ENCYCLOPEDIA of
SCIENTIFIC DATING
METHODS
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ENCYCLOPEDIA OF SCIENTIFIC DATING METHODS

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Professor Charles W. Finkl has edited and/or contributed to more than eight volumes in the Encyclopedia of Earth Sciences Series. For the past 25 years, he has been the Executive Director of the Coastal Education and Research Foundation and Editor-in-Chief of the international Journal of Coastal Research. In addition to these duties, he is Professor at Florida Atlantic University in Boca Raton, Florida, USA. He is a graduate of the University of Western Australia (Perth) and previously worked for a wholly owned Australian subsidiary of the International Nickel Company of Canada (INCO). During his career, he acquired field experience in Australia, the Caribbean, South America, SW Pacific Islands, Southern Africa, Western Europe, and the Pacific Northwest, Midwest, and Southeast USA.

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Scientific dating methods provide the timing, sequence, and rates of geological, archaeological, and biological events and processes. It is no exaggeration to say that quantitative measurements of age (geochronology) provide the foundations for scientific understanding for many disciplines within the earth and archaeological sciences.

The field of geochronology began with early applications of biostratigraphy and a basic understanding of sedimentary processes. The ages and sequences fossils provided the foundation for the geological time scale. At the turn of the twentieth century, our understanding of radioactivity revolutionized geochronology. This led to the flourishing of numerous radiogenic isotopic dating methods. In addition, of particular importance, was the development of radiocarbon dating in 1949, which has since yielded hundreds of thousands of age estimates for earth scientists and archaeologists. Radiation exposure methods, which utilize the effects of background radiation on defects in minerals and biological materials, were developed through the 1960s and the 1990s. More recently, the development of molecular clock techniques has resulted in a new approach to determine ages of events in the history of biological evolution.

This volume is a comprehensive synthesis of the applications and physical basis for scientific dating methods in use in the earth sciences, archaeology, and biology. All widely-accepted scientific dating techniques – physical, chemical, and biological – have been included, as well as the most important materials which are amenable to the application of scientific dating methods.

We trust that this volume will be of use to researchers and students in the earth sciences and archaeology, who wish to understand the scientific basis that underlies our understanding of geological and archaeological chronology. In addition, this volume may be useful to geologists involved in exploration and exploitation of natural resources, natural resource managers, and environmental and archaeological consultants.

Each of the major dating methods is described in a main entry that provides an in-depth review of the underlying scientific principles of that method, including methods, applications, uncertainties, applications, and limitations. If appropriate, the most recent development in each field is discussed. Each of these main entries was authored by a leading expert in that field.

The majority of the entries in this volume are focused on applications of scientific dating methods, and are usually titled according to the material to be dated (e.g., “Carbonates, marine”), with the method in parenthesis. We have attempted to provide comprehensive coverage of organic and inorganic materials, including minerals, rocks, archaeological materials, biominerals, plants, art objects, water, and many more. Some entries focus on rates of geological processes, such as sedimentation, fluid flow, tectonics, cooling rates, and many more. By organizing entries by the application, rather than the methodology, we hope that readers will be able to quickly locate information most relevant for their interests and specific needs.

Finally, this volume includes shorter, mini-entries with key definitions, important materials, or notes on instrumentation.

This volume was only possible through the extensive contributions of the three associate editors and the large editorial board who worked together to establish the range of authors from 18 different countries who agreed to contribute. The online version, which can be updated by the authors as new information becomes available, provides a dynamic dimension in the rapidly changing field of geo-, bio-, and archaeo-chronology.

The field of dating methods continues to grow rapidly through research scientists thinking of new ways to apply the methods. Though it cannot be said that every single application of dating methods is included, this volume significantly expands the availability of knowledge through its broad scope in each area in the field of dating.
Acknowledgments

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Dendrochronology, Volcanic Eruptions
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Synonyms
Dust veil; Extrusive volcanism; Tephra deposition

Definition
Dating of events associated with volcanism that leaves a permanent marker in tree-ring records. Such events include air temperature cooling, deposition of ash layers, lava flows, and magmatic degassing.

