The Age and Origin of Soil Mounds on Manastash Ridge in Kittitas County, Washington

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Abstract

Soil mounds located on Manastash Ridge, in Kittitas County, share similar shapes and compositions to those found elsewhere on the Columbia Plateau (Kaatz, 1959). Numerous theories attribute mound formation to erosion, deposition, burrowing animals, and cold climate processes (Washburn, 1988). Theories in support of mound development during the mid to late Holocene, such as burrowing animals, suggest the features are younger than 7,500 years (Cox, 2012) While those in favor of the cold climate theory argue mounds formed, prior to the Holocene, 11,700 years ago (Tullis, 1995). Preliminary thermoluminescence (TL) dating of mounds located in the Kittitas Basin suggest they formed in the early to mid-Holocene, 5,600 to 7,800 years ago (Bandow, 2001). In addition, absolute and relative dating results from this study of three soil mounds located on Manastash Ridge, suggest that the soil mounds are less than 2,000 years old. The young age of the soil mounds indicates that they are not cold climate features. Analysis of soil stratigraphy further suggests that burrowing animals and erosional processes are less likely to be responsible for soil mound formation. Based on these results, it is likely that the soil mounds formed in the late Holocene and are the results of depositional processes.

Introduction

Soil mounds and stone rings creating patterned ground features are present throughout the Columbia Plateau (Tallyn, 1980; Johnson and Burnham, 2012). Mounds located on Manastash Ridge, in Kittitas County, share similar shapes and compositions to those found elsewhere on the Plateau (Kaatz, 1959). The "Manastash Mounds" are circular to oval, 6 to 40 meters in diameter, and ~1-meter-high (Figure 1 and Figure 2). Mounds are typically more circular on level ground and elongate as slope angle increases (Figure 3). The soil heaps are irregularly spaced, and the intermound areas are composed of weathered basalt lying under shallow, rocky soils. Sorted stone rings, wholly or partially, border the mounds (Figure 4).

Figure 1. Soil mound approximately 1 meter high. Image from Ellie Myers, 2018.

Figure 2. Aerial view of soil mounds. Image from Google Earth, 2018.

Figure 3. Example of soil mound elongation down slope Image from Google Earth, 2018.

Figure 4. Example of stone ring surrounding soil mound. Image from Ellie Myers, 2018.

Numerous theories attribute mound origins to erosion, deposition, burrowing animals, and cold climate processes (Washburn, 1988). Mounds occur on surfaces of varying age, parent material, locations, and elevations on the Columbia Plateau. Identifying a single cause of formation is difficult.

Brunnschweiler (1962), Kaatz (1959), and Bandow (2001) previously studied soil mounds on Manastash Ridge. Kaatz (1959) and Brunnschweiler (1962) speculated that the Manastash Mounds where frost action features that formed under a periglacial climate. They argued that patterned ground found in high latitudes best resemble the soil mounds and stone rings found in Kittitas County.

For patterned ground to develop under a cold climate regime on the Columbia Plateau, temperatures here would have to be ~8.5°C cooler than they are today (Tallyn, 1980). Pollen dates, from Carp Lake on the Plateau, suggest such a climate persisted 25,000-10,000 years ago

(Barnosky, 1985). To support the cold climate theory mounds on Manastash Ridge need to have developed during the late Pleistocene and early Holocene, no later than 10,000 years ago (Fryxell, 1964).

However, in a recent study using thermoluminescence dating, Bandow (2001) proposed that soil mounds found in Kittitas County are early to mid- Holocene features. Bandow (2001) analyzed mounds in three locations, Thorp Prairie, Manastash Ridge, and north of Ellensburg. He collected soil samples from one mound at each location to determine their limiting age. Dates from sediment collected at Manastash Ridge and Thorp Prairie suggested that the mounds formed 7,800 ± 700 and 5,600 ± 500 years ago.

Although Bandow's (2001) limiting ages suggest they are mid-to-late Holocene features, old age should not be ruled out. It is plausible that these features are older than the data collected by Bandow (2001), given the evidence of bioturbation and cryoturbation in the mounds upper soil horizons. Bandow (2001) also advises that his data might not be reliable because there are no other absolute dates to correlate with his TL ages, such as a tephra layer.

Purpose

The purpose of this research was to use absolute and relative dating techniques to determine the ages of three soil mounds located on Manastash Ridge in Kittitas County, Washington. The absolute age of the soil mounds was determined using optically stimulated luminescence (OSL) dating. Similar to TL dating, OSL dating can be used to determine the last time buried soil particles were exposed to solar radiation. However, as Bandow (2001) stated, there is potential for error with absolute dating techniques due to translocation of surface soils to lower horizons. To ensure absolute dating accuracy, relative age indicators, including soil color, structure, consistence, texture, and calcium carbonate concentrations, were analyzed alongside OSL.

Significance

The findings of this study were significant because they helped resolve questions about the Manastash Mounds origins by providing an approximate age of two mounds. Theories in support of mound development during the early to mid-Holocene, such as erosion and burrowing animals, suggest the features are younger than 7,500 years (Cox and Hunt 1990; Reed and Amundson, 2012; Horwarth Burnham et al., 2012; Cox, 2012). Those in favor of the cold climate theory contest the notion of new features and argue mounds formed, before the Holocene warming, about ~ 7,500 years ago (Fryxell, 1964; Prych, 1973; Nelson, 1977; Tallyn, 1980; Tullis, 1995).

Background: Mound Origin Theories

Erosion

Many authors have attributed soil mounds and stone pavement formations to erosional processes (LeConte, 1873; Piper, 1905; Waters & Flagler, 1929; Freeman, 1932; Wilson & Slupetsky, 1977; Knechtel, 1952; Ritchie, 1953; Washburn 1988). The general idea is that soil mounds represent a once continuous soil mantle that was eroded by water, wind, or ice.

LeConte (1873) studied the "prairie mounds" of John Day Valley, north of the Deschutes River in Oregon and was the first to suggest that soil mounds were the result of erosional processes. He assumed that the mounds were a "result of irregular surface-erosion under particular conditions" (LeConte, 1873, p. 366). The conditions under which the mounds formed were two discontinuous layers of glacial till lying on top of a pebbly bedrock and a treeless terrain. A layer of fine, movable till sat on top of a more consolidated layer. Then, surface-erosion cut through the two layers to the pebbly bedrock and removed the finer layer of till. Vegetation anchoring prevented further erosion, and the more consolidated layer remained. LeConte (1873) attributed

the size of the mounds to the thickness of the more consolidated soil, and the round to elliptical shape to the slope angle. A treeless landscape was an essential element for the formation of the mounds because, without abundant vegetation, there was nothing to hold the continuous soil surface together. He further supported his surface-erosion theory by noting the broad pebbly intermound areas between the features as evidence that the mounds were remnants of a once even surface.

Waters and Flagler (1929) studied soil mounds on the Columbia Plateau in Eastern Washington. They proposed that mounds formed from fluvial erosion over ashy deposits lying over basalt bedrock. Fluvial processes stripped the ashy deposits from the intermound area, leaving behind furrows. As more fluvial processes acted upon the ashy surface, the furrows grew deeper and wider, eventually leaving behind the soil mounds. They believed that the mounds were remnants of a once continuous soil surface.

Freeman's (1932) theory of mound origin in the Scablands of eastern Washington accounts for evidence of fluvial erosion presented by Waters and Flaggers (1929). He suspected that volcanic eruptions distributed ash throughout Eastern Washington sometime after the Ice Age floods (Freeman, 1932). Vegetation growing in depressions on the basalt bedrock retained the falling ash. Intermound areas that lacked soil moisture for vegetation growth had increased rates of erosion. The loess continued to accumulate in the depressions while fines were removed from the intermound areas, exaggerating the soil mound features.

Wilson and Slupetsky (1977) referred to soil mounds on the western Snake River Plain as features resembling patterned ground found in periglacial environments. They attributed patterned ground origins to fluvial erosion. Running water stripped fines away and left behind piles of lag on the basalt bedrock surface. They theorized that soil surfaces were left behind due to fluvial

drainage systems. The mounds became more exaggerated over time as sediment in the intermound area was removed via fluvial erosion. They emphasized the importance of slope angle and its correlation to mound elongation. Wilson and Slupetsky (1977) also addressed the concentration of fragmented materials found in intermound areas and attributed them to frost action processes.

Knechtel (1952) attributed mound formation to a combination of columnar jointing of basalt bedrock and fluvial erosion. He examined photographs of mound features studied by Waters and Flagler (1929), concluding that furrows were not a result of random fluvial erosion the authors had described (Knechtel, 1952). Instead, the particular formations were interpreted as "expressions of cracks in the basalt floor" that created a vast system of the polygonal patterned ground. Cracks originated from joints in basalt bedrock were sometimes up to many feet in diameter.Soil mounds formed in the center of these polygonal cracks as fluvial erosion continued to remove sediment.

Deposition

The deposition theory suggests that soil mounds are sand dune-like features composed of wind-blown sediment (Freeman, 1926; Olmsted, 1963).

Olmsted (1963) supported the depositional origin of silt mounds in the Channeled Scablands in Eastern Washington. He concluded that the silt mounds were a type of dune or obstacle-caused drift because the mounds have convex slopes on both windward and leeward sides (Olmsted, 1963). Olmsted (1963) insisted that the available sediment sources, dry climate, and westerly winds in eastern Washington make the Columbia Plateau an ideal place for sand-dune formation. Eastern Washington lies in the Cascade Range's rain shadow, so precipitation is around 23-60 centimeters annually on the Scablands. The wind blows almost daily as well. This dry and windy setting results in the daily transport of sediment throughout the summer months.

Olmsted (1963) suggested that sediment-rich, dry air was cooled and carried to high elevations as it traveled east across the Plateau (Olmsted, 1963). Relative humidity rose as air temperature dropped. The suspended sediments absorbed H_2O in the air, became heavy, and settled evenly over the area. Pitted surfaces occur where the Ice Age floods removed sediment and bedrock on the Channeled Scablands, and selective erosion removed sediment from areas higher than the depressions.

As sediment accumulated in the depressions and built up to the same level as elevated areas, vegetation and moisture began to slow down wind erosion so that deposition continued to exceed erosion within the depressions (Olmsted, 1963). As vegetation anchored sediment in the depressions, moisture in the mounds, called vadose water, moved upward due to capillary action from water evaporating at the soil surface. Vadose water slowed down the rate of erosion compared to the rate of deposition by consolidating the silt particles.

