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Key Points:
- Yellowstone's Old Faithful Geyser stopped erupting for many decades in response to severe multidecadal regional droughts in the thirteenth century
- Wood is preserved for over 650 years because silica-rich alkaline waters deposit amorphous opal on cellular films
- Because climate models project increasingly severe droughts by mid-21st century, eruptions could become less frequent or completely cease

Supporting Information:
- Supporting Information S1

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Yellowstone's Old Faithful Geyser Shut Down by a Severe Thirteenth Century Drought

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Abstract To characterize eruption activity of the iconic Old Faithful Geyser in Yellowstone National Park over past centuries, we obtained 41 new radiocarbon dates of mineralized wood preserved in the mound of silica that precipitated from erupted waters. Trees do not grow on active geyser mounds, implying that trees grew on the Old Faithful Geyser mound during a protracted period of eruption quiescence. Rooted stumps and root crowns located on higher parts of the mound are evidence that at the time of tree growth, the geyser mound closely resembled its current appearance. The range of calibrated radiocarbon dates (1233–1362 CE) is coincident with a series of severe multidecadal regional droughts toward the end of the Medieval Climate Anomaly, prior to the onset of the Little Ice Age. Climate models project increasingly severe droughts by mid-21st century, suggesting that geyser eruptions could become less frequent or completely cease.

Plain Language Summary The rarity of natural geysers reflects the special conditions needed for their formation, including an abundant supply of water. Therefore, severe droughts of extended duration could have led to large variations in the frequency and intensity of geyser eruptions. To characterize potential changes in eruption activity of the iconic Old Faithful Geyser in Yellowstone National Park over past centuries, we collected mineralized wood samples from its mound and used radiocarbon to date when these trees grew. Because trees do not live on active geyser mounds, we infer that the trees grew during a protracted period without eruptions. The dated fossil trees are from the thirteenth and fourteenth centuries during a time with severe multidecadal droughts in the region. Because climate models forecast increasingly severe droughts by mid-21st century, geyser eruptions could become less frequent or completely cease.

1. Introduction

Droughts in the western United States and the Greater Yellowstone region commonly exhibit strong variability on interannual to multidecadal time scales, with recent decadal droughts being unusually severe due to regional warming (e.g., Calder et al., 2015; Cook et al., 2004; Gray et al., 2007; Martin et al., 2019a, 2019b, 2020; Meko et al., 2007; Meyer & Pierce, 2003; Millspaugh & Whitlock, 1995; Stegner et al., 2019; Whitlock et al., 2008). Severe droughts of extended duration could have led to large variations in hydrothermal discharge and more specifically, to the frequency and intensity of geyser eruptions.

The rarity of natural geysers reflects the special conditions needed for their formation: a supply of water, an area of recent or active magmatism to supply heat, and the right geometry of subsurface fractures and cavities to permit episodic discharge. Because of the delicate balance between these controlling parameters, geysers are transient with periods of activity and dormancy affected by earthquakes and climate (Hurwitz & Manga, 2017).

About half of the ~1,000 geysers worldwide are in Yellowstone National Park, mostly in the Upper Geyser Basin (UGB; Figure 1), including Old Faithful Geyser (OFG; Figure 1). Ferdinand V. Hayden who led the 1871 geological survey of northwestern Wyoming, leading to the establishment of Yellowstone as the first U.S. National Park in 1872, wrote about OFG: "*This geyser was named by Mr. N. P. Langford, and well sustains the reputation given it by the Doane and Washburn expedition of 1870. It has been called the Guardian of the Valley. It is so regular in its operations and they occur so frequently that it has afforded*

