Irish tree rings, Santorini and volcanic dust veils

M. G. L. Baillie & M. A. R. Munro

Palaeoecology Centre, Queen's University, Belfast BT7 1NN, UK

There has recently been renewed interest in the dating of the violent eruption of the Aegean island of Santorini in the second millennium BC, both by its possible effects on tree-ring growth in the United States[1] (suggesting a date of 1628–1626 BC), and by acidity peaks in ice cores from South Greenland[2] (suggesting 1645 BC). We now show that oak trees growing on bogs in Northern Ireland produce significant concentrations of extremely narrow rings within a few periods less than 20 years long and that these periods correspond to the dates suggested by other methods for major volcanic eruptions. In particular, one of them, corresponding to a short period beginning in 1628 BC, was probably caused by Santorini. This date is qualitatively better than those derived from carbon-14 or ice cores, because it is based on an absolute tree-ring chronology.

In 1984 LaMarche and Hirschboeck[1] claimed that bristlecone pines growing near the upper tree line at several sites in western United States had been damaged by severe frosts, apparently caused by stratospheric dust veils produced by major volcanic eruptions. In particular they suggested that a significant frost ring, which was found in 1626 BC, might relate to the Santorini eruption and if so would date the eruption to that year or to 1-2 yr previously. More recently Hammer *et al.* have revised their original dating of Santorini[3] of 1390 ± 50 BC, based on acidity peaks in Greenland ice cores, to 1645 ± 7 BC, based on new evidence from South Greenland[2]. Both of these dates are in broad agreement with ^{14}C evidence for a seventeenth century BC date for the eruption[3].

The completion of the Belfast 7,272-yr oak-tree-ring chronology by 1984[4,5], and the subsequent archiving of the original ring-width measurements used in this chronology allow one to examine these data at specific dates. An initial survey of the 22 ring patterns that grew in the decade of 1620 BC showed that at least some trees put on narrow bands of rings at that time. In particular, two trees from Garry Bog in the north of Co. Antrim put on unmeasurably narrow rings in this decade. Trees from other sites showed very narrow rings at the same time. One tree, Q5392 from Sentry Hill, Co. Antrim, showed a colour change beginning in 1628 BC and another, Q1276 from Derrylard, Co. Armagh, showed anomalously small earlywood vessels (SEVs) (which elsewhere have been linked to anomalous weather conditions)[6] in the growth ring for 1625 BC. This provides circumstantial evidence for an event in Irish bog oaks (oak trees that originally grew rooted in the peat of raised bogs), at a date suggested by other workers.

Figure 1 shows the ring patterns of four trees from 1626 BC. After 1628 BC there is a period when the rings in these trees are generally narrower than at any time in the previous century; furthermore, in each tree, one of these rings is the narrowest ring in the entire lifetime of the tree.

This coincidence in itself is a remarkable confirmation that the American frost-damage evidence represents a large-scale event, but is open to several objections. Some Northern Irish trees which grew at this time do not show such obviously narrow rings. There are other trees that have bands of narrow rings at dates when no major volcanic eruptions have been suggested. So one must survey the entire prehistoric period to see if oak growth was significantly impaired in the 1620s BC.

The narrow rings and narrow bands of rings close to 1626 BC suggested that some quantification of narrowness was needed. In theory the narrowest ring width (or widths where several rings are equally narrow) should be related to the worst growth conditions that the tree experienced during its lifetime. In Irish bog oaks the width of the band of spring vessels which comprise the early wood in each growth ring is approximately equal (and is conditioned by food reserves from the previous year). The overall ring width tends therefore to be a minimum in years where there is no summer growth and the width of the growth ring is merely the width of the spring vessels. But there is a relatively rare condition (SEVs)[6] where the spring wood itself is reduced and disorganized; when this coincides with missing summer growth the tree may put on its narrowest ring. Because of the wide variety of possible causes of suppressed growth, the long lives of Irish oaks, and the fact that they were not all growing over the same period, one would expect the dates of the narrowest rings to cluster only to the extent to which cross dating between trees tends to align narrow rings.

