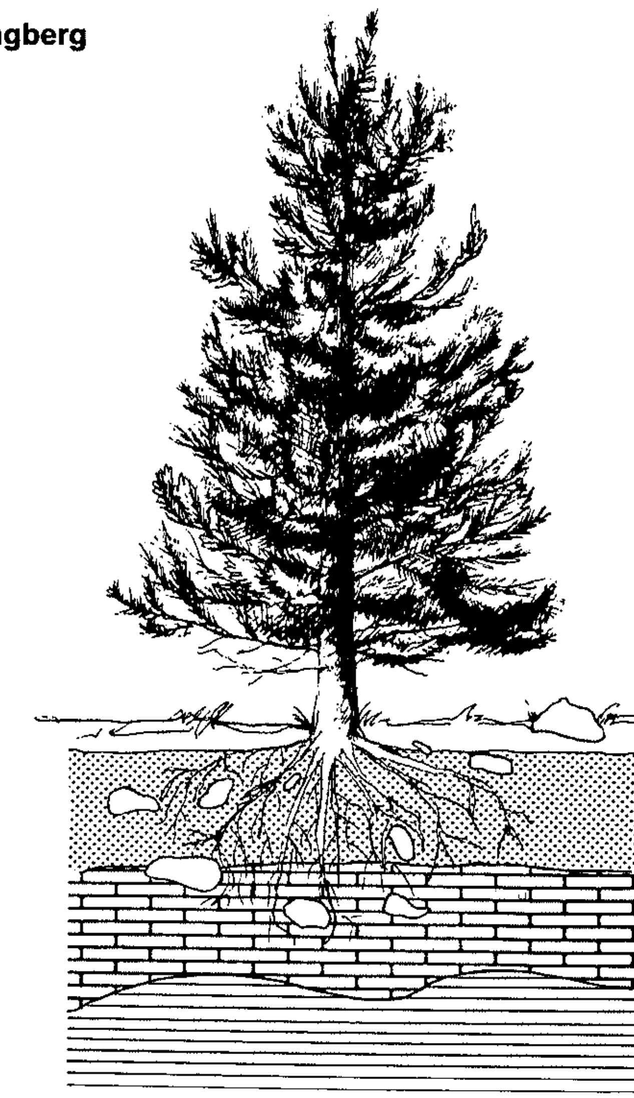
FOREST SOILS AND LAND USE

Proceedings of the
Fifth North American Forest Soils Conference
Colorado State University
Ft. Collins, Colorado
August, 1978

Edited by
Chester T. Youngberg



RELATIONSHIP OF CLAY MINERALOGY TO LANDSCAPE STABILITY[1]

R. D. Taskey, M. E. Harward and C. T. Youngberg[2]

Erosion by mass wasting is the major problem facing land managers working with the volcanically derived forest soils of the northwestern United States. Slope failures are common on the undisturbed mountainous lands, and their occurrence and severity are greatly increased by activities such as road building and timber harvesting. Unfortunately, some of the most productive forest lands in this region are also some of the most unstable—a fact which presents a significant management challenge in concentrating timber producing activities on the most productive sites. To help determine the underlying reasons for differences in stability from one site to another, and hence to better characterize unstable and stable sites, we have evaluated the nature of the clay fractions of a number of volcanic soils which are subject to various degrees of stability and to various types of mass movements. An understanding of cause and effect relationships is requisite to evaluation of remedial practices. The study is also of interest because it provides a predictive tool for diagnosing unstable areas.

The study was concentrated in Oregon's Western Cascade Range, which is characterized by adolescent, rapidly developing stream drainage systems and an overall hummocky appearance. Steep slopes, high annual precipitation and a history of seismic activity are combined with clayey soils formed predominantly from low-strength pyroclastic tuffs and breccias to make the mountainsides highly unstable. To a great extent, the Cenozoic volcanic materials which comprise the bulk of the geology control the distribution, frequency of occurrence and types of land failures. The highly weathered pyroclastic tuffs and breccias of the Little Butte Volcanic Series (late Eocene to early Miocene) are notorious for their susceptibility to mass movement (Burroughs et al., 1976; Dyrness, 1967; Path et al., 1971; Pope and Anderson, 1960; Swanson and James, 1975). In many parts of the Range, the Little Butte Volcanics are capped by an overburden of harder andesite or basalt, principally of the Sardine Formation (late Miocene). The rock of these lava flows often occurs as a colluvial deposit which has weathered to a soil mantle two

[1]Technical Paper No. 5046. Oregon Agric. Exp. Sta., Oregon State University, Corvallis, OR 97331.

[2]Assistant Professor of Soil Science, California Polytechnic State University, San Luis Obispo, and Professors of Soil Science, Oregon State University, Corvallis.

to four meters thick over the altered pyroclastics. Some of the most unstable land in Oregon is situated at the peripheral contacts of these two geologic units.

Methods

Since the study was intended to be broad scale, areas in the Western Cascades were first delineated on the basis of their geology as determined from geologic maps (Wells and Peck, 1961; Peck et al., 1964; Ramp, 1972). Then, following extensive reconnaisance and preliminary analysis, 43 sampling sites (yielding 123 soil samples) were selected from within these areas to represent differing weathering environments, degrees of stability and failure processes. The processes noted were categorized as one of several types of translational (i.e., planar) movements, rotational slumps, or deep seated soil creep. The translational movements included debris avalanches, debris flows, and earthflows. These are distinguished from each other primarily on the basis of water content and degree of sorting (Varnes, 1958; American Geological Institute, 1972; Swanston, 1970). Mudflows were not identified separately, but instead were simply included in the debris flow category.

Translational failures of the debris avalanche and debris flow types were normally sampled so as to determine the nature of the clay above, below, and within the zone of failure. It was not possible, however, to collect reliable samples from above and below failure surfaces or deformation zones of large ancient earthflows and sites of deep creep. Therefore, these were sampled by digging and augering into roadcuts or deeply incised stream banks at several locations within the mass. In the case of relatively well defined, fresh slumps, samples collected from the failure surface, scarps and debris pile were considered representative.

The clay fractions were separated from the samples by disaggregation of the soil in distilled water in an electric blender equipped with rubber policemen, instead of cutting blades, followed by centrifugal fractionation. Oriented specimens of each of the clay fractions were then mounted on glass slides and characterized by X-ray diffraction (XRD) on a Phillips-Norelco diffractometer. Characterization treatments for identification included combinations of ion saturation, solvation, humidity control and response to heating (Harward et al., 1969; Carstea et al., 1970). Additionally, the clay fractions of certain samples were observed by transmission electron microscopy (TEM) on either a Phillips EM 200 (60 kv) or a Phillips EM 300 (80 kv), using Formar-coated copper grids (Gard, 1971).

Clay Mineralogy of Various Types of Failures

Since several different types of mass movement, as well as stable conditions, are represented by the numerous study sites, it is necessary to consider the mineralogy of various sites with respect to particular erosional processes and stability conditions. In order to avoid unnecessary repetition, only a few sites and mineralogical analyses have been selected to demonstrate the various relationships (Taskey, 1978).

Debris Avalanche

A common situation in the Western Cascades is one in which coarse textured, cohesionless, relatively dry soil with little clay development overlies a steeply sloping surface of either bedrock or cohesive clay. The soil mantle of these kinds of sites is subject to avalanching whenever the shear stress acting on it exceeds its shear strength—as may happen when support is removed by undercutting or when the soil is rapidly saturated by intense rainfall.

