CONSERVATION ASSESSMENT AND EXPERIMENTAL MECHANICAL PINNING TREATMENT OF PETRIFIED *SEQUOIA AFFINIS* STUMPS AT FLORISSANT FOSSIL BEDS NATIONAL MONUMENT, COLORADO

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All figures by the author unless otherwise indicated.
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1.0 Introduction

This research is supported by the National Park Service through the Cooperative Ecosystem Studies Unit National Network (CESU) for the Colorado Plateau on behalf of Florissant Fossil Beds National Monument (FLFO) and the University of Pennsylvania's School of Design, Graduate Program in Historic Preservation and the Architectural Conservation Laboratory (ACL).

This project examines the feasibility of stabilizing the large petrified stumps at FLFO. These petrified stumps constitute one of the major natural resources of the park. Of the nine stumps currently exhibited on the Petrified Forest Loop several of these are visibly deteriorating due to cracking, spalling and the loss of large fragments of petrified wood. This project addresses an urgent need for conservation. While the research focuses on remedial methods of stabilization, the overall goal is to create a stable environment for the long-term preservation of the stumps in situ. This thesis develops site-based methods for the conservation of petrified trees in order to benefit the park's mission to conserve its fossil forest. The monument is interactive with other petrified forest sites internationally, thus enabling broad sharing of methodologies for the conservation of petrified trees. As part of the research agreement the following periods were spent preparing for this research:

August 20-November 2, 2016: This period was spent amassing available primary documentation and secondary literature relevant to the conservation of petrified wood and specifically the history of excavation, preservation, and display at Florissant Fossil Beds National Monument (FLFO).

November 8-December 1, 2016: This period has been spent organizing data and reformulating a testing program considering newly acquired information.

Excavation and in situ presentation of FLFO stumps over the past 130 years have resulted in their continued deterioration including cracking, spalling, and loss that compromises the integrity of these important fossil specimens. Their current condition has been investigated through a general condition survey and an environmental assessment of their immediate context. One stump, P-47, was selected as an ideal specimen for in-depth examination and physico-chemical analysis in order to establish baseline conditions and to explain deterioration mechanisms at large. P-47 exhibits almost every deterioration pattern observed at the park. This specimen is also ideal because it was excavated by dynamite blasting and because it is situated at the centre of an unsheltered excavated depression. A conservation treatment program, and lab tested, focuses on mechanical pinning to address large scale loss and detachment.

2.0 Literature Review

The first funded paleontological survey west of the Mississippi was in 1849 by David Doyle Owen, followed by the F.V. Hayden Survey of 1874 where Charles Peale described a variety of paleontological finds including the subject silicified tree stumps at Florissant Fossil Beds National Monument (FLFO).[1] King and Wheeler were recording paleontology before these more famous expeditions.[2] Since the late 19th century the paleontological resources at FLFO have been identified as possessing great scientific value and scenic touristic values by McChristal and Leopold and Meyer.[3] The site and its petrified tree stumps rank among the world's great paleontological resources, and it is currently counted among nearly two dozen National Parks whose enabling legislation specifically identifies them as a Paleopark.[4]

Paleontological resources in the NPS, including fossil forests, have been enshrined as national monuments as early as 1906 (Petrified Forest National Park was designated by Theodore Roosevelt through the Antiquities Act, 1906). Petrified wood and fossil forests as a resource type have been identified and studied as a unique resource type since before the NPS was founded.[5]

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1 Peale, 1874; Fodd & Kirkland, 2009
2 Meyer, Personal Communication, 2016.
3 Peale, 1874; Scudder, 1881; Helprin, 1896; McChristal,1994; & Leopold & Meyer, 2012.
4 McGintie, 1953; United States of America's Committee on Interior and Insular Affairs, 1969; Meyer, 2003; & Santucci, 2009.
5 Knowlton, 1914 & Lucas et. al., 2006.

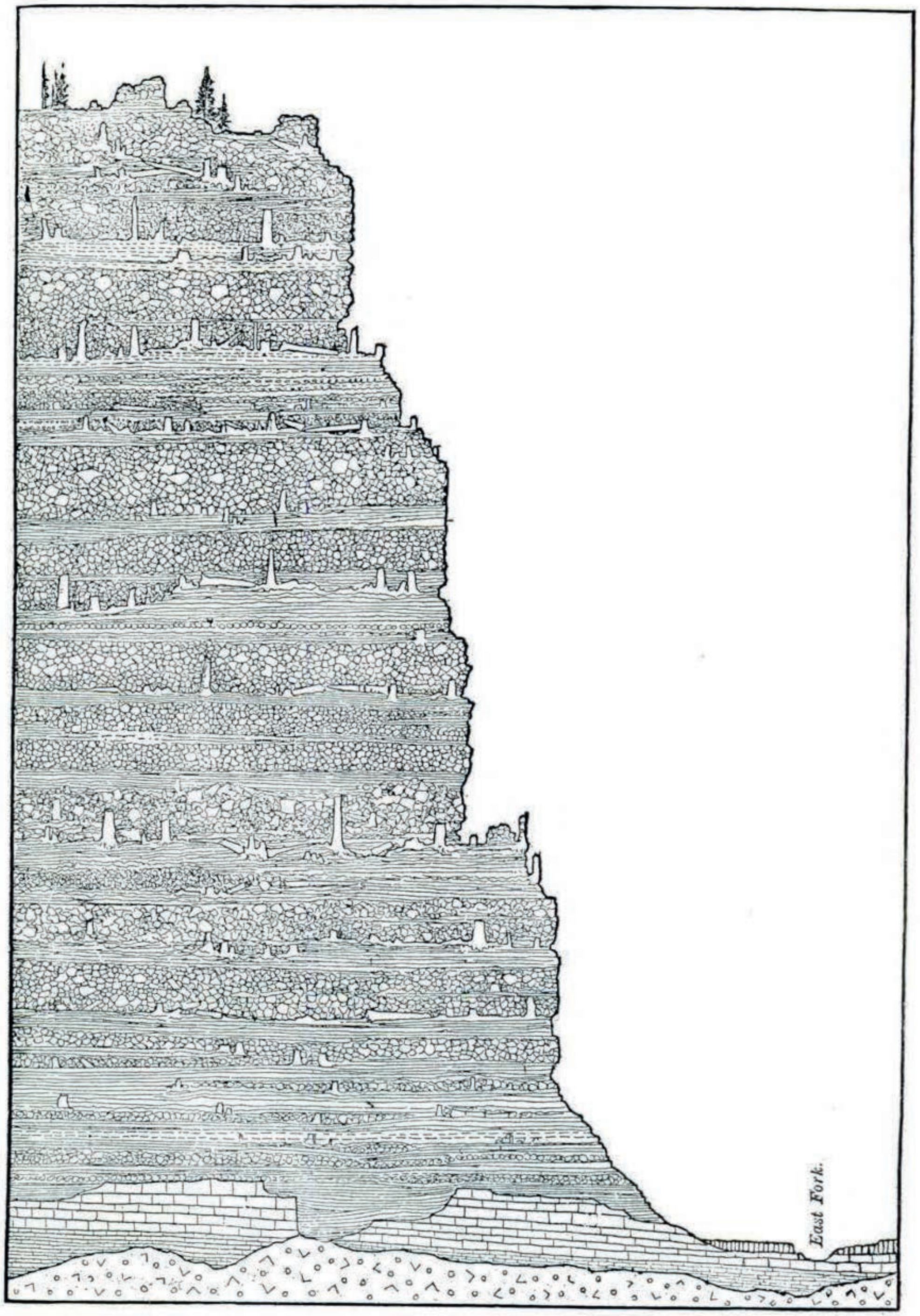

FIG. 4.—IDEAL SECTION THROUGH 2,000 FEET OF BEDS OF SPECIMEN RIDGE, SHOWING SUCCESSION OF BURIED FOREST. AFTER HOLMES.

Figure 2.1: Stratigraphy of successive fossil forests from Knowlton's publication, "The Fossil Forests of the Yellowstone National Park." (Source: Knowlton, 1914)

Since then, the incorporation of paleontologists into regular NPS park management has been growing, and more than 258 NPS sites have been identified as having paleontological resources.[6] Since 1992 four paleontological research volumes (significant NPS funded or written papers about paleontological resources from their sites, 1992-1999), conference proceedings from the 3rd to the 10th Federal Fossil Conference (1992-2014), and a regular Paleopark newsletter (1998-2004) were published by the NPS.[7] However, the most significant publications on FLFO are a focused monograph by the Geological Society of America, a Denver Museum of Nature and Science publication, and works associated with FLFO park paleontologist Dr. Herb Meyer.[8]

There has been no technical conservation literature published by the NPS on *in situ* conservation of paleontological resources, and almost none researched by its employees, with exception of the efforts associated with Dr. Meyer.[9] Of side note is a BLM subject-site poster about a conservation treatment at George W. Lund forest in Nevada, designed and performed by a paleontologist without conservation training.[10] In recent years, there has been an international movement for parks with similar resources to connect with each other and share their case-study conservation problems and solutions.[11] In 2009 there was a special

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6 Ibid.; NPS, 2016.
7 Ibid.
8 GSA, 2008; *Proceedings of the Denver Museum of Nature & Science, 2001;* & Meyer 2003, 2008, & 2011.
9 Young, 2004, Young et. al. 2008, & Meyer, 2011.
10 Erwin et. al, 2006.
11 Meyer, *Connecting Geoheritage Sites Having Common Assets: Links between Petrified Forests in Colorado, Peru, and Thailand*, 2016.

publication specifically on the management and conservation of Paleoparks based on contributions from the 32nd International Geological Congress and the 2nd International Paleontological Congress in 2004 & 2006 respectively.[12] A forthcoming publication by Meyer addresses FLFO as a case study of the challenges presenting the conservation and management of paleoheritage resources (Meyer, 2017).

A baseline understanding of FLFO silicified stump mineralogy was established by George Mustoe where he was principal investigator with an NPS permit, and this was published in the Geological Society of America's special monograph on Florissant Fossil Beds National Monument (2008).[13] In this monograph another article of significance to this research was the Young, Meyer, & Mustoe's study of the deterioration and conservation treatment tests for FLFO silicified stumps.[14] This understanding is significant because it informs the assessment of stump pathology and subsequent conservation treatment design. Geochemical studies of fossil wood silicification pathways have evolved from Buurman's 1972 paper including narratives of linear diagenetic transformations from organic wood -> opal-A -> opal-CT -> chalcedony to Mustoe's assertion, in his study of FLFO stumps, that these minerals can individually be directly nucleated without requiring the aforementioned linear phase transformation.[15]

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12 Lipps & Granier, 2009.
13 Mustoe, 2008.
14 Mustoe, 2008 & Young et. al., 2008.
15 Buurman, 1972; Leo & Barghoorn, 1976; Sigleo, 1978; Scurfield, 1979; & Mustoe 2008.

Literature discussing the peculiar processes of tree taphonomy and diagenesis is useful to establish causative reasons for deterioration patterns of FLFO stumps. It is now commonly understood that silicification proceeds along a multitude of pathways, including secondary, tertiary, etc., mineralisations as the fossilised plant material becomes part of the geological record and geochemically responds to its changing environment.[16] The findings of a team of Japanese researchers placing a fresh log into a siliceous hot-spring for ten years concluded that complete permineralisation and organic replacement could create perfect petrification on the order of tens to hundreds of years, quite a difference from previous researcher conclusions of timespans requiring tens or millions of years.[17] However, siliceous hot springs are very unique geochemical environments and the exception as opposed to a general rule. Understanding the taphonomy in combination with the historical record of the site and stone conservation literature surrounding the effects of blasting and jointing is integral to current conditions assessment and understanding of FLFO stump material integrity.[18]

[16] Daniels & Dayvault, 2006; Viney, 2008; & Mustoe, 2015.
[17] Hisatada et. al, 2004.
[18] Winkler, pp80-83, 2013 & Leopold & Meyer, 2012.

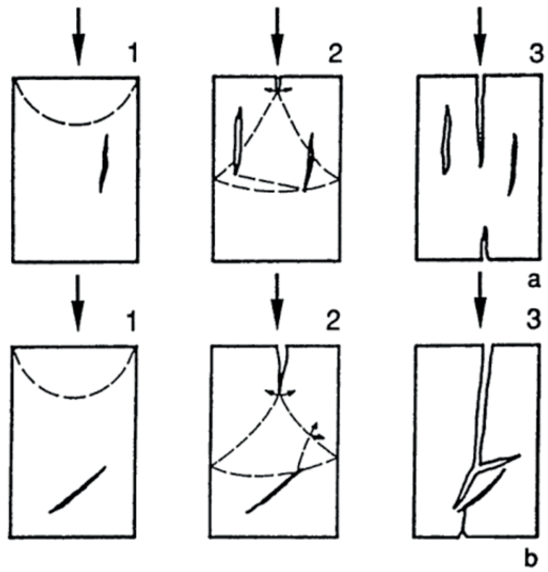

Fig. 3.23. Direction of shockwaves. Opening of fractures by an advancing blast wave. **a** Shock-wave encounter runs parallel to fracture; **b** shock-wave encounter runs at an angle of near 45°. (Mueller 1964)

Figure 2.2: Consideration of the effects of blasting on stone. *(Source: Winkler, 2013)*

Because there is little to no technical literature available on the conservation of fossil wood, the author has taken an interdisciplinary approach, researching geotechnical engineering, architectural stone conservation, materials testing standards, and sculpture conservation. These sources have been compiled into a bibliography of salient literature for a testing program that could evaluate the efficacy of mechanical pinning of detached and incipient fragments that compromise the integrity of the petrified tree stumps at FLFO. For instance, geotechnical engineering literature routinely assesses, categorizes, and treats highly fractured rock masses that are reminiscent of the poor fossil stump rock quality at FLFO, however their solutions are very aggressive and contrary to site values.[19] A variety of ASTM tests relate to the evaluation of mechanical pinning treatments, including pullout tests, three-point bending, compression, shear, petrography, water absorption, vapour transmission, and accelerated weathering that have been adapted from masonry and concrete testing. In addition, international standards are available from organizations such as the International Society of Rock Mechanics (ISRM), RILEM, and ASTM. Adhesives and pins used in a mechanical test can be made from a variety of well-developed selection matrices, catalogues, and conservation treatment testing programs.[20] The field of architectural stone conservation is focused on treatments that aesthetically merge structural solutions for *in situ* stone resources, minimizing visual detractions.[21] In the evaluation of fracture reinforcement, sculpture conservators have used engineering simulation software such as finite element analysis as predictive analysis of the mechanical behavior of pinning treatments.[22]

The lack of research or publication on the topic of *in situ* conservation of paleontological resources, including the sub-set typology of fossil wood, suggests it is a vastly under researched and under serviced resource type. Many questions remain unanswered, such as:

1) What are the mechanisms of deterioration that operate on different types of fossil wood?

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[19] Hoek, 2016.
[20] Glavan, 2004; Federico, 2008; Horie, 2013; & Wheeler et. al. 2016.
[21] Ashurst & Dimes, 1998; Winkler, 2013; Henry & Odgers, 2012.
[22] Wheeler et. al., 2016.

2) While it is well known and acknowledged that there is a wide array of incomplete, partial, and total silicification, can we turn this into useful description or classification of fossil wood to more rapidly assess their unique forms of deterioration?
3) What simple environmental controls can be utilized to slow rates of deterioration at open unprotected sites?
4) Could a standard identification, or grouping, of characteristics of material performance collated in a matrix of potential conservation treatments or approaches allow international literature to be of greater use to the conservator and paleontologist? For instance, one of the sole academic resources available on the conservation of silicified wood is from a Greek fossil forest.[23] But how comparable is that climate and material that is "perfect petrification," to FLFO? A system of classification, a silicification profile based on the intrinsic and extrinsic stress and material make up, could be useful to understand these differences for comparative reasons.[24]
5) If such a standard were possible, could it help a researcher more easily interpret the context and findings in relation to their own resource's unique petrification status?
6) How would conservation treatments such as consolidation affect the scientific value (e.g., composition) of fossilized wood?
7) What is the role of accessory minerals such as iron oxides and relict organics in petrified wood decay processes.

[23] Zouros, 2003 & Kyriazi & Zouros, 2011.
[24] Ibid.

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3.0 Site Description

Florissant Fossil Beds National Monument, hereinafter referred to as Florissant or FLFO, is located in a high mountain valley about half a mile south of Florissant, Colorado. The monument is located west of Pikes Peak and 35 miles west of Colorado Springs, Colorado (Figure 3.1). The site is 6,278 acres, principally covering the Florissant Valley.[25] FLFO's recently built visitor complex (2012) houses an interpretive center and paleontological research laboratory. Older buildings nearby provide for the maintenance staff and serve as an archive.

[25] United States of America's Committee on Energy and Natural Resources, pp.1-6, 2016.

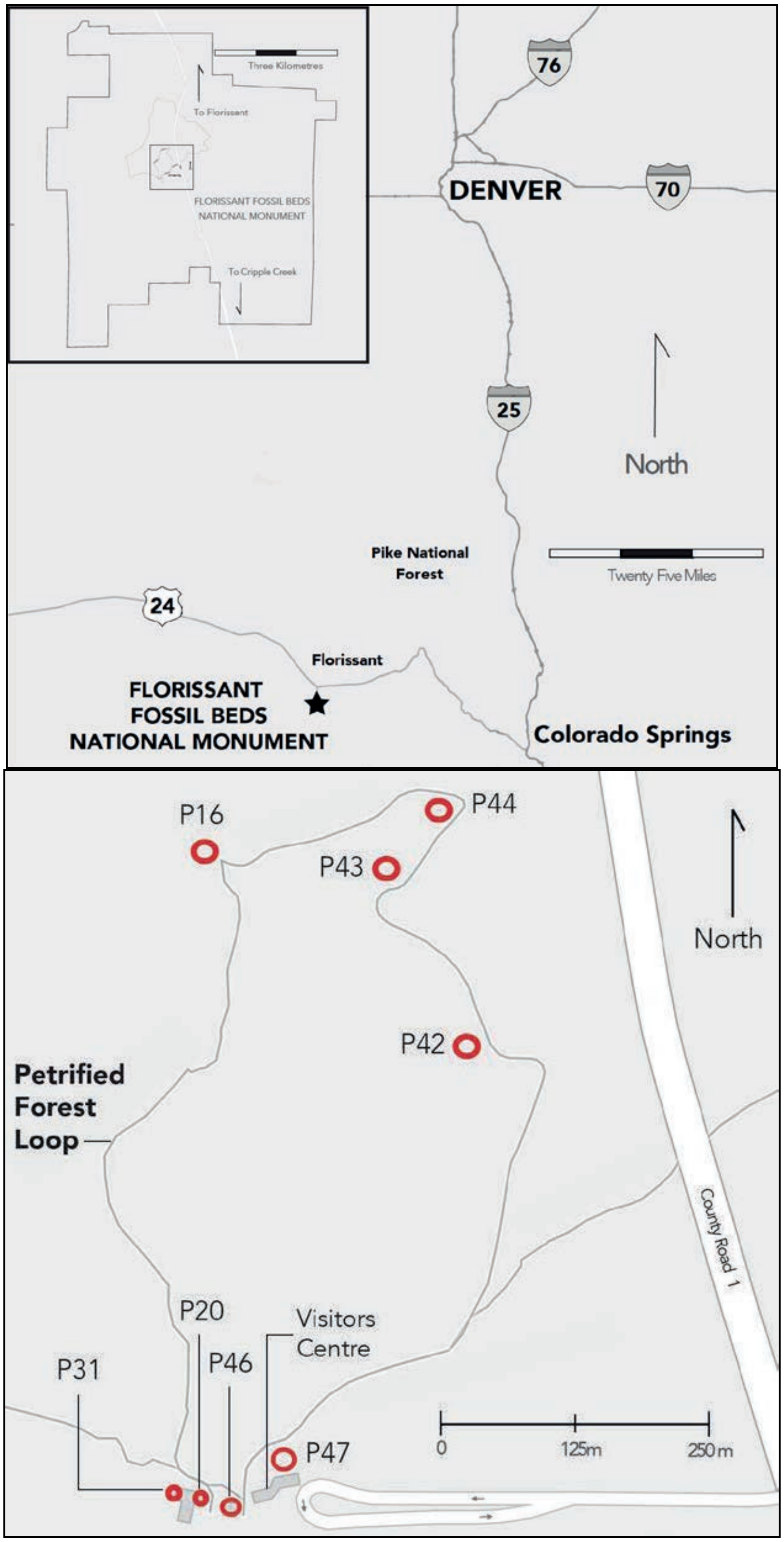

Figure 3.1: Regional FLFO locator map on top, and petrified forest loop on bottom. (Source: Author, 2016)

3.1 Climate

At an elevation of approximately 8500 feet, FLFO has a dry and cool mountain environment, identifiable by ASHRAE as climate zone 5B.[26] In 2007, recorded by Young *et al* (2008), an environmental monitoring device recorded 119 freeze-thaw cycles on the surface of an exposed petrified stump, and 95 cycles on the surface of a stump protected by a roof shelter over a cold period of 289 days.[27] Despite a 50 year linear trend of a -0.7° Celsius temperature drop at FLFO, climate change projections predict a low-high range increase between 1.6° – 5.1° Celsius over the next century. Higher temperatures will probably be accompanied by a projected 4-7% precipitation increase.[28] Looking into the future, Monahan & Fisichelli's comprehensive revision of climate projections for all NPS units (2014) suggests that there will likely be an increase in acute weather events such as cold snaps, drought, storm surge, extreme heat, and floods.[29]

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[26] Climate Zone 5B is described by *ASHRAE 169-2006* with IP Units 5400 < HDD65ºF ≤ 7200 and SI Units 3000 < HDD18ºC ≤ 4000. United States Department of Energy, 2017 & OpenEI, 2016.
[27] Young *et. al.*, 2008, pp. 141.
[28] Gonzalez, 2014, p 1.
[29] NPS, 2014 & Monahan & Fisichelli, 2014.

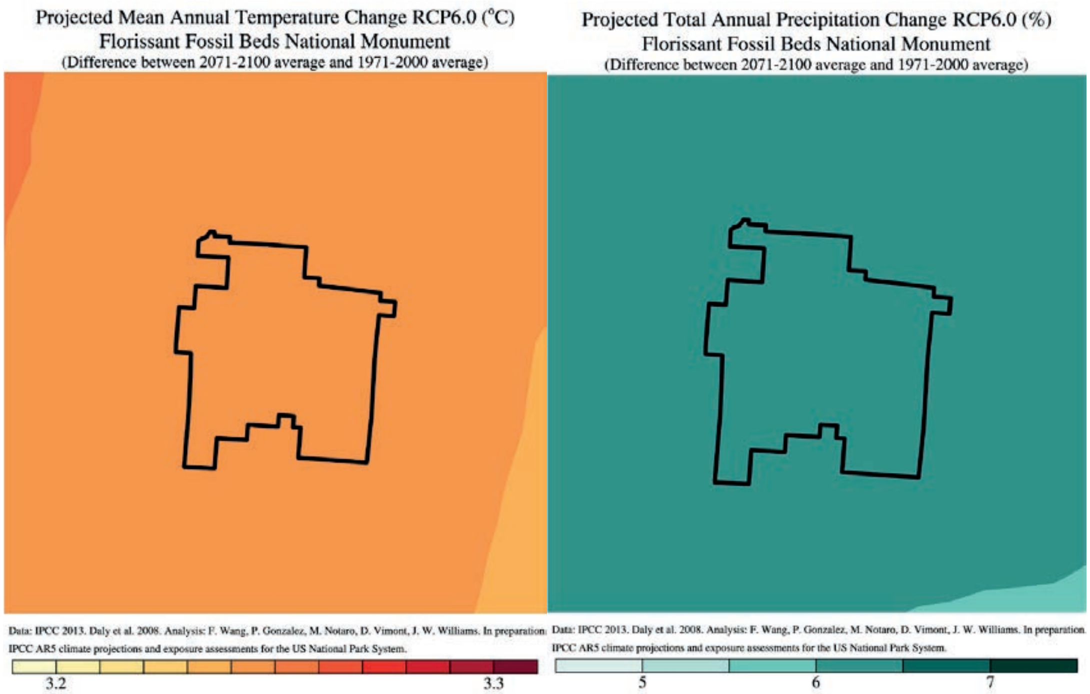

Figure 3.2: Predicted temperature change on left in absolute values (~3.25ºC) and projected precipitation increase in relative values (~6.25%) on right. (Source: Gonzalez, 2014)

3.2 Local Geology

The contemporary geography of the monument has been defined by four major geological formations: [30]

1) Pre-Cambrian Pikes Peak Granite: ~1.08 Ba,
2) Wall Mountain Tuff Formation: ~36.7Ma, a Rhyolitic welded tuff, or ignimbrite, originating from a caldera over 80 kilometres west of Florissant. Lithogenesis is described as originating in "instantaneous, catastrophic eruptions that send off an incandescent cloud of pyroclastic ash, crystals, volcanic glass, and rock fragments suspended in gasses superheated to more than 700° Celsius."[31]
3) Thirtynine Mile Andesite: Ashfalls, lava flows, domes, and lahars followed the Mountain Tuff Formation originating from a volcano field 16 kilometres west of Florissant. Its pyroclastic material was responsible for the first iteration of the paleolake eponymously named Florissant.
4) Florissant Formation: ~34.7 Ma, informally subdivided into six units of shale, pumice, conglomerate, and lahar deposits. Volcanic ash & its weathered form as clay provided abundant silica for diatoms and was interlayered by these biogenetic sediments. At least two lacustrine periods are known, previous

[30] Evanoff, 2001, pp 1-17. & Meyer et. al., 2004, pp. 154-155.
[31] Foos & Hannibal, 1999.

> iterations being either breached by lahar or in-filled by sedimentation, burying the subject stumps, to create an alluvial valley. Pyroclastic material originated from the Guffey volcanic centre 16 kilometres to the southwest of Florissant.

The subsequent Quarternary deposits have not been fully studied, but likely over time there has been a complex sequence of various erosional, alluvial, lacustrine, fluvial, and eolian sedimentations. The local stratigraphy is visible throughout the paleovalley, providing visitors with tangible views of past geological processes.[32]

[32] Evanoff, 2001, pp 1-17. & Keller, 2006, pp 3-4.

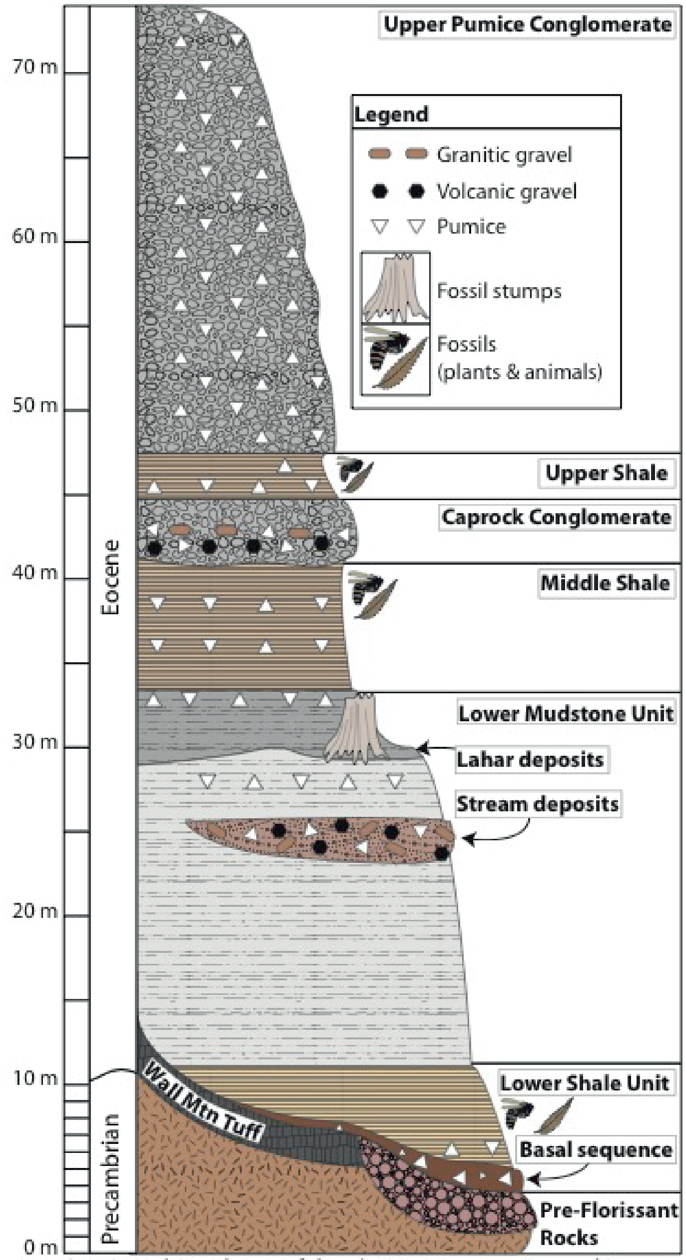

Figure 3.3: Geological stratigraphy at Florissant can be described as a layering of volcanic materials, conglomerations, lacustrine sedimentations, and erosional depositions. (Source: NPS, 2017)

The site's primary value lies in its geological heritage but includes some historically built resources.

3.3 Florissant Fossil Forest Taphonomy & Paleobotany

As part of the geological record, the stumps at Florissant have undergone biological decay, changing pressures of weight, a series of mineralisations, and seismic events. Taphonomy is the subsection of Paleobiology that studies this transmutation of the biological into the lithosphere. It is concerned with, "processes between death, decay, decomposition, transportation and burial."[33] This field is critical to understanding FLFO's stumps because the history of this diagenetic transformation, and the events that passed during its voyage through geological timespans help explain silicified wood performance and pathologies, fossil weathering processes being determined by stump taphonomy. This story begins near the end of the Eocene-epoch, (55.8-33.9 Ma), at the Oligocene boundary, in the Florissant Fossil Formation (See Appendix A).[34]

H.D. MacGinitie's classic, *Fossil plants of the Florissant beds, Colorado* published in 1953, provides the first conclusive evidence that the fossil plants, including the fossil stumps, dated to the Eocene-epoch.[35] Considering the global geological timeline, the continental arrangement during the Eocene was relatively similar to today, but the paleoclimate was radically different. CO_2 levels have been inferred at six times the current level and global mean average temperatures were on average 25°-30° Celsius.[36]

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33 Cadée, 1991.

34 Dates of geological time periods are based on the International Commission on Stratigraphy's International Chronostratigraphic Chart: International Commission on Stratigraphy, 2016.

35 This was established through plant and fragmented mammal fossils. Past interpretations variously supported Pliocene, Miocene, Oligocene, or Eocene time periods. MacGinitie, 1953; Evanoff, 2001; & Keller, 2006.

36 Cirbus, 1994 & UCMP, 2017.

Even the global poles were essentially ice free; at Axel Heiberg and Ellesmere Island in the extreme north of the Canadian Arctic there were forests of *Metasequoia* over 80 feet tall.[37] This warm wet climate allowed *Sequoia affinis*, an analogue of the contemporary coastal redwood, *Sequoia sempervirens,* and Giant Sequoia of the Sierra Nevada, *Sequoiodendron giganteum*, to flourish in what is now a dry and cold climate in central Colorado.

Eocene epoch Colorado was volcanically active, being near the chronological end of the uplift of the Rockies, a part of a wider process known as the Laramide orogeny (See Appendix A for the International Chronostratigraphic Chart).[38] The paleoelevation of Florissant during the growth of the *Sequoia affinis* forest is still debated; for instance MacGinitie's estimates in 1953 of 300-900 metres have been superseded with suggestions, based on leaf physiognomy and lapse rates, between 1700-4100 metres.[39] Nevertheless, based on annual tree ring growth the forest was growing in much more favourable conditions than either present day *Sequoia sempervirens* or *Sequoiadendron giganteum*.[40]

The nearby Guffy volcano sent multiple lahars into what was then the Florissant Valley, and one of these pyroclastic mudflows encased the *Sequoia affinis* trunks in siliceous material. The energy of this event was significant. Lahars are capable of moving at speeds of 100km/h, and can reach boiling temperatures.[41] In 1995, the entire

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[37] Williams, et. al., 2003; & Dr. David R. Vann, Personal Communication, 2017.
[38] USGS, 2017 & Johnson & Evanoff, 2001.
[39] Johnson & Evanoff, 2001
[40] Gregory-Wodzicki, 2001.
[41] USGS, 2017.

village of Nevado del Ruiz in Armero, Colombia, with over 20,000 people, was destroyed by the destructive forces of one such lahar. Contemporary Sequoia have been recorded as often sprouting roots higher up their trunks to avoid being oxygen starved after mudslides, suggesting the magnitude of trauma these trunks suffered. Lahar impact and the abrasion related to flow could have caused structural damage to stump wood like cracks and fissures. The exposed *Sequoia* treetop presumably broke and rotted away. It has been noted by paleobotanist Elizabeth Wheeler that there is no remnant bark on the stumps, likely a function of the abrasive scouring by the lahar.[42] What could be wood decay at the cellular level is confirmed visually by petrographic analysis of FLFO wood, general cellular distortion can also be attributed to the pressures of burial.[43]

[42] Personal conversation with Dr. Herbert Meyer who explained some of Dr. Elisabeth Wheeler's paleodendro findings. Florissant Fossil Beds National Monument. Meyer, Personal Communication, 2 November 2016.

[43] Mustoe, 2008, pp. 135-136 & Fearon, 2016.

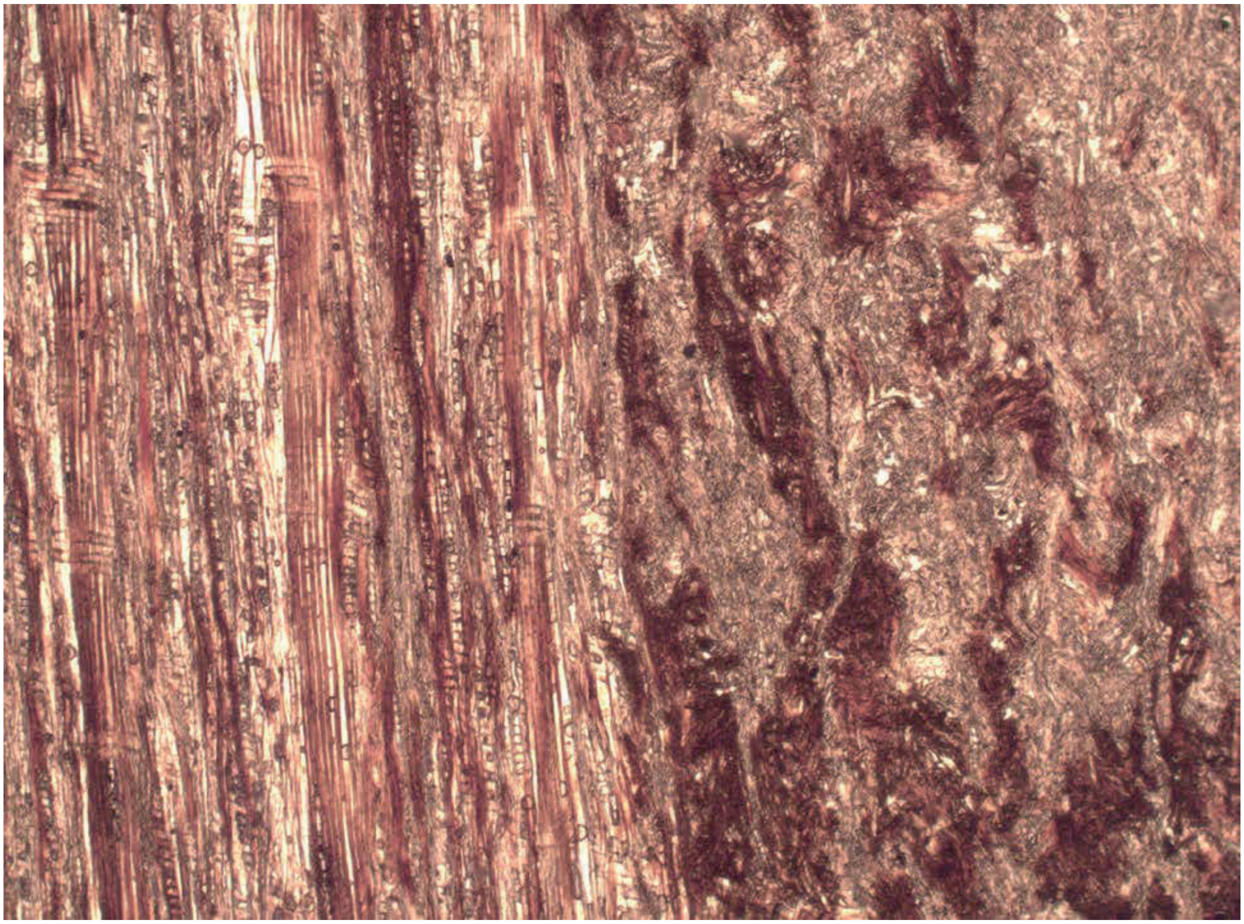

Figure 3.4: Radial view of FLFO wood. What might be spalted or pocket rot occurs on the right as opposed to healthy radial wood at left. Sample U1_R viewed in Plane Polarized Light at 50x. (Source: Author, 2017)

Petrographic analysis of the fossil wood in different orientations exhibits distorted wood cells, sometimes torn and fragmented, and very similar to that of fungal attack in modern wood.[44] Subsequent cycles of lacustrine submerging and desiccation could have caused organic materials to alternately rot and silicify.[45]

Studies of Mt.Rainier's post-explosion landscape offer analogues and comparison in understanding the destructive capacity of this type of geological phenomenon. The Electron Mudflow, circa 1400CE, buried a comparably sized Douglas Fir, *Pseudotsuga*

[44] Phenomenon of distorted wood cellular structure first noted at FLFO by Michael Arct, although he did not posit possible reasons: Arct, 1982.

[45] Evanoff, 2001, pp 1-17. & Meyer et. al., 2004, pp. 154-155.

menziesii, 30' in circumference at breast height in a similar depth of 20' of material. Discovered and excavated in association with a development in 1993, it was determined that the post-event water table submerged the wood in an anaerobic environment, which isolated it from bacterial and fungal decay.[46] Given enough time and the correct geochemical environment it is possible that this stump would have undergone diagenetic silicification similar to FLFO wood.

Figure 3.5: Excavated Douglas Fir Stump, buried by a lahar stemming from Mt. Rainer, visible in the background. This photos shows the stump plucked out from its deep burial location. (Source: Pringle, 2007)

3.4 Taxonomy

The stumps at Florissant, were first described by Lesquereux in 1876 as *Sequoia affinis* based on cones and foliage alone,[47] *and* renamed *Sequoioxylon pearsalli* by H.N.

[46] Pringle, Patrick & Scott, Kevin, 2001.
[47] Lesquereux, 1876 & Knowlton, 1916.

Andrews in 1936 based on the wood.[48] MacGinitite synonymised these names. The suffix –*oxylon* means '-bearing an affinity to' any preceding subject, in this instance the *Sequoia* genus, or sub-family *Sequoioideae*. 35 million years of evolution has probably created many differences between *Sequoia affinis* and the sole survivor of the *Sequoia* genus, *Sequoia sempervirens.* Differences described by MacGinitie includes thinner foliage flattened into branch axis, appressed, and female cones that are 50-70% the size of contemporary *Sequoia*. Meyer has postulated that *Sequoia affinis* could be ancestral to both the coastal redwood, *Sequoia sempervirens,* and the Sierra Nevada's Giant Sequoia, *Sequoiadendron giganteum*.[49]

[48] Andrews, 1936.
[49] Meyer, pp. 75-87, 2003.

Figure 3.6: Branches from Sequoia affinis, #3547 University of California Museum of Paleontology. (Source: UCMP Research Associate Harry D. MacGinitie, 1953)

Sequoia sempervirens, commonly known as coastal redwood or redwood, are the tallest trees on earth, reputedly reaching up to 131 metres in height, but more commonly known to range from 67-91 metres.[50] As a structural building material, redwood, a softwood, has been described as, "Light, soft, and close-grained [...] easy to split."[51] Through microscopy its wood can be identified in comparison to other softwoods in section, because of its diagnostic features of:[52]

1) Abrupt early to latewood transition.

[50] Hough, 2007, 176.
[51] Hough, 2007, 176.
[52] Hoadley, 1990, pp. 17, 19, 22, 80, 143, & 162-164.

2) Up to four bordered pits in early wood radial walls.

3) Abundant and diffuse longitudinal parenchyma with smooth-nodular end walls.

4) Absent resin canals & fusiform rays.

5) Tracheid diameter of 50-80µm.

6) Large, "textbook," cross-field pitting of Taxodid form in radial section.

7) Coarse and open pore texture in cross-section.

8) Widest uniseriate rays among conifers, these are isodiametric (generally square), sometimes exhibiting 2-3 seriate rays.

The resolution of silicified cellular anatomy at FLFO is very detailed and can be seen with a compound microscope. The taxodid bordered pits that sequoias are known for are templated with detailed resolution, and can be viewed at higher magnifications in radial section. Cross-field pitting can also be seen (See Figure 3.7). While Redwood is famously known to be rot resistant, it is not as high performing as lesser known species like Black locust, Osage-orange, Red mulberry, or Yew for instance.[53] Furthermore, there are specific fungal pathologies that are known to affect Redwood that are exhibited as a type of spalted wood, commonly known as a pocket rot.[54] In Redwood, this can take the form of cubical cross-breaks and might be an intrinsic reason for specific FLFO conditions (Site Survey, Section 5.0, stump P31 basal erosion).

[53] Hoadley, 2007, p 60.
[54] Hoadley, 2007, p 61.

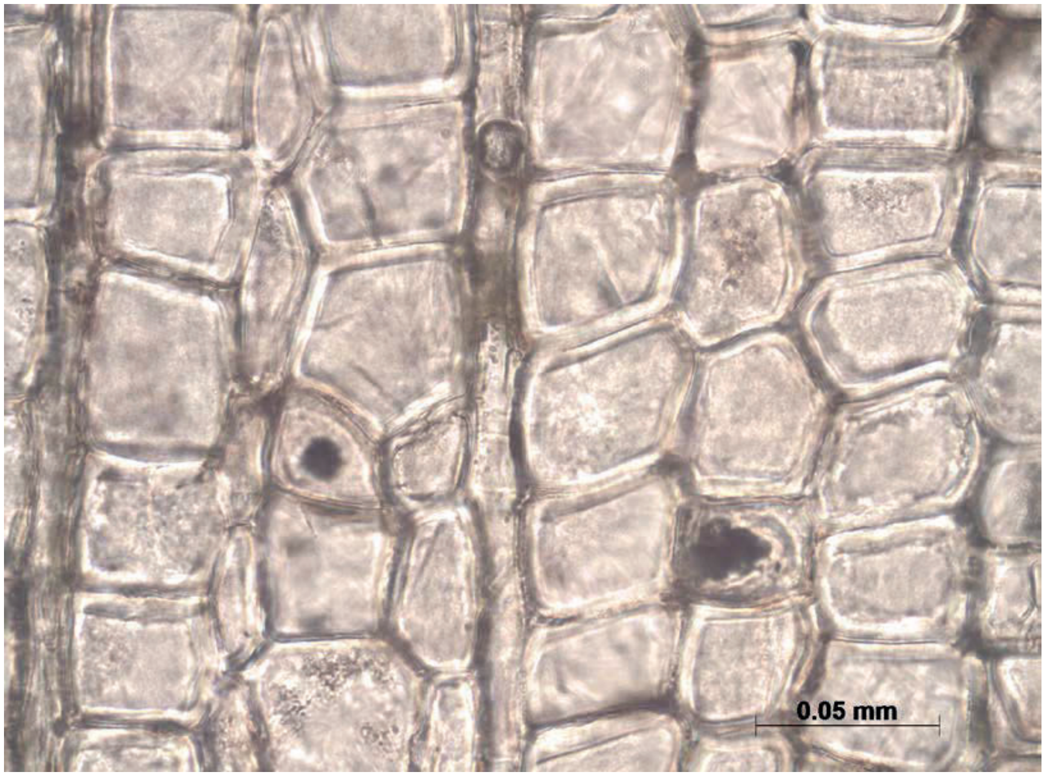

Figure 3.7: Resolution of FLFO cellular detail of tracheid double cell walls, lumen, in transverse grain. Viewed in Plane Polarized Light at 400x magnification, Sample U1_R
(Source: Author, 2017)

3.5 Florissant Fossil Stumps in the Historical Record

> *I must admit that congress in its infinite wisdom has not seen fit to pass legislation protecting fossil beds in general. However, if someone had found the original Constitution of the United States buried on his land and then wanted to use it to mop a stain on the floor, is there any doubt they could be restrained?*[55] *–Victor Yannacone*

The following section is a brief sketch of the human occupied time-period at FLFO. McChristal (1994), Meyer (2003), and Leopold & Meyer (2012) offer more detailed histories than presented here.[56] Little is known about the prehistory of the area except that the Uncompahgre Utes, also known as the Tabeguache, were the most dominant tribe in the Florissant Valley during early European/American colonist

[55] Leopold & Meyer, 2012. p. 60.
[56] McChristal, 1994 & Leopold & Meyer, 2012.

settlement of the area. Culturally modified trees bear witness to their inhabitance of the region, confirming that the Uncompahgre likely knew about Florissant fossil wood.[57] The Homesteaders Act of 1862 was a watershed moment in the settlement of the American West, spurring new populations, and native dispossession, of the Florissant Valley.

In 1867, the *Rocky Mountain News* alluded to silicified wood near Florissant, but the first specific historical record mentioning the Florissant stumps dates to 1869,

> *Mr. N.H. Rice has placed us under obligation to him for a large fragment from the remarkable petrified stump west of Pikes Peak. Although imperishable stone, it yet retains its woody fibre and appearance. The stump is 14 feet in diameter. There are many other petrifactions in the same neighborhood.*[58]

A local newspaper, the *Daily City Central Register*, in 1871, described "a petrified forest near which are found, between sedimentary layers, beautiful imprints." By 1876, the area must have been widely known to locals, as A.C. Peale, member of the Hayden Survey, relates, "one mile south of Florissant, at the base of a small hill of sandstone, capped with conglomerate, are 20 or 30 stumps of silicified wood. This locality has been called 'Petrified Stumps' by the people in the vicinity. The specimens of wood are not particularly good."[59] As early as 1876, landowners of the Big Stump (P-16) Adam & Charlotte Hill explored the idea of sending the stump to the Centennial Exhibition in Philadelphia.[60] The Hill's listed their occupation as specimen collectors in an 1880

[57] McChristal, 1994, p.2-3.
[58] McChristal, 1994, p 3.
[59] Peale, 1874, pp 193-273.
[60] Leopold & Meyer, 2012, 10.

census, confirming the acceptability of the use of fossil curiosities as a consumable economic resource.

Figure 3.8: Broken saw blade left in place circa 1880. (Source: Author, 2017)

Estimated over 60 tons, specimen P16 had scaffold erected around it in 1880 to cut the stump into more manageable sections to send to the Columbian Exhibition of 1893 in Chicago. This attempt failed because of the difficulties of sawing the hard lithified stump. In addition, narrow train tunnels could not accommodate the wide size of the stump.[61] Evidence of these efforts remain visible with rusted saw blades still stuck in place. However, the site was also busy with palaeontologists who were happy to work with locals for Florissant's more famous resource, its shale beds laden with high quality fossils. In the 1880s the palaeontologist Samuel Scudder famously discovered over 600 new species of insects alone.[62] Working with the Hills, he described the stumps in 1881 as:

> ...*huge, upright trunks, standing as they grew, which are reported to have been five or six meters high at the advent of the present residents of the region. Piecemeal they have been destroyed by vandal tourists, until now not one of them rises more than a meter above the surface of the ground, and many of them are entirely leveled; but their huge size is attested by the relics, the largest of which can be seen to have been three or four meters in diameter.*[63]

Although these heights are suspicious, and unconfirmed, the early problems of pilfering by residents, tourists, collectors, and scientists were rampant. It was even recorded that professors from Colorado College took Florissant wood by the wagonload.[64] Further commercialisation of paleontological resources expanded when the Colorado Midland Rail established a station at Florissant in 1887, further enabling tourists to take shale-split fossils from trains originating from Colorado Springs. Photos confirm tourists clambering on top of the Big Stump using the remnants of that scaffolding for access.

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[61] Leopold & Meyer, 2012, 10.
[62] Leopold & Meyer, 2012, p XXIII.
[63] Scudder, 1881, pp 283-284.
[64] Leopold & Meyer, 2012, p 10.

Figure 3.9: Touristic display and visitation circa 1890. (Source: FLFO Archive Still Image Collection – S1B1, 1890)

The site's value was acknowledged by many early on, and cries for preservation were heard in 1892 in a local newspaper:

> The oldest settlers thereabout remembered that 20 years ago there were 20 of these petrified trunks standing erect beside numerous petrified logs lying over the found. All have been removed by tourists and relic hunters until now one of the greatest and rarest natural curiosities of the world has been despoiled. The trunks and logs have been sawed up and broken to pieces and taken East...[65]

The wasteful collection by tourists was identified by the famous fossil collector Theodore Cockerell, writing in 1916 that,

> It is very unfortunate that inexperienced collectors throw away many valuable specimens, looking only for conspicuous ones, while from time to time very fine things are preserved by the non-scientific as curiosities and are eventually broken or lost [...] in spite of the richness of the field it is

[65] The Creedle Candle, 2/10/1893, as quoted in McChristal, 1994, p 6.

