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ORIGINAL ARTICLE

Multiple dendrochronological responses to the eruption of Cinder Cone, Lassen Volcanic National Park, California

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Abstract

Two dendrochronological properties – ring width and ring chemistry – were investigated in trees near Cinder Cone in Lassen Volcanic National Park, northeastern California, for the purpose of re-evaluating the date of its eruption. Cinder Cone is thought to have erupted in AD 1666 based on ring-width evidence, but interpreting ring-width changes alone is not straightforward because many forest disturbances can cause changes in ring width. Old Jeffrey pines growing in Cinder Cone tephra and elsewhere for control comparison were sampled. Trees growing in tephra show synchronous ring-width changes at AD 1666, but this ring-width signal could be considered ambiguous for dating the eruption because changes in ring width can be caused by other events. Trees growing in tephra also show changes in ring phosphorus, sulfur, and sodium during the late 1660s, but inter-tree variability in dendrochemical signals makes dating the eruption from ring chemistry alone difficult. The combination of dendrochemistry and ring-width signals improves confidence in dating the eruption of Cinder Cone over the analysis of just one ring-growth property. These results are similar to another case study using dendrochronology of ring width and ring chemistry at Parícutin, Michoacán, Mexico, a cinder cone that erupted beginning in 1943. In both cases, combining analysis with ring width and ring chemistry improved confidence in the dendro-dating of the eruptions.

Keywords: Cinder Cone; Lassen Volcanic National Park; Dendrochronology; Dendrochemistry; Volcano; Dating

Introduction

In order to date a cinder-cone eruption using dendrochronology, several requisites must be satisfied (Brantley et al., 1986): (1) trees with visible, dateable growth rings must be growing near the cinder cone. (2) tephra must deposit over soils where trees are growing and affect ring growth of those trees; the thickness of tephra needed to change tree-ring growth might vary with other environmental factors. (3) The eruption must have occurred during the lifespan of affected trees.

Volcanic eruptions can affect ring width in trees (Yamaguchi and Lawrence, 1993), but interpreting ring-width changes alone as evidence of an eruption is not straightforward because many forest disturbances can cause similar changes (Sheppard et al., 2005). In

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addition to ring width, variability in elemental concentrations in tree rings can reflect environmental changes caused by an eruption (Hughes, 1988). Dendrochemistry is the measurement and interpretation of elemental concentrations in tree rings (Smith and Shortle, 1996), and it has been applied widely in environmental research, including regional-, hemispheric-, and global-scale explosive volcanic eruptions (Hall et al., 1990; Padilla and Anderson, 2002; Ünlü et al., 2005; Pearson et al., 2005; Battipaglia et al., 2007). Dendrochemistry has not worked well on Mount Etna, a volcano with frequent, persistent eruptions, but dendrochemistry might fare better with volcanoes having single eruptions and lacking other confounding pollution (Watt et al., 2007), which accurately describes remote cinder cones. For example, dendrochemical responses to the 1943 eruption of Parícutin, a cinder cone in Michoacán, Mexico (Luhr and Simkin, 1993), include increases in tree-ring sulfur and phosphorus at the start of the eruption (Sheppard et al., 2008).

Parícutin is a single case of combining dendrochemistry with ring-width analysis to demonstrate multiple dendrochronological responses to a cinder cone eruption, but replication at other sites is needed to validate this concept. As an additional case, cinder cone in Lassen Volcanic National Park in northeastern California (Fig. 1) meets the criteria listed above and was investigated for multiple dendrochronological responses, including tree-ring chemistry. Cinder Cone is thought to have erupted in the mid 1600s (Clynne et al., 2000; Clynne et al., 2002). Key evidence for dating Cinder Cone is a 4-year period beginning in AD 1666 of below-average ring width in one tree found 0.2 km west of the crater (Finch, 1937). However, the tree used to date Cinder Cone to AD 1666 has another 4-year period of below-average ring width beginning in AD 1567 (Finch, 1937). The date of AD 1567 is not possible for the eruption of Cinder Cone (Clynne et al., 2000), so below-average growth at that time must have been caused by some other factor. The objective of this

