The Other White Rock in Coombsville Vineyards

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Introduction

Figure 1. Diatomite is often confused with tuff (a rock formed from volcanic ash). Shown side by side, the two rocks appear similar, despite completely different origins. Can you tell which is which? The diatomite is on the right (Photo by N. Madden, 2023).

A local newspaper article shows a picture of hands holding rocks taken from a prominent Coombsville vineyard. The rocks are light buff in color and look chalky, given the powdery residue on the person's hands. The rocks also give the impression of being soft, as it appears the rocks were broken into pieces before the picture was taken. The caption reads "…a piece of Tufa rock from their Mt. George Vineyard." The term tufa may be familiar to some and is mistakenly used to refer to volcanic rocks. The correct term is tuff, a rock made primarily of volcanic ash. Though tufa and tuff sound similar, they are geologically very different (Maltman, 2022). But were the rocks even tufa, or tuff, or whatever, to begin with? Maybe it was another white rock…diatomite? (Figure 1). A rock made from the remnant cell walls of diatoms, and not volcanic ash.

Tuff *is* found in many Coombsville vineyards. After all, Coombsville's geology is part of the "Cup and Saucer" volcanic center; the "Cup" being the raised area towards the western part of the Coombsville AVA and the "Saucer" being the horseshoe-shaped ridge to the east (Federal Registrer, 2011; Figure 2). The volcanic rocks in Coombsville consist of a lower sequence of lava flows, volcanic agglomerate, and lithic tuff, covered by a thick section of 5-million-year-old ash-flow tuffs and lava flows, associated with two nested calderas (Sweetkind et, al., 2011); commonly referred to in the singular as the Coombsville caldera. Tuff can come in many different colors, but Coombsville tuff is commonly off-white to grayish in color. Diatomite can also have similar colors and resemble tuff to the casual observer, but there is more to it than meets the eye. Our research has found diatomite is often mistaken for tuff in Coombsville vineyards.

Diatomite and an Ancient Lake in Coombsville?

The eastern remnant of the Coombsville caldera, or cauldron-like hollow, can be made out from aerial imagery, but the western ridge of the caldera is missing. The same crustal forces that uplifted the Vaca Mountains, also caused the western ridge of the caldera to collapse as a large landslide. Over time, the Napa River removed most of the landslide debris from the valley (Federal Register, 2011; Swinchatt, 2009). Like many calderas of the world, the Coombsville caldera probably contained a large, freshwater lake, analogous to the lake we see today in Crater Lake, Oregon. In this lake lived many creatures, including one, in particular, that has relevance to this story…diatoms, the makers of diatomite, the other white rock in Coombsville.

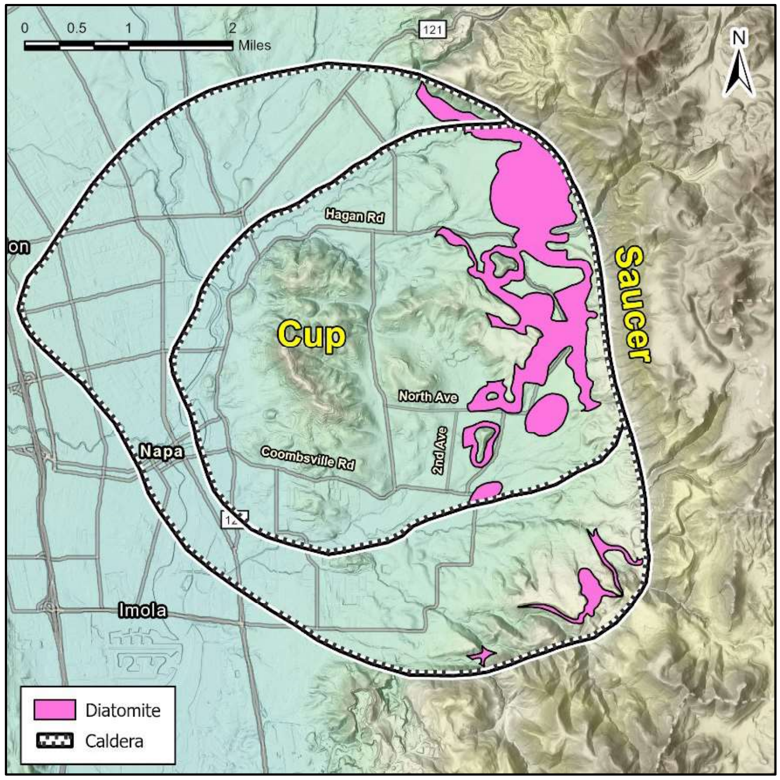

Figure 2. Hillshade map showing the Coombsville AVA, the location of the calderas (Sweetkind et. al., 2011), and the diatomite deposits (Bezore et. al., 2004).

Diatoms are very small (2 to 500 µm; human hair is about 100 µm wide), single-celled, photosynthetic algae that live in glass houses, called frustules (pronounced FRUS-chew-als) (diatoms.org, 2023). Diatoms are the only organism in the world that have cell walls (i.e., frustules) made out of opaline silica. Frustules are beautifully varied and ornate, and geometrically rival any medieval gothic cathedral in Europe. During the Victorian era (1837 to 1901), it was

