TEXTURE AND MINERALOGY: HOW SOIL CHARACTERISTICS HELP TO UNDERSTAND SOIL FORMATION

By Sarah Brookins
Department of Geological Sciences
University of Colorado at Boulder

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Thesis Advisor:
Kathryn Snell, Department of Geological Sciences

Defense Committee:
Kathryn Snell, Department of Geological Sciences
Lon Abbot, Department of Geological Sciences
Eve-Lyn Hinckley, Environmental Studies Program
William Preston Cumming, Center for Teaching and Learning

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Abstract

The formation of pedogenic inorganic carbon in soils is important for the terrestrial carbon cycle, improving agriculture processes and providing a paleoclimate record for the geologic past. One form of pedogenic carbonate that is useful for the geologic record is calcium carbonate ($CaCO_3$) nodules. Previous research has shown that soil grainsize, clay minerology, soil structure, and organisms all impact a nodule's formation. This project investigates how different combinations of these elements influence nodule characteristics by looking at three different soil orders in northeastern Colorado, mid-eastern Colorado, and northwestern Nebraska. First, I investigate how environmental factors impact soil formation. Then using soil texture and mineralogy, I investigate how nodules reflect the soil they formed in. Methods in this study include soil pit analysis, particle size analysis, X-Ray diffraction analysis, and nodule thin section analysis. Soils reflect their combined formation history that is then translated into nodules' characteristics, which makes understanding nodule formation in different soil orders all the more important for environmental studies moving forward.

1. Introduction

Soils are an important part of life for both survival and the progression of environmental studies. They support numerous ecosystems and organisms, including humans by means of agriculture and food production. One element that affects soils productivity, characteristics and chemical processes is pedogenic carbon. Understanding pedogenic carbonate formation has applications both in modern environments and in the geologic past (e.g., Zamanian et al., 2016). Inorganic soil carbonate has been an area of interest recently due to its role in the carbon cycle (Hsieh,1993; Qualls and Brigham, 2005) and its abundance at shallow depth in semi-arid and arid soils (e.g. Díaz-Hernández et al., 2003; Emmerich, 2003; Shi et al., 2012; Kramer and Chadwick, 2018) In the geologic past, pedogenic carbonate nodules have been used to infer information about temperature, precipitation style and quantity, vegetation, and past atmospheric CO_2 levels (e.g. Cerling, 1984; Cerling and Quade, 1993; Breecker et al., 2009).

The past work regarding how calcium carbonate ($CaCO_3$) nodules form and what influences their morphology is very limited. Wieder and Yaalon have published two studies regarding the influence on matrix composition on carbonate nodules (1974) and the influence soil characteristics had on the micromorphology of the nodules (1982). The key to these studies showed that soil structure stability, soil texture, existing soil carbonates, soil clay minerology, and the presences of organisms affected the carbonate nodule formation. These two studies are the backbone of research done for what soil characteristics influence carbonate nodule formation and leaves room for further exploration: specifically, regarding different soil orders, their histories and the factors that created them.

This project investigates three sites, each categorized as a different soil order. These locations have been sampled to compare the soil's texture, mineralogy, history, and formation factors to the calcium carbonate nodules that are formed within them. The work conducted aims to fill in gaps in the understanding of carbonate formation, provide specific examples in a range of environments, and explore how other soil components influence the soil and in turn, the nodules. This work complements other work done in the Snell stable isotope lab.

2. Background

2.1 Soils

Soils are a made up of varying proportions of mineral grains, organic matter, and organisms. Soils can be described and classified in multiple ways, with the largest subcategory being orders (12) , and the most narrowed down subcategory being soil series (25,000); all based off their properties (Brady and Weil, 2014). Soil properties are a direct result from the environmental characteristics they form under, specifically: climate, organisms, relief, parent material, and time (collectively known as CLORPT) (Jenny, 1994). In each soil, there are 6 potential horizons that may develop given the soil's formation factors: O, A, E, B, C, or R. Not all soils will display all 6 horizons, and it is possible to have sub-horizons. Based on the soil texture (grain size), soils may be classified into soil types. They may also be described by the mineralogy that composes them. Altogether, the sum of the soil horizons, grain size and mineralogy can be used to determine soil order.

2.1.1 Soil Development factors

Soils are created when rock (known as parent material here) is converted into soil under the series of factors mentioned above as CLORPT (Jenny, 1994). Climate, organisms, relief, parent material, and time are all considered independent variables, meaning that under the combination of all five factors, one specific type of soil forms and accounts for its characteristics (Jenny, 1994).

Climate is the behavior of weather conditions in an area over a long period of time. Elements of climate include precipitation, humidity, and temperature, which all have one thing in common: water. Water percolation through the soil column causes minerals and nutrients to be dissolved, translocated, or precipitated (Jenny, 1994) while when water is evaporated, being taken up by vegetation, or stopped by impenetrable horizons, these processes are put on hold. Chemical weathering agents such as this tend to “speed up” a soil’s path to a state of equilibrium or maturing and further development of horizons.

Organisms affect nutrient cycles and availability within soils. In terms of soil development, surface horizon of a soil is most impacted by the vegetation, given that plants are reincorporated into the top of the soil after it dies (*Washington Soil Formation*, 2021). Micro-organisms break down nutrients (*Washington Soil Formation*, 2021) and therefore impact the chemistry of the soil and the rate at which chemical reactions happen.

Relief influences drainage, erosion, and deposition of an environment (*Washington Soil Formation*, 2021)). An area with high relief would most likely be well drained because the slope does not allow water to pool. This impacts the water driven chemical reactions that drive development of horizons by continually moving water out of the system. These environments are also likely to have higher erosion rates because high relief correlates to higher energy environments (e.g., mountains).

It has been agreed on that these five factors all have influence on soil formation, but parent material has been the element most debated. Across different soil classification schemes, only a fraction of them consider parent material (i.e., within the 12 soil orders only 2 consider parent material), but there have been multiple studies (e.g., Wilson and Berrow, 1978; Vizcayno Munoz et al., 1979; Gray et. al, 2011) investigating the influence of parent material on the mineralogical properties and development of the soils that come from them, which showed significant impact (Wilson, 2019). A review of the role of parent material by Wilson (2019) encourages scientists to investigate this element of CLORPT more fully in their soil studies as it helps to understand all other aspects that go into classifying a soil. The last factor, time, is the variable that shows how long the processes that develop soil have been able to happen. When looking at soils of different ages, younger soils usually have less established horizons while older soils have much clearer distinctions between horizons in comparison (Washington *Soil Formation*, 2021). This is a general rule of thumb, but it is important to remember age is not analogous to level of development or maturity in all cases. Although an older age allows for more time for these processes to occur, it is ultimately the factors of climate, organisms, relief, and parent material that determine the rate of development (Jenny, 1994).

2.1.2 Soil horizons

O is the hummus or organic layer found on the top layer of certain soil, characterized by a dark brown color from decomposed organic matter (Jenny, 1994). This usually shows up in woodland areas, which are continually supplied leaves, twigs, and pine needles. The A horizon is referred to as the topsoil and meets the surface if the O horizon is not present. An E horizon represents the eluviated horizon (Jenny, 1994). It is characterized by being lighter than the above A horizon from containing less organic matter and having a lower clay content than the A horizon, leaving mainly silt and sand. This horizon is often found in older, more developed soils because minerals, organic matter, and clay have more opportunity to be leached by the movement of water passing through the soil column. The B horizon is an accumulation of illuviated materials and is often rich in clay, silicates, iron, and or carbonates. This leaves room for many different variations of B horizons and can result in multiple subcategories within a soil column (Jenny, 1994). One example is a subdivision of the B horizon with a large presence of calcium carbonate denoted as “Bk”. This portion of the B horizon is usually lighter in color than the B horizon above and or below it. The B horizon is often referred to as the subsoil and serves as a bridge between the upper and lower soil components. A C horizon is made up of broken up parent material with little to no organic matter present (Jenny, 1994). This is the material that is the basis for the A and B horizons, contributing important indicators of the soils starting mineralogical composition. Lastly, the R horizon is made of bedrock. This is a continuous rock mass that is not broken up, deep below all other soil components (Jenny, 1994).

2.1.3 Soil Type

Soil type is determined by its particle size distribution and gives a general idea of its physical properties. The three particle sizes used for classification are sand, silt, and clay, and within those categories, there are further descriptions: ranging from coarse to fine (Brady and Weil, 2017). Using the relative proportion of each size class, soils can be fit into one of the basic soil types.

Sand refers to particle sizes between 0.05 mm and 2 mm and is often made up of quartz (SiO2) (Brady and Weil, 2017). Silt ranges from larger than 0.002 mm to no bigger than 0.05 mm and is also predominantly made up of quartz. Because of this size, silt is unable to be seen with our eyes alone. It can, however, be felt as a gritty texture when rubbing in between your fingers or against your teeth. Clay is the smallest size fraction, being less than 0.002 mm in diameter, and is described as very smooth to the touch. This is not to be confused with clay minerals; other mineral types can be ground down to a clay size but is not necessarily made of clay itself. Clay plays an important role in this project and will be a point of interest at each location regarding both grain size and mineralogy. When the term loam is used, it is referring to a soil that has at least 60% silt fraction and will often time have a grain size descriptor if either clay or sand are secondary (ex: sandy loam).

Soil type is important because it impacts how much water that soil can hold and the rate at which water moves through it. For example, sand has a low specific surface area due to its size and therefore areas with sandy soils are drought prone because they cannot hold much water (Brady and Weil, 2017). The low specific area also allows water to move through sandy soils quickly, meaning they have a high permeability. Clay is the opposite. Clay rich soils can hold a lot of water because of clay's relatively large specific surface area, causing clays to stick together when wetted (Brady and Weil, 2017). These effects can go on to impact other processes and characteristics, such as the type of vegetation able to grow and formation of different horizons.

2.1.4 Soil Mineralogy

Soil mineralogy reveals information about a soil's parent material and the environmental conditions under which it formed. Soil mineralogy can be observed directly in the field, particularly when it comes to oxide secretions, carbonate nodules, or more comprehensively through lab analysis such as x-ray diffraction.

Quartz and feldspar are the two most observed minerals in soils (Brady and Weil, 2017). Both minerals are highly resistant to both chemical and physical weathering and, therefore, persist often in a large range of soils. Other minerals can tell us more details about the soil's history and development.

Not to be confused with the size fraction, clay minerals play an important role in the mineralogy of soils. Clay minerals are a product of chemically weathered rock and are a part of the structural group phyllosilicates due to their sheet-like structure. Clay types vary in structure, but each have at least one tetrahedral or silica sheet and at least one octahedral or gibbsite sheet (Brigatti, 2006). A tetrahedral sheet is made up of a chain of bounded tetrahedral units, where one tetrahedral unit is comprised of a silicon ion surrounded by for oxygen ions (Brigatti, 2006). A gibbsite sheet is comprised of a chain of octahedral-alumina units linked together, where an octahedral-alumina unit is an aluminum ion surrounded by six hydroxyl ions (Brigatti, 2006).

Isomorphic substitution can occur with an octahedral sheet, in which the aluminum ion within the octahedral unit is substituted with a different ion with the same size (Brigatti, 2006). This results in a similar structure with a different chemical make-up, creating a different mineral (Barton, 2002). Based on the sheets and their bonds, the clay minerals this project is concerned with can be broken down into the following groups: 1:1 non-swelling, 2:1 non-swelling and 2:1 swelling clays.

1:1 clays are made up of one tetrahedral sheet and one octahedral sheet that are held together by hydrogen bonding (Brigatti, 2006). This contracted bond does not allow for expansion from hydraulic interactions because water is not able to come in. This results in the external surfaces being the area to react with outside stimulus (Barton, 2002). When soils have an abundance of 1:1 clay, they tend to have lower fertility and their capacity for absorbing cations is small (Barton, 2002). One example of a 1:1 clay is Kaolinite. It is the most common clay mineral, which is used globally for pottery and ceramics. This clay type shows up in abundance in heavily weathered soils, and forms from taking up aluminum and silica that have been weathered from primary and secondary minerals (Schulze, 2005). Other than being a byproduct of the chemical weathering of a soil, kaolinite can also be deposited into a soil from the erosion of a clay-rich sedimentary parent material (Schulze, 2005).

2:1 clays are structured by an octahedral sheet sandwiched between two tetrahedral sheets (Brigatti, 2006). This clay type has both swelling and non-swelling clays depending on which ions are involved. In 2:1 swelling clays, each tetrahedral-octahedral-tetrahedral layer is bonded together with a Van der Waals bond and the outside of each of the layers has a negative charge (Barton, 2002). The Van der Waals bond is weaker than the hydrogen bonding in 1:1 clays, allowing for water to get in between the sheets (Barton, 2002). This paired with negatively charged perimeter draws water in and causes the clay to expand (Brigatti, 2006). Smectite falls into this category and is important in vertisols and soils with vertic properties. It has been shown that smectite most successfully forms in moderate hydrothermal conditions that transform a glass, gel, or another aluminosilicate. There must also be enough magnesium most be present (Kloprogge,1999).

2:1 non-swelling clays contain different ionic bonds that do not allow water to get in as much, and therefore, do not cause extensive swelling (Barton, 2002). For example, the 2:1 non-swelling clay illite has potassium bonds opposed Van der Waals bonds (Brigatti, 2006). The non-exchangeable potassium bond is stronger than the Van der Waals bonds and does not allow a large amount of water to get in and expand the clay (Brigatti, 2006). Illite is classified as a 2:1 non-swelling clay and in paleosols, can be formed from the wetting and drying of smectite, or the weathering of feldspars (Pollastro, 1985).

Certain minerals are also telling of the weathering processes that have taken place. An example of this is the accumulation of authigenic or inherited clays. Authigenic refers to the clays that have formed since the soil has been there through weathering processes and chemical reactions. Inherited clays are from the material that makes up these soils.

2.1.5 Soil Orders

Soil orders are a way to distinguish soils from one another by one or more biological, physical, or chemical factors (Brady and Weil, 2017). For example, a gelisol is defined by the presence of permafrost (W. Cumming, personal communication 2021). There are 12 soil orders, and in this project, I will focus on 4 of them: mollisol, alfisol, aridisol, and vertisol.