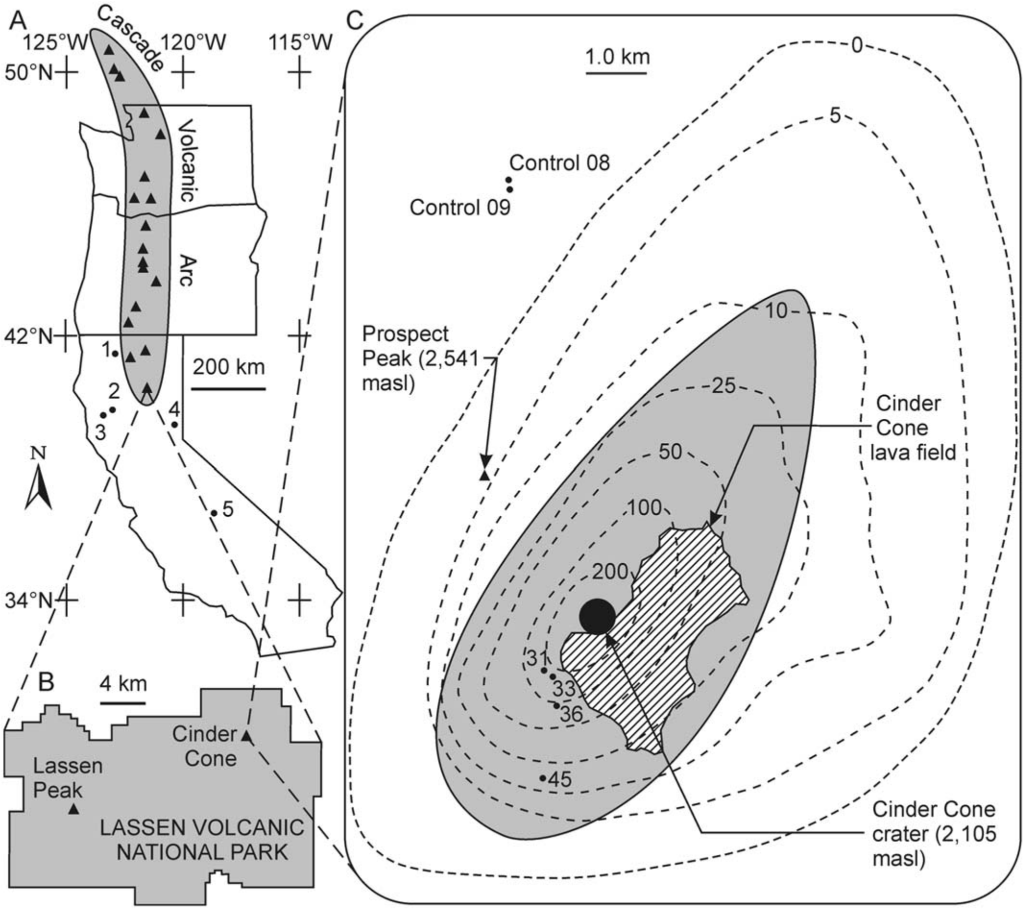

Fig. 1. Map of (A) Pacific Coast states of the US showing location of the Cascade Volcanic Arc and selected Jeffrey pine tree-ring chronologies from the International Tree-Ring Data Bank (dots with numbers), (B) Lassen Volcanic National Park showing location of Cinder Cone, and (C) Cinder Cone showing tephra isopach depths (dashed contours, in cm, Heiken, 1978), area searched for old trees (shaded area), and trees analyzed herein (dots with numbers). Control Trees 08 and 09 are located on ~15,000-year-old lava on the north side of Prospect Peak, away from tephra of Cinder Cone. The 0-cm isopach line indicates where no discrete tephra layer exists in the soil, but it does not necessarily mean that no tephra at all was deposited outside that line.

research is to document dendrochemical responses to the eruption of Cinder Cone and to further refine the analysis of multiple tree-ring responses for dating cinder cone eruptions.