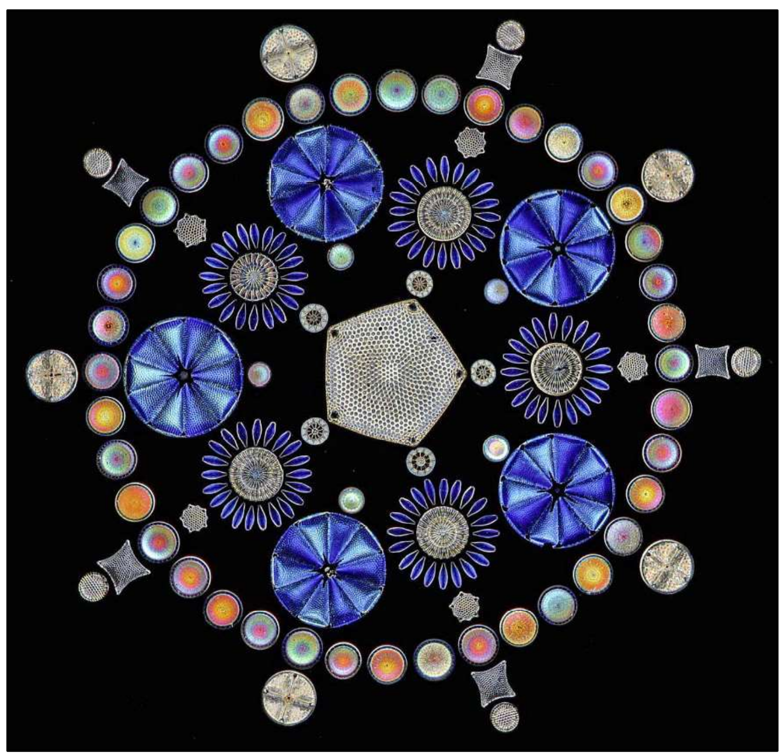

Figure 3. Diatom arrangement by Johann Diedrich Möller, 1889. Photo by Matthias Burba, Naturwissenschaftlicher Verein, Hamburg, Germany, 2007.

chic for microscopists to mount and illuminate these dazzling frustules in various patterns under microscopes and photograph them (National Geographic, 2017) (Figure 3). Though small, diatoms are mighty. Estimates of the number of diatom species range from 20,000 to 2 million, with new species discovered every year (Diatoms.org, 2023). On a global scale, diatoms fix 10 to 20 billion metric tons of carbon per year, which is comparable to all rainforests combined (Pierella Karlusich et., al., 2021). Enjoy breathing? Thank a diatom. Through photosynthesis, diatoms produce 20 to 30% of the oxygen we breathe (Alverson, 2014). Diatoms have also been called “Oil Rigs of the Future” since a quarter of their total mass is made of oil suitable for use as biofuel (Das, S., 2009).

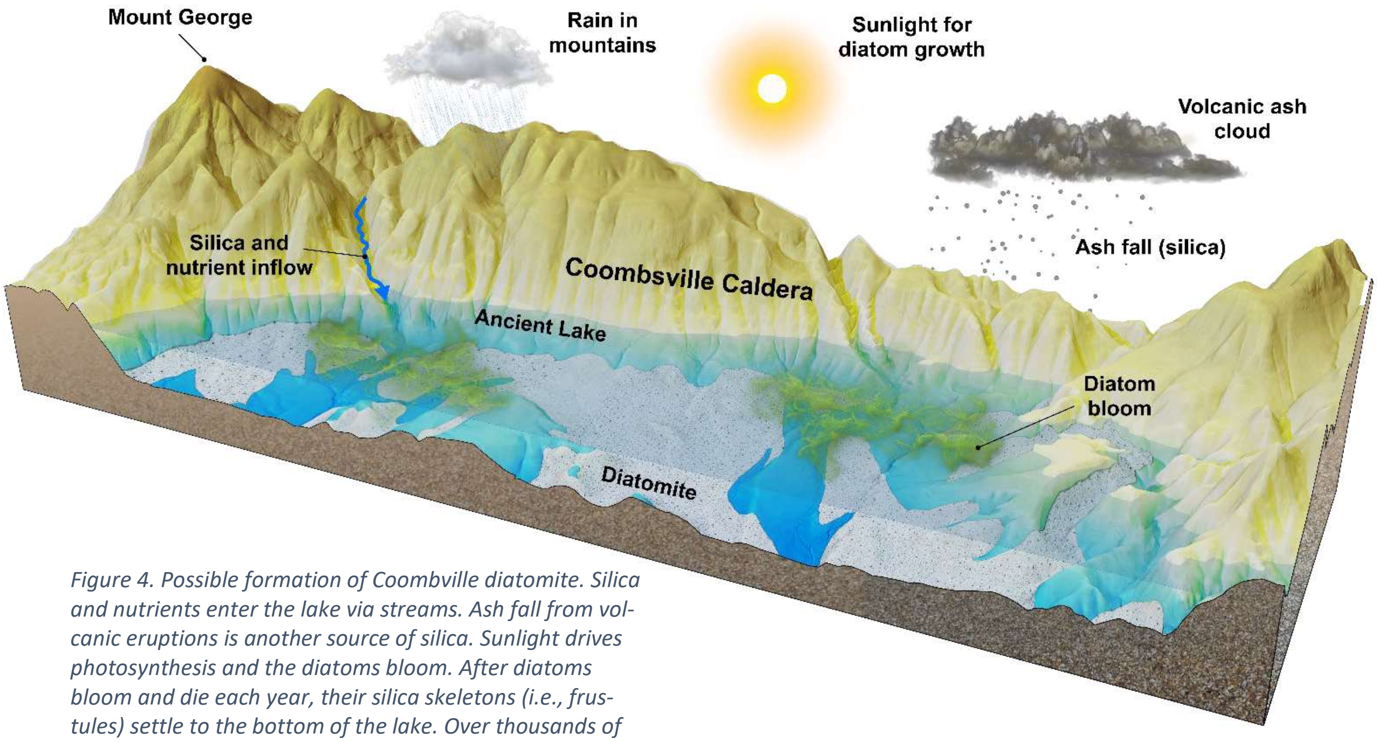

Figure 4. Possible formation of Coombville diatomite. Silica and nutrients enter the lake via streams. Ash fall from volcanic eruptions is another source of silica. Sunlight drives photosynthesis and the diatoms bloom. After diatoms bloom and die each year, their silica skeletons (i.e., frustules) settle to the bottom of the lake. Over thousands of years, these frustules accumulate to form a sedimentary layer of diatomite (Madden and Keiser©2023)