> impossible to have any assurance that species so represented will ever be found again [...] To lose or destroy them is like removing a brick from some splendid building; the building will not fall, but the offense is intolerable.[66]

Earlier, in 1908, he had valorised the Florissant area as a "Miocene Pompeii," comparing the resolution of Roman life embodied at Pompeii to Florissant's fossilisation of Eocene-Oligocene life.[67]

Figure 3.10: Tourists and fossil collectors taking advantage of the Midland Rail stop at the Florissant fossil-laden shale beds. (Source: Colorado Historical Society, 1900)

Later in the 20th century, private ownership, collection, excavation, and display began new stump weathering processes. However, despite private ownership, the fate of FLFO sharply contrasts with the unfortunate case of Cycad National Monument

66 T.D.A. Cockerell, "Colorado a Million Years Ago." American Museum Journal. 1916. 16, no. 7. pp420-450., as quoted in Leopold & Meyer, 2012, p. 6.

67 Leopold & Meyer, 2012, p XX.

(1922-1957), which was withdrawn as a NPS resource unit because vandals stole or destroyed every visible remain. John Coplen, brother of Charlette Hill, purchased the land associated with the Big Stump in 1883, selling it in 1927 to Palmer and Agnes Singer. The site name changed from Coplen Petrified Forest to the Colorado Petrified Forest. These families exploited the tourist potential of their land, and their facilities included a lodge with a petrified tree fireplace, display cases of collected fossils, and had an ancillary function as a dude ranch.

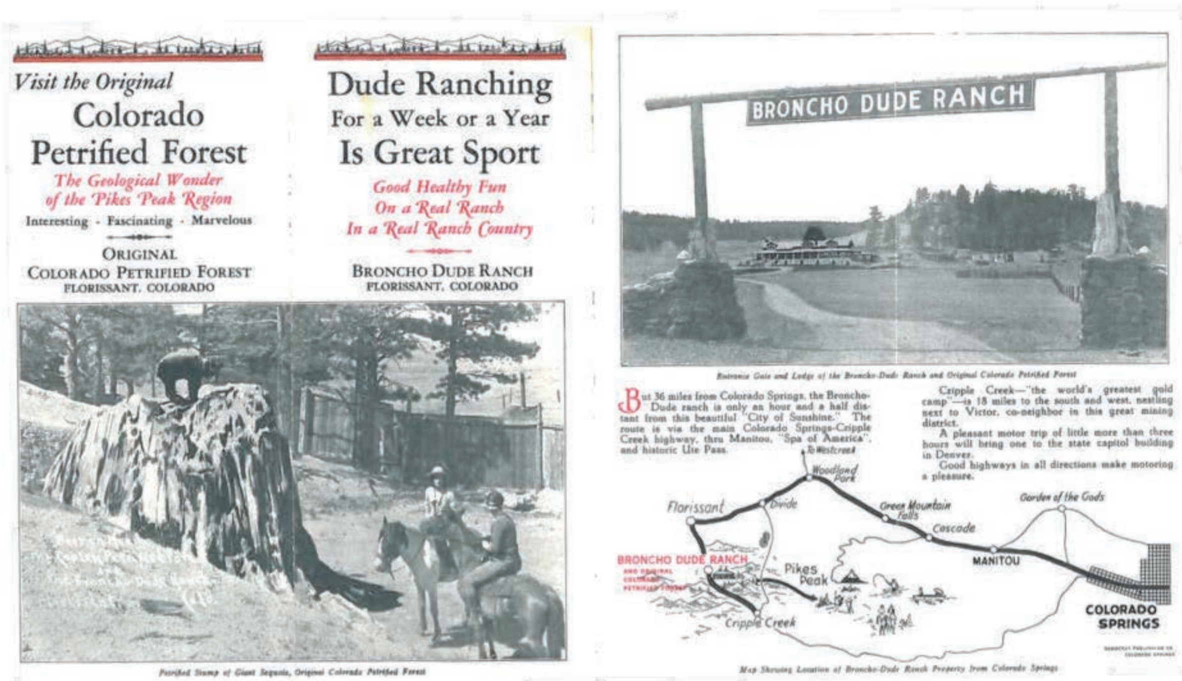


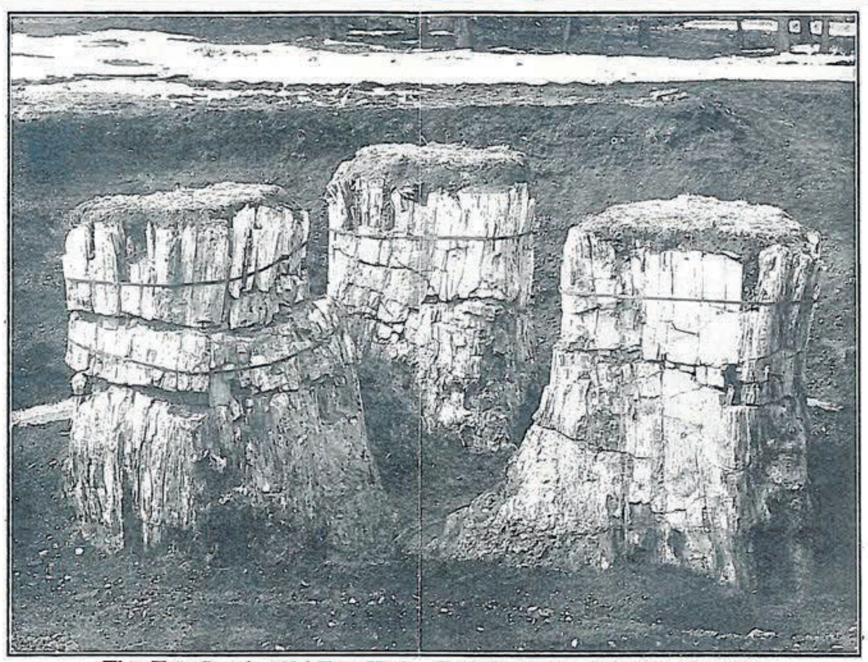
Figure 3.11: Brochure for early 20th Century Tourism at the Bronco Dude Ranch and Colorado Petrified Forest. (Source: Colorado Historical Society, 1900)

In 1918 the Cripple Creek Touring Company uncovered three large stumps, perhaps in response to dwindling tourist drawing resources, but also to compete with the income generating tourist attraction that Coplen had developed.[68] There is an old farmer saying in Lancashire, England that the most profitable crop to raise is "bricks

68 Leopold & Meyer, 2012, p 12.

and mortar," but in this part of rural Central Colorado it was sometimes the presentation of the curiosities of natural history. These stumps were speculatively curated in 1922 by property owners David and Ira Henderson on land to the south of the Coplen Petrified Forest and Big Stump and developed what would become the competing tourist attraction named the New, then Henderson, and finally Pike Petrified Forest. Their efforts were rewarded with the highlights 'Trio' P20, P31, P46, & P47.

This group stands 5 feet high—diameter 5 feet—about 5 feet apart



This Trio Stands 13½ Feet High. Each Sprout Is 6 Feet in Diameter.
Diameter of Trio at Base, 27 Feet. Only Petrified Trio in the U. S.

Figure 3.12: P20 Trio on the left recently excavated in the 1920s, and further excavated by the 1950s on the right. (Source: FLFO Archives, 1920s & 1950s)

These are very dramatic stumps, one over 4.1 metres in diameter, and the Trio being a clone with three trunks like no other in the world. It has been anecdotally noted that dynamite was used during the excavations, and while there is insufficient archival evidence to confirm this it correlates to their unique pathologies.[69] John Baker bought the land from Hendersons in the 1950s, and a feud began with the Singers. Baker strongly felt that the Singers had an unfair advantage of being the first roadway entrance south of Florissant. A series of entranceway reconfigurations ensued, culminating in Baker spreading nails on the Singers driveway. Baker received a gunshot to the stomach from the Singers and he was lucky to escape with his life.[70]

Figure 3.13: Walt and Lillian Disney with FLFO stump at Frontierland circa 1950. (Source: The Gazette, 1950s)

69 Leopold & Meyer, 2012, p. 13. In personal conversation Dr. Herbert Meyer recollects seeing a letter confirming this in the FLFO archive from someone who knew the Hendersons.
70 Meyer, Personal Communication, 2016.

Private ownership to protect petrified wood was pragmatic at best, and it did not stop Hollywood producer Walt Disney from purchasing a large stump for $1,650 from Baker in 1956 while on holiday at the extravagant Broadmoor Hotel at the base of Pikes Peak near Colorado Springs. He had the eight foot petrified stump shipped to California as a present to his wife Lillian Disney. Lillian didn't like the stump in her garden and it ended up in Disneyland in front of a short-lived natural history exhibit named Mineral Hall. This five ton stump remains on display in Frontierland today.[71]

In the Summer of 1969 the Colorado state court in Denver heard one of the first strictly environmental legal cases. Relations were heated between the Defenders of Florissant, Inc. and real estate developers wishing to turn the valley with its enormous collection of fossils into a housing development.[72] There is no doubt that the primary source of heritage value at FLFO is its paleontological resources, and for this reason the lawyer Victor Yannacone argued that to bulldoze Florissant fossil lands would be akin to, "using the rosetta stone for grinding corn."[73]

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71 Leopold & Meyer, p. 14, 2012.
72 Ibid., p XVIIIII.
73 Ibid., p. XXVI.

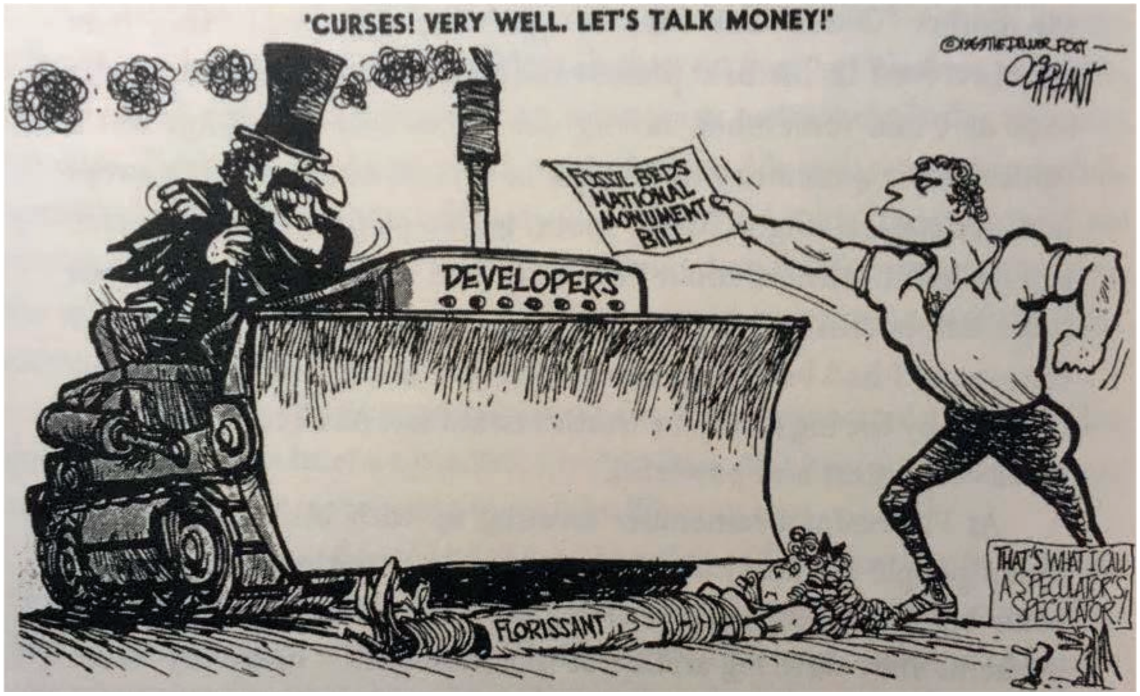

Figure 3.14: A depiction of the battle between the Defenders of Florissant from the newspapers at the moment of the National Monument bill. (Source: Pat Oliphant's cartoon in Leopold & Meyer, 2012)

This lively legal representative of the Defenders of Florissant, made numerous similar hyperbolic comparisons, also suggesting that housing developments on Florissant would be equal to allowing the "dead sea scrolls to be used to wrap fish."[74] Private interests ultimately lost this legal battle, and Florissant Fossil Beds National Monument was officially enacted in 1969.[75]

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74 Ibid., p XXI.

75 United States of America's Committee on Energy and Natural Resources, 1969, pp. 1-5.

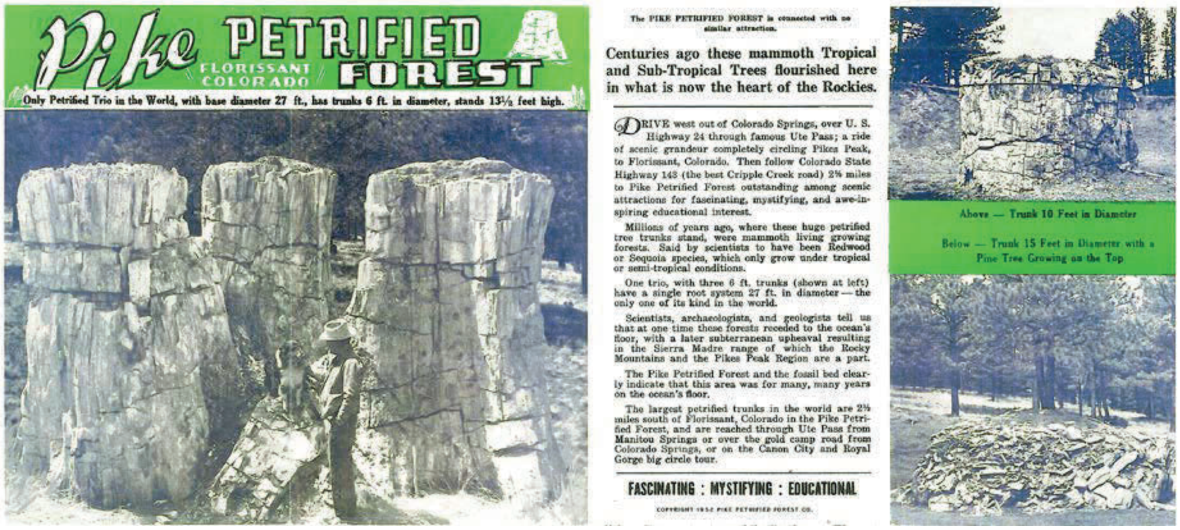

Figure 3.15: Pike Petrified Forest tourist brochure. (Source: NPS Archives, 1950s)

Over time, touristic display at the Pike Petrified Forest, and with NPS control, involved various podiums and walkways, including two different podiums directly on top of P46, and later the NPS crater walkway named the "Then And Now Trail" from the 1970s.

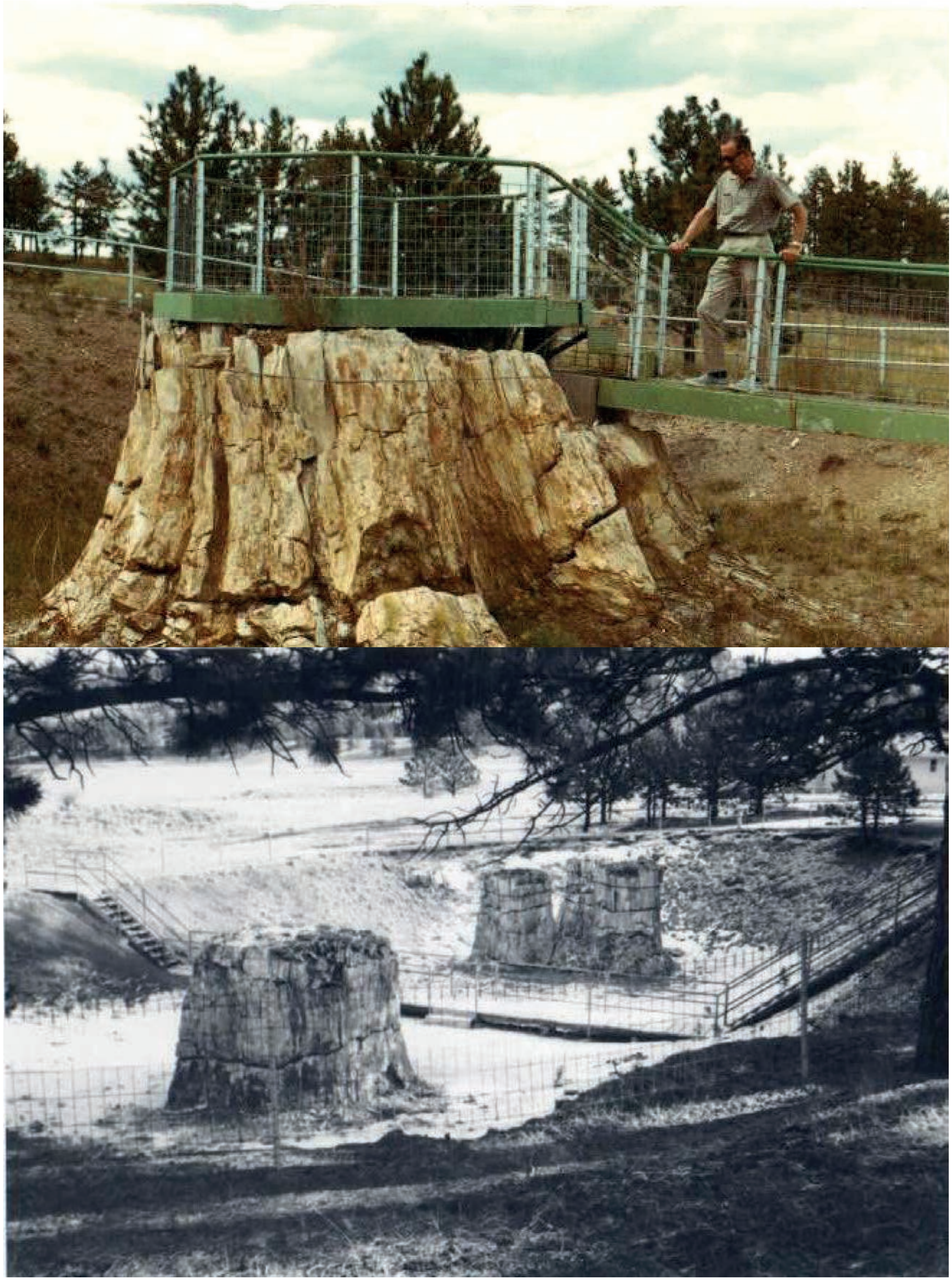

Figure 3.16: Second iteration of a stump top podium on P46, top, first was wood. The NPS Then and Now Trail between P20 & P31, photograph taken in 1978, below. (Source: FLFO Archives, 1963 & 1978)

In the late 1990s the most vulnerable stumps, those excavated by dynamite, were enclosed in temporary Yurts until permanent wall less shelters were erected. The old Pike Petrified Forest building became the NPS Visitor Center, which was demolished in 2011 to make way for the contemporary visitor, research, and maintenance complex.[76] Today, FLFO would be considered a cultural landscape, an aggregate of interrelated natural and cultural heritage resources including the National Historic Register listed Adaline Hornbek Homestead dating from 1878, landforms of ditches and terraces dating from 1930s CCC potato farms, and possibly trees scarred from cultural modification by the Utes, and of course its significant paleontological resources. Given the monument's remote location and freedom from light pollution the monument currently operates Night Sky programs in conjunction with the Colorado Springs Astronomical Society (CSAS). FLFO continues its tradition as a site of scientific interest, and excavations occur periodically and specimens are revised or newly described under the leadership of Dr. Herbert Meyer.

[76] Leopold & Meyer, 2012, p. 92.

Figure 3.17: Stump Trio P20 enclosed in temporary Yurts, photograph taken 1997. (Source: NPS Archive, 1997)

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4.0 Silicified Fossil Wood Petrification Processes

Some of the earliest scholarly research on the diagenesis of petrified wood includes descriptions of permineralisation and replacement (or templating).[77] Permineralisation has been described as the infilling of cellular and intercellular space with precipitated, and sometimes colloidal, minerals.[78] Replacement or templating has been described as the attack of existing carbon molecules by silicic acid, and subsequent deposition of new material. Wood petrification has been identified as occurring with over 58 minerals, including hematite, malachite, barite, fluorite, carbonates, sulfates are common, and sometimes even gold and uranium.[79] Some of these specimens are incredibly colourful, lustrous, and highly sought-after by collectors. The majority of global petrified wood is silicified, unsurprising considering that silicon constitutes around 28% of the earth's crust.[80]

The four predominant mineralogical forms of silicified wood at Florissant consist of opal-A, opal-CT, chalcedony, and quartz.[81] All four are part of the silicate mineral class subgroup tectosilicates, also known as framework silicates.[82] Silica precipitation is dependent upon factors of environmental chemistry like temperature, pH, and dissolved Si concentration. For instance, quartz (SiO_4) forms in much lower silica

[77] Iler, 1979, pp. 88-93 & Stein, 1982, p 1277.
[78] Daniels & Dayvault, 2006
[79] Daniels & Dayvault, 2006.
[80] Grotzinger, et. al., p. 9, 2007.
[81] Mustoe, 2008.
[82] Nesse, 2013, pp. 134-139.

concentrations than opal ($SiO_2 \bullet {}_nH_2O$).[83] Scholarship on petrification processes began in earnest in the 1970s, and these early classics describe silicification as following a linear phase transformation processes from opal-A -> opal-CT -> chalcedony -> quartz.[84] It is well documented in nature that this is the typical phase transformation for these minerals.[85] However, Mustoe has demonstrated using stump mineralogy at Florissant that silicification can occur in multiple stages, for instance the direct hydrothermal precipitation of quartz.[86]

4.1 Templating & Permineralisation

Buried wood silicification begins with available soluble silicates in the environment put into solution by water in the form of monomeric silicic acid.[87] This can be expressed chemically as:

$$SiO_2 + 2H_2O = [SiO_x(OH)_{4-2x}]_n$$

The exact type of silicic acid that is formed varies with environmental chemical factors such as temperature, pressure, and pH. Silicic acid enters buried woody tissues by way of natural checks, hollow cores, fractures, and wood pores – and can attack vulnerable remnant cellulose and hydroxylise with lignin OH bonds.[88] During this process it is possible that excess carbon is reduced from wood structure by way of carbon dioxide production.[89] In this scenario, hydrogen bond formation occurs between available

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[83] Mustoe, 2008.
[84] Ibid.
[85] Tucker, 2001.
[86] Mustoe, 2008.
[87] Stein, p. 1277, 1982.
[88] As proposed by Leo & Barghoorn, 1976 & Scurfield, 1979.
[89] Iler, p. 90, 1979.

oxygen in silicic acid and woody tissues. After the initial coating of *SiO_2*, additional silicic acid provides for the necessary conditions of siloxane polymerisation, or silica oxidation. This film formation process is sometimes named templating because of its preservation of histological detail of relict wood anatomy from initial silica coating.

Wood opalisation can follow a process whereby spheres of $SiO_2 \bullet {}_nH_2O$ ranging from 20-50nm in diameter can agglomerate with others to become even larger aggregated spheres. In rare instances, precious opal forms when spheres are packed in a highly ordered manner, but as in FLFO, they are usually packed in a disordered way. The other common form of opal nucleation in petrified wood is opal-CT, which is typified by a disordered interlayering of cristobalite and tridymite. Another process of silicification that can occur separately or concurrent to templating relates to blockages in lumina and intercellular spaces. If wood anatomy of xylem has plumbing as an analogy then silicification can become clogged during silicification. However, stress induced fracture formation can lead to new avenues of further petrification as secondary or tertiary permineralisations, as exhibited in thin-sections from Florissant in section 5.3.3.[90]

[90] Mustoe & Marisa, 2016.

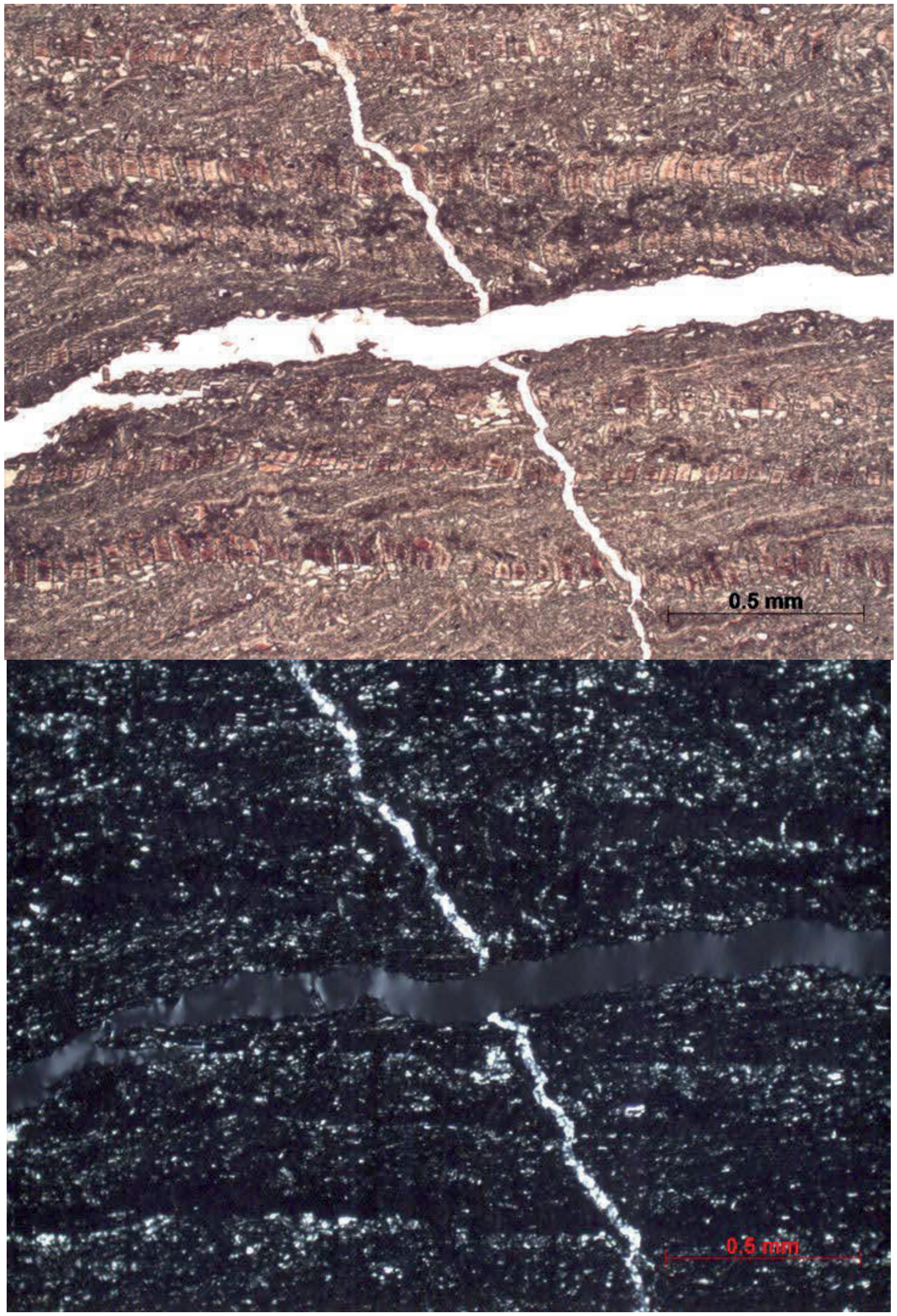

Figure 4.1: Transverse view of detail of microcracks infilled with secondary mineralisation, another avenue of silicification. Viewed at 100x in Plane Polarized Light left and Cross Polarized Light right, sample U1_X (Source: Author, 2017)

4.2 Chemical & Biological Environments During Petrification

Environmental conditions that are necessary for, or modify type and rates of, petrification include:

1) pH
2) Availability of soluble silicates
3) Temperature
4) Aeration
5) Pressure
6) Burial

Not coincidently, these same criteria generally apply to the necessary conditions for biological growth.[91] Some writers have claimed that white rot fungal related deterioration, which decays structural lignin, could be responsible for larger cellular cavities which increase avenues for colloidal silica permineralisation and hydroxyl bonding for templating.[92] However, lignin is much more tenacious than cellulose because of its hydrophobic carbon bonds. Lignin is typically the most durable, the last to be replaced, and never fully eliminated from petrified wood. Post-silicification carbon content of fossil wood can range from 0-20%, although percentages tend to hover around and below 10%, and samples at Florissant were found to have 2.02-2.3% carbon in samples analysed by Mustoe.[93] According to Ralph Iler, carbon possibly recombines with silica to find new forms by way of carbon dioxide.[94] Biological agents like fungal expiration of carbon dioxide or microbes during wood decay could play a

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91 Leo & Barghoorn, p. 4,1976.
92 Jefferson, 1987
93 Mustoe, p. 104, 2016.
94 Leo & Barghoorn, 1976; Iler, pp. 88-91,1979; Mustoe, 2008; Mustoe, 2016.

role. For instance, fungal hyphae are sometimes represented in petrification.[95] Relict carbon is visible in fossil wood at Florissant and is readily identified with its brown colour as demonstrated in Section 5.0.[96]

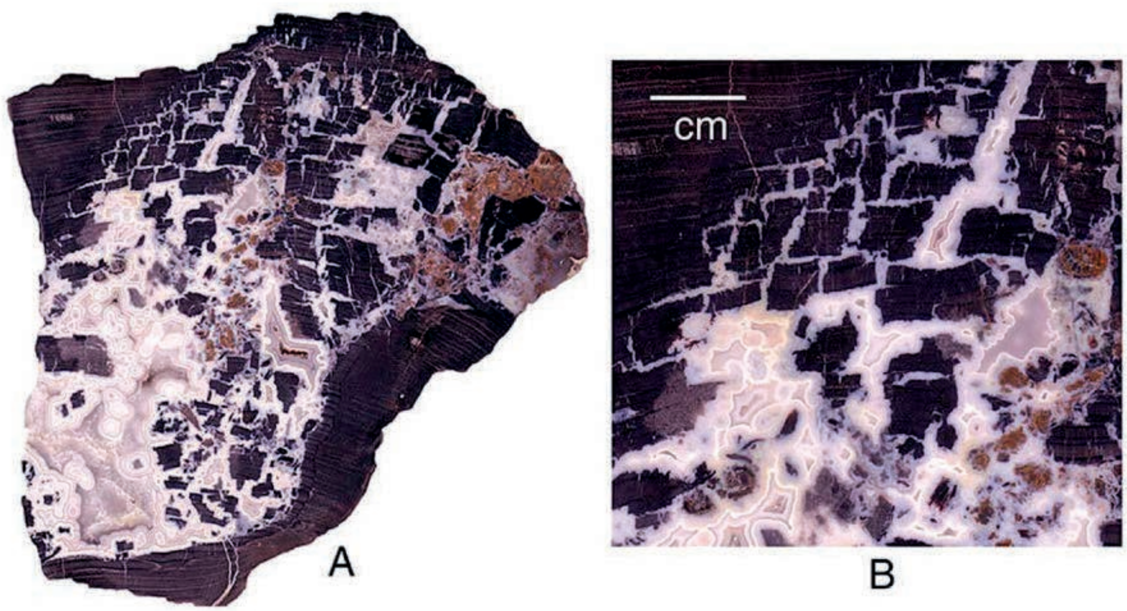

Figure 4.2: Brecciated wood, tabular or cubic form cross-breaking likely a result of fungal decay. This specimen is from Tom Miner Basin, Gallatin County, Montana, and is Eocene Epoch in age. (Source: Mustoe, 2016)

4.3 Rates of Silicification

Not all fossil wood is equally silicified, some are partially silicified and others are in an environment that does not preserve cellular anatomy because of rates of decay and silicification are variable. For instance, some wood can be buried for over 45 million years, such as the case of Axel Heiberg, and never become petrified because of their

---

95 Mustoe, 106, 2016.
96 Mustoe, 2008 & Mustoe, 2016.

physical environment. Other examples include the findings of a team of Japanese researchers who placed a fresh log into a siliceous hot spring for ten years concluding that complete permineralisation and organic replacement could create perfect petrification on the order of tens to hundreds of years.[97] More recent studies of a tree branch from Yellowstone Park also concluded similar results, again quite a difference from researchers who have concluded the necessity of timespans on the order of geological periods for petrification.[98]

Leo & Barghoorn's artificial petrification attempts with ethyl silicates demonstrated that oxidising agents like sulfuric acid can attack and remove organic agents while retaining intact silicified templates; this represents one of the first attempts to view the physical pathways of petrification in relation to wood anatomy. The study of incipient silicification in the case of Yellowstone has demonstrated that wood xylem, its vascular system, is the primary transportation of initial deposition, both templating and permineralisation, while secondary processes follow from wood deterioration such as cracks and fissures.[99]

---

[97] Leo & Barghoorn, 1976; Iler, 1979, p91; Furuno et. al, 1986; Hisatada et. al, 2004; & Viney, 2008. Iler posits that no more than 1mm of silica deposition could occur in 1600 years under conditions of "ordinary temperature".

[98] Hellawel, et. al, 2015.

[99] Hellawel, et. al, 2015.

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5.0 Stump Survey and Material Characterisations

Archival research and site survey were conducted, the latter from 4-7 November 2016. Stump assessment has been significantly informed by Young *et. al.* (2008), where temperature and humidity data was recorded over a winter and microporosity between tracheids was first noted. A glossary of conditions, specimen survey, and a conditions matrix were compiled. Archival research was performed after site familiarisation to inform the survey. The results of this survey, site research, and material characterisation led to the design of the mechanical pinning treatment testing program to follow in Section 6.0. The stump survey is as attached below:

PETRIFIED SEQUOIA STUMP SURVEY
15807 County Road 1, 80816
Florissant Fossil Beds National Monument, Florissant, Colorado
SPONSORED BY AND FUNDING FROM: National Park Service, Florissant Fossil Beds National Monument

Frank Matero - Project Director, University of Pennsylvania
John Hinchman - Project Supervisor, University of Pennsylvania
Evan Oxland - Field Team, University of Pennsylvania

ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

SHEET IDENTIFICATION:
FLFO - CS

SHEET DESCRIPTION:
Cover Sheet

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland
Ariana Miranda

PETRIFIED FOREST LOOP

FLORISSANT FOSSIL BEDS NATIONAL MONUMENT
NATIONAL PARK SERVICE, COLORADO

ARCHITECTURAL CONSERVATION LABORATORY

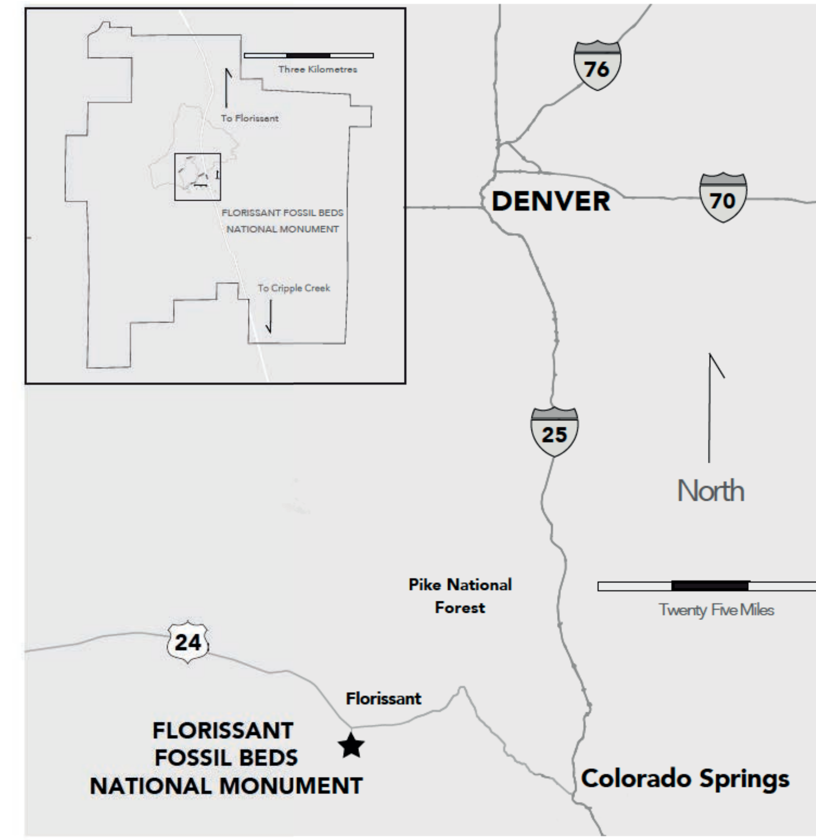
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN
UNIVERSITY OF PENNSYLVANIA

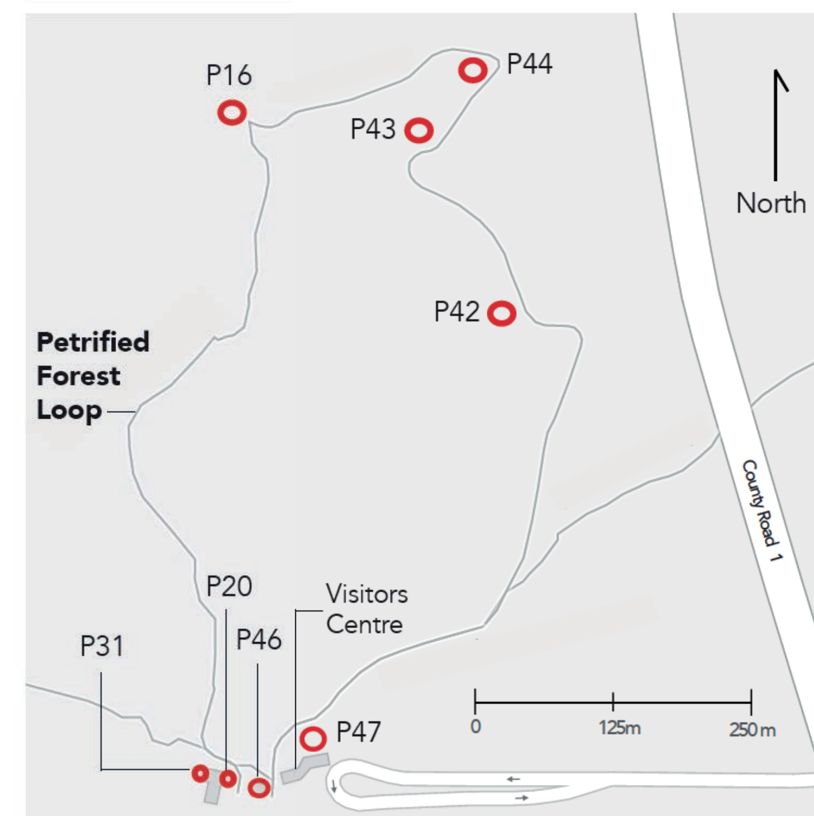
FRANK MATERO, PROJECT DIRECTOR
JOHN HINCHMAN, PROJECT MANAGER
EVAN OXLAND, GRADUATE RESEARCHER

SPONSORED BY:
NATIONAL PARKS SERVICE, DEPARTMENT OF THE INTERIOR & CESCU-CP

NATIONAL PARK SERVICE

PennDesign





Stump Legend:

- Exposed stump in deep excavated pit.
- Partially sheltered stump in deep excavated pit.
- Partially sheltered clone-stump in excavated pit.
- Exposed stump cut into hillside, & subsidence.
- Exposed stump site on gradual grade.
- Low exposed stump in excavated pit.

Drawing Sheet List

CS - Cover Sheet
IG1 - Illustrated Glossary of Conditions
IG2 - Illustrated Glossary of Conditions
P47 - Petrified Sequoia Stump P47
P46 - Petrified Sequoia Stump P46
P20 - Petrified Sequoia Stump P20
P31 - Petrified Sequoia Stump P31
P16 - Petrified Sequoia Stump P16
P44 - Petrified Sequoia Stump P44
P43 - Petrified Sequoia Stump P43
P42 - Petrified Sequoia Stump P42
CM - Conditions Matrix

PETRIFIED SEQUOIA STUMP SURVEY
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SHEET IDENTIFICATION:
FLFO - IG1

SHEET DESCRIPTION:
Illustrated Glossary of Conditions

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland
Ariana Miranda

Horizontal Fracture +3":
Large straight through cracks endemic to P20, P31, & P46, likely a result of both taphonomic processes and excavation by dynamite. Some appear to be the result of secondary mineralisation.

Tabular Cross Checking:
A pattern typically associated with brown rot in wood, it occurs in recognised block-like patterns.

Exfoliation:
A pattern of delamination typically associated with face-bedded masonry, but in partially silicified wood it is likely due to the susceptibility of tangential wood section to freeze-thaw cycling.

Dimensional Loss:
Light coloured blonde, or unweathered, stump fabric is apparent and is evidence of recent material loss - sometimes detached but nearby. Large tabular detachment typically occurs at microcracks, or lines of secondary mineralisation.

Stump Top Disaggregation:
An agglomeration of different deterioration patterns. Fragmentation of stump top materials includes fractures, splintering, exfoliation, fibrous disintegration, microcracking, loss of section, and biocolonisation. These are held together by different deposits and in some cases metal strapping.

Mechanical Damage:
Saw grooves in P16 date back to 1893 and core holes in P46 date to 1989. Grooves and cores can exacerbate deterioration if they provide areas for ice jacking.

Soil Deposit:
Accumulation of aeolian deposits on stump tops and sometimes in hollow stump cores. Can be an agent of deterioration with freeze-thaw cycling.

Lahar Deposit:
Isolated coatings on stump exteriors and substantial deposits in many cores.

Metal Straps:
Ferrous-metal bands and cables dating back to the 1930's, holding detached stump fabric together.

Iron Staining:
Ferrous-metal corrosion, or in isolated instances accessory mineral migration, causes rust stains.

PETRIFIED SEQUOIA STUMP SURVEY

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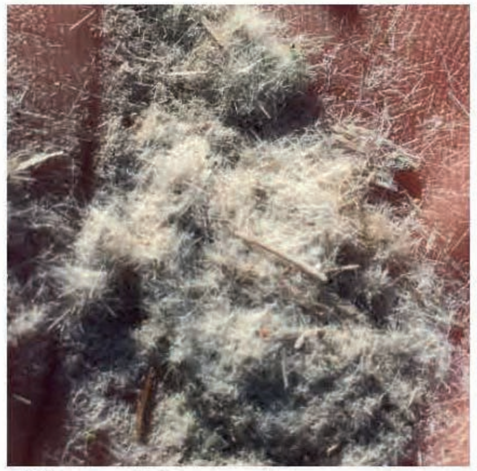
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland
Ariana Miranda

SHEET DESCRIPTION:
Illustrated Glossary of Conditions

SHEET IDENTIFICATION:
FLFO - IG2



Fibrous Disintegration:
Advanced staged splintering results in tracheid dissagregation in the form of petrified fibres.

Microcracks:
Transverse to the longitudinal grain appears to be secondary mineralisation, and is often texturally separate and botryoidal in form. Tabular detachment typically separates on these lines.

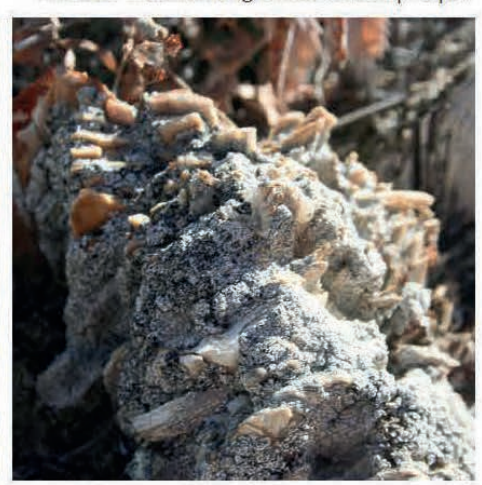
Splintering:
Splintering occurs along annual growth rings and mimics patterns of wood deterioration.

Fracture:
A substantial crack that is not superficial, and deeply penetrates petrified fabric, crossing at least two surface planes. Greatly compromises structural integrity, can be a result of taphonomic processes.

Basal Erosion:
Loss of section specific to the stump at grade. Likely due to deletrious effects of rising damp, freeze-thaw cycling, snow, pooling water, and ice.

Algae:
A green coloured biocolonisation. Usually situated in shade prevalent locations, often the northside of a stump.

Lichens:
A wide variety of biocolonisation, manifesting in a plethora of textures and colours. Often taking hold on stump tops.



Herbaceous Vegetation:
A variety of non-woody plant growth. Usually taking root on stump tops and cores, and surrounding base.

Woody Perrenials:
Perrenial wood producing plant growth, particularly tenacious and destructive. Only varieties like *Rubus Rosa* were noted.

Animals:
Animal burrowing includes birds and small mammals. The photographed stump cavity is an animal's burrow.

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SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland
Ariana Miranda

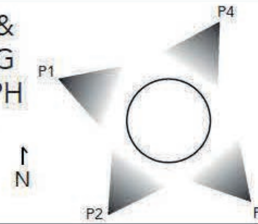
SHEET IDENTIFICATION:
FLFO - P47

SHEET DESCRIPTION:
Stump Profile

BRIEF HISTORY:

P47 is thought to have been excavated around the same time as nearby P20, P31, & P46. In 1922, David and Ira Henderson excavated the Trio, P20, and a few other large stumps nearby. P47 was likely among these, suggesting that P47 has been exposed for 85 years. Anecdotal historic evidence suggests that methods of excavation included the use of dynamite. These specimens became a part of a tourist attraction known as Pikes Petrified Forest, purchased and operated by John Baker in the 1950s. In 1989, Kate Gregory, dug a hole into the core of the stump by shovel, reaching two feet in depth before stopping. This hollow stump core is probably largely filled with recent quatenary top soil deposits. The NPS Inventory & Monitoring program began in 1994, photographs regularly taken since 2004.

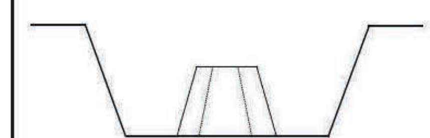
INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT

Splintering, Cracking, Biocolonisation, Hollow Core, Soil Deposit, Loss of Section, Fragmentation, Poor Drainage, & Exfoliation

STUMP SITE SECTION



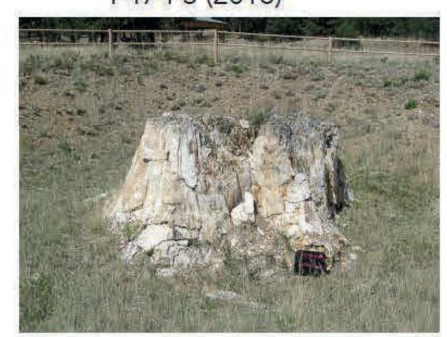
CHARACTERISTICS

Species: *Sequoia affinis*
Height: 6'
Diameter: 10'3"
Circumference: 32'6" Measured @ Stump Base
Mineralogy: Opal & Quartz

P47-P1 (2016)

P47-P2 (2016)

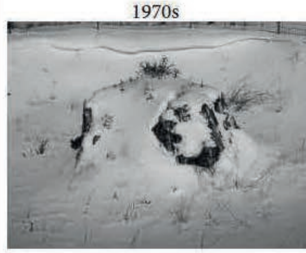
P47-P3 (2016)



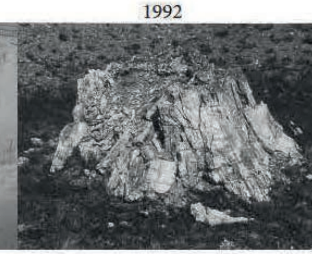
P47-P4 (2016)

P47 - Stump Top (2016)

1970s



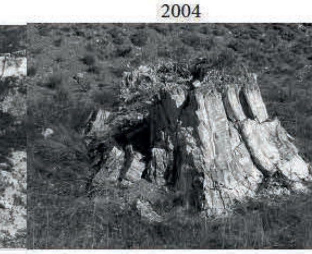
1992



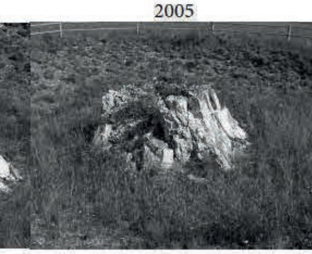
1993

1998

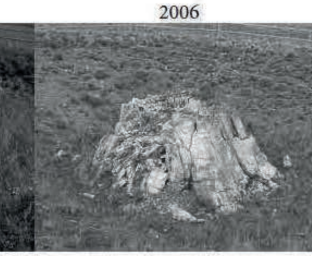
2004



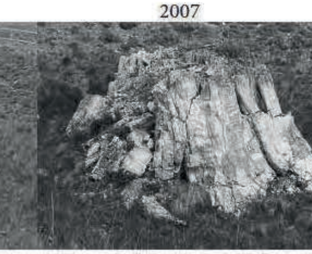
2005



2006

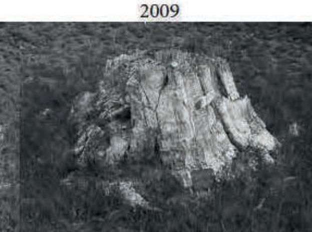


2007



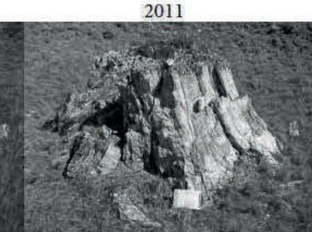
2008

2009

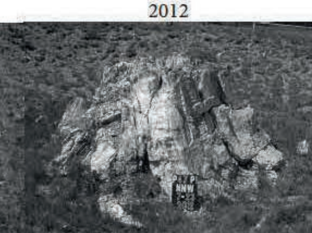


2010

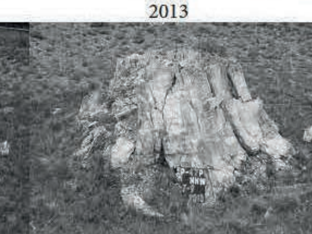
2011



2012

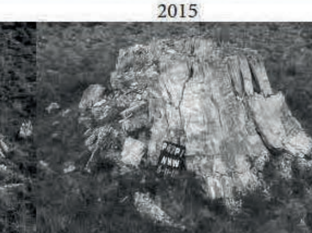


2013



2014

2015



PETRIFIED SEQUOIA STUMP SURVEY

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SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

SHEET IDENTIFICATION:
FLFO - P46

SHEET DESCRIPTION:
Stump Profile

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

BRIEF HISTORY:

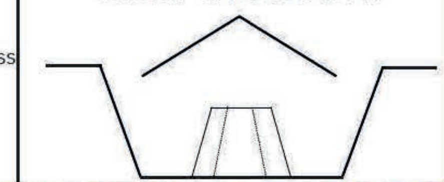
P46 is thought to have been excavated around the same time as nearby P20, P31, & P47. In 1922, David and Ira Henderson excavated the Trio, P20, and a few other large stumps nearby. P46 was likely among these, suggesting that P46 has been exposed for 85 years. Anecdotal historic evidence suggests that methods of excavation included the use of dynamite. In 1989, Kate Gregory, cored a hole into the stump finding "mudflow", either original lahar or subsequent deposit. Photographic evidence shows a fresh timber walkway and platform built on top of the stump in the 1950s and a metal platform in the 1960's which was removed by 1976. Metal cables were initially added to bind the stump top material, and wider banding was added for reinforcement in 2009-2010.