Introduction
The geological applications of dendrochronology cover a wide range of topics, from paleoseismology (Jacoby 1997) to paleovolcanism and its effects on climate (Zielinski 2000). With specific regard to volcanic eruptions, tree-ring records have been used in multiple ways to date events associated with explosive and effusive volcanism, including magmatic degassing. Because wood formation is influenced by environmental factors (Plomion et al. 2001), tree species that are directly or indirectly impacted by volcanic eruptions can record such events in their growth layers. Datable volcanic effects on woody species range from annihilation (death dates) to rebirth (establishment dates) but also include growth changes in surviving trees (Yamaguchi 1993). Such changes can be abrupt, hence only detectable in single rings. These individual growth layers can be very small (“microrings”), down to the point of not being present (“locally absent rings”) in one or more samples collected at a site (Biondi et al. 2003). Individual tree rings that are typically not so small can show anatomical damage from freezing (“frost rings”) in response to the sudden reduction of sunlight and its associated air temperature drop, caused by volcanic dust veils (LaMarche and Hirschboeck 1984). Depending on the type of extrusive materials (tephra deposition, lava flows, emission of sulfuric gases, etc.), surviving trees can present gradual, rather than abrupt, changes over multiple consecutive years. Such departures from previous tree-ring patterns can be positive (increased growth, or “release”) or negative (decreased growth, or “suppression”). The diversity of volcanic effects on trees depends on the variety of materials that can be ejected, as well as on the location, species, size, and age of the trees, together with other site conditions, from elevation and topography to vegetation features. On one hand, such richness of potential information has generated a long tradition of tree-ring applications to volcanology. On the other hand, the difficult task of identifying what, when, and how trees were impacted by specific past volcanic events has caused multiple, heated, and prolonged scientific debates.

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Historical Development

Modern dendrochronology, which is the study of past changes recorded by wood growth, is based on the rigorous application of crossdating techniques to assign calendar dates to tree rings (Fritts and Swetnam 1989). When so defined, this branch of science was established in the western United States at the beginning of the twentieth century by Andrew E. Douglass, an astronomer at the University of Arizona in Tucson (Webb 1983; Nash 1999). Tree-ring dating is closely connected with the study of wood formation, and relevant studies, for example, on the anatomy of frost rings (Rhoads 1923), also date back about a century. On the other hand, while the hypothesis that exceptionally cold years could be caused by volcanic eruptions is found in Benjamin Franklin’s (1785) writings, the global atmospheric radiative effects of volcanic aerosols could only be tested with the advent of satellite and remote sensing technology in the 1980s (Ramanathan 1988). At about the same time, the Volcanic Explosivity Index, or VEI (Newhall and Self 1982), was introduced to describe the magnitude of past explosive eruptions in a semiquantitative manner.

Impacts of extrusive eruptions on tree rings at sites located near a volcano were first described in the 1960s, but sample sizes were small (i.e., less than ten trees), ring boundaries were uncertain either because of poor sample preservation and surfacing (Druce 1966) or because of species growth patterns and anatomical features (Eggler 1967), and no crossdating was used. A notable exception was the A.D. 1064–1065 dating of Sunset Crater, Arizona (Smiley 1958), where a larger number of samples from archaeological ruins were investigated and tree-ring dates were assigned by crossdating. On the other hand, less than ten trees showed a distinct growth reduction after 1064, and nonvolcanic disturbances can cause similar effects in ring widths of the same species in this geographical area (Sheppard et al. 2005).

A major catalyst for dendro-volcanology came from the 1980 eruption of Mount St. Helens in the Pacific Northwest region of the USA. The blast that occurred on May 18 of that year with an estimated VEI of 5 (the maximum is 8) removed the top 400 m of the mountain and rose to 24 km into the stratosphere (Brantley and Myers 2000). It was the deadliest and most economically devastating volcanic event in United States history, exceeding a billion dollars in damage. A total of about 60 people, including a volcanologist, and more than nine million cubic meters of valuable timber were among the losses suffered over the nearly 600 km² ravaged by the eruption (McLean and Lockridge 2000). Several studies were published shortly thereafter on tree growth responses to the eruption (Mahler and Fosberg 1983; Hinckley et al. 1984) and on dendrochronological dating of previous events (Yamaguchi 1983, 1985). The enhanced interest in past volcanic histories, and the realization of potential long-range temperature effects from volcanic dust veils, prompted an extensive study of frost rings in the wood of high-elevation bristlecone pines (LaMarche and Hirschboeck 1984). Another anatomical feature, i.e., the “light rings” caused by reduced latewood formation in conifers growing at high elevations or latitudes, was investigated for their potential connection with reduced temperatures associated with volcanic eruptions (Filion et al. 1986). Extensive networks of tree-ring sites, whose analysis was then facilitated by advances in computational power and numerical processing, became the target of sophisticated statistical methods to detect changes in tree-ring-reconstructed climatic variables that could be linked to volcanic eruptions (Lough and Fritts 1987).