Mollisols are the most abundant soil order in the United States, making up around 22% of the land cover, and are characteristic of grassland environments (Brady and Weil, 2017). The name ‘mollisol’ means “soft” in Latin and they are identified by a dark mollic epipedon, formed from the accumulation of calcium-rich organic matter from grass roots (Brady and Weil, 2014). The mollic epipedon is typically observed at a depth of 60cm-80cm. At the surface, aggregates are made up of clays or organic matter and do not become hard when drying occurs (Brady and Weil, 2014). Mollisols are moderately weathered soils and considered ‘intermediate’ when describing the degree of development (Brady and Weil, 2014).

Alfisols make up 13.9% of the land surface in the United States, and are characteristically found in in a cool, moist forested environments (Brady and Weil, 2014).The name comes from the word pedalfer, which means aluminum and iron. When describing an alfisol, a key element is the subsurface horizon where concentrations of metals (Al, Fe) and clay silicates have gathered into the B horizon by illuviation (Brady and Weil, 2014). Alfisols are characterized as moderately weathered soils that are intermediately developed (similarly to a mollisol) (Brady and Weil, 2014).

Aridisols make up 8.3 % of the land surface in the United States, and are characteristically found in, as the name suggests, arid or semi-arid climates (Brady and Weil, 2014). In these environments, desert shrubs and grasses are the dominant vegetation. An aridisol is characterized as a soil that remains dry for at least half of a growing season and does not remain moist for more than 90 days in a row (Brady and Weil, 2014). These soils are considered less mature and have undergone less development than both alfisols and mollisols (Brady and Weil, 2014).

Vertisols make up just 2% of the land surface in the United States. They are characterized by at least 30% clay composition and little organic (Brady and Weil, 2014). Vertisols form in regions with distinctive wet and dry seasons (Brady and Weil, 2014). These components together are the driving factor for the distinctive shrinking and swelling periods that this soil order is known for. When a dry season causes the soil to lose its water content, the clays shrink and wide cracks going vertically down the soil column form (Brady and Weil, 2014). The surface of the soil develops granules which then fall into the cracks and cause vertical mixing. This is where the name “vertisol” comes from. Vertisols are darker in color, despite the low organic matter content (1-6%) and have similar degrees of weathering and development to that of an aridisol (Brady and Weil, 2014).

2.2 Calcium Carbonate Formation

Following oceans and fossil fuels, soils are the third largest reservoir for carbon on the planet (Zamanian, 2016). Soils store carbon in both organic and inorganic forms; most soil carbon is stored as organic carbon (Kramer and Chadwick, 2018). Soil inorganic carbon is an area of study that is gaining more interest in recent years and has been historically understudied compared to its organic counterpart (Zamanian, 2016; Kramer and Chadwick, 2018). This shift has been attributed to two main reasons: (1) the understanding that inorganic carbon’s significantly longer residence time causes it to play a large part in the carbon cycle (both regionally and globally) (Hsieh,1993, Qualls and Brigham, 2005) and (2) the dominance of inorganic carbon compared to organic carbon in the shallower depths of soils in arid or semi-arid environments (Díaz-Hernández et al., 2003, Emmerich, 2003, Shi et al., 2012). To explore the mechanisms and environmental conditions that cause this phenomenon in arid or semi-arid climates, it is first important to understand the types of inorganic carbon found in soils.

There are three sources of a soil’s inorganic carbon: biogenic carbonate, geogenic carbonate and pedogenic carbonate (Zamanian, 2016). Biogenic carbonate is formed through the structures of living organisms (i.e., shelled organisms, calcified seeds), geogenic carbonate is introduced by the deposit of calcareous sediments (dust deposits) or by weathering of the parent material, and pedogenic carbonates are the result of existing inorganic carbon in the soil dissolving and precipitating again (Zamanian, 2016). Of all the different structures that can come of pedogenic carbonate formation, this project focuses on the carbonate nodule.

Carbonate nodules are spheroids of calcium carbonate that form in soil during shifts in climate in both semi-arid and arid regions (Zamanian, 2016). This form of soil inorganic carbon is useful for analyzing modern environments and the geologic past because the nodules can be used for stable isotope analysis (e.g., Cerling, 1984; Cerling and Quade 1993). The carbon isotopes reflect information about vegetation on the landscape, and the oxygen isotopes reflect information about soil water and the temperature at which the nodules formed (e.g., Cerling, 1984; Cerling and Quade 1993). Additionally, the carbon isotope composition of a soil calcium carbonate nodule has been used to infer CO_2 levels in the geologic past (e.g., Breeker, 2013). These factors make them a point of interest in paleoclimate studies, which make better understanding nodule formation a critical area of study.

2.2.1 Texture

Among many observed formation influences (bulk density of peds, hydrologic influence, dust deposition, soil development), this project is focusing on characteristics of the soil matrix and how that impacts the nodule’s characteristics. In previous studies, it has been determined that grain size of the matrix dictates the size and growth of calcite crystals in the nodule; notably when clay minerals are present (Wieder and Yaalon, 1974; Durand et al. 2018). The beginning stages of nodule formation vary depending on the grain size, if the soil is calcareous or non-calcareous, presence of clay minerals, soil structure stability and the activity of organisms.

(Wieder, 1982). Through thin section analysis, it is also possible to identify if the nodules formed in situ, partially in situ, or have been inherited from another soil, which gives insight to the soil's history (Wieder and Yaalon, 1974).

Depending on the environment they form different carbonate nodules have different microfabrics and developed textures, known as the nodule's morphology (Wieder, 1982). One study in 1974 by Wieder and Yaalon concluded that when looking at coarser grained sandy soils, other minerals have room (when under proper forming conditions) to precipitate and fill gaps within nodules. They also reported that the presence of clay minerals in the matrix composition had an impact the size and growth of the nodules' calcite crystals because they impede the recrystallization and succeeding growth of calcite crystals.

2.2.2 Orders

Different soil orders produced these nodules uniquely, whether that be varying depths of the calcium carbonate horizon (Bk), the frequency, size, etc. The current leading hypothesis of pedogenic calcium carbonate formation is that dry down events are a large factor in their creation in soils due to a process called carbonate supersaturation (e.g., Breecker et al., 2009; Hough et al 2014; Burgener et al., 2016; Huth et al., 2019; Kelson et al., 2020). Dry-down may be more prominent for some soil orders due to the type of environment they are prone to form in. Breeker and his collaborators (2013) investigated vertisols due to the way seasonal changes impact their characteristics. The formation of the calcium carbonate nodules was found to occur during the dry down events, which are associated with low soil CO2 due to the escape of soil CO_2 through the dried-out soil cracks. Given that there are 12 soil orders, it is inevitable that they each possess unique mechanics that could potentially effect carbonate formation.

3. Field Sites

Figure 1. Map of field sites. Blue dot is the Oglala Grassland site, yellow dot is the Briggsdale site, and the red dot is the Seibert field site.

3.1 Briggsdale, Colorado (40.594793, -104.318627)

This location is in Northeastern Colorado near the Pawnee National Grassland (Fig. 1). The climate of this area is that of a typical grassland: medium to high wind movement, low humidity, sufficient sunshine, and light rainfall (seasonally dependent) (Rasmussen et al., 1971).

Topographically, the Pawnee Grasslands are in a catchment basin, meaning the water supply is heavily dependent on precipitation, as there are not any rivers flowing through this region (Rasmussen et al., 1971).The geologic formation underlying this soil is the Laramie Formation (upper Cretaceous) which consists of shale, claystone, sandstone, and major coral beds (Tweto, 1979).

Previous work in the Snell stable isotope lab by R. Havranek has dated carbonate nodules from Briggsdale using ^{14}C dating to be 6980 ± 20 years, 8200 ± 25 years, and 8155 ± 25 years.

The Briggsdale site is in the geographical area impacted by the Dust Bowl. In the 1930's, an extreme drought combined with prolonged agricultural practices that were not suited for the climate and wind erosion caused a period of intensive dust storms known as the Dust Bowl (Bayvele, 2011). These storms tore up and transported millions of tons of topsoil across the United States throughout this time, influencing the soils we see today (Bayvele, 2011). It has resulted in a sandy topsoil composition, which decreases a soil's ability to hold water and impacts the type of vegetation that can be grown (Brady and Weil, 2017). This historical context is important to keep in mind when thinking about original and developed grain size distribution and mineral composition at this location.

Though this site is not currently used for agriculture, active agriculture sites are <100 m from the site. During the summer of 2021, those fields were used for corn.

3.2 Seibert, Colorado (39.118569, -102.925037)

The next site is in Siebert, Colorado which is in central eastern Colorado (Fig. 1). The climate of Seibert, CO can be described as a semi-humid agricultural area. The geologic formation underlying this soil is the Ogallala Formation which is comprised of well-cemented gravel and sand that dates to the late Miocene into the Pliocene (Tweto, 1979). This formation also features limestones and volcanic ash beds (Scott, 1978). Previous work in the Snell stable isotope lab by R. Havranek has dated carbonate nodules from Seibert using ^{14}C dating to be 9680 ± 30 years, and 7655 ± 25 years.

Like the Briggsdale, CO site, the Seibert site was likely affected by the Dust Bowl of the 1930's. More recently, this site plot was used as cow pasture.

3.3. Oglala National Grassland, Nebraska (42.960089, -103.597926)

The last site is located on the western end of Nebraska near the Oglala National Grassland (Fig. 1). The climate of the Oglala National Grassland can be described as semi-arid with, similarly to Briggsdale, light precipitation, varying daily temperatures, moderate to high winds and plenty of sunshine (Rasmussen et al., 1971). Geologically, this area has been subjected to volcanic ash deposits, from eruptions happening in the Eocene (36 M.Y.- 58 M.Y.) and then again in the late Pliocene (2 M.Y- 6M.Y.) (Terry and Lagarry, 1998). According to the Geologic History of Toadstool State Park (>15 miles south of site), in between these eruptions, there was a considerable amount of deposition of eroded material from the mountains west of this region. The geologic formation underlying this soil is the White River Formation. This formation consists of sandstone, siltstone, mudstone, minor conglomerates, and volcanic tuffs (Terry and Lagarry, 1998).

The Oglala National Grassland was acquired from homesteaders in the 1930's in response to financial challenges exerted by the drought and Dust Bowl.

4. Methods

4.1. Field Sampling

Before going to the field, background research was done using the *California Soil Resource Center Data Base* to predict how far down elements of interests would be (soil horizons, carbonate nodules). When digging the pit, the soil was broken up with a pickaxe, and then removed with a shovel until the desired depth. A tarp was placed to the side to lay out the soil dug up, so it could be put back roughly to reduce the impact of disturbance.

At each site, the pit was dug to reach roughly 60-80cm, with additional coring using a soil auger down the at least 100 cm. Samples were taken from the depths 0-10cm, 25cm, 50 cm, 75cm, 100cm, and any other depths with features of interest (large cracking, color differences, etc.) with a soil knife. Each pit was characterized and described with initial textural and mineralogical observations, and characterization of the surrounding environment.

4.2. Lab Analysis

The laboratory work for this project was done under the guidance of laboratory manager Wendy Freeman on East Campus at the Sustainability, Energy, and Environment Community (SEEC) and the Sustainability, Energy and Environment Laboratories (SEEL) in the Sediment/Plant Analysis and Processing Lab and XRD/Soil Processing Lab June 26th, 2021, through August 11th, 2021.

4.2.1 Grain Size Analysis

To measure the particle sizer distribution, I used the Mastersizer 3000 in Sedimentology Lab (SEEC). Before the samples can be tested, they had to be prepped through several processes to make to analysis more accurate.

The samples were first split down from each of their gallon sized bag to 3x4 2MIL bags. During the splitting process, we took care to take a representative sample of the whole sample at each step. Following splitting, roughly 1g of each sample was weighed out and underwent a hydrogen peroxide treatment. The purpose of this treatment is to get rid of as much organic matter as possible with the reaction of hydrogen peroxide and heat. For this preparation, technical grade 34-37% hydrogen peroxide was used. Each 1g sample was placed in a 600ml beaker along with approximately 5ml of hydrogen peroxide and at least 50ml of distilled water. Under the fume hood, three hot plates were set up: 2 on a lower heat (notch two) and 1 on a higher temperature (level under the highest). The samples were set up on a ‘circuit’, where samples spent 10 – 15 minutes on each hotplate before moving to the next. Completing this circuit was considered one round of treatment. The reaction is indicated by white bubbling. The samples went through as many rounds of treatment as needed, until white bubbling was no longer observed.

Next, the samples underwent wet sieving to try to remove any remaining organic material. The sample is passed through a series of sieves into a new 600 ml beaker. Three sieves sized were used: 2mm, 850µm and 125 µm. Anything greater than 2mm was put to the side and labeled with the corresponding sample identification number. The sample left on the sieve is then rinsed into a small bowl where the water on top was carefully poured off with the goal of having remaining organic matter go with it. The remaining sample is then recombined in the new 600ml beaker with the rest of the sample less than 850µm. The same process is repeated with the 125 µm sieve.

Once wet sieved, 8-10ml of chloride phosphate is added to each sample and is covered with a watch glass overnight. The chloride phosphate helps the particles to settle. Once the sample has settled to the bottom, the water is decanted off. Each sample is then centrifuged for 25 minutes to pour off the little water that remained after decanting. Approximately 20ml of sodium metaphosphate was added as a dispersant and left to sit for 24 hours.

Following this, the Malvern Mastersizer 3000 was used to measure grain size. A vial containing the prepared sample and sodium metaphosphate was divided using a splitter, first into halves then into fourths and so on. The number of times a sample was split was determined by obscuration range. For example, samples with a higher amount of clay sized particles needed to be split more times because the clay is light enough to float in the water column and increase the obscuration. The Malvern uses a laser to measure the grain size distribution where two rounds of 5 measurements are taken, resulting in 10 measurements total. The program then produces a curve for analysis.

4.2.2 X-Ray Diffraction

Determining the mineralogy of the sample was done by using x-ray diffraction (XRD). X-ray diffraction is the processes of bouncing a beam of X rays off a sample of sediment to get a read on what minerals are present. Due to the unique and uniform spacing of atoms in different crystals, the X rays create an interference wave pattern specific to different mineral types when they exit the sample. That pattern is then matched up with known mineral data and the mineral composition can be determined. The XRD used in this study uses a copper anode to produce x-rays with a characteristic wavelength of Cu K-alpha, 0.15418 nm.

To prepare samples for the XRD machine, 1.00g of each was weighed out and combined with 0.111g of zinc oxide. The zinc oxide is used as the internal standard for the machine to pick up on. This mixture is then poured into a mill container filled with cylindrical stones to grind the sample up, along with at least 4ml of methanol alcohol. This is then sealed shut and loaded into the mill for five minutes and once finished, dried in the oven overnight.