INVENTORY & MONITORING PHOTOGRAPH LOCATIONS

CONDITIONS PRESENT

Splintering, Cracking, Biocolonisation, Hollow Core, Soil Deposit, Loss of Section, Fragmentation, Poor Drainage, & Exfoliation

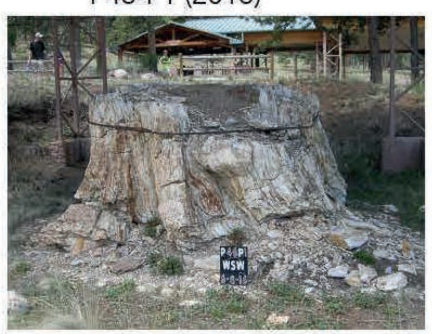
STUMP SITE SECTION



CHARACTERISTICS

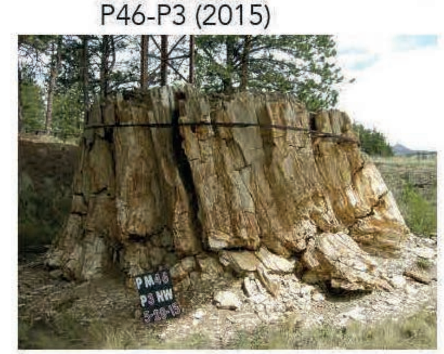
Species: *Sequoia affinis*
Height: 8'
Diameter: 12'
Circumference: 37'6"
Mineralogy: Unknown

P46-P1 (2016)



P46-P2 (2016)

P46-P3 (2015)



P46-P4 (2015)

P46 - Stump Top (2016)

1950s

1955

1965

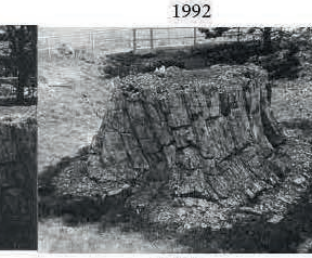
1976

1977

1984

1989

1992

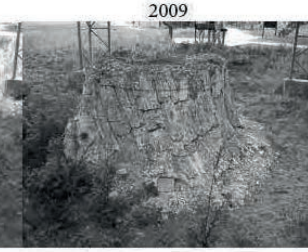


1993

1998

2006

2009



2011

2013

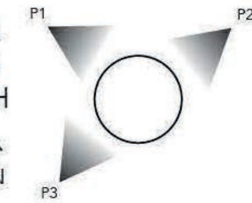
2014

2015

BRIEF HISTORY:

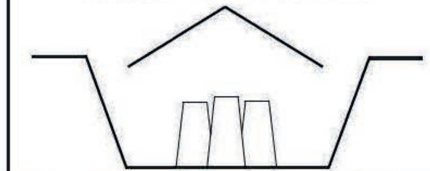
P20 is thought to have been excavated around the same time as nearby P31, P46, & P47. In 1922, David and Ira Henderson excavated the Trio, P20, and a few other large stumps nearby. However, photographic evidence suggests that this may have been staged over a period of years. First excavation did not include metal bands, but they were installed by the1950s. P20 has been exposed for 95 years. Anecdotal historic evidence suggests that methods of excavation included the use of dynamite, which might help explain the magnitude and prevalence of fracturing. This stump was once a larger tree, upon dying it sprouted clones. It is thought to be the only fossilised specimens of their kind in the world. Water and ice pools around the specimen base with precipitation and stump tops often hold snow. A temporary Yurt was erected over the specimen as an enclosure in the 1990s, and a permanent shelter was built by 2002. Metal cables were added to bind the stump top material, and wider banding was added for reinforcement in 2009-2010.

INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:
Splintering, Cracking, Biocolonisation, Hollow Core, Soil Deposit, Loss of Section, Fragmentation, Poor Drainage, & Exfoliation

STUMP SITE SECTION



CHARACTERISTICS:
Species: *Sequoia affinis*
Heights: 9'
Diameters: 6'6"
Circumferences: 20'6"
Mineralogy: Unknown

P20-P1 (2016)

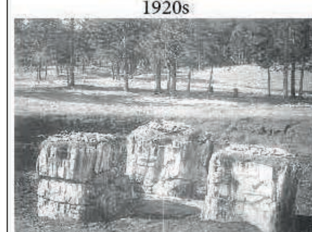
P20-P2 (2016)

P20-P3 (2016)

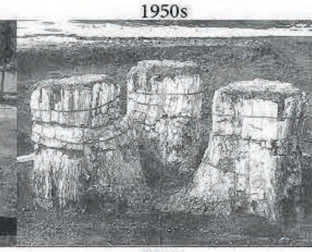
P20 - East (2016)

P20 - Stump Tops (2016)

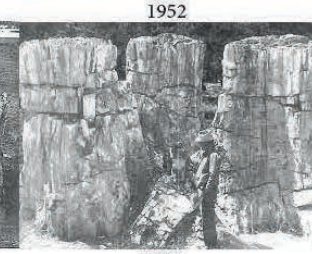
1920s



1950s

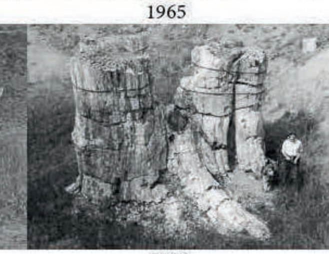


1952

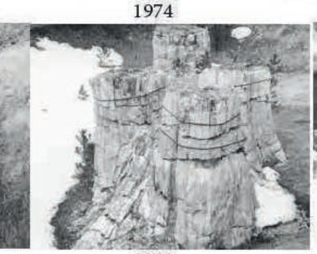


1965

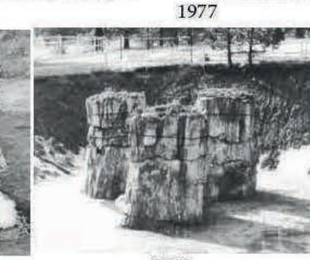
1965



1974



1977

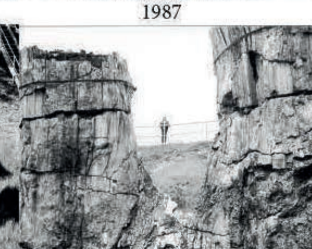


1978

1984

1984

1987



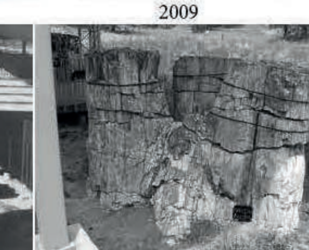
1992

1993

2001

2002

2009



PETRIFIED SEQUOIA STUMP SURVEY
15807 County Road 1, 80816
Florissant Fossil Beds National Monument, Florissant, Colorado
SPONSORED BY AND FUNDING FROM: National Park Service, Florissant Fossil Beds National Monument

Frank Matero - Project Director, University of Pennsylvania
John Hinchman - Project Supervisor, University of Pennsylvania
Evan Oxland - Field Team, University of Pennsylvania

ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

SHEET IDENTIFICATION:
FLFO - P20

SHEET DESCRIPTION:
Stump Profile of the "Trio"

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

PETRIFIED SEQUOIA STUMP SURVEY

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Evan Oxland - Field Team, University of Pennsylvania
ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS: Evan Oxland

SITE RECORDING: Evan Oxland (UPenn), Ariana Miranda (NPS)

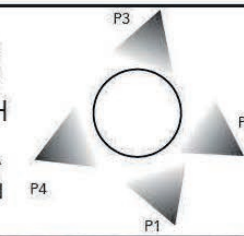
SHEET IDENTIFICATION: FLFO - P31

SHEET DESCRIPTION: Stump Profile

BRIEF HISTORY:

P31 is thought to have been excavated around the same time as nearby P20, P31, P46 & P47. In 1922, David and Ira Henderson excavated the Trio, P20, and a few other large stumps nearby. P31 was likely among these, suggesting that P31 has been exposed for 95 years. Anecdotal historic evidence suggests that methods of excavation included the use of dynamite. Water and ice pools around the specimen base with precipitation and stump tops often hold snow. A temporary Yurt was erected over the specimen as an enclosure in the 1990s, and a permanent shelter was built by 2002. Metal cables were added to bind the stump top material, and wider banding was added for reinforcement in 2009-2010.

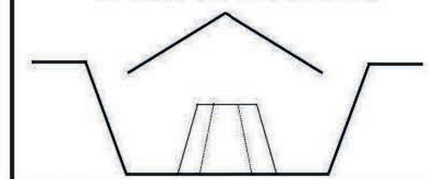
INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:

Splintering, Cracking, Biocolonisation, Hollow Core, Soil Deposit, Loss of Section, Fragmentation, Poor Drainage, & Exfoliation

STUMP SITE SECTION

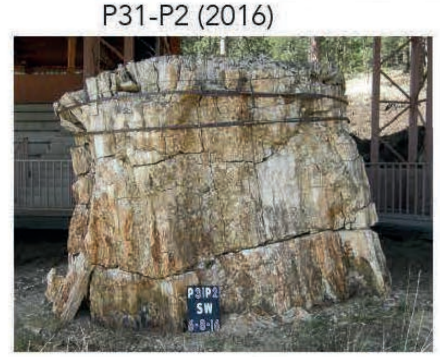


CHARACTERISTICS:

Species: *Sequoia affinis*
Heights: 8'
Diameter: 10'
Circumference: 31'6"
Mineralogy: Unknown

P31-P1 (2016)

P31-P2 (2016)



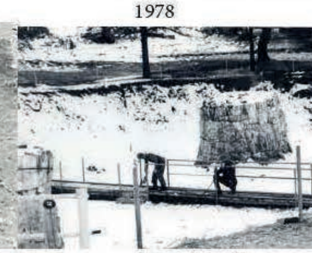
P31-P3 (2016)

P31-P4 (2016)

P31 - Stump Top (2016)

1920s

1978



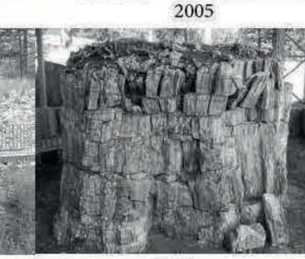
1999

2001

2002

2004

2005



2006

2007

2008

2009

2010

2011

2013

2014

2015

PETRIFIED SEQUOIA STUMP SURVEY

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GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

SHEET IDENTIFICATION:
FLFO - P16

SHEET DESCRIPTION:
Stump Profile of the "Big Stump"

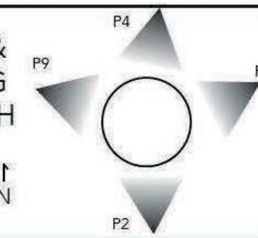
DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

BRIEF HISTORY:

P16 is thought to have been excavated by the 1870s. Adam and Charlotte Hill considered exhibiting the stump at the Centennial Exhibition in Philadelphia in 1876. First managed as a tourist site by John Coplen c.1883 who acquired the property from his sister Charlotte Hill, Coplen attempted to saw the stump into chunks for transport on the Midland Rail to Chicago for the International Columbian Exhibition, but failed. The saw blades and vertical grooves remain. By the 1890s a timber frame was erected around the stump so tourists could clamber overtop. In the 1920s when the Bronco Dude Ranch was operating and a bear was kept on the stump for tourists. This stump was not excavated with dynamite, and is in fair condition.

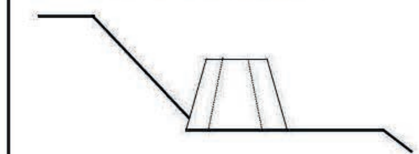
INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:

Splintering, Cracking, Biocolonisation, Hollow Core, Lahar Deposit, Loss of Section, Fragmentation, & Exfoliation

STUMP SITE SECTION

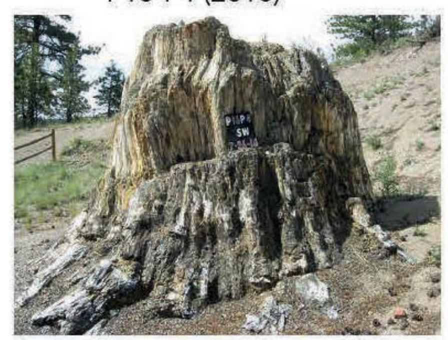


CHARACTERISTICS:

Species: *Sequoia affinis*
Heights: 12'
Diameter: 11'
Circumference: 34'6"
Mineralogy: Opal CT, Quartz, & Organics

P16-P2 (2015)

P16-P4 (2016)



P16-P5 (2016)

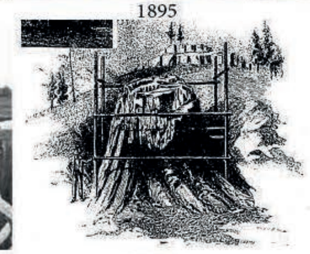
P16-P9 (2015)

P16 - Stump Top (2016)

1890

1893

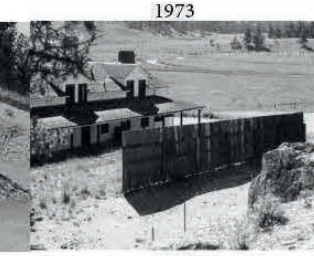
1895



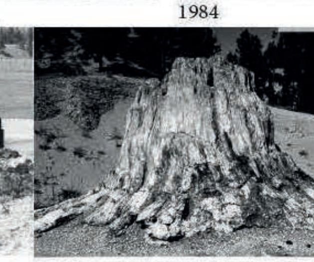
1929

1966

1973



1984



1997

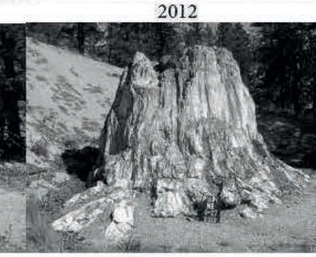
2006

2008

2009

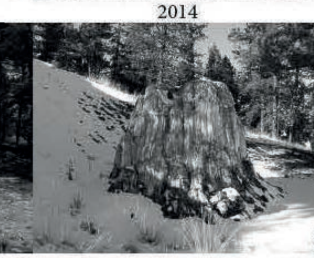
2010

2012

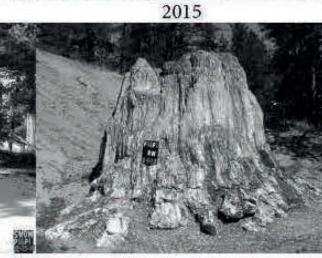


2013

2014



2015



PETRIFIED SEQUOIA STUMP SURVEY

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ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

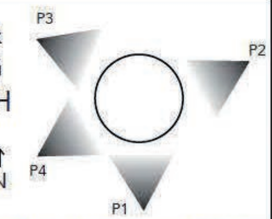
SHEET DESCRIPTION:
Stump Profile

SHEET IDENTIFICATION:
FLFO - P44

BRIEF HISTORY:

P44 was excavated by the Coplen's sometime in the 1920s, and appears to have been showcased by the 1930s based on photographic evidence. At this time there was a ladder so that visitors could enter the pit to view the stump. It is unknown when this stump was backfilled. There is no evidence of substantial lahar deposit. Drainage is excellent, but biocolonisation needs to be planned and monitored.

INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:

Splintering, Tabular Checking, Cracking, Biocolonisation, Missing Features, & Exfoliation.

STUMP SITE SECTION

CHARACTERISTICS:

Species: *Sequoia affinis*
Heights: 1′6″
Diameter: 7.2′
Circumference: 22.5′
Mineralogy: Unknown

P44-P1 (2015)

P44-P2 (2015)

P44-P3 (2015)

P44-P4 (2015)

P44 - Stump Top (2016)

1930s 1992 1993 2002 2006 2007 2008 2009

2010 2011 2012 2013 2014 2015 2016

PETRIFIED SEQUOIA STUMP SURVEY

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SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

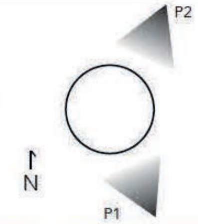
SHEET IDENTIFICATION:
FLFO - P43

SHEET DESCRIPTION:
Stump Profile

BRIEF HISTORY:

P43 was excavated by the Coplen's sometime in the 1920s. It is sited in a very shallow crater with adequate grade and an exit drain. It is unknown whether or not there is soil, solid petrified stone, or lahar in its centre.

INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:

Splintering, Spalling, Cracking, Biocolonisation, Deposit, Missing Features, Fragmentation, Poor Drainage, & Exfoliation

STUMP SITE SECTION

CHARACTERISTICS:

Species: *Sequoia affinis*
Heights: 3'
Diameter: 9.9'
Circumference: 31'
Mineralogy: Unknown

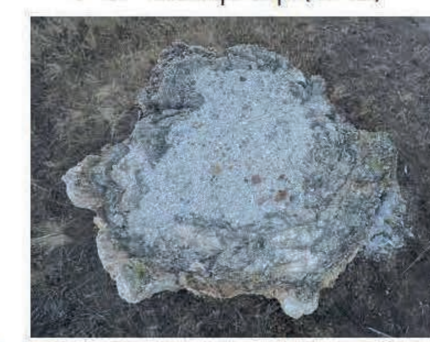
P43-P1 (2016)

P43-P2 (2016)

P43 (2016)

P43 (2016)

P43 - Stump Top (2016)



1992 1993 1997 2004 2005 2006 2007 2008

2009 2010 2011 2012 2013 2014 2015 2016

PETRIFIED SEQUOIA STUMP SURVEY

15807 County Road 1, 80816
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Evan Oxland - Field Team, University of Pennsylvania

ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland (UPenn)
Ariana Miranda (NPS)

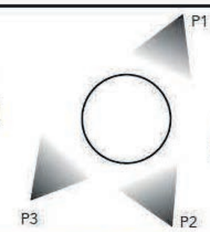
SHEET DESCRIPTION:
Stump Profile

SHEET IDENTIFICATION:
FLFO - P42

BRIEF HISTORY:

P42 was excavated by the Coplen's sometime in the 1920s, and appears to have been showcased by the 1930s based on photographic evidence. At this time there was a ladder so that visitors could enter the pit to view the stump.

INVENTORY & MONITORING PHOTOGRAPH LOCATIONS



CONDITIONS PRESENT:

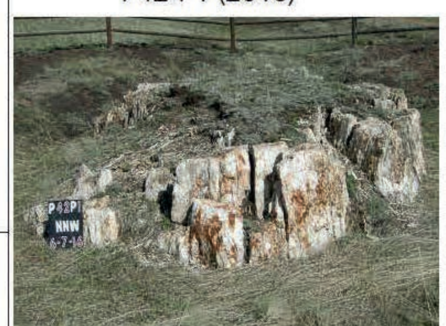
Splintering, Spalling, Cracking, Biocolonisation, Deposit, Missing Features, Fragmentation, Poor Drainage, & Exfoliation

STUMP SITE SECTION

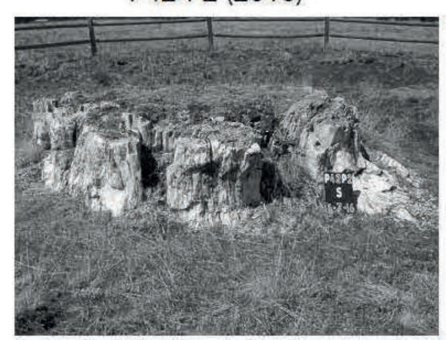
CHARACTERISTICS:

Species: *Sequoia affinis*
Heights: 3′
Diameter: 14.3′
Circumference: 45′
Mineralogy: Unknown

P42-P1 (2016)



P42-P2 (2016)



P42-P3 (2016)

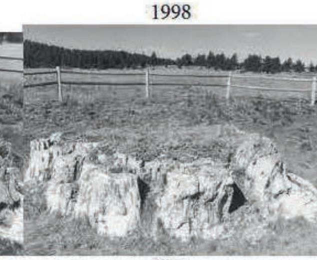
P42 - Stump Top (2016)

1930s

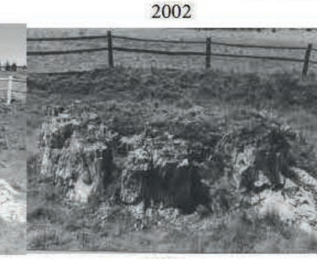
1992

1993

1998

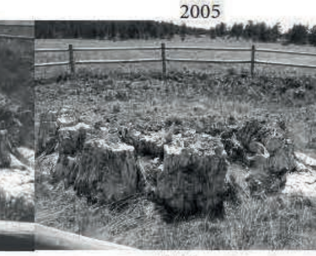


2002

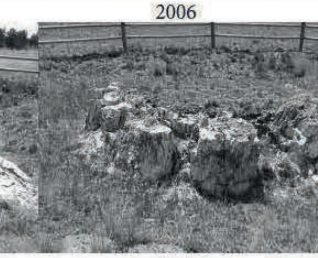


2003

2005



2006



2007

2008

2009

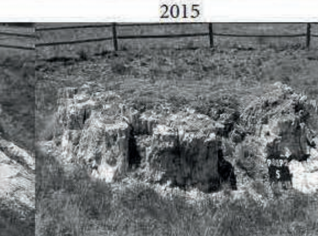
2010

2011

2012

2013

2015



Profile Typology	Characteristic	*P16 (Big Stump	P20 (Trio)	P31	P42	P43	P44	P46 (Cored)	P47
Bio-Colonisation	*Algae*	2	0	1	0	2	0	0	0
	Lichen	2	1	1	3	2	4	1	2
	Herbaceous	2	0	0	4	1	4	0	3
	Woody	0	0	0	1	0	3	0	2
	Animal	0	2	3	2	2	3	2	2
Alteration	*Fibrous Disintegration*	1	1	1	2	3	0	1	3
	Micro-crack	3	3	3	3	3	3	3	3
	Splintering	2	4	4	3	3	3	4	4
	Fracture	3	3	3	3	3	0	4	4
	Horizontal Fracture	1	5	5	0	0	0	0	2
	Tabular Cross Checking	3	4	5	1	1	0	4	3
Material Loss	*Exfoliation*	3	4	4	3	3	0	4	4
	Loss of Section	3	4	4	4	1	0	4	4
	Mechanical Damage	4	0	0	0	0	0	2	0
Deposits	*Iron Stain*	4	4	3	0	0	0	3	0
	Soil	0	3	3	4	1	1	4	4
	Lahar	2	0	4	0	0	0	4	0
Mechanical Reinforcement	*Metal Straps/Blades*	3	3	3	0	0	0	3	0
Landscape Site	*Poor Drainage*	2	5	5	4	1	0	5	5
Conditions Score	*Total*	40	46	52	37	26	21	48	45
General Condition	**0-25 Good** **26-35 Fair** **36-55 Poor**	**Poor**	**Poor**	**Poor**	**Poor**	**Good-Fair**	**Good**	**Poor**	**Poor**

*Paleontological site enumeration as per FLFO Inventory & Monitoring (I&M) program.

**All subject stump sites are in a crater except for P16 & P-44

***Enumeration from 1-5 refers to condition. 0 = Absent; 5 = Abundant

PETRIFIED SEQUOIA STUMP SURVEY
15807 County Road 1, 80816
Florissant Fossil Beds National Monument, Florissant, Colorado
SPONSORED BY AND FUNDING FROM: National Park Service, Florissant Fossil Beds National Monument

Frank Matero - Project Director, University of Pennsylvania
John Hinchman - Project Supervisor, University of Pennsylvania
Evan Oxland - Field Team, University of Pennsylvania

ARCHITECTURAL CONSERVATION RESEARCH CENTER
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

DELINEATORS:
Evan Oxland

SITE RECORDING:
Evan Oxland
Ariana Miranda

SHEET DESCRIPTION:
Conditions Matrix

SHEET IDENTIFICATION:
FLFO - CM

5.1 FLFO Archival Research & Stump Core

FLFO archives revealed critical information about the internal composition and physical integrity of the stumps. The most significant is a series of recent correspondence between Kate Gregory (now Gregory-Wodzicki) and then FLFO superintendent Noel R. Poe. It details a proposal by Gregory, then a PhD candidate, to core into the sides of three stumps to obtain information that could be used for dendrochronology techniques to predict the Eocene-Oligocene boundary paleoclimate at Florissant.[100] Superintendent Poe granted authorisation to Kate in a letter dated 8 July 1989.[101] Based on photographic evidence and a later report Gregory used a mining core drill at stump P46.

[100] Gregory, Kate. *Petrified Wood Drilling Proposal*. 8 July 1989.
[101] Poe, Noel. 8 July 1989.

Figure 5.1: Photographs of Industrial Core Drill and Air Compressor (Source: Gregory, 1989)

As noted in her addenda dated 27 & 28 August 1989, Gregory also intended to core P47 and P16, however, technical difficulties associated with site and water access hindered these attempts.[102] However, she did hand dig two feet into P47 soil depositions.

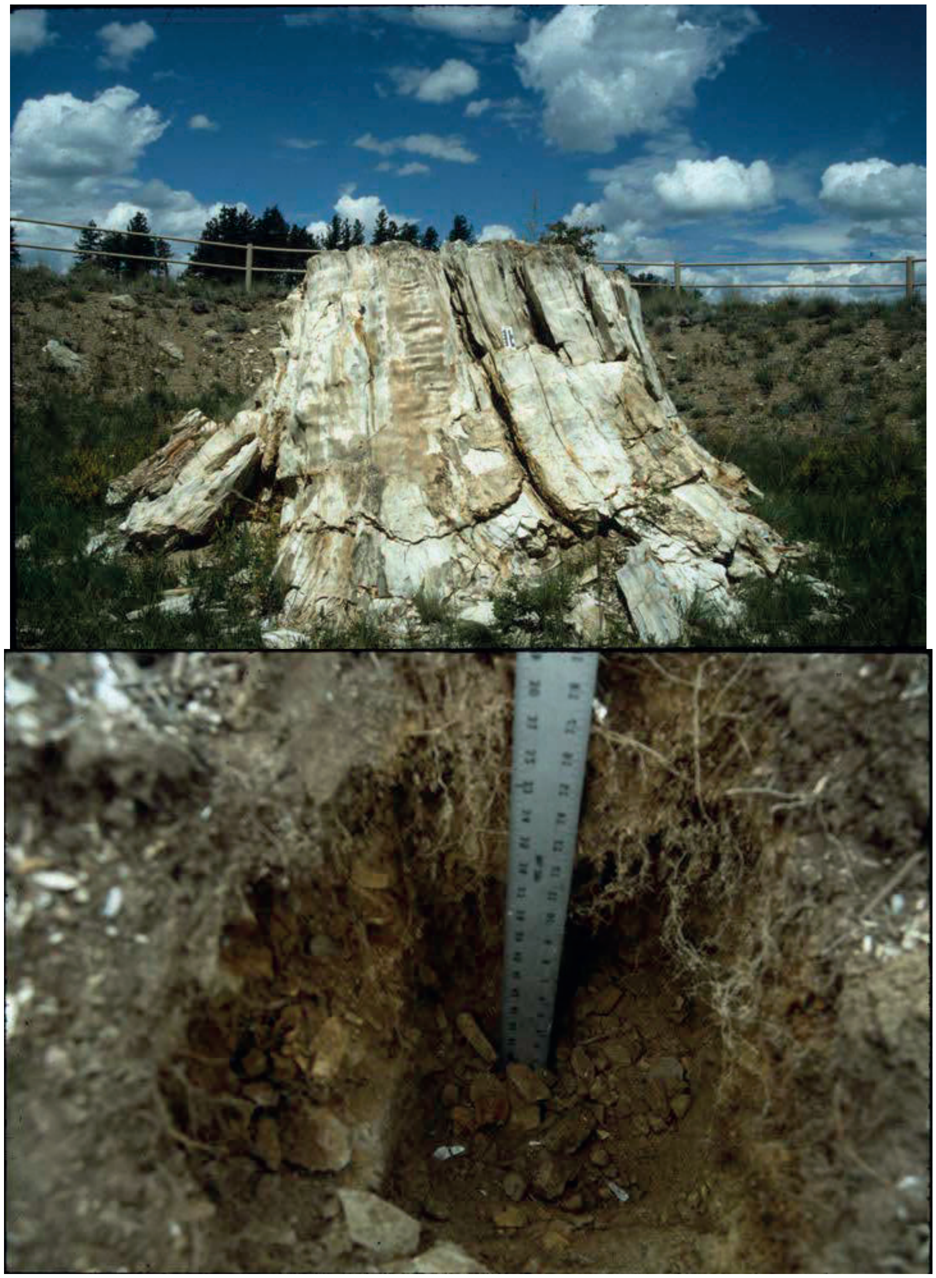


Figure 5.2: Photographs of Stump P47, top, and core soil deposits and likely wood fragments, bottom (Source: Gregory, 1989)

[102] Gregory, Kate. *Drilling Report* 28 August 1989 & letter dated 27 August 1989.

In her *Drilling Report*, Gregory describes the process of obtaining two cores from P46 as being very difficult because of the lamellar nature of stump fabric. Gregory accompanied her report with a separate letter, again highlighting the fractured nature of the stumps as:

> *The first few inches of drilling water pumped into the core hole to cool the drill flowed back out the core hole. However, the drill soon encountered fractured zones filled with soil, or zones of wood fibre which had negligible hardness. Once these fracture zones were encountered, all water disappeared into the stump, indicating the zones were pervasive. In fact, fracture zones were so numerous that the core came out in 1-2 inch pieces instead of one continuous sequence. Thus, the stump is a ring of petrified wood that surrounds a fractured and intensely decayed center.*[103]

Figure 5.3: Photograph of a Highly Fractured Core (Source: Gregory/NPS, 1989)

Park personnel quickly named these rediscovered documents the "Dead Tree Scrolls."[104] Gregory's discovery brought about many questions about the integrity of

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103 Gregory, Kate. Letter "To whom it may concern," dated 28 August 1989.
104 Meyer, Personal Communication, 2016.

the stump core, and mused that coring effluent might be "mudflow," meaning lahar. It is very common for mature Sequoia trunks to have hollow centres near their base. Nevertheless, more research is needed to determine if a stump core is hollow and what it might be filled with. Differential hygroscopic coefficients of expansion and discontinuities in thermal conductivity could cause pathologies of differential movement and result in further fracturing.

Figure 5.4: P47 Stump hollow, bottom, appearing much like a Sequoia sempervirens with hollow core at Muir Woods, California, top. (Source: Author & Oxland, 2016)

5.2 Stump Conditions & Deterioration Systems

Geoengineers have developed the term Rock Quality Designation (RQD) as a method of *in situ* evaluation of the quality of a rock mass as determined by fractures and jointing through core analysis. In her letters, Gregory mentions that the core operators found it very difficult to core into P46.

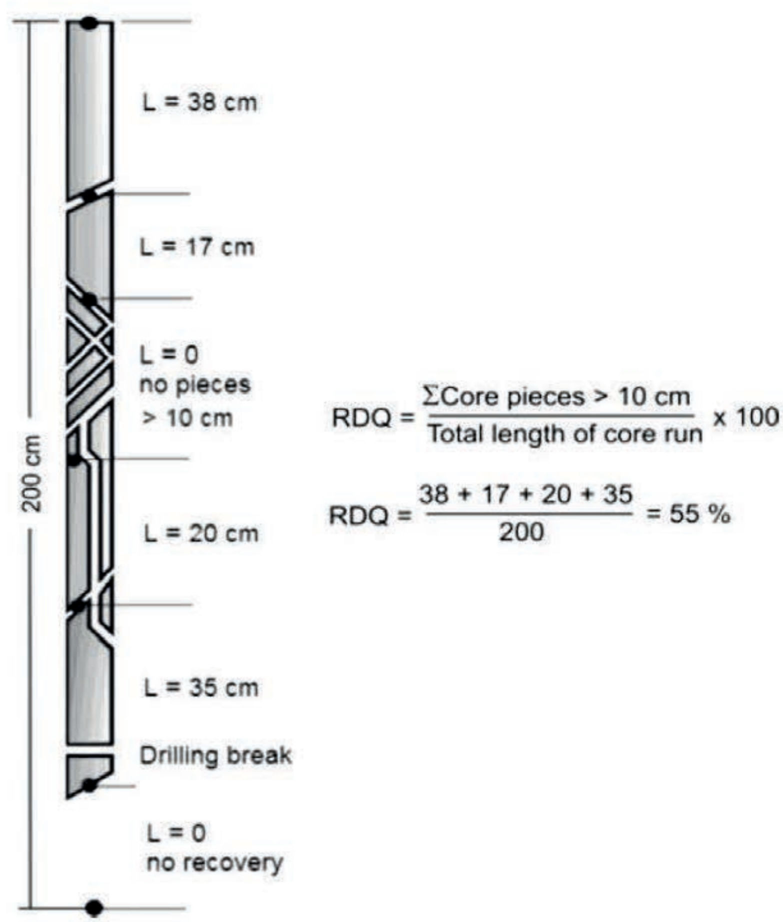


Figure 5.5: Example of an RQD equation for the in situ evaluation of a core. (Source: Hoek, 2016)

How sensitive the operators were during this operation is very significant because any fractures caused by either handling or the drilling process must be discounted. Rock Mass Quality appraisals can become much more complicated than that illustrated above, primarily being tailored to the geotechnical requirements of the mining industry, but any of these methods of evaluation would describe P46 as a very poor quality rock mass.[105] The rock mass quality of P46 directly relates to its taphonomic origins, including silicification, likely excavation by dynamite, and subsequent weathering. However, while geotechnical assessment may be of use, its conventional solutions such as faceplate pinning, webbing, and shotcrete are not compatible with preservation intent, site value, or touristic display of FLFO stumps. Santucci & Koch have listed some of the common forces of degradation that in-situ paleontological resources may endure:

[105] Hoek, "Rock Mass Classification," p. 1-21. 2016.

Table 1. Factors that Affect the Stability of In Situ Paleontological Resources

SURFACE

Physical	Chemical	Biological	Human
Tectonics • seismicity • folding/faulting • extrusive events (lava flows) *Weathering/Erosion* • solar radiation • freeze/thaw • wind • water • fire • gravity • mass wasting • abrasion during transport	• surface water • soil/rock pH • mineral replacement • oxidation (rust, pyritization)	*Displacement* • pack rats • harvester ants *Destruction/Damage* • burrowing organisms • trampling ungulates • vegetation (root and lichen growth)	• construction (buildings, roads, dams) • mining • military activities (construction, vehicles, ballistics) • theft/vandalism • poor science and recovery techniques • livestock • agriculture • recreational activities (offroad vehicle travel)

SUBSURFACE

Physical	Chemical	Biological	Human
Tectonics • seismicity • folding/faulting • intrusive events • metamorphism *Weathering/Erosion* • freeze/thaw (permafrost) • water movement (piping, cavern formation) • gravity • mass wasting • compaction • rock falls	• groundwater • soil/rock pH • mineral replacement • metamorphism (partial melt, recrystallization)	*Displacement* • root growth • bioturbation *Destruction/Damage* • burrowing organisms • root growth	• construction (buildings, roads, dams) • mining • military activities (construction, ballistics) • theft/vandalism • poor science and excavation technique (dynamite)

Source: Santucci and Koch (2003).

Figure 5.6: Risks that may threaten in-situ paleontological sites, such as the stumps at Florissant. (Source: FLFO Geologic Resources Evaluation Report, 2006)

In addition to the above listed threats, systemic environmental pathologies that specifically affect FLFO stumps have been illustrated in the attached survey. Large excavated FLFO stumps such as P16, P20, P31, P46, & P47 have deterioration patterning that can be grouped in three zones:

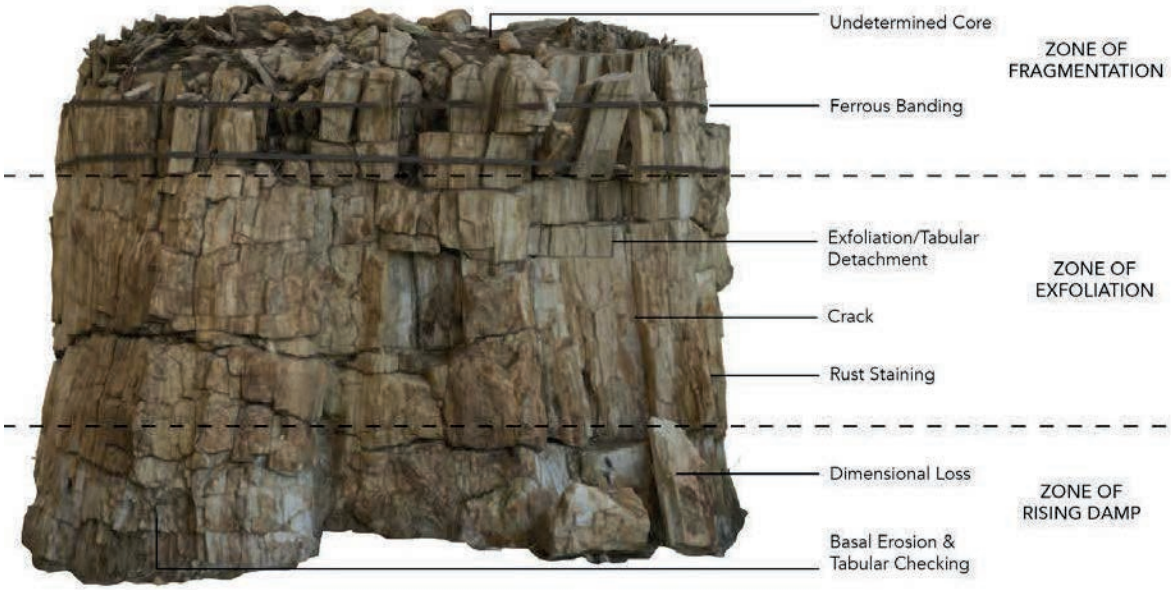
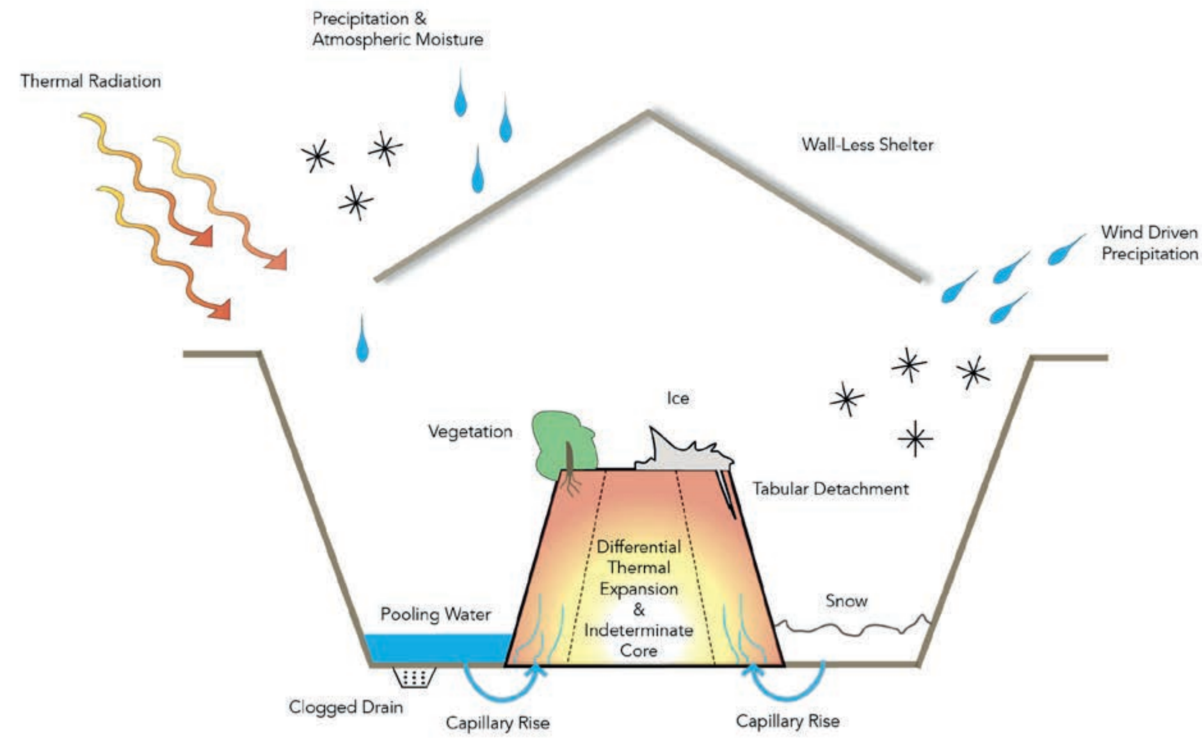


Figure 5.7: Stump P31, example of zonation of stump conditions. (Author, 2017)

1) **Zone of Fragmentation**, the upper-most area of the stump exhibits splintering, fibrous disintegration, vegetative growth, fractures, animal burrowing, and is subjected to the most water from direct precipitation: snow, ice, and rain, more constant loading from thermal radiation, and mechanical interventions such as metal strapping bound to halt fragmentation and sectional loss. This area has the worst material integrity.
2) **Zone of Exfoliation**, the middle area of a stump suffers from dimensional loss due to secondary mineralisations, fractures, lamellar exfoliation, and can have discolorations due to corrosive metals or biocolonisation. This area has the best material integrity.
3) **Zone of Rising Damp**, stump base absorbs water through capillary flow and snow piling. The resultant undercutting, buttress root fracturing, or basal deterioration is the result. There is no evidence of salt efflorescence.



Number of recorded freeze-thaw events on stump exterior under wall-less shelters: **95,** and no shelter, **119**. (Source: Meyer et.al., 2008)

Figure 5.8: Sources of environmental stump stress. (Source: Author, 2017)

The following list is hierarchically ordered in terms of the magnitude of stump deterioration systems, and are as a direct result of the environmental stresses depicted above:

1) **Freeze-thaw cycling** occurs when temperatures drop below 0°C. Water penetrates stump pores and core, and with freeze-thaw cycling can cause destructive ice crystal expansion and associated hydraulic pressures from unfrozen water. Sources of water include rain and snow. Stump craters are particularly susceptible to deterioration from rising damp. Even those stumps with roofs suffer from this problem because their sides remain open to the elements and rooflines fall short of excavated rims.

2) **Intrinsic material characteristics** such as stump fabric heterogeneity resultant from silicification processes, have created incongruous, heavily jointed, lamellar rock masses that may also have substantial amounts of residual organics. As demonstrated and discussed more below, the resolution of relict wood anatomy helps us identify a pore structure that corresponds to biological material configuration. The degradative forces of water and the stresses of thermal and hygric expansions likely exploit these. Tabular detachments and exfoliation corresponds to discontinuities of texture at intersections of fractured jointing infilled by secondary mineralisations of botryoidal chalcedony. Basal erosion and tabular cross-checking mimics patterns of brown rot. The inevitable phase transformation of Opal A-> Opal-CT->Quartz and associated volumetric changes that might play a role of deterioration at the level of microstructure.
3) **Historic Explosives** are anecdotally noted to have been used in the excavations of P46, P31, and P20. Explosives likely introduced substantial new cracks, for instance, these stumps are the only to exhibit horizontal fractures of 3"+.
4) **Thermal loads** from solar radiation or convection on structures as heterogeneous as FLFO stumps can cause deterioration due to differential thermal expansion and contraction. This could be compounded by internal arrangements like fractures that can cause breaks in thermal conductivity or orientation such as the north sides of stumps that receive unequal heating and cooling cycles. In addition, for stumps that are essentially collars of jointed rock masses around lahar, or other unknown material, there are likely differences in thermal coefficient and conductivity between an indeterminate core and rock sheath.
5) **Hygric coefficients** of expansion associated with saturation and dessication cycling act much like thermal loading. The stump tops and bottom, as opposed to the centre zone, would likely be subjected to more cycling. It is unknown if undetermined stump cores have differential hygric expansion and contractions to the silicified wood.

6) **Mechanical interventions,** such as the 1880s saw blades lodged in P16, have caused deep incisions allow for continuing water and ice penetration. Discolouring rust stains have followed. Metal banding around stump tops of P20, P31, and P46 are also rusting and staining stump fabric. Further metal loops attached within additional banding to support the deeply incised stump plan. Installed in 2009, while a clever solution for the moment, they are visually detracting and are made of corrosive metal.
7) **Vegetative growth** was routinely sprayed with herbicides until recent years when park employees stopped its use because of concerns about possible damage from subsequent chemical interactions.

The most significant intrinsic reason for material decay is as a direct result of silicification processes and blasting. Stump jointing, a geological term for planes of weakness or preferential cleavage, is a significant reason for deterioration. Site survey and analysis demonstrated that the interface of secondary or tertiary mineralisations of cracks determine areas of tabular detachment. Field microscopy with a hand held digital microscope following visual identification of botryoidal deposition determined that these lines of later mineralisation become the boundaries of material detachment.

Figure 5.9: Planes of secondary mineral infill on P47. Note on left that material has preferentially exfoliated at this interface. (Source: Author, 2017)

Presuming that the primary cause of exfoliation, and larger tabular detachments, is the mechanical ratcheting effect of freeze-thaw cycling, thermal loading, or differential hygric expansion, then it appears that tenacious hard fibres of the silicified wood typically yield at the interface of this texturally heterogeneous later mineralisation.