The clay fractions of the failure materials at these sites generally consist of amorphous materials and low charge, nonexpanding minerals which have relatively large size and low specific surface. These usually include some form of volcanic glass, alumino-silicate gel and allophane in the amorphous phases, and chlorite and chloritic intergrades in the crystalline phases, although X-ray detectable crystalline components are not always present.[3] Various combinations of gibbsite, zeolite, mica, dehydrated halloysite or kaolinite may also be found. Expandable minerals and those with high water holding capacities such as the smectites (montmorillonite group clays) and hydrated halloysite are not likely to be major constituents, unless they are associated with the underlying support material. (The clays of soils which have undergone debris avalanching are very similar to the clays of soils which were judged as relatively stable, as will be shown later.)

A debris avalanche in the North Santiam River drainage (site NS-BC-1) typifies this situation. It involved a soil mantle approximately one meter thick overlying a steeply sloping (50%) surface of cohesive clay. The poorly developed clay fraction of the mantle remaining on the slope consists of amorphous material, poorly crystalline, slightly expandable chloritic intergrade, well developed gibbsite, and perhaps a hint of halloysite (Figure 1, left). Significantly, electron microscope observations revealed tubular and spheroidal halloysite in the sample, as well as microaggregates of these and other clay sized particles held together by strands and films of amorphous components. The highly contrasting material underlying the sliding components consists of montmorillonite, with some halloysite, and probably zeolite (Figure 1, right).

Debris Flows

Debris flows in the Western Cascades have not only greater fluidity than do debris avalanches, but they also involve clay with a higher affinity for water, and they may occur on more gentle slopes. The clay is also likely to exhibit a relatively high sensitivity (i.e., loss of shear strength with disturbance). All of the debris flows investigated involved saturated soil

[3]Chloritic intergrades are those chlorite-like minerals which have partially degraded or poorly developed Al- or Fe-hydroxy interlayers, and which expand and collapse with difficulty. They are also known as swelling chlorites, hydroxyl interlayered smectites or hydroxyl interlayered vermiculite.

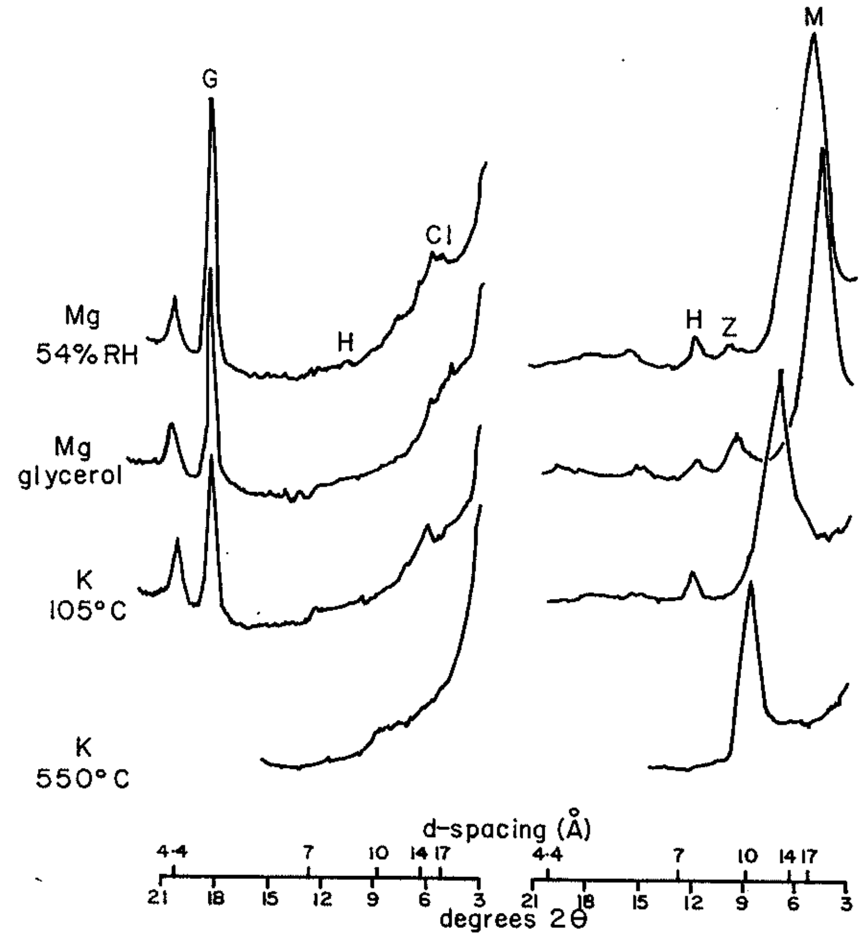


Figure 1. Site NS-BC-1. XRD patterns of clay fraction of soil mantle which failed by debris avalanche (left) and that of underlying montmorillonite-rich sliding surface (right). G = gibbsite, H = halloysite, CI = chloritic intergrade, Z = zeolite and M = montmorillonite. (Original patterns show amorphous band extending beyond 21° 2θ.)

containing amorphous material and hydrated halloysite as the most significant components of the clay fraction. These soils formed in deposits of andesitic or basaltic colluvium (principally of the Sardine Formation) which are often augmented with varying amounts of volcanic ash. The underlying failure surface in each case consisted of montmorillonite-rich saprolite, which had weathered from volcanic tuffs and breccias (principally of the Little Butte Volcanic Series). These smectite layers support perched water tables.

At site SS-SF-1, in the South Santiam River drainage, a forest road was constructed across an ancient slump block of highly altered yellowish to greenish pyroclastic tuff-breccia. The altered volcanics are overlain by soil formed in a deposit of cobbly basaltic colluvium and volcanic ash on a 30% slope. Alteration of the underlying tuff-breccias has produced a highly cohesive clay which is nearly pure montmorillonite, and which supports a perched water table. The soil of the colluvium-ash mixture, approximately two meters thick, has a smeary consistency and a high water holding ability. Its lower portion is saturated throughout the year and flows readily when disturbed. The clay fraction of the unstable soil mantle, which contrasts dramatically to the underlying saprolite, consists of halloysite in various stages of hydration, amorphous material, some gibbsite, and chloritic intergrade with indications of a small amount of smectite (Figure 2). Failure occurred by flowage of this upper soil mantle over the montmorillonitic-rich saprolite following disturbance by road construction.

Electron micrographs of the clay fraction of the soil from above the failure plane show masses of amorphous gel (Plate 1). These gel masses are highly unstable under the electron beam and their disintegration reveals numerous individual clay particles as well as amorphous material which is less sensitive to the beam. It appears that these kinds of masses are analagous to microscopic balloons consisting of a gel-like coating filled with clay particles with a high affinity for water. It seems reasonable to suggest that in the field these "balloons" are also filled with water which would be released upon disturbance of the gel coating. This hypothesis could explain in part the unusual sensitivity of these soils.

A failure, in the Middle Santiam River drainage, (site MS-P-1), is more complex, but still somewhat similar in that it consists of a large, ancient progressive slump and a recent road-related debris flow. The slump is in clayey altered pyroclastic material which supports a perched water table. This material is overlain by wet, highly unstable soil formed primarily from basaltic colluvium. Water emerges from just below the crown of the ancient slump block, several tens of meters upslope from the road. The colluvial soil holds this water very well, and much of the soil is saturated throughout the year; it flows readily when disturbed.