Now the sample is in a powered form and can be packed on the slide for analysis. The slide has a disk to hold the sample and is covered in a thin coat of Vaseline to help the sample stick. Next, the sample is ground up with a mortar and pestle to pass through a 500μ sieve. A glass slide is then secured on top of the disk so the powdered sample can be poured between it and the rim of the disk on the slide. Once packed, the samples were run on the XRD machine, each sample taking approximately an hour and a half (27 and a half hours total). The results are then generated by a program called ROCKJOCK6 for analysis.

4.2.3 Thin Section Analysis

The first step to preparing thin sections was to pick appropriate carbonate nodules. The appearance of nodules showed up in the soil profiles at varying depths, but all in their respective Bk horizons. If the nodules in a soil sample seemed on the smaller side, 3-5 nodules were chosen and if they were on the bigger side, 1-2 were chosen. If there was a mixture of sizes, a range was chosen to show a variety of nodules. Potential nodules were lightly squeezed to rule out if it was a sandy clump held together by calcareous "glue". If the nodule still held together, HCL was dropped on it to ensure that the formation was $CaCO_3$ based. If the acid fizzed, then the nodule was placed aside to be sent off to a different lab to create a thin section.

Once the thin section was created and sent back, the sides were examined under a microscope in plain polarized light and crossed polarized light. This is how the grain size and minerology within the nodule were determined.

5. Results

Images of the nodules in thin section can be found in the appendix starting on page 52.

5.1. Oglala National Grassland

5.1.1 Field Description

The Oglala site is in a grassland environment, with the vegetation consisting mainly of grasses, sage, and prickly pear cacti. The pit was dug to roughly 80cm and samples were collected at 10cm, 25cm, 30-38cm, 50cm, 75cm, and 100cm.

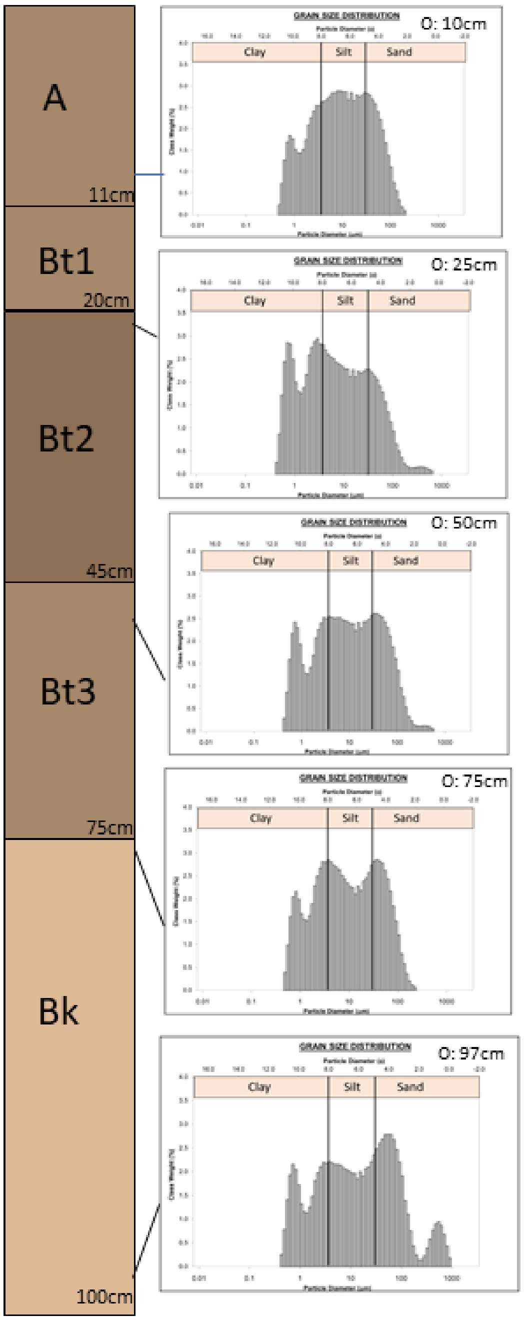
When looking at a wall of the soil pit, the first thing that stood out was the variation of crack sizes. They form from a freshly exposed layer of soil drying out due to the presence of an expanding and shrinking 2:1 swelling clay such as smectite. The cracks appear here mainly horizontally, and the largest cracks are between 20-45cm. The horizons present are a thin A horizon (0-12cm) followed by a B1 horizon(12-20cm), a B2 horizon (20-65cm), and a Bk horizon (65cm->80cm) (Fig. 2). The A horizon is light brown and felt mainly silty. The lower B1 horizon is slightly darker with small horizontal cracking. Below that, the B2 horizon is slightly lighter and has the largest horizontal cracking. In this horizon, there are also color mottling oxides (potentially iron or magnesium). The Bk is much lighter in color and grey/tan instead of brown. It is extremely hard, and nodules are present.

5.1.2. Texture Results

In the field, ribbon tests were performed to get a general idea of clay content across the different layers. A ribbon test is done by taking a ball of soil and squishing it out between your thumb and index finger. The length of the ribbon that can be made is telling of how much clay, silt, and sand is in the sample. For example, longer ribbons produced indicate more clay. The A horizon and the Bk horizon could not make ribbons, but the B horizons were able to. The section with the largest cracking (20-45cm) produced the longest ribbon at approximately 6 cm.

Oglala, CO - Aridisol

Soil Profile **Grainsize Distribution**



Soil Type

	Clay %	Silt %	Sand %
10 cm	16.2	74.3	9.5
25 cm	24.4	66.3	9.3
34 cm	23.6	67.6	8.8
50 cm	19.8	68.0	12.2
52cm	17.6	61	21.4
75 cm	18.6	71.0	10.4
97 cm	13.9	64.6	21.5

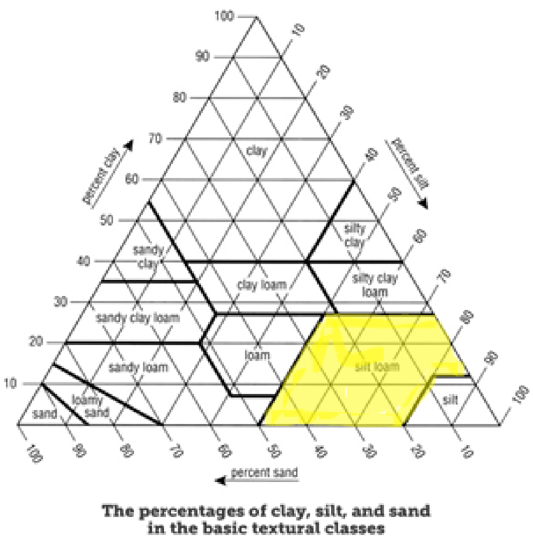


Figure 2. Grainsize analysis for Oglala. Horizons include A horizon (0-11 cm), Bt1 horizon (11 – 20 cm), Bt2 (20-45 cm), Bt3 (45 – 75 cm), Bk (75 – 100+ cm). 5 out of the 7 grain size analyses are shown. I exclude grain size distributions from 34 cm and 52 cm because of their proximity to other samples. Soil type is silt loam at all sampled depths.

The amounts of what makes up the silty loam in each sample changes, but not in a specific pattern.

5.1.3. Mineralogy Results

The XRD data showed this site to have the highest clay mineral percentage, with samples ranging from 24.7-43.7% (Table 1.). Figure 3 shows the breakdown of the total percentage in each sample by either 1:1 non-swelling, 2:1 swelling, and 2:1 non-swelling. Illite and smectite are the dominate clay types. Illite is a 2:1 non-swelling clay, which is the type that is the most abundant in each sample taken. The smectite abundance has its highest values of 7.6% of the clay composition at 25cm depth and 9.6% at 100cm. Smectite is a 2:1 swelling clay and can be created through the chemical weathering of volcanic glass. Oglala had relatively high percentages of volcanic glass as well with the 10cm depth containing 7.0% and both the 25cm and 50cm depth containing 3.5% each.

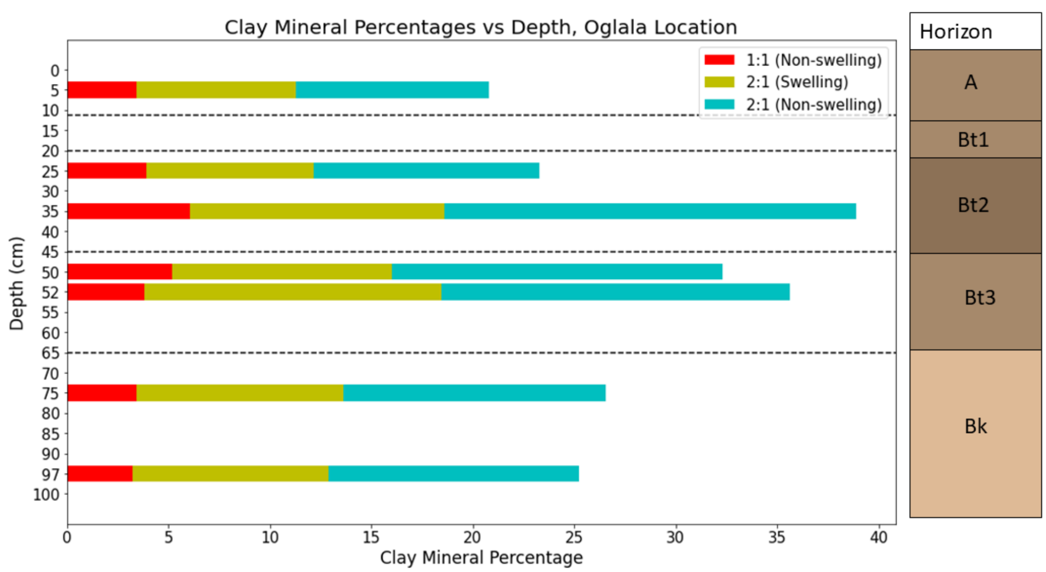


Figure 3. Clay mineral percentages vs. depth. The dominant clay type in most samples is 2:1 non-swelling. The highest total clay abundance was at 34 cm.

Calcite in the Oglala profile shows up at the 75cm measurement with 13.2% of the mineralogy and 12.7% at the 100 cm measurement. Of the three sites, these percentages are the highest.

Table 1.

	Oglala Mineralogy (%)								
	Non-Clays					Clays			
Depth (cm)	Quartz	Alkaline Feldspar	Plagioclase Feldspar	Calcite	Saks glass	Kaolinite (Dry Branch)	Smectite Total	Illite Total	Total Clays
10	40.5	11.2	10.6	0	5.4	3.4	7.9	9.5	23.2
25.0	39.5	12.6	8.8	0	6.2	3.9	8.2	11.1	26.9
34	29.4	10.8	7.4	0	6.6	6.1	12.5	20.3	42.6
50	34.7	9.5	8.4	0	5.9	5.2	10.9	16.3	35.3
52	29.4	11.4	8.1	0	9.1	3.8	14.7	17.2	37.7
75	29.9	9.3	6.6	13.2	6.5	3.4	10.2	12.9	29.2
97	29.2	12.7	4.5	12.7	7.6	3.2	9.6	12.3	30.4

Table 1. XRD mineralogy results for Oglala National Grassland, NE. Feldspars and clays are grouped by mineral groups.

5.1.4. Thin Section Results

The nodules taken from Oglala were the largest nodules of the three sites. Nodules from this site were taken from both 75cm depth and 95cm depth and the two had a similar mineral composition and matrix grainsize. The 75 cm nodule did, however, seem to have larger mineral inclusions within the nodules. There were a few inclusions within the 75cm nodules that appear to be an alteration mineral: potentially sericite. The following minerals were identified using both plane polarized and cross polarized light under the microscope: calcite, quartz, microcline, muscovite, and oxides.

5.2 Seibert

5.2.1. Field Description

The Seibert site is in rural farming country. The vegetation at this site is the most lush and diverse, as it has a variety of different grasses, leafy plants, and even squash. The soil pit was approximately 75cm deep, and samples were taken at 10cm, 25-30cm, 75cm, 87cm, and 100cm. The horizons have been defined as an O horizon (0-9cm), an A horizon (9-35cm), a B horizon (35-60cm), and the Bk horizon (60->75cm) (Fig. 4).

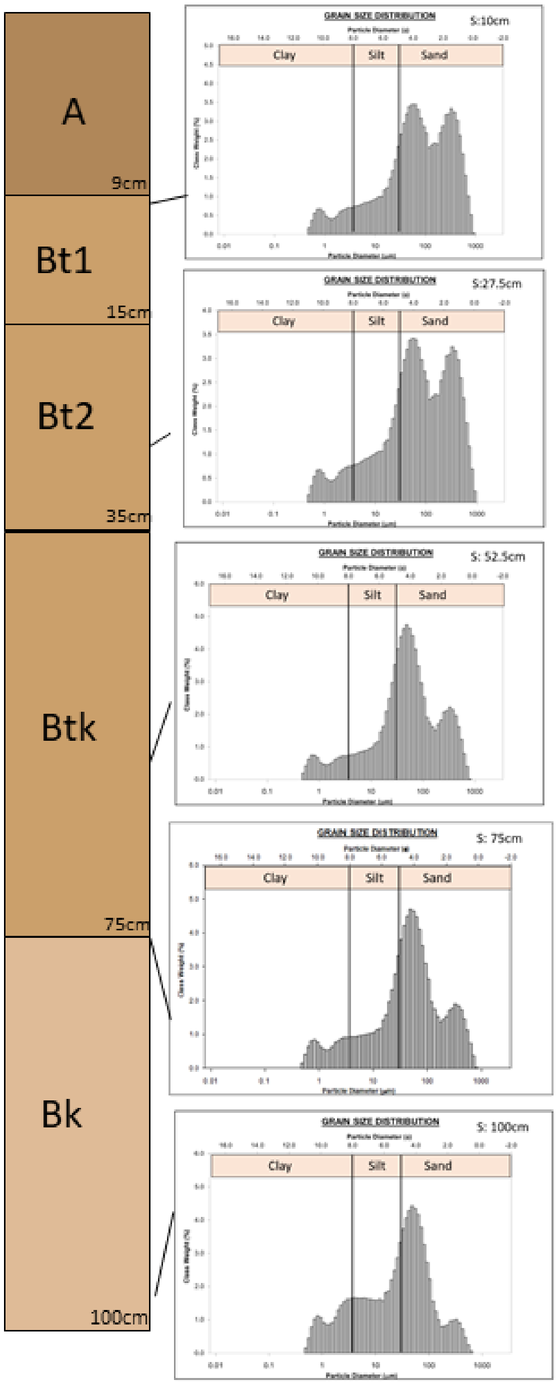
The O horizon is a medium brown, containing small lithics and feels silt dominant. The A horizon is more tannish grey in color. There are quinoa sized lithics that appear to be quartz and feldspar. This layer appears coarser grained and may be the result of leaching. The B horizon is dark brown with grey undertones and feels stickier to the touch, indicating higher clay content. There are small cracks (~3.5 cm), but this layer does not create ribbons.