Yet another method of tree-ring analysis, X-ray densitometry (Polge 1970) had come of age in those decades (Schweingruber et al. 1978), and networks of tree-ring sites sampled in the late 1970s and early 1980s were analyzed using this new technique (Schweingruber et al. 1991). Subsequent research to date has continued to employ the tools elaborated in previous years, from light rings (Szeicz 1996) to densitometry (Jones et al. 1995), expanding the number of sampled sites (D’Arrigo...
and Jacoby 1999) as well as the geographical (Hantemirov et al. 2004) or temporal (Salzer and Hughes 2007) range of previous studies, and applying increasingly complex numerical treatments for identifying volcanic signals in tree-ring proxy records (Breitenmoser et al. 2012). As an alternative to the exhaustive filtering and massaging of large spatiotemporal datasets, other studies in the past few decades have investigated the use of chemical markers in tree rings linked to volcanic eruptions (Pearson et al. 2009), including magmatic degassing in the absence of explosive events (Biondi and Fessenden 1999).

**Basic Principles and Applications**

Trees and other woody plants grow by covering themselves with a new layer of tissue every year (Larson 1994). When seen on a transverse section, such wood layers appear as concentric tree rings. Because tree growth is influenced by the environment, tree rings are then natural archives of past environmental conditions. For instance, less wood is formed near the base of a tree stem when climate conditions are less favorable, producing narrower rings (Speer 2010). If an eruption takes place, trees growing close enough to the volcano can be scorched by hot gases or covered with tephra and may either be killed or survive depending on their species, age and vigor, microsite conditions, as well as the chemistry and temperature of the gases and the thickness and coarseness of the tephra layer (Segura et al. 1994). Surviving trees typically experience abrupt suppression of radial growth (Hinckley et al. 1984), including locally absent rings (Yamaguchi and Hoblitt 1995). This immediate decline can be followed by a prolonged period of reduced radial increment (Segura et al. 1995) or by its opposite, i.e., greater than normal growth rates, often in connection with concurrent stand dynamics and resulting competitive interactions (Abrams et al. 1999).

Major explosive volcanic eruptions that inject dust and aerosols into the stratosphere are capable of causing large-scale surface cooling (Minnis et al. 1993). Distant, large-scale networks of tree-ring chronologies from temperature-limited sites can reflect those eruptions in anatomical xylem features, such as frost damage (D’Arrigo et al. 2001) or reduced latewood formation (Jacoby et al. 1999). Freezing damage to coniferous species causes the formation of deformed and collapsed xylem cells depending on the intensity of the frost, the degree of cambial activity at the time of the temperature drop, the tree species and size, and possibly other factors (Day and Peace 1934). Frost rings have been reproduced experimentally (Glerum and Farrar 1966), and their cross-sectional features are clearly distinguishable on a well-prepared wood sample at the magnification (10–50×) normally used in tree-ring studies. While crossdating among a large enough number of samples guarantees accurate dates, the year assigned to a frost ring may have some uncertainty if the injury occurs at a ring boundary, so that it could represent either a late frost in a year or an early frost in the following year. This situation is more frequent as ring widths become smaller (<0.1 mm), but using well-dated frost rings to resolve uncertain cases leads to potential bias and should be either avoided or well documented. With regard to “light rings”, the reduced cell wall thickening in latewood that causes their name also causes minimal density and can be caused either by low air temperature or by insect defoliation (Liang et al. 1997).