As diatoms bloom and die each year, the frustules settle to the bottom of their aquatic environment (e.g., wetland, lake, or ocean) and form thin sedimentary layers. These blooms can be huge, consisting of billions of individual diatoms, and can easily be seen from outer space. Diatom growth relies on access to sunlight, silica, nutrients, and a suitable water pH (i.e., a measure of hydrogen ion activity) (Figure 4). Volcanic ash from nearby eruptions is a good source of silica for the formation of frustules, and the most important nutrient for growth is phosphorus (P), derived from the weathering of rocks. Lakes that do not have P-rich rocks in the surrounding area generally do not produce diatomite deposits. This is also true if the water pH is too high (i.e., alkaline) (Wallace, et. al., 2006), at least for freshwater diatoms. Over many thousands of years, these layers accumulate and are subsequently compressed and lithified into a rock known as diatomite. Marine diatomite (think Santa Rita Hills) is commonly found in association with a wide variety of other rock types, but freshwater diatomite is almost always associated with volcanic rocks and ash. Each diatomite deposit is different, with varying mixtures of diatoms and other sediments. For example, clayey diatomite has about 10% volcanic ash, 30 to 45% clay minerals, and 45 to 65% frustules. “High-quality” diatomite is over 80% frustules. Most of the diatomite samples we collected from Coombsville and sent to UC Berkeley (Department of Earth and Planetary Sciences SEM facility) for analysis were primarily composed of frustules, with minor amounts of clay minerals, such as halloysite and montmorillonite.

Figure 5. Leaf fossil found in diatomite sample from Comis Estate Vineyards, Coombsville. A fossil within fossils (Photo by N. Madden, 2022).

Diatomite is an uncommon, biogenic sedimentary rock. Diatomaceous earth is an alternate name, but diatomaceous earth more appropriately refers to the powder or unconsolidated form of the rock. Interestingly, the word diatomite forms part of the word “dynamite”, after Alfred Nobel discovered nitroglycerin could be stabilized if first absorbed in diatomaceous earth. Diatomite is normally light in color (off-white to buff), powdery, and very lightweight, due to its low bulk density (0.1 to 0.8 g/cm^3; water has the density of 1 g/cm^3) and high porosity (65 to 85%, by volume). It will float on water until it becomes saturated. The rock is soft, but the individual silica particles are much harder, making it a mild abrasive used in some toothpastes and metal polishes. Diatomite can also be used as an insecticide, an anti-caking agent in fertilizers and animal feed, an ultra-absorbent in face masks and deodorants, and a matting agent in paints and coatings. Because diatomite is essentially chemically inert and full of tiny pores, it is also useful as a filtration medium (e.g., swimming pool filters). Diatomite filtration is a popular method in winemaking. The pores within these filters are so small they can trap bacteria, clay particles, and other suspended solids to produce a cleaner wine (Dicalite, 2023).

Misidentification of Diatomite

Diatomite can visually be confused with other light-colored rocks or clay minerals. The appearance of diatomite closely resembles chalk; however, chalk is calcareous (composed of calcium carbonate), and will bubble in acid - diatomite does not. Chalk is also much denser than diatomite, having a bulk density three to four times higher. Diatomite can also look like some clay minerals, like bentonite. However, bentonite will shrink and swell and become sticky when wet – diatomite does not. Diatomite does not stick together very well, and when piles are left in the rain, they slowly disintegrate and wash away. How does diatomite compare with tuff? Tuff also does not bubble in acid or have clay-like properties when wet; but like chalk, tuff is denser than diatomite. Both tuff and diatomite can contain beautiful plant fossils that are simply amazing (Figure 5). Tuff can also be relatively soft, depending on how it was deposited, but is usually much harder and "welded" compared to diatomite. Also, tuff does not normally split into any distinct shapes, but diatomite can fracture into rhombohedral shapes (Zeeb et., al., 1996). Tuffaceous deposits also contain volcanic ash, pumice, and fragments of volcanic rock – diatomite is made from biogenic silica.

Evidence of Diatomite in Coombsville

The California Geological Survey clearly delineates the Diatomite mapping unit in the preliminary Mt. George 7.5' quadrangle (Bezore et. al., 2004) (Figure 2). The Coombsville AVA petition, also mentions "diatomaceous lake deposits occur along the northeast edge" of the viticultural area. A 1960 USGS publication on groundwater supply in Napa and Sonoma Valleys mentions a "diatomaceous member" in Coombsville varying in purity, sorting, thickness, and lateral extent (Kunkel and Upson, 1960). Some diatomaceous deposits had a large amount of pumice, sand, silt, and clay, whereas other deposits were mostly diatoms. This makes it difficult to distinguish between tuff, tuffaceous sandstone, and diatomite, especially in the field.

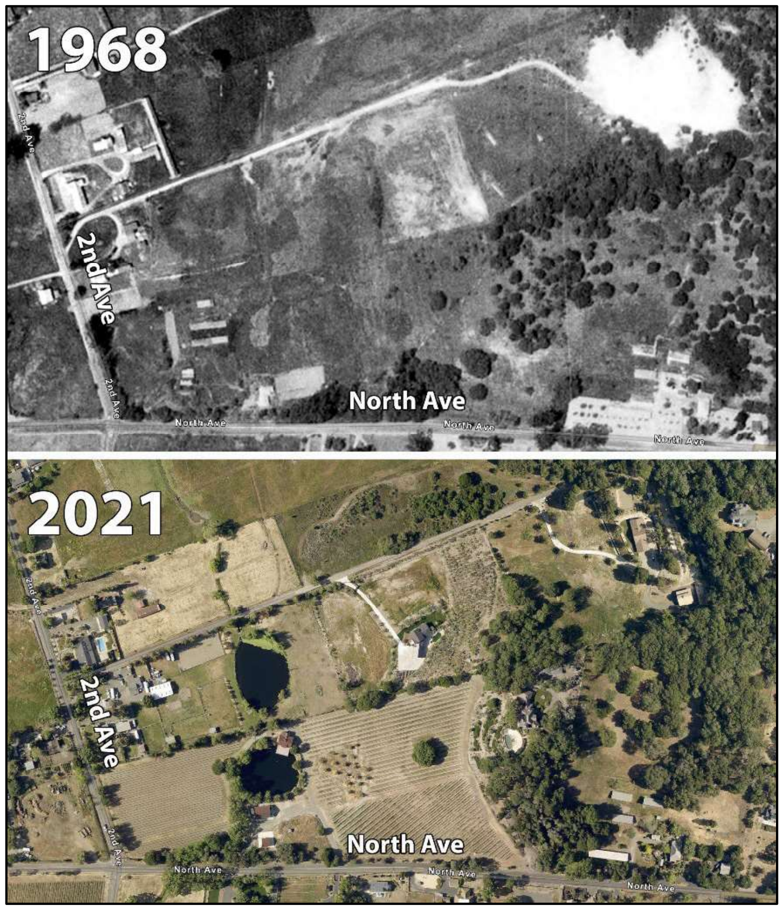

Figure 6. The old Basalt Rock Co. diatomite quarry in 1968 (Source: NETRonline) and what it looks like today (Source: Napa County GIS). The quarry was located on 2nd Ave, north or North Ave across from the Covert Estate Winery and Vineyard.