Olmstead (1963) believed that vadose water accounted for mound formation because moisture should effectively slow wind erosion. He attributed elongation of the silt mounds to less friction on the windward and leeward sides of the features resulting in growth in the direction of the prevailing wind because the deposition exceeded erosion.

Freeman (1926) suggested that soil mounds in the Scablands of eastern Washington were the result of sediment deposition in depressions in basalt bedrock made by the Ice Age floods (Freeman, 1926). Sediment caught in the depressions was protected from wind erosion and developed into soils. Vegetation began to grow in the depressions where soils formed due to moisture entrapment. Vegetation acted as an anchor and trapped incoming sediments causing elevated features to rise from the depressions.

Burrowing Animals

A widely supported theory for soil mound and stone pavement formation throughout the Pacific Northwest is bioturbation via burrowing animals (Larrison, 1942; Scheffer, 1947; Scheffer, 1958; Price, 1949; Cox, 1984; Cox et al., 1987; Cox & Hunt, 1990; Cox, 2012; Reed & Amundson, 2012; Irvine & Dale, 2012; Horwarth Burnham & Johnson, 2012; Horwarth Burnham, et al., 2012; Johnson & Johnson, 2012).

Larrison (1942) studied soil mounds found on Rocky Flat near Wenas, Washington. After reviewing Dalquest and Sheffer's (1942) hypothesis on Mima mound origins in southwestern Washington, Larrison concluded that pocket gopher activity was responsible for the formation of the "mound-shaped features" (Larrison, 1942, p. 35). The author theorized that pocket gophers penetrated the rock surface layers on the plateau and burrowed out in multiple directions. All displaced soil was translocated by the gophers back to the original surface opening. Continual burrowing activities below the rocky surface resulted in the buildup of mound-like features within the animal's central territory. Over time, vegetation growth on top of the mounds resulted in more pocket gopher activity within the soil features. The soil was further displaced and deposited on the mound slopes rather than the top causing their slopes to steepen and the tops to flatten.

Larrison (1949) noted that the mounds were composed of more soil than was available on the surface at Rocky Flat, near Wenas, Washington. He observed other locations on the Columbia Plateau as being more level compared to the soil mound areas and attributed the concave nature of the intermound areas to the soil being translocated from the subsurface to the surface. He attributed the rest of the mound soil volume to excess tunneling outward and the "fluffiness" of the soil via pocket gophers.

Sheffer (1947; 1958) studied soil mounds near the southern extent of the Puget Sound in western Washington and concluded that pocket gophers were responsible for soil mound formations. He believed that the gophers "footed" through thin, gravely outwash deposits in search of roots. The gophers eventually burrowed into the finer outwash deposits lying under the coarser material and displaced finer soils at the surface.

Sheffer (1958) suggested that the pocket gophers deposited sediment in circular soil heaps because they tend to tunnel outward from a central location. His theory was supported by the lack of large and immovable material found within the mounds. The material in the mounds was small enough for pocket gophers to move. He speculated that the cobbled rings around the mounds were extra material too big for the gophers to move that they instead worked around. The mounds also only appeared where thin soils overlie impermeable parent material and bedrock. Sheffer concluded that pocket gophers constructed the mounds because they are only able to survive in well-drained soils. Before the mounds where constructed that shallow intermound soil would have been seasonally waterlogged.

Cox et al. (1987), Cox and Allan (1987), Cox and Hunt (1990), and Cox (2012) theorized that pocket gophers were responsible for soil mound and stone circle formation in the Lawrence Memorial Grassland Preserve Wasco County, Oregon. The authors assumed that gophers created mounds in areas of poorly developed and thin soils to prevent waterlogging. They also addressed the stone circles surrounding the mounds, which previously has been attributed to cold climate processes, and suggested that pocket gophers were responsible for their formation as well.

Their research concluded that pocket gophers were most active in intermound areas during dry seasons where soils are not waterlogged. They suggest that the gophers dig tunnels under the intermound areas during dry seasons. The translocated soils are moved to a central location (i.e.,

soil mound). Then the hollow tunnels fill in with fine sediments from the intermound surface during wet seasons. The fines that settle into the tunnels are moved by the gophers and deposited on the soil mounds. Eventually, all fines are removed from the adjacent areas bordering the mounds. The stone circles wholly or partially surround the mounds and are approximately a meter wide. The stone circles change with increasing slope because the upper edges of the mounds exhibit higher concentrations of soil moisture compared to the lower areas where a "moisture shadow" occurs (Cox et al., 1987 p. 1404). The pocket gophers are more active in these moist areas, so stone circles are more developed in the upper areas of mounds located on slopes.

Cold Climate

The cold climate phenomenon has been used to explain soil mound and stone pavement formations on the Columbia Plateau (Pewe, 1948; Newcomb, 1952; Kaatz, 1959; Malde, 1961; Malde, 1964; Fryxell, 1964; Fosberg, 1965; Pyrch, 1973; Nelson, 1977; Tallyn, 1980; Johnson, 1982; Washburn; 1988; Tullis 1995) (Table 4). Cold climate processes, better known as periglacial, were first introduced in 1909 by Walery Lozinski as a classification for environments surrounding Pleistocene glaciers experiencing frozen ground geomorphology due to frequent freeze-thaw events.

The term periglacial was expanded to a wide range of tundra and alpine environments that experience annual temperatures below 1.7°C, mass wasting, and frost action regardless of frozen ground association or glacier situation. Frost action is a fundamental feature of periglacial environments because ice segregation can result in diverse forms of frost wedging, frost heaving and thrusting, mass displacement, frost cracking, and frost sorting. The effectiveness and severity of frost action depend on opened or closed systems, available moisture, temperature, pressure, mineralogy, and particle grain size (Washburn, 1980). If these conditions are just right, frost action

processes can produce patterned ground. Washburn (1980) classified patterned ground into five groups: circles, nets, polygons, steps, and stripes. Circles, nets, and polygons typically occur on relatively flat surfaces and elongate into steps and stripes as slope angles increase.

Detailed frost action processes that link physical geography to patterned ground formation can either be dependent or independent from cracking such as general frost cracking, desiccation cracking, and dilation cracking (Washburn, 1980). Desiccation cracking results in the cracking of ground as soils dry due to clay and salt content in the system. The cracking usually leads to dome-shaped patterns that are less than 1 meter in diameter. Dilation cracking is the result of stretching ground, although it is not common for circles to form this way. Where cracking is not a factor, sorting is the initial instigator for patterned ground. Primary frost sorting and mass displacement are the main factors here, along with sub-sorting processes such as salt heaving, and differential thawing and eluviation. Salt heaving results from expansion due to salt crystal growth, and differential thawing and eluviation occurs when temperature gradients cause movement in the system.

Kaatz (1959) studied patterned ground on the Manastash Ridge and assumed that mounds formed under intense frost action during a periglacial climate. He argued that, during the glacial maximum in the Pacific Northwest, areas adjacent to glaciation, yet not glaciated, were still subject to a colder climate. Permafrost could have formed in soils formally located where patterned ground is found today, but Kaatz (1959) emphasized that the impermeable basalt bedrock layer could have behaved similarly to frozen ground. Waterlogging of soils over the impermeable basalt bedrock would have created intense frost action processes that could have potentially led to ice wedges. Seasonal warming and cooling led to contraction and slumping due to melting ice wedges. Fines and course material would have sorted out from one another due to multiple freeze-thaw events,

causing polygonal cracks to form and the ground to mound up. Kaatz also (1959) suggests that sorted stone pavements surrounding the mounds were formed after the "segmenting of the unmounded mantle" because the stone patterns are found alongside the mounds, not beneath them (Kaatz, 1959, p. 154). He argued that seasonal freeze-thaw would have continued to heave fractured basalt upward within polygonal cracks.

Brunnschweiler (1962) studied the periglacial zone of the United States during the late Wisconsin glaciation and concluded that intense frost action under a cold climate was responsible for the formation of sorted circles, polygons, and stripes. He provided evidence of frost action features found on the Columbia Plateau such as block streams and boulder fields, and non-glacial gravel, sorted stone rights and stripes, involutions, ice-wedge casts, and aeolian deposits. Brunnschweiler (1962) argued that the frost action features would have formed during a climate colder than the one experienced today. Along with a formerly colder climate, Brunnschweiler (1962) emphasized that shallow soils overlying an impermeable layer were needed if the patterned ground was to form. Brunnschweiler (1962) suggested that mounds and stone circles are products of the same formation processes and developed accordingly to one another as differential heaving and thrusting moved fine materials towards the center of the mounds and more coarse materials laterally outwards because all the material lying above the impermeable layer would have been subject to frost action at the same time.

Malde (1961; 1964) studied patterned ground on the central Snake River Plain and concluded that a cold climate under a periglacial regime was responsible for soil mound formation. Polygon and circular patterns formed as a once evenly distributed soil surface rapidly thawed and cracked. Many freeze-thaw events due to "sudden cooling" of the frozen ground would have created fissures where moisture began to concentrate and weathered more massive boulders into

smaller angular fragments. Frost action resulted in differential heaving of material, so that coarse fragments migrated towards patterned ground edges and debris islands, consisting of the fines, mounded in the feature's centers. Stone pavements formed as frost action further sorted stone materials which decreased in size with an increase in ground depth, and fluvial erosion carried away weathered fines. Intermound erosion exaggerated mound relief.

Fosberg (1965) credited solifluction under a Pleistocene periglacial climate as the process responsible for patterned ground features on the Snake River Plain in Idaho. He assumed that patterned ground formed by contracting permanently frozen ground under a dynamic freeze-thaw environment. Surface soils thawed due to warming during the Late Pleistocene and slumped over the lower frozen ground, downslope. The thawing ground then slumped into mounds within the polygonal cracks. The consistency of the clay-rich B horizon under the soil mounds suggests that an uninterrupted soil mantle extended across the surface. Mound features further developed as erosion carried away material from the intermound areas, lowering drainage-way relief areas and exaggerating mound height. Stone pavements consisting of gravel, cobbles, and boulder pavements occur in Y-shaped forms around the mounds. The linear and uphill position of the pavement suggests that the sorted features formed before the mounds because those areas are from erosion.

