Book Chapter Template

Detecting Wildfire Emissions in the Indoor Environment

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Abstract

Wildfires do billions of dollars of damage each year. A significant part of that cost is due to smoke damage. Verifying exposure to smoke from a wildfire often requires laboratory analysis. The analyst should have knowledge of the biome and the plant parts burned by wildfire. It requires a familiarity with common sources of combustion particles and black particles not from combustion that are found in a home. There are many sources of combustion particles in indoor environments. These include cooking, fireplaces, wood stoves, candles, and smoking. There are many other sources: electric heater elements, electrostatic air cleaners, incandescent light bulbs, and others. There are sources outside that infiltrate the building over time. These include vehicular traffic, industrial furnaces and boilers, open burning of refuse or yard wastes, land clearing, area emissions from fireplaces, and others. Some of these are sources year around. Others may be seasonal but persist for days, weeks, or months. Emissions from wildfires can be distinguished from these sources. Wildfire emissions have unique characteristics based on the biome burning and the parts of plants that are burned by a wildfire. The collection, identification, and quantification of particles from wildfires by biome is addressed.

Keywords: Wildfire, Biome, Particles, Light Microscopy, Tapelifts, Assemblage Analysis, Particles of Combustion, Infiltration Factor, Forest Fire, Savannah Grassland Fire, Chaparral Fire, Leaf Structure, Bark Structure, Wood Structure, Stomata, Phytoliths, Calcium Oxalate, Cross-field Pores (Pits), Wood Pore (Pit) Structure, Polarized Light Microscopy, Circular Polarized Light, Reflected Darkfield Illumination, Whewellite, Weddellite, Ash, Char, Oblique Illumination, Human Vision, Fit-For-Purpose Analysis, Attention Blindness

1. Introduction

A wildfire insurance fund of 21 billion dollars was set aside to compensate victims of the 2017-2018 wildfire season in California [1]. According to the Insurance Information Institute, this covers the liability for 2017 and will have to be doubled to cover 2018 [2]. Worldwide wildfires have cost additional billions of dollars from 1980 to 2012 [3]. Most of these expenses were the result of crops and structures destroyed by the fire. The United States is unique in that a significant part of the costs associated with recovery is due to claims of damaging exposure to the smoke.

1.1 Particles of Combustion

Identifying the plant source for combusted or composted biomass using the light microscope has a long history. It has been used for the characterization of peat deposits in Northern Germany and studies of the charred plant material in four-hundred-million-year-old sedimentary deposits [4-15]. The identification of the sources of charred plant material is a standard technique in archeology. Books have been written containing information on the morphology and optical properties of particles that are predominantly carbon [16-20]. Reflected light microscopy was used to identify the charred particles and transmitted light was used to characterize the ash or phytoliths in the deposits. The techniques first developed by Weber and published in 1908 are still applicable today [4]. They benefit by over 110 years of development in our knowledge of plant structure, materials sciences, and in optics. These observations developed to study coal, peat, and residues in archeological sites are applicable to the study of particles from wildfires that may infiltrate a building. The book, FIRE ON EARTH, by A.C. Scott, et al, recommends these techniques for characterizing wildfire debris [20]. These are not new untested techniques but the application of well tested and well documented methodology.

A wildfire is a rapidly moving, uncontrolled fire that consumes specific parts of every plant in its path [21, 22]. The charred or ashed fragments of the plants are carried in the smoke. A building exposed to this smoke will contain, to some extent, particles from that fire. These particles together identify the wildfire.

A building acts as a leaky filter [23-33]. The doors, windows, and ventilation systems act as large holes in the filter. The building shell acts as the main filter. It still allows particles from outside but is much more size selective. The rate at which particles enter a building is its infiltration factor. The infiltration factor for particles smaller than 2.5 micrometers is estimated to be about 70% with windows and doors closed and the ventilation system filtered with a high efficiency (HEPA) filter. The infiltration factor drops as the particle size increases but is still over 50% at 10 micrometers.

Particles that enter the indoor space may exit to the outside or deposit on surfaces. Particles will accumulate on indoor surfaces until that surface is cleaned or particles are resuspended by local turbulence [25, 34].

The analysis of particles on indoor surfaces testify to the entry of particles from outside. Pollens, spores, road wear, tire wear, plant parts, and fireplace, vehicle and industrial emissions are common. Exposure to smoke from a wildfire will result in some of the particles from that source being deposited. The amount of outdoor particles deposited will depend on where in the building the sample is collected, the time since that surface was last cleaned, the airborne concentration over the collection period, the concentration outside, the average infiltration factor, the resuspension frequency, and other factors.

Indoor spaces can be quite complex [25, 34-36]. A single sample from a single surface is not adequate to assess exposure to outdoor sources. Knowing the location and type of surface is important information. Windowsills are not the same as desktops, bookshelves, or floors. A sample from a fireplace mantle may provide information on possible interferences. Windowsill samples can provide information on that site of particle exchange. Critical to assessing exposure are samples from the living spaces in the home. Knowing which fire generated the smoke of concern is essential for assessing wildfire exposure. Each fire has its own signature collection of combustion particles. [37-44].

1.2 Human Vision and Analysis of Combustion Particles

Every instrument has a component dedicated to the generation of a signal and another component, the detector, that detects the signal generated and creates an output. The output is interpreted by an analyst familiar with the types of signals created and able to read the output from the detector unit. Microscopy is no different. It is unique in that the detector and the analyst are the same.