5.2.2. Texture Results

Of the three locations, Seibert was in between Oglala and Briggsdale in respect to sediment size. The dominant sediment size in each sample gets smaller with depth (Fig. 4). In the A(10cm) and B (27.5cm) horizons, the proportions of sediment size cause the soil type to fall under the classification of sandy loam (85-50% sand, 0-20% clay and 0-50% silt). At the 52cm sample, there is a switch to the remaining samples being a silt loam (20-50% sand, 0-27%clay, and 73-88% silt). This is a large shift between soil types, and the most extreme between the three

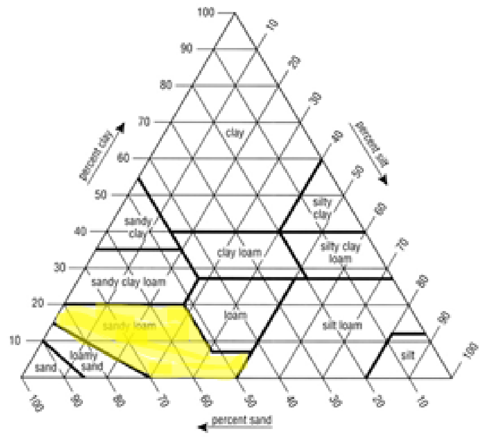
Seibert, CO - Alfisol

Soil Profile | **Grainsize Distribution**



Soil Type at 10cm and 27.5cm

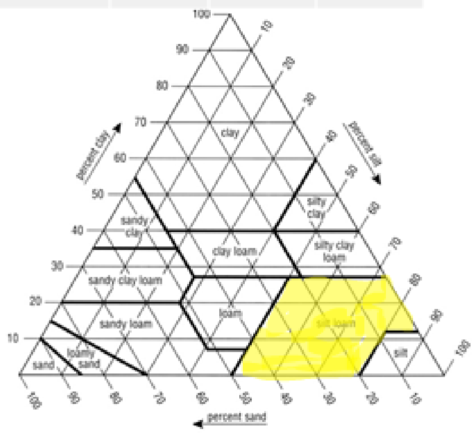
	Clay %	Silt %	Sand %
10 cm	6.6	40.6	53.8
27.5 cm	5.7	41.8	52.5



The percentages of clay, silt, and sand in the basic textural classes

Soil Type at 50cm, 76cm, and 109.5cm Depth

	Clay %	Silt %	Sand %
52.5 cm	6.1	52.8	41.1
75 cm	7.1	53.8	39.1
89.5 cm	12.2	70.0	18.8
100 cm	9.9	63.7	26.5



The percentages of clay, silt, and sand in the basic textural classes

Figure 4. Grainsize analysis for Seibert. Horizons include A horizon (0-9 cm), Bt1 horizon (9 – 15 cm), Bt2 (15-35 cm), Btk (35 – 75 cm), Bk (75 – 100+ cm). 5 out of the 6 grain size analyses are shown. I exclude grain size distributions from 89.5 because of their proximity to other samples. Soil type is sandy loam at 10cm and 27.5 cm and silt loam for the remaining.

sites. Seibert fell in the middle of the spectrum when it comes to amount of clay content, containing a range 16.8-34.7% (Fig. 4) depending on sample depth.

5.2.3. Mineralogy Results

The most dominant clay types were smectite (5.3-8.4%) and illite (6.6-9.2%). As seen in Figure 5., 2:1 non-swelling is the dominate clay type at each sampled depth. Calcite at this location did appear minimally at the shallower depths of 10cm and 27.5cm at 0.2%, which is not seen at the other two locations. The calcite percentages at the greater depths in the Bk layer are as follows: 75cm contains 5.2%, 89.5cm contains 7.9% and 109.5cm contains 7.2%.

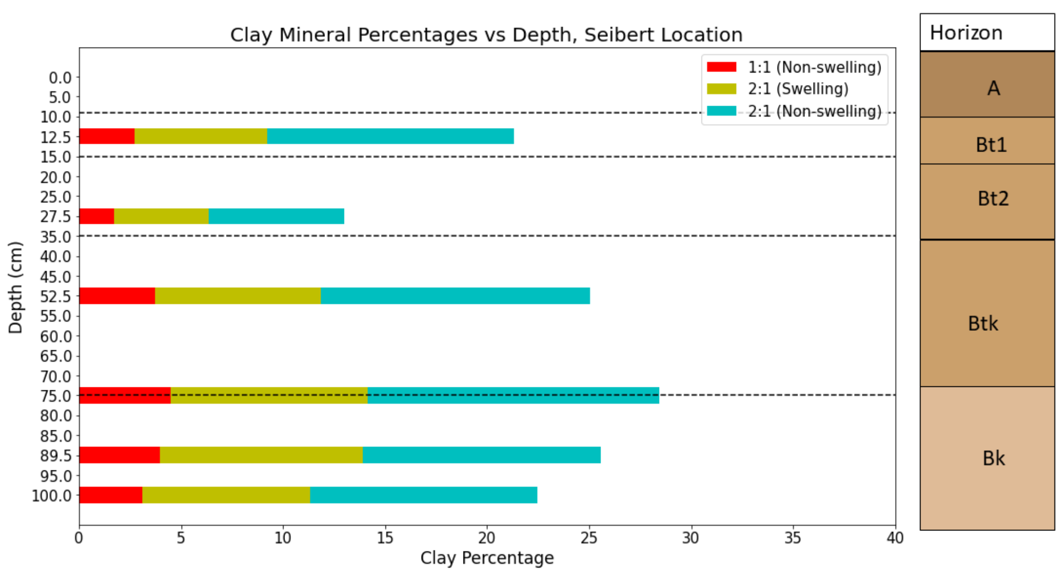


Figure 5. Clay mineral percentages vs. depth for Seibert, CO. The dominant clay type is 2:1 non-swelling. There is an unexpected decrease in total clay quantity at 27.5 cm.

Table 2

	Seibert Mineralogy (%)								
	Non-Clays					Clays			
Depth:	Quartz	Alkaline Feldspar	Plagioclase Feldspar	Calcite	Saks glass	Kaolinite (Dry Branch)	Smectite Total	Illite Total	Total Clays
10cm	36.8	17.8	9.8	0.24	6.4	2.7	6.5	12.1	23.1
27.5cm	47.2	16.9	11.9	0.23	5.7	1.7	4.6	6.6	14.5
52.5 cm	35.4	15.3	12.2	0	6	3.8	8.1	13.2	27.4
75 cm	30.8	13.5	9.6	5.2	6.7	4.5	9.7	14.3	30.9
89.5cm	28.8	14.0	9.2	8	6.8	4	9.9	11.6	29.3
100cm	32.2	14.7	9.1	7.2	6.6	3.1	8.2	11.1	24.2

Table 2. XRD mineralogy results for Seibert, CO.

5.2.4. Thin Section Results

The Seibert nodules have fine grain size and calcite crystal size of the three locations. Nodules were sampled from 75cm, 83cm, and 100cm depths and from sample to sample, no major differences are immediately identifiable. Inside them, quartz, biotite, amphibole, plagioclase, microcline, oxides, and zircon fragments were identified. The majority of these are common rock forming minerals besides zircon. The zircon is identifiable by its high relief, rectangular shape, and dark brown halos surrounding the edge of the mineral indicating radioactive decay of uranium.

5.3 Briggsdale

5.3.1. Field Description

The Briggsdale site is a grassland environment, with the vegetation consisting of grasses, shrubs, and a few trees. The soil pit is approximately 100cm deep and samples were taken at 10cm, 25cm, 75cm, 86cm, and 100cm. The horizons have been defined at 0-14cm as the A horizon, 14-46cm as the B horizon, and 46->100cm as the Bk horizon. It is important to note that using a soil auger allowed looking at deeper soil characteristics, and there was a significant color change at 104cm from light grey to light brown tones.

This site is quite sandy compared to the other sites. The first 9cm of the A horizon are predominantly sand with lithics of feldspars. It is medium brown in color and does not contain any calcium carbonate, as seen with an HCL fizz test.

5.3.2. Texture Results

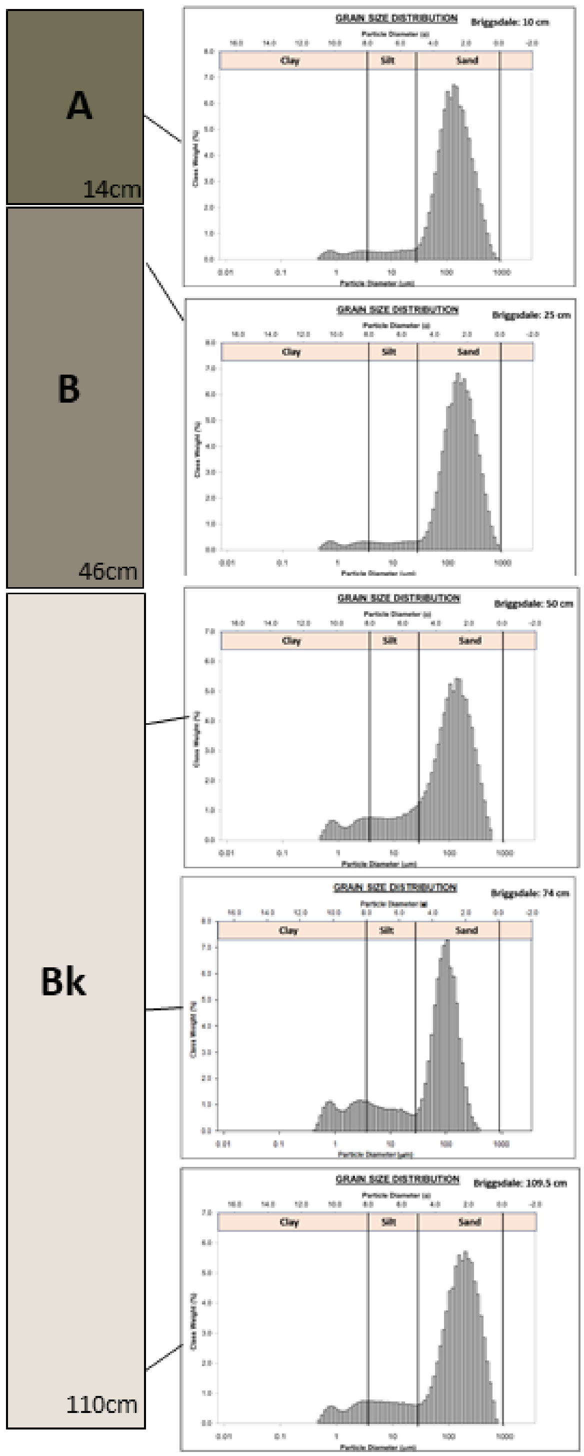
Briggsdale is the coarsest grained soil sampled. In the field, ribbon test could not be conducted, which was not a surprise given how sandy it was. The soil type changes moving down the soil column. For the A horizon and B horizon, the soil type falls under loamy sand while within the Bk horizon (Fig. 6), the soil is categorized as a sandy loam. To be a loamy sand soil, a sample must be 97-70% sand, 0-15% clay and 0-30% silt. When moving downward to a sandy loam, a sample then must be 85-50%sand, 0-20% clay and 0-50%. This means that the percentages of clay and silt are increasing with depth while the percentage of sand sized sediment is decreasing with depth. This is similar trend as what is seen at Seibert.

5.3.3. Minerology Results

The Briggsdale location had the lowest overall clay content, ranging from 12.4-22.4% respectively (Table 3). The most prominent clay types here were smectite (6.2-7.5%) and illite (4.2-7.6%). Looking at figure 7, 2:1 swelling clays are the dominant type in the A horizon and at the deepest measurement of the Bk horizon (100cm). In the other samples, 2:1 swelling and 2:1 non-swelling clay are nearly even while 1:1 non-swelling is the least prominent across the board.

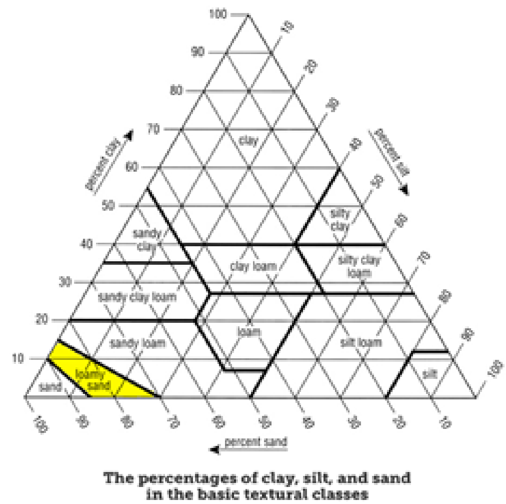
Briggsdale, CO - Mollisol

Soil Profile **Grainsize Distribution**



Soil Type at 10cm and 20cm Depth

	Clay %	Silt %	Sand %
10 cm	2.8	16.0	81.2
25cm	2.7	12.1	85.2



Soil Type at 50cm, 76cm, and 109.5cm Depth

	Clay %	Silt %	Sand %
50 cm	5.6	30	64.4
76 cm	9.8	32.8	57.4
109.5 cm	5.0	21.5	73.4

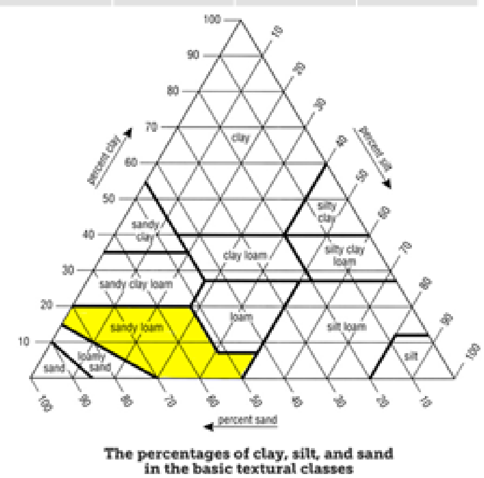


Figure 6. Grain size analysis for Briggsdale, CO. I observed an A horizon (0-14 cm), B horizon (14 – 46 cm), and Bk horizon (46 – 110 cm). Soil type at 10 and 25 cm is a loamy sand, and soil type at 50, 75, and 109.5 cm is a sandy loam.