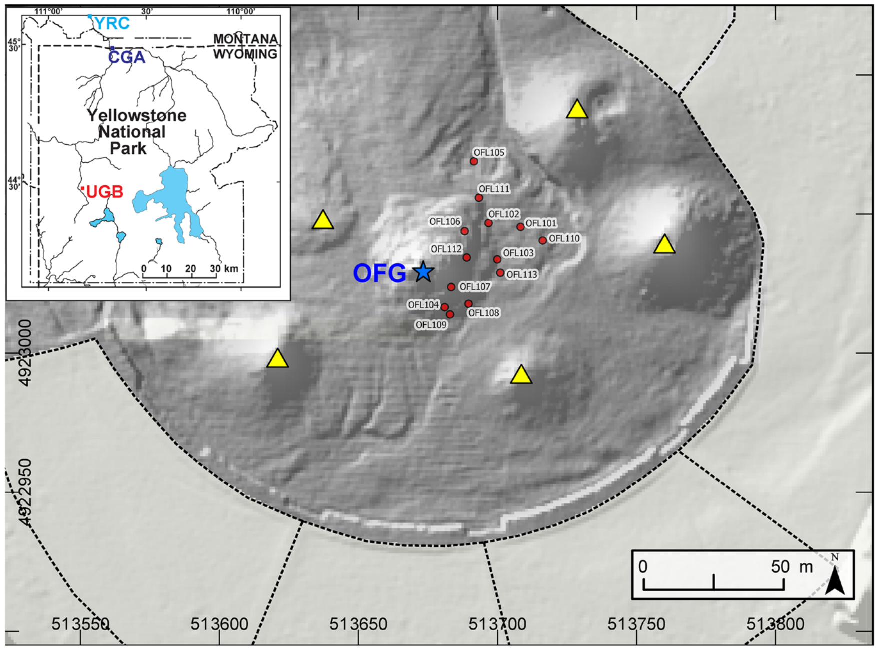

Figure 1. Map of the Old Faithful Geyser area showing geyser mounds (yellow triangles) and mineralized wood remnants (red circles) around the Old Faithful Geyser vent (OFG and blue star). Split Cone discharges thermal water, but without a spout. The easternmost mound has a mixed age stand of lodgepole pine. Black dashed lines are boardwalks. Coordinates are in Universal Transverse Mercator (UTM) Zone 12. The inset shows a map of Yellowstone National Park with the locations of the Upper Geyser Basin (UGB), the gauge (USGS Gauge# 6191500) on the Yellowstone River at Corwin Springs (YRC) and the Chinese Garden Expanded tree chronology area (CGA).

unusual facilities for observation" (Hayden, 1883, p. 220). Since the establishment of Yellowstone National Park, observations indicate that the OFG interval between eruptions (IBE) has changed considerably. The average annual IBE of 60–65 min in the 1950s gradually lengthened to 90–94 min since 2001 during the "Turn-of-the-Century" drought (ca. 2000–2010; Martin et al., 2020). These IBE changes were mainly in response to three large regional earthquakes (Hurwitz et al., 2014). In addition, years with less (more) precipitation exhibit longer (shorter) IBE on average, suggesting drought may influence eruption frequency at OFG (Hurwitz et al., 2008). The precipitation itself does not directly feed the eruptions but it recharges groundwater that in turn increases the hydraulic head that promotes surface discharge. Despite the variations in IBE, concentrations of major dissolved species in the geyser's erupted water have remained nearly constant for >120 years, suggesting that no major changes have occurred in the thermal state of the UGB hydrothermal system (Hurwitz et al., 2012).

To obtain further information on the potential relation between OFG eruptions and long-term regional drought variability or subsurface geologic change due to earthquakes, we used radiocarbon analysis to date mineralized remnants of trees that previously grew on the geyser's mound. These dates were then compared against tree-ring-based streamflow hydroclimatic records from the Yellowstone Region and published geophysical records of large earthquakes. Additionally, scanning electron microscopy (SEM) was used to provide information on the link between geyser activity and long-term deadwood preservation. This is relevant to why the wood remained on the landscape for more than a few centuries.

