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INTRODUCTION

Forested soils formed in volcanic parent materials are an important group of soils in Montana. Having unique chemical and physical properties, they are some of our most productive soils.

Two groups of volcanic parent materials are recognized in Montana: old materials deposited over a very long period of geologic time and Recent ash (Klages 1978). The older materials occur mostly as small, isolated pockets of bedrock throughout the central and western part of the state. The second group of volcanic materials is a mantle of ash that covers extensive portions of the western part of Montana. This paper concerns soils formed in the second group.

The three volcanoes that contributed most ash to Montana are in the Cascade Mountains: Mazama (now the site of Crater Lake) in Oregon; and Glacier Peak and Mt. St. Helens, in Washington. Ash from Mt. St. Helens is the youngest and least extensive in Montana, covering a limited area in the northwest tip of the state. See Table 1.

In Montana, Mazama ash mantles three to four times as much area as Glacier Peak ash. Two studies have determined the thickness of each ash in the same profile and have found Mazama ash four or five times thicker. Mehringer et al. (1977b) found that Mazama ash was 8cm thick and Glacier Peak ash was 2 cm thick at Lost Trail Pass (the southern limit of the ash in Montana). Lemke et al. (1975) found the thickness for the same two ashes in Teton County, Montana, to be 15cm and 3cm, respectively. The main lobe of Mazama ash fall runs through Libby, Montana, in a northeast direction from the eruption, and extends at least to Edmonton, Alberta. See Table 2.

Table 1: Some Quaternary ash deposits in the Pacific Northwest (summarized from Powers & Wilcox 1964 and Fryxell 1965)

Ash	Source	Age (BP)	Miminum Area Covered (KM^2 x 1000)
Mt. St. Helens "Y"	Mt. St. Helens, WA	3,000	40
Mazama	Crater Lake, OR	6,600	900
Glacier Peak	Glacier Peak, WA	12,000	260

Table 2: Extent of the National Forests in Montana west of the Continental Divide mantled by volcanic ash. Forests arranged from north to south.

Forest	Percent mantled with volcanic ash*	Hectares mantled with volcanic ash
Kootenai (Northwestern Montana)	70	600,000
Flathead	70	735,000
Lolo	70	731,000
Bitterroot	20	132,000
Helena	2	9,000
Deer Lodge (Southwestern Montana)	2	10,000
Total		2,217,000

*Estimates of Forest Service soil scientists.

MINERALOGY

The unique properties of soils formed in volcanic ash can be traced to the deposit's mineralogy, especially the clay mineralogy. The mineralogy of ashes common to the Pacific Northwest has been reviewed by Harward and Borchardt (1969). They show that the widespread ashes (including Mazama and Glacier Peak) have a mineralogical composition similar to dacitic rocks. Dacite is intermediate in composition between rhyolite and andesite.

Ash has two components: a glassy matrix and crystalline minerals. The ratio of the two components varies among ashes but is not considered reliable for separating different deposits of ash (Harward and Borchardt 1969). The proportion of glass in the Mazama ash has been studied along a 450-km transect, from the source to Dick Springs in northeastern Oregon (Harward and Borchardt 1969). The percent of glass increases with distance from the source. At Dick Springs, the most distant site, ash is 72 percent glass. This suggests that the Mazama ash as it was deposited in Montana should have been at least 72 percent glass, although mixing with underlying materials and loessial contaminants has diluted the glass content.

The glass component in ash is important for a number of reasons. It weathers more rapidly than other silicate minerals. It is vesicular and, therefore, influences soil density. Glass content is a criterion in soil taxonomy. Glass abundance and shape have been used as a means for characterizing various ashes (Smith et al. 1968).

Harward and Youngberg (1969) consider the physical and chemical properties of the ash to be intimately related to internal pores in the glass. Smith et al. (1977 and 1977b) have photographed glass in Mt. St. Helens ash. Their micrographs show the vesicular nature of glass and voids that are mostly less than 20 microns in diameter.

Mazama ash pore size decreases with particle size: the mean size of the pores in the silt fraction would be less than six microns according to the data of Borchardt et al. (1968).