Nelson (1977) studied soil mounds and stone rings in north-central Oregon and suggested that frost action due to a cold and wet Pleistocene climate was responsible for the features. Frost heaving and frost thrusting sort and eject stones within soils during reoccurring freeze-thaw cycles. Larger stones within the soils where translocated before finer materials because water freezes more quickly around them due to their low surface area. A concentration of coarse material forms around the central areas where stones were heaved because of differential freezing. Heaving caused the

surface soil to lower where stones concentrate, which increased the rate of erosion. Mounds form where drainage networks surround areas of high centered fines.

Tallyn (1980) studied scabland mounds in the Cheney, Washington quadrangle southeast of Spokane, Washington and attributed their origin to frost action caused by a former periglacial climate. The author suggested that the polygonal network surrounding the features was a result of flattened angular fragments in the ground. Frequent freezing and thawing due to the periglacial climate caused differential frost sorting, which resulted in the sorted stone borders around the mounds. Restriction of groundwater infiltration due to an impermeable permafrost layer was likely the cause of the exaggerated soil mound relief. Tallyn argued further that a colder climate capable of frost action processes to this extent could have occurred. According to Tallyn (1980), pollen records suggested a cooler climate 13,000 years ago that would have reflected temperature 13° C colder than they are today. The Pend Oreille Lobe of the Wisconsin Ice Sheet sat north of the Spokane River and would have influenced this periglacial climate. Tallyn (1980) argued that mounds were not depositional features from the floods because they lack alluvial sediment. She also concluded that the mounds were younger than 13,000 years old because they would not have withstood the Ice Age floods.

Johnson (1982) researched patterned ground on the Lawrence Memorial Grassland Preserve, located in Wasco County, Oregon, and attributed mound formation to frost sorting geomorphic processes along with secondary wind and water erosion. He concluded that mound distribution was most likely a result of frost action deep, less clayey soil, topography, geology, and prevailing west winds. This explained why soil mounds and the patterned ground where found on the east-facing slopes. Johnson also found that mounds tended to follow joints in the underlying basalts that enhanced segregated ice growth. Due to this, mound elongation would have been

influenced by the underlying bedrock rather than slope angle. Debris islands, frost boils, and rock nets were observed on the preserve that further supported the role of frost action.

Tullis (1995) studied mound fields on the eastern Snake River Plain in Idaho and concluded that mounds originated from cold climate processes. The author described the landscape, before cold climate processes, as having a continuous cover of silty aeolian, fluvial, and slope wash sediments that "smoothed" over the rough basalt bedrock, alluvial fans, braided streams, and buried surface soils. The textural differences between the surface silts and course bedrock created a capillary barrier preventing moisture movement beyond the course material. The barrier increased soil moisture content in the surface sediments enough for an ice lens to form. Seasonal freezing caused differential heaving to move sediments, and with the added moisture content created by the capillary barrier, heaving pressures increased. Ice wedges, near-vertical fractures, and involutions in some buried soils formed as well. Multiple freeze-thaw events would have resulted in mound features. Secondary processes of erosion and preferential intermound runoff which stripped intermound of sediments and steepened mound walls would have exaggerated mound relief. Sediment transport and animal activity reduced mound erosion through deposition of loess in krotovinas.

Study Area

Location

Patterned ground covers roughly 20 kilometers of shrub-steppe land west of the Yakima River (Figure 5). For this study, three representative soil mounds with corresponding stone borders were selected for sampling on the south slope of Manastash Ridge (Figure 6). The section of Manastash Ridge that lies west of the Yakima River has "the most ubiquitous distribution" of mounds found in Kittitas County (Kaatz, 1959, p. 147). The three locations are spread out over 6 kilometers within the study area. The average latitude and longitude for the study area are 46˚ 54' 39.73" N, and 120˚ 36' 46.28" W, and the average elevation is approximately 815 meters. The city of Ellensburg is located approximately 10 kilometers below Manastash Ridge in Kittitas Basin. Umptanum and Durr roads access the study areas via Ellensburg.
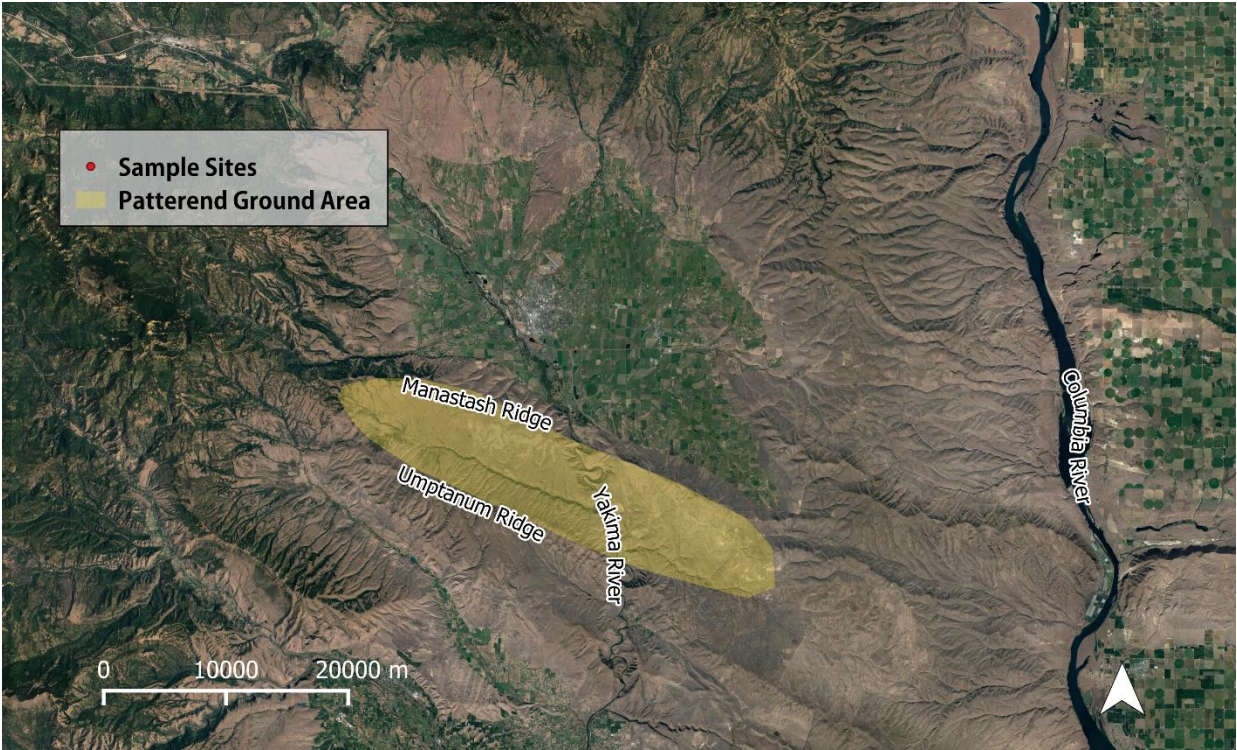
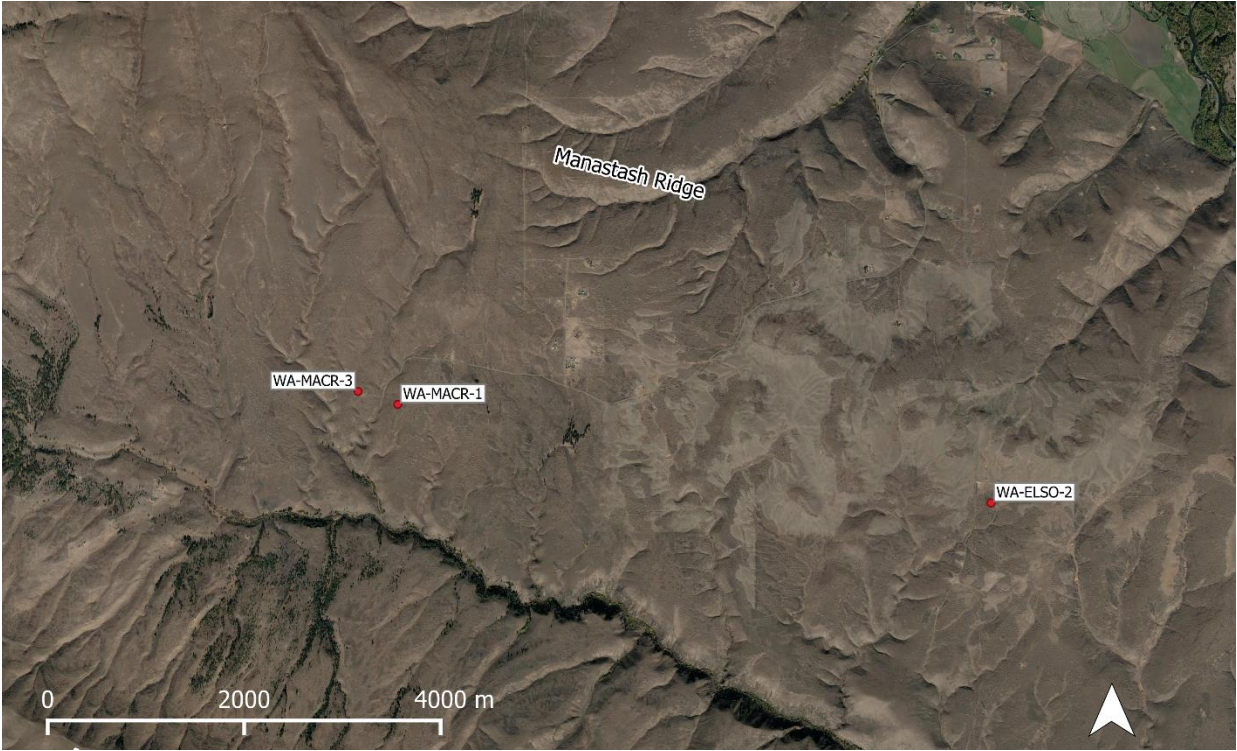Figure 5. Study area. Image from Google Earth, 2019.

Figure 6. Soil mound sample locations. Image from Google Earth, 2019.