Methods

Study site

Lassen Volcanic National Park (Fig. 1) is within in the Sierra Steppe–Mixed Coniferous Forest Ecoregion (Bailey, 1995). Climate of the area is wet, with a mean annual precipitation of over 1000 mm that falls predominantly as snow during winter, and cool, with a mean annual temperature of 6 °C, as determined from climate data collected within Lassen Volcanic National Park (Parker, 1991). Surface geology of Lassen Volcanic National Park, located at the southern end of the Cascade Volcanic Arc (Fig. 1A), is dominated by Pliocene to recent volcanic landforms and glacial till derived from volcanic rocks (Williams, 1932). Cinder Cone, located in the northeast corner of the park (Fig. 1B, 40° 32′ 55″N, 121° 19′ 10″W, 2,105 masl), is surrounded by 0.032 km^3 of tephra covering 96 km^2 in area distributed along a north–northeastward axis (Fig. 1C; Heiken, 1978). The eruption produced a lava-flow field, a ~210-m-high composite cinder cone, and two distinct tephra fallout units. The lava-flow field and tephra units correlate such that earlier tephra and lobes of erupted lava flow are similar geochemically but are distinct from later fallout and flow. Cooling and oxidation relations indicate that the entire sequence was erupted in one continuous, short-lived event.

Tree-ring analysis

Old trees were searched for in areas of tephra deposited from Cinder Cone in a broad ovate swath around the crater and its lava field (Fig. 1C). Although suitability of tree species for dendrochemistry should be considered in planning dendrochemical research (Cutter and Guyette, 1993), the most practical determinant of which species to sample is what actually grows at the site of interest (Watmough, 1997). At middle elevations of Lassen Volcanic National Park, vegetation is mixed conifer with Jeffrey pine (*Pinus jeffreyi*), ponderosa pine (*P. ponderosa*), western white pine (*P. monticola*), sugar pine (*P. lambertiana*), lodegepole pine (*P. contorta*), white fir (*Abies concolor*), and California red fir (*A. magnifica*) (Nelson, 1962; Taylor, 2000). Most trees at Cinder Cone are not old enough to predate the eruption of ~350 years ago. The oldest trees around Cinder Cone happen to be Jeffrey pine, and 25 Jeffrey pines were sampled within the area of Cinder Cone tephra. Four sampled trees have at least 350–400 rings, that is, dating back to the early 1600s or late 1500 s.

For comparison purposes (Forget and Zayed, 1995), old pines were sampled outside the area of Cinder Cone tephra but still within the same local bioclimatic area. Again, sufficiently old trees are rare even away from Cinder Cone, but two old Jeffrey pines growing on ~15,000-year-old andesitic lava to the north of Prospect Peak (Fig. 1C) were found and sampled. These trees are beyond the 0-cm isopach of Cinder Cone tephra (Heiken, 1978), and their substrate of blocky lava would not permit accumulation of ash in any case. Therefore, the eruption of Cinder Cone should have had little to no effect on these trees.

Core samples were collected from trees using a standard tree increment borer (Phipps, 1985) and sanded to expose finely polished transverse views of growth rings. Crossdating of ring growth emphasized identification of ring-width and anatomical anomalies in the time period of the presumed eruption date of the 1660s, and ring width was measured to ±0.01 mm (Robinson and Evans, 1980). Five long Jeffrey pine chronologies held in the International Tree-Ring Data Bank (Grissino-Mayer and Fritts, 1997) were merged into a regional master series that served as an external control for crossdating. These chronologies are from sites of northern and central California (Fig. 1A) and of approximately the same elevation as Cinder Cone (Table 1). These chronologies extend back to at least the early 1500 s, and they cross-correlate strongly with each other (Table 1).

For core samples that were old enough to have pre-eruption rings, the sanded surface was removed using a stainless steel razor to eliminate sanding as a source of cross-ring contamination (Pearson et al., 2005). Samples were separated into 5-ring groups counting back in time from bark using a stainless steel chisel, thereby ensuring adequate sample mass and reducing the expense for chemical measurement.