The detector is the human visual system. It detects contrast, color, edges, shape, and size [45-61]. It is an energy demanding system and can be easily overwhelmed if not tuned to a limited number of features or objects of interest [62-64]. The cognitive portion of the brain considers diffraction, light scatter, interference, polarization, refraction, reflection, wave theory, and morphological analysis, to tune the visual system [65-70] and configure the illumination system of the microscope to make significant features of the objects easily detectable [71-75]. The analyst (microscopist) must be familiar with the optical properties and morphology of the objects of interest [76, 77]. This takes training, experience, expectation, and familiarity. Training begins the process of creating new neural networks. These networks are physical structures in the brain. They take time to develop, six months or more, and continue to become more efficient for years. Experience, in the form of positive feedback, is required to set these neural -networks. Training and experience establish object libraries that are relevant to specific analytical problems. Expectation is the neurological response to an analytical problem. Expectation loads a relevant object library that can be quickly assess as present to some degree or absent [78]. Familiarity is the range of objects the microscopist can recognize by type. Familiarity detects differences or interferences that may require modification of the library of objects.

Objects are characterized by how they reflect or scatter light in the everyday world. The training to recognize objects begins in infancy. Years of experience makes the recognition of many thousands of objects almost instantaneous. Objects viewed though the microscope are vastly more complex optically. Each type of object, pollen, spore, diatom, mineral, hair, fiber, insect fragment, plant part, combustion particle, requires training and experience to create the necessary neural networks. Additional networks are required to form the mental assemblages of objects, the object library, queued by an expectation. Familiarity grows over years as the number of accessible object libraries increases. The number of these libraries is severely limited if the analyst is only familiar with one type of microscope illumination.

2. Method

Light microscopy is the method of choice. The method described here is designed to take advantage of what the human visual system does well and to minimize the cost of variance in the results. There is always a balance between cost and analytical detail. In the case of light microscopy that becomes a balance of time per slide, number of slides per sample, and the limitations of human observation.

The rate at which brain solves an object recognition problem is a function of complexity [49-69]. The more complex the problem the more energy demanding and the longer the process to recognition. The brain is capable of rapidly recognizing and tracking about seven things per tenth of a second in a field of view [64]. The addition of one more thing more than doubles the time. The brain must reload a new library and then rescan the field of view. Adding up to seven more thing has little impact on the time until the fifteenth thing is added. The actual number of objects varies slightly from person to person, but the concept is the same.

A “thing” in the field of view is a mental construct. With a little training we can rapidly recognize a bird. With training and experience a birdwatcher can almost as quickly identify the type of bird and the number of different types in the field of view. The same thing is true of a field of view looking through the microscope. Training and experience significantly reduces the energy require to process an image and reduces many forms of the same object to one "thing". Assemblage analysis, the recognition of particle types that belong together, takes advantage of this mental construct [49-69]. The assemblage becomes the thing and may consist of tens of different types of particles, all now basically one mental construct.

The particles on different surfaces in different parts of a home vary widely. Multiple surfaces in the home must be examined to assess exposure. It is not useful to try and reduce analytical variance on one slide to a minimum when the variance from one area to another on the same surface, even the same slide, can vary by -orders of magnitude. The Fit-For-Purpose approach to analytical design will be used throughout [79-81]. A semi-quantitative analysis is more than adequate once the particle assemblage characteristic of a given wildfire has been established. That helps control costs by reducing the amount of time spent on each slide.

2.1 Particle Collection and Sample Preparation

The challenge in collecting particles from surfaces for an environmental analysis is to collect them without altering the particles or their pattern of distribution. Tapelifts of surfaces retain the spatial relationships between particles and at the same time are very efficient collecting particles from surfaces. Quantification of particles by type, per unit area, or as a fraction of the different particle types is possible with accuracy and precision [82-88]. The tapelift records the variability of particle concentrations in the environment if sufficient surface area is represented. If each tapelift is approximately 2 centimeters by 8 centimeters (3/4 inch by about 3 inches) and multiple tapelifts are collected, generally 10 or more, then the variability in the environment is reasonably represented. The number of tapelifts is dictated by the variability of the particle distribution on surfaces in a home. The environment of a windowsill is very different than that of the dinning room table, the base of the television, the top of a bedroom dresser, or the top of the refrigerator. Micro-environments at each of those locations require the larger tape sample. The windowsill next to the glass of the window is a different micro-environment than that of the sill farther from the glass. The particles that collect at the edge of a table are frequently different than those closer to the center of the table. The variability of particle distributions in the home is large compared to the analytical variability of a single tapelift analysis.

There are a variety of adhesive tapes available but the analysis to be performed dictates the optimal tape. A cellulose ester tape with an acrylic adhesive is the best for environmental studies, including wildfire debris analysis [89]. The cellulose ester plastic film can be removed with acetone and the acrylic adhesive is unaffected by the acetone. Few environmental particles of interest are soluble in acetone. The particles from the wildfire remain stuck in the adhesive and bound to the slide. A mounting medium with the same refractive index as the adhesive makes the adhesive disappear. The particles that were on the original surface are now just as they were on the surface but in a free optical space. Any desired illumination system can now be used without interference. Subtle optical effects can be easily detected. That significantly reduces time to recognition.

2.2 Microscope

The particles in the plume of a wildfire are opaque, translucent, transparent, anisotropic, isotropic, monotypic, polytypic, agglomerates, and shadow-structures. The diversity of optical properties requires that the microscope be configured to gather information for all these particle types. Table 1 shows the identifying properties of different types of particles marking a wildfire. Table 2 shows the type of illumination required to detect those properties.

PROPERTIES	Morphology	Reflectivity	Light Scatter	Birefringence	Isotropic	RI	Optical Density
Ash	X		X	X		+	X
Charred Bark	X	X					X
Charred Wood	X	X					X
Calcium Oxalate	X		X	X	X	+	X
Silica	X		X		X	-	
Fire Retardant	X	X		X			X
Burnt Clay		X		X		+	X

Table 1: Important Properties by Particle Type

The variety of properties shown by different particles generated by a wildfire keys to their identification. Morphology is a catch-all term including the outline shape, internal structure, texture, heterogeneity, shapes of surface features, shapes of internal features, size, aspect ratios, and the relative sizes of different features. Reflectivity includes the pattern of the reflection, the relative intensity of the reflection, and the color of the reflection. Light scatter has a relative intensity and a pattern that is related to the number of scattering elements per unit volume or area. Birefringence is a property of the bond polarity within a material. For a single crystal the three-dimensional bond polarity is fixed. A material is isotropic if bond strengths are the same in all directions. The Refractive Index (RI) is relative to the mounting medium in this case. It is either higher (+) or lower (-). The optical density refers to how much light transmits through the particle. It ranges from opaque to transparent and includes transmission color.