Geology

Knechtel (1952), Kaatz (1959), Brunnschweiler (1967), and Bandow (2001) mention soil mounds in Kittitas County, on the folded basalt bedrock of Manastash Ridge, sedimentary deposits of the Ellensburg formation north of the city of Ellensburg, and Pleistocene valley glacier moraines near Thorp. For research purposes, only soil mounds on Manastash Ridge were studied. Mounds on sedimentary deposits of the Ellensburg formation and Pleistocene moraines presented questions that might lead to confusion because their diameters appear to double in size and their height is less than half of those found on Manastash Ridge. The Manastash mounds are the focus of this paper because they are the "most obvious of the patterned ground phenomenon" (Kaatz, 1959, p. 147).

Manastash Ridge is a north-trending, west extending anticline located in Central Washington. Manastash Ridge forms the southern boundary the Kittitas. Kittitas County extends south over Manastash Ridge where it meets Yakima County. It extends west towards the Cascade Mountains where it ends at an elevation of 1,800 meters. The Columbia River is 29 kilometers away from Manastash Ridges' eastern extent.

Soil mounds are found overlying basalt bedrock on the southern slopes of Manastash Ridge. The bedrock belongs to the Yakima Basalt subgroup of the Columbia River Basalts (Hooper, 1982; Campbell, 1988; Landinsky & Kelsey, 2012). The Yakima Basalt subgroup consists of Grand Ronde, Saddle Mountain, and Picture Gorge Basalts that formed in the western portion of the Columbia Basin 16.5 to 6 million years ago.

The Columbia River Basalts began forming 16 ± 0.03 million years ago near the southern extent of the Snake River Plain (Waitt, 2016; Balbas et al., 2017). Volcanic activity near the Snake River Plain filled the Columbia Basin with crystal-rich lava. Hooper (1982) estimated about 120

to 150 lava flows within the Columbia Basin. Each flow was about 15 to 30 meters in thickness. The total thickness of the Columbia River Basalts averages 1,500 meters (Hooper, 1982).

During the late Miocene epoch, compression deformed the basalt bedrock's planar surface into asymmetrical anticlines running perpendicular to the Cascade Mountain Range (Livingston, 1969; Ladinsky, 2012; Last et al., 2012). Southward induced stress caused by the San Andreas Plate pushing against the Pacific Plate forced north and northwest movement of the Yakima Basalts. Numerous anticlines' running perpendicular to the Cascade Mountains form the Yakima Fold Belt (Last et al., 2012). Thrust faulting from the south is indicated by the asymmetrical anticlines gently sloping south faces and steep north faces that sometimes display fault scarps. The ridges also display gentle east slopes that increase in elevation towards the west before they end abruptly in the foothill of the Cascades.

Anticlines within the Yakima Fold Belt typically trend west or sometimes southwest, but ridges located in the northern extent of the Belt do not display this characteristic (Last et al., 2012). Ridges including Manastash and Umptanum instead trend northwest. This redirection is believed to be a product of the Olympic- Wallowa Lineament (OWL) (Ladinsky, 2012; Last et al., 2012). The Olympic- Wallowa Lineament is a northwest-southeast trending structure line supposedly composed of hard rock that extends from the Olympic Peninsula to Walla Walla. Anticlines that formed within or around this hard rock feature show signs of abruptly stopping then reforming in the direction of the OWL.

Climate and Weather

The southern extent of Manastash Ridge experiences a semi-arid climate with warm, dry summers and cold, wet winters. Weather data is regularly collected 13 kilometers north of Manatash Ridge in Ellensburg. Approximately 23 centimeters of precipitation accumulates in the

Kittitas Basin annually (WRCC, 2016). Precipitation is usually in the form of snow, falling between November and April. Annual snow depths in the Basin are 71 centimeters; it can be assumed that Manastash Ridge experiences deeper snowpack than the Basin due to higher elevations resulting in cooler temperatures.

Temperatures recorded near Ellensburg have an average annual high of 15.5˚C and an average annual low of 2˚C (WRCC, 2016). Manastash Ridge should display temperatures approximately 2˚C cooler than those experienced in the Kittitas Basin due to the environmental lapse rate. Freezing temperatures occur between late September and early May in the Kittitas Basin, although due to the ridge's elevations freezes may occur before this in the fall and extend well into May.

Prevailing westerly winds are most common in Central Washington. Annual wind speeds in Ellensburg are 15 kilometers per hour (WRCC, 2012). Summer months tend to experience the most wind with an average of 23 kilometers per hour during July. Wind direction commonly comes from the northwest throughout the year, except November and December when winds typically come from the east.

Biota

Flora

A community of drought-and-cold-tolerant shrub-steppe flora occupies the habitat of Manastash Ridge. Shrubs, perennial grasses and herbs, and annual grasses and wildflowers have adapted to low annual rates of precipitation, winter snow cover, freezing temperatures, and high wind speeds (WNPS, 2012). Plants are small, slow or fast-growing, and have low water requirements. Some perennial and annual herbs and wildflowers that are found on the ridge are

common in alpine settings as well. This resemblance occurs because spring snowmelt on the ridge resembles a summer alpine meadow setting.

Wyoming big sage (*Artemisia tridentata*) and hopsage (*Grayia spinose*) are common shrubs found on Manastash Ridge (WNPS, 2015). Wyoming big sage is an indicator for deep soils on the ridge because they only grow where soil mantles exceed one meter. Hopsage thrives on the rocky intermound surfaces and can sometimes be found growing on soil mounds where big sage does not cast shadows.

Perennial grasses are found growing on soil mounds in shadows cast by big sage shrubs (WNPS, 2015). Perennial grasses include bluebunch wheatgrass (*Festuca idahoensis*), needle-and-thread (*hesperostipa*), Idaho fescue (*Festuca idahoensis*), and Sandberg's bluegrass (*Poa secunda*). Herbaceous annuals that grow in the rocky intermound areas between the soil mounds are yarrow (*Achillea millefolium*), shooting stars (*dodecatheon*), woody sunflower (*Helianthus californicus*), cushion daisy (*Bellis perennis*), yellow bells (*Tecoma stans*), and arrow buckwheat (*Douglas ex benth*). Perennial grasses and herbs tend to be very productive within days of snowmelt, flower in late May to early April, and then return to dormancy during dry summer months. By early June, much of Manastash Ridge is covered in brown annuals and perennials. Annual wildflowers and grasses are active in the intermound area as soon as soils are exposed to sunlight in the spring as well (WNPS, 2015). They become active in early to late spring, flower, then die during summer and spread their seeds. Wildflowers common to the area are phlox (*Polemoniaceae*), mariposa lily (*Calochortus*), fleabanes (*Erigeron*), and locoweed (*astragalus*). Cheatgrass (*Bromus tectorum*) is an invasive annual grass that grows on both intermound and soil mounds.

Fauna

Native fauna found on Manastash Ridge include elk (*Cervus canadensis*), mule deer (*Odocoileus hemionus*), pronghorn (*Antilocapra americana*), bighorn sheep (*Ovis Canadensis*), badger (*Taxidea taxus*), coyote (*Canis latrans*), raccoon (*Procyon lotor*), deer mouse (*Peromyscus maniculatus*), and sage-grouse (*Centrocercus urophasianus*), (FWS, Wenas Wildlife Area, 2017) (FWS, L.T Murray Wildlife Area, 2017). The Northern pocket gopher (*Thomomys talpoides*) is the prominent burrowing species in the area (FWS, Wenas Wildlife Area, 2017). Pocket gophers are nocturnal mammals that spend most of their lives underground. They are only active above ground for prolonged periods of time when a continuous, deep snowpack is covering the surface. "Soil coils" litter the ground following seasonal snowmelt where gophers filled in snow tunnels with soil. Pocket gophers tend to dwell in well-drained soils where fleshy, rooted vegetation is found growing.

Soils

Larrison (1942), Kaatz (1959), and Brunnschweiler (1962) reported soil characteristics of the Manastash Mounds on the Ridge. Larrison (1942) suggested there was a correlation between the weathered, angular, "gravel-like," basalt fragments and soils along the ridges. However, Kaatz (1959) and Brunnschweiler (1962) proposed that the parent material was wind-blown sediment. Kaatz (1957) compared the soils on Manastash Ridge to the Renslow and Ritzville silt loams that developed in thick loess on the Palouse in eastern Washington. Brunnschweiler (1962) noted that the soils "expressed a homogenous texture of silt loam with inclusions of sharp-edged basalt fragments" (Brunnschweiler, 1962, p. 4). He suggested that the soils parent material derived from loess that pre-dated or was from early Wisconsin stages of glaciation on the Plateau.

Soils on Manastash Ridge are mollisols found in grassland environments. According to the Web Soil Survey, the soils are Palexerolls, Argixerolls, and Haploxerolls. Palexerolls are relic soils that formed during the mid to late Pleistocene. Argixerolls are also old and have distinctive argillic B horizons. Haploxerolls are younger mollisols in early stages of their development with a weak evolution of clay and carbonate illuviation. The soils from under a xeric moisture regime, so the winters are wet, and the summers are dry. The present parent material for the soils is residuum and colluvium from basalt bedrock, loess, and volcanic ash.

The NRCS also provides descriptions of soils on Manastash Ridge in the Soil Survey of Kittitas, WA (Soil Survey of Kittitas County, 2003). The Mozen and Simcoe series are found on Manatash Ridge and fit Kaatz (1959) and Brunnchwieler's (1962) soil descriptions. Both soils are composed of deep silt loams with "homogenous texture" and low percentages of gravels. The silt loams average depths of 74-94 centimeters from the top of the soil mound down to impermeable fractured or unweathered basalt.

The Mozen soil series is found on hillslopes from 3 to 30 percent and between elevations of 730 to 850 meters (Soil Survey of Kittitas County, 2003). The parent material is loess mixed with volcanic ash and basalt alluvium and residuum. Horizons within the Mozen soil profile are A1, A2, AB, 2Bt, 2Btkb, 2Btb, 2Bwb, and 3R. The A horizons are dark grayish brown to brown silt loams with clear smooth to wavy boundaries. The buried 2B horizons are brown to pale brown clay loam and loam with clear to abrupt wavy boundaries. A mollic epipedon formed within the first 56 centimeters of the soil and has mixed vitrandic features the first 33 centimeters. An argillic horizon lies below the mollic epipedon from 33-92 centimeters and consists of all the 2B horizons. The 2Bt horizon is suspected to be Lakedale-Wisconsin Age of the Pleistocene glacial maximum (Soil Survey of Kittitas County, 2003). There was no indication of gravel content within the soils.