One of the best exposures of diatomite was found at the former Basalt Rock Company quarry on 2nd Ave, across from the Covert Estate Winery and Vineyard, Napa, CA (Figure

6). The diatomite bed there was about 150 ft thick. Fossil plants were also found in the diatomite quarry and dated to Late Pliocene (~3.0 million years ago). The dominant diatom genus found in the samples was *Stephanodiscus*, which is often the dominant genus in diatom deposits of the same time period around the world (Zeeb et., al., 1996). *Stephanodiscus sp.*, as well as *Aulacoseira and Pinnularia spp*., were also found in the Coombville diatomite sample sent to UC Berkeley (Figure 7). Many of the frustules range from 5 to 20 µm, which is similar to the USDA size classification for silt (2 to 50 µm); as well as, crushed bits and pieces as fine as clay (< 2 µm). All diatoms mentioned are freshwater diatoms that either live as free-floaters in open water (planktonic) or attached to underwater surfaces (periphytic).

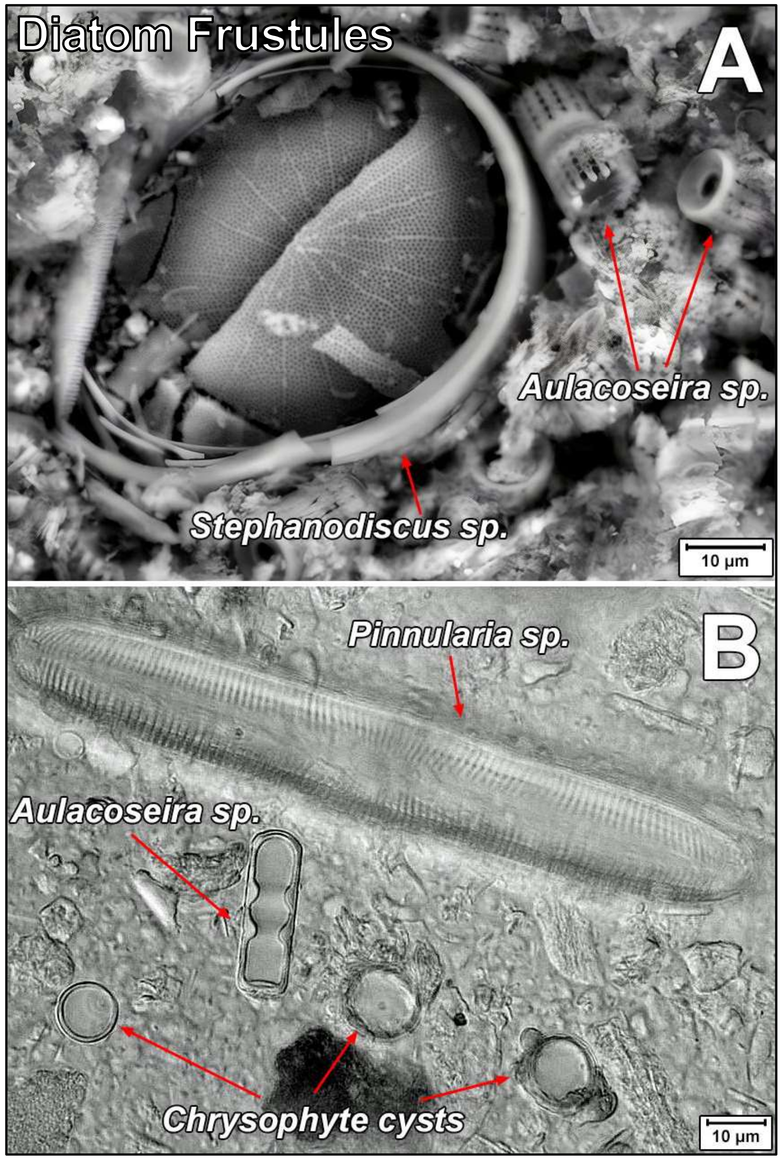

Figure 7. (A) Scanning Electron Microscope (SEM), and (B) Light Microscope (LM) images of diatom frustule from Coombsville diatomite samples (Source: SEM from John Grimsich, UC Berkeley; LM from Dr. Rosalina Stancheva Christova, California State University, San Marcos).

Besides the old Basalt Rock Company diatomite quarry off of 2nd Ave, other accessible spots to see diatomite around Coombsville are: 1) at the corner of Coombsville Rd and 4th Ave, 2) along North Ave, between 2nd and 3rd Ave, and 3) the hill surrounded by the first nine holes at the Napa Valley Country Club (Figure 8). There are also diatomaceous deposits in a road cut along the northeast side of Silverado Trail, about 1200 ft northwest of its intersection with Zinfandel Rd (Zeeb et., al., 1996); that most of us thought was just tuff.

Coombsville Vineyards on Diatomite

If diatomite in Coombsville has been documented previously, what's the big deal? Why all this discussion? Many vintners and growers probably are not able to distinguish diatomite from tuff, and most likely even fewer are aware of the wide extent of diatomite in

Coombsville. This is not a criticism, as we were also unaware. Diatomite is an uncommon rock in California vineyards, and only the Coombsville and Santa Rita Hills AVAs contain significant deposits. By merging current geological and soil data with our data from mapping and managing soils in Coombsville, growers will have access to better information to optimize their vineyards on diatomaceous soils.