ILLUMINATION	Reflected Darkfield	Transmitted Oblique	Circular Polarized	Linear Polarized	Transmitted Brightfield	Transmitted Darkfield
Morphology	X	X	X	X	X	X
Reflectivity	X					
Light Scatter	X				X	X
Birefringence			X	X		
Isotropic			X			
Refractive Index		X				
Optical Density					X	X

Table 2: Illumination Systems Needed to Investigate Wildfire Particles

The configuration of the microscope as described in the Methods section permits rapid transitions between these illumination systems without moving the particle. These transitions may involve pressing a button or pulling a filter. They are made in a second or less and the change in the image of the particle is often sufficient to identify the particle, its source, and its history.

Figure 1: Microscope for Wildfire Particle Analysis

A petrographic microscope capable of both transmitted linear and circular polarized light and objectives mounted with a ring-light for reflected darkfield illumination is used for the analysis (see Figures 1 and 2). A phase contrast substage condenser provides transmitted brightfield, darkfield, and oblique illumination. A 20X objective and a total magnification of 200X or more is required to see the necessary features.

Figure 2: Ring Light for Reflected Darkfield Illumination

2.3 Assemblage Analysis

No uncontrolled particle source produces a pure stream of a single product. Assemblage analysis is an analytical approach designed to identify the source of particles found in a sample [90-94]. Wildfire debris requires an assemblage analysis approach to verify the source.

Each biome and micro-biome included in the wildfire has its own collection of signature particles [95-99]. The key is the identifiable variety of plant types and parts, from char to ash, and other associated particles typical of uncontrolled wildfire. It is the variety that distinguishes the wildfire particles from a fireplace backdraft, backyard pit fire, Autumn leaf burning, or other source. The assemblage identifies wildfire.

2.4 Quantification

The debris from a wildfire is too complex to quantify by one specific set of optical properties. In some locations the majority of debris from the wildfire may be black and opaque. In another location the dominant particle type may be white/transparent ash. The interfering particles for any given sample will be different for every location. An automated approach is impractical because the algorithm would have to be modified for each application [100, 101]. A human observer can quickly scan many thousands of particles looking for the particles of interest. A computer must look at each particle to determine if it fit the criteria for inclusion. Many thousands of particles would need to be scanned on each tapelift.

The approach taken for studies in our laboratory is to create a lower boundary for exposure based on the total area of each tapelift that needs to be examined in order to identify a sufficient variety of particles to establish exposure to the wildfire. The larger the area that needs to be examined the lower the exposure. That lower limit may then be adjusted upward once exposure is confirmed by attributing more of the combustion particles in the sample to the wildfire.

This method of quantification was developed because it is often necessary to examine hundreds of fields of view with many hundreds of particles per field. The human visual system can do that very effectively if looking for a specific set of particle types that can be highlighted using the right type of illumination.

3. Identification of Wildfire Particles in Indoor Environments

3.1 Char Reflectivity and Thermal History

Many characteristic plant structures survive combustion and/or composting, even for hundreds of millions of years [6-16]. Those characteristics help in identifying the plants and often record the conditions under which they were created. Composted plant material looks very different than combusted material from the same plant. Both are black but the thermal history is recorded in the reflectivity of the particle. Table 3 shows the change in reflectivity as a function of history and temperature. Wood with a refractive index around 1.55 has a reflectivity of about 4% and is transparent. Humus, biologically degraded plant material is black and has a reflectivity of about 0.1% or less. Vitrinite, a coal maceral, is black and has a reflectivity around 1% but increases toward 2% with exposure to higher pressure over time. It will not exceed 2% without exposure to temperatures of 400 degrees Celsius or higher [6, 12, 15]. Plant material coked at 400 degrees Celsius has a reflectivity of about 2% and the reflectivity increases with temperature up to about 6% and higher. Graphite has a maximum reflectivity of about 24% [17].

TEMPERATURE	Wood	Humus	Vitrinite	400° C	600° C	850° C
REFLECTIVITY	4%	0.1%	1%	2%	5%	6%

Table 3: Reflectivity of Biomass as a Function of Temperature

The reflectivity of the charred particle is not measured directly as part of the analysis but the contrast of the part of the particle that is reflecting the light from the reflected darkfield illuminator contrasted with the black of the particle not reflecting that light is an indication of the thermal exposure. The relative reflectivity is not used as an identifier of the particle but as an indicator that it is a combustion residue. The identity of the particle's origin is based on the morphology of the particle. The relative reflectivity documents the particles history.

3.2 Calcium Oxalate and Thermal History

Calcium oxalate phytoliths record thermal exposure in the chemical changes that occur, as shown in Table 4. Calcium oxalate phytoliths record the possible plant of origin by their shape and their thermal history by the characteristic chemical changes [102, 103]. Most calcium oxalate phytoliths are whewellite, the monohydrate. The variety of calcium oxalate phytolith shapes are genetically determined for each plant. The shape is constant through the thermal transitions listed in Table 4.