The nature of the clay constituents at the Middle Santiam site is different at various locations in the vicinity. A sample taken from relatively dry, stable soil upslope from the crown of the ancient slump contains primarily amorphous material and chloritic intergrade and only a trace of halloysite. This contrasts to a sample taken downslope from the crown in the unstable colluvial soil lying just above the recent road-caused failure. The latter contained considerable hydrated halloysite as well as amorphous

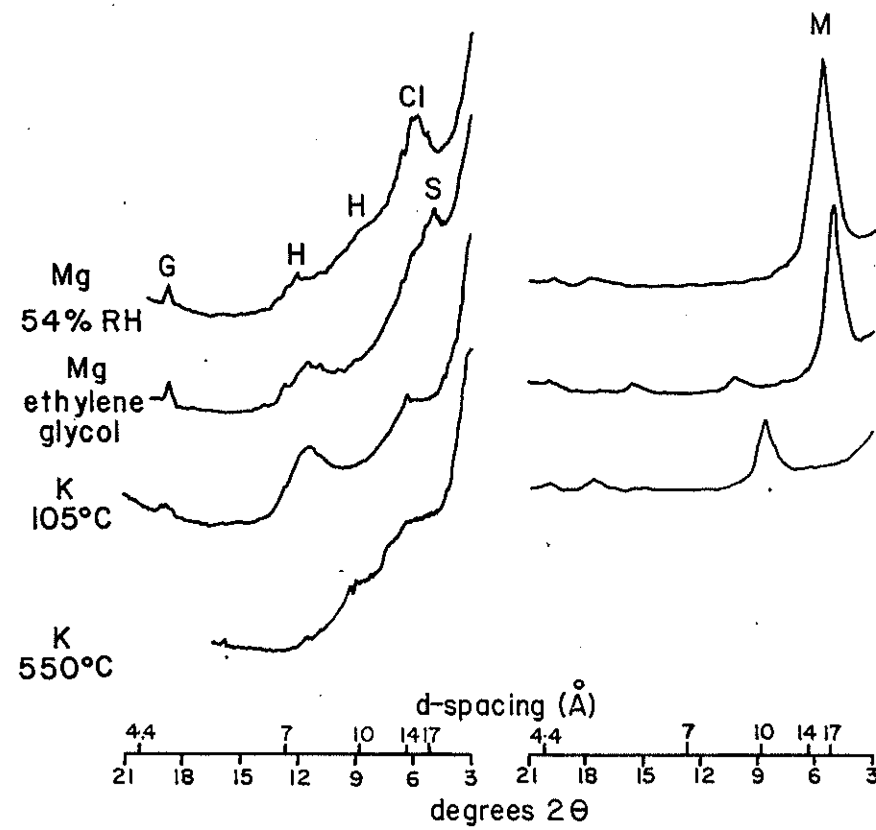


Figure 2. XRD pattern of flowing soil from near top of perched water table (left) and mottled plastic clay which supports perched water tab (right) at site SS-SF-1. G = gibbsite, H = halloysite, CI = chloritic intergrade and S = smectite.

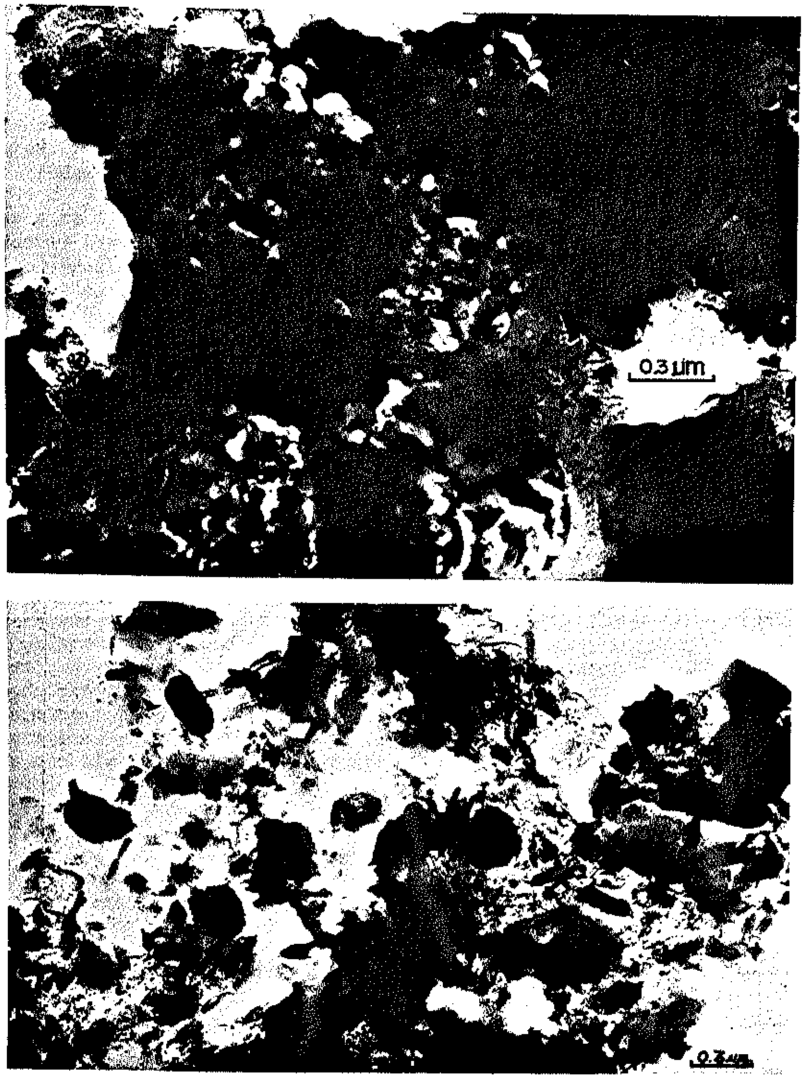


Plate 1. Site SS-SF-1. Electron micrographs of clay sample above the debris flow failure plane before (upper) and after (lower) disintegration of amorphous gel under the electron beam (different areas of the sample holding grid). Lower micrograph reveals halloysite, suspected chloritic intergrade and more amorphous material beneath the gel coating.

material and chloritic intergrade (Figure 3). These XRD interpretations were supported by observations made with aid of the electron microscope. Although the two soils are somewhat similar in macroscopic appearance, there are major differences between them. The components in the up-slope sample are bound together by a network of films and strands which resemble imogolite (Plate 2 upper). The less stable, saturated soil clearly contains a greater abundance of tubular and spheroidal halloysite (Plate 2 lower). Additionally, its amorphous component appears more gel-like, and has a tendency to occur in relatively large masses similar to those described for the SS-SF-1 sample. The greater abundance of halloysite in the saturated, less stable soil, and the different forms of amorphous material noted in the two samples most likely play a key role in the water holding characteristics and strength characteristics of the two soils.

A comparison of the XRD patterns of the more stable soil at this site (Figure 3 left) and those of the debris avalanche soil at site NS-BC-1 (Figure 1 left) shows the two clay fractions to be very much alike, except for the strong presence of gibbsite at site NS-BS-1 which is subject to more direct sunlight and to warmer, drier conditions in summer. Furthermore, the microaggregate shown in Plate 2 is similar to those found in the debris avalanche samples. Similar comparisons were made with the soils of a number of different sites of these types.