This location had the highest quartz percentages overall, containing 53.1% in horizon A at the 10cm measurement (Table 3.). Comparatively, Ogalala's highest quartz percentage was 40.1% and Seibert's was 47.2%. The calcite shows up at 50cm with 5.1% $CaCO_3$ followed by 8.5% at 74cm depth and 2.1% at 109cm depth, like that at Seibert. Calcite appears at the shallowest depth of the three locations.

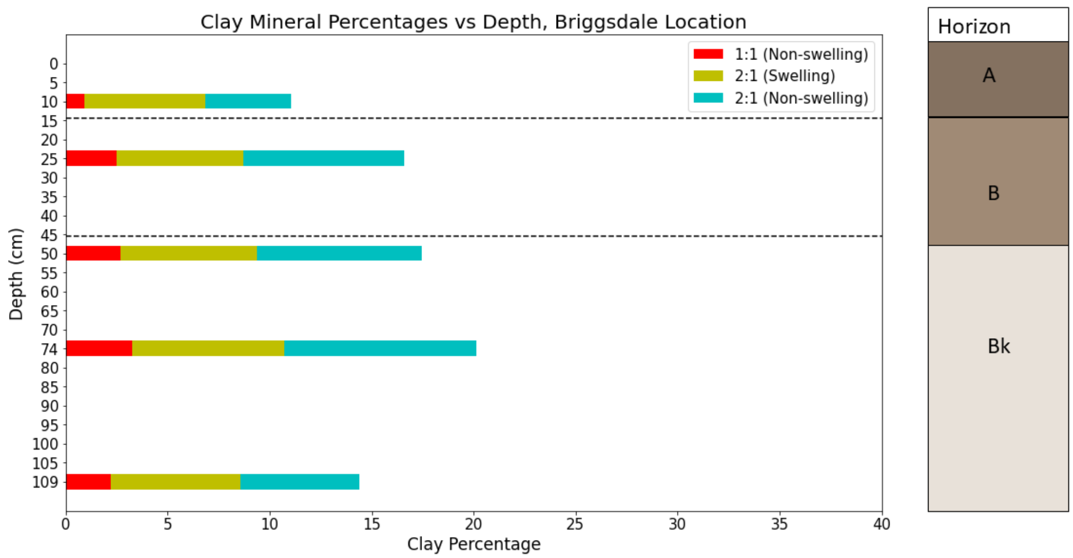


Figure 7. Clay mineral percentages vs. depth for Briggsdale, CO. 2:1 swelling and 2:1 non=-swelling clays are evenly distributed in the soil.

Table 3.

	Briggsdale Mineralogy (%)								
	Non-Clays					Clays			
Depth:	Quartz	Alkaline Feldspar	Plagioclase Feldspar	Calcite	Saks glass	Kaolinite (Dry Branch)	Smectite Total	Illite Total	Total Clays
10 cm	53.1	16.0	9.7	0.009	5.9	0.9	5.9	4.2	12.3
25cm	49.7	15.3	8.3	0.04	5.8	2.5	6.2	7.9	18.2
50cm	42.7	14.8	8.1	5.1	6.2	2.7	6.7	8.1	19.1
76cm	40.5	14.5	5.0	8.5	6.8	3.3	7.5	9.4	22.4
109.5cm	47.1	16.3	8.2	2.1	6.3	2.2	6.3	5.8	15.8

Table 3. XRD mineralogy results for Briggsdale, CO

5.3.4. Thin Section Results

The Briggsdale location had the smallest nodules and coarsest grainsize and calcite crystal size of the three sites. Unlike the other locations, the nodules sampled at Briggsdale (50cm and 105cm) look very different from each other under the microscope. Within the nodules at 50cm, the minerals present another than calcite are biotite, plagioclase, clinopyroxene, iron oxides, and quartz. Within the 105cm nodule, quartz and calcite dominate. The size of the quartz inclusions are much smaller than those included in the 50cm nodules.

6. Discussion

6.1 Soil Characteristics as they Relate to Soil Formation Factors

6.1.1 Oglala National Grassland

The Oglala National Grassland site has 5 soil horizons identified between 0-100cm depth: A, Bt1, Bt2, Bt3 and Bk. A Bt horizon is used to describe a horizon that has an accumulation of silicate clay that have either formed in situ or been transported into that horizon by illuviation. When seeing 3 different Bt horizons, this is a sign of a soil working through the formation processes to sort out these components. I observed abundant horizontal cracking in the Bt horizon, which plays a role in transport of the clays through drying and wetting. The shrink-swell behavior of this soil is consistent with the abundance of smectite in the soil pit. The abundance of calcium carbonate in this soil is consistent with a semi-arid climate because we would expect carbonates too be leeched from the upper sols in a moister environment.

Given the above factors, this soil is consistent with an aridisol with vertic properties. I refrain from calling this soil a true vertisol because there is horizon development, which I would not expect if it were a true vertisol.

6.1.2 Seibert

Seibert has 6 distinctive soil horizons including: A Bt1, Bt2, Btk, and Bk. In the Bt2 horizon, there is a decrease in clay which suggests leaching or the movement of clays in or out of this horizon (Fig. 5) This is likely the result of water coming in by either rain or by land maintenance (watering system, agriculture, etc.) A Btk horizon is a horizon with both calcium carbonate content and clays (Table 3.) likely formed similarly to Bt1 and Bt2 but with the supply of $CaCO_3$ from parent material. The parent rock here has a combination of limestone and volcanic ash deposits. The limestone is a source of $CaCO_3$ while the volcanic ash supplies volcanic glass that can then be chemically weathered over time and develop different clay characteristics in the respective horizons. The climate of this region is the most humid of the three sites, averaging 62% humidity daily which helps drive the hydrological processes associated with soil devlopement. This land is on a residential property and the details of the recent history are not available currently, leaving future analysis on those elements at Seibert.

6.1.3 Briggsdale

Briggsdale has 4 distinctive soil horizons identified between 0 cm - 110 cm depth: A, BA, B, Bk (Fig. 6). I did not observe a mollic epipedon in this soil as I might have expected given the location, surrounding organisms, and climate. It is very likely that this mollic epipedon previously existed, but the agricultural history of this site caused its absence.

Apart from typical formation factors, the unusual anthropogenically caused climate during the 1930's that deposited thick layers of dust might have been an influence on this. The Dust Bowl was created by a combination of poor farming practices and drought. This on its own could have destroyed the mollic epipedon. Then, the Dust Bowl itself displaced and deposited massive amounts of sediment.

This soil is in a prairie environment with a climate suitable for the growth of different grasses and that supports the formation of mollisols. The surrounding plots in this area were used for growing corn crops this past summer, meaning the soil here can support agriculture. The components to focus on in the Laramie formation are the claystone and the coral beds. The clay minerals in this formation are montmorillonite (smectite group), kaolinite, and illite (Gude, 1950) and corals have a skeleton of $CaCO_3$. Given the degree of impact and chemical influence this parent material has on the soil, this could supply calcium carbonate to the soil and be used to infer the clays here as potentially detrital.

6.2 Relating Texture and Mineralogy to Site History

6.2.1 Oglala National Grassland

The texture at Oglala kept the soil type consistent throughout the depths sampled as a silt loam. This can be attributed to the parent material and history of eroded mountain sediment deposition. Firstly, the White River Formation has siltstone, mudstone, sandstone, and many volcanic ash deposits. When the parent rock was being broken down and transformed into soil, there was already a smaller grain size to work with. As rock material is being eroded and transported out of a mountain environment, breaking down of the grains occur. The further away from the starting point sediment gets, the more opportunity that sediment has to break down in size and create rounder grains. Given that this location is ~ 500km east of the Rocky Mountains, the sediment that ended up being deposited in the location would likely be part of these smaller particle size categories.

Looking at the mineralogy of Oglala, the amount of glass, smectite, and illite across the soil profile is likely because of the area's volcanic history. The other two sites had a considerable amount as well, but Oglala had the highest (Table 1.). The two periods of volcanic eruption known in this area would be a likely source to have brought the glass into the parent material, which was eventually incorporated into the soil profile. From there, the weathering of these glasses over time would lead to not only the creation of smectite, but potentially the illite as well. The semi-arid climate allows for the repetitive dry and wet alteration require for smectite to create illite, suggesting some clays here to be formed in situ.

The number of mineral inclusions and basic rock forming minerals found here also aligns with the location and history of this region. The erosion of material in the Rocky Mountains being deposited eastward to the plains of the Oglala Grassland provides a variety of minerals. This could explain the largest values of kaolinite here. Kaolinite is usually a sign of a well-developed soil and because this is site has moderately defined horizons, I believe these quantities may have been deposited by mountain sediments.

6.2.2 Seibert

As mentioned in the field description, the Seibert site was likely impacted by the Dust Bowl of the 1930s. The top two depths sampled are coarser grained than the remainder of the profile sampled, and this could be due to the deposits from the powerful dust storms. The uniformity of soil type classification of the depths below the coarser grained samples supports the idea that this increase of grainsize is from an additional deposit of material or from variey grain sizes in the parent material.

The mineralogy of Seibert had similarities to Oglala, but in lesser quantities. This can be seen in the notable amount of glass, smectite and illite at this location (Table 3.). Looking at the parent material of the soil, it is shown to have layers of ash deposits that could have supplied the soil with the base to have similar weathering reactions. The climate in Seibert is described as semi-humid and having less than 15 inches of rain per year, providing the wetting, and drying required to have clays such as authigenic illite from smectite which can form from volcanic glasses. The parent material at Seibert contains limestones, which are made from calcium carbonate. Depending on the parent material influenced this specific soil formation, this could be a source of carbon in the soil’s system.

6.2.3 Briggsdale

Briggsdale's texture results are reasonable due to the high impact of the Dust Bowl in this area. The shallower samples are coarser than the proceeding and this result is interpreted as both the loss of organic material from unsustainable agricultural practices as well as the deposit of storm transported material. The larger grain sizes may also come from the parent formation having a bigger grainsize to begin with.

The effects of the Dust Bowl can also be seen in the observed mineralogy. Given that this site contains the greatest amount of quartz, it is reasonable to stay that those sand sided particles had been composed SiO_2. As mentioned in the soil formation section, the Laramie Formation (parent material) could be a large source of calcium carbonate and clay minerals (smectite, kaolinite, and illite). This location does have the least amount of clay minerals, but the dominant types are smectite and illite.

6.3 Relating Nodule Characteries to Texture

When comparing the grain sizes inside the nodules to those of the soil profiles from which they came, the data shows a direct correlation. As seen when comparing textures across field sites (Figure 2;4;6), Briggsdale had the largest percentage of sand sized particles at each depth sampled (sandy loam classification) and the nodules collected from the Bk horizon contained the coarsest matrix of the three locations. Similarly, the Seibert and Ogalala nodules came from soils with finer grain compositions (silt loam classification) and the grain size within the nodules reflected that. This is what previous research on nodules suggests: larger grainsizes leaves larger gaps calcite to precipitate out in larger grain sizes (Wieder and Yaalon, 1984).

When comparing the two nodule samples from Oglala, the 75cm sample had larger mineral inclusions inside them than the 95cm sample despite the 75cm soil sample being finer. This may have to do with the space provided for calcite to precipitate out. When the grain size of the soil is smaller (providing smaller pathways), more opportunities occur for other crystals to be roped into the nodule. With larger gaps, nodules may have the chance to precipitate larger sections of 'uninterrupted" calcium carbonate. This is shown in the nodules taken from 105cm depth in Briggsdale. The $CaCO_3$ forms in much larger patches with the only other mineral in large enough quantities to identify being quartz. These look much different from the other Briggsdale sample at 50cm. Of the soil samples containing nodules, the 105cm depth had the coarsest sediment composition at 73.4% sand sized particles while the 50cm sample contained 64.4% sand composition.

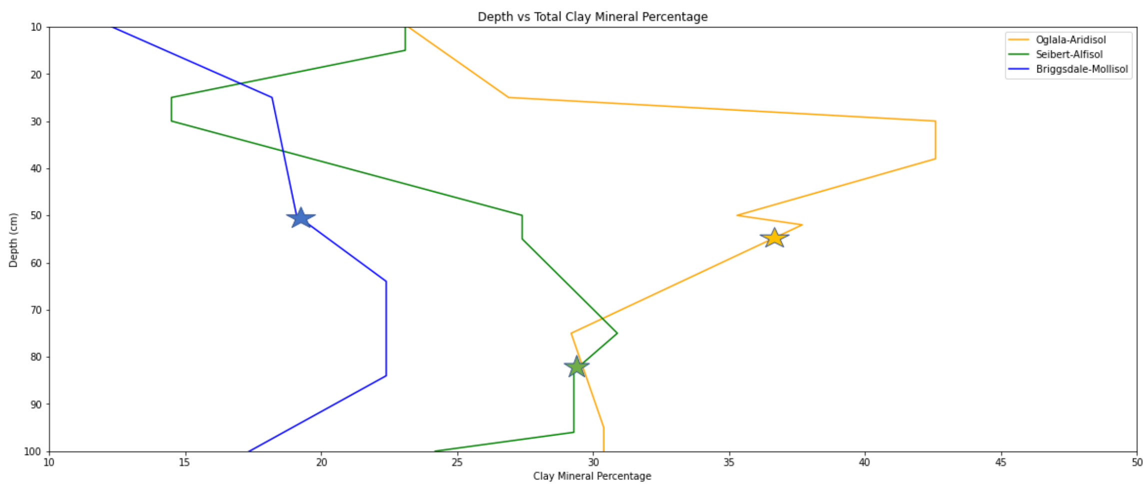


Figure 8. Total clay mineral abundance vs. depth for all three sites. The blue line is Briggsdale, CO, Green line is Seibert, CO and the yellow line is Oglala, NE. Stars represent depth of Bk horizon at each site.