TEMPERATURE	Ambient	120-235° C	420-520° C	620-860° C
WHEWELLITE CHEMISTRY	$Ca(C_2O_4)$-(H_2O)	$Ca(C_2O_4)$	$CaCO_3$	CaO
WHEWELLITE OPTICAL PROPERTIES	δ 0.16 α 1.490 β 1.553 γ 1.650	Cloudy, δ 0.14 Low Light Scatter	Poly-crystalline 1st Order Colors High Light Scatter	Isotropic Low Light Scatter
WEDDILLITE CHEMISTRY	$Ca(C_2O_4)$-$2(H_2O)$	$Ca(C_2O_4)$	$CaCO_3$	CaO
WEDDILLITE OPTICAL PROPERTIES	δ 0.02 ω 1.523 ε 1.544	Cloudy, δ 0.03 Low Light Scatter	Poly-crystalline 1st Order Colors High Light Scatter	Isotropic Low Light Scatter

Table 4: Optical Properties of Calcium Oxalate Phytolith with Temperature

Shape is the main identifier for black particles of combustion. Weber [4] noted the value of fragments of monocotyledon "epidermen" for identifying grasses and conifers in peat deposits. Structures of the leaf stomata, veins, cells, and hairs persist as fossils in carbonaceous shales, coal, peat, and in the smoke plume of a wildfire. Some of these structures are faithfully recorded in the opalescent silica phytoliths and deposits on the surfaces of grasses and other plants.

Cell structures of barks and woods are also definitive and can be used to identify the type of plant or even the species. The collection of plants and plant types identified by their thermally modified particles found in a home identify their source biome. If the biome is consistent with the biome burned by the wildfire then the extent of smoke intrusion can be confirmed and measured.

Identifiable fragments of these plants fill the smoke plume from a wildfire with markers. Many of these identifiable fragments are below ten micrometers in aerodynamic diameter and can travel hundreds of miles in the plume. These small fragments of plants are flakes of cell walls or fragments of leaves that naturally orient themselves on surfaces in exactly the position that renders them identifiable. Tapelifts retain that orientation.

3.3 Monocotyledon and Gymnosperm Leaf Structures

The leaf epidermal cells of monocotyledons (monocots) and Gymnosperms have a characteristic structure (see Figure 3). The epidermal cells tend to be uniformly elongated and the elongated sides are roughly parallel. The terminations may form a rectangle, or they may be angled. The elongated sides are often serrated with an interlocking structure along the long edge of the cell (see Figure 3a). This pattern is faithfully recorded in the silica film protecting the surface of the leaf or by other leaf residues. The result is an elongated rectangular shape that retains the serrated wall structure. The ash of fully combusted leaves often retains this structure as an ash shadow (see Figure 7) if collected by tapelift. These delicate structures can often be identified on particles as small as five micrometers.

Silica phytoliths often mimic the shape of the epidermal cells though they can take a number of other forms [104-106]. These silica phytoliths easily survive wildfire and become a marker in the smoke. They may show evidence of their exposure to the fire by increased reflectivity due to light scattering sites created by the loss of loosely bound water or by a coating of carbon. These particles have a small aerodynamic diameter due to their large surface area relative to their volume. Silica phytoliths from grasses are common in buildings. Transmitted oblique illumination increases the resolution and contrast while showing that the particles have a lower refractive index than the mounting medium when nearly every other particle has a higher refractive index (see Figure 4).

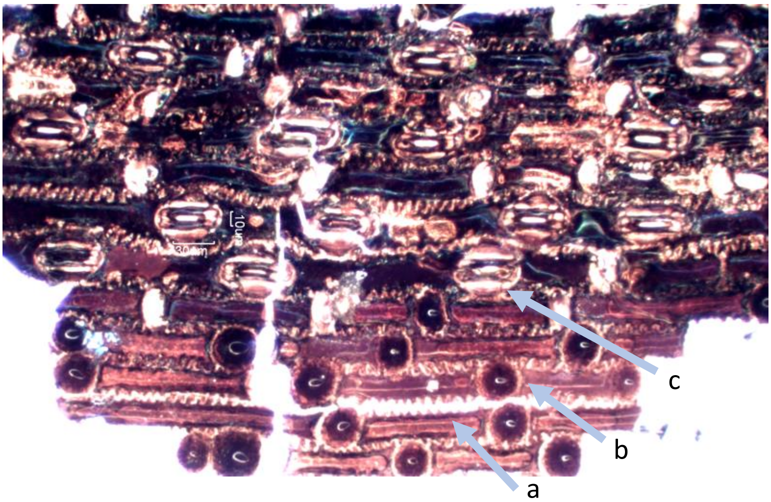

Figure 3: Epithelial Leaf Cell Pattern for Monocotyledons and Gymnosperms

This is a charred grass leaf. The serrated edge (a) of the longitudinal epithelial cells are characteristic of all Monocotyledon and Gymnosperm leaves. The cells are coated with a layer of silica that retains this pattern even when the carbon is burned away. The attachment scar of a plant hair (b) is located between the cells. Stomata (c) are all oriented in the same direction.

The grasses including bamboo, lilies, and other monocots, and Gymnosperms share these patterns with distinctive variations that mark Genus and even species.

The stomata of monocots and Gymnosperms are arranged with their long axis parallel to the long axis of the leaf cells (see Figure 3c). They are in rows and there are generally multiple rows separated by a few rows of other cells. The structure of stomata is typically preserved through fire because the guard cells that form the stomata are fuel-rich and tend to be carbonized. Reflected darkfield illumination will demonstrate the reflectivity of the carbonized cells. That shows that they are a pyrolysis product rather than a bacterially composted leaf fragment.

Grasses are typically protected by numerous plant hairs [107]. Charred plant hairs are common in wildfire emissions (see Figure 5).

Some of the Gymnosperms add distinctive calcium oxalate phytoliths. Most of the pines are characterized by elongated bipyramidal calcium oxalate phytoliths. Spruce and Douglas fir have pseudo-cubic calcium oxalate phytoliths. Calcium oxalate phytoliths, as mentioned above, record

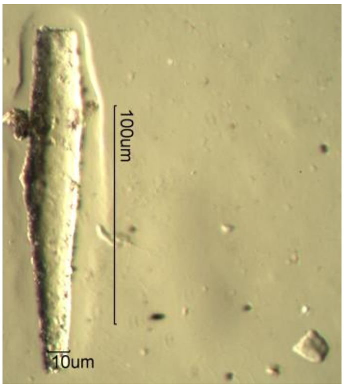

Figure 4: Silica Phytolith from the Saddleridge Wildfire

The phytolith is on the left and is bright on the right side. The mineral grain on the lower right and all the other particles in the image are dark on the right side. Only silica phytoliths of common household dusts have refractive indices below 1.48.