Wood samples were freeze-dried to a constant weight and then weighed into pre-cleaned, pre-weighed, trace-metal-free polypropylene centrifuge tubes. All reagents were doubly distilled in two-bottle Teflon stills at ~50 °C. For every 25 mg of sample, 1 mL of 7 M nitric acid (HNO_3) was added. Samples remained in the acid at room temperature for 2–3 days, and solutions were then heated to 70 °C for two days. Samples were placed in an ultrasonic bath for 3 h to complete the digestion.

Following digestion, sample tubes were reweighed to calculate exact dilution factors. After thorough mixing, aliquots (approximately 0.25 g) of the digestates were taken and gravimetrically diluted by a factor of approximately 20 with ultrapure water (18.2 MΩ-cm water that was then distilled in 2-bottle Teflon stills) and spiked with internal standards (Sc and Rh).

For elemental measurement, samples were analyzed using a VG Axiom multi-collector inductively coupled

Table 1. Jeffrey pine chronologies from the International Tree-Ring Data Bank (Grissino-Mayer and Fritts, 1997) used to create a regional master series for crossdating Jeffrey pine growth at Cinder Cone.

Site number on Fig. 1A	Site name	Elevation (masl)	Time span	Correlation with master series
1	Mt. Eddy	2134	1388–1981	+0.718
2	Blue Banks[a]	1598	1318–1980	+0.775
3	Hell's Half Acre[a]	1922	1497–1980	+0.771
4	Donner Summit[a]	2265	1510–1980	+0.764
5	Buena Vista[a]	2280	1434–1981	+0.660

The base of Cinder Cone is 1900 masl.

[a] From Holmes et al. (1986).

plasma mass spectrometer (MC-ICP-MS), which is capable of resolving most interferences caused by molecular ions that pose problems for quadrupole ICP-MS instruments. Solutions were measured for Na, Mg, Al, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Sr, Ag, Ba, La, Eu, Ta, and Pb. Resulting data were calibrated using a series of linearity standards prepared from multi-element calibration standards obtained from High Purity Standards. Sc and Rh internal standards were added to the linearity standards. Five standard points were used to calibrate the instrument for all elements of interest. Concentrations for all standards were calculated and these data were used to create the linear calibration curve of instrument response versus concentration (for each analyte). Some measured elements are major constituents in volcanic rocks or plant macronutrients (Kramer and Kozlowski, 1979). Other elements on this list have no direct connection with volcanoes or plant nutrition but were measured in order to provide a background pattern of temporal variability unrelated to the eruption (Hall et al., 1990).

Results

Ring-width responses to the eruption

Quantitative crossdating of sampled Cinder Cone Jeffrey pines with the regional Jeffrey pine master series is moderately strong. Cross-correlations between each tree and the regional master series range from −0.01 (no correlation) to +0.49 (Table 2). It is not due to low interannual variability in ring width that these cross-correlations are only moderately strong, as the mean sensitivity values (Fritts, 1976) are typical for dendrochronology, ranging from 0.185 to 0.288. Notably, Tree 31 does not correlate with the regional master series in spite of having the highest mean sensitivity. Even with quantitative crossdating being only moderately strong, we believe that these ring sequences are dated accurately. Ring growth of these trees is well defined and clearly visible, and missing rings are probably not common at this site because this region receives ample winter precipitation. Mesic site conditions should result in consistent annual ring growth such that ring counting is reasonably safe for dating.

Table 2. Statistics of ring-width series of each Cinder Cone Jeffrey pine analyzed herein.

Tree number on Fig. 1C	Cross-correlation[a] with master series[b]	Number of rings	P value for significance of correlation	Mean sensitivity[c]
08	+0.26	395	<0.01	0.209
09	+0.14	478	<0.01	0.185
31	−0.01	376	0.88	0.288
33	+0.27	443	<0.01	0.219
36	+0.42	393	<0.01	0.187
45	+0.49	468	<0.01	0.225

[a] Cross-correlations are with white-noise residual series.

[b] Master series is all five chronologies of Table 1 merged together.

[c] Absolute difference of two consecutive rings divided by their average, averaged across the entire series (Fritts, 1976).