Busskohl (1979) has determined the amount of glass in various particle sizes of ash horizons in six soils in western Montana (Table 3). He found no glass in the very coarse, coarse or medium sand fractions and only a few percent in the fine sand fraction. The bulk of the glass is in the very fine sand and silt and clay fractions; in fact the percent glass in these two fractions varied from 32 to 77 percent. When the particle size distribution (Table 4) is weighted by glass content, it shows that about 75 percent of the glass in these soils is in the silt fraction. These data demonstrate that the medium, coarse and very coarse sand material are contaminants, either loessial or from lower sola.

Two of Busskohl's samples (Nos. 4 and 5) are from the Stillwater area north of Kalispell, in direct line with the main lobe of the Mazama ash fall and with the transect reported by Harward and Borchardt (1969). These data suggest that the glass content of the ash increases to the northeast from the source, but it plateaus and is constant after about 445km from the source (the farthest sampling point reported by Harward and Borchardt). Further work is necessary to explain glass distribution in ash horizons in western Montana.

The clay mineralogy of soils formed in Mazama ash in Oregon has been studied by Harward and his students (Chichester et al. 1969 and Dudas and Harward 1975a and 1975b). Invariably these authors and others working in other areas found an amorphous component (probably allophane) to be the dominant clay mineral.

Table 3: Glass shard content of various particle sizes in some ash soils from western Montana (taken from Busskohl 1979).

Glass Content (Percent) by Size Class

Sample No.	fine sand 0.1-0.25mm	very fine sand 0.05-0.10mm	silt & clay <0.50mm
1	2	56	55
2	2	77	32
3	4	50	53
4	4	60	70
5	4	70	75
6	3	62	35
Average	3	62	53

Dudas and Harward (1975a) propose the following weathering sequence for Mazama ash: Volcanic glass → allophane → hydrated halloysite → metahalloysite. Their data indicate that there has been relatively little weathering of Mazama ash in well-drained soils in Oregon.

Chichester et al. (1969) found some 2:1 phyllosilicates in soils formed in Mazama ash but these were later attributed to lithic contaminants or material mixed into the ash from the underlying solum (Dudas and Harward 1975b).

Klages (1978) characterized the clay mineralogy of Montana soils formed in volcanic ashes of a number of ages, from Recent (including Mazama) to Cretaceous. The clay mineralogy varied with ash age: amorphous clay was the dominant mineral in soils formed in Recent ash and mixed 2:1 clays in older volcanics. These data would seem to support adding a 2:1 phyllosilicate to the weathering sequence of Dudas and Harward under certain weathering conditions.

Amorphous clays play such a major role in the properties of soils formed in Recent ash that they deserve special mention. Amorphous clays differ from the more common crystalline clays, such as montmorillonite, in having a more random order to their atomic structure (Fieldes 1966 and Fieldes and Furkert 1966). The atoms in montmorillonite occur in a repetitive pattern but in amorphous clays there is much less order to the atomic structure. This becomes evident in the x-ray diffraction patterns of amorphous clays. The x-ray patterns of crystalline clays have sharp peaks but those of amorphous clays are fuzzy with subdued peaks.

Wada (1977) recognizes two major amorphous clays that occur in soils formed in volcanic ash: allophane and imogolite. They have very similar properties but differ in their Si-Al ratio. In this report the term *allophane* is used to cover the hydrous aluminosilicates that appear amorphous to x-ray diffraction.

Allophane is an important soil colloid (Fieldes and Claridge 1975). It is highly reactive: a small amount has great impact on a soil's physical and chemical properties. It commonly forms from glass, the structure of which is also largely random.

Wada (1977) discusses the physical and chemical properties of allophane. Allophane occurs as very small particles or aggregates of particles and has a very large surface area, much larger than montmorillonite. Because of its large surface area allophane has very high moisture-retention values.

Allophane has a high cation and anion exchange capacity with a large pH-dependent component. Flouride ions, for instance, seem to form a strong bond with aluminum after replacing OH groups from Al-OH linkages. Allophane forms complexes with organic matter that increase the latter's resistance to decomposition.