6.4 Relating Nodule Characteries to Minerology

Most of the minerals found in the nodules that were not calcite were basic rock forming minerals and reflect the XRD data of the corresponding soil samples (Table 1;2;3). Quartz and different feldspars (microcline and plagioclase) are in large quantities both within most of the nodules and the soil profiles. The exception to this is the zircon found in the Seibert site nodules. Zircons are considered an accessory mineral and are highly resistant to chemical weathering. The XRD data did not test for zircon in the soil material but was identified in thin section and stood out as unique in comparison to the other sites' nodule mineralogy.

The size of the nodules aligns with the amount of calcite available at each site. The largest nodules found at Oglala formed in soil samples with the highest calcite percentage (13.2% and 12.7%) while the smallest nodules formed at Briggsdale in soil samples with the lowest calcite percentage (5.1%, 8.5% and 2.1%). The size of the nodules may be a result of different properties such as how much time they have gotten to form or s dry-down events more readily precipitating pedogenic carbon, but there is still more calcite to work with in Oglala, where the nodules are the greatest size.

One element of these results that piques interest is that the largest nodules are found at the site with the highest clay content (Fig. 2). Wieder and Yaalon reported that the presence of clay impedes remineralization of $CaCO_{3,}$ which leads to the question of how much clay needs to be present to make an impact. The sites do reflect, however, that nodules in finer grained sediments have finer calcite crystals and coarser sediments have nodules with larger calcite crystals.

Lastly when concerning the radiocarbon dates for Seibert and Briggsdale, the Seibert nodules are larger than the Briggsdale site, but they are of a similar age. Given these two sites being moderately similar, (largest distinction Seibert is semi-humid while Briggsdale is semi-arid) I believe Seibert's nodule size being larger is a result of calcite availability and potentially the climate.

6.5 Future Work

When reviewing my results, I wanted to touch on the sources of the clay in these field sites, whether they formed in the soil or were brought into the system (via deposition, parent material, etc). Using other observations, I was able to form evidenced ideas, but more laboratory analysis of whole soil thin sections would need to be done to say with certainty. When researching methods on how to do so, I found methods such as Potassium/Argon dating and scanning electron microscopy (SEM).

In the beginning of my project, I had planned to use cathodoluminescent (CL) analysis for the nodule thin section. Under this method, textures are easier to observe and would provide more detail to my thin section work. This is helpful when trying to distinguish if a carbonate formed in situ (more randomly oriented texture) or have been modified more than once through diagenesis (more orderly texture) (Havranek, personal communication). This would be useful when looking at the Briggsdale nodules, as they display different calcite crystal sizes inside the nodules. In the future, this is a tool I would like to learn to use to provide more in-depth description of the characteristics I am seeing and the weathering processes occurring in the soil.

7. Conclusion

In this study, I analyzed the characteristics of three soils and how that related to the traits of the calcium carbonate nodules found within them. The Oglala site featured a grassland area of low relief with an arid to semi-arid climate, and defined soil horizons with high clay content which leads this site to be classified as an aridisol with vertic properties. The parent material at this site includes volcanic ash and the nodules contain feldspars undergoing alteration. These suggests the clays here formed in situ (authigenic). The Seibert site is in a humid to semi humid agricultural environment which features a parent material composed of shale and limestone, low relief, and the wideset variety of plant types. The soil profile shows the development of an E horizon and the accumulation of clay silicates in the proceeding horizon (Bt). With all these factors considered, the Seibert soil is referred to as an alfisol. The clay types provided by the parent material suggests the clays at this location are detrital. Lastly the Briggsdale location features a grassland environment with low relief, a $CaCO_3$ rich parent material, and moderate sunshine and rainfall to describe its climate. Give the soils horizons development and the land use practices that impact key features of the soil profile, this soil is considered a mollisol. The parent material in this location is thought to be the supplier of the clay types, making them detrital. This work could be improved in the future by use of whole soil thin sections to better determine authigenic verses detrital clay and by utilizing cathodoluminescence (CL) to improve carbonate texture analysis.

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Works Cited

Amundson, R., Graham, R.C., and Franco-Vizcaíno, E., 1997, Orientation of carbonate laminations in gravelly soils along a winter/summer precipitation gradient in Baja California, Mexico: Soil Science, v. 162, p. 940–952, doi:10.1097/00010694-199712000-00009.

Barton, C.D., and Karathanasis, A.D., 2002, CLAY MINERALS:

Baveye, P.C., Rangel, D., Jacobson, A.R., Laba, M., Darnault, C., Otten, W., Radulovich, R., and Camargo, F.A.O., 2011, From Dust Bowl to Dust Bowl: Soils are Still Very Much a Frontier of Science: Soil Science Society of America Journal, v. 75, p. 2037–2048, doi:10.2136/sssaj2011.0145.

Berrow, M.L., Wilson, M.J., and Reaves, G.A., 1978, Origin of extractable titanium and vanadium in the a horizons of scottish podzols: Geoderma, v. 21, p. 89–103, doi:10.1016/0016-7061(78)90019-8.

Brady, N.., and Weil, R., 2017, Soil Architecture and Physical Properties, in The Nature and Properties of Soilds, Pearson.
Brady, N.., and Weil, R., 2014, Soil Classification, in Elements of the Nature and Properties of Soils,.

Breecker, D.O., Bergel, S., Nadel, M., Tremblay, M.M., Osuna-Orozco, R., Larson, T.E., and Sharp, Z.D., 2015, Minor stable carbon isotope fractionation between respired carbon dioxide and bulk soil organic matter during laboratory incubation of topsoil: Biogeochemistry, v. 123, p. 83–98, doi:10.1007/s10533-014-0054-3.

Brigatti, M.F., Galan, E., and Theng, B.K.G., 2006, Chapter 2 Structures and Mineralogy of Clay Minerals, in Developments in Clay Science, v. 1, p. 19–86, doi:10.1016/S1572-4352(05)01002-0.

Cerling, T.E., Quade, J., Wnag, Y., Bowman, J.R., 1989. Carbon isotopes in soils and palaeosols as ecology and palaeoecology indicators. Nature 341, 139-139, doi:10.1038/341138a0

Díaz-Hernández, J.L., Barahona Fernández, E., and Linares González, J., 2003, Organic and inorganic carbon in soils of semiarid regions: A case study from the Guadix-Baza basin (Southeast Spain): Geoderma, v. 114, p. 65–80, doi:10.1016/S0016-7061(02)00342-7.

D.G. Schulze, in Encyclopedia of Soils in the Environment, 2005

Durand, N., Monger, H.C., Canti, M.G., and Verrecchia, E.P., 2018, Calcium Carbonate Features: Elsevier B.V., 205–258 p., doi:10.1016/b978-0-444-63522-8.00009-7.

Emmerich, W.E., 2003. Carbon dioxide fluxes in a semiarid environment with high car- bonate soils. Agric. For. Meteorol. 116, 91–102

Gray, J.M., Humphries, G.S., Deckers, J.A., 2011. Distribution of World Reference Base soil groups relative to soil-forming factors. Geoderma 160, 373–383.
Gude, A.J., 1950, Clay Minerals of Laramie Formation, Golden, Colorado, Identified by X-ray Diffraction: AAPG Bulletin, v. 34, p. 1699–1717, doi:10.1306/3D934001-16B1-11D7-8645000102C1865D.

Hsieh, Y.-P., 1993, Radiocarbon Signatures of Turnover Rates in Active Soil Organic Carbon Pools: Soil Science Society of America Journal, v. 57, p. 1020–1022, doi:10.2136/SSSAJ1993.03615995005700040023X.

Huggett, J.M., and Cuadros, J., 2005, Low-temperature illitization of smectite in the late eocene and early oligocene of the Isle of Wight (Hampshire basin), U.K.: American Mineralogist, v. 90, p. 1192–1202, doi:10.2138/AM.2005.1674.

Jenny, H., 1994. Factors of soil formation: a system of quantitative pedology. Courier Corporation.

J.M. Huggett, in Encyclopedia of Geology (Second Edition), 2021

Kelson, J.R., Huntington, K.W., Breecker, D.O., Burgener, L.K., Gallagher, T.M., Hoke, G.D., and Petersen, S. V., 2020, A proxy for all seasons? A synthesis of clumped isotope data from Holocene soil carbonates: Quaternary Science Reviews, v. 234, doi:10.1016/j.quascirev.2020.106259.

Kloprogge, J.T., Komarneni, S., and Amonette, J.E., 1999, Synthesis of Smectite Clay Minerals: A Critical Review: Clays and Clay Minerals 1999 47:5, v. 47, p. 529–554, doi:10.1346/CCMN.1999.0470501.

Kramer, M.G., and Chadwick, O.A., 2018, Climate-driven thresholds in reactive mineral retention of soil carbon at the global scale: Nature Climate Change, v. 8, p. 1104–1108, doi:10.1038/s41558-018-0341-4.

Pollastro, R.M., 1985, Mineralogical and Morphological Evidence for the Formation of Illite at the Expense of Illite/Smectite: Clays and Clay Minerals 1985 33:4, v. 33, p. 265–274, doi:10.1346/CCMN.1985.0330401.

Rasmussen, Bertolin, and Almeyda, 1971, Technical Report No. 127 Grassland Climatology of the Pawnee Grassland:, https://mountainscholar.org/bitstream/handle/10217/16014/IBP127.pdf?sequence=1&isAllowed=y (accessed October 2021).

Scott, R.B., Bryant, B. and Perry, W.J., 2002. Late Cenozoic deformation by evaporite tectonism in the Grand Hogback monocline, southwest of the White River uplift, Colorado. SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA, pp.121-148

Sternai, P., Caricchi, L., Pasquero, C., Garzanti, E., van Hinsbergen, D.J.J., and Castelltort, S., 2020, Magmatic Forcing of Cenozoic Climate? Journal of Geophysical Research: Solid Earth, v. 125, p. 1–22, doi:10.1029/2018JB016460.

Terry, D.O., LaGarry, H.E., and Hunt, R.M., 1998, Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America):, doi:10.1130/spe325.

Tweto, O., 1979, Geologic map of Colorado.:
Qualls, R.G., Bridgham, S.D., 2005. Mineralization rate of 14C-labelled dissolved organic matter from leaf litter in soils of a weathering chronosequence. Soil Biol. Biochem. 37, 905–916, doi:10.1016/j.soilbio.2004.08.029.

Washington Soil Formation, 2021, https://www.nrcs.usda.gov/wps/portal/nrcs/detail/wa/soils/?cid=nrcs144p2_036333.

Wieder, M., and Yaalon, D.H., 1974, EFFECT OF MATRIX COMPOSITION ON CARBONATE NODULE CRYS-TALLIZATION.:

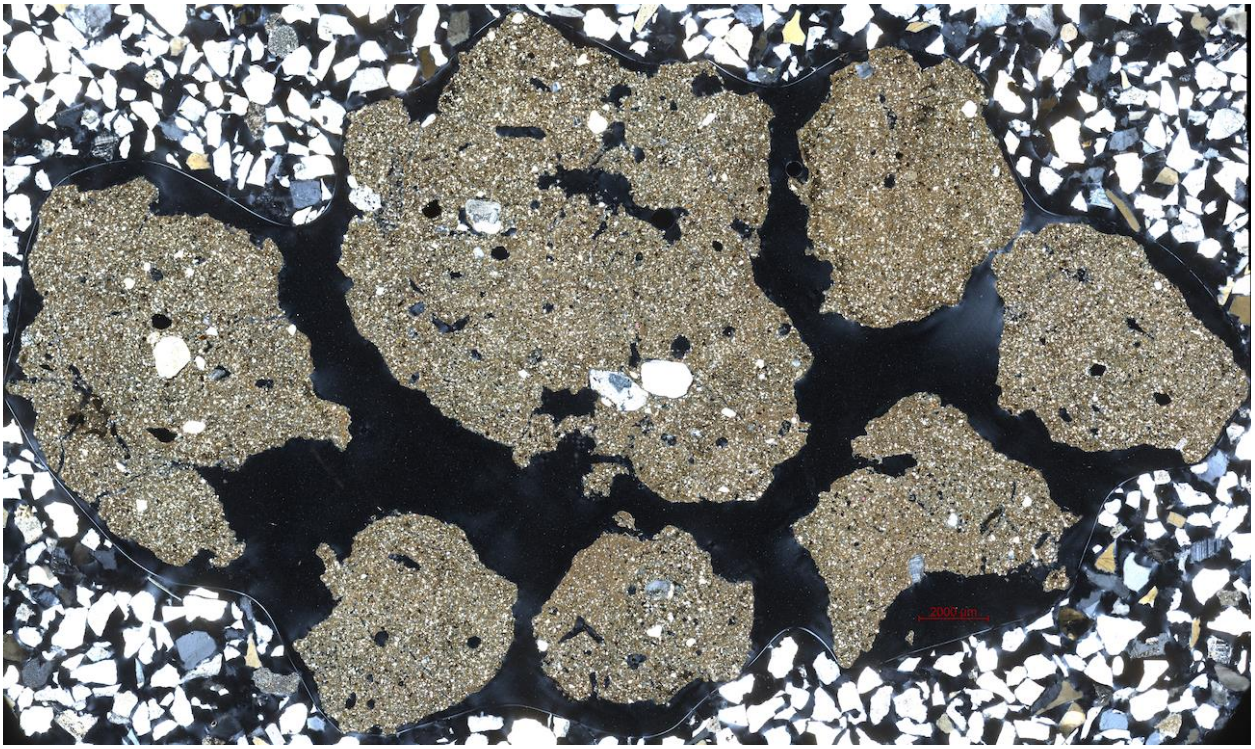
Wieder, M., and Yaalon, D.H., 1982, MICROMORPHOLOGICAL FABRICS AND DEVELOPMENTAL STAGES OF CARBONATE NODULAR FORMS RELATED TO SOIL CHARACTERISTICS.