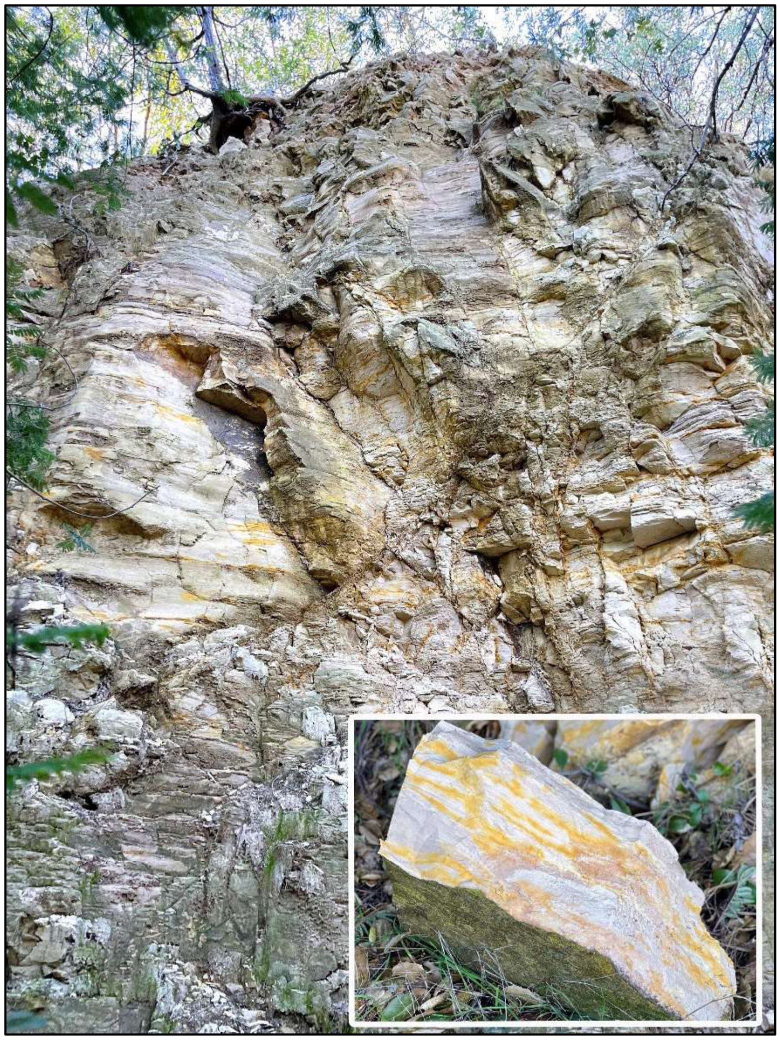

Figure 8. A towering hill of diatomite at the Napa Valley Country Club, along the 3rd and 4th holes. Notice the beautiful tiger striping in the diatomite (Photo by B. Keiser, 2023).

About 15 years ago, while mapping soils in Coombsville, we first came across a white rock that looked very much like tuff. However, it was softer, even spongy, if a rock can be described as spongy. When we asked vintners and consultants their thoughts, most said tufa, or tuff; others said bentonite. It wasn't until we talked with Jonathan Swinchatt, co-author of *The Winemaker's Dance*, that we got the idea it was diatomite. Sure enough, after studying geologic maps, there it was…diatomite (Just a note: not all geologic maps of Coombsville show diatomite, so be sure to look at the most recent maps with the largest scale). Unfortunately, there is no mention of diatomite or soils forming from diatomite in the Soil Survey of Napa County (Lambert and Kashiwagi, 1978) Over the last five years during planting or re-planting, we found many vineyards had diatomite present, but was incorrectly identified as tuff.

The vast majority of diatomite is located in the heart of the Coombsville AVA, between Olive Hill Lane to the north, Coombsville Rd on the south, 2nd Ave on the west, and along North 3rd Ave to the east. There is also a small area of diatomite mapped in the southeast corner of Coombsville, near Porter Family Vineyards. According to Napa County data, there were about 2,500 acres of vineyards in the Coombsville AVA in 2016 (the size of the AVA is about 11,000 acres). If one were to overlay the geological "Diatomite" mapping unit over the vineyard area, only about 19% to 36% of Coombsville vineyards are on diatomite, depending on the referenced geologic map; not a huge percentage, but significant. Obviously, this percentage will fluctuate after further visual or analytical confirmation, as we have already found unmapped diatomite.

The mapped diatomite is under both well-known and newer Coombsville vineyards. These vineyards are identified in Figure 9 and include Silverado Mt. George, Farella/Realm, Arcadia, John's Creek/Far Niente, Palmaz, Rewa, Bydand, Comis Estate, Duhig, among others. Given the mature age of some of these vineyards (e.g., Farella Vineyard was first planted in 1979) and their long history as sources of high quality fruit and outstanding wines, the white rocks present in these soils have long been part of that history; but the rocks are often described as tuff. It is important to note that the geologic mapping of diatomite under a particular vineyard does not mean diatomite is near or present at a soil surface, where it can potentially influence the vines. Diatomite may be present in only a portion of a vineyard or below the surface at depths ranging from a few feet to more than a hundred. It may also be mixed with other soil types or not present at all. This is why verification is important.