The Simcoe soil series is native to Yakima County and Kittitas County on Manastash Ridge (Soil Survey of Kittitas County, 2003). The soils are found in uplands on slopes 0 to 30 percent and from elevations of 300 to 700 meters. Soil soils developed from weathered basalt, loess, and minor amounts of volcanic ash parent materials. The soil profile horizons are Ap, B21t, B22t, B3t, and R. The Ap and B21t horizons are grayish brown silt loams with smooth to gradual wavy boundaries. The lower B2 horizons are brown to yellowish-brown clay loams with gradual to abrupt wavy boundaries. The mollic epipedons ranges from 25-50 centimeters thick with an argillic horizon underneath — the argillic epipedon average from 25 to 35 percent clay. The soil included more than 15 percent particle coarser than sand, with concentrations increasing towards the unweathered basalt.

The Renslow series fits the description of soil mounds provided by Kaatz (1959); however, the soils are not mapped on Manastash Ridge. The soils formed in well-drained loess and are found on slopes 0-40 percent. The profile horizons are Ap, AB, Bt, Bk1, Bk2, and Bk3. The Ap, AB, and Bt horizons are brown silt loams with clear wavey boundaries. Horizons Bk1, Bk2, and Bk3 are pale brown to yellowish-brown silt loams with clear wavey boundaries. The soils are strongly alkaline and have well-developed accumulations of calcium carbonate in the Bk horizons. The Bt argillic horizons have a clay percentage higher than 20% and clay film coatings. The mollic epipedon is 45 centimeters thick, and the total depth of the sol is 154 centimeters.

The Ritzville soil series is found on the Palouse in eastern Washington. Kaatz (1959) compared the soil mounds to the Ritzville series, although they do not form on Manastash Ridge. The Ritzville series is a well-drained soil that formed in loess and is found on slopes 0-70 percent. The soil horizons are Ap, AB, Bw, Bk, C1, and C2. Horizons Ap and AB are brown silt loams with clear and abrupt wavery boundaries. Bw and Bk are a pale brown silt loam with gradual

wavery boundaries. C1 and C2 are pale brown loams with massive hard structures and abrupt irregular boundaries

Land Use

Dryland wheat farmers cultivated crops on Maanstaash Ridge during the late 1800s to the early 1990s. Furrows are still visible running along the surface of the continuous, deeper soil surface. Soil mounds were mostly left alone because of their small diameters. Now, private residential homes and rangeland reside along Umptanum and Durr roads. Washington State acquired 218 square kilometers of shrub-steppe on Manastash Ridge in 1968 for the L.T Murray Recreation (FWS, L.T Murray Wildlife Area, 2017). The land was purchased to protect winter range for deer and elk and improve upland game bird habitat. Soil mounds are found on 85 square kilometers of the recreation area. The study area lies within 426 square kilometers of the Wenas Wildlife area used for wintering elk (FWS, Wenas Wildlife Area, 2017). Washington State Fish and Wildlife manages both areas which are also used for recreational hiking, hunting, and shooting.

Methods

The goal of this study was to use absolute and relative soil dating techniques to determine the ages of three soil mounds on Manastash Ridge. Steps for the soil analysis included: site and mound selection; mound excavation and sample collection; in-lab relative soil dating techniques; and off-campus OSL dating at Baylor University's Geoluminescence Research Laboratory.

Site and Mound Selection

Manastash mounds are found on the south-facing slope of Manastash Ridge. They occupy an area of land between the Yakima River and Douglas fir lower tree line. Three sites were selected using Google Earth, and topographic quadrangles to locate soil mound features and identify accessible public lands (**Error! Reference source not found.** and **Error! Reference source not found.**). Sites were visited in the field, and soil mound sampling sites were selected based on mound roundness, diameter, height, and presence of a stone ring. Once selected, soil mound locations were recorded using GPS. Mounds sampled for this study include WA-MACR-1, WA-ELSO-2, and WA-MACR-3 (**Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**).

Figure 7. WE-ELSO-2. Image from Google Earth. 2019.

Figure 8 WA-MACR1 and WA-MACR-3. Image from Google Earth. 2019.

Figure 9 WA-ELSO-2. Image from Google Earth. 2019.

Figure 10 WA-MACR-1 -2. Image from Google Earth. 2019.

Figure 11 WA-MACR-3. Image from Google Earth. 2019.

Mound Excavation and Sampling

A shovel was used to dig a 1.0-meter wide by 1.5-meter deep pit from the surface of the mound down to the impermeable basalt bedrock layer. To obtain accurate absolute and relative dates, the sample sites needed to have as little soil disturbance as possible, so the pits were dug towards the center of the mounds. Once the pits were wide enough for a person to examine each soil horizon while kneeling, a trowel was used to clean the soil profile face. After the in-field descriptions were recorded, 5 kilograms of soil from each horizon were collected, bagged, and labeled with the site location, date, and horizon depth.

OSL

A 30g soil sample was collected from the lowest horizon of each of the three mounds for absolute OSL dating. WA-ELSO-2 was sampled first, followed by WA-MACR-1 and WA-MACR-3. Black ABS tubing, 15-centemeters long and 5-centimeters wide, was hammered horizontally into the lowest soil horizon using a wood block and sledgehammer. After the tubing was hammered into the soil, at least 5 centimeters past the initial opening, the tube was removed and double-checked to ensure that the sediment in the tube was packed tight enough to restrict movement. If an error was assumed, the samples were retaken until it met all the minimum requirements. An additional 30 grams of sediment from the same horizon was gathered as a dose rate for the OSL analysis. The samples were sent to the Geoluminescence Laboratory at Baylor University. Samples were collected in August and December of 2017.

Two of the three initial samples sent in for OSL dating came back with questionable results. The laboratory claimed the samples were challenging to date because of difficulty extracting quartz grains for dating the intrinsic low light levels and high over-dispersion percentage in equivalent dose values. Two more samples were collected and resubmitted from WA-MACR-3 at 45 centimeters and 99 centimeters in August of 2018.

Soil Color

Soil color can be an indicator of soil age in dry climates (Harden, 1982). Semi-arid soils that have well-developed mollic epipedons and lighter subsurface horizons where clays and carbonates accumulate can suggest an old age. Mollic epipedons must be 18 to 25cm thick and have high values according to the Munsell Soil Color chart due to the darkening of soil via organic matter accumulation (USDA, 1999). The surface horizons in mollisols must have a Munsell value less than 5 when dry and less than 3 when moist and a chroma less than 3 when moist. The

subsurface horizons should be one unit lighter than the mollic epipedon when both dry and moist. Alternatively, light colors throughout the soil profile can suggest younger ages in dryland environments due to lack of time for organic and clay accumulations.

The soil horizons colors were classified using the Munsell Color Chart. The Munsell Soil Color Chart separates color into hue, value, and chroma. Hue colors, like reds, yellows, and browns, are the first features recorded when analyzing color. Soils hues can indicate properties, including clay content, geographic location, aeration, and time. The value is the lightness or darkness of the soil, with darkness increasing as the number decreases. Soils darken over time with the introduction to organic matter. Soils can also lighten over time due to translocation of minerals from one horizon to another. The chroma is the paleness or strength of the soil color, with paleness decreasing with number decrease. Soil colors for each horizon were recorded when both dry and moist.

Structure and Consistence

Structure and consistence are indicators of age in semi-arid soils because the structure grade and type, and consistence hardness, increase with age (Harden, 1982; USDA, 1999). Newer soils should have single-grained, structureless soils with loose consistence. Dryland soils with mollic epipedons will have moderate, medium granular structures with friable consistence associated with dry and hard argillic and calcic B horizons.

The structure and consistence of the soil horizons were characterized using the NRCS Handbook for Describing Soil (NRCS, 2012). The soil structure was measured by taking a handful of sediment and shaking out the fines — the remaining peds were measured for the grade, size, and type. Consistence was measured by placing a soil ped between the figures and squeezing to

analyze the easiness at which the peds rupture. Peds that rupture easily are soft while those that take more effort are hard.

Soil Texture

Soil texture can be used to determine a soil's relative age in dryland environments because coarse materials tend to be younger than finer materials (Harden, 1982; USDA, 1999; Sochan, Ryzak, & Dobrowolski, 2012). Coarse material weathers into fines at the surface where the minerals are exposed to heat and moisture. The smaller particles are translocated to lower horizons via water. The fines accumulate in the subsurface and, over time, may form a Bt argillic horizon. Well-developed argillic horizons can be tens of thousands of years old in semi-arid climates where weathering processes are slow and drawn out. Furthermore, in young soils, there is no evidence of clay illuviation and clay skins forming on peds. Distinction of particle size, clay content, and clay skins at the surface compared to the subsurface can help determine if the mounds are old or young features.

To classify a horizon as argillic it must have either; 1) a thickness of 7.5cm or be at least one-tenth as thick as the sum of all overlying horizons if the soil texture is coarse-loamy, fine-loamy, coarse-silty, fine-silty, fine, or very-fine or is loamy or clayey; 2) or have a horizons 15cm thick if the soil texture is sandy or sandy-skeletal. Clay illuviation must be evident in one of the following forms: oriented clay bridging the sand grains; clay films lining pores; clay films on both vertical and horizontal surfaces of peds; thin sections with oriented clay bodies that are more than 1 percent of the section; if the coefficient of linear extensibility is 0.04 or higher, and the soil has distinct wet and dry seasons, then the ratio of fine clay to total clay in the illuvial horizons is greater by 1.2 times or more than the eluvial horizons. The illuvial horizon must contain more clay than

the eluvial horizon. If the eluvial horizon has less than 15 percent total clay, the argillic horizon must contain at least 3 percent more.

Because the soils have less than 15 percent clay in each horizon, the clay content needs to be three percent higher in the B horizons than in the overlying eluvial horizon, for the lower soils to be considered and argillic horizon.