2. Radiocarbon Dating of Mineralized Wood

We identified and mapped 23 remnants of mineralized wood on the OFG mound (Hurwitz et al., 2020), a subsample of the total assemblage. The mineralized wood ranges from degraded fragments <2 cm in length to >2 m largely intact stems (Figure 2). Rooted stumps and obvious root crowns on higher parts of the geyser mound are evidence that at the time of their growth, the mound closely resembled its current appearance. This observation also implies that the geyser was erupting for a long time (centuries to millennia) prior to tree growth to create the mound. Some remnants are loose on the surface of the mound while others are

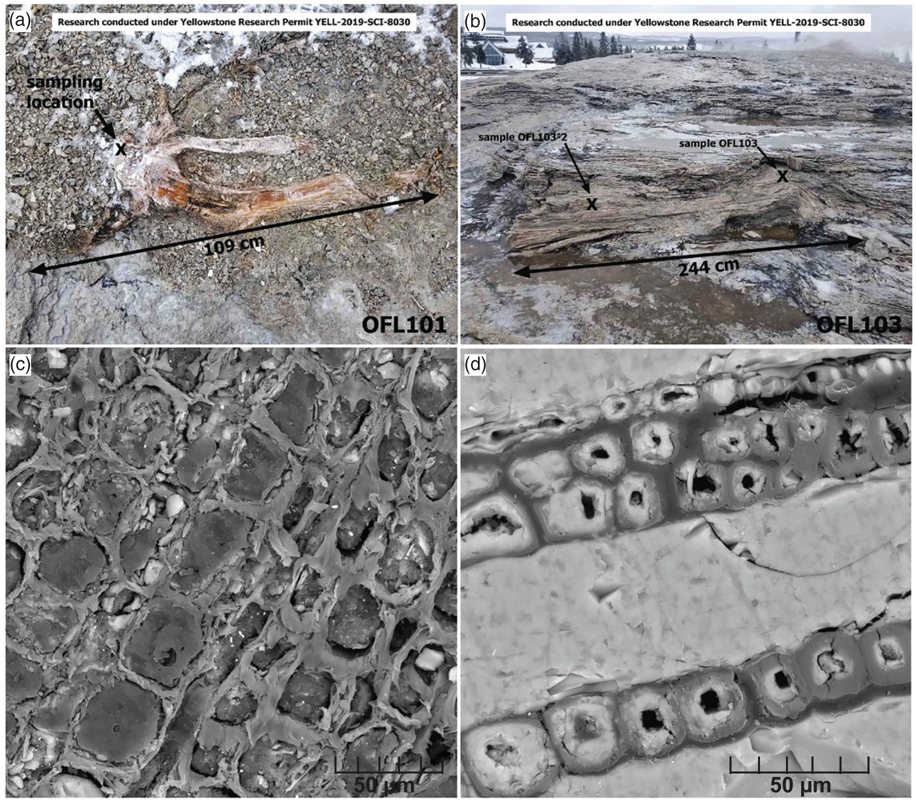

Figure 2. (a) Photo of OFL101 in situ, (b) photo of OFL103 in situ, (c) SEM backscattered electron (BSE) micrograph of OFL101, and (d) SEM BSE micrograph of OFL103. In the BSE images, the lightest gray areas show silica mineralization, medium gray areas show remaining plant cells, and black areas are pore space.

partly or completely entombed in sinter deposits. Mineralized wood remnants were not found on other mounds surrounding OFG (Figure 1).

From 13 mineralized wood specimens ranging in size from 30 to 70 g we obtained 41 new radiocarbon (^{14}C) dates (Hurwitz et al., 2020). Three samples with low levels of mineralization (OFL101, OFL102, and OFL110) were identified as lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.). The remaining highly friable mineralized samples lacked the cellular definition needed for species identification. We were able to isolate and date individual annual rings from rooted stump Samples OFL101 and OFL102 (11 and 8 rings, respectively; Hurwitz et al., 2020). For the rest of the more mineralized specimens, samples likely reflect multiple growth years. We sampled the oldest (OFL103) and youngest (OFL103-2) parts of the largest mineralized tree, approximately 2.4 m long (Figure 2). The age difference between the oldest and youngest parts of the tree (81 ± 24 years) provides an estimate for the number of years it was alive.