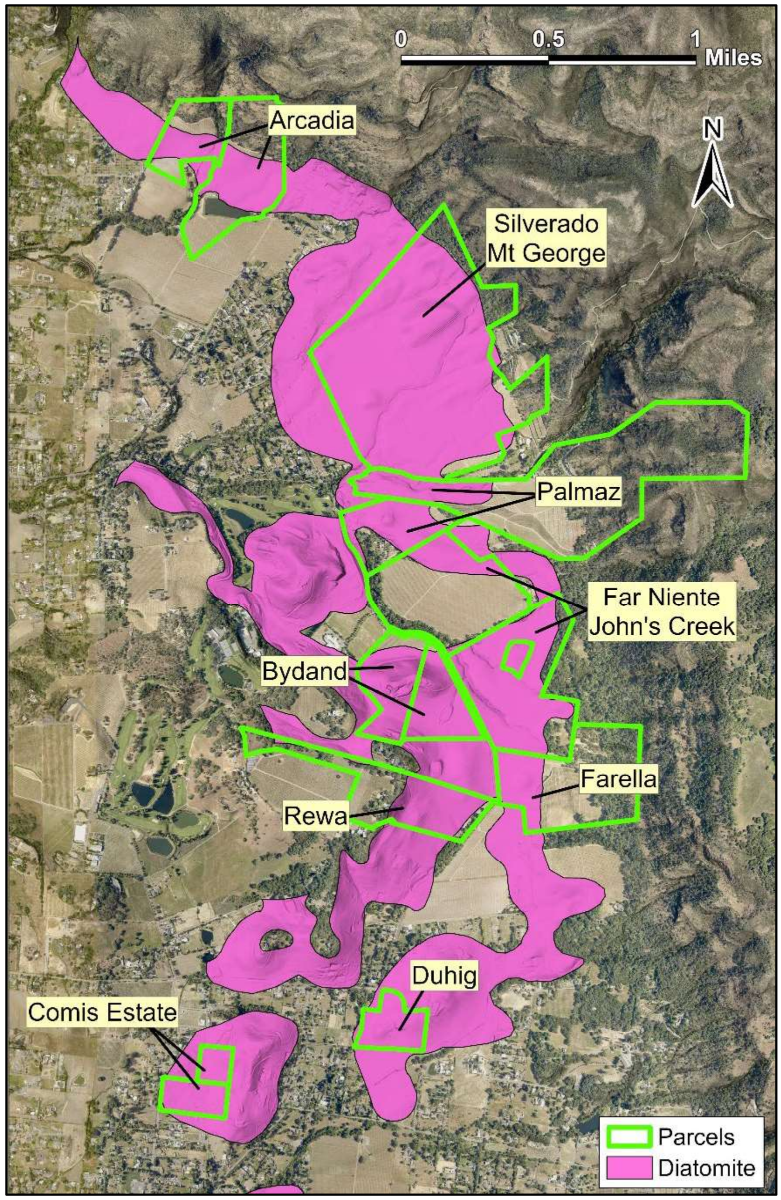

Figure 9. Examples of vineyard parcels in Coombville that are on diatomite, based on USGS data (Bezore et. al., 2004) and authors' verification (soil pits and visual assessments). Basemap from Napa County GIS.

A Soil Mix Up

The soil series currently mapped in the Coombsville AVA include the Bale, Cole, Egbert, Perkins, and Yolo (younger alluvium, usually deep and dark, found near streams and on floodplains); the Coombs and Haire (associated with alluvial fans and older stream terrace deposits); the Hambright (shallow, rocky soil mainly found on lava flows and breccias);

the Kidd (another shallow, rocky soil usually forming on lithic tuff); the Forward (ashy soil found on tuff or tuffaceous deposits); and the Sobrante and Guenoc (moderately shallow soils with clay-enriched subsoils, forming from volcanic and metavolcanic rocks). None of these soils are described as diatomaceous.

When looking at a simplified soil and geology map of Coombsville, side-by-side, the soil and rock types line up relatively well, but not perfectly. Remember, parent material (e.g., rocks or sediments) is only one of the five soil forming factors, the others being climate, biota (organisms), topography, and time; so, soil formation involves a lot more than just rock type. The soil series that match up well with the diatomite are the Kidd, Forward, and Coombs (Figure 10). This makes sense from what we know about the difficulty in distinguishing diatomite from tuff in the field. Both the Kidd and Forward can form from tuff, but if that tuff is actually diatomite, then we may have a very different soil, indeed.

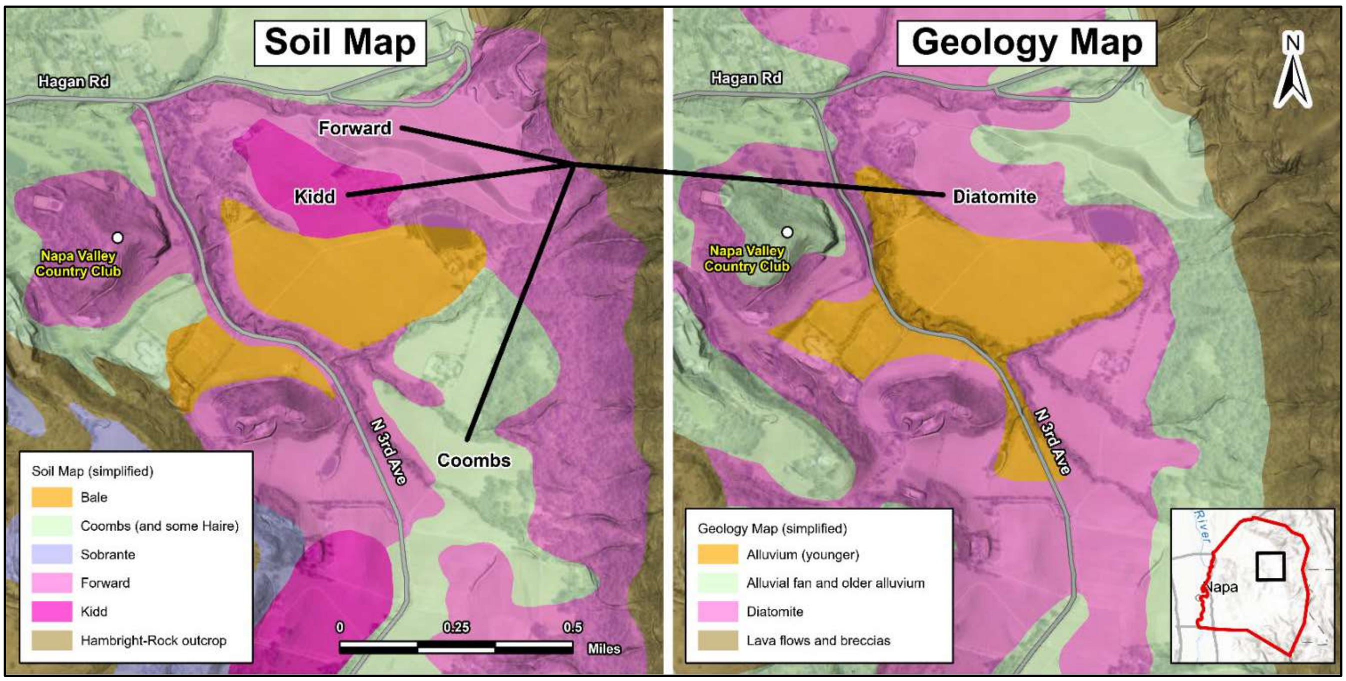

Figure 10. Simplified soil and geology maps of the area around the Napa Valley Country Club in Coombsville (Source: modified data originally from Lambert and Kashiwagi, 1978 and Bezore et. al., 2004). Coombsville AVA boundary in red. The Forward, Kidd, and Coombs soil series match up well with the diatomite deposits. The Kidd and Forward can form on tuff, which was probably misidentified. The Coombs series, an alluvial soil, is covering the diatomite in some areas.