Additional samples of material from different depths were collected from just above the road cut at site MS-P-1. Although the XRD patterns showed the strong presence of montmorillonite in a sample of the mixed failed material, they also exhibited the strongest peaks for hydrated halloysite of any of the samples from the site (Figure 4 left). This sample originated from just near the debris flow failure plane in the perched water zone. The montmorillonitic-rich, halloysite-poor sample (Figure 4 right) originated in the weathered pyroclastic material beneath the failure plane.

The soils of the slopes bordering the failure area are coarse textured, well drained and relatively stable. As expected, the clay fraction is poorly developed, and consists of chloritic intergrade, zeolite and only possible traces of halloysite and amorphous material.

Several additional sites exhibit similar transitions from relatively dry, stable soil to wet, unstable soil subject to failure by the debris flow process. In each case, the more stable soil is represented by a poorly developed clay fraction containing individual glassy particles lined by strands of partially cystallized gel (Plate 3) and/or microaggregates bound by networks of amorphous material. It is reasonable to assume that a significant percentage of the microaggregates in the soil are larger than clay size, and that they develop considerable interlocking strength. The less stable soils exhibit well developed hydrated halloysite and "balloons" of amorphous gel containing clay particles. In the field, these components would be expected to hold a considerable amount of water between the layers of the halloysite (Askenasy et al., 1973) and beneath the gel coatings of the balloons. These materials, then, would help to maintain relatively high pore water pressures in the soil throughout the year, and water would be readily released upon disturbance of the soil.

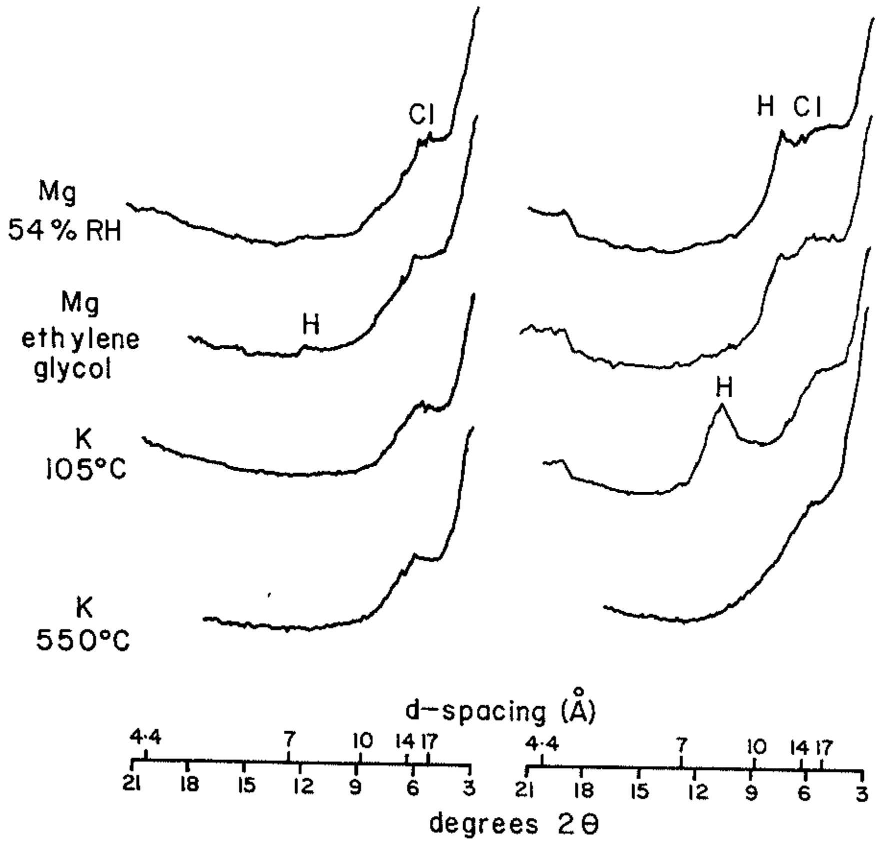


Figure 3. Site MS-P-1. XRD patterns of dry, stable soil upslope from failure (left) and of wet flowing soil in failure (right).

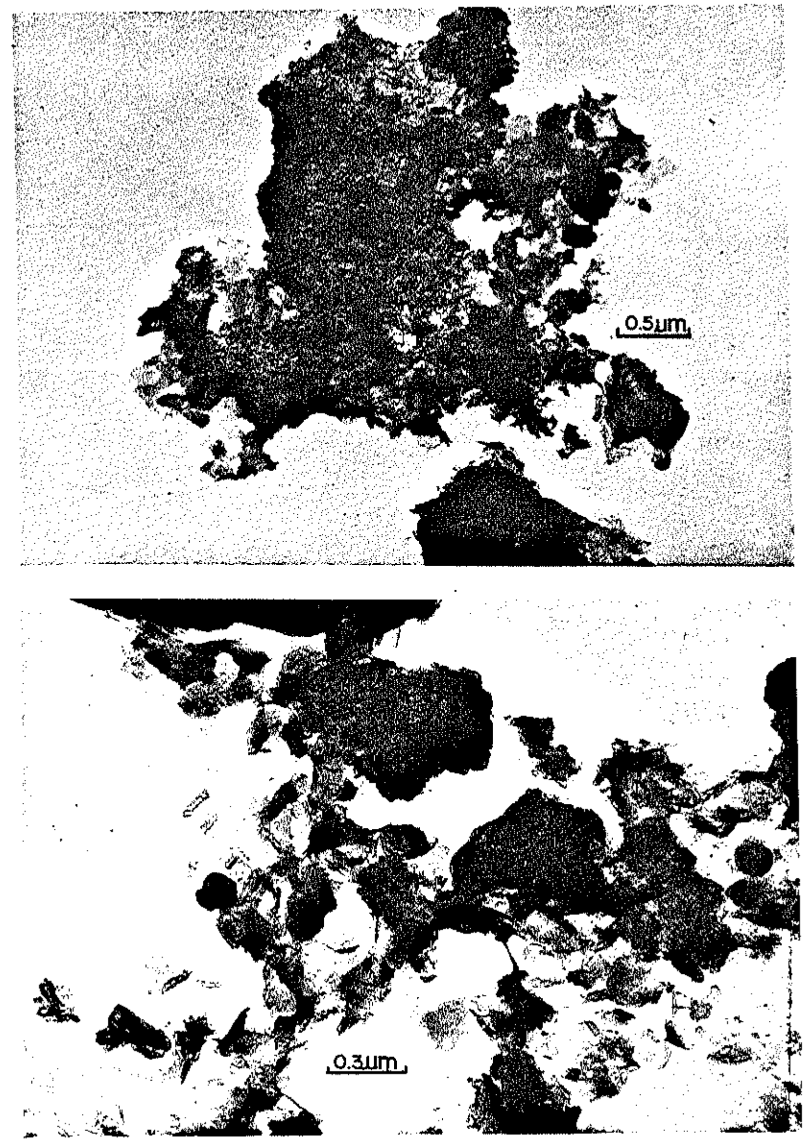


Plate 2. Electron micrograph of micro-aggregate from drier, relatively drier stable soil (upper) and saturated unstable (lower) at site MS-P-1.