WEATHERING ENVIRONMENT

Weathering of ash, which determines the characteristics of the soils formed in it, is a function of climate and vegetation as well as the land forms on which it occurs. In general ash occurs only on moist sites, never in areas of less than about 56cm of precipitation. The common condition in the 56-to-100cm precipitation zone is to find ash on the north and gentle slopes but not on the south or steep slopes. Above 100cm of precipitation, ash occurs on almost all landforms and aspects.

In western Montana two factors are responsible for precipitation distribution: orographic lifting and topographic features. Because of orographic lifting, a gradient of increasing precipitation with elevation exists: precipitation is greater near the tops of the mountains than in the valley bottoms. However, some local topographic features cause interception of moisture and areas of relatively high precipitation at low elevations. Thus ash is normally found on the mountains, but in certain areas of relatively high precipitation it occurs at low elevations.

The presence of ash on north aspects and its absence on adjoining south aspects is one of the anomalies of ash distribution. One theory to explain this pattern is that the ash was filtered out of the atmosphere by raindrops and deposited on all aspects. Because there is more vegetation on the north aspects, the ash was protected and did not erode off the surface. However, if this had occurred, a tremendous amount of ash would have eroded off these mountain slopes in the last 12,000 years. An accumulation of ash at the base of many slopes should exist: its absence casts considerable doubt upon this erosion theory. Another possibility is that ash was blown off the south slopes onto north slopes.

While ash is generally restricted to moist sites, the air temperature in areas where it occurs is variable. In Trout Creek, Montana, (elevation 800m), one of the lower areas where ash occurs, the mean annual air temperature is 7°C. Near the alpine zone (elevations from 3000m to 2200m) the mean annual air temperature is 0°C. Because ash occurs in both areas, 7°C represents the minimum range of air temperature in areas of ash soils.

The vegetation which occurs in association with ash is characteristic of mesic forests (Nimlos 1963) and includes the following species:

<u>Overstory</u>

Thuja plicata	western redcedar
Tsuga heterophylla	western hemlock
Abies lasiocarpa	subalpine fir
Pinus contorta	lodgepole pine
Picea engelmanii	Englemann spruce
Pinus monticola	western white pine
Larix occidentalis	western larch

<u>Understory</u>

Clintonia unifolia	queencup beadlily
Vaccinium spp.	huckleberry
Xerophyllum tenax	beargrass
Menziesia ferruginea	Menziesia

These species are in habitat types of the following series (Pfister et al. 1977): *Picea, Abies grandis, Thuja plicata, Tsuga heterophylla, Abies lasiocarpa,* and *Pinus contorta*. In the northwestern part of the state, where ash is most widespread, ash frequently supports species of habitat types in the *Pseudotsuga menziesii* series. This series occurs on slightly drier sites than those listed above.

Mehringer, Arno and Petersen (1977) reported the pollen history in a bog near the southern limit of Glacier Peak and Mazama ash falls. Their data indicate the following floral history:

Steppe	Whitebark pine	Douglas-fir Lodgepole pine	Subalpine fir
12	7*	4	0

Years before present x 1000

*Mazama ash fall

These data show that the vegetation since the deposition of Glacier Peak and Mazama ash has not changed significantly and that for almost all of the time since ashfall the vegetation has been what we now would characterize as a dry, cool forest. Under these climatic conditions weathering and pedogenesis would be relatively limited, especially since the ash deposits are young (less than 12,000 years old).

PHYSICAL PROPERTIES

The physical and chemical properties of soils formed in volcanic ash vary with distance from the source, mineralogic composition of ash and purity of the deposit. This report considers only relatively pure ash as it occurs in Montana.

Density. The most distinctive morphological feature of Recent ash is its light, fluffy character. Whereas the bulk density of surface horizons of most uncultivated, forested soils is from 1.0 to 1.3gm/cc, volcanic ash mantles have densities between 0.75 and 0.90gm/cc. Even when soil is compacted, densities remain surprisingly low; studies on the Kootenai National Forest (Kuennen et al. 1979) indicate that while underlying horizons may approach densities of 1.8 gm/cc when compacted, ash will only compact to 1.1-1.3gm/cc.