All four trees growing in Cinder Cone tephra show abrupt changes in ring width at AD 1666. These changes include short-term decreases (Fig. 2A and B) or long-term increases (Fig. 2B–D). These synchronous ring-width responses confirm the dating of these tree-ring sequences. In contrast to these ring-width changes of trees growing in tephra, Control Trees 08 and 09 show no ring-width anomalies throughout their life spans, including at AD 1666 (Fig. 2E and F). These control trees show the typical ring-width trend of negative exponential decline with an associated decrease in interannual variability with smaller rings (Fritts, 1976). These control trees establish the background pattern of normal tree growth of the area since at least AD 1600.

The regional dendrochronology created from merging existing Jeffrey pine chronologies from California (Fig. 1A, Table 1) shows no unusual changes in growth since 1500 (Fig. 2G). This chronology reflects a combination of moisture availability and/or growing season temperature, so macroclimate of the area could not have caused the abrupt ring-width changes at 1666 in trees growing in Cinder Cone tephra.

As for AD 1567, only Tree 45 has a sufficient number of rings dating before that year to evaluate a change in width. In Tree 45, there is no unusual ring-width change at AD 1567 (Fig. 2D). This does not support the earlier dendrochronological finding that Cinder Cone erupted in AD 1567 (Finch, 1937), but more replication of this non-response would be needed to confidently rule out AD 1567 as a tree-ring date related to Cinder Cone.

Interpretation of the AD 1666 ring-width responses in trees growing in tephra is not without ambiguity. In Tree 31, the ring-width pattern at AD 1666 is not distinct from the rest of the series (Fig. 2A), and it would be difficult to conclude an eruption date from this tree using ring width alone. Additionally, in Trees 36 and 45, relative changes in ring growth at AD 1666 are not substantially different from changes in the early 1900s (Fig. 2C and D). Although AD 1666 is a reasonable date of the eruption based on these trees, the similar ring-width signal in the early 1900s illustrates how eruption-like patterns in ring width can occur without an eruption. Only Tree 33 has a change in ring width at AD 1666 that is not matched in other time periods (Fig. 2B), which might allow a conclusion of the eruption date based on ring width alone. Therefore, even though the replicated ring-width responses of trees growing in tephra support the earlier dendrochronological finding that Cinder Cone erupted in AD 1666 (Finch, 1937), it would be preferable to have additional evidence of the eruption besides just ring width.

Dendrochemical responses to the eruption

Most elements measured in Cinder Cone tree rings show little temporal variation, thereby establishing a background pattern of no particular variability related to the eruption or anything else. By contrast, in some Cinder Cone trees, ring phosphorus content changes during the late 1660s and therefore is potentially related to the eruption. In Tree 45, ring P increases during the late 1660s and remains high for the rest of the series (Fig. 3). In Trees 33 and 36, ring P also increases during the late 1660s but then returns to pre-eruption levels within the next ten years. On the other hand, in Tree 31, ring P does not change during the late 1660s. As expected for Control Trees 08 and 09, ring P does not change during the late 1660s. The presence of a ring P signal in some but not all trees replicates