Figure 5: Charred Plant Hair from the Saddleridge Wildfire.

the likely plant of origin in their shape and their thermal history by their change in optical properties [102, 103, 108]. Pyrolyzed calcium oxalate that has been converted to polycrystalline calcium carbonate standout brightly with reflected darkfield illumination. Those that have just lost their waters of hydration or have transitioned all the way to calcium oxide stand out best viewed with transmitted oblique off-crossed circular polarized light.

The presence of pyrolyzed monocot and Gymnosperm leaf structures reduces the likely source fire. Grassland wildfires are dominated by these monocot structures. Gymnosperm forest wildfires are rich in pyrolyzed calcium oxalate phytoliths and charred needle debris. Backyard waste fires burning lawn cuttings and other garden wastes, agricultural stubble burns, cane fires, and controlled burns to reduce understory fuels can be other sources of monocot structures. These more controlled fires tend to be much more limited in species represented. Fireplace emissions, wood stoves, backyard firepits, and structural fires are eliminated because Gymnosperm needles and grasses are not a common fuel for these sources.

3.4 Dicotyledon Leaf Structures

Dicotyledon (dicot) structure is not so linearly organized. The epidermis of a dicot leaf has a web-like structure of veins forming islands of cells (see Figures 6 and 7). The shape of these islands and the cells in these islands is the result of the pattern of major and minor veins on the leaves. These patterns vary from species to species [109]. The patterns are often present in the ash. The type of illumination required to bring out these patterns depends on the leaf of origin and the thickness of the veins and the island cells.

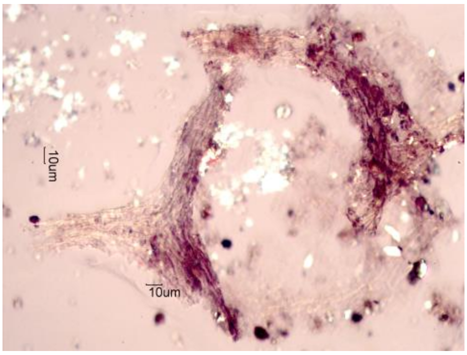

Figure 6: Leaf Ash

The vein structure typical of a Dicotyledon leaf can be seen in the tapelift of ash collected in a home.

Many plants in arid environments secrete resins to reduce loss of moisture. These resins often form fuel-rich beads that may persist as small, black, carbon globules on flakes of white ash. High reflectivity, about 6%, is typical for these carbon residues. The reflection of the reflected darkfield ring illuminator is roughly circular, which indicates the globular form of the particle. The reflectivity may be a little hard to see due to the high light scatter of the white ash surrounding the charred resin globule.

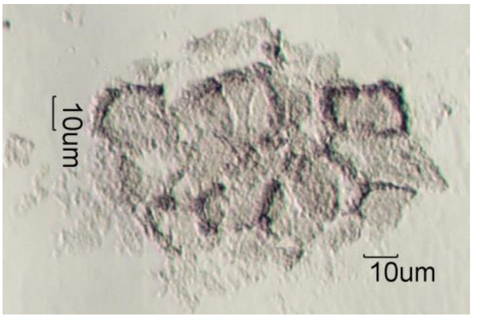

Figure 7: Leaf Ash Cell Island

This very fragile leaf structure is preserved by a tapelift. These shadow-like structures can be a significant part of the total sample.

The stomata are more randomly oriented and tend to be more common on the lower surface of dicot leaves (see Figure 8). The arrangement of guard cells around the stomata vary from a single pair of cells to much more complex networks of cells that may extend out from the stomata a couple of cell thicknesses [110, 111].

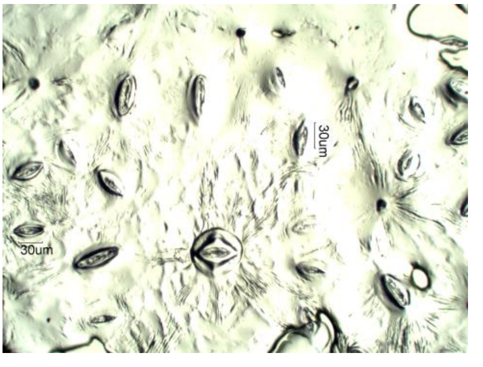

Figure 8: Stomata, Cottonwood Leaf Cast

The stomata on Dicotyledon leaves tend to be randomly oriented.

Leaf pubescence, plant hairs, nobs, or spines may char and be found on a fragment of burnt leaf or they may become free particles in the plume [107]. Many of these structures are silica or are coated with a layer of silica, which makes them more stable in the flames. Because of the variety of optical properties that may be shown by charred leaf pubescence reflected darkfield, transmitted oblique, crossed circular polarized light is used to make these particles stand out. Reflected darkfield illumination brings out the reflectivity of the pyrolyzed carbon and the light scatter of the froth created by the loss of moisture in hydrated silica structures. Transmitted, oblique, crossed circular polarized light provides the best outline of the particles.

Smoke from the burning of leaves in the Fall will be dominated by burnt fragments of the leaves of deciduous trees. If the wildfire was in a deciduous forest during the after leaf-fall then charred bark becomes a more reliable feature of the debris from the wildfire. Reflected darkfield illumination is required to identify charred bark.

3.5 Bark Structure

The bark for all woody plants performs a similar purpose of protecting the woody tissue. Part of the protection from insect pests is provided by calcium oxalate phytoliths, as was the case with leaves. Bark is a major source of pyrolyzed calcium oxalate phytoliths and ash from biomass fires [112-116]. Fireplace backdraft is typically characterized by the pyrolyzed phytoliths of the bark of the wood used as fuel. Wildfire is characterized by phytoliths from a number of plants and from both the leaves and bark of those plants.