Very little work has been done on the reason for the low density. David (1970) measured particle densities of Mazama ash in Saskatchewan, Canada, and found it to be 2.46gm/cc. Also Schruger (1979) found the particle density of Recent ash in western Montana to be from 2.33 to 2.62gm/cc, which is within the range of most minerals. Thus, low bulk densities cannot be attributed to unusually low particle densities.

The vesicular nature of some Recent ash has already been described. Harward and Youngberg (1969) present some data on porosity taken from Doak (1969), indicating that the porosity of the coarse sand fraction of Mazama ash is 0.8-1.0ml/gm, which is bulk density of 1.0 to 1.2gm/cc. The authors state that porosity decreases with particle size. The particles in Montana are smaller than coarse sand and should have a lower porosity and higher bulk density although this is not the case. (This is a subject for further study.)

The low bulk density may also be due to particle aggregation. Samples of Recent ash were recently cleaned with hydrogen peroxide and a reducing agent; the samples were studied microscopically. When the cleaning treatment is not prolonged, aggregates of particles are common in the sample. Also Harward and Youngberg (1969) report that some of the coarse sand of Mazama ash they studied appeared to be aggregate lapilli. The vesicular nature of ash, the aggregating of the particles and the complexing of the organic matter must combine to create low density.

Color and Feel. The color of ash mantles is quite uniform. The most common color is dark yellowish brown (10 YR 4/4) although in areas of relatively pure ash the chromas may be 6 or even 8 (all notations follow the Munsell color system). In reduced environments (wet bogs) or when the soil has been treated to dissolve iron coatings, the color is light brownish grey (10 YR 6/2). The feel of ash material has been described as "smeary" or "greasy" (Ottersberg 1977).

Particle size distribution. Table 4 presents the particle size distribution for typical ash mantles as they occur in Montana. These data show that the dominant fraction is silt with minor amounts of clay. The coarse sands are probably loessial (non-ash) contaminants. The long distances traveled by ash should have caused uniform textures throughout its distribution and indeed this is the case. Textures are normally loam, sandy loam or silt loam.

Table 4: Particle size distribution by weight in some ashes in Montana (Forest Service 1972).

Size Fraction	Holloway	Craddock	Truefissure
Very Coarse	-------percent by weight-------		
(2.0-1.0)*	6	7	4
Coarse			
(1.0-0.5)*	4	6	4
Medium			
(0.5-0.25)*	2	2	3
Fine			
(0.25-0.10)*	6	5	11
Very Fine			
(0.10-0.05)*	12	10	14
Silt			
(0.05-0.002)*	65	63	55
Clay			
(<0.002)*	5	7	9

*mm

Water Retention and Transmission. Soils formed in volcanic ash store considerable volumes of water. This is crucial to the ecology of this area because soils are recharged with moisture only in the spring. This reservoir must sustain plant growth during the growing season. In the spring, water can be wrung from these materials by squeezing them in hand, as with organic soils. Data of Fosberg et al. (1979) and the U.S. Forest Service (1972) demonstrate the high water-holding capacities of these soils. Their data show that the field moisture capacity (the amount of water the soil will retain against the force of gravity) and the permanent wilting coefficient (the amount of water a soil will retain against the force of plant absorption) are two and four times higher in ash than in lower horizons without ash.

The soils also have very high infiltration rates. Kuennen et al. (1979) found infiltration rates of 20cm/hr after 15 minutes of wetting in an undisturbed soil formed in ash. Infiltration rates in soils formed in other materials are commonly less than 5cm/hr under similar wetting conditions.

Boundary. The boundary between ash and underlying materials is abrupt, a feature commonly used for identification of ash mantles. Fosberg et al. (1979) have found very little mixing of ash in the Mission soil of northern Idaho. Field observations of the Cabinet soil (and others without coarse fragments) in Montana support this view.