Radiocarbon dating of the mineralized wood was performed at the U.S. Geological Survey's (USGS) Radiocarbon Laboratory in Denver, Colorado; details of the analytical procedures and calibration are provided in Hurwitz et al. (2020). The $\delta^{13}C$ values of eight samples (−21.0‰ to −23.8‰) are within the range expected for tree cellulose and lignin (−21 to −26‰; Loader et al., 2003) indicating either no or minimal contamination by dissolved inorganic carbon, which in Yellowstone has values ranging between −4.7‰ and −0.7‰ (Bergfeld et al., 2019). Contamination by old carbon sources in sinter organic carbon can be recognized by anomalously heavy $\delta^{13}C$ (e.g., Churchill et al., 2020; Munoz-Saez et al., 2020).

Several dated samples that are considered unreliable were removed from further data analysis. Specimens OFL112 and OFL113 had very low carbon contents and yielded much older ages (Hurwitz et al., 2020). Three individual samples (OFL101-Ring 11, OFL102-Ring 6, and OFL106c) are not in sequence or are inconsistent with the dates of other samples from the same specimen. The range of ^{14}C calibrated ages for all samples after removal of outliers is 1233 to 1362 CE (Table 1).

Table 1
Calibrated ^{14}C Dates of Mineralized Wood Specimens From the Old Faithful Geyser Mound

Sample	*n*	Minimum date	Maximum date
OFL101	6	1304	1362
OFL102	4	1342	1350
OFL103	5	1233	1362
OFL104	4	1299	1361
OFL105	3	1343	1356
OFL106	3	1283	1296
OFL107	2	1277	1301
OFL108	2	1244	1352
OFL109	2	1357	1357
OFL110	2	1350	1352
OFL111	2	1267	1269

Although multiple samples from individual specimens provide different ages, apart from Specimens OFL101 (58 years), OFL103-2 (66 years), OFL104 (62 years), and OFL108 (108 years) the difference between the minimum and maximum dated samples is <25 years (Table 1). A single wood sample from the OFG mound (likely the same specimen as OFL103) was dated in one of the earliest applications of the radiocarbon method to 730 ± 200 years (Marler, 1956), which after calibration corresponds to 703 ± 200 BP, or a date of 1247 ± 200 CE. This date is within the range of the newly dated samples (Table 1).

3. Hiatus in Geyser Eruptions Coincident With a Regional Drought

Lodgepole pine trees dominate ~80% of the total forested area in Yellowstone National Park and the preponderance of its saplings over competing species indicates its resilience (Despain, 1983). Both serotinous and nonserotinous cones are found on lodgepole pine in Yellowstone (Tinker et al., 1994) implying that a variety of disturbances including fire can lead to successful tree regeneration. Lodgepole pine are largely excluded from growing on active geyser mounds, probably because alkaline erupted water (pH ~ 9.0–9.4; McCleskey et al., 2014) reduces their germination and seedling growth (Abouguendia & Redmann, 1979). This implies that when lodgepole pine grew on the OFG mound in the mid-13th to mid-14th centuries, the geyser was not erupting for many decades given the age of tree OFL-103.