The bark also provides protection from the exterior environment. It helps with water retention, forms a thermal barrier, and provides protection from abrasion or physical attack. Cork cells, stone cells, fibers, and resin deposits aid in this capacity. The cork cells tend to be rectangular and hollow to provide insulation. Some trees have thick layers of cork cells that help shield the tree from fire. Pines are an example, as is the Cork Oak. Other barks have a high proportion of tracheids and tends to be stringy. Cedar bark is an example.

Charred bark has a number of morphologies [117] but the walls of cork cells and hub-and-spoke structures are common (see Figure 9). These require reflected darkfield and transmitted brightfield to be characterized.

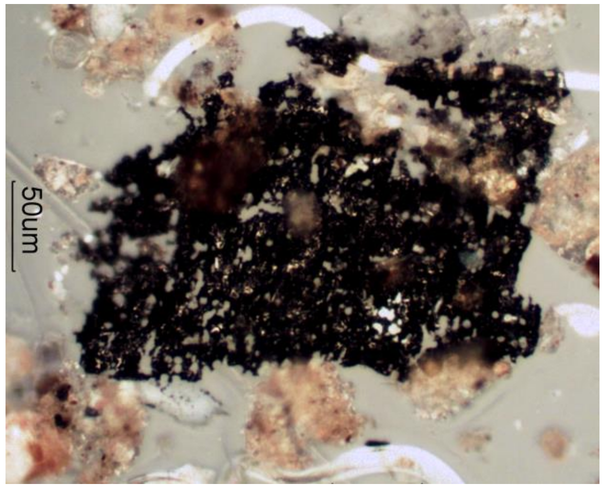

Figure 9: Charred Bark and Burnt Soil

The charred bark of many woody plants shows this spongy structure. Smaller particles may still show the hub-and-spoke pattern evident here.

The burnt soil turns brick-red as a result of oxidation in the flames.

3.6 Gymnosperm Wood Structure

The tracheid fibers that make up the bulk of the wood for Gymnosperms tend to be larger in diameter than in Angiosperms and tend to have a much more obvious pit (pore) structure [16, 118-122]. The pore structure can be definitive to the Genus level and sometimes to the species level. The pit may be circular or elliptical. There is an anulus around the pit that may have a width that is less than, equal to, or greater than the diameter of the pit. The pits may be uniserial, biserial, opposite, or adjacent. The anulus of the pit is much thicker than the cell wall. As a result, the anulus may be found as a discrete particle in the smoke from a wildfire. The structure of these pits is best seen using reflected darkfield illumination.

There is a second type of pitting found on the tracheids of Gymnosperms. They occur were the ray cells cross the longitudinal cells (see Figure 10). These cross-field pits are also distinctive. They

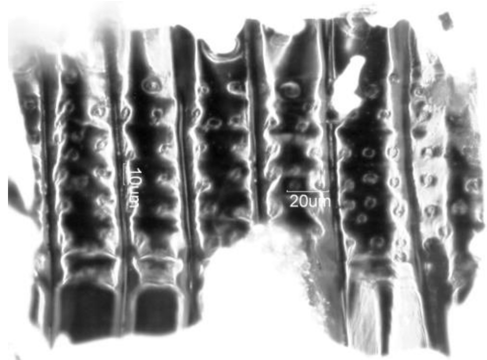

Figure 10: Cross-Field Pitting

The majority of this particle shows cross-field pitting. At the upper edge-center is part of a normal pit.

help in the identification to the Genus level and more. Darkfield illumination brings out the structures of these pits.

Some of the Gymnosperms carry another distinctive marker, helical thickening. Helical thickening is a periodic thickening of the cell wall that runs around the cell. These may be at a characteristic angle to the long axis of the cell and may be at regular or irregular intervals, depending on the tree species (see Figure 11). In thinner charred wood that transmits some light these show up as dark bands. In opaque fragments they are made visible by reflected darkfield illumination.

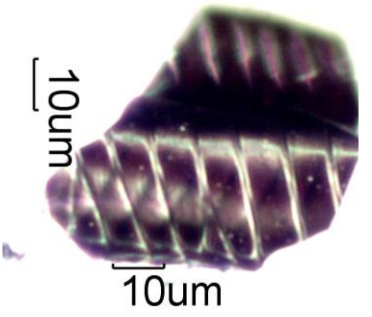

Figure 11: Helical Thickening

This fragment of charred wood shows helical thickening with very regular spacing across a tracheid fiber. The regularity of the spacing eliminates Yew and identifies this as a Douglas fir fragment. Douglas fir and Yew are the only tracheids that show helical thickening.

3.7 Angiosperm Wood Structure

Vessel cells are the most diagnostic parts of Angiosperm charred wood. The Gymnosperms don't have dedicated vessel cells. Vessel cells are generally much larger than any Gymnosperm cell and are much shorter than Gymnosperm tracheids. They have a variety of unique structures that survive charring. The vessel cell walls typically have large numbers of smaller pits with distinctive shapes that may or may not have a visible anulus (see Figure 12). The pits may be at an angle to the long axis of the cell. The pits may be opposite or adjacent. Vessels may have helictical thickening. They often have a "ladder" structure, the scalariform perforation plate, that may survive the fire. Many vessel cells have talos structures. These are thin flakes of tissue that are found in the vessel cells of some Angiosperm species. They look the same as the larger cork cell walls from Cedars when they char. Reflected darkfield illumination is required to see these structures and document their combustion origin.

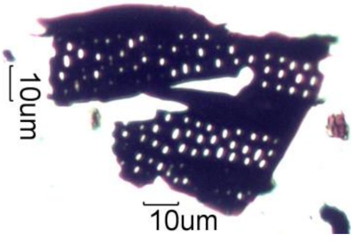

Figure 12: Vessel Cell Fragment

Tracheids of Angiosperms tend to be much thinner than those of Gymnosperms (see Figure 13). The charred cell walls of the Angiosperm tracheids tend to be narrow. The joints where three cells come together often survives the fire and appears as a very thin, straight, black fiber. These can be distinguished from commercial carbon fiber by the lack of diffraction colors when viewed by reflected darkfield illumination. Commercial carbon fiber forms a shrinkage surface that acts as a diffraction grating.