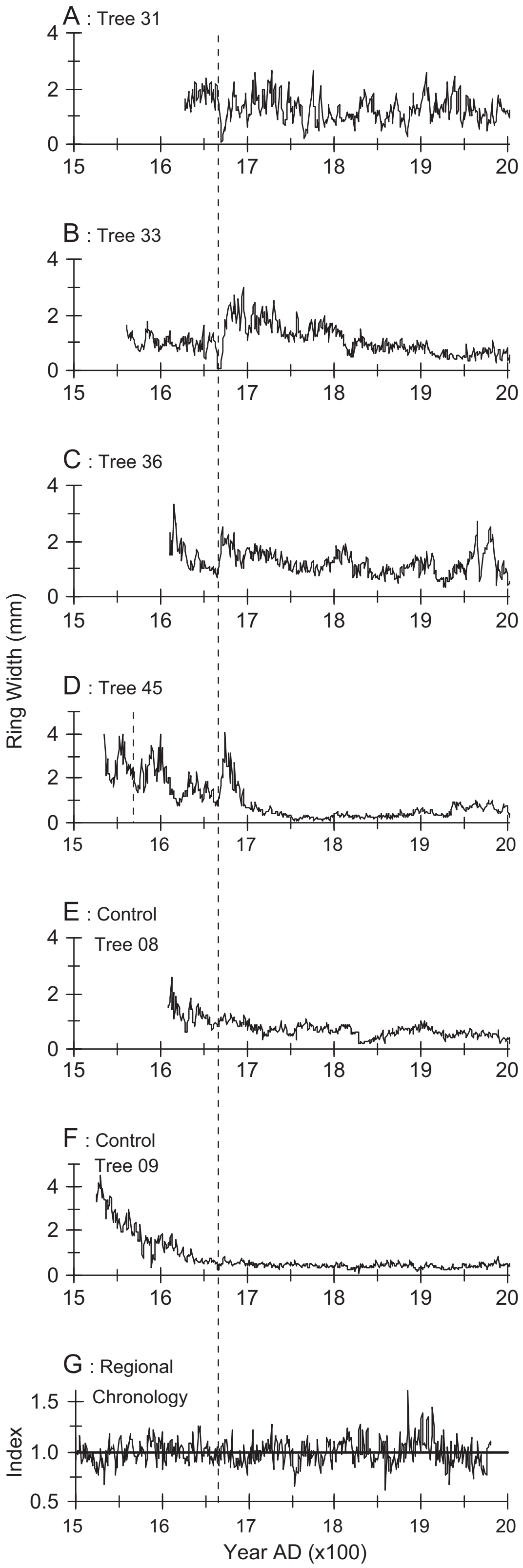

Fig. 2. Time series of ring widths of (A–D) four Jeffrey pines near Cinder Cone and (E–F) two Jeffrey pines well away from Cinder Cone, as well as of (G) index values of a regional ring-width standard chronology created by merging existing Jeffrey pine chronologies (Fig. 1A, Table 1) into a single series. The long vertical dashed line marks AD 1666, the eruption date based on earlier ring-width dendrochronology (Finch, 1937). Tree 45 has another vertical line at AD 1567, a proposed eruption date based on ring-width dendrochronology (Finch, 1937).