Soil texture was measured using the Bouyocous hydrometer analysis, Mastersizer soil particles analysis, and Mastersizer combined with the Camsizer soil particle analysis. Three different methods were used because the hydrometer analysis is known for overestimating clay content and the Mastersizer is known for underestimating clay content (Bohn & Gebhardt, 1989; Miller & Schaetzel, 2011; Sochan, Ryzak, & Dobrowolski, 2012; Šinkovičová et al., 2017). The camsizer was used for one of the analyses to measure particles larger than 0.063 millimeters because the lab did not want larger particles measured in the Mastersizer 2000. To conclude the most accurate soil texture results, these methods were compared to one another to estimate each mounds' soil textures.

Hydrometer Analysis

Soil texture was first determined using the Bouyocus hydrometer analysis in the CWU Geography Department's Geomorphology and Soils lab. This method calculates the rate at which different particle sizes settle out in the water (Bohn & Gebhardt, 1989).

Sample preparation: A sample of 50-60 grams from each soil horizon was weighed using a digital scale. After being weighed, each sample was slightly agitated using a mortar and pestle to break apart large soil peds. The ground samples were sieved using a 2mm screen to separate material and size and smaller from gravels. The portion of each sample smaller than 2mm was weighed then placed into a mixing cup and labeled (*Figure 12*). The mixing cups were filled 1/3

full of deionized water and 10ml of a dispersing agent and left to sit for 15 minutes. After sitting

for 15 minutes, the cups were attached to a mechanical mixer for another 15 minutes to disperse

smaller soil aggregates.

Procedure: The mixed solutions were transferred into 1000ml graduated cylinders with

corresponding labels. A spray bottle full of deionized water was used to remove all the sediment

from the mixing cups. Once all the sediment was removed, the cylinders were filled to the 1000ml

mark with additional deionized water (*Figure 13*).

Figure 12. Mixing cup. Image from Ellie Myers, 2018.

Figure 13. 1000ml graduated cylinder after agitation. Image from Ellie Myers, 2018.

A rubber stopper was used to seal the graduated cylinders, and the contents within them

were agitated for one minute (*Figure 13*). After a minute of agitation, the cylinder was placed on

a flat surface, and the stopper was removed. The Bouyoucos hydrometer was lowered very slowly

into the cylinder to get an accurate reading (*Figure 14*). The hydrometer reading was recorded 40

seconds after placing the cylinder down. The agitation process was repeated three times or until

all recording was within 0.5 of each other. The temperature of the water was measured for three

minutes after each of the samples the last agitation. After the last agitation samples where not touched for 24 hours (Bohn & Gebhardt, 1989). After 24 hours, the hydrometer and temperatures were re-recorded. Each hydrometer analysis was performed twice to ensure accuracy.
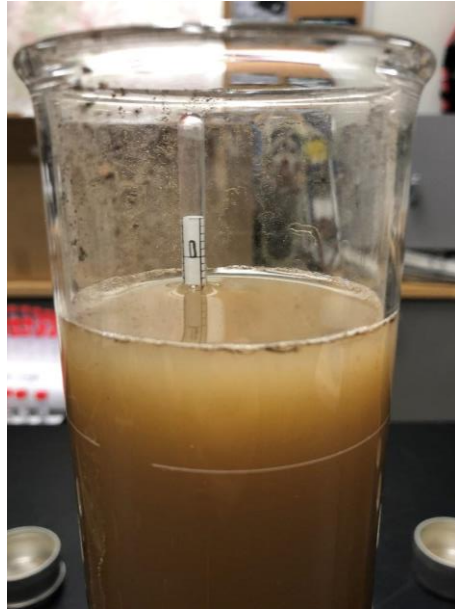

Figure 14. Bouyoucos hydrometer reading. Image from Ellie Myers, 2018.

Calculations:

1. Temperature correction factor, T (may be different for each reading):

    T = (Observed temperature - 20°C) * 0.3

2. Corrected 40-second reading:

    40-sec(c) = 40-sec - Blank + T

3. Corrected 2-hour reading:

    2-hr(c) = 2-hr - Blank + T

4. % Sand (2-0.05mm) $= \dfrac{\text{(OD soil wt.)-(corrected 40 sec reading)}}{\text{OD soil wt.}} * 100\%$

5. % Clay (< 0.002mm $= \dfrac{\text{corrected 2 hr reading}}{\text{OD soil wt.}} * 100\%$

6. % Silt (0,05-0.002 mm) = 100% - (%Sand + % Clay)

<u>Malvern Mastersizer 2000 Soil Particle Analysis</u>

The Malvern Mastersizer 2000 was designed to measure the particle size and particle distribution of fuel injectors but was adapted with a hyrdo 2000MU to measure the particle size of soils (Šinkovičová, 2017) (Figure 15). The Mastersizer uses laser diffractometry to measure the sizes of particles 3.5mm and smaller. Laser diffraction works off two theories: the Fraunhofer Model and Mie Theory. The Fraunhofer Model predicts the scattering pattern created when a particle or opaque disk of a known size is passed through a laser beam. The Mie Theory predicts the way light is scattered by spherical particles and deals with the way light passes through or absorbed by a particle. For this study, the Mie Theory was used to calculate the size of the soil particles based on their scattering pattern.
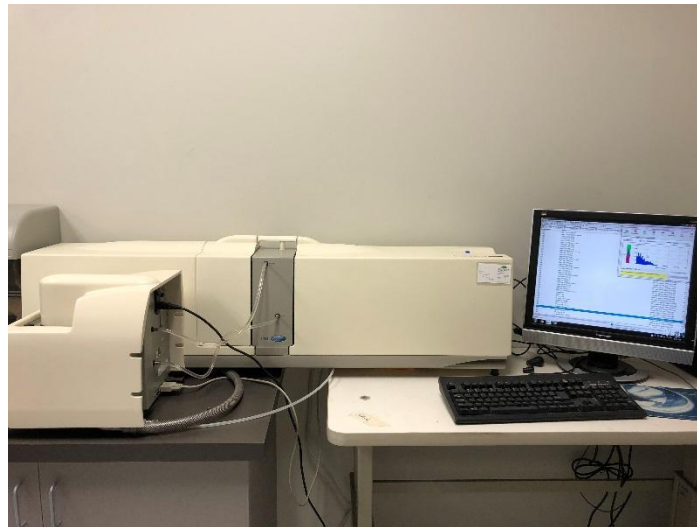

Figure 15. Malvern Mastersizer 2000. Image from Ellie Myers, 2018.

Sample Preparation: The Mastersizer can analysis soil particles 3.5mm and smaller. However, for this study, only samples smaller than 1mm were passed through the Mastersizer.

Two sets of samples were analyzed using the Mastersizer 2000 located in the Geography Department at CWU. The first was smaller than 0.063mm and the second was smaller than 1mm.

Before the fines were separated from coarser materials, each sample was placed in the furnace at 450˚F for 2 hours to burn off organic materials. Samples that had reactions with HCL were left in a diluted HCL bath overnight to remove calcium carbonates. After the organics and carbonates were removed, the samples were placed over a 2mm screen stacked on top of either a 0.063mm or 1mm screen. The screens were placed on the sieve shaker for 10 minutes to separate the fines and course materials. Organics and carbonates were removed, so particle size was not impacted.

After the organics were separated out, particles 2mm and larger were sifted out of the sample. The remaining sample was divided into two groups consisting of samples smaller than 0.063mm and larger than 0.063mm.

Mastersizer Analysis: Prepared samples were measured out in the Hydro 2000MU connected to the Mastersizer 2000. The Hydro 2000MU is a dispersion chamber where the soil particles are agitated and flocculated in water before they are sent into the laser chamber. Once the measurement was complete, the Malvern program calculated the particle size and distribution in a sample.

The total volume of the fines passed through the Mastersizer 2000 were calculated depending on the weight of the sample. Since only about 0.05g of sediment was analyzed with the Mastersizer 2000, a ratio was created between the two volumes to calculate the percent by volume particle distribution. The new volume was multiplied by the total volume of fines and coarse samples below 2mm.

The volume and soil particle percent for materials larger than 0.063mm were measured using the Retsch Camsizer P4. For the analysis where fine samples 1mm and smaller where tested in the Mastersizer 2000, volumes of the coarse materials were calculated using water displacement analysis.

Retsch Technology Camsizer P4

The first set of sieved samples that were larger than 0.063mm were analyzed using the Restch Camsizer P4 for coarse particle size distribution. The Camsizer P4 was located in the Geology Department at CWU.

The Camsizer P4 is an opto-electric instrument used to measure particle size and distribution of dry, pourable (free-flowing) materials, 20 micrometers to 30 mm in size. The Camsizer has a dual-camera system that can measure small and large particles without compromising resolution or particle detection. Whole samples were emptied into a funnel and slowly released onto a vibrating chute (Figure 16). The vibrating chute moved the samples towards a slit where they fell, unconsolidated, and pass through the LED strobe light source (90Hz) where the dual cameras took photos of the particles.

Figure 16. Camsizer P4 vibrating chute. Image from Ellie Myers, 2018.

The measurement parameters were set to measure particles smaller than 0mm and larger than 100mm to give a wide range of particle size options. The feeder control fast forward level was set to 65, and the max distribution fast forward was set to 30. Covered areas CCD basics were 3% and covered areas CCD for zoom where 5%. The starting levels for measurements where 55. Max control was 76, the nominal covered area was 0.5%, and base control was 20. Particle size distribution was based on volume with a size definition of xc_min.

Chittick Apparatus

Carbonate percentages in soil horizons can be used to date landforms in semi-arid climates. Carbonate concentrations form when minerals are eluviated from A horizons into lower sub-horizons as rainwater quickly moves through the soil. The water is later evaporated from the soils and leaves behind calcium carbonate deposits. In semi-arid climates, this is a slow process because of low precipitation rates. Calcium carbonate buildup goes through five stages (Bachman & Machette, 1977):

- Stage 1—Soils have filaments and faint, discontinuous coatings on lower surfaces of peds and gravel.
- Stage 2—Soils have firm carbonate nodules that are isolated from one another and a continuous coating around peds and gravel.
- Stage 3—Consolidated carbonate nodules.
- Stage 4—Platy and massive indurates and carbonate matrix with the well-developed laminar layer.
- Stage 5—Massive, multi-laminar cemented caliche.

Calcium Carbonate concentrations within the soil profiles were determined using the Chittack Apparatus located in the Geography Department at CWU (Figure 17). The Chittick

Apparatus was designed to determine the volume of CO_2 evolution from carbonates reacting with acid (Branham & Shepherd, 1939; Dreimanis, 1962; Bachman & Machette, 1977; Loeppert et al., 1984).