Figure 13: Charred Hardwood Tracheids

These are charred white oak tracheids. Hardwood tracheids tend to be narrower than Gymnosperm tracheids.

3.8 Calcium Oxalate Phytoliths

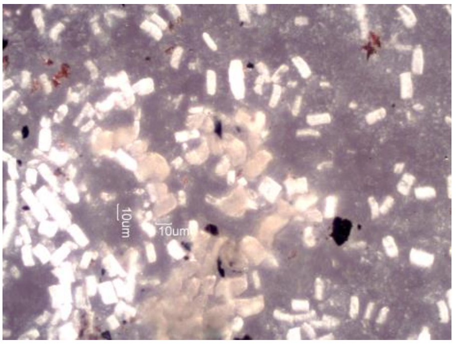

Figure 14: Charred Prunus Bark, Reflected Darkfield Illumination

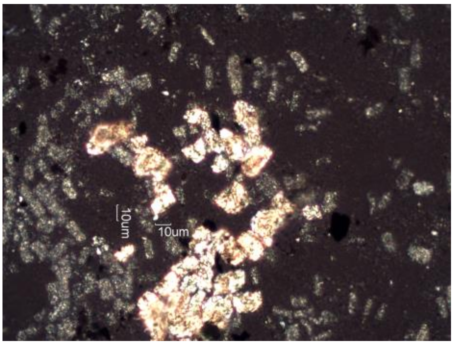

Figure 15: Charred Prunus Bark, Cross Circular Polarized Light Illumination

Pyrolyzed calcium oxalate phytoliths are one of the very common particles in the plume of a wildfire. Table 4 documents the changes in optical properties that occur as a result of exposure to temperature. Figures 14 and 15 shows the highly light scattering phytoliths that have exceeded 450^{o} Celsius, white in Figure 14, and those that are still highly birefringent, bright in Figure 15, that have not. The characteristic shapes of these particles varies from plant to plant and from one part of the plant to another. The phytoliths in the leaves may differ from those in the bark. Transmitted crossed linear polarized light, transmitted oblique off-crossed circular polarized light, and reflected darkfield illumination are all useful in characterizing these particles.

3.9 Silica Phytoliths

The plant generated opal is common on and in the leaves of many plant families. Gymnosperm needles and grasses are coated with elongated silica flakes. These often show the serrated edges typical of the epidermal cells. Grasses and many other plant families are covered with silica coated plant hairs. These hairs break free and become airborne as the leaves burn. When they are generated by wildfire they may be associated with carbon on their surface or internally. Transmitted oblique off-crossed circular polarized light and reflected darkfield illumination help characterize these particles as was pointed out in the discussion of silica phytoliths from Monocotyledons and Gymnosperm needles.

3.10 Other Char

Pollens, lichens, fungal components, and similar carbon-based structures can be found in the smoke plume from a wildfire. These materials are also identified by their morphology. Charred pollens and fungal spores retain their morphology but may become opaque and become more reflective. Charred lichens and fungal mycelia retain their shape and are generally still attached to the substrate on which they grew. Transmitted brightfield and reflected darkfield are best for identifying these structures.

3.11 Burnt Soil

Burnt soil is identified by the oxidation of iron in the clay attached to small minerals or free oxidized iron in particles of clay. This is most useful in areas where the soil is not naturally red, oxidized. Ferrous iron (Fe^{+2}) is a common biogenic ion in soils. The heat from wildfires tends to oxidize the iron to its ferric form (Fe^{+3}) and produce the brick-red color of burnt soil. The winds created by the wildfire loft fine particles of this burnt soil into the plume. Transmitted off crossed circular polarized light and reflected darkfield bring out the red of the burnt clay. The red may not be visible if transmitted light alone is used. Reflected darkfield amplifies the red color.

3.12 Fire Retardant Spheres

Fire retardant is often airdropped to control the direction of the fire and limit its spread. It is dropped as an aqueous slurry. The shear forces acting on the slurry as it is dropped results in a plume of very fine particles trailing the main body of the drop. These fine particles form small spheres and become another possible marker of proximity to the fire front. The fire retardant is typically a mixture of phosphates and sulphates with hematite as a pigment to mark the area already treated. Reflected darkfield is needed to see the bright red of the hematite and transmitted circular polarized light is needed to see the larger phosphate and sulfate salts in the retardant. Red paint spheres may be present in homes or garages where samples are often collected. Red paint spheres don't contain the larger, birefringent, colorless crystals of phosphates and sulfates found in fire retardant.

3.13 Structural Fires

Some wildfires become a series of structural fires as they move through a residential area. Structural fires have a very different set of signature particles. The primary structural wood tends to be Douglas fir. Plywood and oriented strand board (OSB) may have up to five different types of wood in their composition but no bark or leaf material from those trees. Composite shingles, tar paper, paint, plastics, fabrics, and other materials contribute to the particles in a structural fire.

4. Quantification

The claims that require an analysis of wildfire particles in a home are based on potential damage done to the home, its contents, or its surround that is covered by the insurance policy. The damage may be soiling, chemical corrosion, or some aspect of environmental quality that degrades the value of the home attributable to the smoke from the fire. All of the potential damage must be the result of particles from the smoke. The risk to any exposed surface is based on the quantity of wildfire residue per unit area on that surface. The first step is to confirm that the wildfire significantly contributed to the contamination on the surface, the subject of Section 3. Once exposure is confirmed then the extent of that exposure can be determined.

The wildfire source is independent of other particle sources that are represented on that surface. Any potential damage done by the particles from the wildfire is not affected by the particles from other sources. The quantification must be based on the particles from the wildfire per unit area and not on the percent of particles from the wildfire compared to particles from other sources.