Measured annual growth parameters, such as ring width (Fritts 1976) or maximum latewood density (Briffa et al. 1988), are routinely used for dendroclimatic reconstructions. When wood formation is limited by air temperature, as it is usually the case for trees located at high elevations or high latitudes (D’Arrigo et al. 2006), dendrochronological parameters can reflect a volcanic cooling, thereby providing a record of past eruptions (Briffa et al. 1998). Chronologies developed from ring widths present a greater amount of time-series autocorrelation (or “persistence”) than chronologies...
generated from annual density peaks (called maximum latewood density, or MLD), which also tend to reflect growing season conditions rather than integrating environmental signals over multiple years (D’Arrigo et al. 1992). Therefore, it is normally assumed that the temporal lag between volcanic cooling and its incorporation in tree-ring proxy records increases going from frost rings to light rings and from maximum latewood density to ring width chronologies (D’Arrigo and Jacoby 1999).

The main application of dendrochronology to volcanology is the definition of impacts on ecosystems and on human societies, either current, past, or long lost. Besides providing information on ecological processes in forests, tree-ring records of volcanic eruptions contribute to estimating the past frequency of destructive events. This numerical datum can then improve the definition of potential risks, especially with regard to explosive phenomena occurring at short intervals from one another (Yamaguchi 1985). At the same time, because of possible global impacts of volcanoes on climate (Robock and Mao 1995) and biogeochemical cycles (Krakauer and Randerson 2003), well-dated records of past eruptions are needed to improve the accuracy of models used to generate future scenarios linked to anthropogenic emissions of greenhouse gases (Ramanathan 1988). As any other dating tool, tree-ring records of volcanic eruptions can alter historical interpretations simply by changing the order of events. While dates are not by themselves reason for cause-and-effect relationships, they are able to negate theoretical ones as no effect can precede its hypothesized cause.

Current Controversies and Knowledge Gaps

Major volcanic eruptions have been dated using other types of records, from dust layers and chemical properties in ice cores (Larsen et al. 2008) to archaeological and written sources (Stothers 1999). Not all records agree, and in particular, dates assigned to some major eruptions using geochemical markers in Greenland ice cores (Vinther et al. 2006) are currently in disagreement with tree-ring records (Baillie 2010). A particularly important event is the Minoan eruption of Thera, an island in the Aegean Sea now called Santorini, which took place in the mid-second century BC. The date of this volcanic time marker is of critical importance for the stratigraphic and archaeological synchronization of ancient Eastern Mediterranean societies, the cradle of western culture. The eruption, which left a caldera and ash deposits up to hundreds of meters in size, has been linked with the collapse of the Minoan civilization on the island of Crete, 110 km to the south, possibly spurred by gigantic tsunamis. The controversy has lasted for decades, with historical/archaeological dates centered in 1550–1500 BC (Wiener 2009), tree-ring records pointing to 1629–1627 BC (Baillie 2010), ice-core geochemistry focused on 1642–1641 BC (Vinther et al. 2006), and radiocarbon dates spread over 1683–1611 BC (Manning et al. 2006). Each of these sources of evidence has strengths and weaknesses. As an example, radiocarbon dating of an olive branch from the eruption site provided a date range of 1627–1600 BC (Friedrich et al. 2006), but it is difficult to determine if the sample was dead or alive at the time of the eruption (Wiener 2010), and wood anatomical features make any ring analysis problematic for this species (Cherubini et al. 2013). The chemical signature of volcanic eruptions has been proposed as a possible tool for testing the accuracy of tree-ring dates assigned to individual events (Pearson et al. 2005). Because elemental concentrations can vary considerably in the same tree both around the stem and at various heights in the trunk (Watt et al. 2007), clear evidence needs to be presented that specific chemical signals are replicable across samples from the same tree as well as from different trees of the same species and site (Kirchner et al. 2008). When crossdated ring sequences are combined with localized information on geochemical variables, a high degree of accuracy and confidence can be placed in the dating
(Sheppard et al. 2008). This, for instance, was the case with regard to the onset of magmatic degassing in forest stands of the Sierra Nevada, which produced abrupt changes in crossdated ring-width sequences (Biondi and Fessenden 1999) and in their radiocarbon concentrations (Cook et al. 2001).