Figure 17. Chittick Apparatus. Image from Ellie Myers, 2018.

A small sample of sediment from a profile horizon was sieved using a 1mm screen to separate fines from more coarse samples (Dreimanis, 1962). The literature states that 1.70g of

sediment is required to run each test; however, the samples used had a very low accumulation of carbonates, so a sample three times larger was required. Therefore, 5.01g of the fine-grained sediment was poured into the decomposition flask, and the flask was connected to the Chittick Apparatus. The stockcock was opened so that the displacement solution in the measuring barrette could be brought up to the 20mL mark, above the 0mL mark. This was done by raising and lowering the leveling bulb until both water levels in the measuring barrette and leveling bulb are the same. Once level, while leaving the stockcock open, 20mL of 6N HCl (20% diluted) solution was added to the pipette connected to the decomposition flask. The stockcock was closed to a 90-degree angle. Once the stockcock was closed, the leveling build was lowered 2 to 3cm to relieve pressure within the Chittick Apparatus. With the stockcock closed, the water level in the measuring barrette should stay at 20mL. The HCL-filled pipette was opened, and the magnetic stirrer turned on as the acid solution entered the decomposition flask. At the same time as the HCL was filling the decomposition flask one hand was kept on the leveling builds so that its water level remained 2-3 cm lower than the water level in the measuring barrette. The stockcock was closed after 20mL of the HCl solution was added to the decomposition flask. Once the reaction of HCL and calcium carbonates in the soil subsided, the measuring barrettes and leveling build were equalized. The water level in the measuring barrette, room temperature, and room pressure was recorded and used to calculate the total amount of carbonates in the soil samples.

Calculations

$$\%CO_2 = \frac{V \times 273 \times P \times 0.196}{(273 + T) \times 760 \times Sample. \, Wt \, (g)}$$

V= Volume of CO_2 observed (cm3)

T= Temperature Observed (C˚)

P= Pressure Observed (mm hg)

Results and Discussion

OSL

OSL dating provided a firm date of 1945 ± 135 years for sample WA-MACR-3, and 980 ± 75 years and 390 ± 30 years for resampled WA-MACR-1.1 and WA-MACR1.2 (*Table 1*).

Table 1. Approximate OSL age of soil samples form soil mounds located on Manastash Ridge

Soil Mound	Depth (cm)	Age	Conclusive
WA-MACR-1.1	107	980 ±75	Yes
WA-MACR-1.2	102	390 ±30	Yes
WA-MACR-3	90	1945 ±135	Yes

Bandow's (2001) preliminary dates from sediment collected at Manastash Creek and Throp Prairie suggested that the mounds formed 7,800 ± 700 and 5,600 ± 500 years ago. OSL dates collected at WA-MACR-3 provide an approximate age for the mounds thousands of years younger than the TL dates Bandow (2001) collected. The resampled OSL dates from WA-MACR-1.1 and WA-MACR-1.2 support sample WA-MACR-3. The second set of OSL dates also provide evidence of a stratigraphic continuity within the soil mounds. A stratigraphic continuity within the mounds means that the sub horizons are younger than surface horizons. Samples WA-MACR-1.1

and WA-MACR-1.2 indicate that the sediments in the soil mounds might not have been deposited at the same time.

While Bandow's (2001) TL dates and the OSL date on Manastash Ridge are not similar in age, they both provide evidence that the mounds are not Pleistocene features. Although the dates differ by a couple hundred years, the lithologic continuity displayed by the WA-MACR-1.1 and WA-MACR-1.2 dates demonstrates the lack of bioturbation and cryoturbation disturbance. Bandow (2001) claimed that his TL dates could have been contaminated due to disturbance via bioturbation and cryoturbation translocating younger soils to the lower horizons. The OSL samples collected from WA-MACR-1.1 and WA-MACR-1.2 show that there might not be as much disturbance occurring within the mounds as previously believed.

Soil Color

The soil samples from the mounds meet the criteria for mollic epipedons when dry and moist. The soils have dark surface horizons within the first 18-31.5cm of the soil mounds (Table 2 and *Figure 18*). When dry, they get lighter by one unit in both value and chroma with depth. When moist the soils have darker colors than when the soils are dry.

Soils found on Manastash Ridge have semi-developed mollic epipedons that show darkness in the surface horizons. The Ritzville and Renslow soil series described by Kaatz (1959) share similar surface horizon development as well. The soils hues are a mix of 7.5YR and 10YR, highlighting the dark browns, reds, and yellows associated with basalt and loess parent materials (USDA, 1999). All the soils values when dry range between 4 and 5 when dry and 3 and 2 when moist and have chromas of 2 to 3 when moist. The soils all experience an increase in brightness by one unit in the subsurface soil under the mollic epipedons.

Table 2. Munsell soil color classification for soil mounds located on Manastash Ridge.

Soil Mound	Depth (cm)	Munsell Soil Color	
WA-MACR-1		Dry	Moist
A	0-9	10YR 6/3	10YR 3/6
AB	9.0-31.0	10YR 6/3	10YR 3/3
B1	31.0-45.0	10YR 6/3	10YR 3/4
B2	45.0-81.0	10YR 5/4	10YR 3/5
BC1	81.0-99.0	10YR 6/4	10YR 4/3
BC2	99.0-114.0	10YR 5/4	10YR 3/6
WA-ELSO-2			
A	0-9.0	10YR 6/2	10YR 3/3
AB	9.0-31.5	10YR 6/3	10YR 3/3
B1	31.5-44.0	10YR 6/3	10YR 3/4
B2	44.0-69,5	10YR 5/4	10YR 4/3
BC	69.5-90.0	10YR 6/5	10YR 3/4
WA-MACR-3			
A	0-8.0	10YR 5/3	10YR 3/3
AB	8.0-18.0	10YR 5/3	10YR 3/3
B1	18.0-38.0	10YR 5/3	10YR 3/3
B2	38.0-72.0	10YR 6/6	10YR 3/3
BC	72.0-95.0	10YR 6/6	10YR 3/4

Figure 18. Munsell soil color of each horizon from each soil mound.

The color of the surface horizons in the soil mounds suggest that they have a developing mollic epipedon similar to other soils found on Manastash Ridge. Mollisols on the Columbia Plateau formed during the Late Pleistocene and Holocene in thick accumulations of loess (Soil Survey of Kittitas County, 2003 Haploxerolls are the youngest Mollisols found in the area, and the subgroup haplo indicates that they are recent features, still in the early stages of their development. Haploxerolls found on Manastash Ridge have a value and chroma of 4/2 to 5/2 when dry and 2/2 and 2/3 or 3/2 3/3 when moist. Manastash soils have a value and chroma of 5/3 to 4/3 when dry and 3/2 to 2/2 when wet. When dry, Manastash soils are one-unit lighter in the surface horizons compared to the other soils on the ridge. However, when they are moist, the soils have similar values and chromas as neighboring soils. The soil mounds appear to be the same age, or slightly younger than the youngest mollisols found on Manastash Ridge because of their developing soil color associated with a mollic epipedon (Harden, 1982).

The soil mounds might appear to be younger than other soils found nearby due to physical and biological disturbances altering development, or lack thereof. The soil mounds have more surface area compared to the larger continuous soil mantles in the area, and because of their larger surface, the soil mounds might not be efficient at holding water. Water absorbed into the larger soil mantles probably does not evaporate or drain out as quickly, leaving more time for weathering processes. Water in the soil mounds has more opportunity for evaporation, which could mean weathering processes that alter soil color are not happening as quickly.

Structure and Consistence

The soil mounds share similarities in structure and consistence from the surface horizons down into the subsurface horizons (Table 3.). The first two horizons in each of the mounds, where the mollic epipedons are found, have weak, fine granular structures. The structures become more moderate, medium subangular blocky with depth. The lowest horizon in WA-MACR-1 has a strong, fine platy structure (Figure 19).

Table 3. Structure and consistence of soil horizons from each soil mound.

Soil Mound Horizon	Structure	Consistence
WA-MACR-1		
A	Weak granular	Loose and very friable
AB	Weak granular	Soft and friable
B1	Moderate subangular blocky	Soft and very friable
B2	Moderate subangular blocky	Loose and very friable
BC	Moderate subangular blocky	Slightly hard and very friable
WA-ELSO-2		
A	Weak granular	Loose and very friable
AB	Weak granular	Soft and friable
B1	Moderate subangular Blocky	Loose and friable
B2	Moderate Subangular Blocky	Slightly hard and very friable
BC	Moderate subangular blocky	Slightly hard and very friable
WA-MACR-3		
A	Weak granular	Loose and very friable
AB	Weak granular	Soft and loose
B1	Moderate blocky	Soft and loose
B2	Moderate subangular blocky	Soft and very friable
BC1	Moderate subangular blocky	Slightly hard and very friable
BC2	Moderate subangular blocky	Slightly hard and very friable

Figure 19. Example of soil structure difference between the upper and lower horizons.
Image from Ellie Myers, 2018.

When dry, the consistence in the first two horizons in all three mounds is soft, i.e., the peds burst apart without much pressure. With depth, the peds are moderately soft; it does not take much pressure for them to fall apart. Horizons Btc1, Btc2, and Btc3 have some soft peds and some slightly hard peds associated with calcium carbonate nodules. All three soil mounds have hardpans in the lowest horizon that were noticeable during the pit excavation. Although the hardpan was apparent while digging, the soil peds still had moderately soft to slightly hard structures that were easy to break apart when dislodged from the horizon.

Hard pans can often be used as an indicator for older soils that have been acted upon by translocation of fines to lower horizons. Soils also experience hardpans from compaction on the surface. There is evidence that large range animals like deer and elk used Big Wyoming Sage that grow on the mounds for shelter. There are clays found throughout the soils, and although it is not apparent that an argillic horizon exists, there is probably enough clays in the soil to warrant harder

subsurface horizons. Clays, coupled with animal compaction, are possible culprits of hardpans in the lowest horizons.