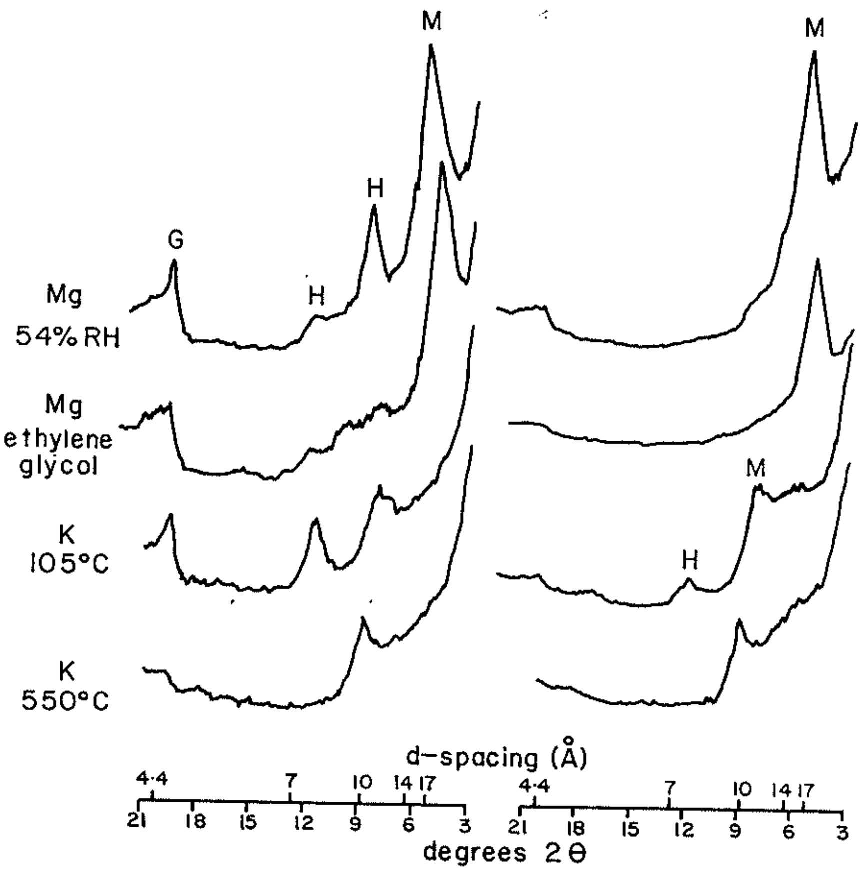


Figure 4. Site MS-P-1 XRD patterns. Random sample of mixed, failed material (left) and plastic clay underlying soil (right) which supports perched water table.

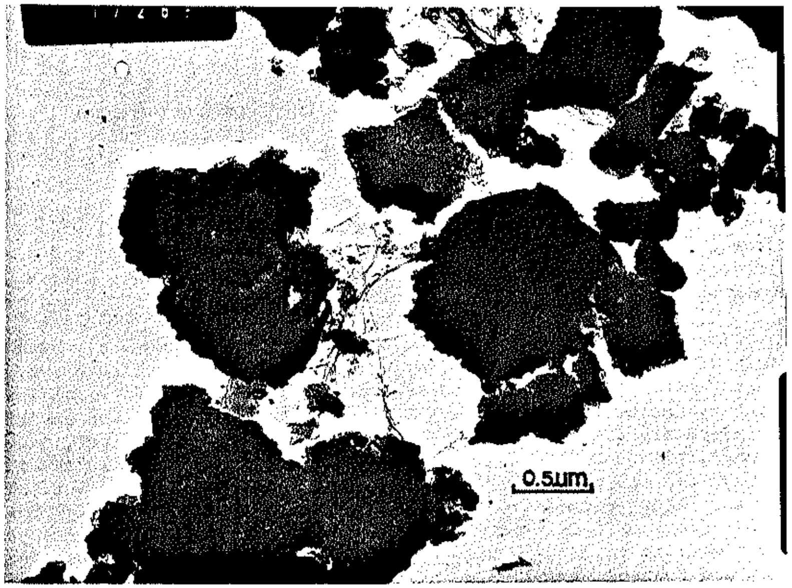


Plate 3. Electron micrograph showing particles of volcanic glass connected by imogolite strands from relatively stable soil at site MK-D-1.

Rotational Slumps

Deep-seated rotational slumps normally develop only in those soils which contain a significant amount of cohesive clay (Carson and Kirkby, 1972; Wu, 1976). Nearly all of the sites which had failed as debris flows over a deposit of cohesive clay had also suffered rotational slumping and/or deep-seated creep at greater depths. At each of these sites, including SS-SF-1 and MS-P-1, the failure surface or zone of major deformation was inferred to have developed in the highly altered, montmorillonite-rich pyroclastic deposit. Smectites were clearly the dominant clays in the failure zones of several recent, small well defined slumps. The XRD patterns of site MS-H-1 indicate nearly pure montmorillonite, whereas, those of site MFW-H-1 indicate montmorillonite plus kaolinite (Figure 5). Although both failures were rotational slumps, the failure surface at site MFW-H-1 was the smoother and less deformed of the two. This phenomenon, which was noted at several other sites, was apparently due at least in part, to a moderating influence of kaolinite.

Earthflows

Rotational slumps frequently initiate earthflow movements, which are translational downslope "flow(s) of slow to very rapid velocity involving mostly plastic or fine-grained nonplastic material" (Varnes, 1958). For purposes here, earthflow landforms are identified by wet soils, large area (several hectares to several square kilometers), considerable depth (several meters), slow rate of movement (a few centimeters per year), low slope gradient (less than about 30%), old age (thousands of years?), and a number of distinctive features, including: tension cracks, pressure ridges, hummocky topography, displaced roads and stream channels, and jackstrawed trees.

The terms "plastic" and "cohesive", which are frequently used in discussions of earthflow materials, imply a dominance of smectite clays. However, smectite was only occasionally observed in the four large earthflows investigated in the Western Cascades. Clay samples from all of the earthflows contained significant amorphous components in the form of gel, imogolite strands, glass shards, and opal phytoliths. Kaolin (usually identified as halloysite) and chloritic intergrade were also commonly present. Three of the earthflows--Lookout Creek (site MK-L-3), Boone Creek (site SFMK-B-1) and Landes Creek (MFS-L-1)-have been under investigation for several years. Their average rates of movement are 7, 25, and 12 cm/yr, respectively (Swanston and Swanson, 1976). The clay mineralogy of the Lookout Creek earthflow appears to be fairly uniform throughout, and quite similar to that of the Boone and Landes Creek earthflows. The major clay constituents are amorphous materials, halloysite with a range of hydration, and chloritic intergrade (Figure 6, Plate 4).