The occurrence of diatomite (more recently identified than when the soil survey was made) might lead to important soil properties that are not typical of other Kidd and Forward soils. As mentioned elsewhere, differentiation of tuff and diatomite can be difficult in the field. From the technical point of view, parent material is not a differentiating characteristic of a soil taxon (e.g., soil series). The soil properties imparted by the parent material can be differentiating characteristics. That a soil is formed from diatomite does not necessarily mean it has properties significantly different from a soil formed from tuff. Again, this is why verification is important. As far as the Coombs series, which is an alluvial soil, some of the diatomite we find in the field can be covered with several feet of volcanic alluvium, burying the diatomite.

Diatomaceous Soils

So, what do diatomaceous soils look like anyway? Since we don't have any series description for diatomaceous soils in Coombsville, one of the closest comparisons we have are the Santa Lucia, Lopes, and Crow Hill soil series found in the Santa Rita Hills, Santa Barbara County. These soils formed from the diatomite and siliceous shale of the Sisquoc and Monterey Formations (early to late Miocene; ~17.5 to 5 million years ago) (Dibblee and Ehrenspeck, 1988), and the soils tend to be shallow and acidic. The Santa Rita Hills diatomite is from marine diatoms, and not freshwater diatoms. Marine diatomite usually contains more genera and variation in size and shape compared with freshwater diatomite, and is preferred in certain filtration applications (Engh, 2000). The diatomite deposits just south of Lompoc, CA, are the world's largest source of diatomite being mined today.

Figure 11. Typical diatomaceous soil profiles found in Coombsville vineyards. Both these soils are mapped as Forward series. Measurements are in feet (Photos by N. Madden, 2019).

The Santa Lucia, Lopez, Crow Hill soil series are somewhat excessively to well drained, shaly clay loams and silty clay loams, on strongly sloping uplands (Shipman, 1977). Of these three soil series mentioned, the Crow Hill series most closely resembles the diatomaceous soils we find in Coombsville (Figure 11). The Crow Hill series has a surface layer of very dark gray, silt loam to silty clay loam, with granular to subangular blocky structure. The subsoil is very dark grayish brown silt loam to silty clay loam, also with subangular blocky structure. Soft fractured diatomaceous shale is at a depth of 20" to 40", with thin dark brown clay films on the upper portion of the rock. The Crow Hill series is slightly to very strongly acidic and acidity decreases with depth. Bulk density is less than 1 g/cm^3, and averages about 0.85 g/cm^3.

Management of Diatomaceous Soils

Due to the uniqueness of the parent material, diatomaceous soils can impart behavior that is different from other soils. First, diatomaceous soils hold more water than similarly-sized silt or clay particles, due to the internal voids/pores within the frustules. As a result, diatomaceous soils have a high liquid limit (i.e., water content where a soil behaves as a liquid instead of a sold), a high saturation percentage (i.e., water content when all pores are filled with water), high compressibility (i.e., ability to collapse into a smaller volume by compression), and yet high shear strength (i.e., resistance to deformation by shear or lateral stresses), likely due to the irregular particle shapes of the frustules (Caicedo et. al., 2018; Evans and Mong, 2020).

Despite the soil's sponge-like ability to absorb more water, the availability of this water for plants needs further research. In studies on edaphic (i.e., soil) control of natural vegetation in California, Cole (1980) found rock types differ in their ability to absorb and retain moisture. After one hour of drying, diatomite samples averaged 60% water retention, by volume. This compares with 32% for mudstone, 10% to 28% for sandstone, and 7% for granite. The diatomite samples still retained 30% water by volume after 135 hours. Burger et. al., 2001, showed that diatomaceous earth can have two distinct pore-size distributions, one for the larger pores between particles and one for the smaller pores within particles. As the soil dries, the water in some of the larger pores will be trapped until there is enough suction in the soil to first drain the much smaller pores; a kind of bottleneck effect. How these properties play out in irrigation scheduling or deficit irrigation in vineyards is still not widely known.

Acidic soil pH is also an important edaphic control on vegetation in diatomaceous soils. The soil pH governs the biological availability of plant nutrients and potential toxicities. Generally, problems related to soil pH become more serious for winegrapes as the pH drops below 5.5 or goes above 7.5. Phosphorus becomes increasingly bound to the soil surface and unavailable for plant uptake as the pH drops below 5.5. Potassium also becomes increasingly susceptible to leaching below a pH of 5.2. Availability of other macronutrients, such as calcium, magnesium, and sulfur, also become limiting in low pH soils. This is made worse by the already low quantity of these ions in the soil to begin with, since diatomite is primarily silica. The optimal soil pH range for maintaining the bioavailability for most plant nutrients is 5.8 to 6.8. In diatomaceous soil samples we have collected, the topsoil pH is around 5.5, but the subsoil pH is below 4; 100 to 1000 times more acidic than a typical valley floor soil.

Aluminum becomes increasingly soluble and toxic as the pH drops below 5.0. Critical values for toxic aluminum have not been firmly established for winegrapes. However, based on data toxicity is initiated at 250 to 300 mg/kg soluble aluminum, and moderate to severe toxicity starts around 500 mg/kg. In diatomaceous soil samples we collected, soluble aluminum concentrations can be as high as 1502 mg/kg. When aluminum is taken into roots, most remains there and little is translocated to shoots, except in tea plants.

Therefore, leaf tissue analysis is not a good diagnostic tool for aluminum toxicity. Aluminum damages membrane sites in the roots where calcium is normally taken in and restricts cell wall expansion. Roots cannot grow properly and water and nutrient uptake is substantially reduced. Soil bacteria are also affected by high soluble aluminum, such as those that carry out transformations in the nitrogen cycle (Weil and Brady, 2017). One strategy to solve this problem is to raise the topsoil pH above 6.0 with a liming agent (most likely dolomitic lime) to ensure the bioavailability of affected nutrients; and apply gypsum (i.e., calcium sulfate) to precipitate out aluminum in the subsoil as one or more forms of aluminum sulfate (Zoca and Pen, 2017).