Large earthquakes can potentially terminate geyser eruptions (Hurwitz & Manga, 2017). The lack of large ($M > 7$) documented regional earthquakes during that period (DuRoss et al., 2019; Larsen et al., 2019) does not support this hypothesis as the mechanism behind Old Faithful's extended quiescence. A hydroclimatic explanation, however, is supported by the temporal coincidence of geyser dormancy with extended, severe drought. The new ^{14}C dates of mineralized wood coincide with the end of the Medieval Climate Anomaly (MCA) that occurred approximately between 800 CE and the onset of the Little Ice Age at 1300 CE (Cook et al., 2004; Mann et al., 2009; Rodysill et al., 2018). Tree-ring reconstructions of the Palmer Drought Severity Index (PDSI) and sediment core studies reveal a series of severe multidecadal droughts in the southwestern, southeastern, and central United States during the MCA (e.g., Rodysill et al., 2018). These persistent droughts had a tremendous impact on several Indigenous cultures, including the Anasazi, Fremont, and Lovelock cultures (Benson et al., 2007; Bird et al., 2017; Thomson et al., 2019). In the Yellowstone Region, the twelfth and thirteenth centuries saw the largest sustained low- and high-stream-flow anomalies of the past 1,200 years. The most severe and sustained drought on record occurred in the mid-13th century (Martin et al., 2019a), coincident with the onset of tree growth on the OFG mound (Figure 3).

To assess potential hydroclimatic drivers associated with the hiatus of OFG eruptions, we compare the ^{14}C dates against several tree-ring-based drought records (Figure 3 and Figure S1 in the supporting information). Though each hydroclimatic reconstruction potentially shares an unknown percentage of underlying tree-ring data, the local ring-width record and regional reconstructions reflect different dominant seasonal water balance influences at OFG. The primary record used is a 1,200-year reconstruction of annual water year streamflow for the Yellowstone River at Corwin Springs, YRC in Figure 1 (Martin et al., 2019a). This record reflects the regional total annual moisture balance, capturing the dominant influence (~50–80%) of cool-season (October–April) precipitation on regional surface and groundwater hydrology (Martin et al., 2019a; Wise et al., 2018) for the Yellowstone region. For a regional record predominantly reflective of summer (June–August) soil moisture conditions we use the reconstructed PDSI data from the North American Drought Atlas version 2b (grid point no. 100) from Cook et al. (2004) (Figure S1b). As a final check on inferred local moisture conditions, we also compare against the predominantly spring (May–June) precipitation sensitive (Figure S2) Rocky Mountain Juniper (*Juniperus scopulorum*, Sarg.) standardized ring-width chronology from King (2016), known as Chinese Garden Expanded (Figure S1a) using methods designed to preserve low-frequency hydroclimatic variability described in Martin et al. (2019a). For comparison of the records, and to identify the relative magnitude and duration of associated multidecadal moisture anomalies, all records were smoothed using a 50-year cubic smoothing spline (Figures 3 and S1).