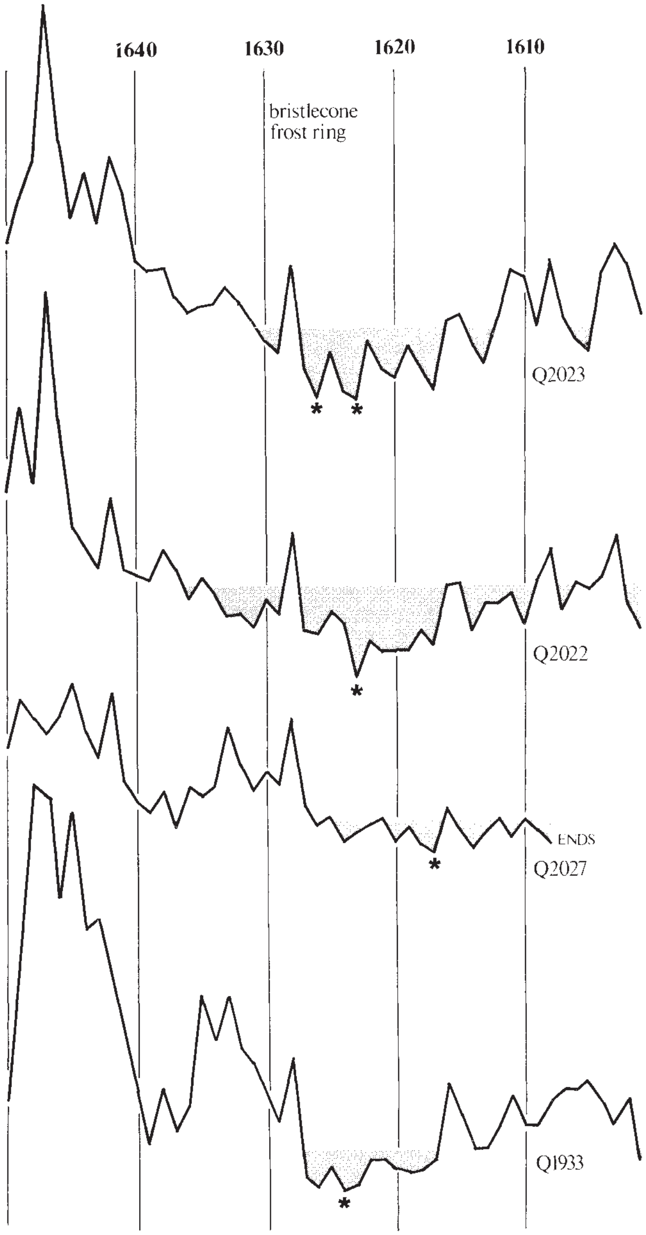

Fig. 1 Four trees from Garry Bog, Co. Antrim, Northern Ireland, showing curtailment of growth (the shaded areas are rings <0.5 mm wide), associated with the narrowest rings in the lifetime of each tree (marked by asterisks). All the trees have more than 220 rings. The shaded square marks the American bristlecone pine frost ring dates for the eruption of Thera[1].

Figure 1 shows that the dates of narrowest rings are spread over a period of as much as a decade within a particular narrow