Conclusion

Figure 12. Diatomite outcrop under the vines at the Farella Vineyard in Coombsville (Photo by N. Madden, 2022).

Diatomite, the other white rock of Coombsville, has had a “tuff” life. Whether it’s been misidentified or overlooked, the Coombsville diatomite is a very unique rock that can produce very unique soils, at least in terms of management, and impart diverse and interesting characteristics in wines. We hope this information can be utilized by viticulturists, growers, and winemakers to further study and identify the unique geology and soils of their vineyards. Our investigation in vineyards mapped over diatomite continues and, no doubt, will add to the fascinating and complex story of the Coombsville AVA.

References

Alverson, A., 2014. The Air You're Breathing? A Diatom Made That. Live Science. https://web.archive.org/web/20180430115059/https://www.livescience.com/46250-teasing-apart-the-diatom-genome.html. Accessed 11 March 2023.

Bezore. S.P., Sowers, J.M., and Witter, R.C., 2004, Geologic map of the Mt. George 7.5′ quadrangle, Napa and Solano Counties, California: A digital database: California Geological Survey Preliminary Geologic Map, scale 1:24,000. https://www.conservation.ca.gov/cgs/rgm/preliminary. Accessed 11 March 2023.

Burba, Mattias, 2017, Diatom arrangement by Johann Diedrich Möller (1889), Naturwissenschaftlicher Verein, Hamburg, Germany. https://www.nikonsmallworld.com/galleries/2007-photomicrography-competition/arrangirte-diatomeen-1889-diatoms. Accessed 11 March 2023.

Burger, C.A. and Shackelford, C.D., 2001, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 127, No. 9, pp. 790-800.

Caicedo, B., Mendoza, C., López, F., and Lizcano, A., 2018, Behavior of diatomaceous soil in lacustrine deposits of Bogotá, Colombia, Journal of Rock Mechanics and Geotechnical Engineering, Vol 10, Issue 2, pp. 367-379.

Cole, K., 1980, Geologic Control of Vegetation in the Purisima Hills, California, In: Madroño; a West American Journal of Botany, Berkeley, California Botanical Society, Vol. 27, pp. 79-29.

Das, S., 2009, Oil Rig of the Future: A Solar Panel That Produces Oil, Scientific American, https://www.scientificamerican.com/article/biofuel-diatoms/, Accessed 11 March 2023.

Diatoms.org, 2023, What are diatoms?, https://diatoms.org/what-are-diatoms, Accessed 11 March 2023.

Dibblee, T.W. and Ehrenspeck, H.E., ed., 1988, Geologic map of the Lompoc Hills and Point Conception quadrangles, Santa Barbara County, California, Dibblee Geological Foundation, Dibblee Foundation Map DF-18, 1:24,000.

Dicalite Management Group, 2023, https://www.dicalite.com/, Accessed 11 March 2023.

Engh, K.R., 2000, Diatomite, In: Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed., Vol. 8, pp. 108–118, Celite Corporation.

Evans, T.M., Moug, D., 2020, Diatomaceous soils: a less than cromulent engineering material. In: Duc Long, P., Dung, N. (eds) Geotechnics for Sustainable Infrastructure Development. Lecture Notes in Civil Engineering, vol 62. Springer, Singapore.

Federal Register, 2011, Establishment of the Coombsville Viticultural Area, Doc. Num. 2011-32018, Vol. 76, pp. 77677-7768.

Lambert, G., and Kashiwagi, J.H., 1978, Soil survey of Napa County, California, U.S. Dept. of Agriculture, Soil Conservation Service.

Kunkel, F. and Upson, J.E., 1960, Geology and ground water in Napa and Sonoma Valleys, Napa and Sonoma Counties, California, Water Supply Paper 1495, USGS. https://pubs.er.usgs.gov/publication/wsp1495. Accessed 11 March 2023.

Pierella Karlusich J.J., Bowler C., and Biswas H., 2021, Carbon Dioxide Concentration Mechanisms in Natural Populations of Marine Diatoms: Insights from Tara Oceans. Front. Plant Sci., Vol. 12.

Maltman, A., 2022, Tuff, tufa, tufo, and tuffeau: A tangled world, News & Features, The World of Fine Wine, (https://worldoffinewine.com/news-features/tuff-tufa-tufo-tuffeau-vineyard-soil).

National Geographic, 2017, These Kaleidoscopic Masterpieces Are Invisible to the Naked Eye, https://www.youtube.com/watch?v=qxkbSk--EUY&t=1s. Accessed 11 March 2023.

Shipman G., 1977, Soil Survey of Santa Barbara County, CA, South Coastal Part, U.S. Dept. of Agriculture, Soil Conservation Service.

Sweetkind, D.S., Rytuba, J.J., Langenheim, V.E., Fleck, R.J., 2011, Geology and geochemistry of volcanic centers within the eastern half of the Sonoma volcanic field, northern San Francisco Bay region, California, Geosphere, 7 (3): 629–657.

Swinchatt, J., 2009, The Geologic Origin of the Coombsville Area, EarthVision, Inc. (article not available on-line).

Wallace, A.R., Frank, D., Founie, A., 2006, Freshwater diatomite deposits in the western United States, USGS Numbered Series 2006-3044.

Weil, R.R. and Brady, N.C., 2017, The Nature and Properties of Soils, 15th Ed, Pearson, New York.

Zeeb, B.A., Smol, J.P., and VanLandingham, S.L., 1996, Pliocene Chrysophycean Stomatocysts from the Sonoma Volcanics, Napa County, California, Micropaleontology Vol. 42, No. 1, pp. 79-91.

Zoca, S.M. and Penn, C., 2017, Chad Penn, An Important Tool with No Instruction Manual: A Review of Gypsum Use in Agriculture, In: Advances in Agronomy, Editor(s): Donald L. Sparks, Academic Press, Vol. 144, Pages 1-44.