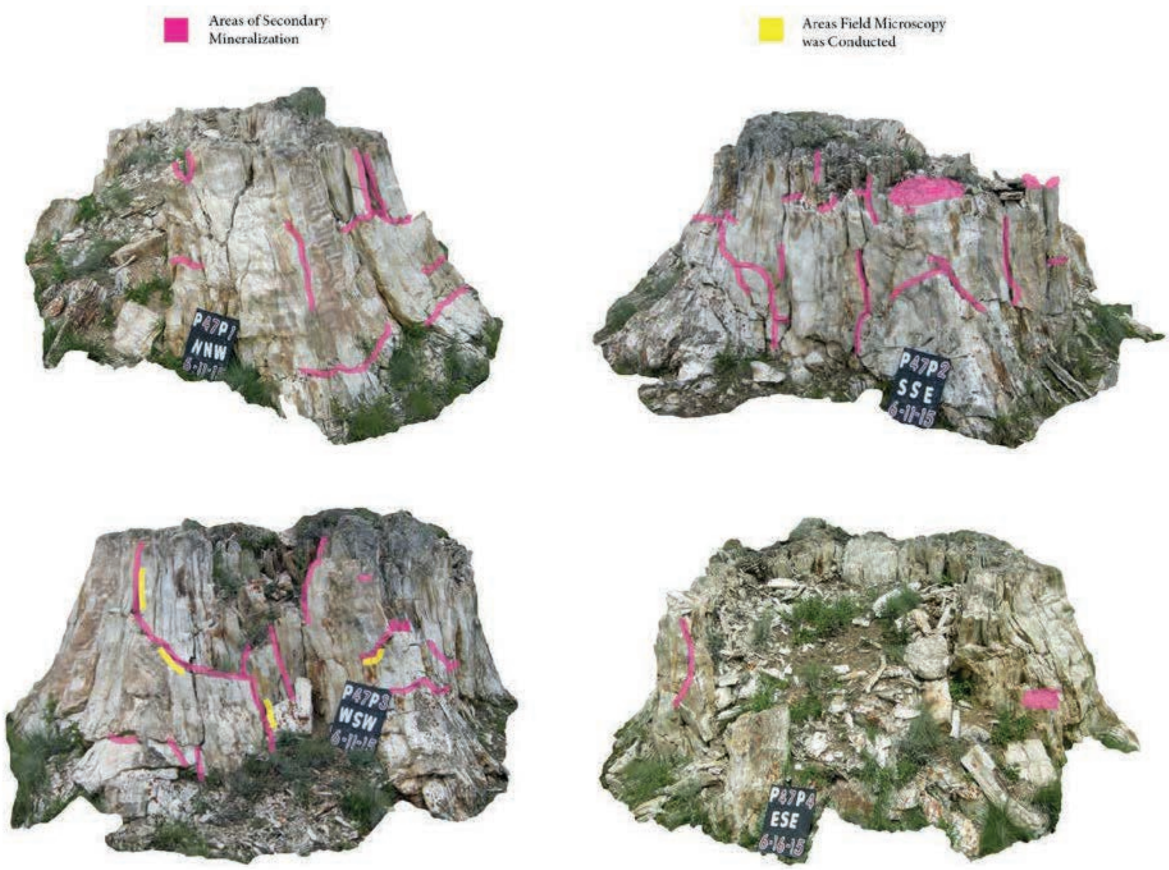


Figure 5.10: Planes of weakness: fractures, microcracks, incipient spalls, and dimensional loss due to secondary mineralization in *P47. (Source: Author, 2017)*

5.3 FLFO Silicified Wood Characterisations

Material characterisation tests performed include:

1) Gross Physical Characteristics: Bulk Density, Specific Gravity, and Colour
2) Water Absorption
3) Microscopy: Stereoscope, Polarised Light, and Scanning Electron Microscopy
4) Thermal Linear Coefficient of Expansion
5) Mechanical Properties

The purpose of these measurements is to understand the material properties of FLFO silicified wood behaviour in order to influence the decision-making process of mechanical pinning treatment design. Samples available for destructive analysis were procured from FLFO during a site visit in November 2016. Samples were sourced from material found during excavations for a new visitors centre in 2011, or came from FLFO stump P-47. All material is property of the National Parks Service, and will be returned to FLFO following the conclusion of this study.

5.3.1 Gross Physical Characterisation: Bulk Density & Colour

Petrified wood density has been calculated from the preparation of a representative sample measuring 7 ¾" x 1 ¾" x 3 ½"(198 x 90 x 38mm). This brick-like sample was kiln dried over forty six hours at 60°C and then given a two hour cool down period in a desiccation chamber at room temperature with 5% humidity. The sample was then weighed as 1494.65g. Dry density is calculated as:

$$D = \frac{M}{V}$$

D = Density, 2.242g
M = Mass, 1494.65g
V = Volume, 666.749cm^3

Comparison of the density of solids of various stones & minerals as published by the Smithsonian[106]							
FLFO	Sandstone	Soapstone	Serpentine	Granite	Marble	Opal	Quartz
2.242	2.2-2.5	2.6-2.8	2.5-2.65	2.5-3.0	2.5-2.8	2.2	2.65

[106] Forsythe, pp. 84-85, 1954.

Figure 5.11: View of tangential grain of prepared brick-like sample. (Source: Author, 2017)

FLFO's petrified wood typically varies in colour from brown, buff, beige, white, and tan. Isolated areas of colouration include orange, yellow, black, or green colourations which are associated with rust staining, secondary mineralisations of accessory minerals like limonite or hematite, and biological colonisations.[107] Light beige coloured wood is likely a function of weathering, as seen when looking at a section of a freshly cut sample as below.

[107] Mustoe, 2016.

Figure 5.12: White rim surrounding the sample is an example of the weathered surface in contrast to darker colours on the interior, evidence of organics. Note fractures following relict annual growth rings, and surficial botryoidal deposits. Sample from stump P-47. (Source: Author, 2016)

The brown colour in petrified wood is thought to be a good indicator of organics by Mustoe.[108] The exposed fabric of petrified wood organics might bleach over time, as material sheltered within is a dark brown colour. Fresh dimensional loss on stumps exhibit patches of darker colours, these lighten over time.

5.3.2 Water Absorption

To understand the capillarity of FLFO wood a modification of NORMAL 11/85 Capillary Water Absorption and Capillary Absorption Coefficient & RILEM Test No. II 6 Water Absorption Coefficient (Capillarity) tests were conducted. Water vapour transmission (WVT) and nitrogen porosimetry was not possible due to a lack of appropriately sized samples without microcracks. A sample was prepared at the approximate size of a small brick, measuring: 7-3/4"x1-1/2"x3-1/2". The sample was dried in accordance with ASTM C97 – *Standard Test Methods for Absorption and Bulk Specific Gravity, section 7.1,* being placed in a desiccation oven over 48 hours at 60C°.

[108] Ibid.

Samples were then transferred to a desiccation chamber at 16C° temperature with 5% relative humidity and weighed 30 minutes after being removed from the oven.

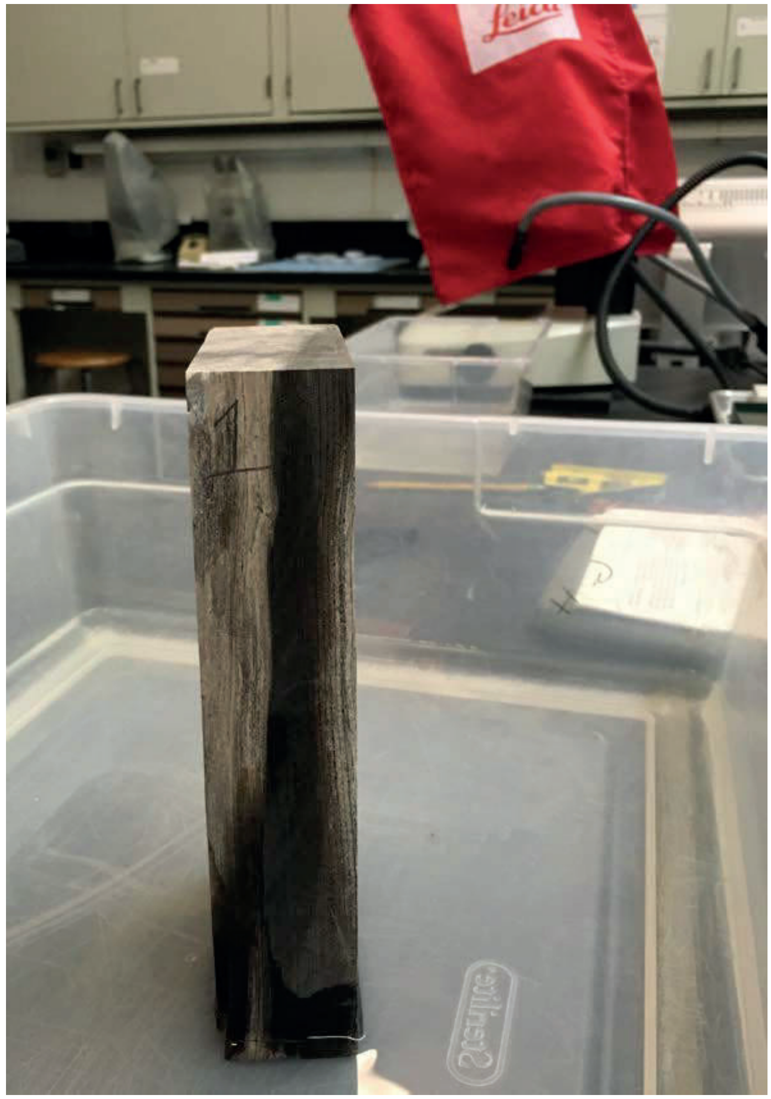


Figure 5.13: Water absorption test, transverse grain measurement. (Source: Author, 2017)

The sample was placed in 1cm of water and the height of capillary rise was measured on all four sides of the prism every minute for the first five minutes, every five minutes until minute 30, and then every 30 minutes until minute 180. The waterline was monitored and maintained over the course of this experiment. Results of prism vertical capillary absorption in the three grain directions are tabulated below:

Sample Dimensions: 7-3/4"x1-1/2"x3-1/2" Dried Weight Before Absorption: 1494.55g Transverse Grain HEIGHT OF DAMP LINE (mm)					
Time (min)	Face 1	Face 2	Face 3	Face 4	Total Mean
0	10	10	10	10	10
1	24	29	28	23	26
2	48	33	32	24	34.25
3	53	57	34	29	43.25
4	57	64	35	30	46.5
5	60	65	38	31	48.5
10	62	65	48	31	51.5
15	64	65	55	31	53.75
20	66	65	65	31	56.75
25	70	65	70	33	59.5
30	71	65	73	33	60.5
60	85	65	80	35	66.25
90	85	65	82	38	67.5
120	95	65	82	40	70.5
150	100	65	82	40	71.75
180	100	65	83	40	72

Sample Dimensions: 7-3/4"x1-1/2"x3-1/2" Dried Weight Before Absorption: 1494.65g Radial Grain HEIGHT OF DAMP LINE (mm)					
Time (min)	Face 1	Face 2	Face 3	Face 4	Total Mean
0	10	10	10	10	10
1	25	18	25	20	22
2	26	19	25	20	22.5
3	26	19	25	20	22.5
4	26	19	25	20	22.5
5	26	19	25	20	22.5
10	26	22	26	26	25
15	26	22	26	26	25
20	27	23	27	26	25.75
25	27	23	27	26	25.75
30	27	23	27	26	25.75
60	27	25	26	28	26.5
90	27	25	26	28	26.5
120	27	25	26	28	26.5
150	29	27	30	30	29
180	29	29	35	34	31.75

Sample Dimensions: 7-3/4”x1-1/2”x3-1/2” Dried Weight Before Absorption: 1494.56g Tangential Grain HEIGHT OF DAMP LINE (mm)					
Time (min)	Face 1	Face 2	Face 3	Face 4	Total Mean
0	10	10	10	10	10
1	22	14	16	17	17.25
2	23	16	16	23	19.5
3	23	16	16	23	19.5
4	23	17	17	23	20
5	23	17	18	23	20.25
10	23	17	18	23	20.25
15	23	17	18	24	20.5
20	23	17	19	26	21.25
25	23	18	19	26	21.5
30	23	18	19	27	21.75
60	23	18	19	28	22
90	25	22	19	28	23.5
120	34	26	19	30	27.25
150	35	26	19	34	28.5
180	35	26	19	34	28.5

The mean rate of capillary-flow or rise is plotted below as height of rise over time:

Grain Direction	Mean Rate of Rise (mm/minute)
Transverse	0.4
Tangential	0.1583
Radial	0.17683

And is plotted as:

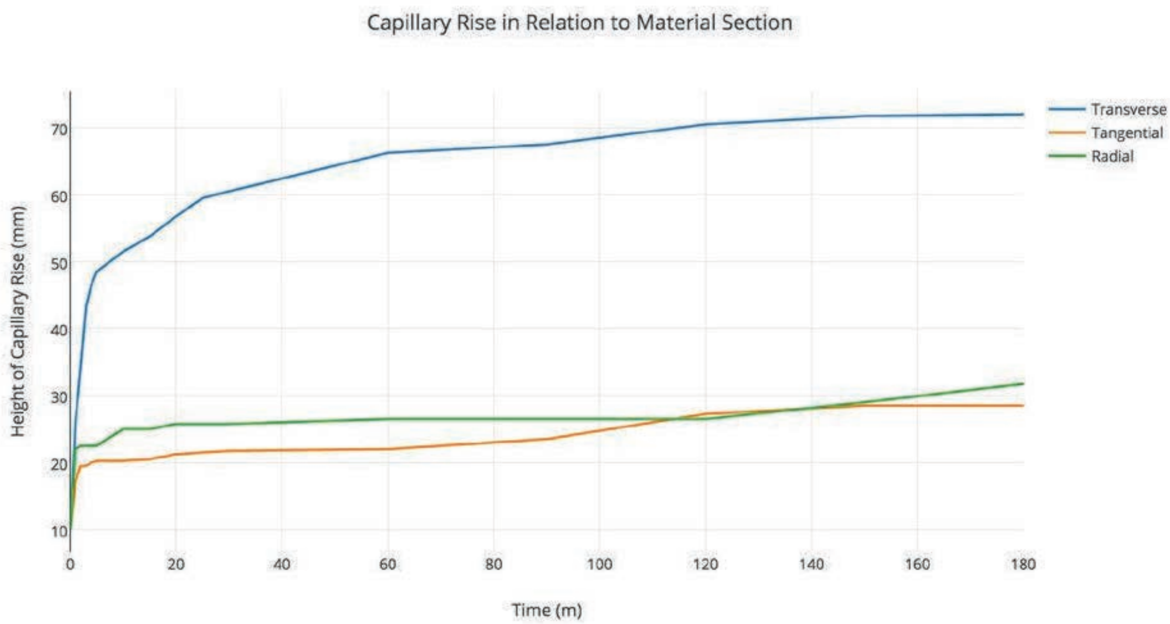


Figure 5.14: Capillary rise in relation to material section. (Source: Author, 2017)

There is a clear relationship between grain direction and capillarity. During this damp rise test it was noted that water absorption preferentially gathered along micro-cracks and rapidly climbed them. Sometimes these cracks were stepped and separated, which accounts for plateaus and sudden spikes in the absorption curve as a slight damp fringe slowly crept from these microcracks. The transverse grain absorbed water at double the rate of radial and tangential grain directions, primarily a function of microcracks.

Observations are in contrast to tests performed under RILEM II Test 5: Water Absorption Tube Test. This test is a common and affordable way to gauge the water absorption potential of masonry units and mortar, and is often used in the building construction industry. Vertical tubes with incremental measurements, one straight to gauge horizontal surfaces another with an elbow joint for application to vertical surfaces, are filled with deionized water. The concept is that the tube of water mimics the pressure and constant water saturation associated with driving rains. The joint between a porous body and RILEM tube is sealed with putty. Areas clear of microcracks were selected in order that the aforementioned capillarity not influence results. RILEM tubes were applied to the three sample sections, filled with water, and measured at increments over an hour, and resulted in no appreciable absorption.

Figure 5.15: RILEM Tube Absorption Test, Left-Right: Tangential, Transverse, and Radial Section. (Source: Author, 2017)

RILEM TUBE ABSORPTION (mm) Dried Weight Before Absorption: 1488.25g Sample Dimensions: 7-3/4"x1-1/2"x3-1/2"			
Time (min)	**Radial**	**Tangential**	**Transverse**
5	0	0	0
10	0	0	0
15	0	0	0
20	0	0	0
30	0	0	0
60	0	0	0

These tests have demonstrated that intact silicified wood, clear of microcracks, is very dense and does not absorb or transport significant amounts of water, however lamellar fissures and microcracks are the likely vehicle of water driven stump decay.

5.3.3 Microscopy

Samples were investigated with low magnification stereoscopy at the Architectural Conservation Laboratory at PennDesign & the Laboratory for Research on the Structure of Matter (LRSM), polarized light microscopy at the Center for Analysis of Archaeological Materials (CAAM) at the University of Pennsylvania's Museum of Anthropology and Archaeology with help from Dr. Marie-Claude Boileau, and scanning electron microscopy at the Singh Center for Nanotechnology after guidance by Dr. Jaime Ford. This investigation yielded information about sample texture, mineralogy, porosity, and weathering processes. Samples for stereomicroscopy were cut at the LRSM using a low speed precision diamond wheel saw calibrated for small sample preparation. They were honed and polished using a Struers polishing wheel, model RotoPol-22. Thin-sections came from Dr. George Mustoe or were prepared by National Petrographic in Houston, Texas.

Figure 5.16: Top, transverse grain viewed with LeicaMZ16 stereoscope, visible light at 2X magnification. Bottom, radial grain viewed with visible light at 5X magnification demonstrating the interface of botryoidal deposition and wood grain. (Source: Author, 2017)

As previously described, *in situ* assessment determined that tabular detachment often occurs along microcracks infilled by secondary mineralisation processes. Cracks, microcracks, and silicified wood texture was therefore investigated with this in mind. The interface between agate infill and relict wood structure was investigated by stereoscopy using cube samples polished up to 12,000 grit. The textural line of this lacuna infill may have occurred simultaneously to silicification of paleowood, meaning that there should be an interlocking of these two textural densities.

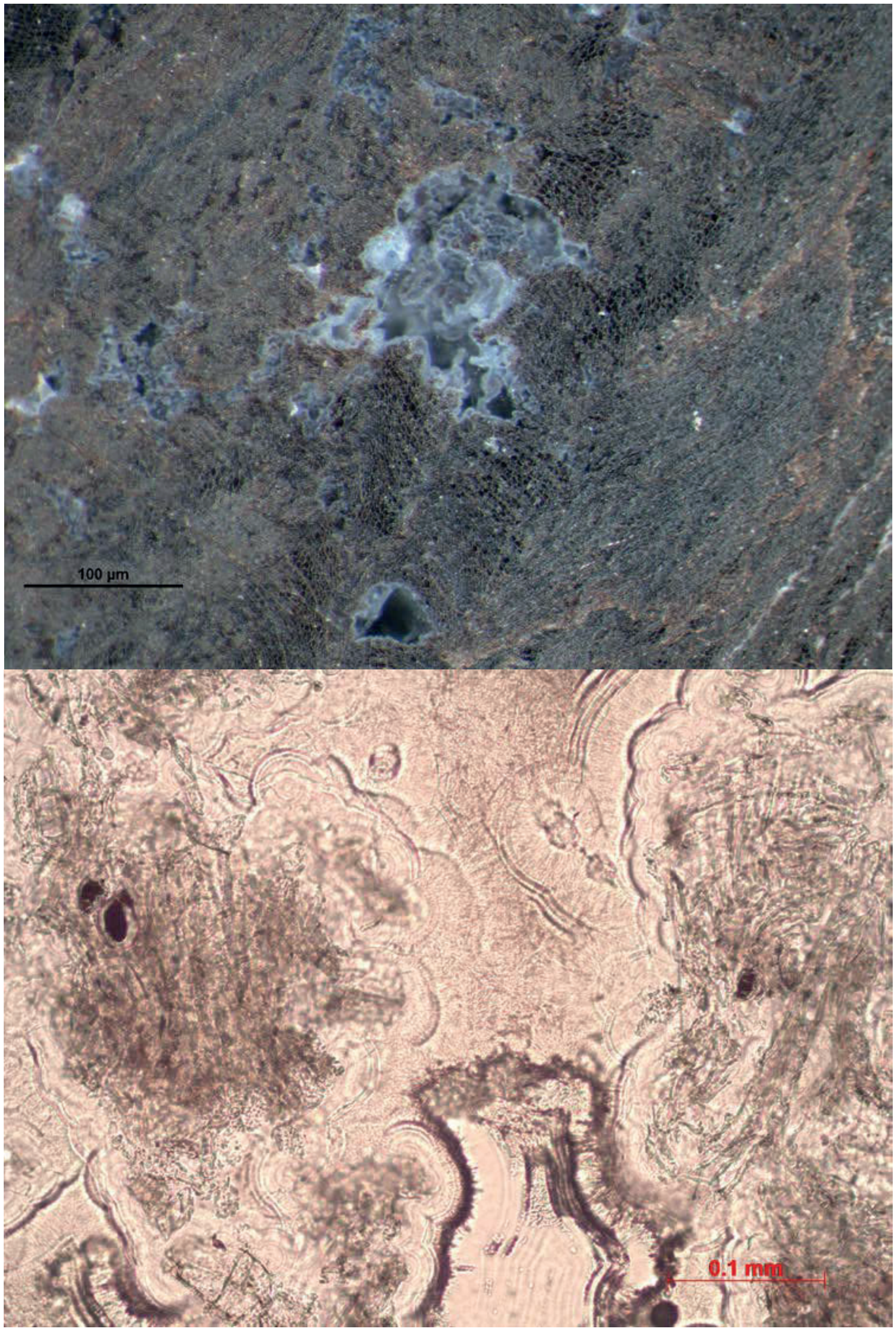


Figure 5.17: Transverse grain viewed at top with LeicaMZ16 stereoscope, agate chamber infill and cell lumens visible light at 65X magnification. On Bottom, detail of agate chamber infill in radial grain, fibrous minerals and billowed horizons suggests cryptocrystalline chalcedony, viewed at 200x in Plane Polarized Light on Zeiss AX10 Research Graphic Petrographic Microscope. (Source: Author, 2017)

Increasing in magnification mineral infill appears fibrous and botryoidal in form, and is likely agate, a form of cryptocrystalline chalcedony (See Figure 5.12).[109] In many locations cellular anatomy is preserved with remarkable detail. Transverse grain exhibits late to early wood transition, its annual rings are legible, and rays separate columns of tracheids.

[109] Nesse, 2013.

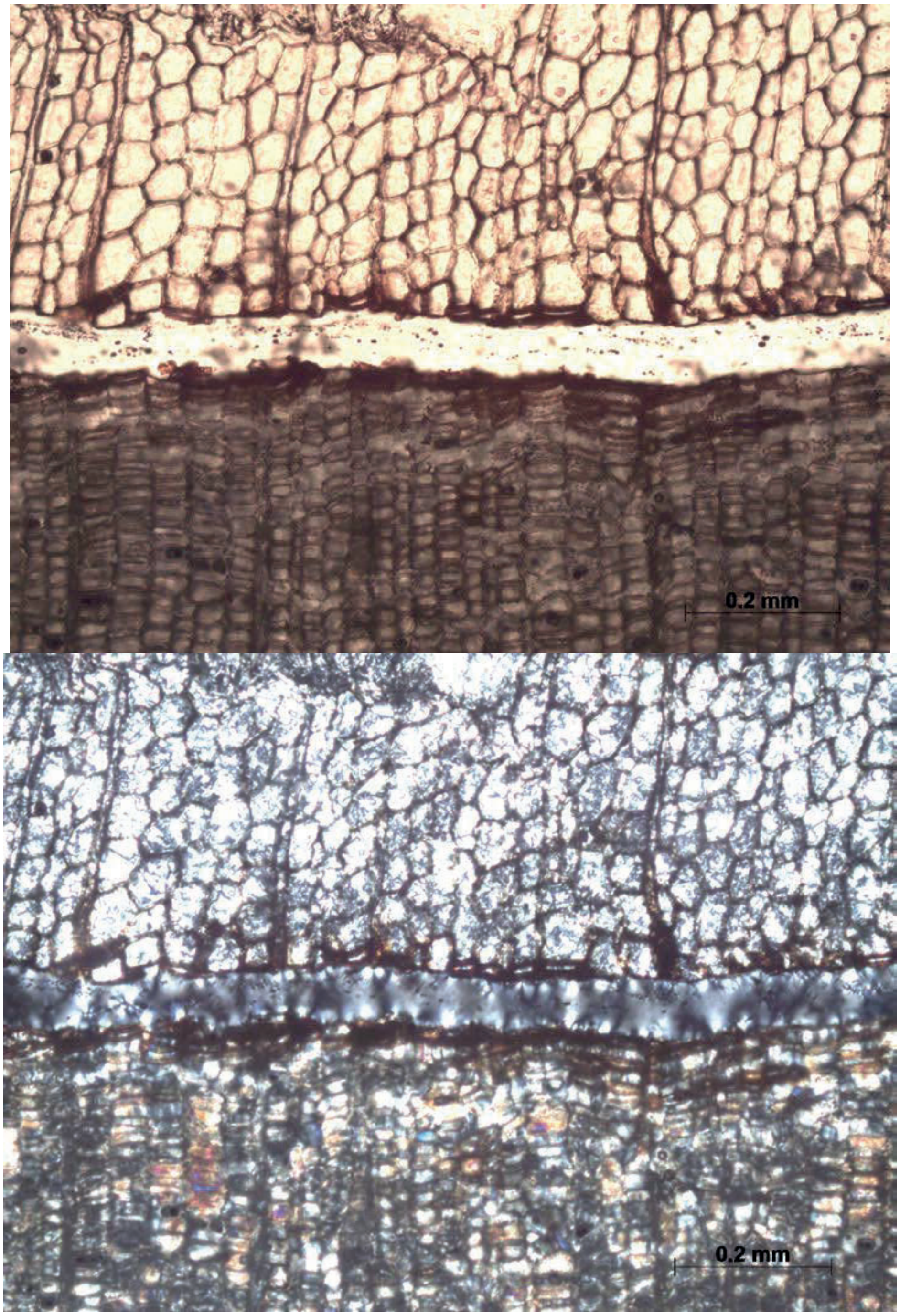


Figure 5.18: Transverse view of detail of microcrack occurring at late to early wood, the annual ring. Anomalous birefringence of quartz or quartz polymorphs, such as chalcedony can be accounted for thickness of section preparation. Paleontologists who view petrified wood often use thicker sections for anatomy details, around 50 microns. Sample P55a, George Mustoe collection. Viewed at 100x in Plane Polarized Light top and Cross Polarized Light bottom. (Source: Author, 2017)

Wood cellular density changes radically at the latewood to spring wood boundary. There is a concentration of what might be relict organics or iron oxides at the interface of this crack. Textural density and mineralogy may help explain why exfoliation or tabular detachment often occurs along annual rings. Radial section anatomy can be seen to correspond to annual rings. The same cracks exhibited in transverse grain can be confirmed as planar fissures when viewed along the radial grain.

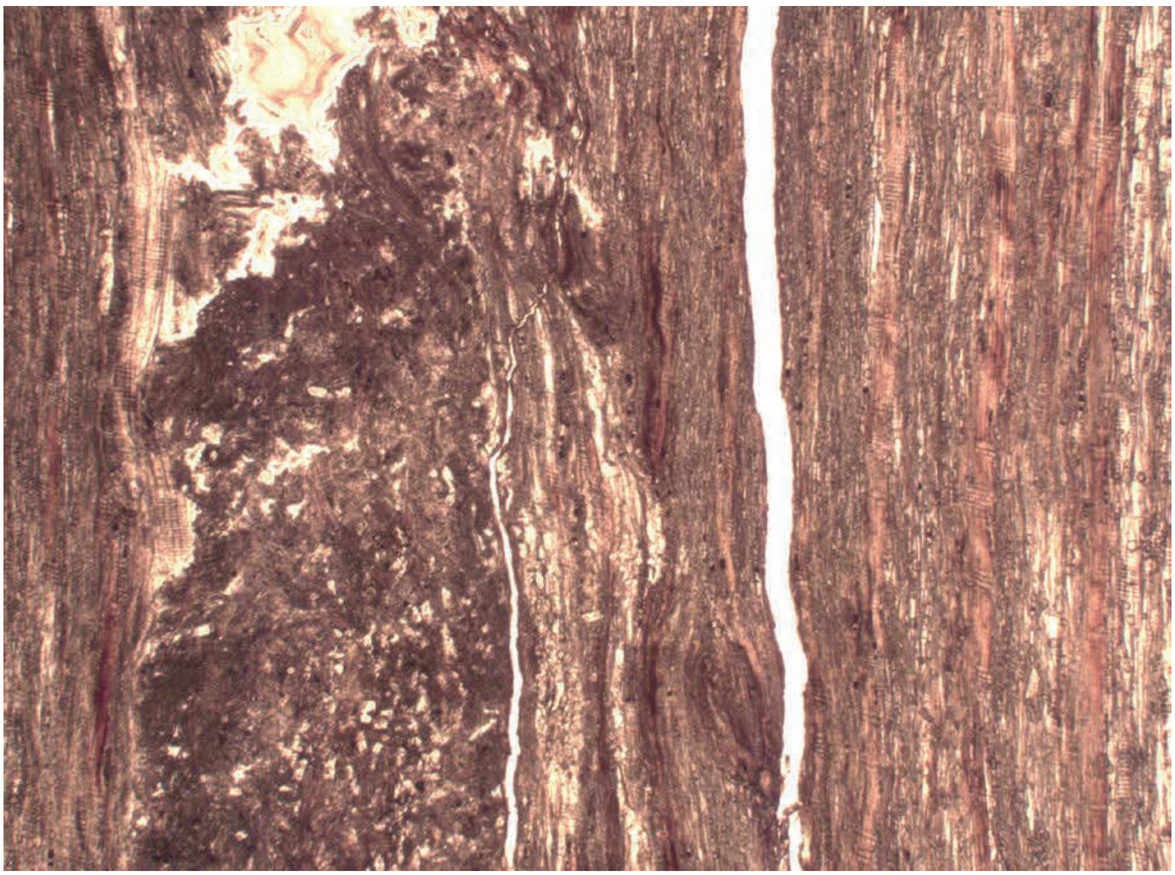


Figure 5.19: The beginnings of tabular detachment, tapering cracks. Sample U1_R viewed at 25x in Plane Polarized Light. (Source: Author, 2017)

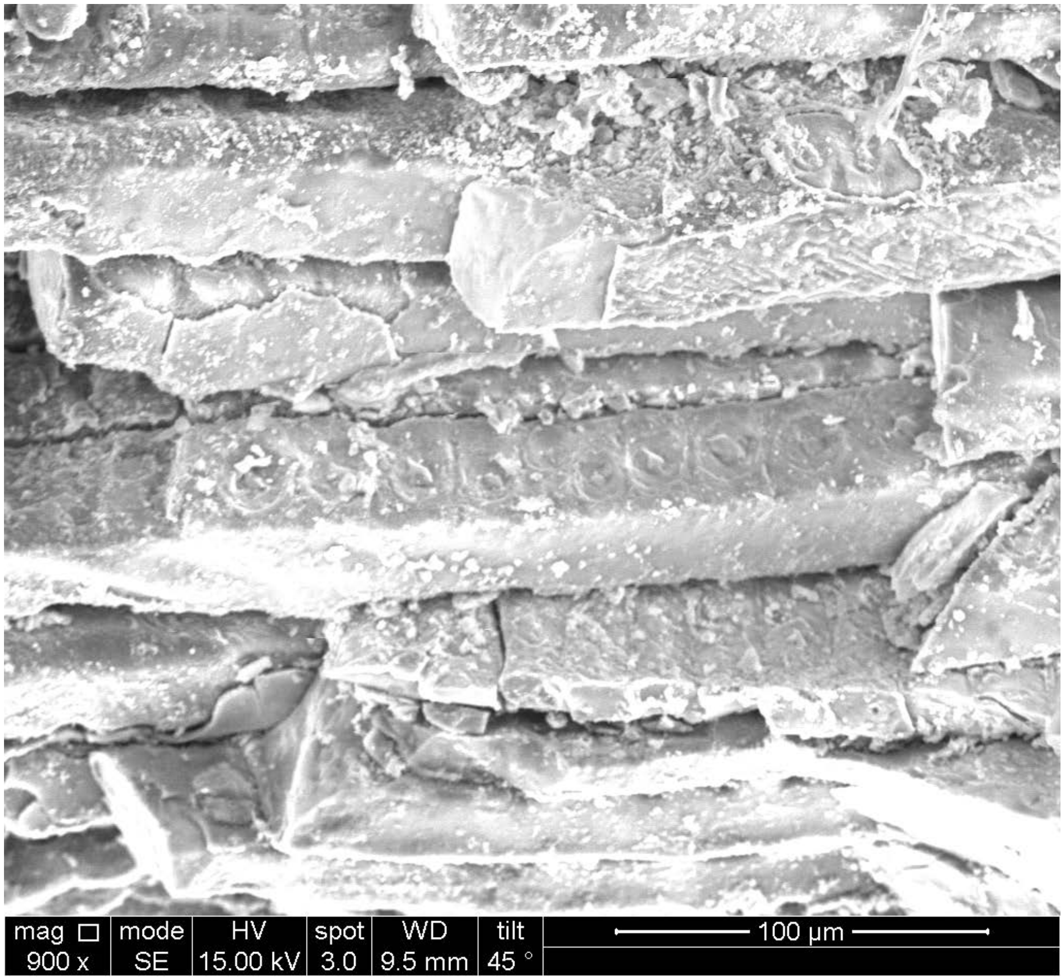
Wood deformation is a common occurrence in the relict cellular texture of FLFO wood. On the left side of Figure 5.19, there is a dark section with highly disordered arrangement of recognisable cellular features, suggesting either a burl-like growth or fungal decay and rot. Other earlier research has contributed to an understanding of FLFO wood at the microscopic level includes a graduate research from the University of Minnesota by Michael Arct. He excavated silicified tree roots, being interested in root bark silicification and was the first to identify the severe deformation of silicified wood at the cellular level.[110]

As previously mentioned soft-rot is a commonly noted feature of Sequoia wood. Another feature of wood deformation at the cellular level is the compression of tangential grain is also exhibited in Figures 4.1 & 5.20. Tracheid walls and ray paths are highly deformed, this is the type of wood one would expect from a "baseball bat".[111] It is quite likely that this deformed grain is a result of either the impact of lahar flow or subsequent taphonomic processes of silicification. During the author's 2016 site visit a sample was procured from the stump top of P16 in order to investigate if the light coloured amorphous mass at stump centre was lahar, as suggested by Gregory's findings. Two samples were lost in a fire at a commercial thin-section laboratory, this last sample came very late in this study. There is very faint evidence of relict cellular anatomy, but this is broken and distorted. It is possible that this is a massing of both lahar and a disordered massing of decayed or deteriorated silicified wood.

110 Arct, 1983.
111 Fearon, Andrew. Personal Communication, 3 April 2017.

Figure 5.20: On top, P16 stump top with material thought to be lahar at centre of stump, note the cuts from the 1880 saw blades. Petrographic analysis by thin section, on bottom, confirmed it to be highly disordered fossil wood, possibly rotted material mixed with lahar. Further instrumental analysis, such as XRD/SEM, could be informative. Magnification at 50x with Plane Polarized Light (Source: Author, 2016 & 2017)

Sub-micro porosity is visible with Scanning Electron Microscopy (SEM) at the boundaries between tracheids, probably as a result of silicate inaccessibility.



5.21: Note the high resolution of bordered pits. Palladium sputter coated sample prepared by George Mustoe and enumerated as #14. Viewed with Scanning Electron Microscopy at 900X. (Source: Author, 2017)

Pore structure is apparent, and defined by relict wood anatomy. It is the boundaries between tracheids that have open space between, in this field of view they are horizontally oriented. This porosity between the tracheids explains conditions like splintering, fibrous disintegration, and suggests that the beginnings of crack formation would occur at these spaces.

Further mineralogical instrumental analysis such as XRD was not performed because Mustoe has already demonstrated that stumps are comprised by the main minerals associated with paleowood silicification, the aforementioned Opal-A, Opal-CT, and Chalcedony (Quartz).[112] Although it has demonstrated that multiple silicification pathways are likely to occur during wood diagenesis, the potential pathological effects associated with volumetric changes. Phase transformation of Opal->Quartz of silicified wood have not been considered, and remain a question.[113]

5.3.4 Mechanical Properties

An evaluation of the mechanical properties of FLFO wood is necessary to understand the dimensional parameters and mechanical behavior of a pinning treatment. A preliminary compression test was executed to gauge in what ways its mechanical properties might be anisotropic, this was followed by a three point bending test in order to understand the modulus of rupture in one specific grain direction of interest.

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112 Mustoe, 2008.

113 Grapes, 2006 & Shackelford et. al., 2010. While these books specifically look at temperature dependent phase transformations of Cristobalite, Tridymite, alpha-Quartz , and beta-Quartz, time and pressure also play roles. Volumetric changes accompany structural atomic realignments.

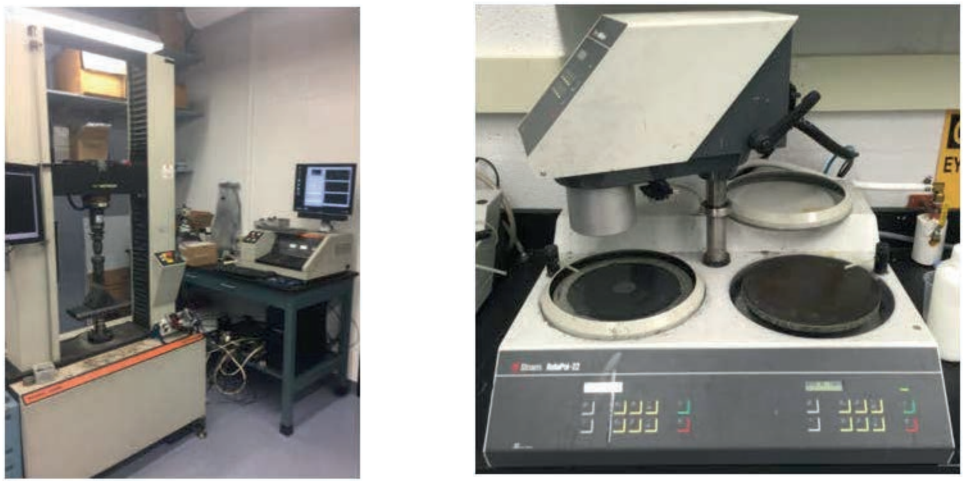

Figure 5.22: Instron 4206 with 5000lb capacity load cell was used for mechanical testing, left, and Streurs RotoPol-22 for polishing and sanding samples. (Source: Author, 2017)

Samples for testing were prepared both for both mechanical strength testing and thermal coefficient of expansion, to be described in the following section, by a combination of continuous-rim diamond bladed brick/stone/CMU table-saw, segmented diamond bladed tile saw, low-speed diamond wheel saw, and petrographic grinding, and polishing wheels.

Figure 5.23: Sample preparation on a precision low speed diamond wheel saw, South Bay Technology Inc. Model 600, left, and a Felker 14" diameter diamond tip saw, right. (Source: Author, 2017)

ASTM C170M-16, *Standard Test Method for Compressive Strength of Dimension Stone*, was consulted for methodology of testing. Samples for compression testing were prepared using long thin sections of FLFO wood. Multiple cubes were cut to dimensions 0.63” x 0.59” x 0.43”. Because sample availability was low only five tests were conducted. The formula for calculating compressive strength is described as:

$$\delta = \frac{F}{A}$$

δ = Stress, compressive strength in psi (Mpa)
F = Force, total maximum load in lbf (N)
A = Area of loaded surface in^2 (mm^2)

Test Sample #	Stress (lbs) (F)	Strain (in)	Unit Dimensions (in)	Area of Loaded Surface (in)	Grain Orientation	Compression Strength (psi)
U3_1	1216.416	0.210	0.63x0.597x0.436	0.376	Tangential	5799.636
U3_2	2572.291	0.197	0.643x0.581x0.436	0.253	Transverse	13056.652
U3_3	161.397	0.309	0.635x0.598x0.432	0.258	Radial	522.912
U3_4	2251.549	0.130	0.632x0.589x0.440	0.259	Transverse	17335.607
U3_5	829.616	0.314	0.658x0.591x0.446	0.389	Tangential	2640.744

The results above indicate that relict grain dimensions play a significant role in the mechanical strengths of FLFO silicified wood.

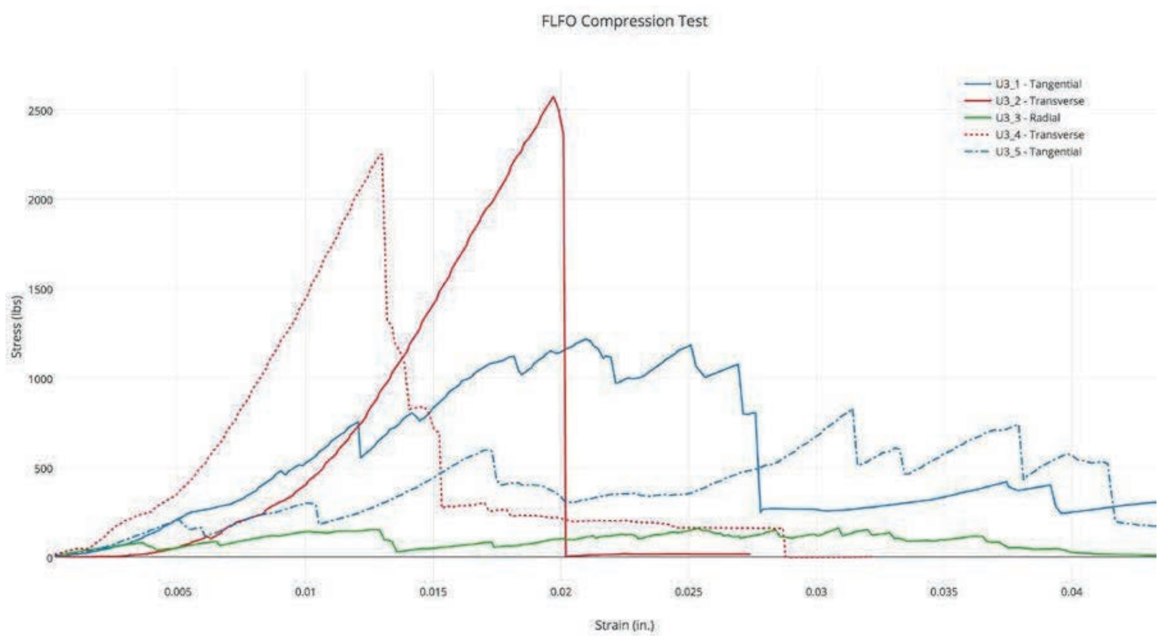

Figure 5.24: Indicator compression test. (Source: Author, 2017)

The transverse grain is more representative of classic brittle failure than the other grain directions. In part this could be due to sample preparation, but it is likely due to fabric heterogeneity. In compression, the transverse grain is significantly stronger than transverse grain, which in turn is much stronger than the radial grain, much like biological wood. When the transverse grain failed in compression a large sound was emitted and fibres were ejected. The textural reasons for this directly relate to information garnered from petrographic and SEM microscopy.

Figure 5.25: Fibres blown out from compression tests are individual tracheids, transverse test. Fibres were confirmed by microscopy after melt mounting fibres on slides. (Source: Author, 2017)

Individual relict tracheids are oriented and grouped like stacked columns in vertical, or transverse, orientation. These are very strong in longitudinal compression, like the columns of a building, but are perpendicularly weak – as most stone is very weak in terms of flexural strength over a long span. As suggested by compressive testing, FLFO relict cellular anatomy influences dimensional mechanical strengths. It is assumed that a pinning treatment reintegrating dimensional loss or for preventative reinforcement be made through the tangential wood grain into the existing stump fabric. Furthermore, the mechanical property of interest during a bending moment of a pinned unit of FLFO wood is the modulus of rupture in tangential grain. This information is essential to designing any pin assembly where the intent is for the pin to fail before the material it is holding.

ASTM C 99-M15, *Standard Test Method for Modulus of Rupture of Dimension Stone*, was consulted for a methodology of testing, although sample preparation dimensions deviated from its specifications due to the limits of material availability. Two cohorts, one of four and the other five samples, were tested. Each cohort was sourced from a unique sample, named U1 (four samples) and U2 (five samples). This material was squared to its largest possible dimensions, yielding 2-1/16"x1-1/2"x1/2" (U1) & 2-1/4"x1-1/4"x1/2" (U2). Calculating the flexural strength of a rectangular prism under load in a three point bending test is described as:

$$\delta = \frac{3FL}{2bd^2}$$

δ =	Stress, total maximum load in. lbf
F =	Force, total maximum load in. lbf
L =	Span between two points in.
b =	Test sample prism width in.
d=	Test sample prism thickness in.

An electromechanical testing machine, Instron 4206, was used with a 5000lbs capacity load cell.

Figure 5.26: Example of three point bending. (Source: Author, 2017)

Test results are recorded below:

Test Sample #	Stress (lbs) (F)	Strain (in)	Dimensions	Prism Width (b)	Prism Thickness (d)	GRAIN ORIENTATION	MODULUS OF RUPTURE (psi)
U1_1	390.591	0.238	½”X1-1/2”X2-1/16”	1.500	0.5	Tangential	1562.364
U1_2	833.518	0.348	½”X1-1/2”X2-1/16”	1.500	0.5	Tangential	3334.058
U1_3	443.543	0.212	½”X1-1/2”X2-1/16”	1.500	0.5	Tangential	1774.172
U1_4	834.173	0.259	½”X1-1/2”X2-1/16”	1.500	0.5	Tangential	3336.692
U2_1	540.528	0.506	½”X1-1/4”X2-1/4”	1.250	0.5	Tangential	2594.534
U2_2	958.113	0.262	½”X1-1/4”X2-1/4”	1.250	0.5	Tangential	4598.943
U2_3	644.545	0.370	½”X1-1/4”X2-1/4”	1.250	0.5	Tangential	3093.815
U2_4	584.409	0.308	½”X1-1/4”X2-1/4”	1.250	0.5	Tangential	2805.163
U2_5	1364.496	0.298	½”X1-1/4”X2-1/4”	1.250	0.5	Tangential	6549.581

Sample Standard Deviation (Variance=/n-1): 1515.83lbs
Range: 1562.36 to 6549.58lbs
Mean: 3294.37lbs

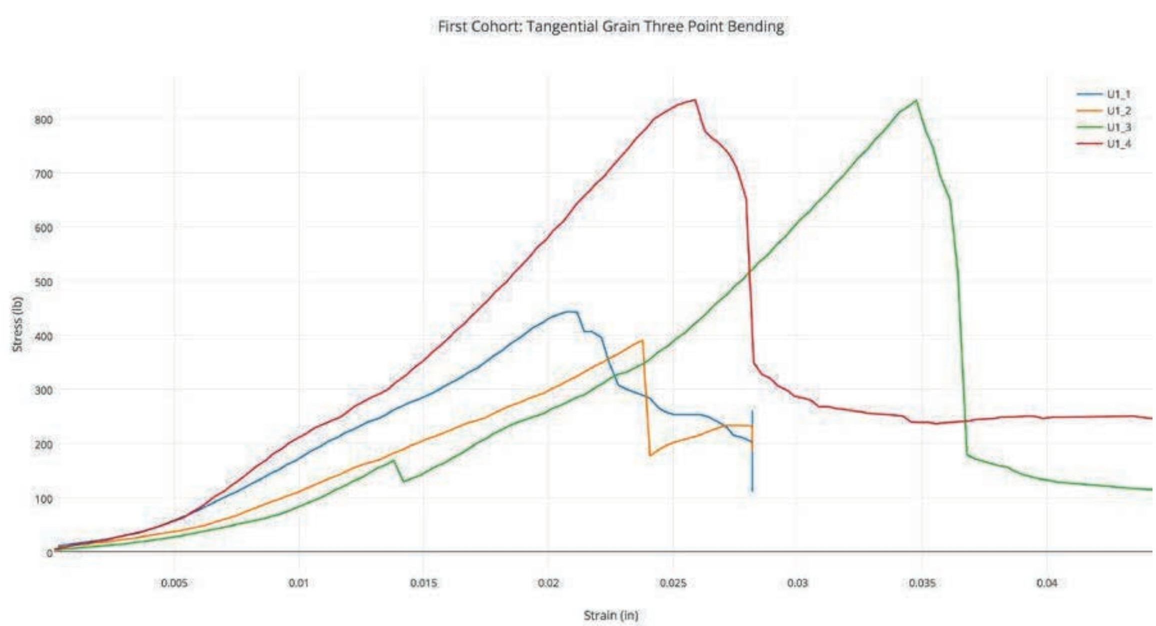

Figure 5.27: First cohort, FLFO tangential grain modulus of rupture. (Source: Author, 2017)

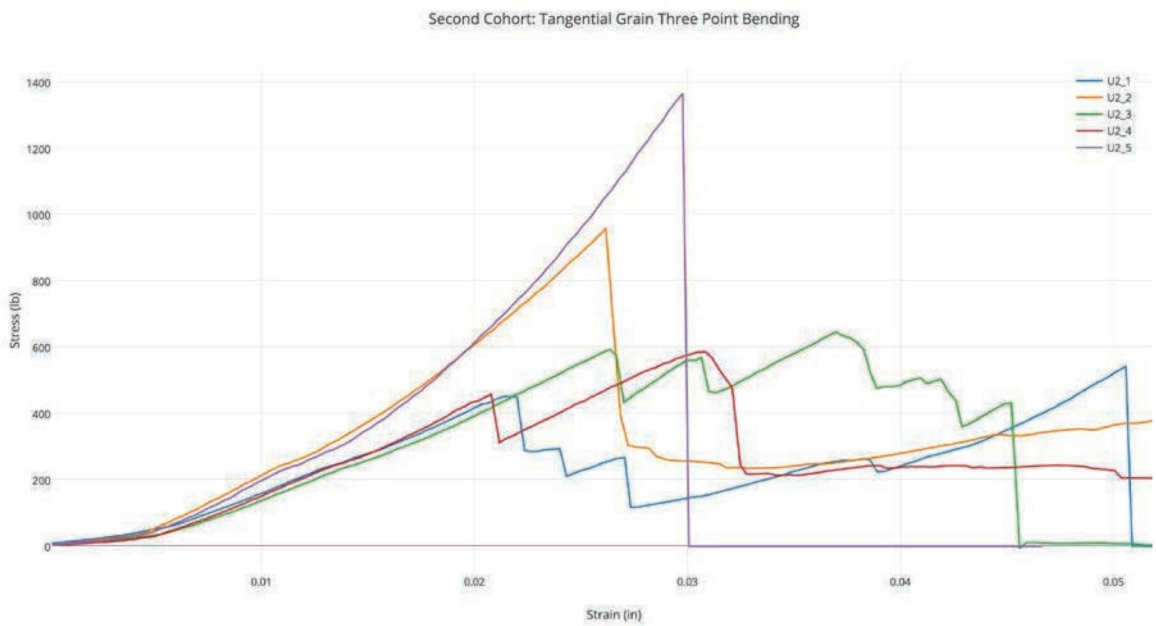

Figure 5.28: Second cohort, FLFO tangential grain modulus of rupture. (Source: Author, 2017)

Some samples exhibited classic brittle failure modes with a consistent slope, if not orthogonal line, until ultimate yield and failure. Others exhibited more plastic deformation, which is more consistent with plastics or wood. During testing a crinkling sound was emitted from these samples, as if fibres were becoming sequentially engaged and then failing, allowing unstressed fibres to take up the load. Again, this could have been due to sample preparation, but it is more likely to have been due to the highly variable nature of the material.