The variability of optical properties for the particles generated by a wildfire preclude automated methods, as discussed in section 2.4. The smoke plume particles change as the fire moves. The particles from the smoke that penetrate the building depend on the building and the smoke at the time of exposure. The interferences are different from one building to another. The coding required would need to be customized for each wildfire and each building. A human observer can make the adjustments required to identify the different particles that may be part of the wildfire assemblage. But human observers are poor at measuring particle concentrations efficiently.

One solution to the problem is to measure the area that must be inspected to conclude that the surface has been significantly exposed to debris from the wildfire. This establishes the lower limit of exposure because it is based on the area that must be scanned to find the least common member of the wildfire assemblage. At high exposures, all members of the assemblage are present within the first scan across the slide at 200X. This is less than 0.4 square centimeters. If up to 3 square centimeters must be examined to confirm the wildfire assemblage, then it is at trace levels and within the range of biomass combustion particles common in homes not exposed to wildfire. At this point the presence of particles from the wildfire has been established. The sample can now be evaluated based on the amount of the more common members of the wildfire assemblage. This correction is an increase in exposure. Measuring the area scanned is an easy task to accurately document.

It is difficult to justify a more rigorous quantification procedure because of the variability of particle populations on surfaces indoors. This is in keeping with the "Fit-For-Purpose" approach to analysis. The variability can be large on a single surface let alone different surfaces in the same building. The infiltration factor varies from room to room. Redistribution over time may even increase the variance as local intermittent turbulence moves particles to more stable quiescent zones. This variability is one reason for the requirement of samples from multiple surfaces. The typical variance for particles on surfaces in a building can span orders of magnitude.

5. Discussion

Identifying the origins of charred plant materials using the light microscope has a long history. Characterizing the biome from which these charred plant materials came was one of the original interests in developing these techniques over one hundred years ago. There have been improvements in the methods but it has always been basically the same approach. The pyrolyzed particles are identified and, as an assemblage, are used to characterize the biome. The same thing is done in determining if the particles of combustion in a home are from the biome consumed by the wildfire in question. This is not difficult, but it does require some training. The analyst needs to know how to use the microscope and have some basic knowledge of the particles that become airborne as a result of a wildfire.

The particles from a wildfire change over time. Many of the reactive particles react with the air within hours or days. The environment associated with the wildfire has been changed and that changes the particles that enter the home. The plant parts, pollens, mold spores, road wear, and other outdoor particles that entered the home, now include charred and ashed particles from the burned environment. Airborne transport and track-in will carry these particles into the building until they become part of the soil. Pets can be a major source of track-in particles. These particles are no longer part of the smoke plume but part of the natural background of the changed environment. These particles are larger and are primarily a soiling risk.

The first part of the wildfire particle assemblage to disappear are the fully ashed particles. They are the most reactive and are hydrophilic. As they absorb moisture from the air they begin to react with carbon dioxide in the air and form stable, less reactive, carbonates. They are largely removed with the first good rain [123-126]. As a result, ash from the wildfire plume is one of the best indicators of direct exposure to the smoke.

The next particles to disappear are the very fragile char particles. Rain will more easily transport these particles and remove them from the environment or incorporate them into the soil. More robust char will persist but will generally be incorporated into the soil or removed by the following winter. The more common charred biomass of fireplaces, fire pits, etc. will become the most common plant combustion particles.

Inside the building the particles from the smoke will persist. The ash particles will slowly react with carbon dioxide but they will still be recognizable until they are cleaned away. The charred particles will be the most persistent in the environment because they will be the least affected by any cleaning activity. A reasonably effective cleaning activity will destroy any ash structure present but the char particles, though most are removed, may still be identifiable in the building long after exposure. Detecting charred biomass in a home is not by itself evidence of exposure to a wildfire.

6. Conclusion

Wildfires have been a feature of this planet for at least the last half billion years. The techniques used to characterize the particles created by those ancient fires have been developed over the last 100 years. These same techniques can be used to identify the particles from modern wildfires. The challenge has been to convert a research project into a commercial product available at a reasonable price to the public. Advances in the knowledge of how the brain processes visual data and better understanding the interaction between light and matter, has been the key. What have we learned?

- Tapelifts using adhesive tape with a cellulose ester backing and acrylic adhesive is the sampling method of choice.
- Multiple tapelifts are required to assess the environment.
- The tape backing must be removed with minimal disruption of the particles.
- The mounting medium must have a refractive index near 1.485.
- The light microscope is the analytical tool of choice.
- The microscope must be configured to examine the same field of view with transmitted oblique crossed circular polarized light and reflected darkfield illumination at the same time.
- The analyst needs training to identify the particles generated by wildfire.
- Concentrating only on the wildfire assemblage speeds the analysis.
- Multiple square centimeters from different areas in the building are required to assess exposure.
- The quantification of wildfire particles by area is the goal.
- Ash particles are a critically important part of the analysis.
- Char is always present in indoor environments.

Vision is a very sophisticated process. The eye is part of the brain and what we think we see is a product of the brain and not what is "out there". Familiarity and expectation are critical to the efficient processing of visual data by the brain. Familiarity and expectation are both the result of training. The brain has limits on the resources it can use at any given time. A familiar image is recognized quickly even though its context may be complex. That is especially the case if there is some expectation of the image. That is where training comes in. Becoming familiar with the combustion products of different types of plants creates a mental library that can be search when confronted with a novel scene. That search is much quicker if we now the "book" that contains the information; expectation.

Familiarity with the particle assemblages created by wildfires enables the analyst to quickly characterize the plants burned. The wildfire assemblage is very different from that of a fireplace, backyard fire pit, or other relatively controlled fires. Common indoor dusts can be ignored. Many thousands of particles can be quickly scanned and the wildfire particles detected as a function of area and not as a function of other particles not related to the wildfire.

Wildfire residues can be identified at very low levels using these techniques. The assessment of damage to property due to the exposure to wildfire smoke is negotiable. The presence of debris from the wildfire can be reliably established.

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