Field observations at Lookout Creek suggest that the mass--which contains a significant percentage of basaltic cobbles, stones and boulders, and which is probably more than ten meters deep is moving over weathered pyroclastic material which is high in smectite. Two clay samples from the Landes Creek earthflow showed a definite contrast in mineralogies. One sample, from the central portion of the earthflow, contained the expected amorphous material,

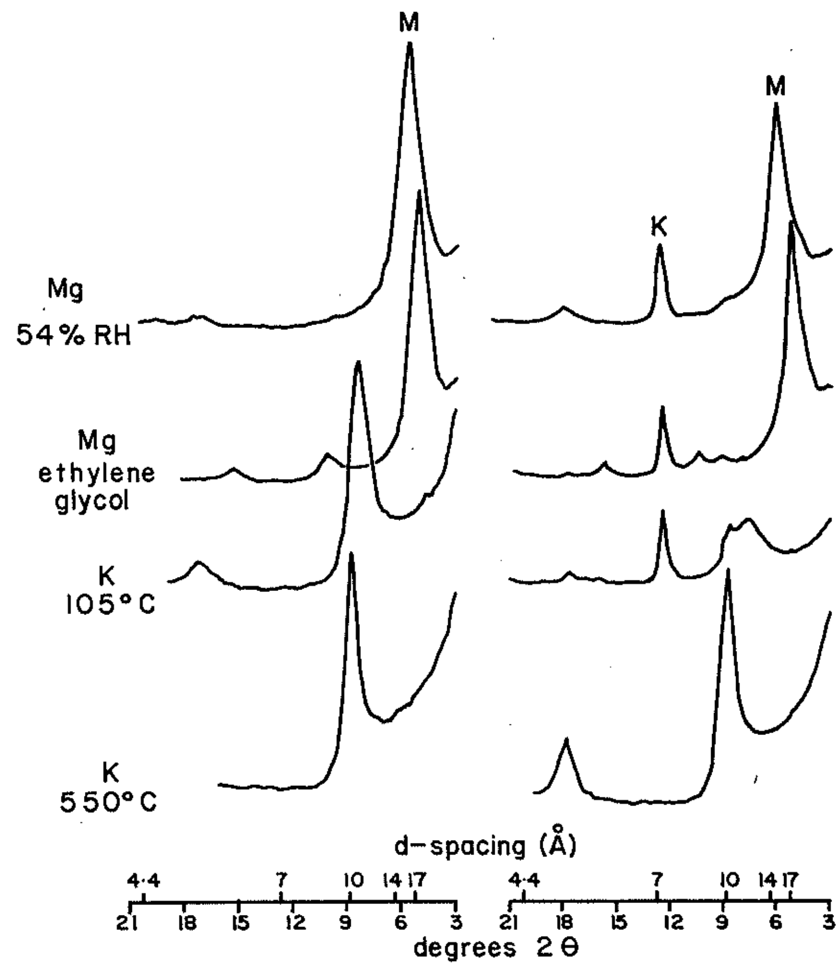


Figure 5. XRD patterns of montmorillonite (site MS-H-1) left, and montmorillonite plus kaolinite (site MWF-H-1) right, involved in rotational slumps.

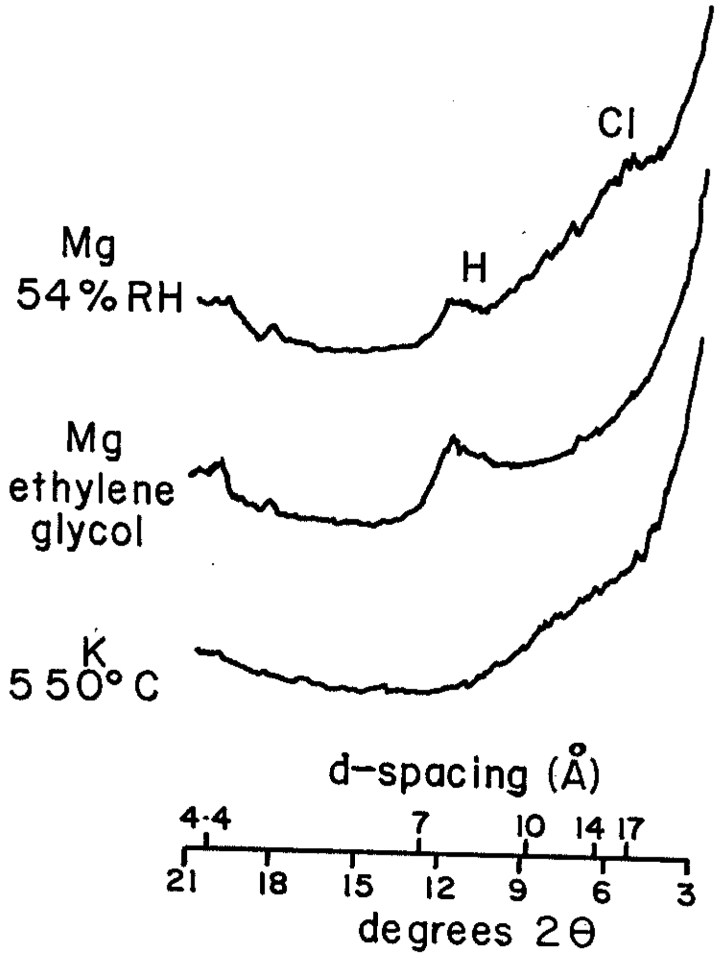


Figure 6. XRD patterns of clay fraction from site MK-L-3 earthflow showing amorphous material, chloritic intergrade and hydrated halloysite.

Plate 4. Electron micrograph of clay from site MK-L-3 earthflow showing tubular and spheroidal halloysite and masses of amorphous gel.

halloysite and chloritic intergrade; whereas, the other sample, from within a prominent pressure ridge, contained primarily smectite with some zeolite and perhaps a trace of kaolin. It is interpreted that this is a rather complex earthflow involving movement of basaltic colluvial soil in the central portion over highly weathered greenish pyroclastic material which is also under stress great enough to cause it to buckle and fold up through the overlying material. It is noteworthy that the pressure ridges at Landes Creek are the most distinctive of all those observed in the Western Cascades.

Creep

Soil creep in the deep seated, rheological sense refers to a time-dependent downslope deformation of the soil mantle under gravitational shearing stress. The rate of movement is controlled by the soil's viscous resistance and to a great extent by the nature of the clay fraction (Mitchell, 1976). Rotational slumps are nearly always associated with creep to some degree. Furthermore, large earthflows are subject to creep, thus making it virtually impossible to distinguish slow flow from creep in many cases. In these cases, however, there is little point in trying to distinguish the two processes. Good examples of this situation occur in the middle to lower reaches of the South Umpqua River drainage, where many land surfaces have a characteristic rumpled appearance, and where small rotational failures are common in the cutbanks of roads and streams. The soils here are high in very plastic, montmorillonite clay which is often saturated during part of the year.

Stable

A relatively small proportion of the volcanically derived materials of the Western Cascades can be considered as stable. Most of this land lies above an elevation of about 1000 meters, which roughly corresponds to the upper limit of the exposed distribution of pyroclastic tuffs and breccias, especially those of the Little Butte Volcanic Series (Peck et al., 1964). Similar observations have been made by Dyrness (1967) and Swanson and James (1975). The land at higher elevation is generally more stable because of greater bedrock control exerted by competent lava flow rock and because of less weathering. Soils are shallow with very poorly developed clay fractions. These soils are generally drier and more permeable than the lower elevation soils, and they would be expected to have greater strength due to greater frictional resistance and better interlocking of soil grains.

The meager clay fractions of these soils gave XRD patterns which are primarily amorphous bands with a hint of chloritic intergrade and perhaps gibbsite (Figure 7). Likewise, the electron microscope revealed little more than bits of devitrified glass linked by amorphous strands. These constituents appeared similar to those seen in the drier, more stable soils flanking the debris flows mentioned earlier (Plate 3).

A number of sites at lower elevations (600 to 400 meters or less) could be judged as relatively stable, except for the occurrence of debris avalanching on steep slopes (50% to 100%). The clay of each of these sites contained kaolinite, as well as various combinations of chloritic intergrade, halloysite and amorphous material. Significantly, the chloritic intergrades had little smectitic character; the halloysites tended to be dehydrated and more often tubular rather than spheroidal; and the amorphous gel appeared to be generally thicker and stronger than that observed in the soil of the less stable sites. In addition, the halloysite tubules were commonly coalesced with the gel to form the beginnings of coherent, plate-like particles (Plate 5).