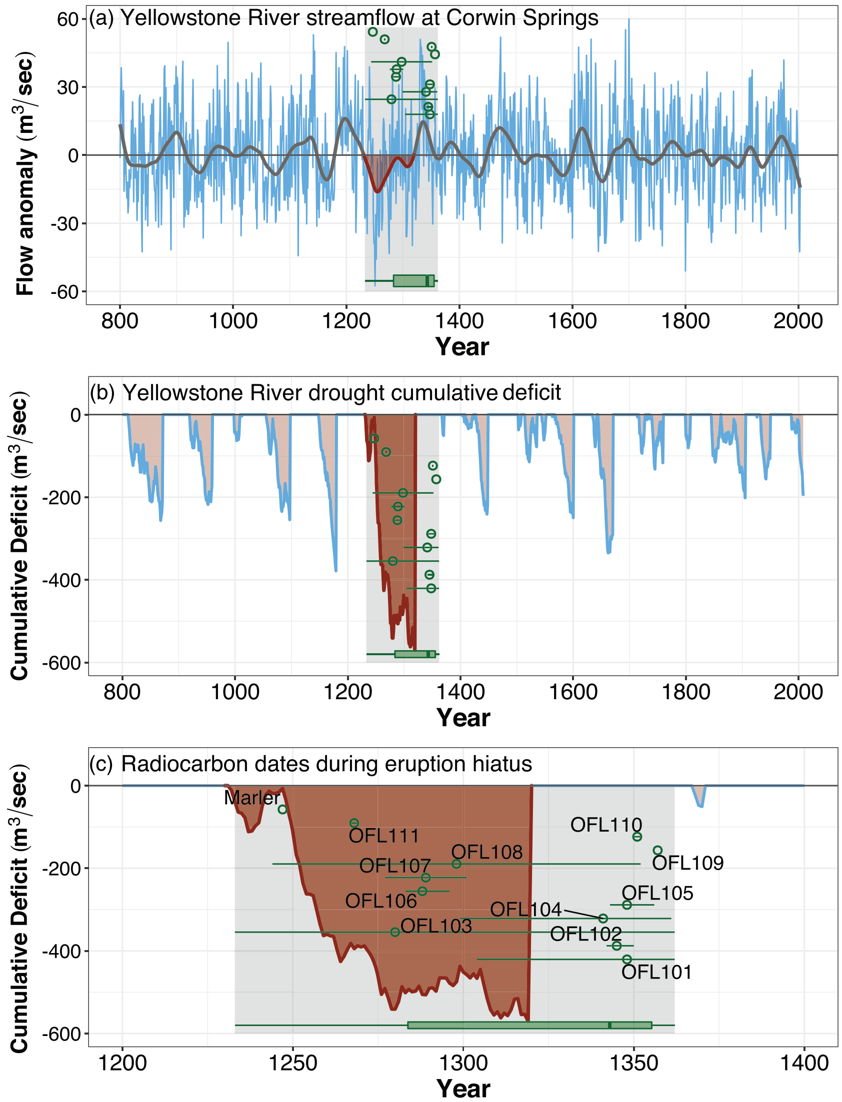

Figure 3. (a) The 1,200-year reconstruction of average water year (October–September) streamflow for the Yellowstone River at Corwin Springs, Montana (Figure 1; blue curve), smoothed with a 50-year spline (gray) to highlight major multidecadal drought and high-flow events. (b) The cumulative streamflow deficits associated with time period of each identified drought event. (c) The time period of the thirteenth century megadrought and the eruption hiatus of the Old Faithful geyser. In all panels the mean annual flow rate is plotted with a black horizontal line and the thirteenth century megadrought is shaded red. The mean ^{14}C dates from each wood specimen and estimated error (green dots and whiskers) are shown along with a boxplot (showing median calibrated date and upper and lower quartiles) of all ^{14}C dates from across the samples. The boxplot at the bottom of the panels shows the total range (1233 to 1362 CE) of calibrated ^{14}C dates. The sample labeled "Marler" represents a ^{14}C date from Marler (1956) after calibration.

Multidecadal drought periods for the Yellowstone River at Corwin Springs reconstruction were identified as periods of negative flow anomalies in the 50-year cubic smoothing spline of streamflow. With drought length defined by the negative flow anomaly of the spline, cumulative streamflow deficits were calculated for each drought period by summation of the unsmoothed annual flow values for each year of the drought (Martin et al., 2020). This method of tallying cumulative hydrologic deficits during extended drought events provides enhanced detail on the evolution of the drought and the growth of hydrologic deficits since intervening wet periods can reduce the intensity of the long-term drought (Figures 3b and 3c). Both the drought event and the cumulative annual value summation of its associated streamflow deficits ends when the 50-year spline of streamflow becomes positive.

Though the magnitude and total duration of the drought slightly varies among the records, each shows a thirteenth century "megadrought" greater than 50 years in duration with the most severe drought years centered on the year 1250 CE (Figures 3 and S1). The negative spline departure in Yellowstone River streamflow suggests the drought initiates around 1230 CE and extends to ~1285 CE with numerous intervening years with average to above average moisture in the latter half of the drought that causes the growth of the cumulative deficit to flatten. The intervening average to wet years, and a sensitivity analyses (Figure S3) using splines of 10, 20, 30, 40, and 50 year lengths suggests that this extended drought was possibly comprised of multiple severe decadal-scale droughts (Figure S3). However, in terms of cumulative deficit this event always ranks as the most severe long-duration event in the record independent of how the drought length is defined. This is also evident in the summer PDSI and the local Chinese Garden Expanded tree chronology area (CGA) tree-ring chronology (Figure S1), even though these records predominantly represent warm season precipitation and moisture deficit conditions. The year-to-year cumulative negative moisture deficit over the duration of this multidecadal drought likely lowered water levels causing cessation of OFG eruptions. We attribute the death of trees in the mid-14th century to the corresponding major pluvial event following the drought that increased water levels in the region (Figure 3) leading to the resumption of OFG eruptions and wetting of the sinter deposits with alkaline water. We were unable to assess whether older extended periods of quiescence permitted trees to colonize the sinter mound. Such a record may exist below the accessible surface, within the sinter stratigraphy.