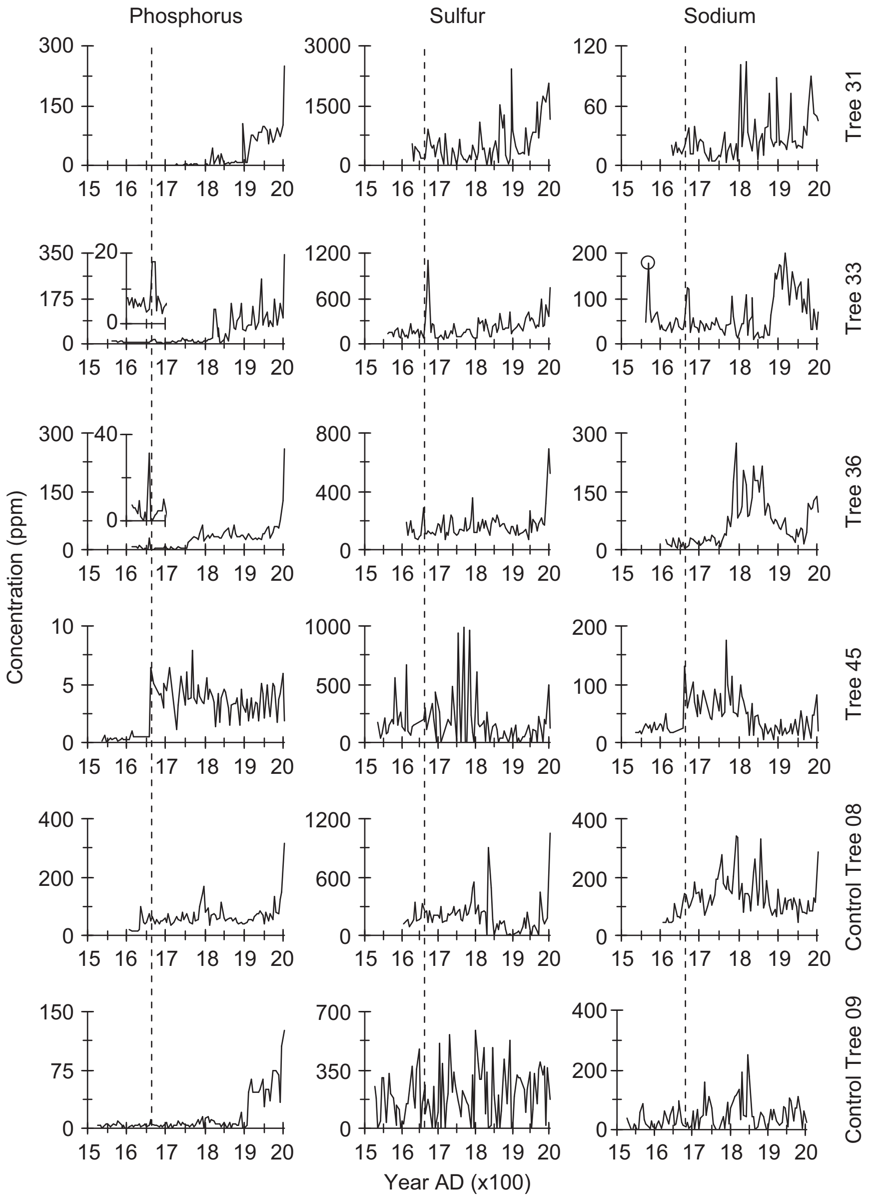

Fig. 3. Dendrochemical concentrations of phosphorus, sulfur, and sodium for Jeffrey pines near Cinder Cone and Control Trees 08 and 09. Vertical dashed lines mark AD 1666, the eruption date based on ring-width dendrochronology (Finch, 1937). For sodium of Tree 33, the AD 1567 value is marked with an open circle. For phosphorus of Trees 33 and 36, insets of the 1600s are given with different y-axis scales.

dendrochemistry results of Parícutin (Sheppard et al., 2008). Volcanic eruptions can change environmental availability of P by directly adding it in tephra fall, as elements adhering to surfaces of the tephra or dissolved in precipitation, and/or by altering the availability of existing soil P (Sheppard et al., 2008).

Ring P can be excessively high in outermost rings (Fig. 3). Physiological accumulation of elements in outermost rings can be an issue in dendrochemistry (Cowling and Merrill, 1966; Szopa et al., 1973; Symeonides, 1979; Arp and Manasc, 1988; Poulson et al., 1995; Colin-Belgrand et al., 1996). Fortunately, the eruption of Cinder Cone is recorded by inner rings, so accumulation of elements in outermost rings is not a confounding factor in this research.

In some Cinder Cone trees, ring sulfur content changes during the late 1660s and therefore is potentially related to the eruption. In Tree 33, ring S spikes up during the late 1660s and then quickly returns to pre-eruption levels (Fig. 3). In Tree 36, ring S also shows a short-term increase during the late 1660s, though this increase is matched by other spikes at other times in the series. On the other hand, in Trees 31 and 45, ring S does not change during the late 1660s. As expected for Control Trees 08 and 09, ring S does not change during the late 1660s. The presence of a ring S signal in some but not all trees replicates dendrochemistry results of Parícutin (Sheppard et al., 2008). Volcanic eruptions can change environmental availability of S by the same mechanisms as for P, and ring S can also be excessively high in outermost rings (Fig. 3), again due to physiological accumulation of elements in outermost rings.

In some Cinder Cone trees, ring sodium content also changes during the late 1660s and therefore might be related to the eruption. In tree 45, ring Na increases during the late 1660s and remains elevated for ~150 years (Fig. 3). In Tree 33, ring Na spikes up during the late 1660s but then quickly returns to pre-eruption levels. Ring Na also shows a high value in Tree 33 during the late 1560s (Fig. 3, data point marked with an open circle). This would seem to support AD 1567 as an eruption date of Cinder Cone (Finch, 1937), but this Na spike could also be anomalous. In any case, Tree 33 does not have enough rings prior to AD 1567 to establish a pre-eruption baseline level for dendrochemistry, so any connection between ring Na in the 1500 s and Cinder Cone would be speculative based on this tree alone. On the other hand, in Trees 31 and 36, ring Na does not change during the late 1660s. As expected for Control Trees 08 and 09, ring Na does not change during the late 1660s. This ring Na signal is unique to Cinder Cone, as it was not evident in dendrochemistry results of Parícutin. Environmental availability of Na can increase after an eruption because of increased water saturation of soils and consequent dissolution of soil Na.