5.3.5 Thermal Linear Coefficient of Expansion

FLFO thermal linear coefficient of expansion is a useful property in order to choose pinning material. The differential expansion and contraction of a pin can cause damage to its host material, meaning that this is a significant material property to determine pinning material compatibility.

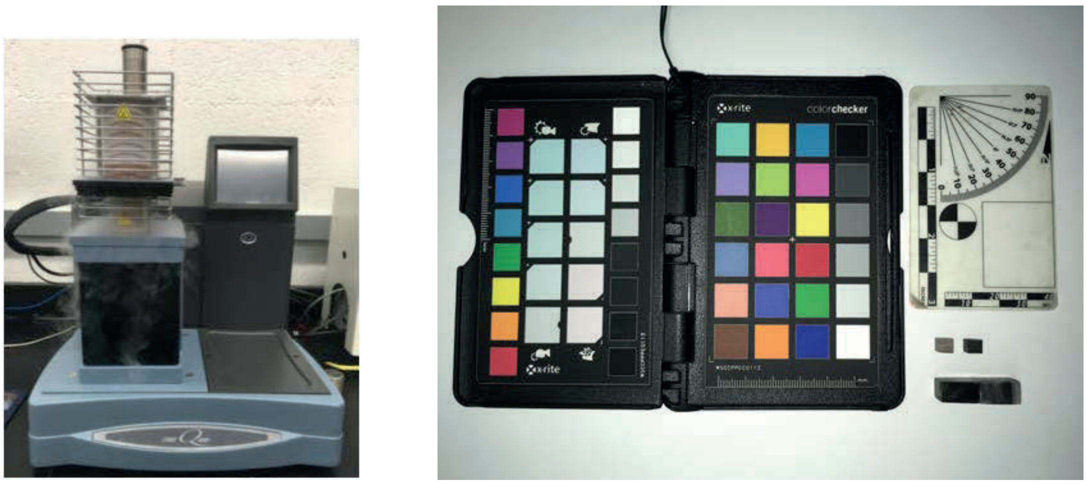

Figure 5.29: TMAQ400, Thermal mechanical analyser in a cooled equilibrating phase on left, and prepared samples on right. Cube samples are smaller than one centimetre.

Measurements were taken with a thermal mechanical analyser (TMA). Model TMAQ400, produced by TA Instruments, was used at the Laboratory for Research in the Structure of Matter (LRSM) at the University of Pennsylvania under the guidance of laboratory manager Steve Szewczyk. The machine can measure solid objects up to 4cm x 2cm x 2cm. Chosen temperature range of measurement was -40°C to 100°C, and was performed according to ASTM E831 – Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis. Although temperatures at FLFO rarely dips below -20°C, this range was used because of the technical requirements of cooling the furnace and thermometer. Liquid nitrogen was added to the machine to cool down the furnace chamber walls, ambient air temperature, sample, and thermometer.

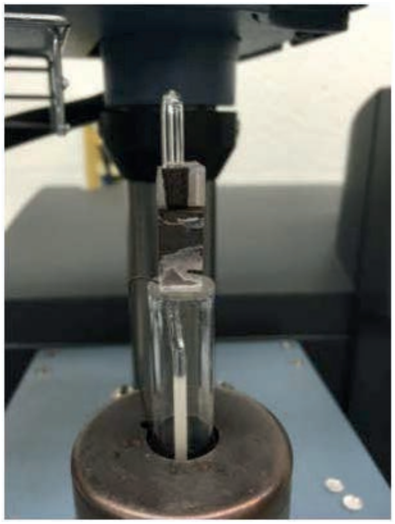 

Figure 5.30: Preparatory FLFO wood used for TMA calibration sandwiching Indium and under the quartz measuring probe on left, the metal wire touching the sample bottom is the thermometer. Cooling the closed furnace chamber with liquid nitrogen on right.

A 20°C gap between the intended range of measurement is used to establish thermal equilibrium, meaning -20°C to 100°C is the actual measured coefficient range. 100°C was chosen as the upper limit to ensure constant linear data over a long range, and higher temperature ranges were decided against because of the volumetric changes associated with mineralogical phase transformation of opal -> quartz with molecular dehydroxylation.

The aspect ratio, or temperature calibration, was performed using 99.9% indium. A thin shaving of this metal was sandwiched between two flat pieces of silicified wood to ensure thorough sample thermal saturation, otherwise the thermal mass, & associated temperature lag, of the wood could be a source of inaccuracy. Cell constant force was calibrated using near pure aluminum stock at 1.0582, and temperature was corrected by negative 0.1°C. Three samples were tested in expectation of anisotropic properties. The first sample deviated from ASTM E831 being more than 10mm in length, however it was chosen because it represented agate infill. Two ASTM dimensionally conforming samples were made, one darker in colour than the other to investigate what the role of organic content might play. The measurement of the thermal coefficient of expansion is expressed as:

$$\alpha_m = \frac{\Delta L_{sp} \times K}{L \times \Delta T}$$

α_m = mean coefficient of linear thermal expansion, µm/(m·°C),
k = calibration coefficient, from Test Method ASTM E1363,
L = specimen length at room temperature, m,
ΔL_{sp} = change of specimen length, µm,
ΔT = temperature difference over which the change in specimen length is measured, °C, and
T = midpoint temperature of the temperature range ΔT.

Results of testing are listed below:

Sample Number	Sample Test	Linear Coefficient of Thermal Expansion µm/(m•°C)			Mean Thermal Coefficient µm/(m•°C)		
		Transverse	Radial	Tangential	Transverse	Radial	Tangential
TCE1 *27.9X 10.8X 7.8mm*	TCE1.1	15.08µm/(m•°C) 0.422µm/°C			14.98 µm/(m•°C)		
	TCE1.2	14.94µm/(m•°C) 0.4177µm/°C					
	TCE1.3	14.92µm/(m•°C) 0.4174µm/°C					
TCE 2 *5.7X 5.5X 5.1mm* **Light Coloured Sample**	TCE2.1	11.75µm/(m•°C) 0.06631µm/°C			12.69 µm/(m•°C)		
	TCE2.2	13.07µm/(m•°C) 0.07373µm/°C					
	TCE2.3	13.25µm/(m•°C) 0.07467µm/°C					
	TCE2.4		12.43µm/(m•°C) 0.06631µm/°C			12.82 µm/(m•°C)	
	TCE2.5		13.59µm/(m•°C)				

			0.07257µm/°C				
	TCE2.6		12.44µm/(m•°C) 0.06445µm/°C				
	TCE2.7			12.83µm/(m•°C) 0.06501µm/°C			
	TCE2.8			12.58µm/(m•°C) 0.06372µm/°C			12.52 µm/(m•°C)
	TCE2.9			12.15µm/(m•°C) 0.0616µm/°C			
TCE3 *5.1X 5.0X 4.5mm* **Dark Coloured Sample**	TCE3.1	12.45µm/(m•°C) 0.06559µm/°C					
	TCE3.2	15.48 µm/(m•°C) 0.08147µm/°C			14.49 µm/(m•°C)		
	TCE3.3	15.54µm/(m•°C) 0.08174µm/°C					
	TCE3.4		15.48µm/(m•°C) 0.08259µm/°C				
	TCE3.5		15.23µm/(m•°C) 0.08102µm/°C			15.33 µm/(m•°C)	
	TCE3.6		15.3µm/(m•°C) 0.08148µm/°C				
	TCE3.7			15.87µm/(m•°C) 0.07823µm/°C			
	TCE3.8			15.68µm/(m•°C) 0.07734µm/°C			15.2 µm/(m•°C)
	TCE3.9			14.07µm/(m•°C) 0.0694µm/°C			

The range of FLFO wood thermal coefficient of expansion in Fahrenheit: 6.9-8.5 µin/(in•°F).

5.4 Implications of Testing Results

The site survey and material characterisation informs a greater understanding of stump deterioration mechanisms and should guide future research endeavours at FLFO such as environmental monitoring, simulation modelling, and the evaluation of other potential conservation treatments.

Comparison of American Building Stone Types with FLFO	Bulk Density (g)	Thermal Coefficient X 10-6 in/in · °F (X 10-6 m/m · °C)	Modulus of Rupture (lbs)	Compressive Strength (lbs)
FLFO Silicified Wood	2.242	6.9-8.5°F (12.52-15.33°C)	Range 1562.36-6549.58 Standard Deviation 1515.83	Radial ~522.91 Tangential ~4220.19 Transverse ~15196.13
Indiana Limestone[114]	2.17-2.49	2.4-3	Range 540-2,220	2,720-17,770
Ohio Sandstone[115]	2.11-2.15	(13-15°C)	Range 772-1177	11,679 (avg)
Slate (343 Sample Average)	2.771	-	11,700	-
Vermont Marble (Shelburne)[116]	2.71	-	Range 1,481-1,524	16,156-22,845
Rock of Ages Igneous[117]		-	Range 1906-3500	23,645-43,524

Compared with other building stone types, on paper, FLFO silicified wood appears to be very robust, for instance, more than the ubiquitous architectural Indiana Limestone. However, the capillarity potential of crack riddled material in combination with little porosity makes FLFO silicified wood very vulnerable to the expansive forces of freeze-thaw cycling and associated hydraulic pressures. In addition, lamellar fissures' potential for capillarity likely provides more available moisture for ice and ever-increasing crack formation leading to eventual exfoliation or tabular detachment.

114 Kessler & Sligh, p 550. & ILI Handbook, p. 10, 2007.
115 Cleveland Quarries Technical Data, 2017 & Somerton, p. 35, 1992.
116 Terrazzo & Marble Supply, 2017 & McGee, 1989.
117 Rock of Ages, 2017.

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6.0 Mechanical Pinning as Part of an FLFO Conservation Program

> *I urge preservation efforts be taken immediately. Steel cables twined around the tree holds chunks of wood in place, but do nothing to stop the weathering within the center of the stump. The stumps need to be protected from the weather in order to maintain their integrity.*[118]
> *-Kate Gregory, 1989*

The following conservation treatment of mechanical pinning should only be considered as one measure, among many, in a holistic conservation program. This program was hierarchically prioritised in terms of predicted treatment beneficial impact and expense. The most pressing solution is the elimination of environmental stress. FLFO stumps are the primary reason for tourist visitation and thus enable monument survival. Stump mothballing being impractical, and contrary to site values of display, the best option is an enclosed or semi-enclosed shelter followed by well-designed environmental controls.[119] The following list is conceived as a program of treatments that are mutually reinforcing:

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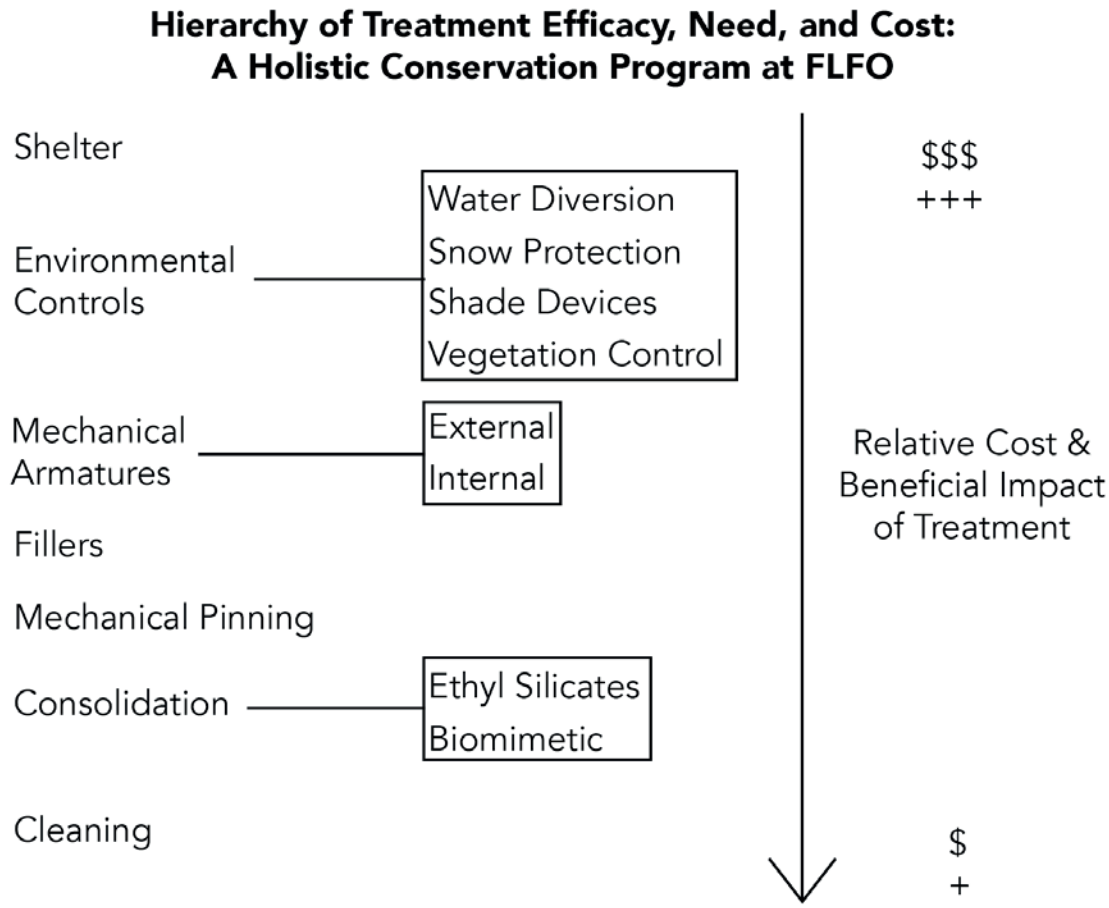
118 Gregory, Letter "To whom it may concern," 1989.

119 Mothballing is a standard procedure for most paleontological resources. See Császár et. al., 2009 for a discussion of the mothballing of a Miocene fossil forest in Hungary. It should be acknowledged that there are processes whereby moveable objects and architectural elements can be totally impregnated with UV stable polymers for total consolidation under pressure in enormous autoclave boilers over months. These processes are very expensive, and are suited for architectural sculptural elements, not enormous, highly fractured, paleontological resources. In addition, not only would severely interfere with the structures' primary scientific values for future research, the only facility executing this work is in Germany. (JBACH & GMAH, 2016)



1) Architectural Shelter: Designs for a controllable environmental enclosure system may be explored by a special seminar at the University of Pennsylvania's School of Design in 2017-18. An enclosed shelter, total environmental protection, is the only way to assure stump preservation.

2) Environmental Control Systems: Landscape designs for preventative conservation can include re-grading crater bottoms, incorporating swales to prevent water pooling, pumps to remove pooling water after spring melts or heavy rainfalls, and the use of plantings or seasonal screens as snow fences and shade devices. Crater slopes can be modified to channel water beyond the zone of capillary rise. For instance, there is a 100 foot+ trench that collects the water from the surrounding landscape and grades directly into the excavated pit of stump P42, this could easily be blocked. This system requires a wall-less roofed shelter in combination with the above mentioned designs. Rooflines should extend past crater rims.

3) Mechanical Armature: A coordinated flexible internal and external armature system could prevent decay in different zones. For instance, stump tops may be researched by Dr. Herb Meyer at FLFO in the future, this might allow for an opportunity for a coordinated armature system installation that ties an external band with flexible wires to central post in the centre of the stump. This could be covered so as not to visually detract from the stumps, and turnbuckles could allow for future tension control. This solution would accommodate the deeply incised or heterogeneous plan of the stumps, reinforcing the zone of fragmentation, without being as visually distracting as the current circular loops within metal banding. Other options include a discrete modification quake-wrap polymer, carbon fibre, or Kevlar webbing. If metals are used they should be highly corrosive resistant, and existing corroding metals should be replaced.

4) Fillers: Surficial crack sealants designed to mitigate water penetration and further dilatancy. Spot-welding adhesives could also play a roll in stump conservation, but would require more testing and research to establish formulations and procedures.

These would only be suggested in a scenario where a shelter or environmental controls are assured.

5) Mechanical Pinning: Reintegration of detached pieces, and mitigation of incipient tabular detachment, might be realised through mechanical pinning. Pinning would only be executed in areas where FLFO wood integrity is sound, and primarily suggested in a scenario where a shelter has been constructed.

6) Consolidation: Application of a consolidant could improve the mechanical strength of FLFO wood. In particular, any detached piece to be reintegrated by mechanical pinning, and the host socket, could benefit from this type of treatment. At the time of writing consolidation methods are being explored by Dr. Ioanna Kakoulli from UCLA with Dr Admir Masic from MIT. Previously Young *et al* (2008) did attempt the use of ethyl silicate consolidants on wood samples, but pre-mechanical characterisation and follow-up treatment evaluations were not performed.

7) Cleaning: The removal agents of deterioration like deposits, staining, and existing corroding metal are significant for interpretation and material integrity.

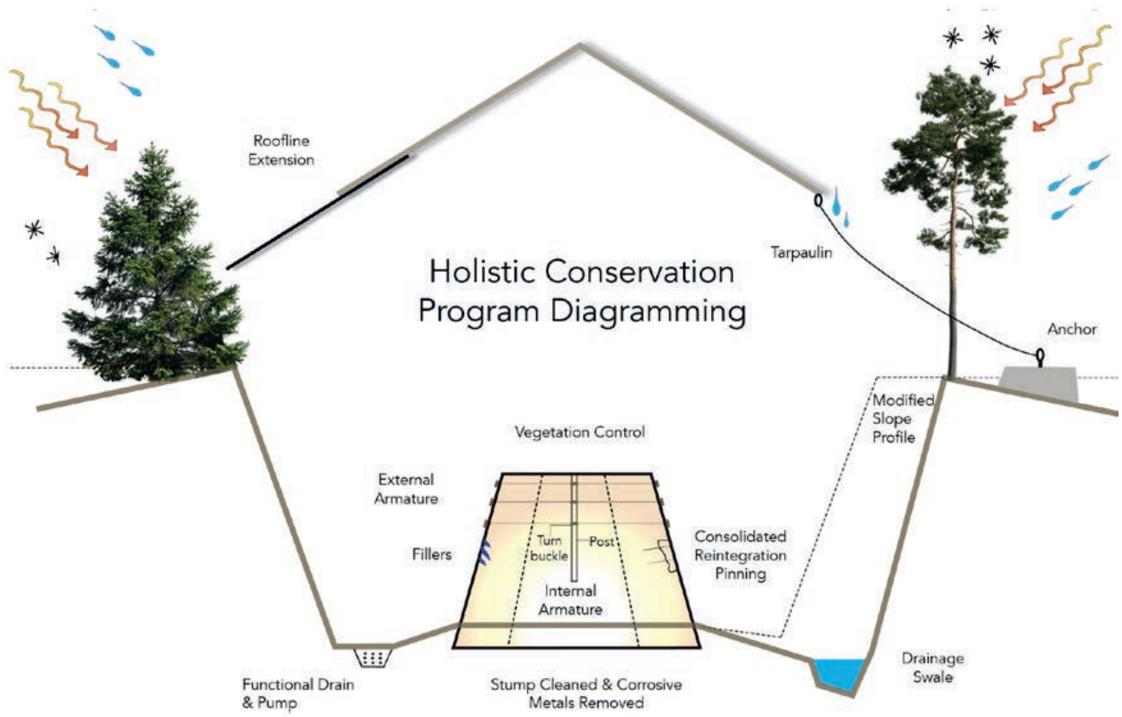


Figure 6.1: A diagrammatic depiction of a holistic conservation program for FLFO.

6.1 Conservation of Stone by Pinning

Mechanical reinforcements of stone as a conservation treatment for heritage materials are typically designed for remedial reinforcement of structural deformation, preventative conservation of predicted decay, and for aesthetic reintegration of fabric, form, and texture.[120] In the built environment it has been used to stabilise structural members of built heritage like window tracery or piers, to reincorporate missing or detached elements like sculptural ornamentation, to consolidate reinforce buttresses, and tie wall-sections together.[121] Reinforcements also take the form of skeleton armatures on the exterior or interior of a resource. The size, shape, integrity, environmental loads, values, and material properties of both the reintegrated and host

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120 Ashurst & Burns, pp. 85-88 & 114, 2007.
121 Ashurst, 2007. Blok-Lok, 2017.

fabric are just a few modifying factors in the selection of mechanical systems and materials.[122] Pinning is but one subset among the wider family of mechanical reinforcement systems.

The subject of pinning as a conservation method for stone as cultural heritage has been explored by a number of authors in publications on the conservation of masonry and sculpture.[123] Evaluations of a wide variety of fixing materials including dowels, threaded rod, reversible mechanical systems, and bone screws have been subjects of a number of mechanical treatment testing programs over the past two decades.[124] The approach this research takes is novel by evaluating the design of pin failure before anchored material failure, and explores failure modes of controlled plastic deformation as a goal. Considering that the stumps at FLFO are highly fractured and subject to a number of environmental forces, all of which likely cause continuous movement, flexible plastic treatments have been explored.

6.2 Pinning Systems & Materials

Mechanical pinning or anchor systems can be broadly categorised as either wet or dry. Wet pinning systems rely on liquid or semi-plastic adhesives or grout. These function as an adherent or gasket at the interface between the socket of host material and a structural dowel. One of the main advantages of wet systems include the elimination of potential moisture condensation and near perfect conformance to

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122 Ashurst & Burns, pp. 319-330, 2007.
123 Henry & Odgers, 2012 & Henry, 2015.
124 Glavan, 2004 ; Federico, 2008; Devreux, Guy & Spada, Stefano, 2013 & 2015; & Wheeler et. al., 2010 & 2016.

irregularities in a prepared socket. However, wet systems are largely not reversible and difficult to retreat. For instance, the ubiquitous Paraloid series of acrylics are a conventional conservation adhesive for many objects in museum contexts, and considered by some to be the de-facto choice for paleoconservation.[125] However, the reversibility of Paraloid in deep holes of a material riddled with cracks is fraught with practical difficulties. Any solvent used to clean a socket would inevitably penetrate lamellar fissures and fall outside of the reach of the conservator. The Paraloid series has seen limited use and research for exterior environments, particularly so in cold climates, and embrittlement and creep are likely. Injection adhesives were ruled out given the blind nature of the cracks and detachments and hidden microcracks below the surface.

Promising reversible dry pinning systems have been explored with the use of non-corrosive metals, reversible inserts, magnets, and even springs. However, these designs are bespoke fabrications outside the budget and schedule for this research, and are well above desirable mechanical performance at FLFO having low flexibility and high strength.[126] Commonly available patented pinning systems used to create new bonds between wythes on high-rise masonry structures include helical anchor ties, which can be grouted or left dry, but these are not reversible, are too stiff, and their diameters too large for the current work. Common concrete anchor systems are wedge anchors, whereby a sleeve is inserted into a socket that expands to create a friction fit when a threaded bolt is screwed into it, but these are far too strong for FLFO wood. Dry wall expansion plugs were considered, but they are of limited lengths.

[125] Russell & Strilisky, 2016.
[126] Devreux & Spada.

6.2.1 Reinforcement Design

This experimental research pursues the concept of expansion bolts as a two-part assembly. A rigid threaded rod or screw being housed in a flexible rubber tube was explored to ensure primary conservation treatment values, such as:

1) Preservation of fabric-centred value of the paleontological stump material;
2) Treatment reversibility;
3) Simplicity or ease of installation and future de-installation; and
4) Customizable dimensions and scalability.
5) Flexibility considering the likelihood that stump structures are in movement.

Assumptions include: material that has detached from a stump's zone of exfoliation should be reintegrated for both structural and aesthetic integrity, and that incipient spalls can be prevented. The structural concept of the two-part assembly is that a rigid pin can be inserted into a polymer sheath or tube, providing the expansive force known as a press fit necessary to secure the assembly. The more rigid pin provides the necessary strength to resist the static load of the reintegrated or pinned material, while the polymer interface can act flexibly accommodating stress as elastic movement without brittle failure or point loading of host material. Again, the design concept revolves around a pin that fails before its host material. In this context, elastic deformation or plastic failure modes are more desirable than sudden brittle collapse. It is emphasised that this treatment method is only intended to be a part of a holistic treatment programme including shelter, environmental controls, fillers, and armature.

6.2.2 Failure Modes

The discipline of engineering and product design for products, services, or assembly processes use the term failure modes and effects analysis (FMEA) as a step-by-step way to avoid avenues for failure in an intended design by identifying all potential risks and threats.[127] The term failure-modes includes the process of a given failure whereas effects analysis studies the results of said failure. This research considered different types of failure modes and considered elasto-plastic deformation, the moment between elastic limit and breaking strength, because of its potential to preserve the integrity of silicified wood at the expense of the designed assembly.

127 ASQ, 2017.

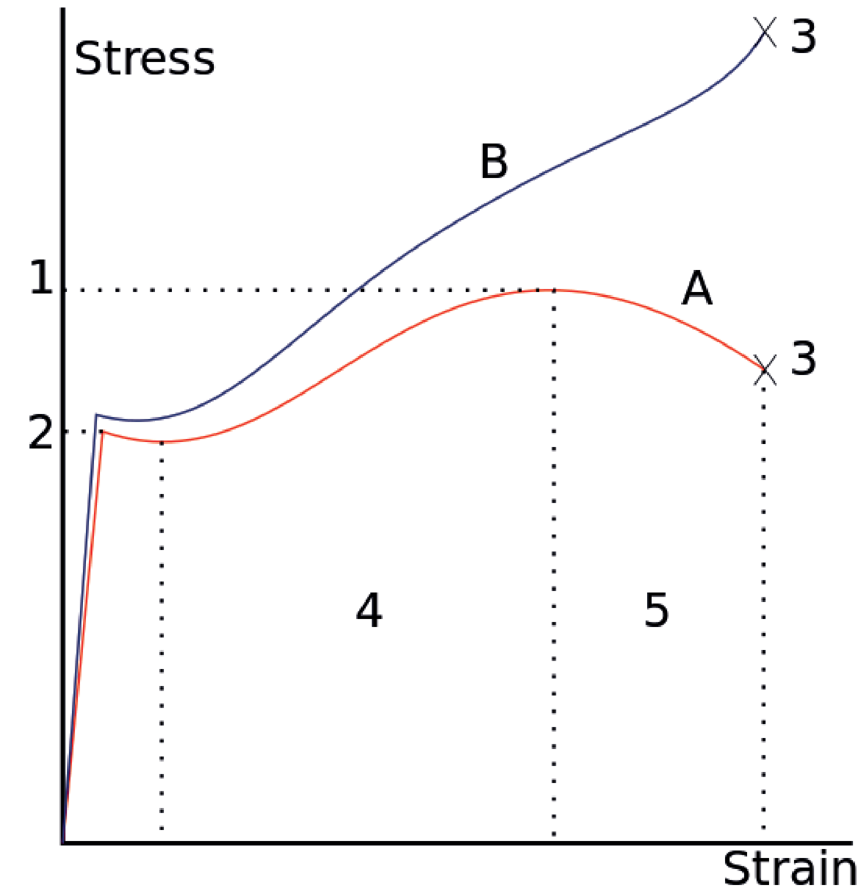

Figure 6.2: Stress-Strain Diagram of Steel. 1:Ultimate Strength 2:Yield Strength 3:Rupture 4:Strain Hardening Region 5:Necking A:Apparent stress (F/A_0) B:Actual stress (F/A) (Source: Wikicommons, Plasticity (Physics); 2017)

It is predicted that a thick strong rigid dowel, like steel, with much higher mechanical strengths on bare silicified wood could fracture the stone under stress, whereas a rubber sheath can absorb and distribute a load more evenly. Other more brittle dowel materials, like stone or ceramic, may fail before silicified wood but will exhibit sudden brittle failure that could lead to petrified wood damage.

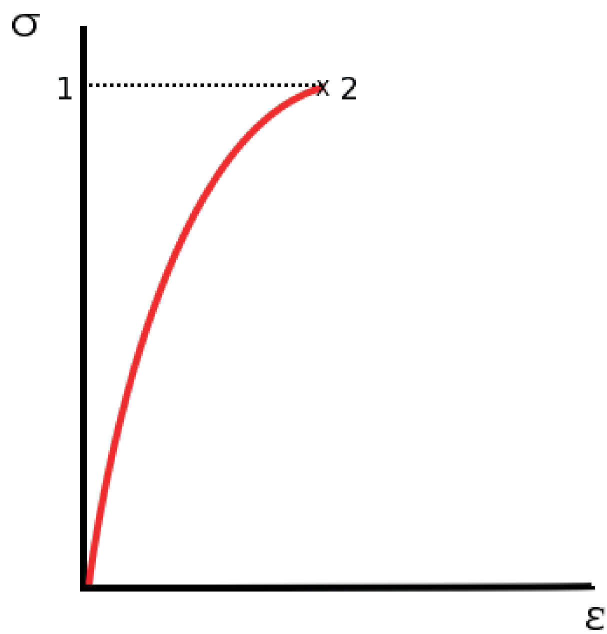

Figure 6.3: Stress/Strain Diagram of Brittle Materials, High Strength and Sudden Failure (Source: Wikicommons)

Thermosets, thermoplastics, rubbers, and elastomers were explored in order to evaluate the potential application of materials that exhibit failure modes that are more elasto-plastic. This concept builds on previous research, designing dowels for pinning headstones in cemeteries whereby brittle nylon was intended to fail in case a vandal tries push it over. The conventional alternative, epoxy set steel dowels, do not fail under loads provided by a person, but instead the valuable stone object fractures at the point of pinning.[128] In this scenario, if a headstone must topple it is presumed preferable that it falls with the least amount of damage. Lower strength pins such as plastic nylon are therefore preferred, unless a metal is of such small diameter that the effects of scalable strength impart flexible properties.

[128] Federico, 2004.

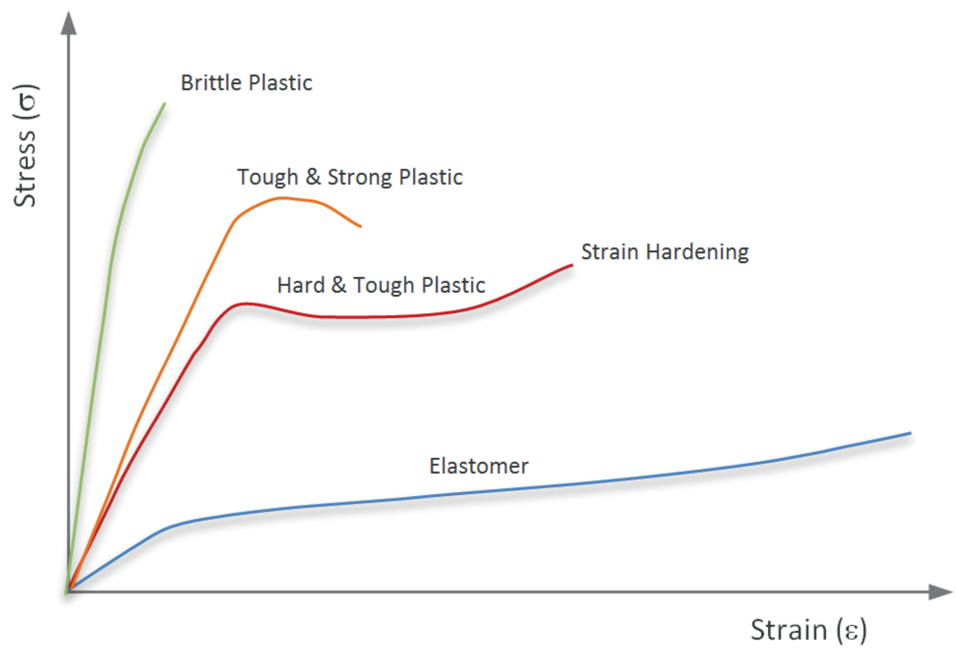

Figure 6.4: Plastic Failure Modes (Source: Polymer Database, http://polymerdatabase.com/polymer%20physics/images/Stress-Strain.png)

6.3 Material Selection Criteria

Investigation of engineering design processes invariably leads one to the Ashby method of material selection, wherein a range of material properties critical to design performance can be identified, compiled, and compared on the software known as the Cambridge Engineering Selector (CES). This can reduce the potential thousands of materials that could be used for pinning to an intelligible number. It helped to identify three material classes, and their subfamilies, for use in the pinning assemblies: 1) Polymers (Thermoset, Thermoplastic, and Elastomers) 2) Brittle Inorganics, such as Ceramics and Stones; 3) and Metals. Only a small range of material was selected for testing because of sampling and schedule limitations.

Nevertheless, for small batch designing the usefulness of CES is limited by variables like cost and availability. A typically expensive plastic can be made affordable by economy of scale and form, instead of being lumped into process-engineering design scale, costing by the tonne. In addition, CES does not relate to the ready availability of form for small batches with middlemen suppliers. For this reason the author familiarised himself with supplier availability and pricing according to form, size, and quantities, and compiled these in a decision making matrix (See Appendix B). Useful resources include literature produced for the cryogenic, automotive, aeronautical, beverage tubing, and gasket industries. The parameters one can consider for material selection in mechanical pinning are numerous, the authors chosen criteria are listed below:

1) *Cost*

Low cost is important for pinning selection because FLFO has over 30 stumps throughout the park. High material costs could render a treatment unfeasible, for instance, a 4” diameter rod made of PEEK costs $1036.20/ft. However, a ¼”-1/2” diameter pin costs between $6.01-$20.07/ft, meaning that the use of some materials might be possible considering pin size requirements. Therefore, some materials may be suggested for small diameter micro-pinning but overlooked for larger diameters.

2) *Mechanical properties, moduli of rupture and elasticity, tensile and shear strengths*

Flexural strengths and tensile strengths are the primary mechanical properties of concern for a pinning assembly subjected to a combination of shear, tensile, and flexural forces, the principle being that the assembly transfers the load of an anchored unit to a larger host. FLFO silicified wood is hard, and in some directions strong, but it is also very fragile, often being riddled with lamellar fractures. Controlled failure modes are desirable, avoiding conical failure modes or fracturing. Compressive strengths are not of great concern because these types of forces are not associated with stump pathology or predicted performance stresses involved with anchoring.

3) Resistance to chemical and weathering alteration

A chosen pinning material should be UV and atmosphere stable, resistant to negligible chemical weathering from airborne pollutants and water as to be expected at FLFO's relatively pristine environment, largely free of salts. Pinning materials must be able to resist creep at temperatures above 60° Celsius and not become embrittled around -30° Celsius (a material should not pass its glass transition-zone where it is more susceptible to elongation or failure under load, unless viscoelasticity is strong enough to regain position).

4) Installation, or ease of workability

A chosen pinning material should be easy to prepare in a simple milling shop (for instance, if threading is necessary) and it should be easy to modify and install onsite.

5) Reversibility, or re-treatability

One of the tenants of the International Council on Monuments and Sites (ICOMOS) Venice Charter (1964) and the American Institute of Conservation *Code of Ethics* (AIC) is that an intervention in cultural heritage should be reversible, in those cases where irreversible treatments are not possible this charter does allow for empirically designed treatments.[129] In recent decades it has been acknowledged that no treatment is actually reversible, and instead what is desired is re-treatability.[130] Any pinning materials and system explored has been chosen under this light of re-treatability.

6) Thermal & hygric coefficients of expansion

The degree to which a pinning assembly expands and contracts in relation to its host material is of great concern. Similar coefficients in both a pin and host material makes for a more compatible pin that is less likely to cause unnecessary pin failure or anchored material deterioration due to dissimilar movement. Nevertheless, pinning assembly socket preparation can design a running clearance to accommodate this linear expansion.

7) Porosity & Water absorption

Low porosity and water absorption/adsorption is significant for freeze-thaw resistance and linear hygroscopic coefficient of expansion in relation to weathering.

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[129] ICOMOS, Venice Charter & AIC Code of Ethics
[130] Serino, 2003 & Barrett, 2017

8) Friction coefficient and surface area or profile in section

A high friction coefficient, or large surface area like a threaded rod, is thought to be an important factor for assembly stability and pull out strength of an assembly.

9) Availability, dimensional costs & supplier lead-times

Decision informing data was obtained from a combination of manufacturer and recent literature. A material property matrix was collated to make relatable comparisons. The parameters above were compared to FLFO material property data, as generated by material characterisations in Section 5.0.[131]

6.3.1 Polymers

As a class of materials categorised in the field of materials science, polymers can be broken down into Thermoset, Thermoplastics, Thermoplastic Elastomers, and Elastomers.[132] Polymers are organic and semi-organic materials with large molecular weights. Thermoplastics and non-vulcanized elastomers are not molecularly cross-linked, where as thermoset, thermoplastic vulcanizates, and elastomers are.[133] Thermoplastics are formed by cooling and regain the ability to move upon reheating. Thermosetting materials cure by way of an exothermic chemical reaction, like a two-part epoxy involving the reactant and an epoxide, these are permanent reactions that

[131] See Section 5.
[132] Osswald et. al., 2006. p. 5.
[133] Osswald et. al., 2006. p. 5.

cross-link during curing.[134] Weather performance, creep, failure modes, flammability (like all organic materials), and thermal coefficient of expansion can be primary concerns with all of these materials.

However, there is a large amount of combinations of polymers because of additives and mixtures which are constantly being designed for custom use. The following materials have been considered in light of these criteria:

Thermoplastics

1) Polyether Ether Ketone (PEEK)

An aliphatic polyester, or polyglycol, is extremely durable, very weather and chemical resistant, and is the best in its class for fatigue resistance with a wide range of working temperatures.[135] PEEK is often used with carbon fibre for extreme applications such as aeronautics. However, PEEK is extremely expensive, except at small diameters.[136] PEEK was only considered for micro-pinning because it is near in strength to steel, which at larger diameters would be far in excess of FLFO modulus of rupture. Small diameter tubing was explored.

2) Polytetrafluoroethylene (PTFE - Teflon)

Discovered at DuPont in 1938, PTFE is only being considered for pinning up to 1/2”-3/4” diameter because of costs.[137] It is part of the wider fluoropolymer family, more

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[134] Osswald et. al., 2006. p. 5.
[135] Osswald et. al., 2006. pp. 620-622.
[136] McMaster-Carr. Website
[137] McMaster-Carr. “Rods made from Teflon PTFE.” Accessed Online 10 February 2017 At: https://www.mcmaster.com/#teflon-(made-with-ptfe)/=16ps294

specifically a fluoro homopolymer, and it has unique thermal properties including a 1.3% volume increase when temperatures decrease at 19°C.[138] PTFE as a wide range of working temperatures, a low coefficient of friction, can be susceptible to creep. However, it has very good service life even at extremely low working temperatures. Tubing was explored at small diameter, larger diameter pins might be possible.

3) Polyvinylidene fluoride (PVDF – Kynar)

Kynar, also a fluoro homopolymer, very corrosion resistant and has low thermal conductivity, and is only reasonably priced up to ½" diameters. [139] Many other types of Polyvinyls (PVA/PVB) are not suggested for museum or collection by NPS because they can release volatile acids.[140] In addition, PVDF is less commonly available. This material was not explored due to expense and availability.

4) Polyamideimide (PAI - Torlon)

Torlon, a proprietary thermoplastic polyimide, is a very expensive engineering material used in aeronautical and aerospace industries working over a wide range of temperatures.[141] It was not explored due to costs.

5) Polyoxymethylene (POM - Acetal/Delrin)

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138 Osswald et. al., 2006. pp. 569-573.
139 Osswald et. al., 2006. pp. 569-573.
140 https://www.nps.gov/museum/publications/conserveogram/18-02.pdf
141 Osswald et. al., 2006. p. 627.

A wide range of working temperatures, this material has a very low coefficient of friction and is susceptible to prolonged exposure to even weak acids.[142] This material was not explored due to expense and availability of form.

6) Polymethyl methyl acrylate & Methyl methyl acrylate (PMMA, & MMA - Acrylic)

A part of the acrylate polymer group, these gained commercial force under Rohm and Haas from the 1930s on. Acrylic is a clear rigid substance with a high thermal coefficient of expansion, but a low embrittlement temperature being below -40°C, and difficulty in obtaining a threaded form, meant that it wasn't explored.[143]

7) Polyethylenes (PE, Low Density – LDPE, High Density - HDPE)

Both polyethylenes bear some of the closest tensile yield strengths to FLFO's flexural strength at 1400-1740psi. LDPE has good low temperature impact resistance and is slightly more flexible than HDPE which has higher strength and is consequently more brittle. LDPE can suffer from stress cracking. PE exhibits excellent low temperature and weathering properties.[144] Difficulty in obtaining a threaded form meant that it wasn't explored.

Thermoset Rubbers and Elastomers

Thermosetting polymers undergo exothermic chemical reactions which create strong and durable cross-links during curing that cannot be recycled by re-heating. With increasing temperature rubbers exhibit the same viscoelasticity of thermoplastics,

[142] Osswald et. al., 2006. pp. 584-586.
[143] Osswald et. al., 2006. pp. 577-580.
[144] Osswald et. al., 2006. pp. 513-522.

except when formed by vulcanization.[145] Vulcanization cross-links macro molecules and can become either soft rubbers like an elastomer or a hard rubber. The elastomers therefore hold an intermediate position between thermoset and thermoplastic polymers, however are not recyclable like thermoplastics.

Rubbers are another type of more durable elastomeric thermoset that also require heat. Elastic polymers like rubbers and tubing can be classified by gross physical characteristics of bending radius and resistance to pressure, some elastomers are thermoplastic. Resistance to pressure is defined by an international standard named Shore Durometer scale as illustrated below:

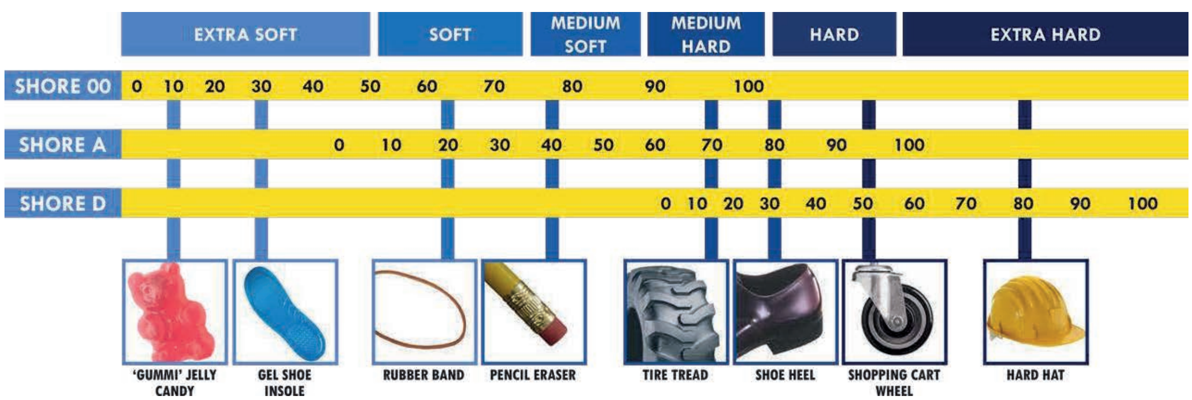

Figure 6.5: Plastic material physical characteristics as classified by the three Shore Durometer scales. (Source: Smooth-On, 2017)

The higher the durometer the more resistance an elastomer or rubber exhibits upon compression. There is a relationship between a material modulus of elasticity and durometer numeration.

1) Polyurethanes (PUR)

[145] Osswald et. al., 2006. pp. 686-690.

PUR is a large, diverse, and versatile group of polymers that are never pure, but share polyisocyanate chemistry in common. They range from rigid plastic to elastomeric rubber, can be weather resistant, and generally embrittle at -40°C. Different proportions of fillers, such as mica, glass, carbon, or silicates for example, can radically change their properties like mechanical strength or elasticity. Adhesives of this class should not be submerged in water for prolonged periods, but rubbers are typically resistant.[146] Some types are weak with exposure to UV.

2) Polychloroprene (Neoprene)

Comprised of polymerised chains of chlorine molecules, it retains elasticity up to -40°C and is available in foam and solid rubber form. Tensile strength is just below FLFO flexural strength.[147]

3) Tygon (Long-Life (Norprene Rubber) & Smooth Flow - PVC)

A commonly used brand of various durometer tubing for liquids in a wide range of industries from chemical laboratories to beverage supply. Proprietary PVC base, Saint-Gobain's product lines have a wide range of material properties tailored to specific applications. 'Long-life' Tygon has a durometer of 60A and very cold working temperatures.[148]

4) Nitrile Butadiene Rubber (Buna-N)

20-50% acrylonitrile content, it is a durable rubber appropriate for exterior use up to -30°C, some grades can withstand even colder temperatures. Availability in useful diameters are not conveniently available for this project.[149]

5) Silicone & Fluorosilicone (Silicone & Fluoroelastomer - Viton)

[146] Osswald et. al., 2006. pp. 635-649.
[147] Osswald et. al., 2006. p. 691
[148] Osswald et. al., 2006. p. 692 & 870.
[149] Osswald et. al., 2006. p. 692.

Often used in aerospace applications, it is chemically resistant, can handle a wide range of temperatures, and UV. The elastomer Viton is prohibitively expensive, but its low tensile strength is very suitable for desirable material properties. Silicone rubbers are able to withstand very cold temperatures and are typically lower on the durometer scale.[150]

6) Fluorosint 500 & 207 (PTFE filled with synthetic mica)

Fluorosint® 500 has nine times greater resistance to deformation under load than unfilled PTFE. Its coefficient of linear thermal expansion approaches the expansion rate of aluminum and is 1/5 that of PTFE, Fluorosint 207 is lower yet, it is 1/3 harder than PTFE, has better wear characteristics but maintains low frictional properties. However, this polymer is prohibitively expensive.[151]

6.3.2 Brittle Inorganics: Ceramic & Stone

Before polymers were explored ceramic and stone was considered because of their highly compatible thermal coefficients of expansion and because they can be chosen to have lower failure strengths than the stone they support.

1) Alumina oxide

This material is incredibly strong and comes in a wide range of customizable shapes, profiles, and sizes, making it particularly ideal for micro-pinning except for its prohibitive cost. It was decided that this material's sudden brittle failure with low displacement makes it less ideal for a flexible constantly moving stump structure.

[150] Osswald et. al., 2006. pp.
[151] Osswald et. al., 2006. pp.

2) Alumina silicate

This material holds potential for future consideration as a material that could have its material properties customized with different firing, soaking, cooling regimes, very low coefficient of thermal expansion, and low modulus of elasticity. However, this material is too expensive and needs to be fired and tested to attain known material property values, and as above, this material's sudden brittle failure with low displacement makes it less ideal for a flexible constantly moving stump structure.

3) Granite

There are a range of different types of igneous stones, commonly named granite, that have low flexural and tensile strengths that make them well suited to pinning, particularly considering their low thermal coefficients of expansion. However, it is costly, only diameters above 5/8^{ths} are easily manufactured, and it can be difficult to mill or thread. In addition, as above, this material's sudden brittle failure with low displacement makes it less ideal for a flexible constantly moving stump structure.

6.3.3 Metals

Two forms of metal pins were considered: threaded rod and screws. Non-corrosive metals with low steel strengths were selected for reasons of cost and availability, for instance, titanium was not considered because of its high costs.

1) Stainless Steel 316

316 have 2-3% molybdenum, which stainless steel does not, this gives this material a much higher corrosion resistance in extreme environments, such as salty seaside

exposure, while its strength properties are comparable to 18-8 stainless series. This steel is austenitic (a face-centred cubic system) and is non-magnetic. This material was considered ideal because of its low cost and easy availability in combination with its corrosive resistance. In addition, at small diameters it is very flexible.