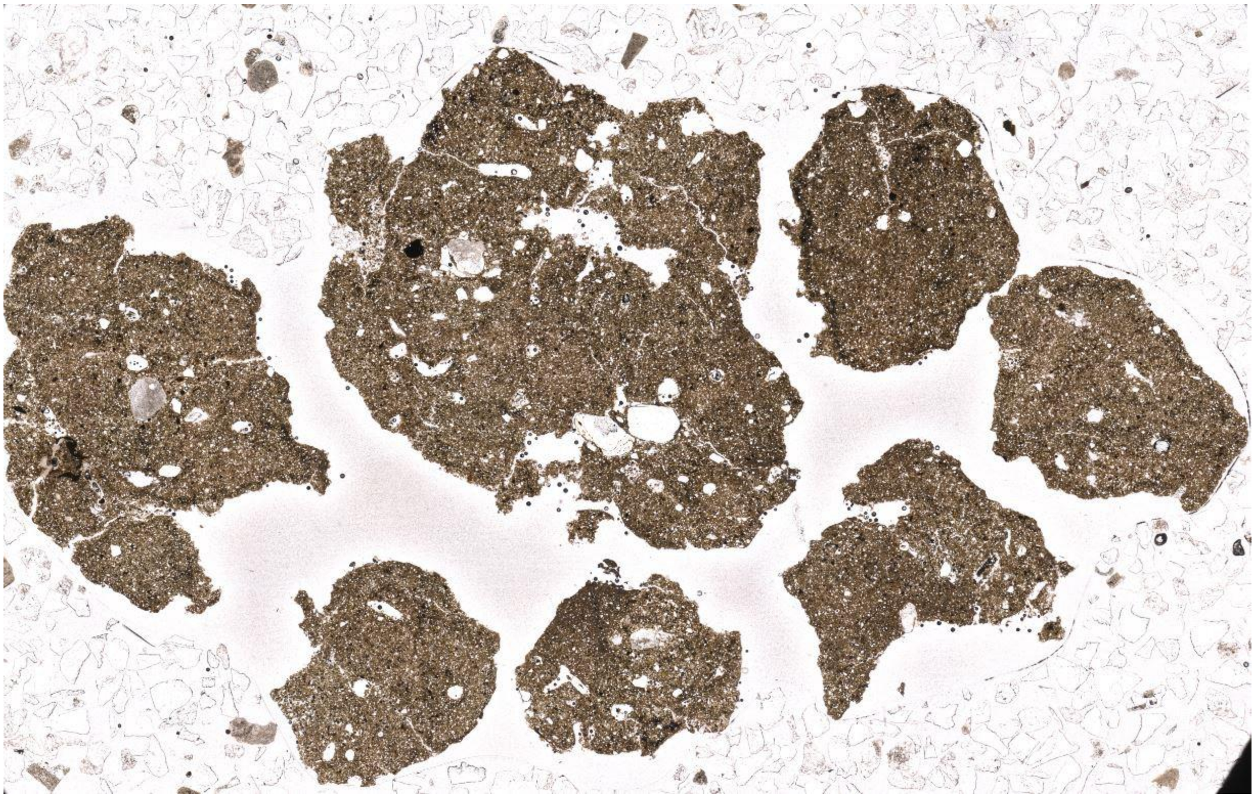
Wilson, M.J., 2019, The importance of parent material in soil classification: A review in a historical context: CATENA, v. 182, p. 104131, doi:10.1016/J.CATENA.2019.104131.

Zamanian, K., Pustovoytov, K., and Kuzyakov, Y., 2016, Pedogenic carbonates: Forms and formation processes: Earth-Science Reviews, v. 157, p. 1–17, doi:10.1016/J.EARSCIREV.2016.03.003

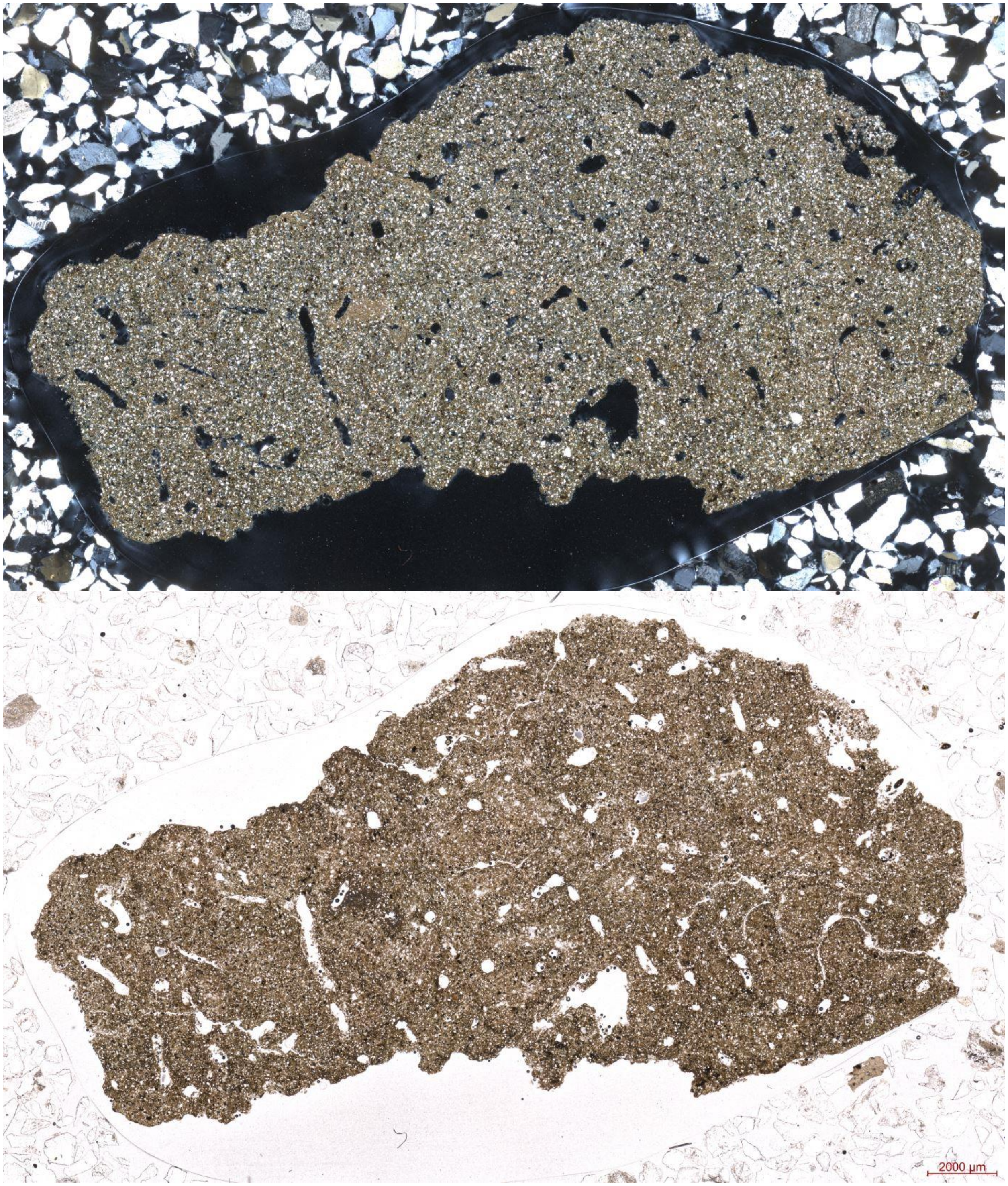
Appendix 1: Thin Section Images

1. Oglala 75cm (Top: XPL, Bottom: PPL)

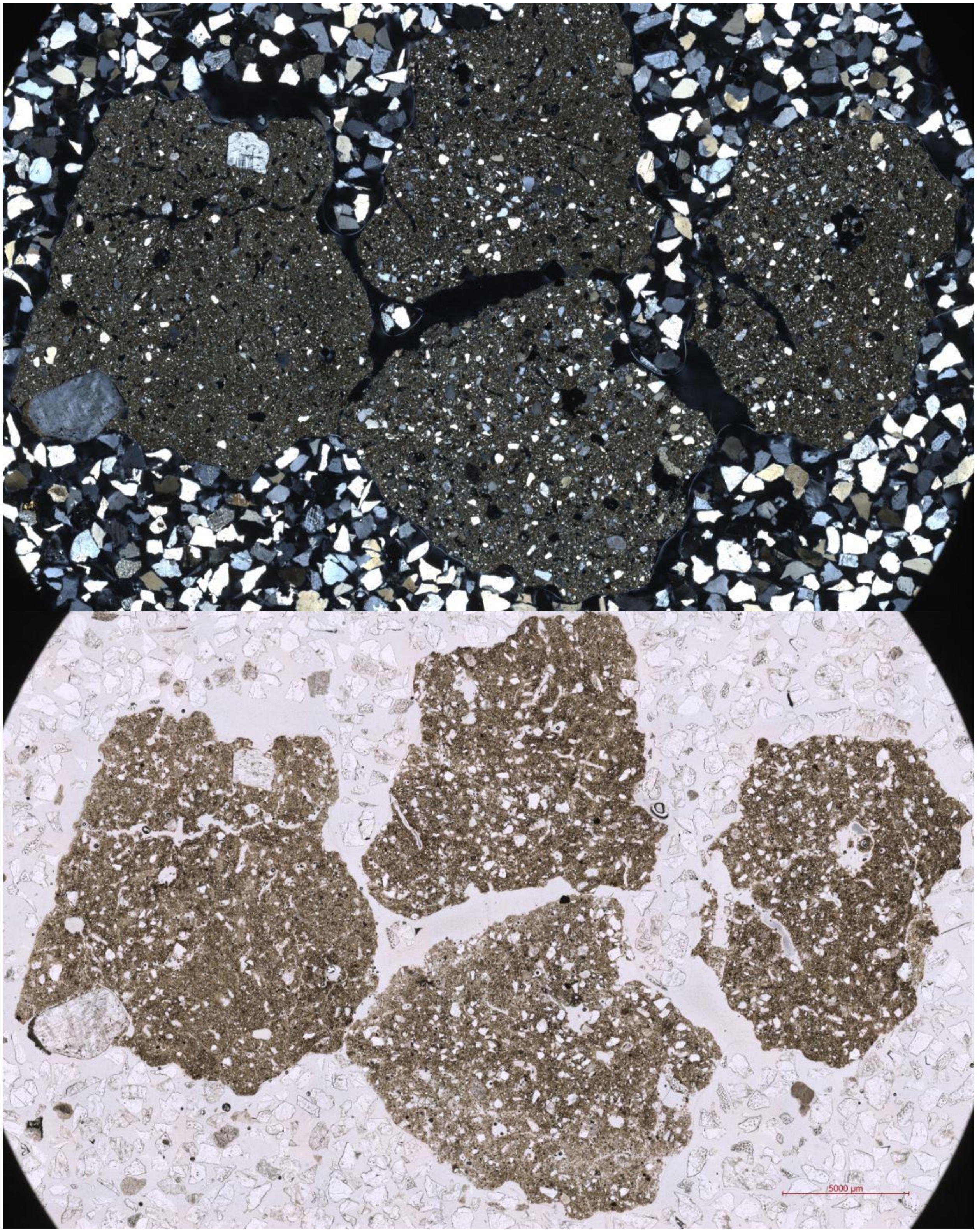




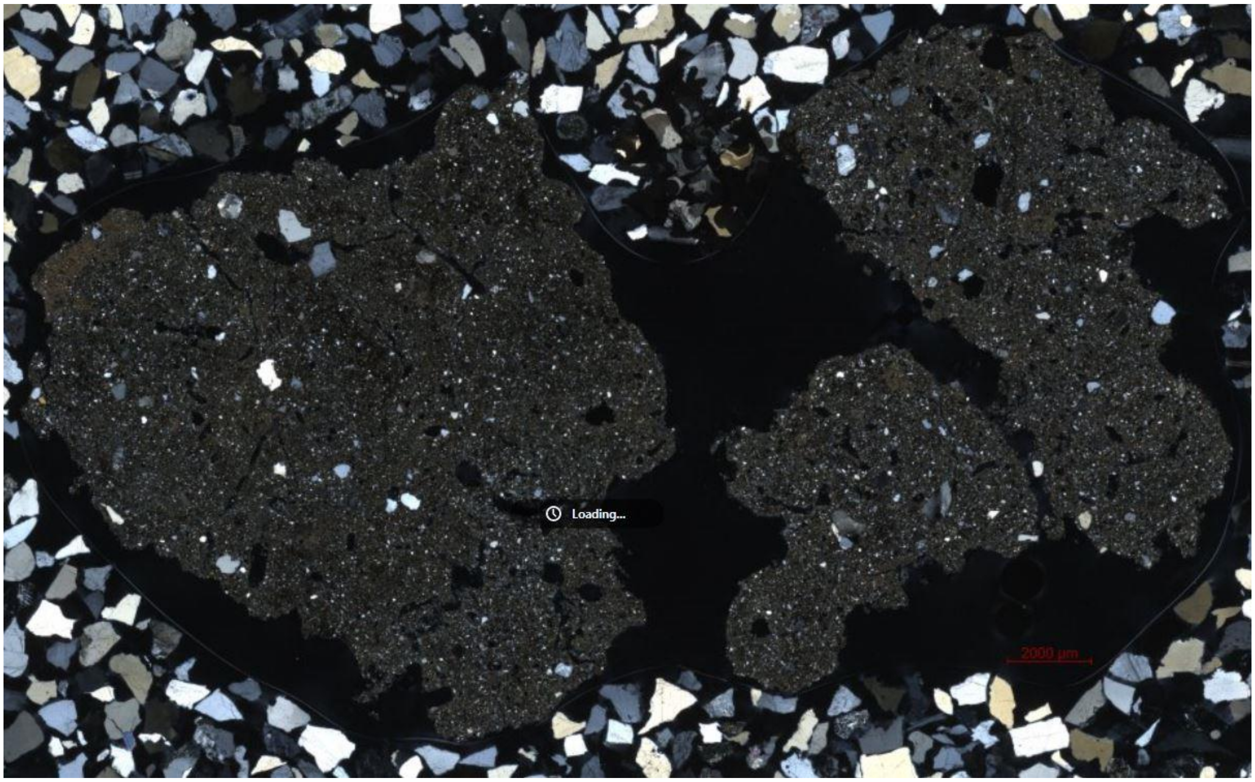
2. Oglala 95cm (Top: XPL, Bottom: PPL)