4. Preservation and Mineralization of Wood on the Geyser Mound

Carbon dating of OFG samples requires preservation of dead tree remnants for >650 years. To consider the potential role of mineralization in preservation, the distribution of silica precipitation in root stump (OFL101 and OFL102) and branch (OFL103-2) samples was imaged by SEM. Details of sample preparation and imaging are available in Hurwitz et al. (2020). The SEM images are consistent with field and hand sample observations which suggest that rooted stump Samples OFL101 (Figure 2a) and OFL102 are significantly less mineralized than stem Sample OFL103-2 (Figure 2b), despite the similar ages. Sample OFL101 retains a high proportion of original wood tissue throughout the annual ring structure (Figure 2c), while Sample OFL103-2 is characterized by a low proportion of original wood tissue largely concentrated in latewood cells (Figure 2d).

The SEM images and observations of in situ specimens show that lodgepole pine exposed to silica-rich alkaline thermal waters can be preserved for many centuries (e.g., Hellawell et al., 2015; Liesegang & Gee, 2020), most likely because it prevents the disintegration of cellulose by fungi, bacteria, and insects (Blanchette, 1995). Mineralization initiates when amorphous opal is deposited on tree stems, and this coating enables the transport of silica-rich fluids into wood tissues by capillary forces (Liesegang & Gee, 2020). Silica is then preferentially deposited in small pore spaces including pit chambers, latewood tracheid lumina, and parenchyma rays (Mustoe, 2017). This type of in situ silicification can be rapid and take only days or weeks (Channing & Edwards, 2003; Liesegang & Gee, 2020). Silica mineralization is also enhanced by the extremely cold winters in Yellowstone, which cause opal-A to precipitate cryogenically (Channing & Butler, 2007) and microorganisms to become fossilized (Fox-Powell et al., 2018). In Yellowstone's nonthermal areas, lodgepole pine deadwood seldomly exceeds 300 years old (Despain, 1983).

Rooted stump Specimens OFL101 (Figure 2), OFL102, and OFL110, located downwind of the mound, are significantly less mineralized than the other 10 specimens, possibly suggesting an additional or different preservation mechanism. The highly alkaline water erupted from OFG makes it unfavorable for fungi and bacteria colonization (Schmidt, 2006). The slow wood deterioration in these less mineralized specimens may have been promoted by a relatively continuous wetting with alkaline water caused by OFG eruptions during the last >650 years.

5. Implications for the Future

Climate models project increasingly severe droughts and large fires by mid-century leading to a major transformation of Yellowstone's ecosystems (Millspaugh et al., 2000; Westerling et al., 2011). Periods of decreased precipitation have been shown in modern observational records to result in less frequent eruptions of OFG (Hurwitz et al., 2008), while the new ^{14}C dates of mineralized wood suggest that severe, long-duration drought events can lead to OFG eruption cessation. If eruptions of OFG and other geysers become less frequent or completely cease, visitors will need to spend more time waiting for geyser eruptions, or possibly not see any at all. This might require readjustment of Yellowstone National Park's infrastructure (Foley et al., 2014).

Data Availability Statement

The Yellowstone River at Corwin Springs stremflow reconstruction and all of the radiocarbon data and SEM images are publicly available in two USGS data releases (Hurwitz et al., 2020; Martin et al., 2019b).

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