Nodules. Under certain conditions small spherical nodules with external colors similar to ash occur in ash mantles. Because their color is similar to the soil matrix it is difficult to separate nodules from coarse fragments. According to the classification system of Brewer and Sleeman (1964), they should be called nodules because concentric rings are not present. Two types of nodules are found in the ash mantles: (1) very small (< 2mm), black-centered; and (2) larger (<8mm), brown-centered. The former are quite common but never constitute a significant portion of the soil volume. They are difficult to locate and have not been studied. The other group of nodules occurs only in ash mantles over silts or clays and may constitute a significant portion of the horizon, as shown in Table 5. These data of the Cabinet series (Andeptic Cryoboralf -- mixed, fine loamy; formed over lacustrine silts and clays) show that most of the nodules are in the 0.5 to 2.0mm size fraction. The maximum diameter measured in the Cabinet series was 8 mm. Fosberg et al. (1979) and Garber (1966) have reported similar volumes of nodules in ash horizons over lacustrine silts and clays in Idaho.

The genesis of the nodules is not clearly understood. Nodules in the Cabinet soil were found to be iron-enriched: 3.32 percent with standard deviation = 0.062 in the total soil and 4.13 percent with standard deviation = 0.057 in the nodules. Fosberg et al. (1979) found similar enrichment of nodules in the Mission soil in northern Idaho. Iron probably plays a role as a cementing agent.

Concretions have been reported in soils that are either poorly drained (Drosdoff and Nikiforoff 1940) or that occur in a moist environment and have underlying, fine-textured horizons (Clark and Brydon 1963). It is this study's hypothesis that the genesis of the nodules must be caused by the restricted drainage enhanced by the fine-textured, subsurface horizons.

Table 5: Nodule size distribution in the ash mantle of two Cabinet soil profiles (percent by weight).

>4.76 mm	2.00-4.76 mm	1.00-2.00 mm	0.50-1.00 mm	0.25-0.50 mm	Total
0.8	7.5	11.2	11.4	8.0	38.9

CHEMICAL PROPERTIES

Cation Exchange Capacity. The cation exchange capacity (CEC) of ash soils is high and pH-dependent. Fosberg et al. (1979) found cation exchange capacities of 15.4 to 29.1me/100gm in ash horizons of a Mission soil in northern Idaho and the U.S. Forest Service (1972) reports 11.4 to 22.0me/100gm for comparable horizons in the Holloway soil (Andic Cryochrept; loamy-skeletal, mixed) in western Montana. These values are very high when compared to the amount of clay (4.5 to 10.6 percent). Exchange capacities for the Holloway soil, for instance, when expressed on the basis of 100gms of clay, are 183 to 268me/100gm in the ash layer and 50 to 84me/100gm in the lower horizons.

Jackson (1965) proposes the delta CEC to indicate the amount of pH-dependent charge. The delta CEC is the difference between the CEC determined at pH 10.7 and 3.5. Fosberg et al. (1979) found the delta CEC in ash horizons of the Mission soil to range from 20.0-42.5me/100gm but from 0.4 to 4.2me/100gm in underlying horizons that did not contain allophane and were not formed in ash.

Phosphorus fixation. Soils formed in volcanic ash are notorious for fixing phosphorus in a form that is unavailable for plant uptake (Jones et al. 1979). Allophane is partly responsible for the fixation as are concretions (nodules) where they occur.

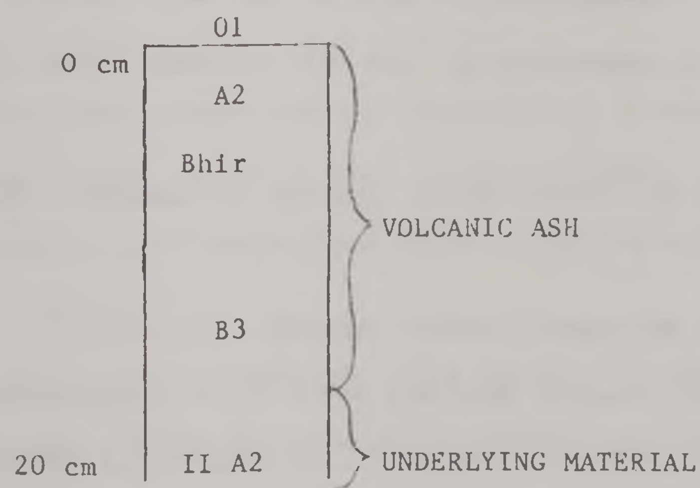
pH. The pH of ash mantles is normally from 5.5 to 6.0. It is lower in the A2 of those profiles with some development in ash.