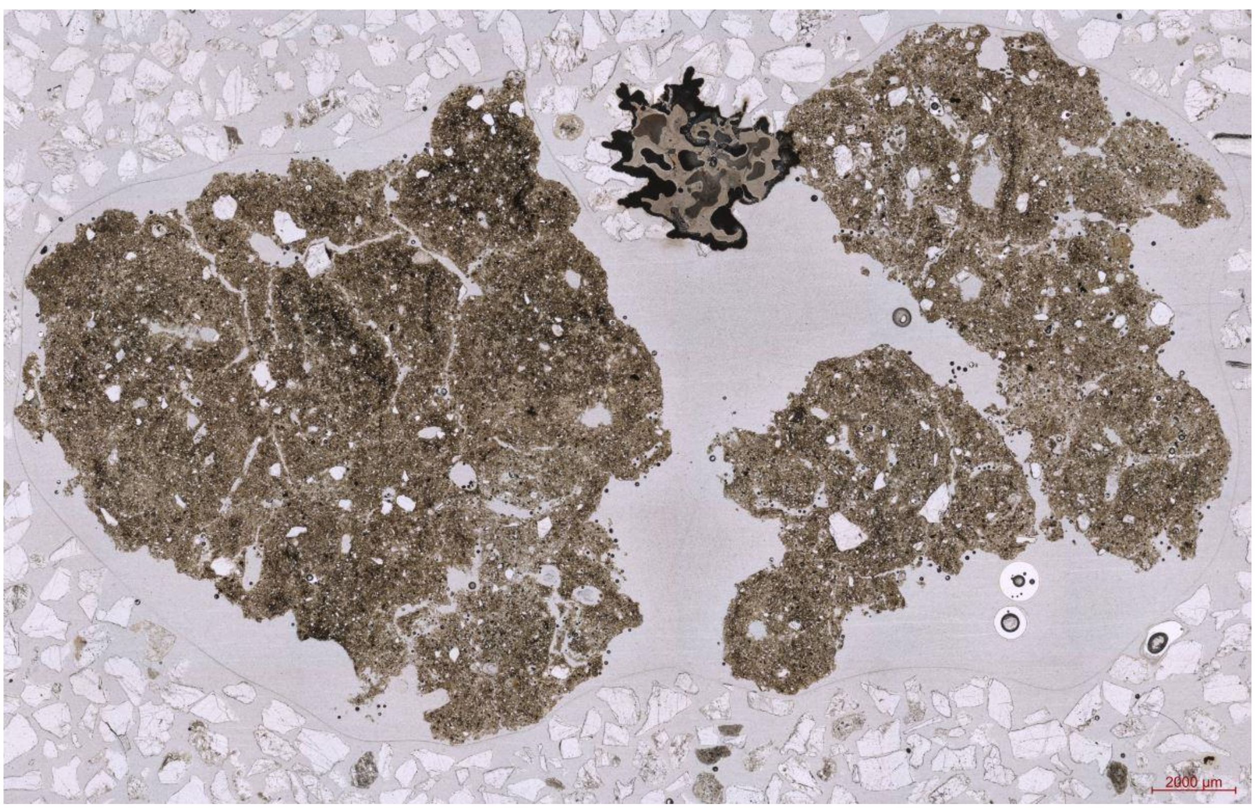


3. Seibert 75cm (Top: XPL, Bottom: PPL)

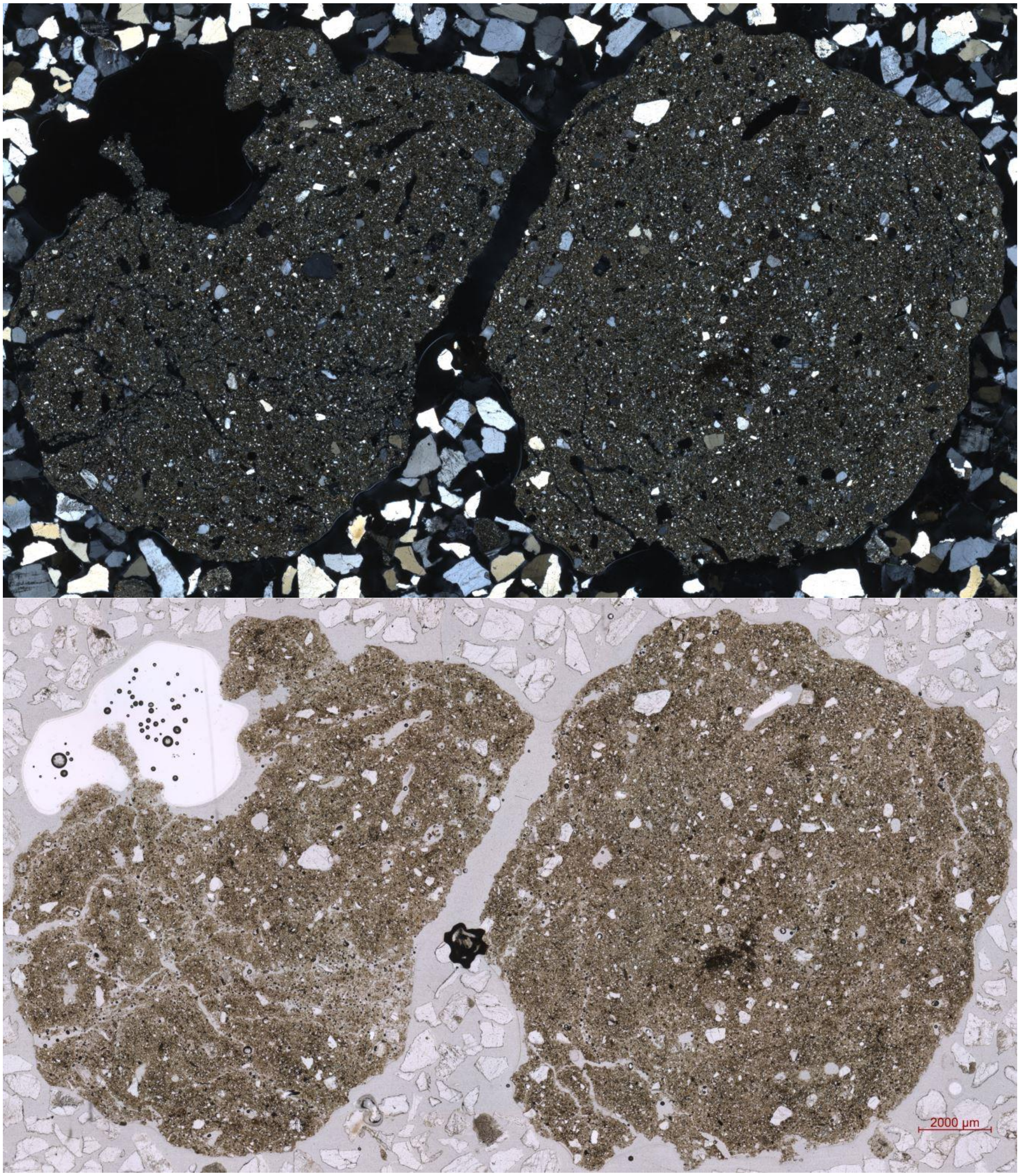


4. Seibert 83cm (Top: XPL, Bottom: PPL)

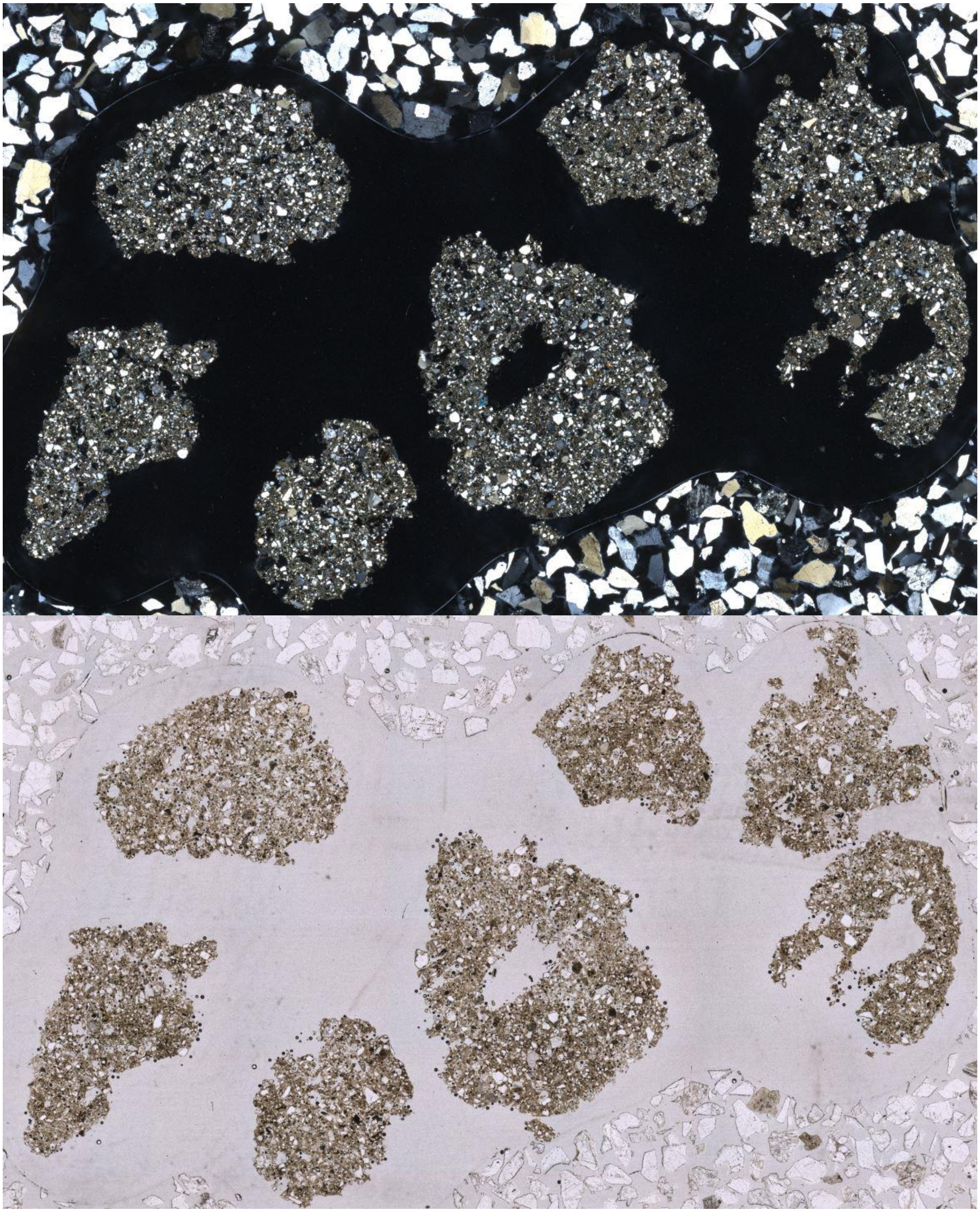




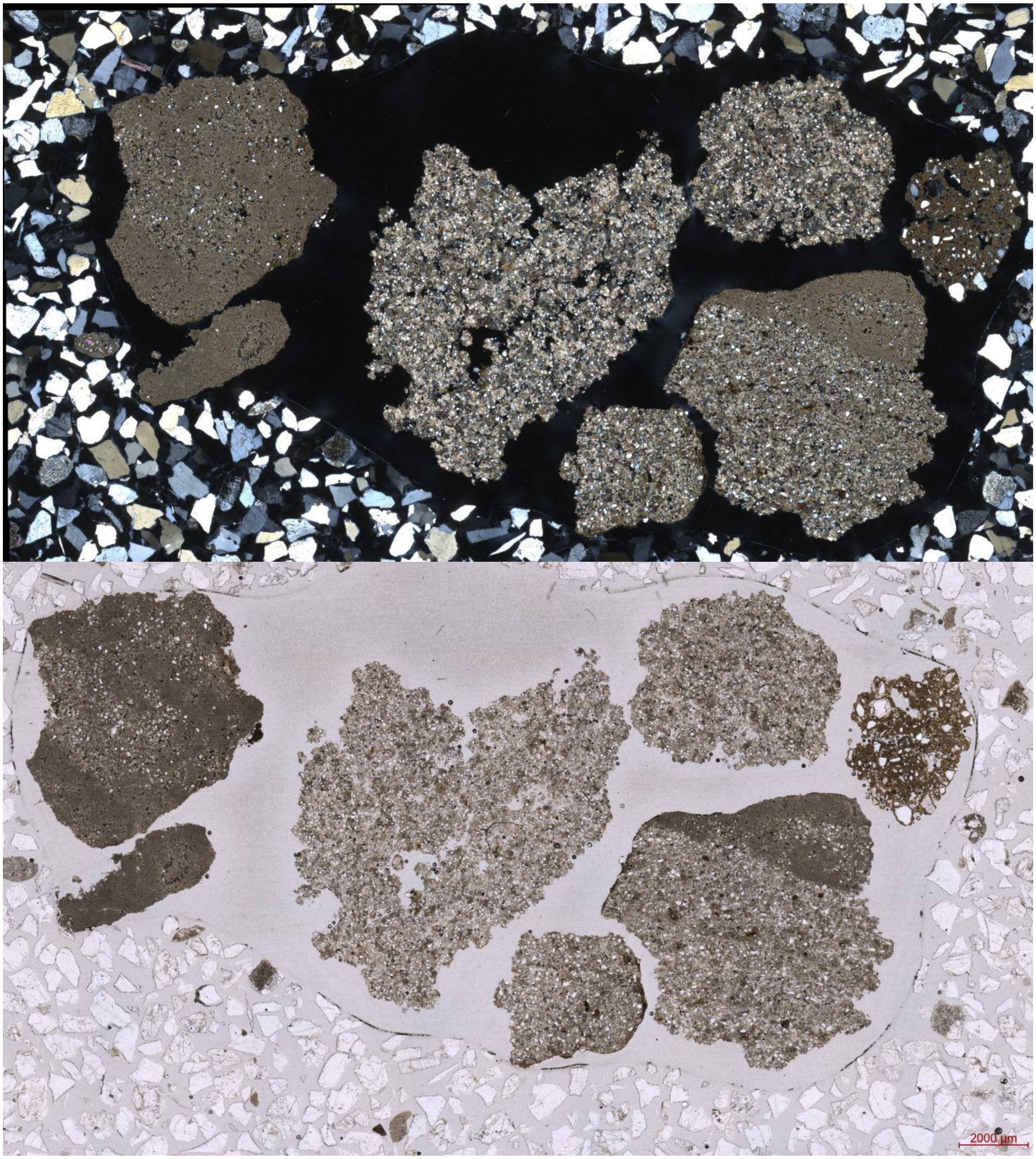
5. Seibert 100cm (Top: XPL, Bottom: PPL)


2000 µm

6. Briggsdale 50cm (Top: XPL, Bottom: PPL)



7. Briggsdale 105cm (Top: XPL, Bottom: PPL)


2000 µm