THE OVERALL SIGNIFICANCE OF CLAY MINERALOGY IN THE WESTERN CASCADES

Relationships to Landscape Development

Interpretations of aerial photographs and topographic maps, combined with on-site observations, suggest that the type of mass movement varies with stream drainage maturity or with position in the drainage. During geologic time, watershed drainage patterns probably have developed by a series of successively receding rotational slumps and subsequent earthflows, with an occasional debris torrent, avalanche or flow.

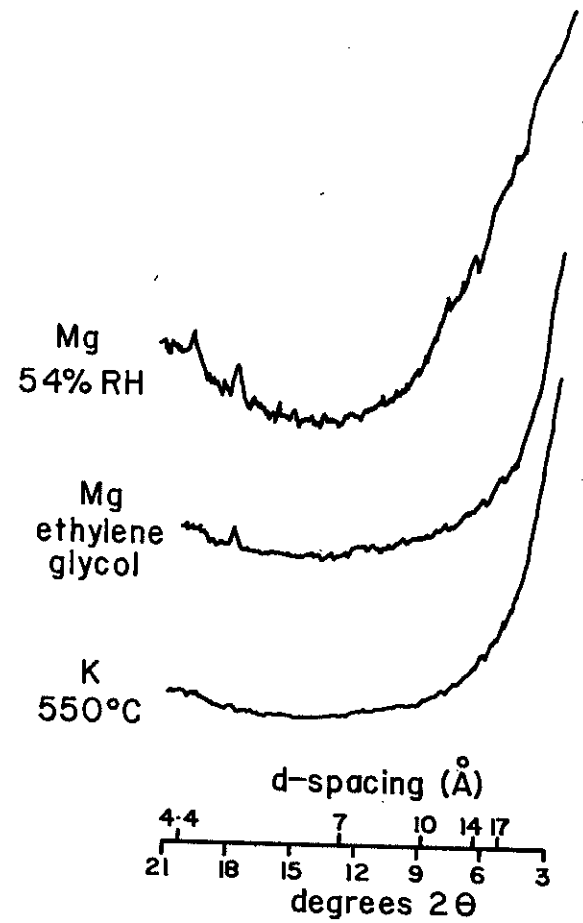


Figure 7. XRD patterns showing the poor clay development of the coarse textured and stable soil at site MK-F-1.

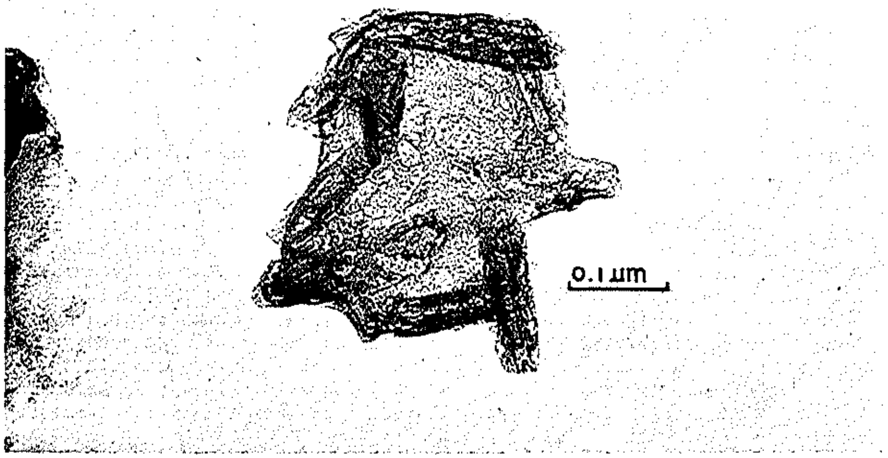


Plate 5. Electron micrograph of tubular halloysite and amorphous material forming an incipient plate-like particle which may be a precursor of kaolinite at relatively stable site SS-SF-7.

Large, well-defined rotational slumps seem to be most prevalent in the headwater regions where weathered pyroclastic deposits are overlain by lava flow rock which provides a substantial overburden pressure (Figure 8). Downcutting of the stream channel proceeds with relatively little resistance in the pyroclastic material, thus creating stream banks whose heights rapidly approach the critical value (Capper and Cassie, 1976; Terzaghi and Peck, 1967). Concurrently, the critical height value decreases due to a reduction in cohesive strength of the slope materials by weathering. The result, once the critical height is attained, is a large rotational slump. The process is especially notable along the contacts of the Sardine and Little Butte Formations--areas which appear to have experienced the most spectacular mass failures. These relationships have also been observed by other investigators (Swanson and James, 1975; Personal communications with F. J. Swanson, Geologist and D. N. Swanston, Principal Geologist, Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service, Corvallis, Oregon).

The situation is exacerbated by the fact that pyroclastic rocks in the Western Cascades weather to clay which is predominantly montmorillonite, which has long been recognized for its susceptibility to rotational slumping. The resultant soils, if they are deep and fairly homogenous, possess cohesive strength sufficient to preclude abrupt shallow failures of their mass. Instead, they are more likely to fail at a depth comparable to the lateral dimensions of the failure, because at that depth shear stress is sufficient to overcome shear strength. Most of the shear strength in homogenous plastic

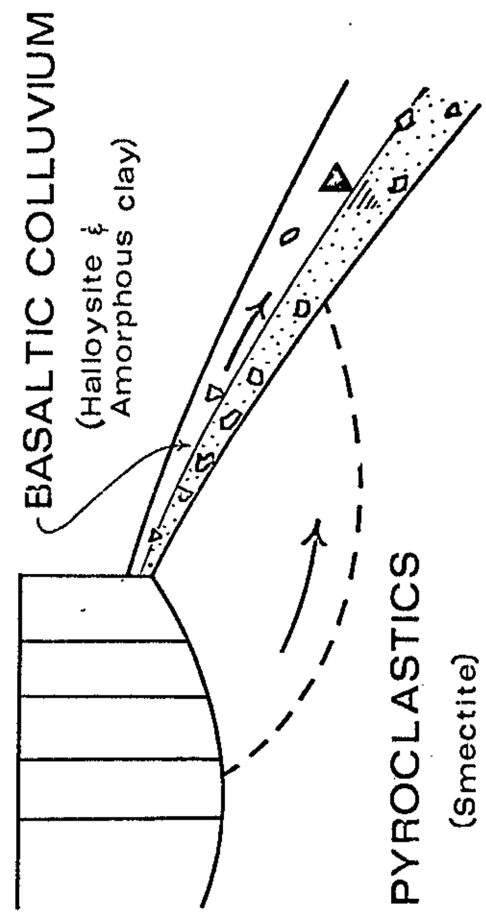


Figure 8. Rotational slump in smectite-rich, decomposed pyroclastic material capped by lava flow rock, and planar failure of basaltic colluvium containing halloysite and amorphous clays and a perched water table.

soils is due to the cohesive resistance, which is greatly reduced under the conditions of high pore water pressure.