2) Stainless Steel 18-8

18-8 refers to a ~18% Chromium and 8% Nickel composition, this series is generally used to describe a range of 300 series (including 302, 302HQ, 303, 304, 305, 384, XM7) which is of import for specific chemical reactivity, it has superior corrosion resistance to the 400 series, but much lower strength. 18/8 has similar, although slightly lower, strength as 316. This material was considered ideal because of its low cost and easy availability in combination with its corrosive resistance. In addition, at small diameters it is very flexible.

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7.0 Pin Assembly Testing

7.1 Anchoring Parameters

Anchoring parameters have been defined by *ASTM C1242 – 16: Standard Guide for Selection, Design, and Installation of Dimension Stone Attachment Systems* & the American Concrete Institute's industry standards for design guidance of anchors and masonry pinning. The significant parameters defined by these standards are listed below:

1) Relationship of pinning diameter to embedment depth:
Depth of pin should be a minimum of two-thirds the thickness of a masonry unit.[152]

2) The relationship between a pin diameter and thickness of material:
Diameter is not to exceed 25% of unit thickness.[153]

3) Spacing of pinning from edge in relation to pin diameter:
An anchor should be placed at least six anchor diameters away from an edge.[154]

Further guidance on design specifications for any masonry application can be consulted in Glavan and Federico's theses, as this research is concerned with the development of a two-part dry press-fit system.

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[152] ASTM C1242 – 16: Standard Guide for Selection, Design, and Installation of Dimension Stone Attachment Systems
[153] ASTM C1242 – 16: Standard Guide for Selection, Design, and Installation of Dimension Stone Attachment Systems
[154] ACI Vol 318-02, 37 02

7.2 Pull out Proxy

Indiana Limestone was used as a proxy for preliminary pull out tests of pinning assemblies because, as previously demonstrated, its modulus of rupture is lower than FLFO wood. In addition, it is easily accessible in North America, and is therefore an ideal candidate to facilitate comparability in future research. Given more time and resources the author may have chosen another accessible stone type with stronger foliation such as Berea, also known as Ohio Sandstone. This experimental phase was designed to observe how different materials and their properties such as durometer, friction coefficient, and the dimensional relationship between tube and pin affect an assembly's performance. Limestone sample P1 measures 10"x10"x3" A grid was laid out with a minimum spacing of 1-3/4" for up to 1/4" holes to accommodate a the above mentioned ASTM recommended anchoring distance:diameter ratio. Limestone sample P2 measures 13"x9"x2-5/8". Material orders are recorded in the attached Appendix C.

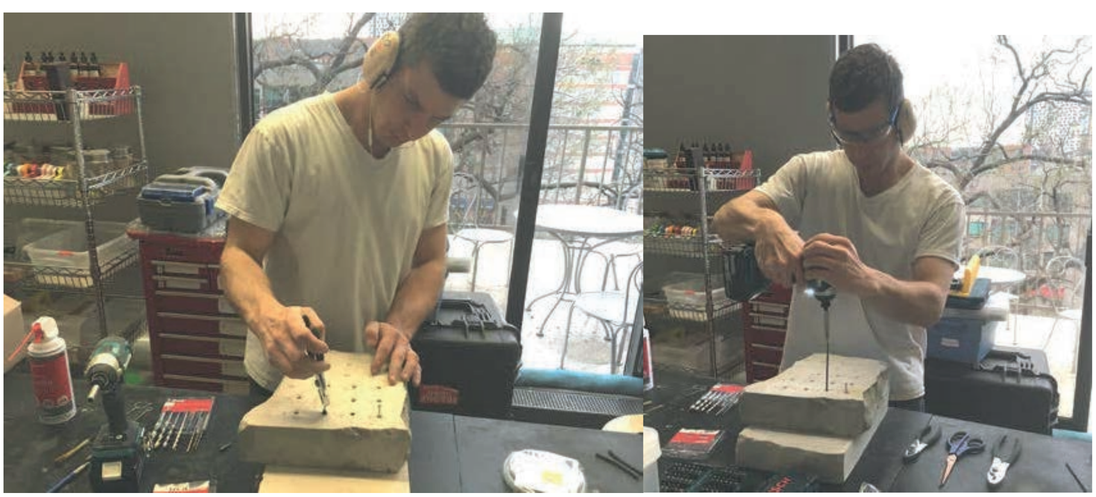
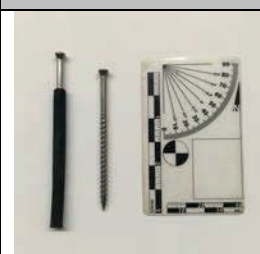
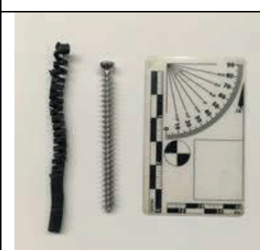
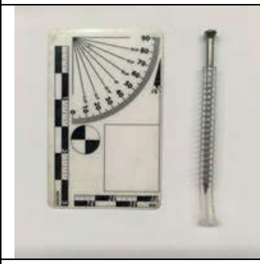
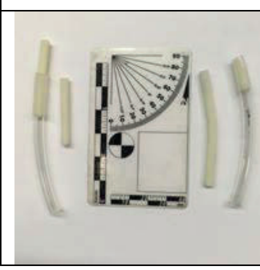


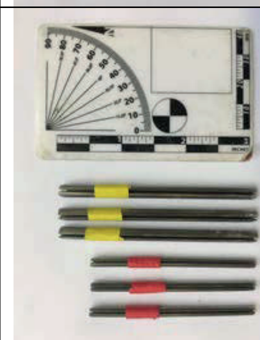
Figure 7.1: Pre-mechanical plier testing of assemblies.

The following assemblies were found to be unsuccessful in that they did not have the ability to resist human pull out strengths. Holes were drilled into the limestone with a cordless Makita Hammer Drill (XPH07) and then cleaned with a bottle brush and compressed air. Pins were threaded into tubing using a cordless Makita Driver Drill (XDT14). A pair of pliers were used by hand to extract failed assemblies. Those that were unable to be extracted were considered to have passed, and would go on to a mechanical pull-out stage. Observations and photographs recorded in the following table are useful in modifying assembly variables such as diameter:dimension:durometer.

HD= Hole Diameter OD= Outside Diameter ID= Inside Diameter VD=Valley Diameter L=Length

Assembly Type Attempt	Hole & Tube Dimensions (inches)	Shore Scale	Pin (inches)	Notes	Photographs of Assembly Failures
A1	Long Life Tygon - Norprene Rubber 1/4OD 1/8ID 1/4OD	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	Tube spun while screw tapped its way into rubber. Assembly was easily pulled out by pliers, five attempts were made.	
A2	Long Life Tygon - Norprene Rubber 1/4OD 1/8ID	60A	Stainless Steel (316) Threaded Rod #6 OD-5/32 (0.16) VD – 0.14 L - 4	First attempt failed when pulled out by pliers before cleaning the socket with a brush & compressed air. The second, third, and fourth assembly (with cleaned socket) could not be pulled out, suggesting that a slightly larger diameter could be more successful (No.8-9).	No Photo
A3	Long Life Tygon - Norprene Rubber 1/4OD 1/8ID	60A	Cancellous Screw Stainless Steel OD – (6.5mm) 0.26 VD – 0.132 L – (80mm)	Screw was removed easily, likely due to the tube section being cut into spiral shape by deep sharp threads.	

			3.15		
A4	Tygon 2475 (Medical - Smooth Flow) 1/4OD 1/8ID	72A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	Tube spun while screw tapped its way into rubber. Assembly was easily pulled out by pliers, two attempts were made.	
A5	Fluorosilicone - Vanguard 1/4OD 1/8ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	Third attempt failed when pulled out by pliers, difficult to remove. Another attempt with the same tube proved to be unremovable by pliers suggesting that a slightly larger screw size (#8) or smaller tube internal diameter/socket would be more tenacious.	No Photo
A6	Tygon 2475 (Medical-Smooth Flow) 3/16OD 1/16ID	72A	Stainless Steel (316) Threaded Rod OD-~3/32 (0.96) L - 4	Two attempts failed when pulled out by pliers, although difficult to remove, suggesting that a slightly larger diameter could be more successful.	
A7	Tygon 2475 (Medical-Smooth Flow) 3/16OD 1/16ID	72A	Stainless Steel (316) Threaded Rod #6 OD-5/32 (0.16) VD – 0.14 L - 4	Two attempts failed when the smaller tube internal diameter: threaded rod diameter caused the plastic to melt and break up, suggesting the use of 1/8" diameter threaded rod.	No Photo
A8	PUR Tube 1/4OD 0.16ID	95A	Nylon Threaded Rod OD - 3/16 L - 4	Two attempts failed when the nylon rod suffered torsional shear. It was very difficult to remove one broken nylon rod, the other was moderately difficult.	

A9	PUR Tube 1/4OD 1/8ID	95A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	Tube spun while screw tapped its way into rubber. Assembly was easily pulled out by pliers, one attempt was made.	
A10	-	-	Slotted Spring Pins – 18/8 Stainless Steel 3/16D & 1/8D 3L & 2-1/2D	Two sizes of spring pins were loose in prepared sockets drilled to correct diameters. Pins should be oversized to be compressed upon insertion.	
A11	PEEK Tube 1/8OD 1/16	-	Stainless Threaded Rod #3-#4&#2 ~7/64 (0.095) & 2- 56D 3L	Two attempts were made, one with a #3-#4 and one that is 2-56. The #3-#4 sized rod is not removable, but brought up a large amount of powdered PEEK, suggesting that it did not function as a tube so much as destroyed the material. However, it is unremovable. The 2-56 rod was too malleable and bent when threading was attempted.	
A12	PUR Tube 5/32OD 3/32ID	95A	Stainless Threaded Rod #5 0.125D 3L	Threaded rod snapped due to torsional forces when operator attempted to release the drill/chuck grip on threading after embedding the rod in the tube.	
A13	Nylon Tube 1/4OD		Stainless Threaded Rod 18/8 #5 0.125D 3L	Tube melted and spun around in hole while threading rod.	

Initial pull out failures suggested that cancellous screws and woodscrews are too aggressively threaded, compromising tube integrity. Nylon threaded rods at small diameters fail torsionally due to a combination drill torque and frictional tube resistance around 1” embedment. Nylon and PEEK tubes are too hard and melt during metal rod threading as a function of high (Shore D+) durometer, or heat generating structural resistance. Other failures can be explained by inadequate relationships of pin diameter to tube outer diameter:tube inner diameter:durometer.

Figure 7.2: Failed assemblies A1 to A13 from left to right.

Ten pinning assembly cohorts were tested in groupings of three members. Additional loner pin assemblies were tested for qualitative information gathering because of the experimental nature of testing with limited schedule and materials. While not statistically robust, loners can be useful qualitative indicators for future testing. All pins were set at a two-inch embedment depth. Stainless steel wood screws and threaded rods were tested as pinning material and different types of rubbers and plastics were tested to establish an ideal press fit tube/pin assembly. The following tables chart pinning assemblies prepared and performance in pull out testing. No assembly pull-outs caused conical shaped failure modes in the Indian Limestone that are typically associated with anchor related stone failure.[155]

OD=Outside Diameter ID=Inside Diameter VD=Valley Diameter L=Length

Sample Assembly	Tube (inches)	Durometer	Pin (inches)	Ultimate Strength (lbs)
P1.1	Teflon PTFE - 1/4OD & 4L	52D	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD (1" Embedment)	96.44
P1.2	Long Life Tygon - Norprene Rubber 1/4OD 1/8ID	60A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	41.31
P1.3	Long Life Tygon - Norprene Rubber 1/4 OD 1/8 ID	60A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	26.38
P1.4	Long Life Tygon - Norprene Rubber 1/4 OD 1/8 ID	60A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	55.08
P1.5	Fluorosilicone - Vanguard 1/4OD 1/8ID	60A	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	39.31
P1.6	Tygon 2475 (Medical-Smooth Flow) 1/4 OD 1/8 ID	72A	Cancellous Screw Stainless Steel 0.26OD 0.132VD 3.15L	DID NOT TEST

155 Federico, 2008 & Glavan, 2004.

P1.7	Fluorosilicone - Vanguard 1/4OD 1/8ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	28.76
P1.8	Fluorosilicone - Vanguard 1/4OD 1/8ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	25.08
P1.9	Teflon FEP 1/4OD 3/16ID	55D	Stainless Steel (316) Threaded Rod OD-1/4 (0.25) 0.21VD & 4L	506.03
P1.10	Teflon FEP 1/4OD 3/16ID	55D	Cancellous Screw Stainless Steel 0.26OD & 0.13VD 2.17L	101.93
P1.11	Long Life Tygon - Norprene Rubber 3/16 OD 1/16 ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	84.64
P1.12	Long Life Tygon - Norprene Rubber 3/16 OD 1/16 ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	106.95
P1.13	Long Life Tygon - Norprene Rubber 3/16 OD 1/16 ID	60A	Wood Screw #7 - Stainless 316 – 3L OD – 0.17 VD - 0.11	106.17
P1.14	Teflon FEP 1/4OD 3/16ID	55D	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	105.37
P1.15	Teflon FEP 1/4OD 3/16ID	55D	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	58.23
P1.16	Teflon FEP 1/4OD 3/16ID	55D	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	147.17
P1.17	PUR Tube (Black Twin) 1/4OD & 1/8ID	85A	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	70.05
P1.18	PUR Tube (Black Twin) 1/4OD & 1/8ID	85A	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	65.01
P1.19	PUR Tube (Black Twin) 1/4OD & 1/8ID	85A	Wood Screw #7 - Stainless 316 – 3L 0.17OD & 0.11VD	42.8

Both P1 & P2 were reoriented and clamped down for each pull-out test. A universal jointed pincer vise clamped around a pin for pull out with the 5000lb capacity load cell. Displacement was set at 1” at a maximum strength of 1000lbs, later changed to 2000lbs for the latter tests of P2. The attached Instron computer records both displacement and strain and compiles them into a .txt file, these are translated and graphed using Microsoft Excel.

Figure 7.3: P1 pull-out testing with Instron.

OD=Outside Diameter ID=Inside Diameter VD=Valley Diameter L=Length

Sample Assembly	Tube (inches)	Durometer	Pin (inches)	Ultimate Strength (lbs)
P2.1	PUR Tube 1/4OD 1/8ID	95A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	63.189
P2.2	PUR Tube 1/4OD 1/8ID	95A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	58.65
P2.3	PUR Tube 1/4OD 1/8ID	95A	Stainless Steel (316) Threaded Rod #8 OD-5/32 (0.16) 0.14VD & 4L	235.77
P2.4	-	-	Slotted Spring Pin – 18/8 Stainless Steel 1/4D & 4L	238.40
P2.5	-	-	Slotted Spring Pin – 18/8 Stainless Steel	113.13

			1/4D & 4L	
P2.6	-	-	Slotted Spring Pin – 18/8 Stainless Steel 1/4D & 4L	583.55
P2.7	NO TEST	NO TEST	NO TEST	NO TEST
P2.8	NO TEST	NO TEST	NO TEST	NO TEST
P2.9	NO TEST	NO TEST	NO TEST	NO TEST
P2.10	PUR Tube 1/8OD & 1/16ID	95A	Stainless Threaded Rod #3 7/64 (0.095)D &3L	689
P2.11	PUR Tube 1/8OD & 1/16ID	95A	Stainless Threaded Rod #3 7/64 (0.095)D & 3L	165.85
P2.12	PUR Tube 1/8OD & 1/16ID	95A	Stainless Threaded Rod #3 7/64 (0.095)D & 3L	401.46
P2.13	PEEK Tube 1/8OD & 1/16ID	-	Stainless Threaded Rod #3 7/64 (0.095)D & 3L	250.16
P2.14	SEE A12 - FAILED	SEE A12 - FAILED	SEE A12 - FAILED	SEE A12 - FAILED
P2.15	NO TUBE	-	Wood Screw #7 - Stainless 316 3L & 0.17OD & 0.11VD	DID NOT TEST
P2.16	PUR Tube 5/32 & 3/32	95A	Stainless Threaded Rod #5 0.125D & 3L	<1100 (1045.22 Recorded)
P2.17	PUR Tube 5/32& 3/32	95A	Stainless Threaded Rod #5 0.125D & 3L	<1100 (1044.78 Recorded)
P2.18	PUR Tube 5/32 & 3/32	95A	Stainless Threaded Rod #5 - 18/8 0.125D & 3L	954.25
P2.19	PUR Tube 5/32 & 3/32	95A	Stainless Threaded Rod #5 - 18/8 0.125D & 3L	953
P2.20	PUR Tube 5/32 & 3/32	95A	Stainless Threaded Rod 18/8 #5 0.125D & 3L	953.73

The following graphs chart the highest ultimate strength sample per cohort as a way to compare different pinning assembly performance. These were grouped as low (0-110lbs), medium (110-250lbs), and high strengths (450-1100lbs) according to the standard deviation of each group. Tests were generally run until one inch of displacement, except when failure was apparent. The highest strength is highlighted because a pinning assembly that will not exceed the modulus of rupture of FLFO wood is desired. Each pull out has been plotted and is attached (See Appendix D for all Mechanical Testing Data).

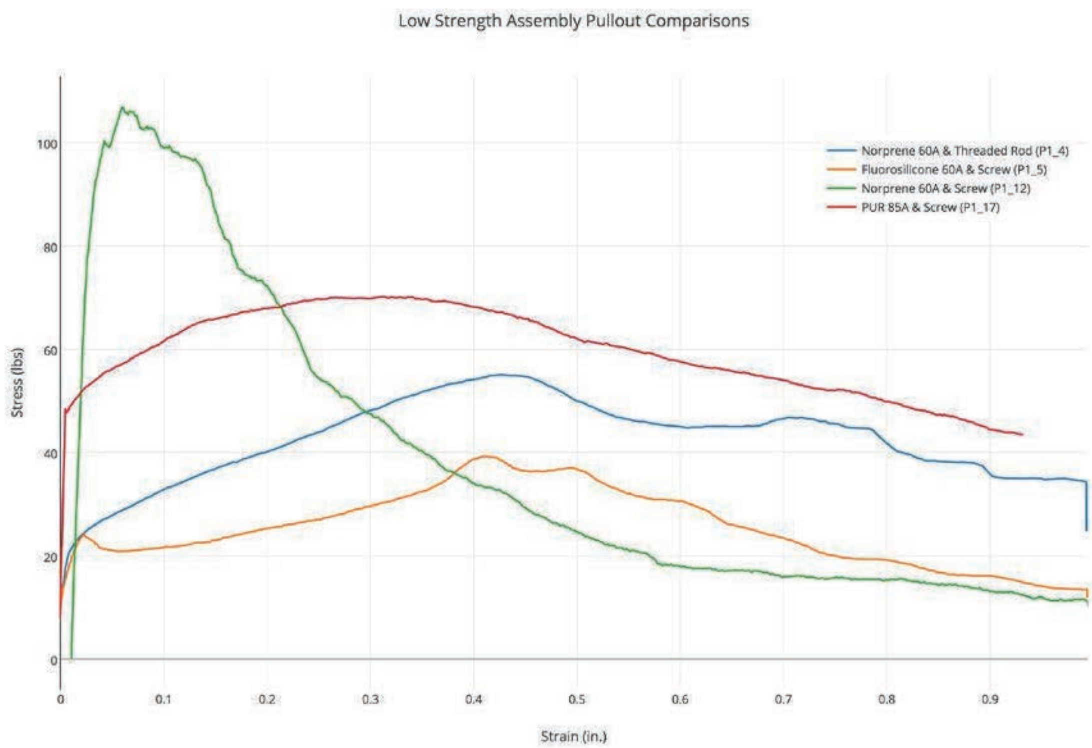


Figure 7.4: Low strength assembly pull out comparisons.

Comparison of P1_4 with P1_12 highlights the relationship between pin diameter and pull out strength is apparent. The wood screw used in P1_12 has a wider diameter and it is likely due to increased load transference through hoop stress that imparts the assembly a higher pull out resistance. However, the sharp and deep threads also cut the tube, apparent in the shredded form observed upon extraction. In comparison P1_4 with its shallower and more closely space threading left the tube intact. However, because there was substantially less hoop stress applied to the tube the assembly was easily extracted intact, meaning the amount of stress or load transference that the assembly was capable of was substantially less, almost by a factor of 2. P1_4, P1_5, and P1_17 exhibit plastic deformation with characteristic elastic rebounds, strain hardening, and necking, these elasto-plastic qualities are more akin to a desirable failure mode at FLFO, however assembly very low pull out resistance precludes them from use.

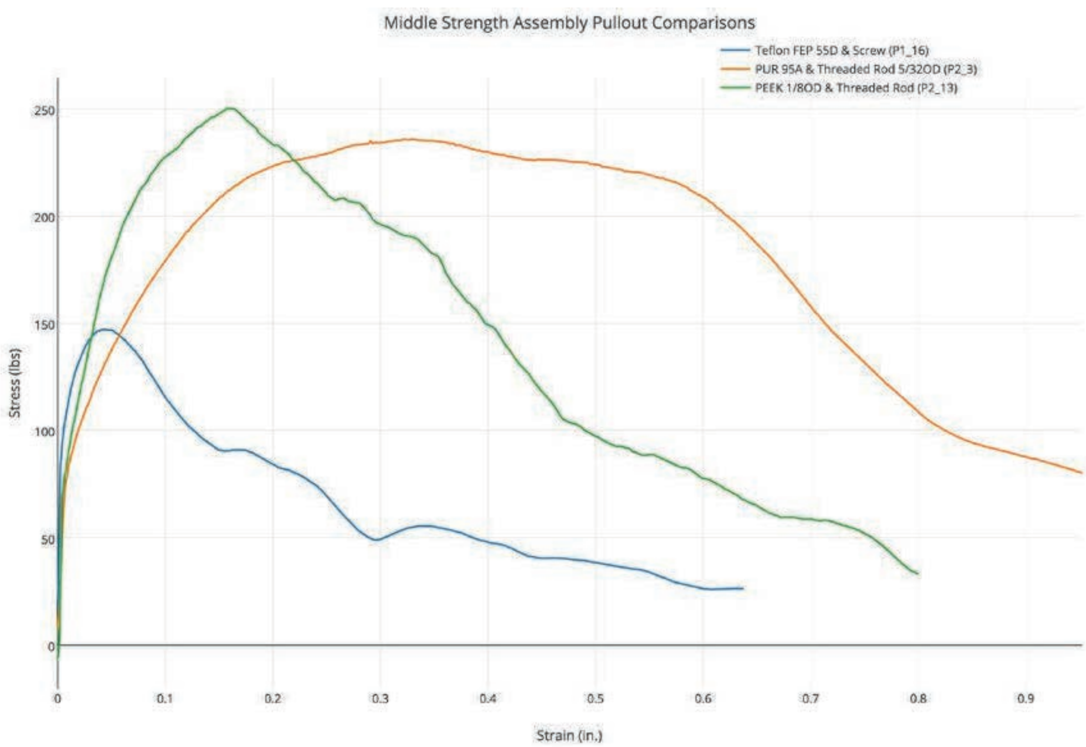


Figure 7.5: Middle strength assembly pull out comparisons.

Prior to testing it was assumed that there would be a relationship between durometer and pull out strength. Plastics with higher durometers usually have lower coefficients of friction, and this was thought to correlate to lower pullout strengths. However, the three lower friction coefficients of samples P1_16, P2_3, and P2_13 was less significant than the greater stiffness and compressive strengths associated with higher durometers. The Teflon and PEEK (P1_16 & P2_13) samples exhibited sharper failure than the more plastic failure mode of elongation and necking seen in the PUR 95A sample (P2_3).

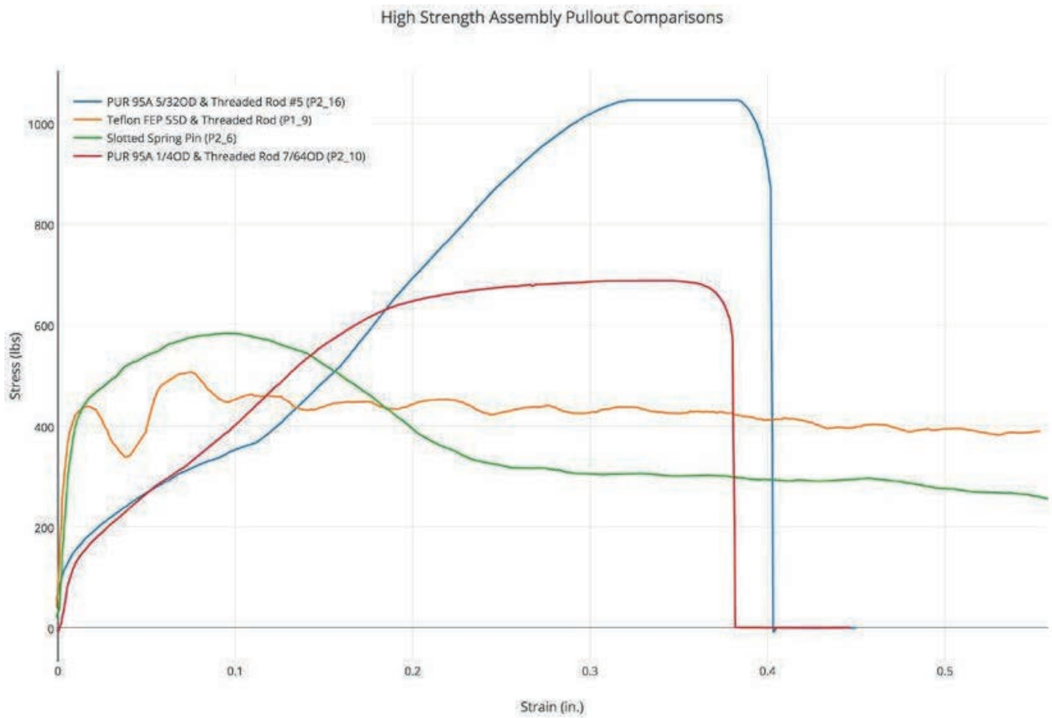


Figure 7.6: High strength assembly pull out comparisons.

Assembly P2_10 in comparison to P2_3 in the middle strength chart above demonstrates that significant higher pull-out strengths can be attained by increasing pin diameter. The Teflon FEP tube, P1_9, exhibited a very long tapering elongation, and was halted at one inch of deflection. P2_16 was remarkably strong, surpassing expected weight limits by about 50lbs. The computer stopped recording at ~1050lbs, explaining the plateau, however the Instron manual recording displayed failure just below 1100lbs. The PUR 95A tubing did not fail, but the pin broke, for both P2_16 & P2_17. Again, the same assembly was used for P2_16-17 with P2_18-20 only with a 18/8 stainless steel substitution. This pin failed around 950lbs for all three pull-outs. This assembly is ideal as failure occurs at puts its ~400lbs below the standard deviation of the modulus of rupture of FLFO wood in tangential direction.

Pin Performance			
Pin Type	Workability *(Installation & Reversibility)*	Tube Compatibility *(Good Press Fit & Tube Integrity)*	Versatility *(Material, Dimensional, & Strength Diversity)*
Threaded Rod	✓	✓	✓
Deep Thread Screws	✓	✗	✗
Spring Pin	✓	**N/A**	✗

7.3 Pinning Assembly Preparation and Bending Moment

The aforementioned FLFO brick sized sample was cut into 10 samples for assembly preparation and mechanical bend testing.

Fig 7.7: Sample preparation and pre-assembly documentation.

Two assembly tests were considered: a three point bend and bending moment. Both tests represent a complex combination of shear, bending, and tension forces on the pinning assembly.

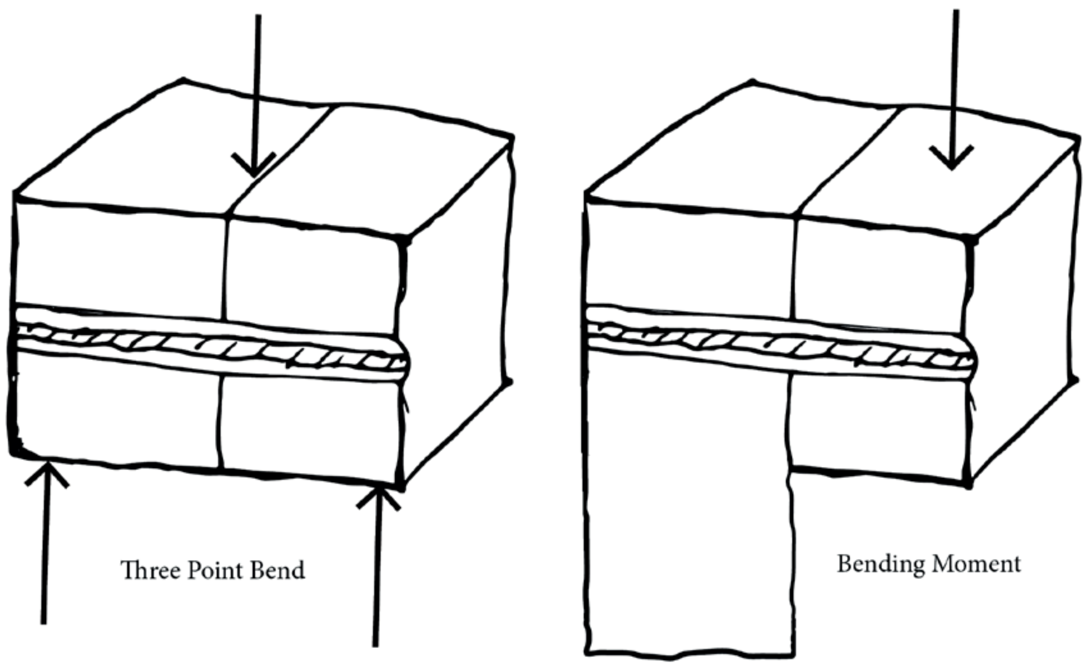


Figure 7.8: A section of the two considered bending tests, arrow downwards represents force, upward arrow on left represents points of support. Assembly on right is presumed to have one half clamped to resist entire assembly bending. Test on left is a three point bending of the pinned assembly, whereas the unit on the right exhibits a bending moment.

A one part fixed bending moment was decided because of the likelihood that a pinning treatment into a stump would create an assembly that has one fixed side (the one being stump embedded end). The bending moment is more representative of a failure whereby load is applied to the top of reintegrated FLFO wood, such as above detached piece introducing new load. The other potential failure of a pin could be due to the expansion of ice directly in the pinning assembly join, this would be more similar to the forces associated with pull out testing which had been tested by proxy above.

Samples were drilled using a General variable speed bench press drill at the Fabrication Laboratory at PennDesign using low speed, ~780 RPM. Two samples were sacrificed for test drilling. Preliminary attempts used diamond coated lapidary and core drill bits. These failed despite constant cooling, one failure causing a test sample to crack.

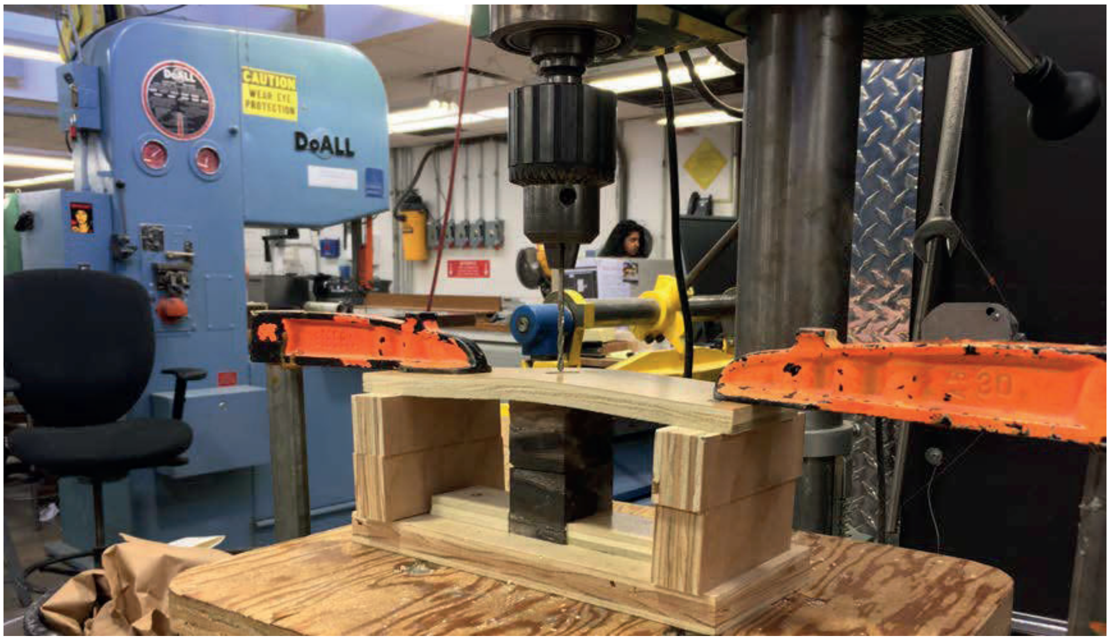


Figure 7.9: Sample drilling jig with blocking to avoid bottom unit rotation, legs of plywood top shelf cut 3/16" short and clamped down to prevent upper FLFO unit rotation. Diamond coated lapidary drill bit exhibited.

General masonry tungsten-carbide tipped drill bits were the most efficient. During drilling of dark coloured sections black effluent was discharged from the samples and were sometimes accompanied by an oily slick, and swamp-like smell. Drilling duration was approximately 20 minutes per sample because the drill bit was removed every 10 seconds and the hole flushed with water to cool the sample and drill bit. Sample compression during drilling effectively avoided large conical failure mode typically associated with through-stone drill puncturing.

Ultimate Pull Out Strengths		
Cohort	Pin Type	Standard Deviation (lbs)
C1 (P1.2 - P1.4)	Rod #8 Norprene Rubber	52.15
C2(P1.5,P1.7-8)	Wood Screw Fluorosilicone	38.74
C3 (P1.11–P1.13)	Wood Screw Norprene	122.22
C4 (P1.14-P1.16)	Wood Screw Teflon FEP	134.44
C5 (P1.17-P1.19)	Wood Screw PUR 85A	74.04
C6 (P2.1 – P2.3)	Rod 5/32 PUR 95A 1/4OD	177.51
C7 (P2.4 – P2.6)	Slotted Spring	452.86
C8 (P2.10-P2.12)	Rod #3 PUR 95A 5/32OD	575.93
C9 (P2.16–P2.17)	Rod #5 0.125D - 316 SS PUR 95A 5/32OD	1477.85
C10(P2.18-P2.20)	Rod #5 0.125D - 18/8 SS PUR 95A 5/32 OD	1167.99

It was decided to test cohort 10 because the pin failed at 2/3's the flexural strength of FLFO wood. C9 was eliminated as a choice because it was too close to FLFO modulus of rupture, leaving little margin for error.

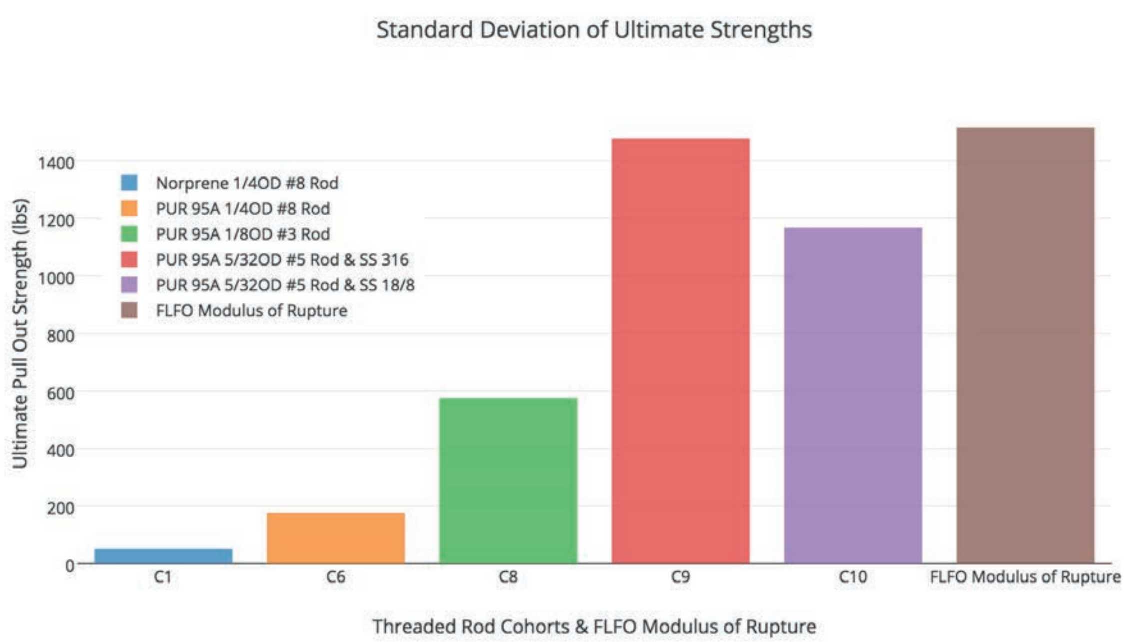


Figure 7.10: The cohorts graphed for comparability and to explain the decision making process in assembly selection for FLFO sample preparation. C10 was chosen.

The standard deviation of assembly C8 had an even wider margin for error, but it was not chosen because its variances were considered to broad. It should be noted that one C10 pin did not fail, but the assembly was pulled out and was intact.

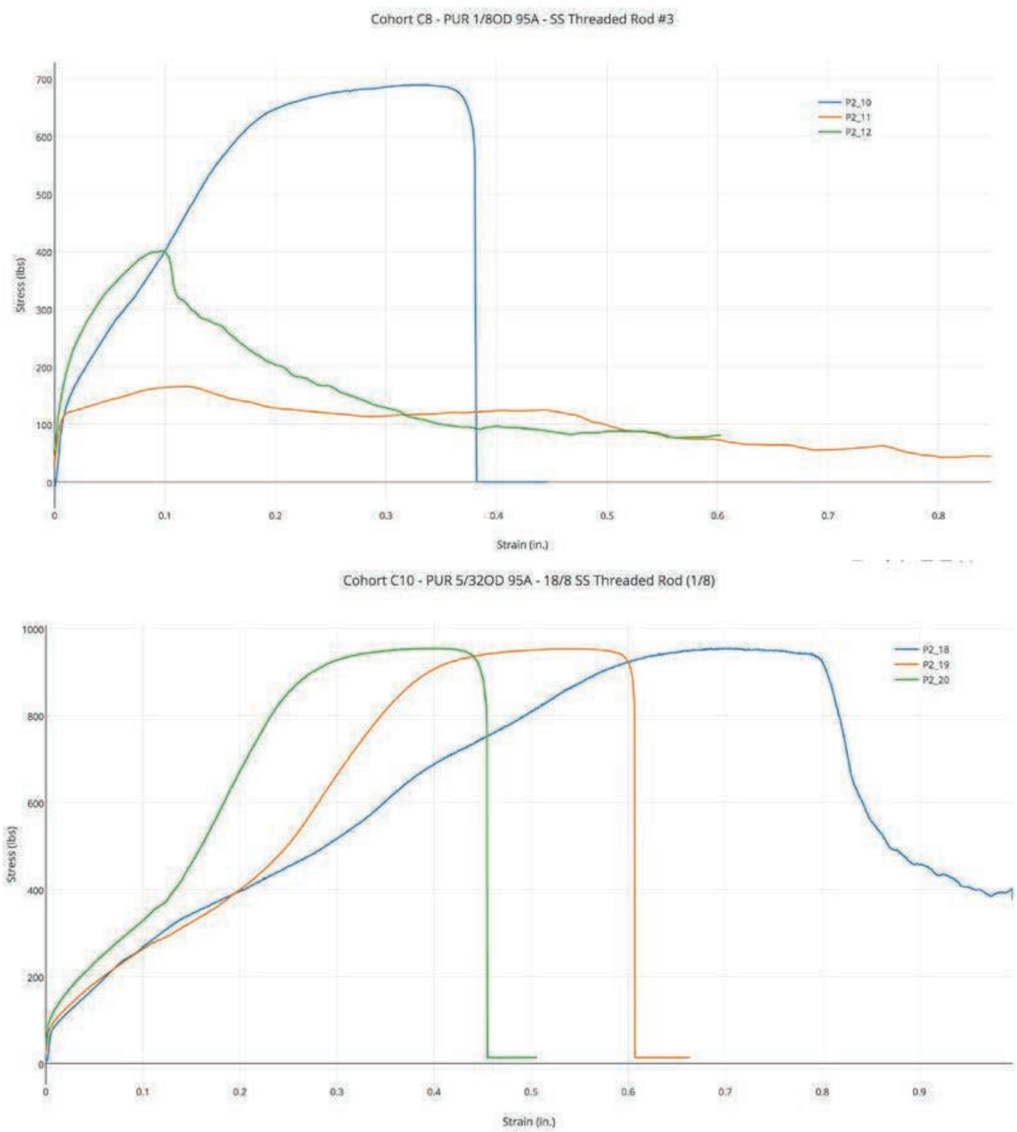


Figure 7.11: C8 stress/strain variances obvious, top, the more reliable pin failure of C10 was chosen, bottom.

During drilling, two samples fractured along pre-existing fractures. All assemblies had at least one unit failure as a result of tube and thread installation, four more samples fracturing. New cracks appeared as preferential radial separation despite this being the thickest section. This represents poor thinking on my part. Engineers refer to the term hoop stress to describe the expansive forces acting upon a cylindrical body like a barrel or tank. I should have forseen that the hoop stresses required to establish a press-fit that resists 1000lb pullout is likely much greater than 1000lbs in its expansive force (although transverse friction redirecting forces could account for part of this resistance). Indicatory compression tests also suggest the weakness of Florissant wood as being as low as 500psi in radial grain, again, the primary direction in which the pinning assemblies failed, and a low Florissant sampling size allowed no margin for error.

Figure 7.12: Sample failure, black effluent, and oily residue, on left. Sample fracture after assembly installation, on right.

Pinning Assembly	Tube (inches)	Durometer	Pin (inches)	Ultimate Strength (lbs)	Thumbnail Photograph
B1	PUR Tube 5/32OD 3/32ID	95A	Stainless Threaded Rod #5 0.125D 3L	N/A	
B2	PUR Tube 5/32OD 3/32ID	95A	Stainless Threaded Rod #5 0.125D 3L	N/A	
B3	PUR Tube 5/32OD 3/32ID	95A	Stainless Threaded Rod #5 0.125D 3L	N/A	
B4	PUR Tube 5/32OD 3/32ID	95A	Stainless Threaded Rod #5 0.125D 3L	N/A	

7.4 Implications of Results

A number of useful relationships were suggested in this exploration of the two part dry press-fit pinning assembly:

1) Threaded rod is an ideal pin form for an easily accessible, installable, retreatable, and dimensionally customizable pinning form.

2) 95A Durometer appears to be ideal hardness for tubing. Higher durometers are so stiff that they melt or fracture during rod insertion, and lower durometers are too weak having a propensity to tear and are to soft to transfer expansive forces to ensure a sturdy press-fit.

3) A material friction coefficients are not as significant as durometer in terms of establishing a durable press-fit for the reasons stated above, load transference and expansive forces (hoop stress) appears to be more significant.

4) A host material's modulus of rupture, and an assembly's hoop stress, needs to be considered in all significant dimensions – including radial and transverse strengths in the case of FLFO wood – to avoid fracturing either the pinned unit or host material.

5) The use of finite element analysis, three-dimensional engineering simulation software, could help predict assembly performance.

Future research of a dry press-fit mechanical pinning assembly using threaded metal rod and polymer tubing should explore the effects of:

1) Linear coefficients of thermal expansion of a pinning assembly. Running clearances could be designed to allow for linear expansion, however, anisotropic expansion could increase hoop stress and cause host failure.

2) Accelerated weathering should be conducted to understand the effects of embrittlement or viscoelasticity (creep and rebound) of an assembly by cycling it through a range of environments over time.

3) The relationship of thread count to length, and how this could affect rod pull-out. UNC, UNF, and UNEF (controlled by the UTS Unified Thread Standard of US & Canada as overseen by ASME/ANSI) are standards which respectively refer to coarse, fine, and extra fine threading. At small diameters UNC coarse

threadings are not available, but there are likely performance differences between fine and extra fine threads as a function of friction and geometry.

4) New and varied materials. For instance, the author self-threaded PEEK rod but was unable to find a compatible tubing size with the materials at hand. There is almost an infinite amount of possible threading combinations. Hard plastic threaded pins with near steel strength of engineering plastics like PEEK could hold great promise.

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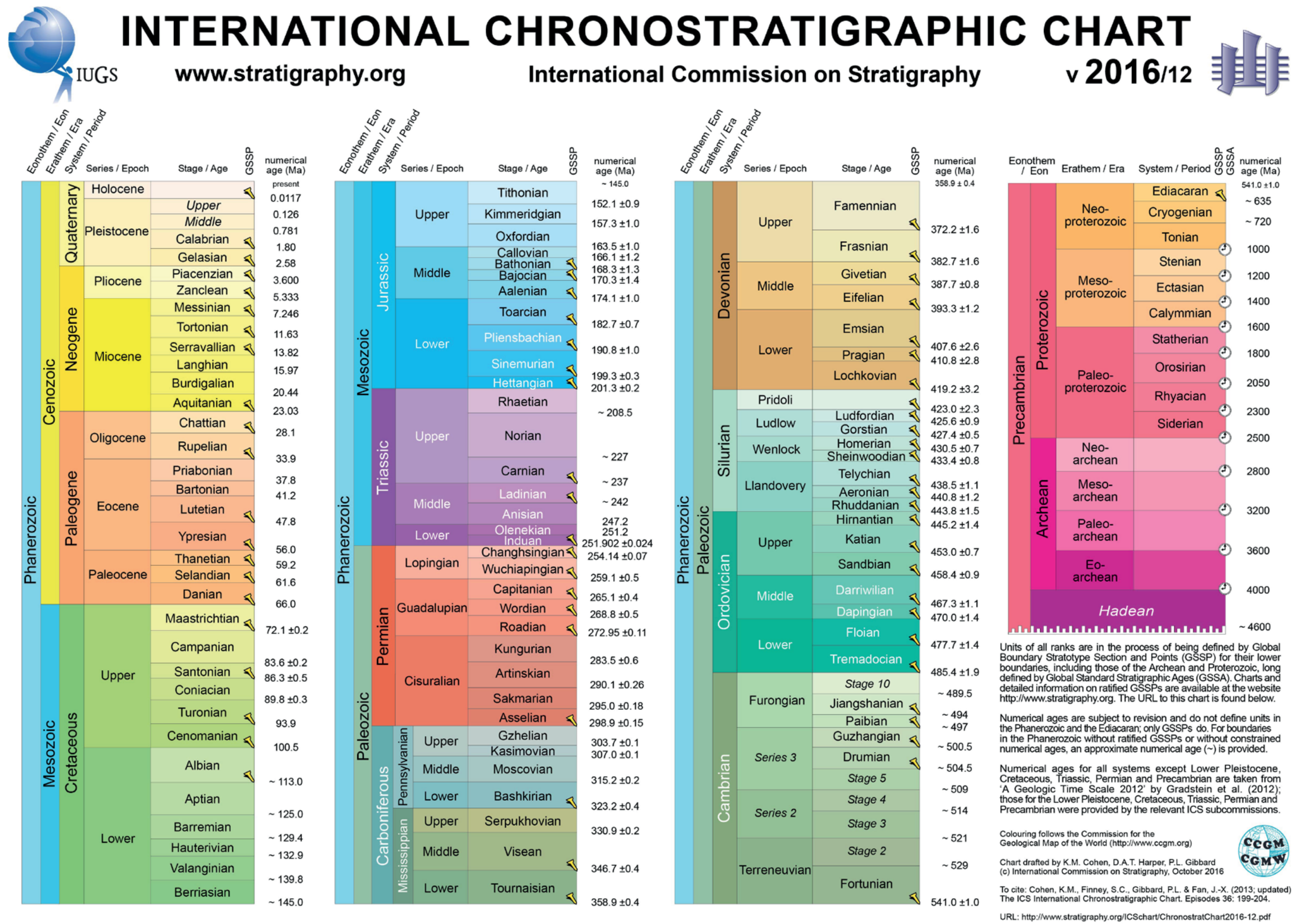
8.0 Conclusion

In conclusion, the developed dry mechanical pinning system as a conservation treatment is not recommended to reintegrate fallen fragments and incipient spalls of FLFO silicified wood or for preventative conservation. Based on the core that was taken by Gregory in 1989, and later sample behaviour in laboratories at UPenn, FLFO wood is highly fragmented and the prospect of crack formation too great. Topics for further research should include:

1) Shelter design
2) Environmental control
3) Environmental Monitoring (To quantify and predict decay)
4) Mechanical armatures
5) Fillers
6) Consolidants

Wet pinning systems could be explored, and have the potential to bridge structural gaps and introduce load transference within the lamellar stump fabric, but even wet-pinning requires drilling, potentially causing new fractures. As a pinning technology the two-part dry press fit technology has great potential for application in a wide range of other conservation scenarios, and the research presented above can be seen as an important first step explicating its complexities.