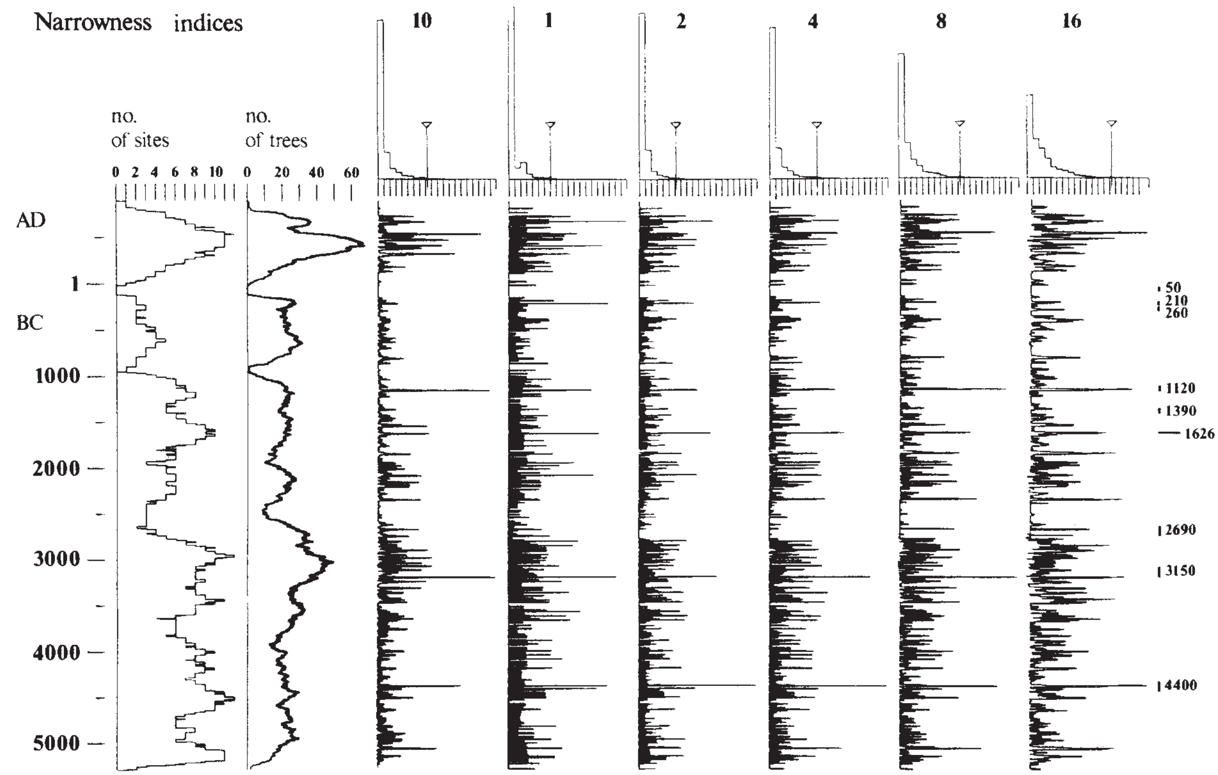

Fig. 2 The jagged vertical curves show the values of the $r \ln(r/\hat{r}) + s \ln(s/\hat{s})$ narrowness index for various window sizes, apart from the 10-yr window curve, which shows the simple *rs* index. The histogram above each curve shows the distribution of the index values, with the upper percentile marked by the arrow. The curves on the left give the total number of trees and sites in Northern Ireland used to produce the indices, and the dates on the right are of the acidity peaks originally identified in the ice core from Camp Century, Greenland[3]. More recent work[2,8] gives a slightly different pattern of dates. The longer line shows LaMarche and Hirschboek's frost ring date[1] in 1626 BC.

band, so we determined the total number of narrowest rings, r, within a period of fixed size passed over the chronology as a moving window. Because purely local effects, such as a landslide blocking the drainage of a bog, might cause all the trees at one site to put on a narrow band simultaneously, we determined the total number of sites, s, where at least one tree had its narrowest ring within the window period, and only considered patterns represented by at least two sites. Most of the trees in the earlier part of the chronology are from Northern Ireland, so for sake of consistency we only considered trees from this area. This means that although the chronology as a whole is continuous, there are two periods, 115–14 BC and AD 895–918, when there are no trees available from Northern Ireland[5]. We paid most attention to the part of the chronology from 5289–116 BC, because this consists almost exclusively of bog oaks, whereas later parts contain increasing numbers of archaeological building timbers derived from a variety of environments; trees growing on peat must always have been vulnerable to adverse conditions, particularly flooding. We did not edit the archived data in any way, apart from correcting one case where multiple measurements of the same three trees had been mistakenly included, and restoring three trees that had been omitted precisely because they contained very narrow bands of rings.

As a preliminary test of this approach (using both the numbers of narrowest rings and of sites showing them) we ranked a very crude narrowness index, the product *rs* computed for a 10-yr window (see Fig. 2). We found that the three highest values in the prehistoric period, at 1153 BC, 3199 BC and 4377 BC, corresponded to three of the six major acidity peaks observed during this period in the Camp Century ice core[3] (1100 ± 50 BC, 3250 ± 80 BC and 4400 ± 100 BC). Furthermore, the highest value in the period 13 BC–AD 894, at AD 541, corresponded to an acidity peak at AD 540 ± 10. This demonstrated unquestionably that some eruptions were associated with clusters of narrowest rings, and persuaded us to investigate better narrowness indices and different window sizes.

The *rs* narrowness index is proportional to the total number of sites n_s and rings n_r in the chronology at a particular date, so it can be improved by expressing the number of narrowest rings as a fraction of these, $rs/(n_r n_s)$, but we found that this exaggerated the importance of periods when there were few trees or sites in the chronology (because small random variations in absolute numbers produced large variations in the index at these periods); in addition, some trees put on more than one narrowest ring. A better index uses the expected number of narrowest rings and sites with narrowest rings rather than the total numbers within the window period.

The expected number of narrowest rings from a single tree in a particular window period is directly proportional to both the total number of narrowest rings in the tree, m, and the number of its rings that fall within the period, w, but is inversely proportional to the length of the tree, l. Thus a crude estimate of the narrowest rings from a single tree is just wm/l, and the estimated total number of narrowest rings, $\hat{r}$, is the sum of this quantity over all the trees. The probability that a tree will not put on a narrowest ring in a particular year is proportional to $((l-m)/l$, thus an estimate of the probability that it will not do so during any year within the window period is given by $((l-m)/l)^w$, and the estimated probability that none of the trees from a site will put on a narrowest ring, $\hat{a}$, is the product of this quantity over all the trees from that site. The probability that a site does have at least one narrowest ring in the window period is $(1-\hat{a})$, so the expected number of sites, $\hat{s}$, is the sum of this quantity over all the sites.