The soil mounds exhibit structure, and they show changes in structure and consistence from their surface horizons down to the subsurface horizons, which indicates that they are not new features, like active sand dunes (USDA, 1999). The formation of the granular structure near the surface indicates that the upper horizons have been exposed to flora, fauna, minerals, and weathering fragments that have altered the soil parent material (Harden, 1982). However, the weak to moderate structure grade suggests that the soil peds are still in an early process of formation because there is still loose sand, silts, and clays that are not aggregated. The soft consistence throughout the mounds indicates that the soils are young because old soils should have harder structures associated with the mineral accumulation and surface compaction. The consistence and structure grade suggest that they are still young features that have only been developing within recent time.

Soil Separates

Soil separate classifications are shown for each mound and their corresponding horizons in Table 4. Each method used to determine soil separates produced slightly different results. The difference in results illustrates the subjectivity and variability when analyzing soil texture. Despite the differences, it is apparent that the soils in all of the mounds consist of mostly sand and silts, with no striking accumulation of clay within any horizon. The results from the hydrometer analysis suggest that the USDA texture for each horizon in WA-MACR-1 and WA-MACR-3 is loam, and WA-ELSO-2 is silty loam (Figure 20, Figure 21, and Figure 22).

Table 4. Percent sand, silt, clay in each soil mound horizon.

| Soil Mound Horizon	Hydrometer			Mastersizer			Mastersizer +Camsizer		
WA-MACR-1	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
A	45	47	9	52	44	3	57	31	2
AB	45	46	8	53	42	3	58	30	2
B1	45	46	8	52	43	3	53	32	2
B2	44	48	8	54	42	3	49	36	2
BC1	44	48	7	52	43	3	49	36	2
BC2	45	48	7	49	46	4	45	40	3
WA-ELSO-2									
A	34	58	7	52	43	4	58	39	2
AB	35	57	8	43	52	4	51	35	2
B1	37	56	8	50	46	3	50	36	2
B2	39	57	5	50	43	3	44	41	2
BC	33	58	9	49	46	3	48	23	2
WA-MACR-3									
A	49	44	7	45	51	4	60	22	1
AB	46	43	10	62	34	2	60	22	1
B1	47	43	10	64	32	2	62	20	1
B2	47	44	10	65	32	2	60	20	1
BC	47	44	8	66	31	2	59	21	1
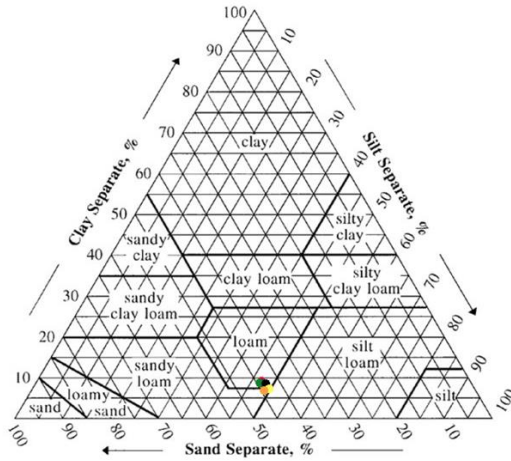
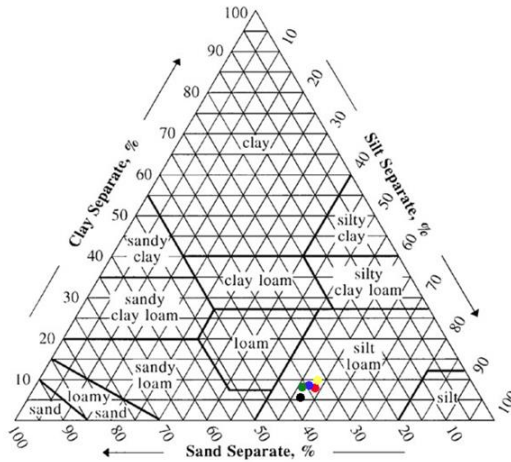Figure 20. WA-MACR-1. Image from NRCS and Ellie Myers, 2018.

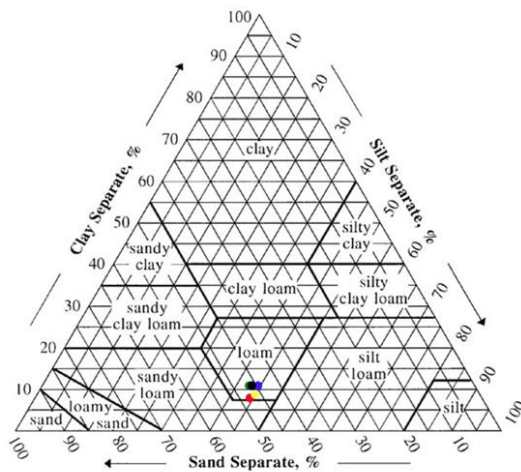Figure 21. WA-ELSO-2. Image from NRCS and Ellie Myers, 2018.

Figure 22. WA-MACR-3. Image from NRCS and Ellie Myers, 2018.

The soils within the mounds have a homogenous texture from the surface down with high amounts of fine sands and coarse silts and low amounts of clay. The distribution of soil particles throughout the features and the low quantities of clay suggest that the soil mound parent materials are loess (Bettis et al., 2003). Loess is a wind-blown sediment composed sand, silt and 5 to 8% clay. Features composed of loess are late Pleistocene to Holocene features depending on their distance from their sediment source. Because of the low clay percentage in the soils, they do not meet NRCS argillic requirements.

Because there is not a horizon with an accumulation of clays 3 percent higher than the horizon lying directly above, the mounds do not appear to be late Pleistocene features. Furthermore, there was no indication of clay skins on peds from all the horizons for each mound. The almost equal distribution of sand, silts, and low amount of clays throughout the soil mounds suggest that their parent material is loess and since loess is a relatively recent deposit on the Columbia Plateau these features cannot be older than the late Pleistocene. Based on the soil texture and particle size analysis, the soil mounds do not appear to be older, well-developed features.

Calcium Carbonate

WA-MACR-1 was the only soil mound to have notable reactions to 1N HCl in the B2, BC1, and BC2 horizons (*Table 5*). There are faint filaments and discontinuous coatings on peds and gravels within all three horizons. Hard carbonate nodules that are isolated from one another are found in BC1 and BC2. The concentrations of calcium carbonate are lowest in B3 and BC2 and are almost not quantifiable. Bc1 has the highest accumulation of carbonates at 1.24%.

Table 5. Calcium carbonate concentration in each soil mound.

Soil Mound Horizons	Calcium Carbonate Concentration
WA-MACR-1	
A	0
AB	0
B1	0
B2	0.001
BC1	1.24
BC2	0.003
WA-ELSO-2	
A	0
AB	0
B1	0
B2	0
BC	0
WA-MACR-3	
A	0
AB	0
B1	0
B2	0
BC	0

The calcium carbonate concentrations in WA-MACR-1 suggest that the soils are between stages 1 and 2 of calcium carbonate genesis. Soils in stage 2 of development are about 2,000 years old in semi-arid regions of the southwestern United States (Bachman & Machette, 1977). The low accumulation of carbonates in the soil mounds indicated that they are less than 2,000 years old, so these soils are not Classified at BK. WA-ELSO-2 and WA-MACR-3 do not have carbonate concentrations, so they appear to be younger than WA-MACR-1. The lack of calcium carbonate build-up suggests that the soil mounds formed during the late Holocene.

Conclusion

The purpose of this research was to determine the absolute and relative age of three soil mounds on Manastash Ridge. The absolute age of three soil mounds was dated using OSL dating to measure the last time the lowest horizon was exposed to sunlight. Relative age indicators were analyzed in the lab and included soil color, structure and consistence, texture, and calcium carbonate concentrations.

The purpose of this research was to determine the age of three soil mounds on Manastash Ridge using OSL dating and relative dating techniques. The age of the mounds is significant in ruling out possible origins of mound formation. The most popular soil mound origins studied on the Columbia Plateau include erosion, deposition, burrowing animals, and cold climate processes. Based on absolute and relative dating techniques, the soil mounds on Manastash Ridge appear to be late Holocene features. OSL dates provide an approximate age no older than 1945 ± 135 years. Relative age indicators, including soil color, structure and consistence, texture, and calcium carbonate content, provide evidence in support of the absolute dates.

For an erosional theory to be true, the soil mounds would have to be relic features of a once continuous soil mantle. However, the soils in the mounds and the soils the nearby continuous soil mantle do not share similar characteristics that would be expected if they were once a joined layer. OSL dates and soil color and texture analysis suggest that the mounds are younger than the surrounding continuous soil mantles. Deep soils on Manastash Ridge, that are not found in the soil mounds, are classified as Simco and Mozen series. These soils are mid-to-late Pleistocene features with observed argillic horizons and clay skins, neither of which were found in the soil mounds.

For bioturbation to be true, significant disturbance between the sub horizons and surface horizons would be evident. OSL dates from WA-MACR-1.1 and WA-MACR-1.2 show a

stratigraphic continuity between two horizons in one soil mound. This distinction of younger soils laying on top of older soils is supported by all three mounds showing continuity from surface horizons down in soil color, structure and consistence, and calcium carbonate concentration. If burrowing animals were responsible for mound formation, there might not be a clear distinction between young and old soils within the mounds due to continuous disturbance.

OSL dates and relative age indicators suggest that cold climate processes did not play a role in soil mound formation on Manastash Ridge. For cold climate processes to be responsible for the formation of the mounds, the soils within the mounds would have to be older than 10,000 years old. The evidence provided does not support this theory.

The deposition is the only theory supported by OSL and relative dating techniques. The soils within the mounds display a homogenous silty loam and loam throughout, indicative of loess. It is possible that they were formed by depositional processes depositing sands and silts where the mounds are found today. The mounds appear to be "dune-like" features that commonly found along the Columbia River. The brownish color of the soil suggest that the loess parent material is basalt and thus the origin of the loess must be the Yakima River and Manastash Creek. If the Columbia River was the source the silt might have a whiter color of granite introduced by the Ice Age floods.

Further Research

This study has shown the apparent differences between soil mounds and the continuous soil mantles on Manastash Ridge. For more accuracy and more data to support the results gathered in the study it is suggested that more soil mounds be excavated and dated using absolute and relative techniques. Soils from the continuous soil mantles should be analyzed alongside soils from soil mounds to determine if clay skins and argillic horizons are present. Other mounds on the

Columbia Plateau need to be dated to see if all the mounds are late-Holocene features and to ensure

that the results collected on Manastash Ridge are accurate as well.

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