Discussion

These multiple dendrochronological responses to the eruption of Cinder Cone, Lassen Volcanic National Park, California, are similar to findings at Parícutin, Michoacán, Mexico. In both cases, ring width alone is suggestive of the eruption dates, but because changes in widths of tree rings can occur in response to other forest disturbances, concluding an eruption based on ring width alone can be difficult. At both Cinder Cone and Parícutin, dendrochemical changes are suggestive of the eruption dates, but because of inter-tree variability in dendrochemical signals, concluding a cinder-cone eruption based on ring chemistry alone can also be difficult. At both Cinder Cone and Parícutin, the combination of dendrochemistry and ring-width analysis improves confidence in dating the eruptions over the analysis of just one line of evidence. Interpreting multiple lines of evidence of environmental change is sounder than relying on just one data type (Reid and Thompson, 1996), and dendrochemistry potentially provides many additional lines of evidence to dendrochronological analysis. In particular, ring P and S increase at the time of eruption in trees at both Cinder Cone and Parícutin.

At both Cinder Cone and Parícutin, dendrochemical signals of the eruption are not consistent across trees, which is hard to explain. For example, at Cinder Cone, Tree 31 appears to be an ideal candidate for responding dendrochemically to the eruption in that it is growing in soil covered by ~1 m of tephra. Yet, Tree 31 shows no dendrochemical changes during the late 1660s. Tree 31 also differs from other trees in its ring-width growth, showing no correlation with existing Jeffrey pine chronologies of the region. It appears that some trees simply do not follow stand, forest, or regional patterns of growth. This could be due in part to soil nutrient availability, which is notoriously variable across small spatial scales (Jackson and Caldwell, 1993, Sheppard et al., 2001), or tephra, which also varies in depth and texture at the microsite scale (Zobel and Antos, 1991). Other sources of inter-tree variability might include slope aspect (Oberhuber and Kofler, 2000) or root mycorrhizal activity (Bruns, 1995). Regardless of causes of inter-tree variability, the practical reality is that many trees should be sampled in this kind of research in order to maximize the chances of replicating eruption signals across at least two trees. It is not necessary that all trees sampled respond alike to an event of the past, but at least some replication of tree-ring signals is needed to improve confidence in dating the event.

Dendrochemistry can be useful for confirming or improving confidence in dating cinder cone eruptions. Cinder cones are the most common type of volcano on land (Vespermann and Schmincke, 2000), and living trees, dead trees, and/or archaeological wood can often be found in areas that have received cinder cone tephra. An example of particular importance in the US is Sunset Crater of northern Arizona, dated to AD 1075 ± 25 years using paleomagnetism, relative ceramic dating, and ring-width dendrochronology (Smiley, 1958; Elson et al., 2002). Improving confidence in ring-width dating of the eruption of Sunset Crater by adding dendrochemistry could result in better understanding of anthropological responses to the eruption.

Conclusions

Using Cinder Cone as an additional case study to Parícutin, a multifaceted dendrochronological response to Cinder-Cone eruptions includes increases in tree-ring S, P, and Na as well as changes in ring width. Tree-ring width can change abruptly for reasons other than volcanic activity, so interpreting width alone might not yield the correct date of a cinder cone. Adding dendrochemical data to ring-width analysis strengthens dendrochronological dating of cinder-cone eruptions, especially in cases where ring-width signals are weak or ambiguous. Because of inter-tree variability in dendrochemistry, sampling and analyzing multiple trees is needed to maximize the likelihood of finding synchronous chemical changes across multiple trees such that a signal can be interpreted (Watt et al., 2007). In Lassen Volcanic National Park, California, tree-ring width and chemistry changes combine to date the eruption of Cinder Cone to AD 1666.

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