A number of confounding factors hamper the use of proxy records for dating volcanic eruptions. Several of these factors can be categorized as false positives or false negatives (Cleland 2002). Considering anatomical markers in tree rings, not all of them are related to major volcanic eruptions (false positives), and known major volcanic eruptions took place without producing such markers (false negatives). In addition, not all cold summers over a region are related to volcanic events, and not all volcanic years produce a cold summer at the majority of sampled sites in a tree-ring network (D’Arrigo et al. 2013). Depending on the prevailing climate regime and ecological requirements of a species, climate-driven responses to major eruptions can even favor tree growth rather than depressing it. Such inverse response was proposed for Thera because the potentially cooler summers generated by the dust veil would have reduced evapotranspiration, resulting in 2–3 years of abnormally high growth in woody species adapted to the normally dry Mediterranean conditions (Kuniholm et al. 1996). These hypothetical responses, albeit reasonable, require further testing, which is best attained using detailed ecophysiological and anatomical studies at sub-monthly time scales (e.g., Rossi et al. 2013). Finally, when evaluating unusual episodes within a time series, it is best to employ a quantitative approach, such as ranking episode features (duration, magnitude, peak) according to predefined numerical criteria (e.g., Biondi et al. 2008).

An additional wrinkle in the protracted debate over tree-ring reconstructions of volcanic eruptions has recently emerged. Climate modelers have tried to reconcile their simulations of regional and global climate impacts from volcanic eruptions by postulating that tree-ring chronologies for northern latitudes or from high elevations are all consistently missing, and in more than one occasion, a year of growth (Mann et al. 2012). The ensuing vigorous responses (Anchukaitis et al. 2012; D’Arrigo et al. 2013; Esper et al. 2013) have concentrated on choices made when modeling tree-ring formation and on correlations with instrumental or proxy records, showing a general disruption of these statistical relationships when tree-ring chronologies are shifted by one or more years. The essential question underlying the debate is the likelihood that collections of tree-ring samples from a single site, or even from multiple sites in a region, would fail to include a year’s growth. The frequency of locally absent rings increases in semiarid environments as a response to drought, but existing tree-ring collections pooled by latitude, species, or elevation include a percentage of “missing” rings that does not exceed 10 % (St. George et al. 2013). A number of other issues have been raised, starting from how evidence deteriorates going further and further back into the past. For relatively recent events, such as the 1815 explosion of the Tambora volcano (Stothers 1984), there is no chance of a universally missing ring given the large number of available proxy and instrumental records. For earlier eruptions, on the other hand, even their dates become less reliable as temporal separation increases (Plummer et al. 2012).

Historical archives and environmental records of past events are notoriously open to multiple interpretations, but so are model outputs and their underlying assumptions. From a tree-ring perspective, not all is known about the environmental conditions required for, and the biological mechanisms leading to, wood formation in areas where long proxy dendroclimatic records have been developed. Anatomical and ecophysiological studies have the potential to uncover such mechanisms without complex numerical analyses (Fonti et al. 2010; Rossi et al. 2012). On the other hand, the impossibility of experimental testing on past events (Biondi 2013), when combined with lack of self-criticism or doubt, could maintain the striking tendency to robust bragging that has become a distinguishing trait of high-profile articles on volcano-climate-proxy records connections.
Summary

Dendrochronological studies of volcanic eruptions employ a variety of techniques, from anatomical to statistical, for detecting the signals left by past events in tree-ring records. When large datasets composed of multiple sites and species are independently analyzed, the resulting tree-ring dates assigned to past events are more reliable than those derived from other proxy records or from modeling exercises. Dendrochronological dates are exact when sufficient sample replication exists, but the correct interpretation of environmental signals, including volcanic ones, that are embedded in wood anatomical markers and growth patterns requires careful consideration of alternative, competing hypotheses.

Cross-References

▶ 14C Dating
▶ Dendrochronology, Dwellings
▶ Dendrochronology, Fire Regimes
▶ Dendrochronology, Palaeoclimate
▶ Dendrochronology, Surficial Processes
▶ Dendroentomology
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