The andesitic or basaltic overburden gradually breaks into cobbles which move downslope, forming a layer of colluvium over the weathering pyroclastic material (Figure 8). Additionally, on many sites volcanic ash from more recent eruptions (e.g. Mt. Mazama) has become mixed with the colluvial deposits. The presence of the underlying montmorillonitic clay which acts as a restrictive layer leads to the development of perched water tables in this soil. The colluvial debris and ash weather to amorphous gel and hydrated halloysite, which in turn help to maintain the soil's relatively high water content throughout the year. The combination of mineralogy, water and slope provides ideal conditions for the debris flows which commonly occur on top of the larger slump blocks.

Further downslope, the large saturated deposits of disintegrating slump blocks and colluvial debris grade into earthflows of mixed lithology. Several of the very large earthflows have soils whose clay fractions consist most importantly of amorphous gels and hydrated halloysite. It is inferred that these masses are sliding and moving downslope on top of a deposit of montmorillonite clay, which may also be moving. These large earthflows easily become dissected by deep V-shaped stream channels. The channels frequently develop along the flanks where they are downcut by waters draining from earthflows and from the lateral hillslopes with which they are in contact.

Debris avalanches contribute to further drainage development by scouring the steep hillslopes and sides of the deeply incised stream channels. The depth of these failures is determined by the presence of subsurface discontinuities, whereas failure is probably initiated by the development of abnormally high pore water pressures. The clay fraction of the soil subject to avalanching consists primarily of amorphous material--mostly devitrified volcanic glass and fibers--and chloritic intergrade, often with associations of gibbsite, dehydrated halloysite, kaolinite, zeolite, or mica. Smectites in relatively small amounts at bedrock contact promote debris avalanching of overlying shallow soil, largely because their presence decreases the soil's frictional resistance and impedes water flow.

Limited observations suggest that the process may be somewhat different in those areas which are more distant from the fringes of contrasting rock layers, and where the geology is composed more uniformily of pyroclastic rock which has weathered to smectite. In these areas, such as the upper reaches of the South Umpqua River, the rotational failures seem to be smaller and better defined than those which involve an overburden of competent lava rock. Earthflows, which may follow the slumping, also appear to be smaller in size and more easily delineated. Deep seated soil creep, which gradually produces a deformed, rumpled landscape, is a much more apparent process in these soils with a high proportion of the smectite type clays.

Summary of Important Clay Characteristics

Although it is well established that smectites are involved in mass movements throughout many parts of the world, the greatest mineralogical significance of this study lies in relating hydrated halloysite and amorphous materials, as well as smectites, to land failures in the volcanic deposits of the Western Cascades. In this area the failures are caused by profile discontinuities between smectite rich materials below the contact, and perched water tables and occurrences of halloysite and amorphous materials above. Amorphous materials and halloysite, particularly the dehydrated form, may also be found on stable sites. The reason for the seeming contradiction is that these soil components take on different forms and behavior under different sets of conditions. Therefore, the broad question of whether they contribute to stability or to instability is immaterial unless conditions are specified.

Water availability (current and historical) seems to be the most important factor controlling the form and behavior of halloysite and amorphous materials. Generally, it appears that in areas where these materials remain wet throughout the year they promote soil instability. Hydrated halloysite, amorphous gels, and imogolite which have not been allowed to dry have very high water holding capacities (Maeda and Warkentin, 1975; Warkentin and Maeda, 1974). The water is thought to be held between the separated layers in halloysite, and in voids between gel linkages and imogolite strands (Askenasy et al., 1973; Fieldes and Furkert, 1966). Electron micrographs produced in this study support these interpretations. Furthermore, they prompt the suggestion that the amorphous gels form microscopic balloons which are filled with water and a random assortment of clay particles. Assuming that the water balloon theory is correct, it is easy to visualize these fragile containers imparting a huge water holding capacity to the soil, and upon disturbance releasing the stored water while at the same time allowing the particles to rearrange themselves into a configuration of lower strength. In support of this, Wells and Furkert (1972) have shown that significant changes in water retention of amorphous materials takes place upon remolding of the soil.

Those relatively stable sites containing dehydrated halloysite and amorphous clays do not have perched water tables. They exist at higher elevations in environments where clay mineral development is minimal, or in areas in which the clays might have dried irreversibly at some time in their history, or at lower elevations in relatively well drained areas. The soils of these sites would be expected to have high frictional resistance in addition to their high permeability. The clay fractions as seen under the electron microscope contain irregularly shaped microaggregates of clay particles which are tightly bound by an intricate net of partially dried amorphous gel and imogolite strands. It is reasonable to assume that a considerable portion of the silt fraction of these soils is also due to aggregates of this type. Each of these aggregates probably acts as a primary soil particle which can have a very high degree of interlocking with its neighbor.

In many soils tubular halloysite conjoins with the gelatinous amorphous component to form what appear to be incipient platelets, which may be precursors of kaolinite. These seem to be more prevalent in well drained soils at lower elevation which give kaolinite peaks in X-ray diffraction; however, this relationship is not certain. These fused particles would be expected to contribute far more to soil shear strength than would the less organized arrangements of similar components on wetter sites.

For the most part, management implications are implicit in the information presented. A knowledge of the nature and behavior of the mineralogical components can aid in the recognition of critical areas. It should be emphasized, however, that once a critical area has been identified in these volcanically derived soils the major effort to control soil movement should be directed at controlling the distribution of water on the site. Usually, this can best be accomplished by intercepting the water upslope and directing it off the site. Amorphous materials and hydrated halloysite are well known for their tendency to dry irreversibly; as the amorphous gels dry they tend to crystallize into gibbsite or to form microaggregates which are presumably relatively stable and of greater strength than the original material. The result would be not only a soil with greater strength, but also one with better drainage characteristics. It must be remembered, however, that the great value of these soils as productive forest land is related to their great water holding ability.

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THE INFLUENCE OF CLEARCUTTING AND ROAD BUILDING ACTIVITIES ON LANDSCAPE STABILITY IN WESTERN UNITED STATES

Henry A. Froehlich[1]

INTRODUCTION

Stability is a highly prized condition in most of the affairs of humanity. If only things were stable, we could plan and act with confidence! Gentle changes--which may produce a greater change over time than periodic sudden events--are seemingly preferred. Applying this concept to soils, landslides have a dramatic and suddenly visual impact and are attention getting. Soil losses by smaller, but more continuous processes may move more soil over time. Although land instability has been the topic of considerable research, such studies have emphasized how society's uses influence slope stability. Much less research has been devoted to studying the occurrences of natural slides--their volumes and long-term impacts on a given landscape. Thus, we still have difficulty accurately assessing how harvesting and road building activities influence landscape stability in the long run.

The purpose of this paper is to review published observations of mass-soil movement. This discussion will focus on the timber harvesting and road building impacts and compare, where possible, the rate of soil movement in the managed areas with the mass-soil movement in undisturbed areas.

FACTORS IN SLOPE STABILITY

In the western United States, the present surface of much of the forest land reflects the influence of various degrees of soil creep, rotational landslides, shallow soil avalanches and massive earth flows which may include a complex of all these forms of soil instability (Varnes, 1958). Over time and space, the rates of soil creep vary enormously as do the frequency and size of mass soil movements. Swanson and Swanston (1977) noted that geomorphic observations and tree-ring analyses indicate that mass movement terrains may have histories spanning centuries, possibly millennia. Background values for evaluating the effect of certain forest land management practices are difficult

[1] Associate Professor, Forest Engineering Department, Oregon State University.
Paper 1291 of the Forest Research Laboratory, Oregon State University, Corvallis.