Appendix A – International Chronostratigraphic Chart



Appendix B – Material Property Data & Decision Making Matrices

Properties	Bulk Density (g)	Thermal COE X10-6 in/in · °F (X 10-6	Modulus of Rupture	Compressive Strength (lbs)
FLFO	2.242	6.9-8.5 (12.52-15.33)	Range 1562.36- 6549.58 Standard Deviation 1515.83	Radial ~522.91 Tangential ~4220.19 Transverse ~15196.13

MATERIAL LEGEND

- Compatible
- Less Compatible
- Less Incompatible
- Incompatible

Sources, Product Sheets provided by : McMaster-Carr, Extreme Bolt & Fastener, Superior Technical Ceramics, & MATweb Material Property Data, Maryland Lava Company Inc, Rock of Ages, Professional Plastics.

Pinning Material Class	METALS			
Material	Titanium Grade 2	Stainless Steel 316	Slotted Spring Pin 18-8	Spira-Lok/Heli-Fix
Water Absorbption	N/A	N/A	N/A	N/A
Compatibiltiy				
Modulus of Rupture (psi)	40,000-65,000		Breaking Strength (Double Shear) 100-5000lbs <1/4"D	?
Flexural Compatibiltiy				
Thermal ExpansionX10-6in./in./f	4.8	16	16	16
Coefficient Compatibiltiy				
Corrosion Resistance				
Availability				
Cost	8$/6"@1/4	2$/6"@1/4	6.48$/10"@3/16"	?
Threads (Red indicates custom order is required)				

BRITTLE INORGANICS					
Threaded Alumina Oxide	Zirconia	Alumina Silicate	Magnesium Silicate	Rock of Ages Granites	Macor Glass Ceramic
		2%			
55,000	100,000	10,000	11,000	~1906-3500	~13000
5	6	2.9-3.6	~8	4.4	5.2
				?	
45$/2"@1/4	70$/3"@1/4	8$/3"@1/4	?	?	25$/3"@1/4

Pinning Material Class	THERMOPLASTICS								
Material	PEEK	Torlon PAI	Kynar PVDF	Acetal Delrin	Vespel Polyamide	Teflon PTFE	Ketron® HPV - PEEK	ABS	Carbon Fiber
Water Absorbption	Below 0.33%	Below 0.33%	Below 0.33%	?	Below 0.33%	Below 0.33%			
Compatibiltiy									
Modulus of Rupture (psi)	25,000	41,000	9,700	14,300	16,000	NA	27,500	10000	260,000
Flexural Compatibiltiy								?	
Thermal ExpansionX10-6in./in./f	26	17	66	?	30	75	0.17	5	
Coefficient Compatibiltiy				?				?	
Corrosion Resistance				?					
Availability									
Cost									
						10$/6"@1/4	6$/6"@1/4	10$/6"@1/4	4$/6"@1/4
Threads (Red indicates custom order is required)									

Pinning Material Class	THERMOPLASTICS		
Material	Acrylic	LDPE	HDPE
Water Absorbption/Weathering			
Compatibiltiy			
Modulus of Rupture (psi)	TS=8000	TS=3100	TS=4000
Flexural Compatibiltiy			
Thermal ExpansionX10-6in./in./f			
Coefficient Compatibiltiy			
Corrosion Resistance			
Availability			
Cost			
Threads (Red indicates custom order is required)			

Pinning Material Class	THERMOPLASTIC VULCANIZATES (TPV) TUBING							
Material	Neoprene	Polyurethane (American Urethane Inc.)	Tygon 'Smooth Flow'	Tygon 'Long Life'	Fluorosilic one	Fluorosint 217	Fluorosint 500	Santoprene	Teflon FEP
Shore Durometer	TS=	A=60 to D=75	70A	60A	60A				
Mechanical Strengths (psi) FS=Flexural TS=Tensile SS=Shear	TS = 1100	TS = 40As: 2,000 psi; 60A 4,400 psi; 75D 7,500 psi; 80A 7,200 psi; 90A 4,000 psi; 95A 5,600 psi	TS=1000	TS=1000		TS=1100 FS=2000	TS=1500 FS=2200		
Flexural Compatibiltiy									
Thermal ExpansionX10-6in./in./f		57.6				24	57		22
Thermal Compatibiltiy									
Corrosion Resistance									
Availability									
Cost									

Adhesive Class	POLURETHANE ELASTOMERIC ADHESIVE						URETHANE PRIMER	EPOXIES
Adhesive	Sika Flex 11FC	Sika Flex 15LM	Sika Construction Adhesive	Loctite PL-Premium	Loctite PL-375	Loctite PL-MarbleMirr	Sika 429	Sika Anchor Fix 500
Tensile Strength (TS=PSI)/ Lap Shear (LS=PSI)/ Flexural (FS=PSI)/Shear (SS)/ Bond (BS) / Compressive (CS)	TS=255 LS=165 (Glass)	TS= 125psi	TS=? LS=? FS=?	SS (Wet Lumber)= 404psi	SS (Frozen Lumber)= 125 psi		N/A	BS - 2500psi CS- 10000psi
Viscosity	Knife	Knife	Knife				LOW	Knife
Thermal Compatibility								
Weatherability								
Availability								
	8$/ Tube	5$/ Cartridge	8$/Tube				30$/ Pint	30$/Tube
Cost								
Testing Costs								

Sources, Product Sheets/Data provided by : SIKA, Kenseal Construction Products, Smooth-On Durometer, Talus Conservation, & MATweb Material Property Data

Adhesive Class	ACRYLICS					SILANE POLYMER	
Adhesive	Sika 23LM	Sika 21LM	Paraloid B72 (EMA)	Paraloid B67 (MMA)	Paraloid B44 (MMA)	Loctite 5572	Loctite 5510
Tensile Strength (TS=PSI)/ Lap Shear (LS=PSI)/ Flexural (FS=PSI)/Shear (SS)/ Bond (BS) / Compressive (CS)	TS= 2000 FS=4800 SS=3000	TS=5800 FS=9600 SS=5670	?	?	?	SS=425 TS=475 LapS (Pine)=325	SS=250 TS=270
Viscosity	Knife	LOW	Difficult	Difficult	Difficult		
Thermal Compatibility							
Weatherability							
Availability							
	250$/ 4Gallon	250$/ 4Gallon	11.5$/0.5lb	11.5$/0.5lb	11.5$/0.5lb	15$/tube	15$/tube
Cost							
Testing Costs							

Professional Plastics Material Property Comparison Chart										
	Specific Gravity (73° g/cm3)	Tensile Strength (psi @ 73°)	Tensile Elongation at Break (% @ 73° F)	Flexural Strength (psi @ 73° F)	Linear Thermal Expansion (x 10-6 in./in./°F)	Heat Deflection Temp. (264 psi) °F	Max. Recommend ed Use Temp (°F)	Thermal Conductivity (BTU-in/ft�-hr-°F)	UL94 Flammability Rating	Dielectric Strength (volts/mil)
ABS Machine Grade - Rods & Sheet/Plate	1.05	4300	20	9200	53	–	194	–		16000
ABS Sheets - Flame Retardant - Forming Grade	1.3	–	–	–	–	–	–	–	V-0	–
ABS Sheets - Forming Grade - General Purpose	1.04	6000	–	–	–	198	–	–	HB	–
Acetal Sheets & Rods (Copolymer)	1.41	9500	30	12000	54	–	180	1.6	H-B	420
Arboron® Phenolic Laminate	1.39	16000	–	15000	–	–	198	–		–
Ardel® - Polyarylate	1.21	10000	50	11000	–	356	–	–	V-0	400
Celazole® PBI (U-60) Molded 100% PBI	1.3	20000	3	32000	1.3	800	600	2.8	V-0	550
Ceramatest 400 - Mica-Filled Ceramic	2.5	6000	–	–	–	–	750	0.87		730
Ceramatest™ 800 - Glass-Mica Composite	2.74	6000	–	–	104.6	–	1600	1.02		–
Cogetherm® - Mica Laminate Insulation Board	2.15	21750	–	33350	–	–	932	1.73	V-0	625
CPVC Sheet - CPVC Rod - Grey	1.56	8700	40	15500	40	140	178	–	V-0	–
DAP per MIL-M-14	1.82	6000	–	13000	16	260	–	–	V-0	380
Delrin® Tubes (Acetal H)	1.41	11000	30	13000	47	–	180	2.5	H-B	450
Delrin® AF Blend - 13% PTFE (Standard)	1.5	8000	15	12000	50	244	180	–	H-B	400
Delrin® Sheet & Rod (Acetal Homopolymer)	1.41	11000	30	13000	47	–	180	2.5	H-B	450
Duratron® XP Polyimide	1.4	16000	4	20000	27	680	580	1.53	V-0	700
Ertalyte® PET-P	1.41	12400	20	18000	33	–	210	2	H-B	385
Ertalyte® TX	1.44	10500	5	14000	45	180	210	1.9	HB	–
FEP Rods & Sheets	2.15	3400	325	–	–	–	400	–	V-0	–

Professional Plastics Material Property Comparison Chart										
	Specific Gravity (73° g/cm3)	Tensile Strength (psi @ 73°)	Tensile Elongation at Break (% @ 73° F)	Flexural Strength (psi @ 73° F)	Linear Thermal Expansion (x 10-6 in./in./°F)	Heat Deflection Temp. (264 psi) °F	Max. Recommended Use Temp (°F)	Thermal Conductivity (BTU-in/ft^2-hr-°F)	UL94 Flammability Rating	Dielectric Strength (volts/mil)
Fishpaper - Vulcanized Fibre Sheet	1.2	16000	--	--	--	--	230	--		125
FluoroPro™ PCTFE	2.1	5700	150	8500	70	167	350	1		500
FluoroPro™ PFA Rods & Sheets	2.15	3600	300	--	--	--	500	--	V-0	--
Fluorosint® 207	2.3	1500	50	2000	57	210	500	--	V-0	200
Fluorosint® 500	2.32	1100	10	2200	25	270	500	5.3	V-0	275
Fulton™ 404 - PTFE Filled Acetal	1.54	7200	10	10.5	--	--	225	--		--
G-10/FR-4 Sheets	1.8	38000	--	65000	6.6	--	284	2	H-B	800
G-3 (NP-504) Glass-Phenolic Laminate	1.85	50000	--	70000	150	--	464	--	H-B	--
G-7 Glass-Silicone Laminate	1.8	20000	--	30000	7.2	--	430	--		--
G-9 Glass-Melamine	1.9	--	--	38000	--	--	284	--		--
GlasGuard® 1130 Angles & Channels	--	14600	--	20400	--	--	--	--	V-0	--
HDPE Sheets & Rods	0.95	4550	100	5800	60	131	180	--		22000
High-Impact Polystyrene - HIPS	1.04	4000	55	8700	42	195	140	--	H-B	45
HolograPEEK XL - Holography Tube	1.44	16000	20	25000	26	320	480	1.75		480
Kapton® HN Polyimide Film	1.42	33500	72	--	--	--	550	--	V-0	--
Kaptrex® Polyimide Film	1.4	--	20	--	--	--	550	--	V-0	--
Kel-F® - PCTFE	2.1	5700	150	8500	70	167	350	1		500
Ketron® HPV - Bearing Grade PEEK	1.44	11000	2	27500	1.7	383	482	1.7	V-0	--
Macor® Machinable Glass Ceramic	2.52	--	--	13600	52	240	1832	10.1		1000
Makrolon® FI - Flame Retardant Polycarbonate	1.2	--	--	--	--	--	--	--	V-0	--

Professional Plastics Material Property Comparison Chart										
	Specific Gravity	Tensile Strength	Tensile Elongation at Break	Flexural Strength	Linear Thermal Expansion	Heat Deflection Temp.	Max. Recommend ed Use Temp	Thermal Conductivity	UL94 Flammability Rating	Dielectric Strength
	(73° g/cm3)	(psi @ 73°)	(% @ 73° F)	(psi @ 73° F)	(x 10-6 in./in./°F)	(264 psi) °F	(°F)	(BTU-in/ft�-hr-°F)		(volts/mil)
Makrolon® LF - FR Polycarbonate - Aircraft Grade	1.2	9500	--	13500	37.5	280	--	--		
MC 901 Heat Stabilized Nylon	1.15	12000	20	16000	3.5	200	260	1.7	HB	500
Meldin® 7001 Polyimide (Unfilled)	1.43	12500	7.5	15200	2.7	682	550	2.15	V-0	450
Meldin® 7003 Polyimide (15% MD Filled)	1.61	9000	4.5	13600	2.87	682	500	--	V-0	--
Meldin® 7021 Polyimide (15% Graphite Filled)	1.51	9500	4.5	15600	2.5	682	500	--	V-0	104
Meldin® 7022 Polyimide (40% Graphite-Filled)	1.67	7500	3.2	13100	2.23	682	500	--	V-0	--
Meldin® 7211 15% Graphite + 10% PTFE	1.55	6800	3.5	11300	2.8	682	500	--	V-0	--
Mycalex MM800	2.74	6000	--	--	10.46	--	1600	1.02		480
Mycalex® Mica-filled ceramic	2.74	6000	--	13500	--	--	1650	7.08		480
NP-318 - Post Forming Grade Phenolic	1.35	7600	--	16500	--	--	255	--	H-B	350
Nylatron® GS Nylon - Extruded	1.16	12500	25	1700	4	200	220	1.7	V-2	350
Nylatron® GSM Blue Nylon (MD+Oil)	1.15	10000	30	15000	5.9	200	200	--	HB	--
Nylatron® NSM	1.15	11000	20	475000	5	200	200	--	HB	400
Nylon 6/6 EXTRUDED, UNFILLED	1.12	11000	250	15000	--	--	210	1.7	V-2	400
Nylon MD Sheets & Rods - Extruded 6/6	1.15	10500	40	17000	5.5	--	220	--		--
Nylon, 30% Glass-Filled	1.17	28300	10	16000	10.6	311	230	1.18	HB	406
Nylon, Oil-Filled - Green (Generic)	1.14	10000	--	13000	5.5	--	220	--		--
PBT - Sustadur® PBT	1.31	8000	30	--	4	--	230	--		400
PEEK - 30% Carbon-Filled	1.42	18000	2	30000	1.7	450	480	6.37	V-0	--

Professional Plastics Material Property Comparison Chart

	Specific Gravity (73° g/cm3)	Tensile Strength (psi @ 73°)	Tensile Elongation at Break (% @ 73° F)	Flexural Strength (psi @ 73° F)	Linear Thermal Expansion (x 10-6 in./in./°F)	Heat Deflection Temp. (264 psi) °F	Max. Recommend ed Use Temp (°F)	Thermal Conductivity (BTU-in/ft�-hr-°F)	UL94 Flammability Rating	Dielectric Strength (volts/mil)
PEEK - 30% Glass Filled	1.54	22800	1.6	33800	1.2	450	480	3	V-0	175
PEEK - VIRGIN Grade - Sheets & Rods	1.31	16000	20	25000	2.6	--	480	1.8	V-0	480
PEEK Tubes & Rings - Compression Molded	1.31	16000	20	25000	2.6	320	480	--		480
PETG Sheet	1.27	4000	110	10000	5.1	245	140	--		18000
PFA Rods & Sheets	2.15	3600	300	--	--	--	500	--	V-0	--
Phenolic - Grade C Canvas Sheets	1.37	12000	--	20000	20	--	255	--	H-B	500
Phenolic - Grade CE Canvas Sheets	1.37	11000	--	17500	1.1	--	257	2	H-B	550
Phenolic - Grade L - Linen	1.34	10000	--	18500	18	--	255	--	H-B	--
Phenolic - Grade LE Sheets & Rods	1.34	13000	--	22000	1	--	285	2	H-B	625
Phenolic - Grade X Paper	1.42	15000	--	16000	0.8	--	257	2	H-B	600
Plexiglass - ACRYLIC SHEET - CAST	1.18	8000	2	12000	5	210	200	--		400
Plexiglass - ACRYLIC SHEET - EXTRUDED	1.18	8000	2	12000	5	210	200	--		400
Polycarbonate - Machine Grade Plate - Sheet	1.2	9500	60	15000	3.9	270	250	1.3	H-B	390
Polycarbonate Sheet - GP Glazing Grade	1.2	9500	60	15000	3.9	270	250	1.3	H-B	390
Polycarbonate Tubing - Extruded	1.2	7000	--	12000	3.75	275	--	4.6		--
Polypropylene FR -	1.38	--	--	--	--	--	--	--	V-0	--
Polypropylene Sheets & Rods - Euro Grey	0.92	3700	--	155000	6	--	230	--		--
Polysulfone PSU 1000	1.24	10000	75	15000	3.1	345	300	1.8	H-B	425
Pomalloy® ESd - ESd Acetal	1.43	--	--	--	--	--	--	--		--
ProtoPEEK® 100	1.51	14700	1.5	20500	1.1	410	--	--		362

Professional Plastics Material Property Comparison Chart										
	Specific Gravity (73° g/cm3)	Tensile Strength (psi @ 73°)	Tensile Elongation at Break (% @ 73° F)	Flexural Strength (psi @ 73° F)	Linear Thermal Expansion (x 10-6 in./in./°F)	Heat Deflection Temp. (264 psi) °F	Max. Recommend ed Use Temp (°F)	Thermal Conductivity (BTU-in/ft�-hr-°F)	UL94 Flammability Rating	Dielectric Strength (volts/mil)
ProtoPEEK® 5025 Bearing Grade PEEK	1.42	18900	3.5	25000	2.5	450	480	–	V-0	–
PTFE - Etched	2.18	–	–	–	–	–	500	–		
PTFE Sheets & Rods (Mechanical Grade)	2.18	–	–	–	–	–	500	–	V-0	–
PTFE Sheets & Rods (Virgin Grade)	2.2	3900	300	–	7.5	132	500	1.7	V-0	1000
PVC Sheets & Rods - Grey (Type 1)	1.5	7000	29	12000	6.1	176	140	0.9	V-0	544
PVDF - Compression Molded	1.77	5800	50	7800	2.2	190	310	–	V-0	22000
PVDF - Extruded Rods & Plates	1.77	5800	50	7800	2.2	190	310	–	V-0	22000
Radel® R-5500 - PPSU Rod & Sheet	1.29	11000	30	15500	3.1	405	300	2.4	V-0	360
Royalite® R-59 Sheet	1.25	5000	–	7800	5.5	175	250	–	V-0	–
Royalstat ® R63 Conductive ABS/PVC	1.22	5000	–	–	–	–	–	–	V-1	–
Rulon® J (Gold)	1.95	2000	200	–	–	–	500	1.7	V-0	200
Rulon® LR (Maroon)	2.25	1500	150	–	3.5	–	500	2.3	V-0	450
Ryton® - PPS - 40% Glass-Filled	1.7	13000	2	23000	0.25	490	450	2.1	V-0	385
Semitron® CMP XL20	–	–	–	600	1.7	532	–	–		–
Semitron® ESd 225 - Acetal	1.33	6100	10	6000	9.3	225	180	–	H-B	–
Semitron® ESd 410C - Conductive ULTEM™	1.41	9000	2	12000	1.8	410	338	2.45	V-0	–
Semitron® ESd 500HR -	2.3	1500	50	2200	5.7	210	500	–	V-0	–
Semitron® ESd 520HR - ESd PAI	1.58	12000	3	20000	2.35	520	500	2.48	V-0	475
Sumika Super S1000	1.35	–	–	–	–	–	500	–	V-0	–
Surlyn® Ionomer	0.95	–	470	–	–	–	–	–		–
Sustamid 6G HS Blue Cast Nylon	–	–	–	–	–	–	260	–		–

Professional Plastics Material Property Comparison Chart										
	Specific Gravity	Tensile Strength	Tensile Elongation at Break	Flexural Strength	Linear Thermal Expansion	Heat Deflection Temp.	Max. Recommended Use Temp	Thermal Conductivity	UL94 Flammability Rating	Dielectric Strength
	(73° g/cm3)	(psi @ 73°)	(% @ 73° F)	(psi @ 73° F)	(x 10-6 in./in./°F)	(264 psi) °F	(°F)	(BTU-in/ft�-hr-°F)		(volts/mil)
Sustason PPSU MG (Radel® R)	1.29	11000	30	15500	0.31	405	300	2.4	V-0	360
Techtron® HPV - Bearing Grade PPS	1.43	10900	5	10500	0.33	240	430	2.1	V-0	500
Techtron® PPS	1.35	13500	15	21000	2.8	--	425	2	V-0	540
Tefzel® - ETFE Sheets & Rods	1.7	6100	300	--	7.3	--	311	--	V-0	1800
Tivar® 88	0.965	--	--	--	--	--	--	--	V-0	--
Tivar® DrySlide UHMW	0.94	4800	200	106	190	116	180	--	HB	--
Tivar® H.O.T.	0.94	5800	300	3500	190	116	275	--	HB	2300
Torlon® 4203	1.41	18000	10	24000	1.7	532	500	1.8	V-0	580
Torlon® 4301	1.45	12000	3	23000	1.4	534	500	3.7	V-0	--
Torlon® 4540 Duratron®	1.46	13000	5	24000	0.2	534	500	--	V-0	--
Torlon® 4XG - Extruded (30% G/F)	1.61	23500	4	30000	--	--	500	2.5	V-0	--
Torlon® 5530 (30% Glass-Filled PAI)	1.61	15000	3	20000	2.6	520	500	2.5	V-0	700
Turcite® A (Blue)	1.49	7600	15	11000	5.2	203	180	--	H-B	--
Turcite® X (Red)	1.46	5900	19	8000	5.2	205	180	--	H-B	--
UHMW Sheet & Rod (Virgin Grade)	0.93	6000	350	--	--	--	155	--		900
ULTEM™ 1000 PEI	1.28	16500	80	20000	3.1	392	340	0.9	V-0	830
Unital® SFX0102M - Metal Detectable POM	1.68	7000	10	10000	--	240	--	--		--
Vespel® SP-1 Balls	1.43	12500	7.5	--	3	--	550	--	V-0	560
Vespel® SP-1 Rod & Plate	1.43	12500	7.5	16000	3	680	550	2	V-0	560
Vespel® SP-21 Rod & Plate	1.51	9500	4.5	16000	2.7	680	500	6	V-0	250
Vespel® SP-211 Rod & Plate	1.55	6500	3.5	10000	3	680	500	5.3	V-0	--

Appendix C – Material Order

McMASTER-CARR.

Order Confirmation

609-689-3000
609-259-3575 (fax)
nj.sales@mcmaster.com

Ship to

University of Pennsylvania
Meyerson Hall
210 S 34TH St
Philadelphia PA 19104

Attention 115
Beauharnois, Nadine

Purchase Order	Order Date
3760783	3/21/17
Ordered By	**McMaster-Carr Number**
Grier Nori	8669016

Line		Product	Ordered	Ships	Price	Total
1	92373A391	18-8 Stainless Steel Slotted Spring Pin 1/4" Diameter, 4" Long, packs of 5	1 pack	today	8.36 per pack	8.36
2	92373A195	18-8 Stainless Steel Slotted Spring Pin 1/8" Diameter, 2-1/2" Long, packs of 25	1 pack	today	9.01 per pack	9.01
3	92373A271	18-8 Stainless Steel Slotted Spring Pin 3/16" Diameter, 3" Long, packs of 10	1 pack	today	6.48 per pack	6.48
4	3077K2	4 Piece Plastic and Rubber Tubing Material Sample Pack, packs of 4	1 pack	today	10.65 per pack	10.65
5	3077K1	5 Piece Plastic and Rubber Tubing Material Sample Pack, packs of 5	1 pack	today	3.58 per pack	3.58
6	3077K3	7 Piece Plastic and Rubber Tubing Material Sample Pack, packs of 7	1 pack	today	7.30 per pack	7.30
7	3077K5	9 Piece Plastic and Rubber Tubing Hardness Sample Pack, packs of 9	1 pack	today	11.41 per pack	11.41
8	51085K41	Extreme-Pressure PEEK Tubing for Chemicals Opaque, 0.005" ID, 1/16" OD, 2 Feet Long	2 feet	today	3.52 per foot	7.04
9	51085K49	Extreme-Pressure PEEK Tubing for Chemicals Opaque, 0.062" ID, 1/8" OD, 1 Foot Long	1 foot	today	11.15 per foot	11.15
10	8624K11	HDPE Rod 1/4" Diameter, 8 Feet Long	8 feet	today	0.67 per foot	5.36
11	8754K42	LDPE Rod 1/4" Diameter, 8 Feet Long Sold In Standard 8-FOOT Lengths	8 feet	today	0.87 per foot	6.96
12	98743A225	Nylon Threaded Rod 10-32 Thread Size, 2 Feet Long, Black, packs of 1	1 pack	today	4.52 per pack	4.52
13	98743A210	Nylon Threaded Rod 6-32 Thread Size, 2 Feet Long, Black, packs of 1	1 pack	today	4.84 per pack	4.84
14	98743A215	Nylon Threaded Rod 8-32 Thread Size, 2 Feet Long, Black, packs of 1	1 pack	today	4.80 per pack	4.80

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McMaster-Carr Supply Company

Page 1 of 2

McMASTER-CARR

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609-689-3000
609-259-3575 (fax)
nj.sales@mcmaster.com

Ship to

University of Pennsylvania
Meyerson Hall
210 S 34TH St
Philadelphia PA 19104

Attention Beauharnois, Nadine
115 Meyerson Hall Historic Preservation

Purchase Order	Order Date
3774036	4/10/17
Ordered By	**McMaster-Carr Number**
Grier Nori	1687913

Line		Product	Ordered	Ships	Price	Total
1	98804A003	18-8 Stainless Steel Threaded Rod 2-56 Thread Size, 2 Feet Long, packs of 1	2 packs	today	1.93 per pack	3.86
2	98804A004	18-8 Stainless Steel Threaded Rod 3-48 Thread Size, 2 Feet Long, packs of 1	2 packs	today	5.00 per pack	10.00
3	98804A005	18-8 Stainless Steel Threaded Rod 4-40 Thread Size, 2 Feet Long, packs of 1	2 packs	today	1.59 per pack	3.18
4	98804A006	18-8 Stainless Steel Threaded Rod 5-40 Thread Size, 2 Feet Long, packs of 1	2 packs	today	2.55 per pack	5.10
5	98804A007	18-8 Stainless Steel Threaded Rod 6-32 Thread Size, 2 Feet Long, packs of 1	2 packs	today	1.45 per pack	2.90
6	98804A009	18-8 Stainless Steel Threaded Rod 8-32 Thread Size, 2 Feet Long, packs of 1	2 packs	today	1.94 per pack	3.88
7	8628K48	Nylon Tube 1/4" OD, 1/8" ID, 5 Feet Long	1 each	today	3.46 each	3.46
8	2905K14	PTFE Rod 1" Diameter, 1' Length	1 foot	today	10.69 per foot	10.69
9	2905K13	PTFE Rod 3/4" Diameter, 1' Length	1 foot	today	5.84 per foot	5.84
10	8546K15	Rod Made From Teflon PTFE 3/4" Diameter, 1' Length	1 foot	today	15.49 per foot	15.49
11	90000A219	Screws for Softwood & Plastic-Wood Composites 18-8 Stainless Steel, Square-Drive, Number 8 Size, 3" Long, packs of 50	1 pack	today	12.51 per pack	12.51
12	8547K29	Tube Made From Teflon PTFE 1" OD x 7/8" ID, 1' Length	1 foot	today	13.82 per foot	13.82
13	8547K22	Tube Made From Teflon PTFE 1/4" OD x 1/16" ID, 1' Length	2 feet	today	4.76 per foot	9.52
14	8547K23	Tube Made From Teflon PTFE 1/4" OD x 1/8" ID, 1' Length	3 feet	today	3.26 per foot	9.78
15	8547K24	Tube Made From Teflon PTFE 5/16" OD x 3/16" ID, 1' Length	2 feet	today	4.47 per foot	8.94

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Meyerson Hall
210 S 34TH St
Philadelphia PA 19104

Attention 115 - Historic Preservation
Beauharnois, Nadine 52628909

Purchase Order	Order Date
3760727	3/20/17
Ordered By	**McMaster-Carr Number**
Grier Nori	8645875

Line		Product	Ordered	Ships	Price	Total
1	9287K133	302 Stainless Steel Torsion Spring 180 Degree Left-Hand Wound, 1.356" OD	1 each	today	9.52 each	9.52
2	8795K373	Abrasion-Resistant Polyurethane Rubber Round Tube Semi-Clear, 4" Long, 1" OD, 95A Durometer	1 each	today (from our Chicago warehouse)	11.93 each	11.93
3	8503K244	Beige PEEK Rod 1/4" Diameter, 1' Length	2 feet	today	6.01 per foot	12.02
4	51085K49	Extreme-Pressure PEEK Tubing for Chemicals Opaque, 0.062" ID, 1/8" OD, 1 Foot Long	2 feet	today	11.15 per foot	22.30
5	5546T11	Extreme-Temperature Silicone Rubber Tube, 1/4" ID, 3/4" OD, 6" Length	2 each	today	5.94 each	11.88
6	50555K95	Joined Polyurethane Tubing for Water 2 Black Tubes, 1/8" ID, 1/4" OD, 10 Feet Long	10 feet	today	1.07 per foot	10.70
7	5648K226	Polyurethane Tubing for Water 1/16" ID, 1/8" OD, Clear, 25 Feet Long	25 feet	today	0.20 per foot	5.00
8	5648K611	Polyurethane Tubing for Water 1/8" ID, 1/4" OD, Clear, 25 Feet Long	25 feet	today	0.58 per foot	14.50
9	5648K236	Polyurethane Tubing for Water 3/32" ID, 5/32" OD, Clear, 25 Feet Long	25 feet	today	0.21 per foot	5.25
10	5648K256	Polyurethane Tubing for Water 5/32" ID, 1/4" OD, Clear, 25 Feet Long	25 feet	today	0.46 per foot	11.50
11	8546K11	Rod Made From Teflon PTFE 1/4" Diameter, 1' Length	2 feet	today	2.29 per foot	4.58
12	8546K31	Rod Made From Teflon PTFE 1/8" Diameter, 1' Length	4 feet	today	1.23 per foot	4.92
13	8546K32	Rod Made From Teflon PTFE 3/16" Diameter, 1' Length	2 feet	today	1.65 per foot	3.30
14	8637K111	Round Multipurpose Neoprene Rubber Tube 3/4" OD, 6" Long	3 each	today	3.17 each	9.51

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Philadelphia PA 19104

Attention 115
Beauharnois, Nadine

Purchase Order	Order Date
3762243	3/22/17
Ordered By	**McMaster-Carr Number**
Grier Nori	8751405

Line		Product	Ordered	Ships	Price	Total
1	98419A216	18-8 Stainless Steel Distortion-Free Screws for Plastic-Wood Composites, Number 10 Size, 3" Long, packs of 10	2 packs	today	8.69 per pack	17.38
2	97830A108	18-8 Stainless Steel Spiral-Shank Nail 10D Size, 3" Long, packs of 50	1 pack	today	11.40 per pack	11.40
3	97830A115	18-8 Stainless Steel Spiral-Shank Nail 20D Size, 4" Long, packs of 25	1 pack	today	17.40 per pack	17.40
4	9665K61	302 Stainless Steel Extension Spring Stock 20" Overall Length, 0.375" OD, 0.062" Wire Diameter	1 each	today	11.51 each	11.51
5	9663K28	Corrosion-Resistant Compression Spring Stock 20" Overall Length, 0.5" OD, 0.356" ID	1 each	today	6.17 each	6.17
6	9627T14	High-Temperature Fluorosilicone Rubber Tubing for Fuels, 1/8" ID, 1/4" OD, 2 Feet Long	2 feet	today	4.56 per foot	9.12
7	51075K21	Long-Life Tygon Rubber Tubing for Chemicals 1/16" ID, 3/16" OD, 10 Feet Long	10 feet	today	0.78 per foot	7.80
8	51075K22	Long-Life Tygon Rubber Tubing for Chemicals 1/8" ID, 1/4" OD, 10 Feet Long	10 feet	today	0.80 per foot	8.00
9	98873A100	Moisture-Resistant Acetal Threaded Rod 10-32 Thread Size, 2 Feet Long	1 each	today	8.46 each	8.46
10	5466K31	Smooth-Flow Tygon Tubing for Food & Beverage 1/16" ID, 3/16" OD, 10 Feet Long	10 feet	today	1.46 per foot	14.60
11	5466K34	Smooth-Flow Tygon Tubing for Food & Beverage 1/4" ID, 3/8" OD, 5 Feet Long	5 feet	today	2.38 per foot	11.90
12	5466K32	Smooth-Flow Tygon Tubing for Food & Beverage 1/8" ID, 1/4" OD, 5 Feet Long	5 feet	today	2.04 per foot	10.20
13	52355K12	Teflon FEP Semi-Clear Tubing for Chemicals Flexible, 1/8" ID, 3/16" OD, 5 Feet Long	5 feet	today	2.22 per foot	11.10
14	52355K57	Teflon FEP Semi-Clear Tubing for Chemicals Flexible, 3/16" ID, 1/4" OD, 5 Feet Long	5 feet	today	2.50 per foot	12.50

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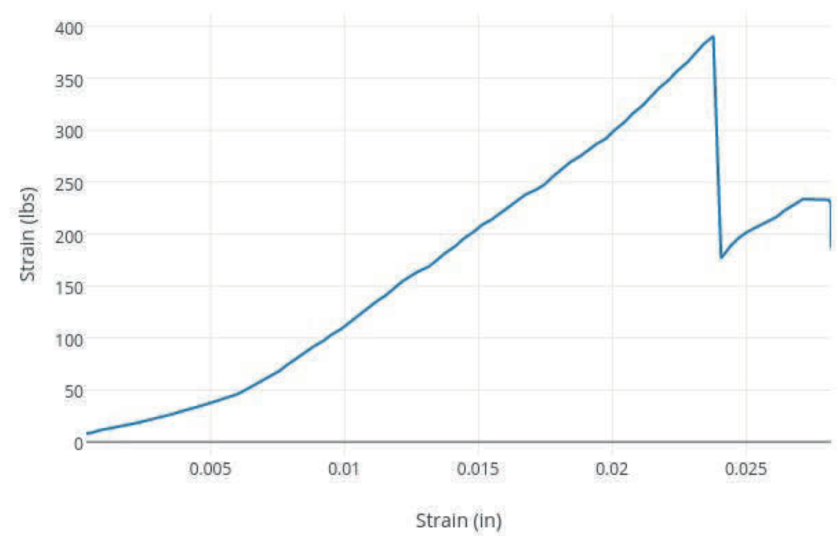
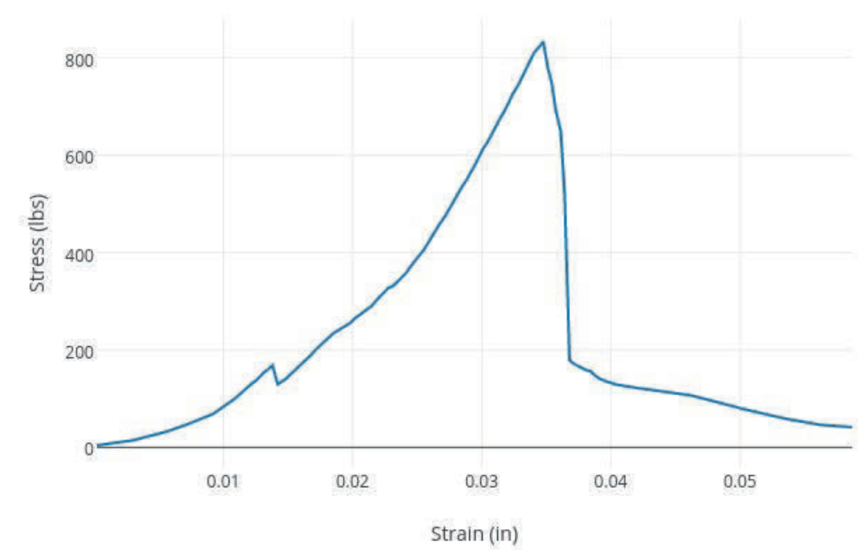
Appendix D – Mechanical Testing Data
MODULUS OF RUPTURE