FIELD IDENTIFICATION

Field soil scientists in Washington State have been using a sodium fluoride quick test to determine ash purity. Fieldes and Perrott (1966) have shown that the fluoride ion replaces some OH groups on allophane, causing a dramatic pH increase proportional to allophane content. Sodium fluoride increases the soil pH in Idaho ash soils four or five units, three units higher than lower horizons (which are allophane-free) (Fosberg et al. 1979).

PEDOGENESIS

Soil development in the ash is minimal: in most cases weak structure is the only indication of pedogenesis. However, some evidence of eluviation and illuviation can be found on gentle, north-facing slopes at elevations of 2000 meters (6000 feet) or more and on wet (but well-drained) sites. The profile has these features:



This morphology is typical of a Spodosol, although no analyses have been made to determine whether the Bhir (a subsurface horizon of iron and organic matter enrichment) meets the chemical requirements of a spodic.

Stone (1978) analyzed the iron distribution in a profile with a morphology like that shown above. He found an iron bulge in the Bhir, indicating that some iron had eluviated out of the A2. Thus it appears likely that the white A2 is not another ash, but is the result of pedogenesis.

TAXONOMY

Soils formed in volcanic ash are recognized at three levels in the taxonomy (Soil Survey Staff 1975): suborder, subgroup, and family.

Suborder. Those soils formed in relatively thick and pure volcanic ash are classified as Andepts. They are well-drained soils, with 35cm or more of volcanic ash that meet requirements 1 or 2 or both.

1. Bulk density (at 1/3 bar water retention) of 0.85g/cc and the exchange complex dominated by amorphous material as indicated by:

   a) The exchange capacity at pH 8.2 is 150meq (milliequivalents) per 100gm measured clay and commonly is 500meq per 100gm.

   b) If there is enough clay to have 15-bar water content of 20 percent, the pH of a suspension of 1gm soil in 50ml 1N NaF is 9.4 after two minutes.

   c) The ratio of 15-bar water content to measured clay is more than 1.0.

   d) The amount of organic carbon exceeds 0.6 percent.

   e) Differential thermal analysis shows a low temperature endotherm.

2. Sixty percent or more of the soil (by weight) is vitric volcanic ash, cinder or other vitric pyroclastic material. Vitric volcanic ash is defined by *Soil Taxonomy* as: (a) glass (b) partially devitrified glass (c) crystalline particles coated with glass.

Andepts (and Andeptic subgroups) occur in Montana but only in the very northwest part of the state. Three established soil series of Cryandepts are recognized in Montana (Hopkins 1979).

Subgroup: Those soils formed in relatively thin and impure volcanic ash are classified as Andic subgroups. Taxonomic requirements for the Andic subgroup are not precisely defined in *Soil Taxonomy*. T.J. McClelland, federal taxonomist formerly with the Soil Conservation Service, has proposed the following requirements for soils in the Andic subgroup.

1) A layer in the upper 75cm with a texture finer than loamy sand.
2) Thickness of volcanic ash between 18 to 35cm.
3) Bulk density (at 1/3 bar water retention) of 0.95gm/cc or less in the fine earth fraction.
4) A ratio of measured clay to 15-bar content of 1.25 or less, or a ratio of CEC (at pH near 8) to 15-bar water content of 1.5 and more exchangeable acidity than the sum of the bases plus KCl-extractable aluminum.

Andic subgroups have a more general distribution in western Montana. They occur from Lost Trail Pass north to the Canadian border, generally at higher elevations. Four established series (and three tentative series) are recognized in Montana (Hopkins 1979).

In addition to the Andic subgroups, two series of Andeptic subgroups are recognized in the state. These soils have ash layers that meet the requirements of the Andept suborder but are recognized at the subgroup level. Three established series (and one tentative series) of Andeptic subgroup are recognized in Montana.

SUMMARY

Soils formed in a surface layer of volcanic ash are common in the mountains of western Montana. They are usually found on moist but well-drained sites. They have many favorable physical properties including high moisture-holding capacity and low density (high porosity). They have high cation exchange capacities but may contain considerable amounts of fixed phosphorus. This paper was written to summarize our understanding of this important group of soils in preparation for research into their genesis.

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