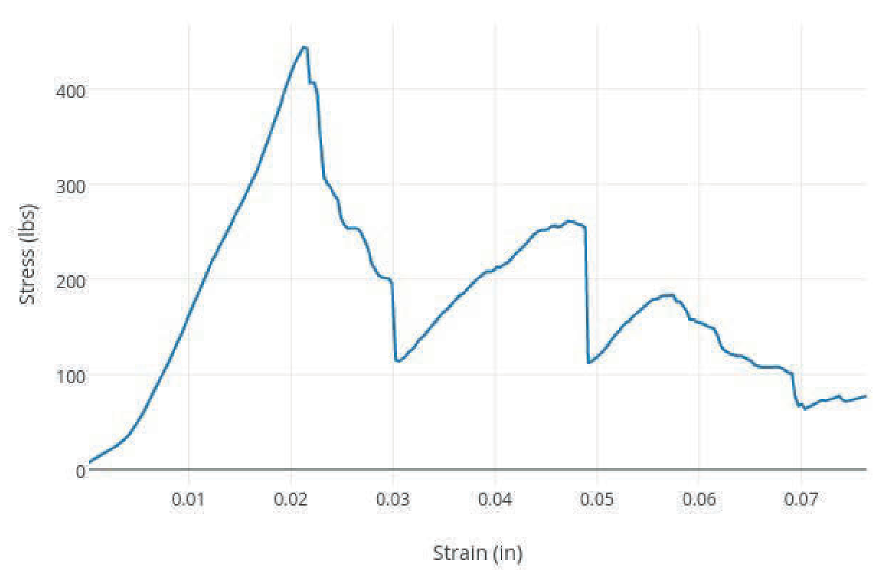
U1_1



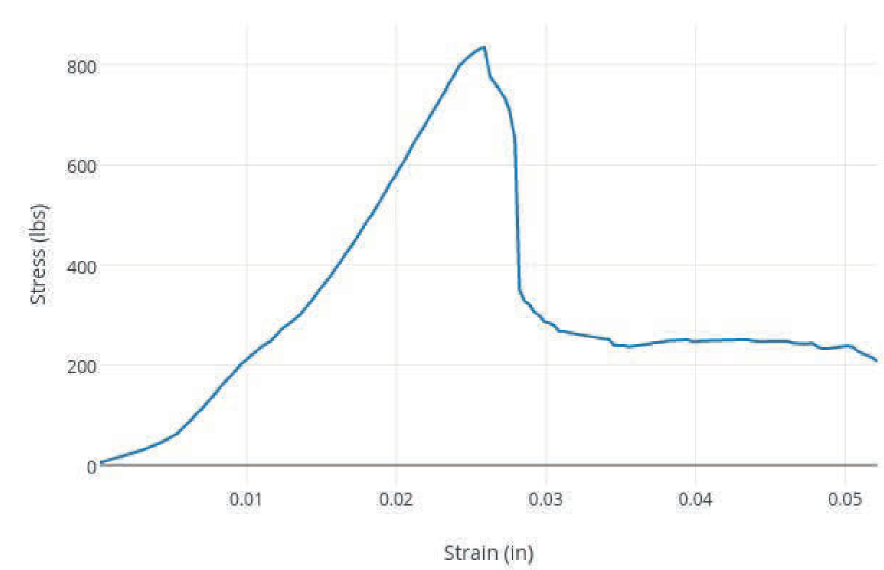
Test U1_2

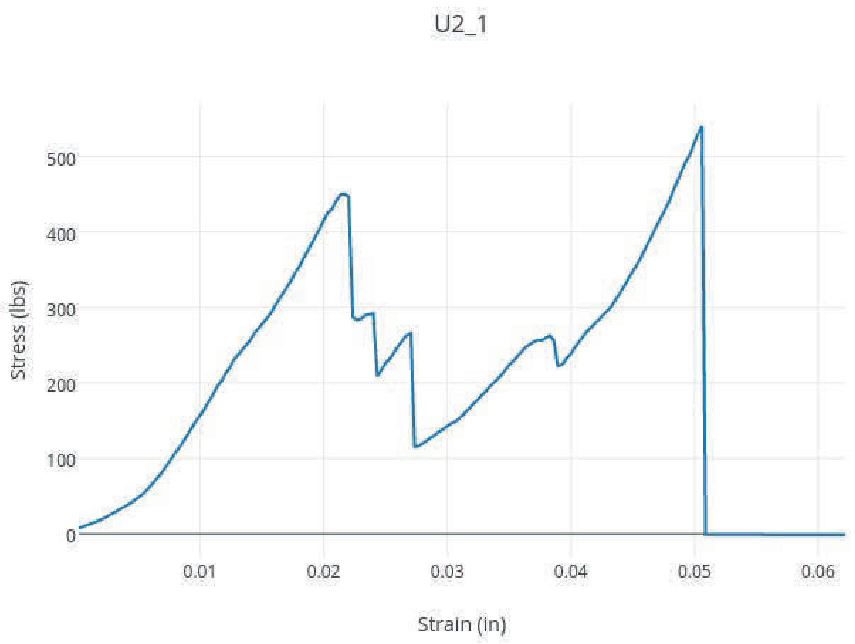


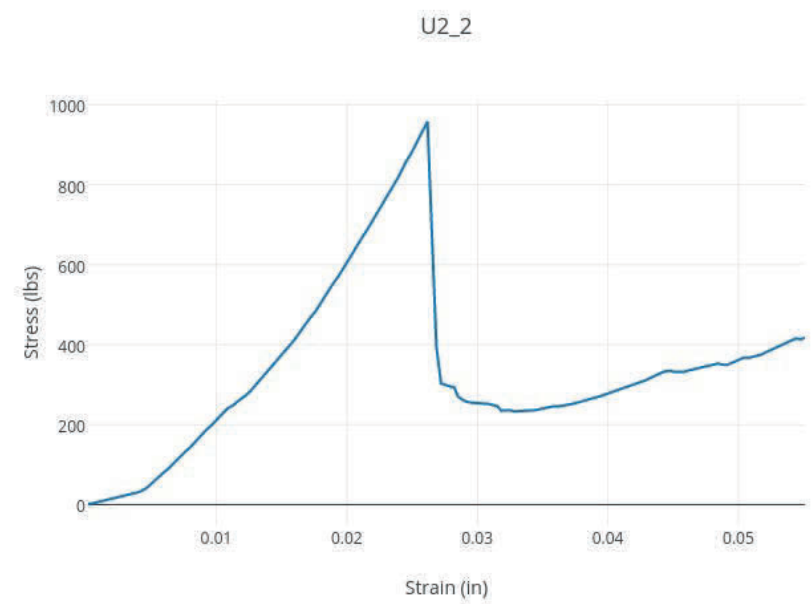
U1_3

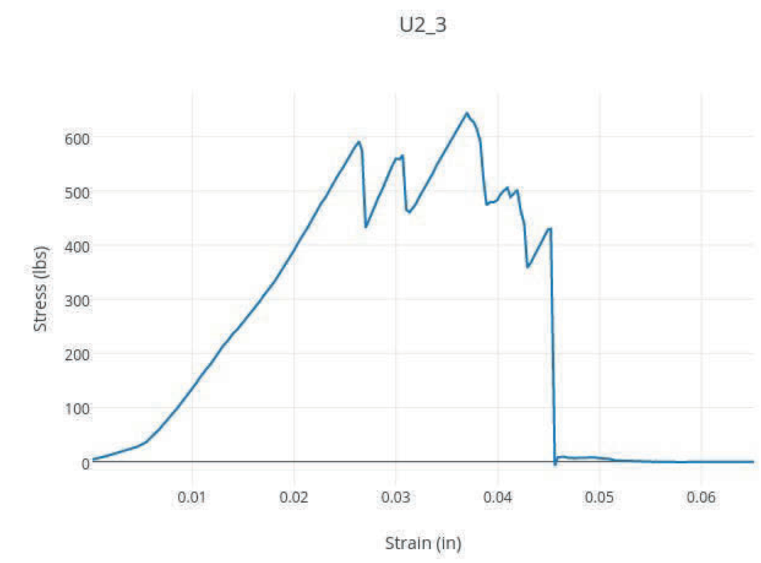


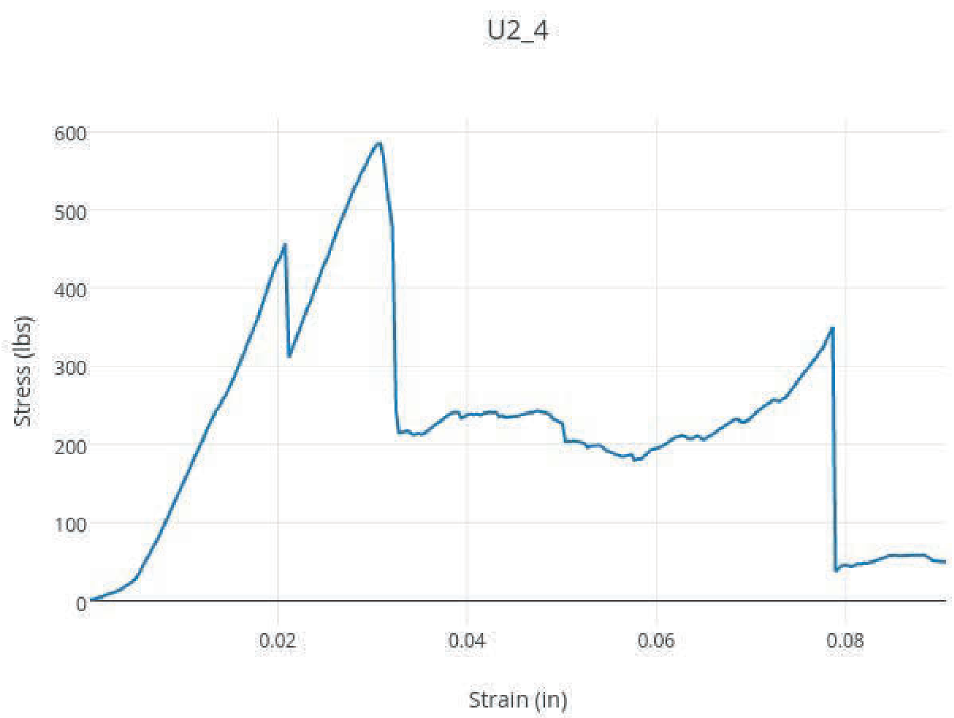
U1_4

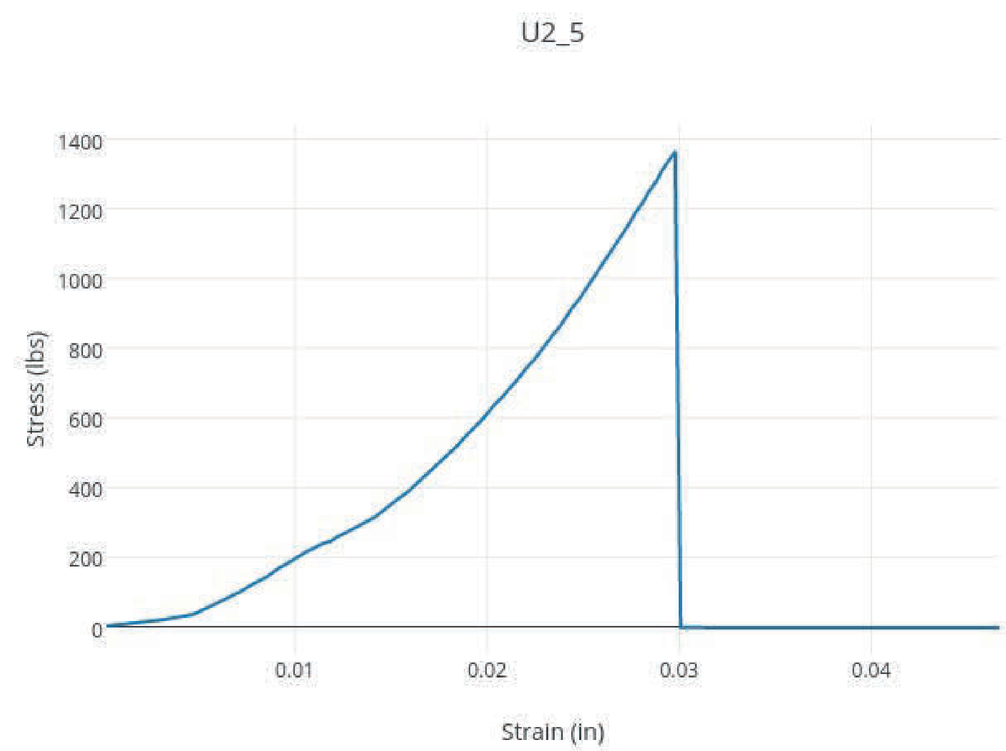




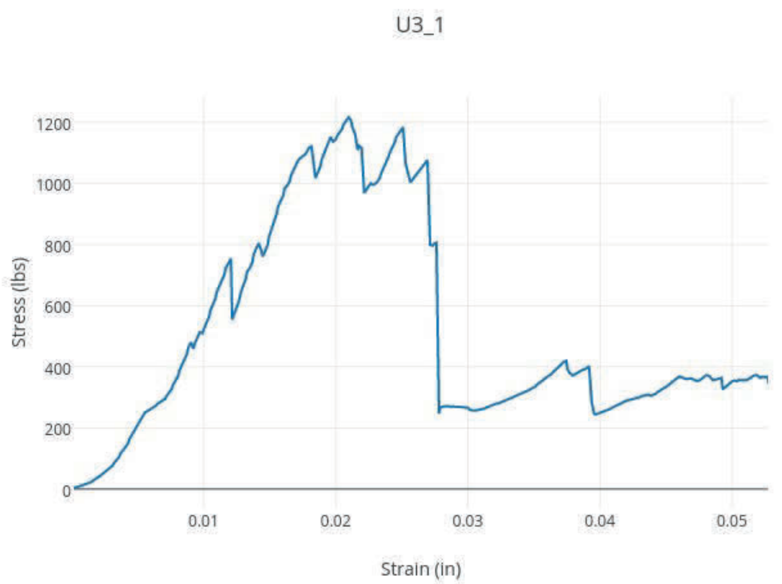


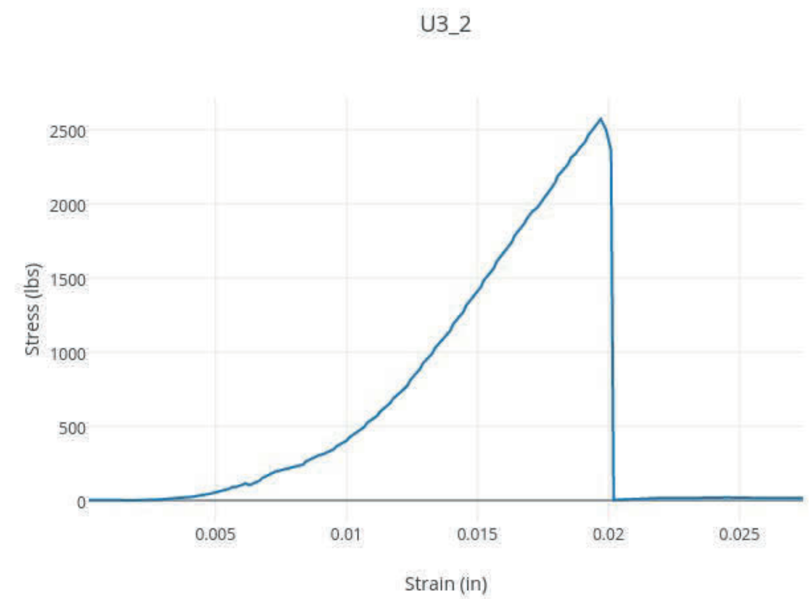


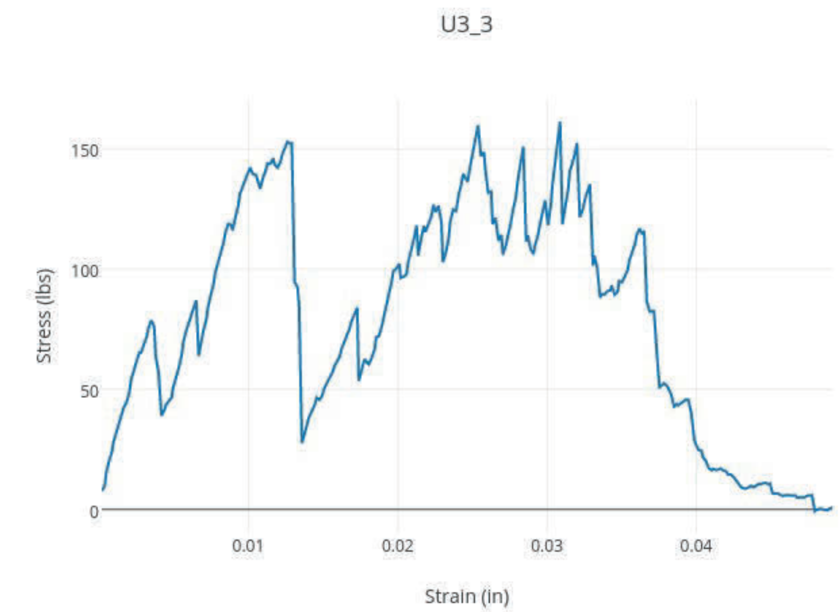


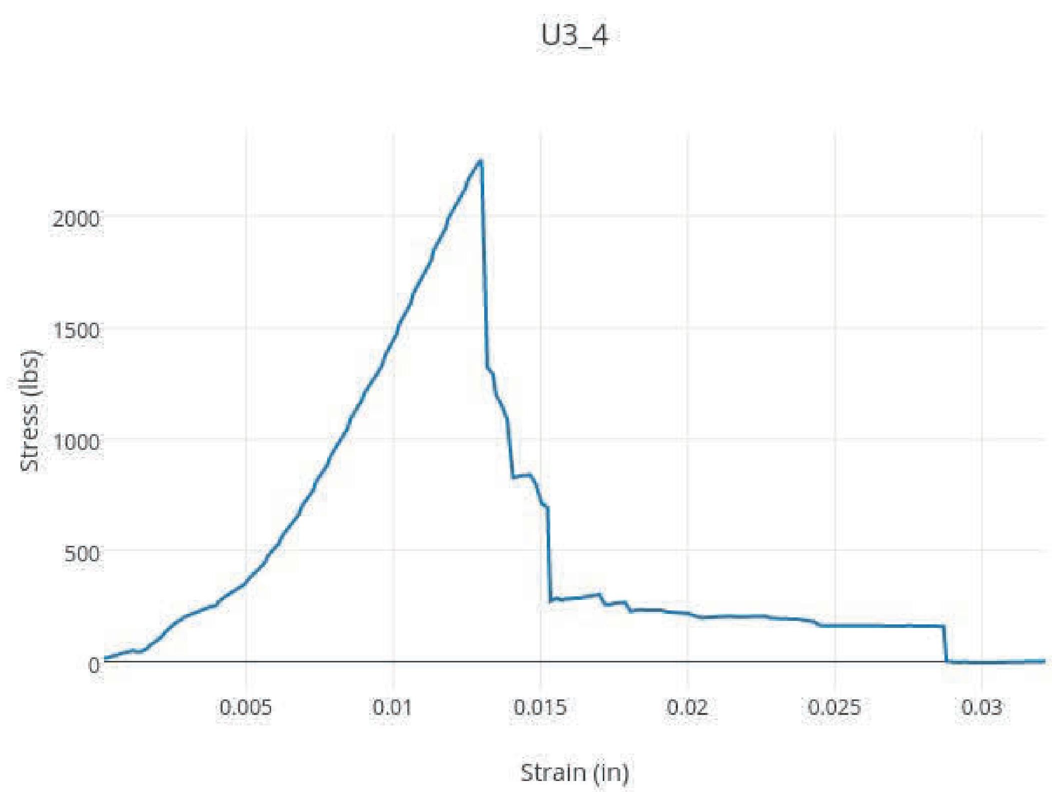


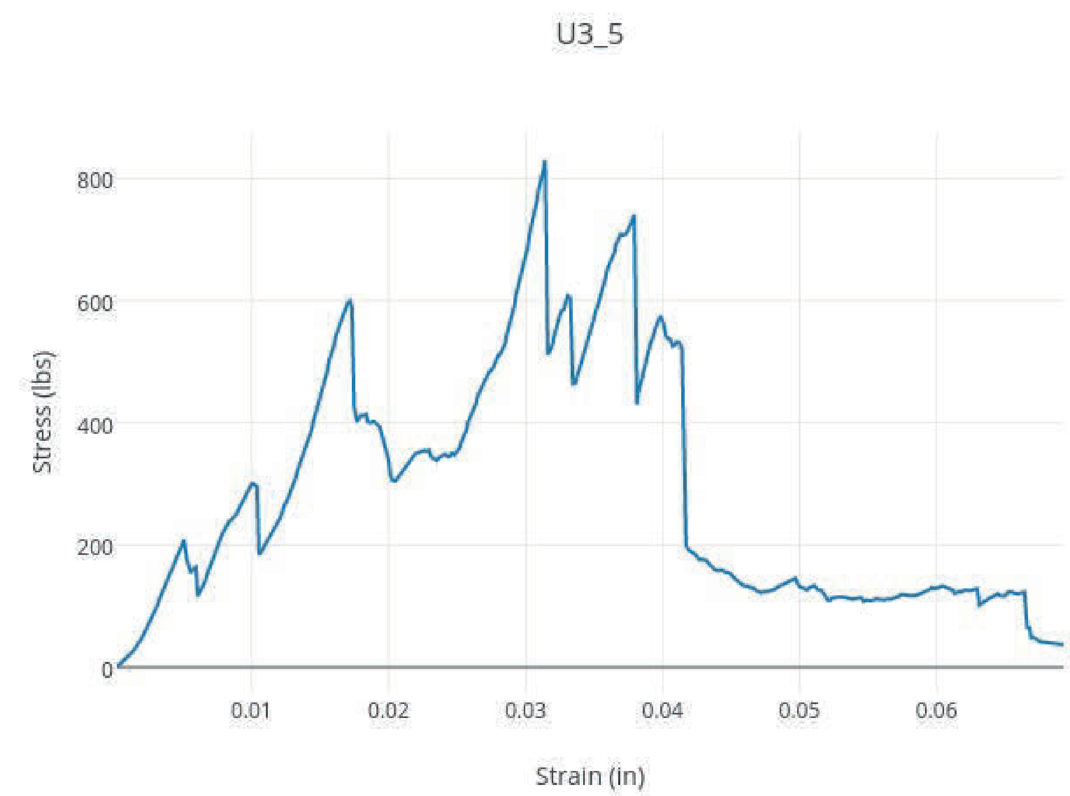
INDICATOR COMPRESSION TESTS (U3_1 & U3_5 Tangential; U3_2 & U3_4 Transverse; and U3_3 Radial)



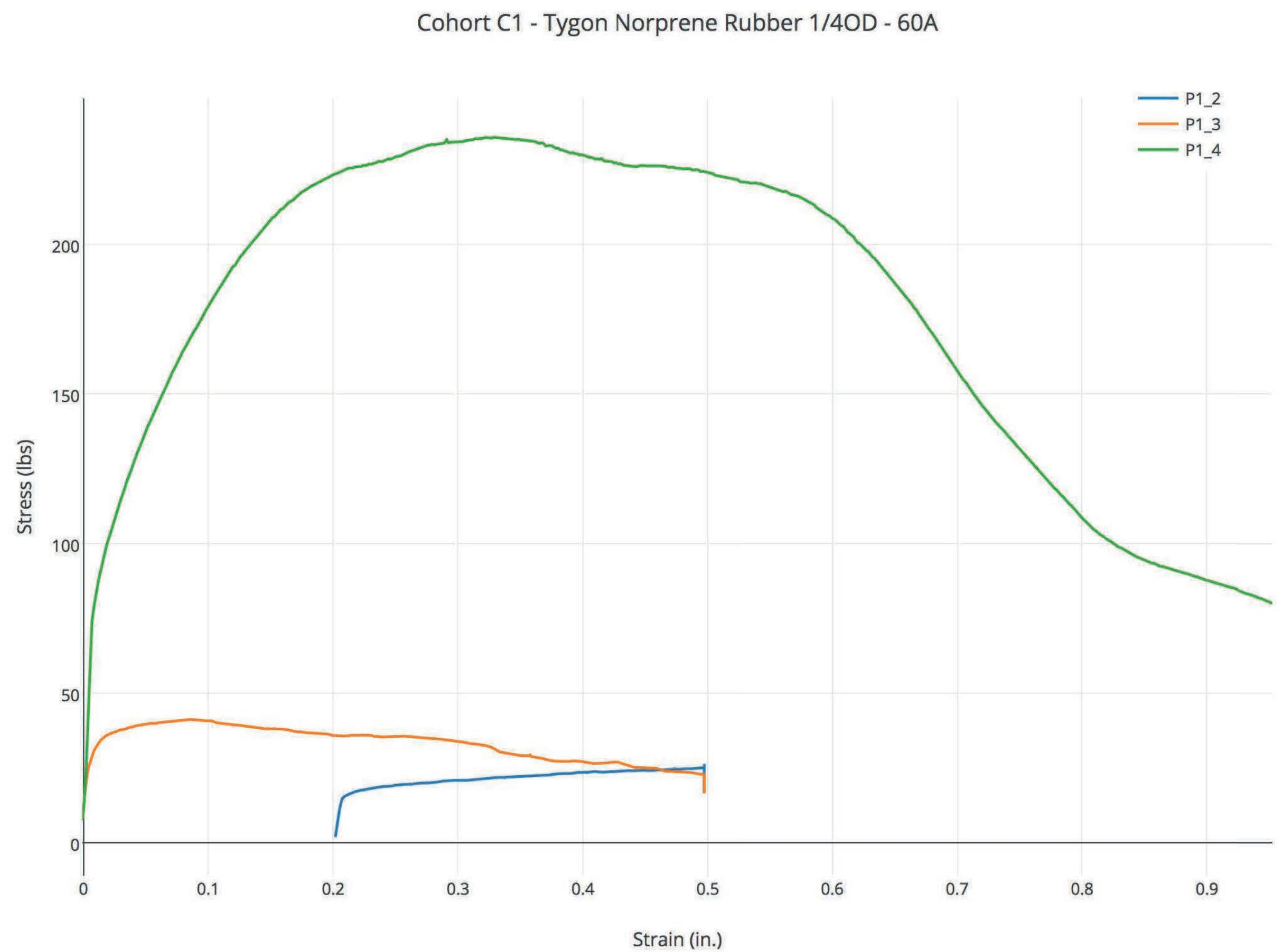


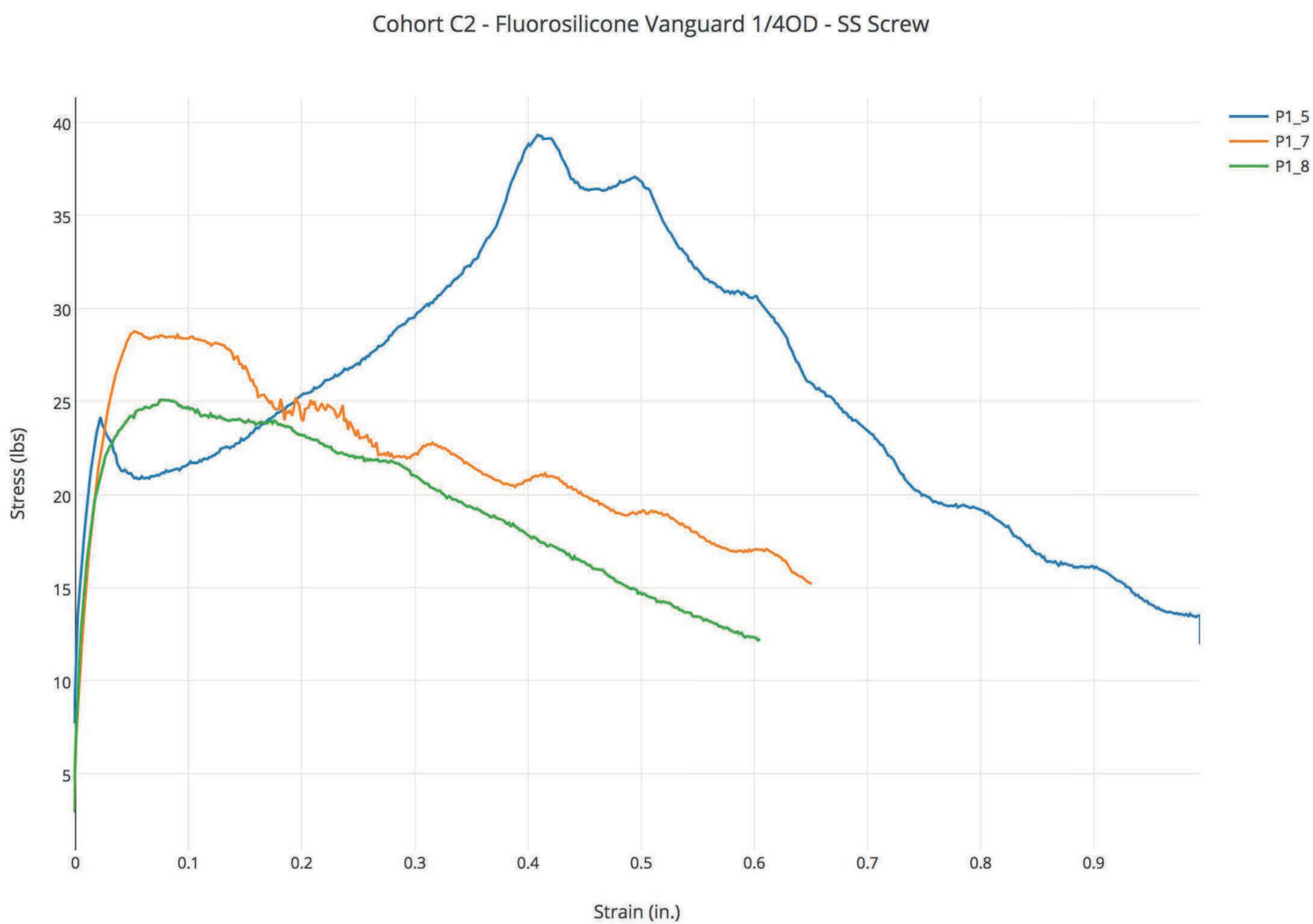




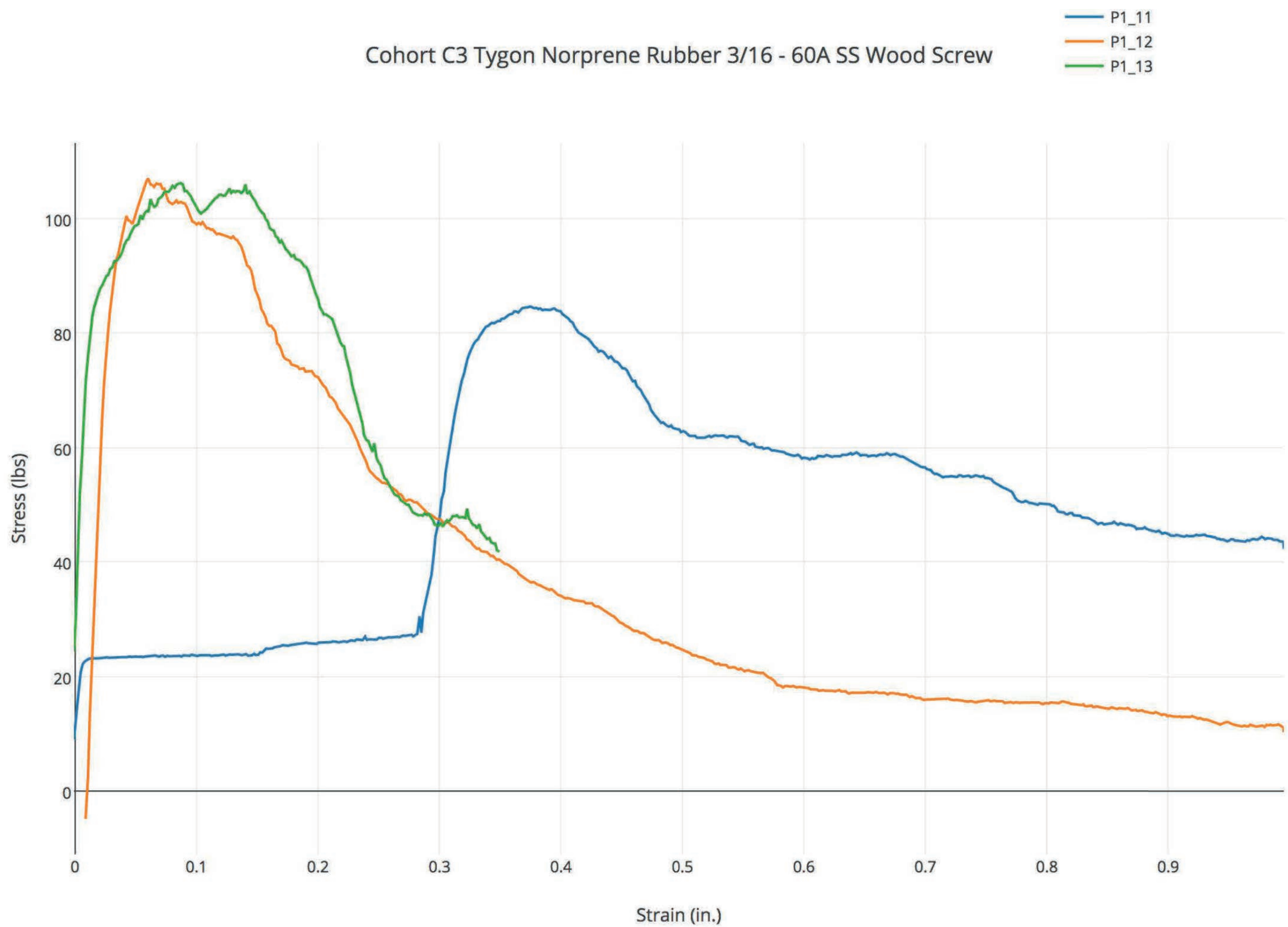


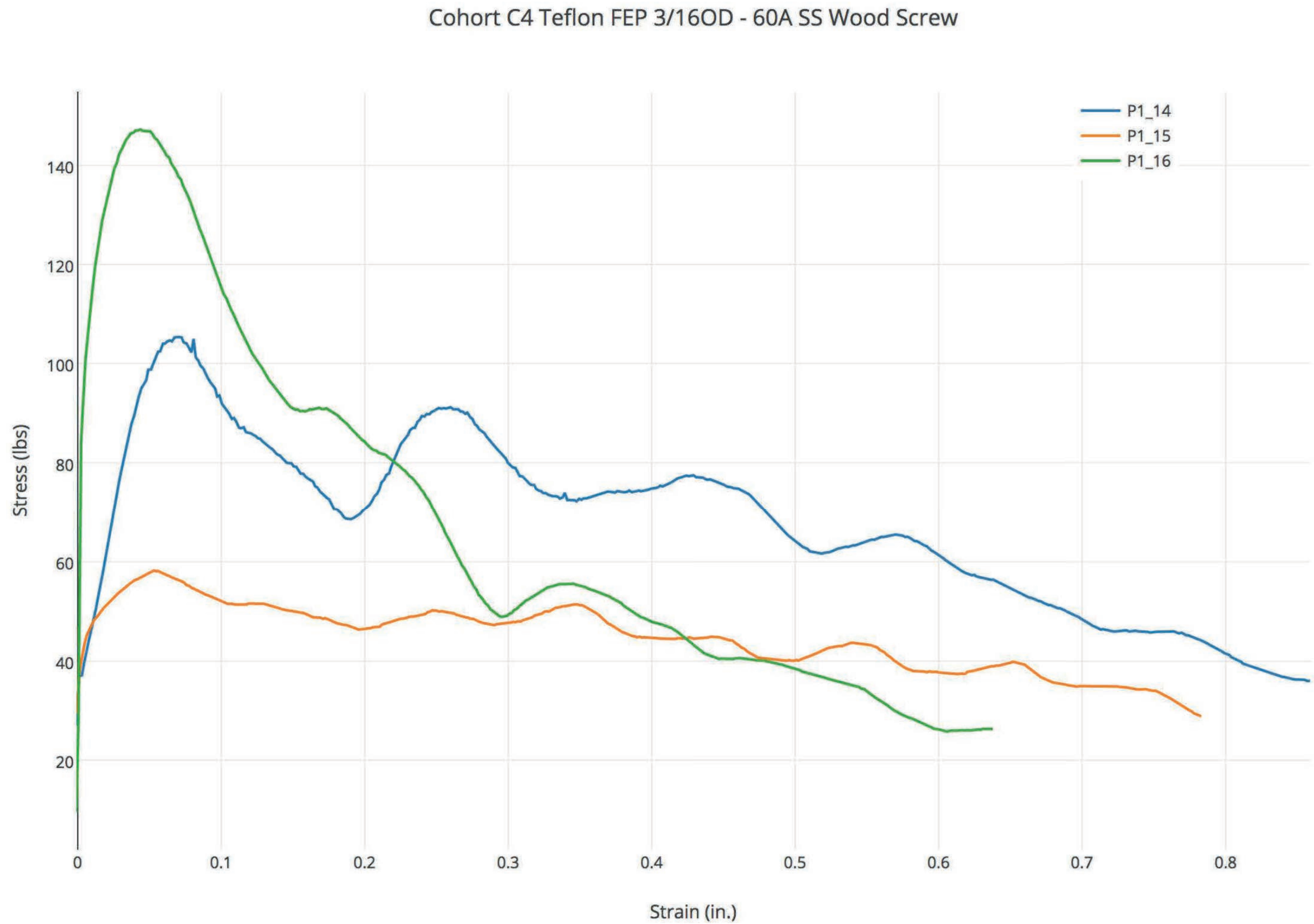
COHORT PULL OUT TESTS

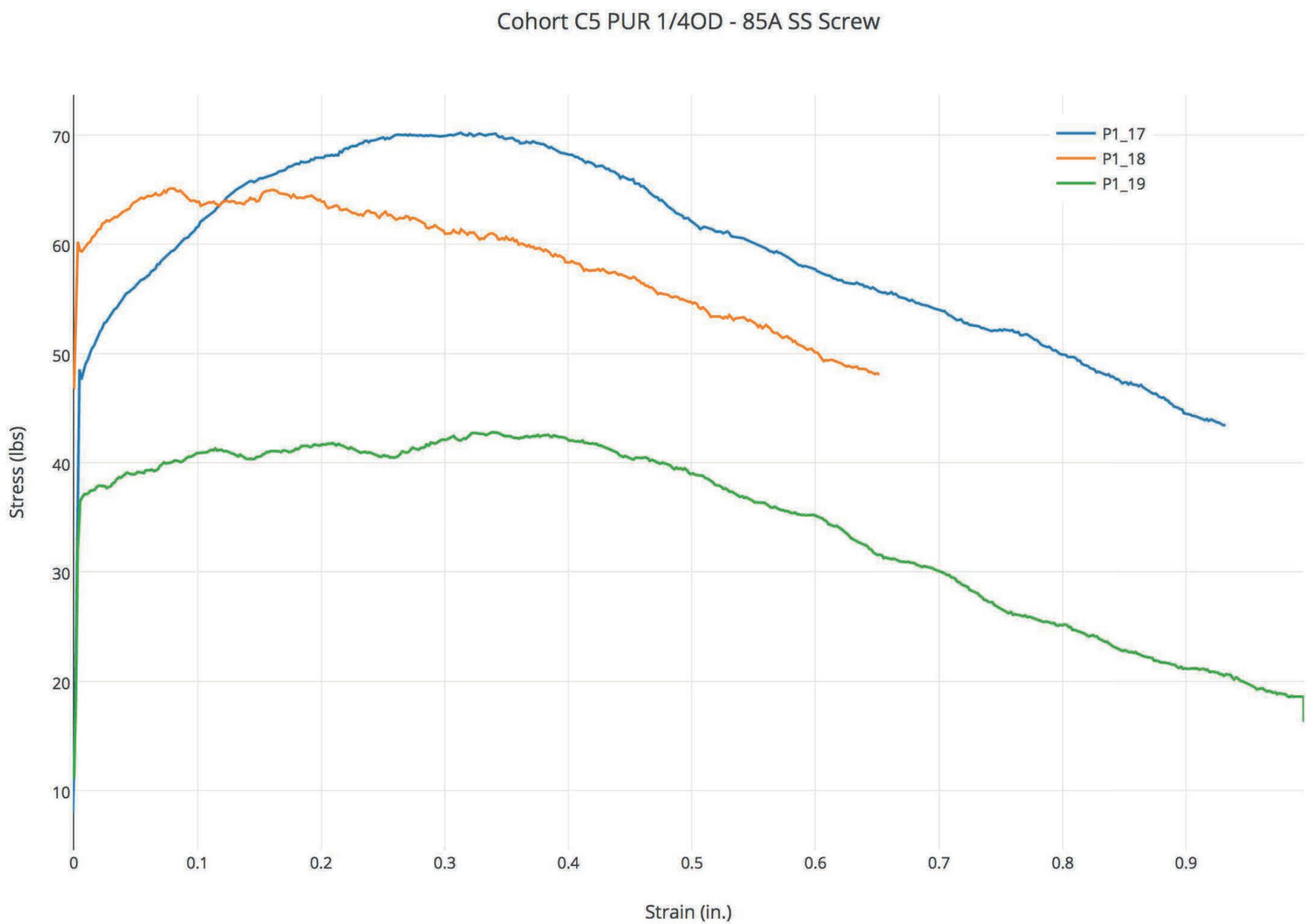

Cohort C1 - Tygon Norprene Rubber 1/4OD - 60A
P1_2
P1_3
P1_4
Stress (lbs)
0
50
100
150
200
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Strain (in.)

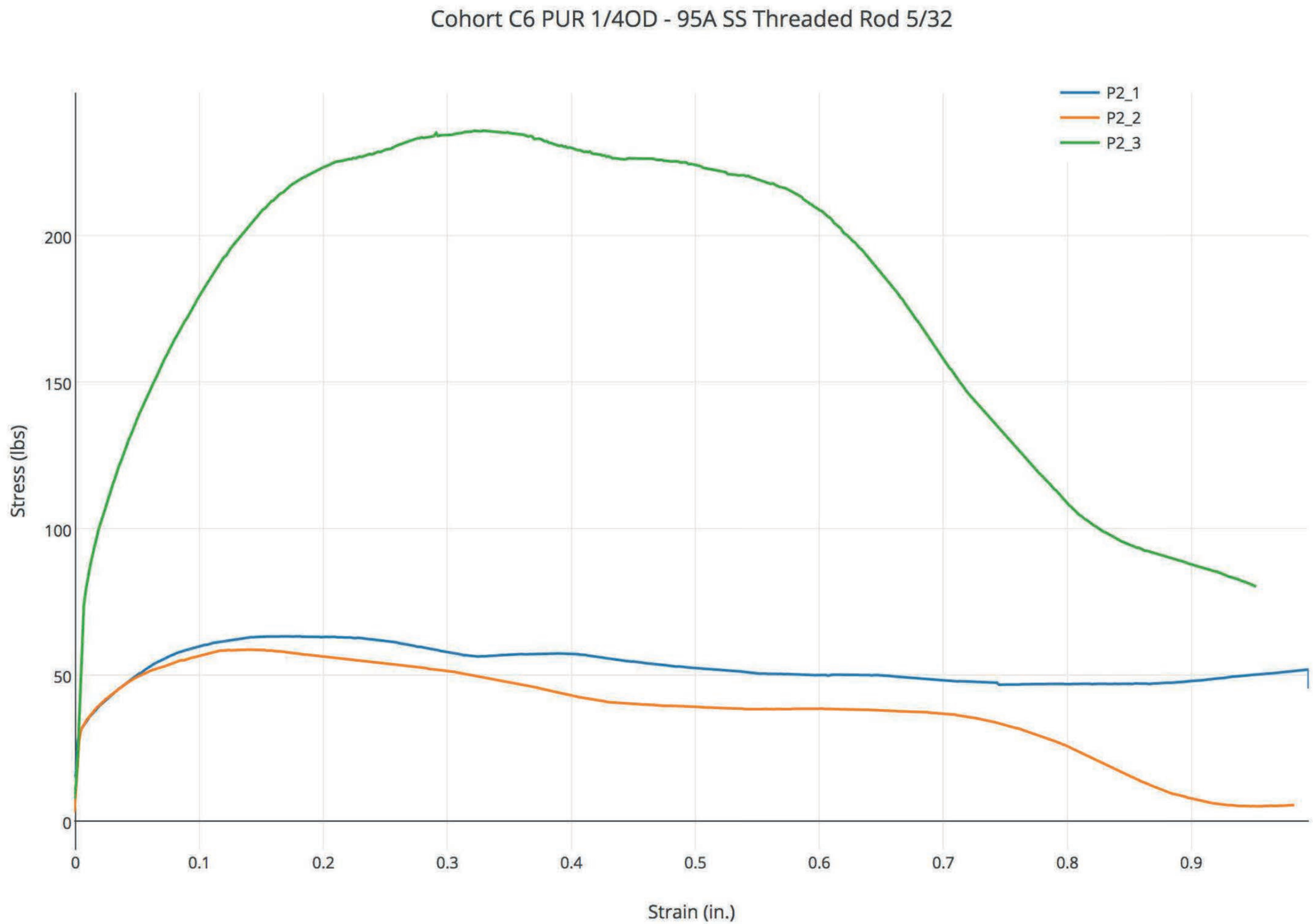


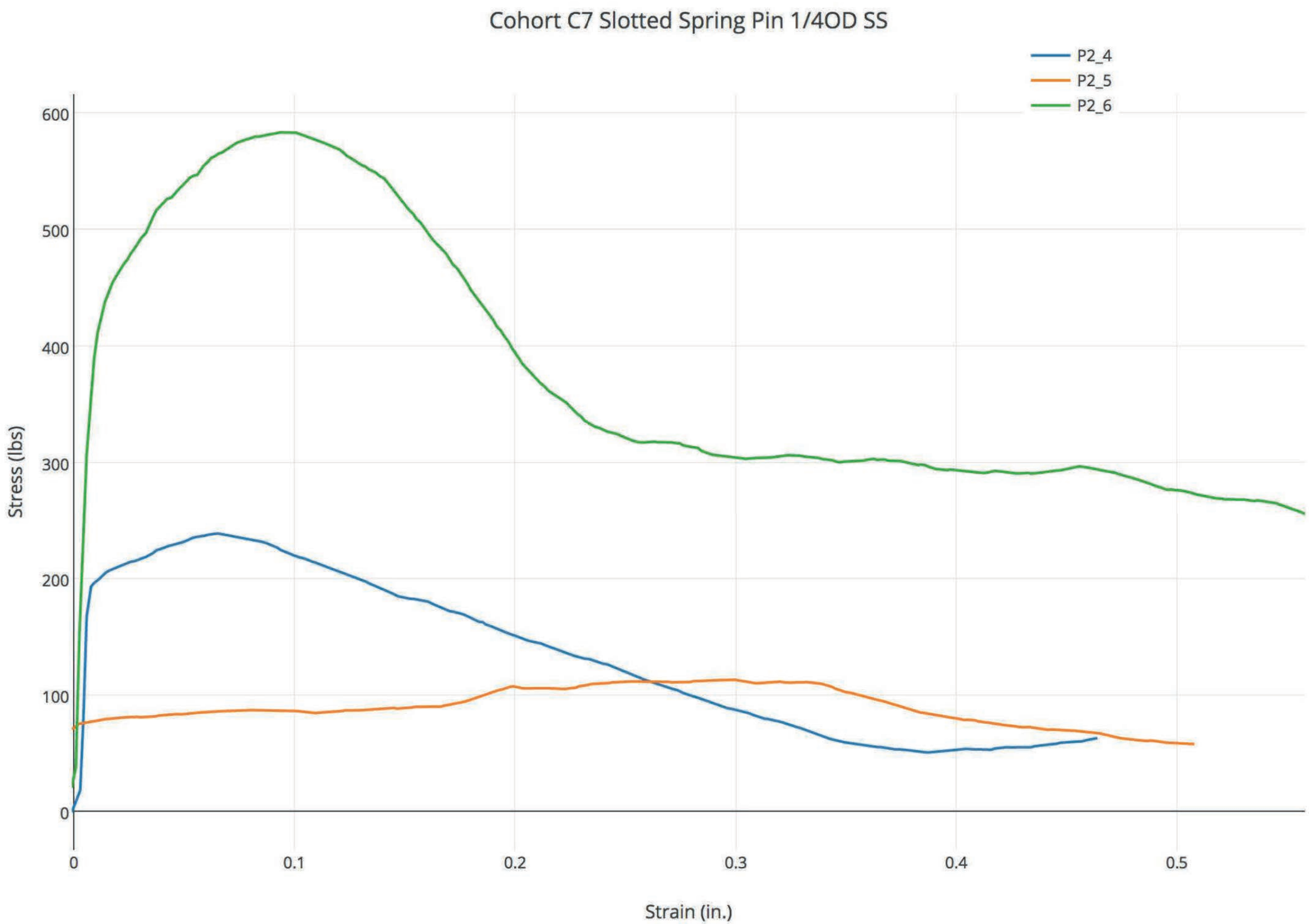
Cohort C2 - Fluorosilicone Vanguard 1/4OD - SS Screw
P1_5
P1_7
P1_8
Stress (lbs)
40
35
30
25
20
15
10
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Strain (in.)

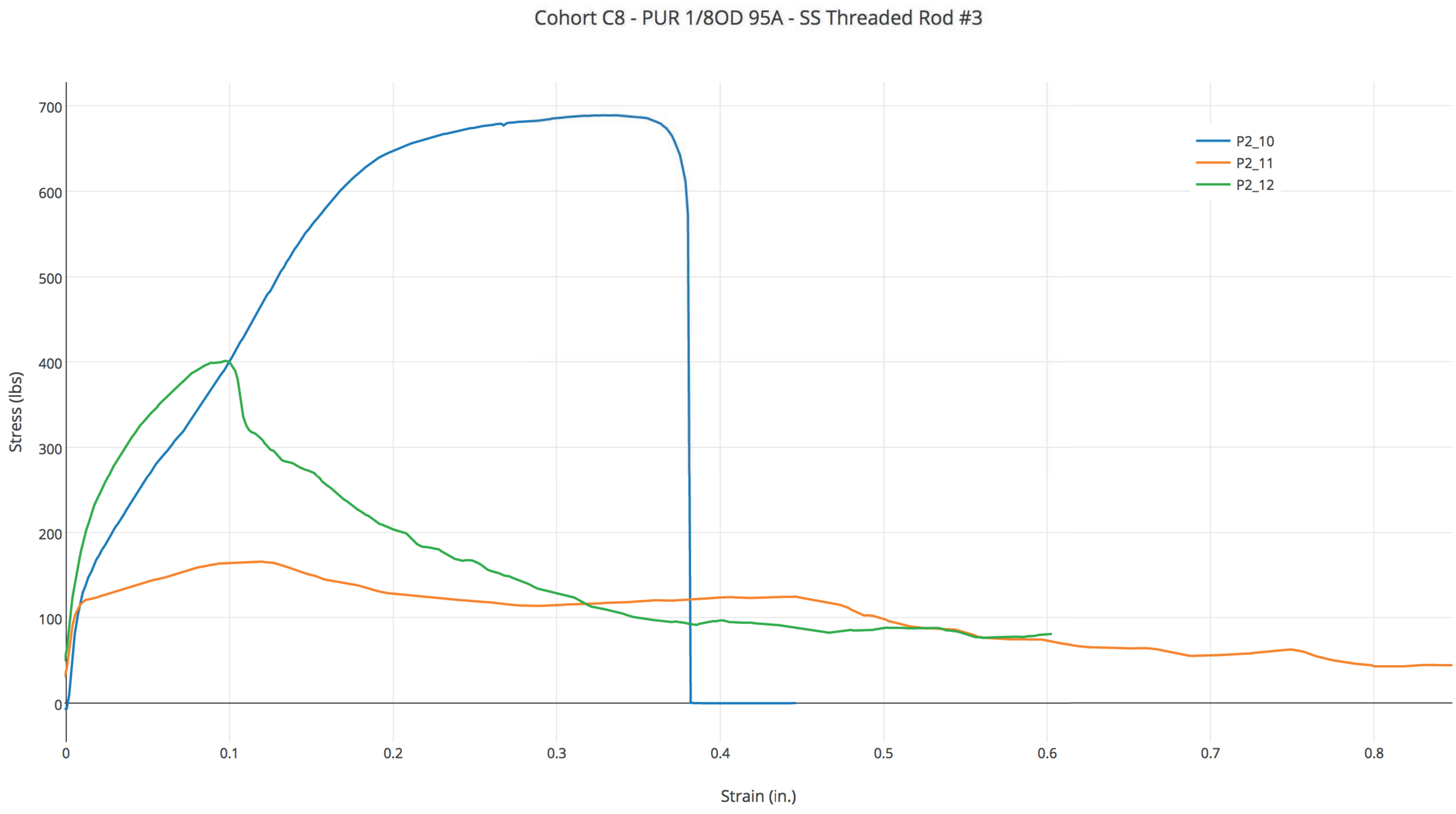

Cohort C3 Tygon Norprene Rubber 3/16 - 60A SS Wood Screw
P1_11
P1_12
P1_13
Stress (lbs)
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Strain (in.)

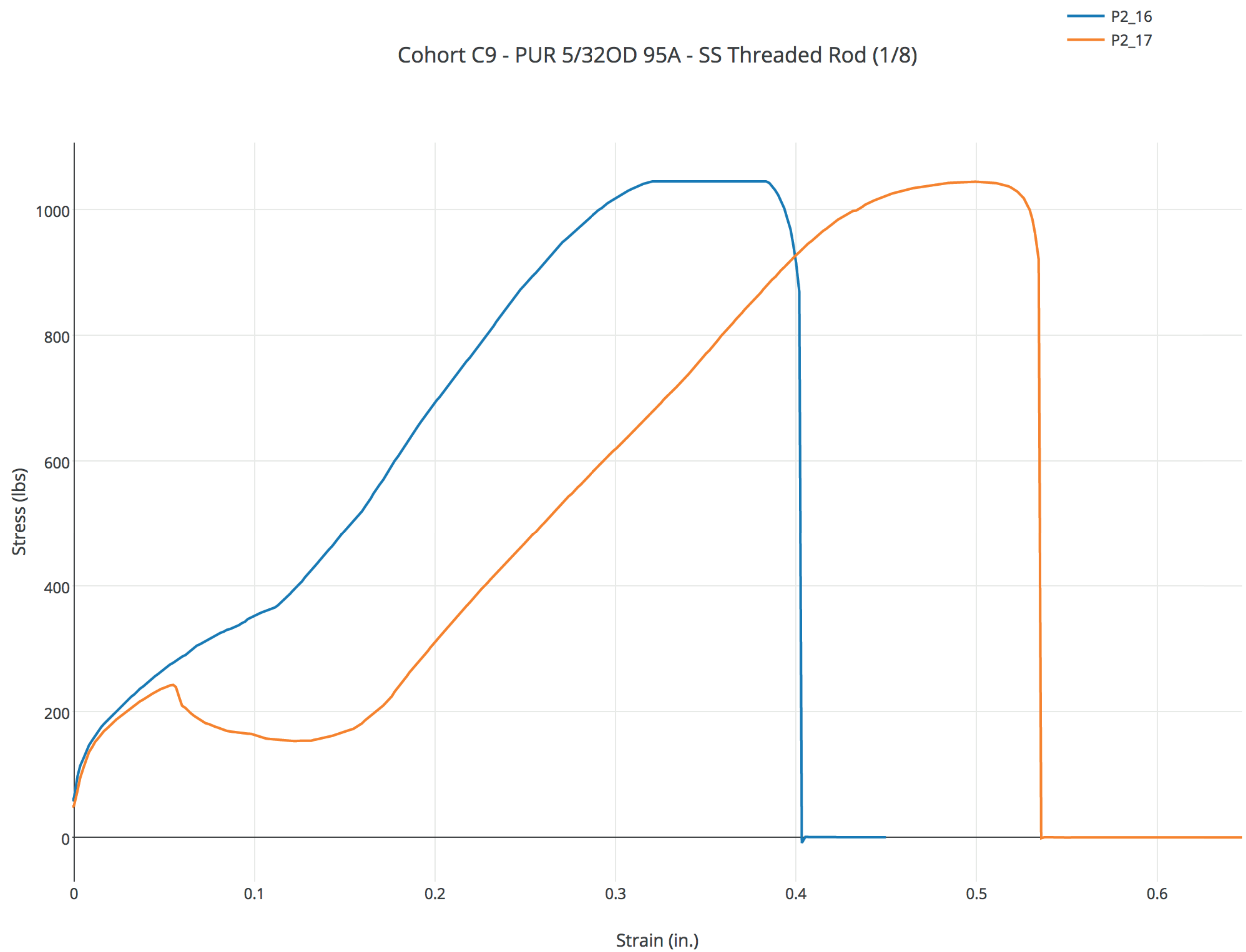

Cohort C4 Teflon FEP 3/16OD - 60A SS Wood Screw
P1_14
P1_15
P1_16
Stress (lbs)
Strain (in.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
20
40
60
80
100
120
140


Cohort C5 PUR 1/4OD - 85A SS Screw
P1_17
P1_18
P1_19
Stress (lbs)
Strain (in.)
10
20
30
40
50
60
70
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

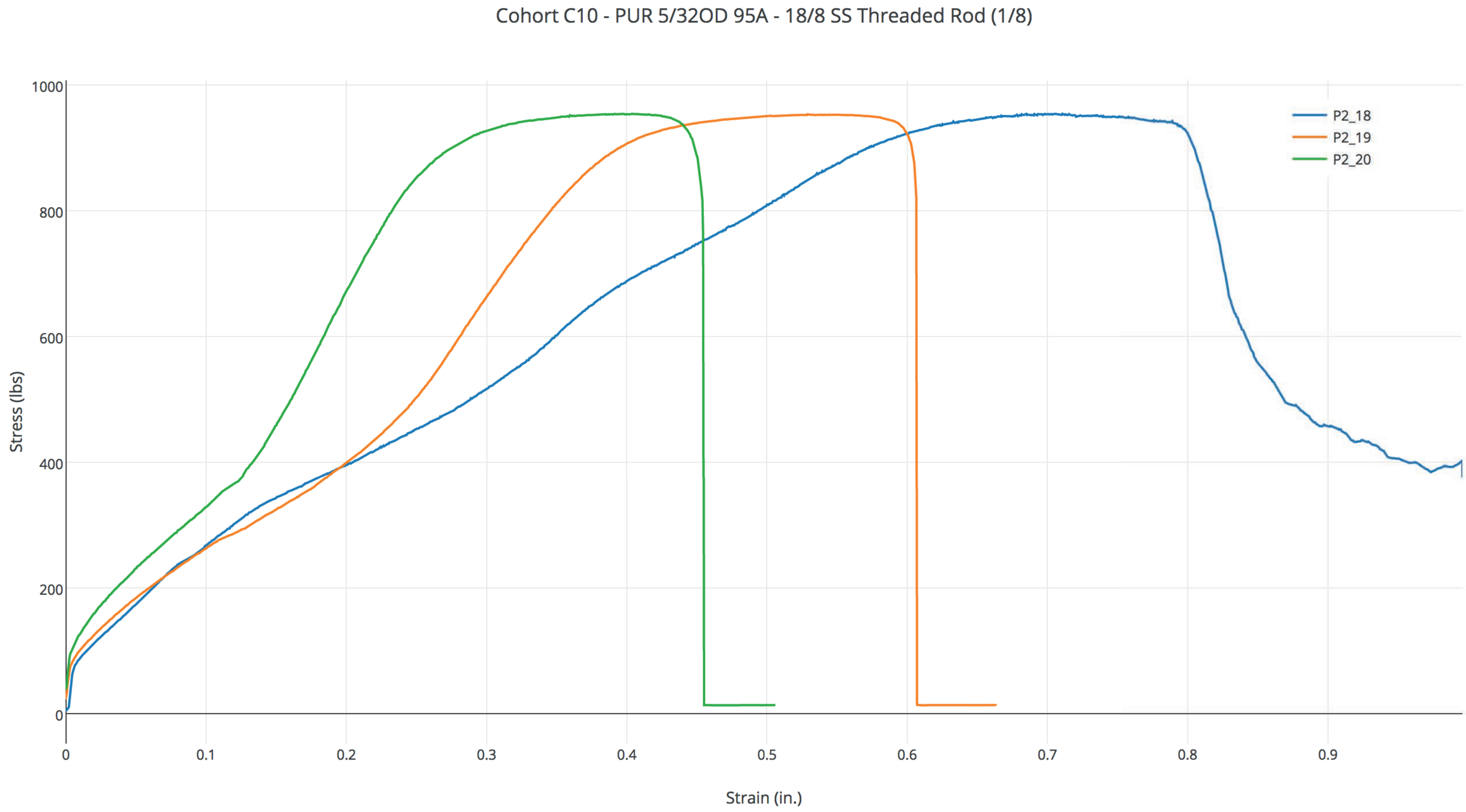

Cohort C6 PUR 1/4OD - 95A SS Threaded Rod 5/32
P2_1
P2_2
P2_3
Stress (lbs)
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Strain (in.)


Cohort C7 Slotted Spring Pin 1/4OD SS
P2_4
P2_5
P2_6
Stress (lbs)
0
100
200
300
400
500
600
0
0.1
0.2
0.3
0.4
0.5
Strain (in.)


Cohort C8 - PUR 1/8OD 95A - SS Threaded Rod #3
Stress (lbs)
700
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Strain (in.)
P2_10
P2_11
P2_12



Cohort C9 - PUR 5/32OD 95A - SS Threaded Rod (1/8)
P2_16
P2_17
Stress (lbs)
0
200
400
600
800
1000
Strain (in.)
0
0.1
0.2
0.3
0.4
0.5
0.6


Cohort C10 - PUR 5/32OD 95A - 18/8 SS Threaded Rod (1/8)
Stress (lbs)
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Strain (in.)
P2_18
P2_19
P2_20

Index