The index $r \ln(r/\hat{r}) + s \ln(s/\hat{s})$ is based on the departures from these expected values, and includes weightings by the total number of trees and sites to diminish the effects of small sample sizes. Unfortunately one cannot compare it directly with a theoretical distribution such as x^2 because s is dependent on r; moreover because the trees in the chronology cross-date with each other they must be correlated, and some clustering of dates for narrowest rings should be expected, although the methods used to produce the expected numbers of trees and sites do not take this into account.

Figure 2 shows that major peaks in the index values occur at dates that previous workers[2,3] have suggested for major prehistoric eruptions, from evidence that was not connected with tree rings. Such coincidences count as strong independent support for the eruptions dated at ~1150 BC, ~1626 BC, ~3195 BC and ~4375 BC. There is no supportive evidence for eruptions associated with our consistent index peaks at ~2345 BC and ~5060 BC, the former in particular appears to be a local single-site event. Interestingly our 207 BC single year peak suggests support for the 210±30 BC ice-core evidence. Hammer *et al.*[2] have been unable to replicate the 1390±50 BC peak seen at Camp Century (North Greenland) in the Dye 3 core (from South Greenland), and would now interpret it as a high latitude eruption whose acidic fallout did not extend to South Greenland. Although such an eruption could still have produced an extensive dust veil, one should not accept this until the acidity spike has been confirmed at other sites.

The narrowness index peak for the 1620s BC coincides with the 1628–1626 BC bracket of LaMarche and Hirshboek. Inspection of the Northern Irish tree samples from this period suggests that they are variously affected from dates after 1630 BC. Although this differs slightly from the 1645 BC ice-core date, the tree rings must take precedence because every tree containing frost-damaged or narrow rings is absolutely dated. Such tree-ring dates cannot be shifted, even by a single year, without a complete redating of the chronologies that support them. This is impossible, because the Belfast chronology is strongly replicated internally and has been verified against other European chronologies[5]. The North American bristlecone pine chronologies are equally sound.

The ice-core date is expressed, however, as '... 1645 BC with an estimated standard deviation of ±7 yr, and an estimated error limit of ±20 yr'[2], so the tree-ring date already falls within the error limits. It also gives a result more in agreement with the ^{14}C dates for the Santorini eruption discussed by Hammer *et al.*, falling well within the date range produced by calibrating the 2σ limits.

These results may have implications for interpreting the effects of volcanic dust veils. Even if volcanic ash clears from the stratosphere after 2-3 yr, the Belfast tree-rings show effects that last much longer (~10 yr), suggesting that an initial trigger event (flooding?) caused severe long-term problems for trees growing on bogs; other biological systems may show similarly extended responses. There are possible implications for the impact on human societies, which might suffer the effects of runs of bad harvests, poor pasturage and impeded communications. We draw attention to the 1150 BC event, which shows up as an extremely narrow band of rings in 90% of the trees covering the period. The effect begins dramatically in 1159 BC and recovery is not general until 1140 BC. 43% of trees on six sites have their narrowest rings during this period. There can be little doubt that this event is the Hekla 3 eruption observed by Hammer *et al.*[3]. .

A perfectly plausible mechanism to explain how dust veils could cause adverse growth conditions on Irish bogs comes from Kelly and Sear's study[7] of the climatic impact of explosive eruptions. They show that pressure changes in the northern hemisphere months after northern eruptions can produce a negative pressure anomaly over the British Isles. Such anomalies, associated with increased precipitation in middle latitudes, could provide exactly the conditions that might tip the balance against trees growing on marginal bog environments.

This work was begun by M.G.L.B. during a sabbatical term as Visiting Professor at the University of Arizona, Tucson.

Received 5 October 1987; accepted 4 January 1988.

1. LaMarche, V. C. Jr & Hirschboeck, K. K. *Nature* **307**, 121–126 (1984).
2. Hammer, C. U., Clausen, H. B., Friedrich, W. L. & Tauber, H. *Nature* **328**, 517–519 (1987).
3. Hammer, C. U., Clausen, H. B. & Dansgaard, W. *Nature* **288**, 230–235 (1980).
4. Pilcher, J. R., Baillie, M. G. L., Schmidt, B. & Becker, B. *Nature* **312**, 150–152 (1984).
5. Brown, D. M., Munro, M. A. R., Baillie, M. G. L. & Pilcher, J. R. *Radiocarbon* **28**, 279–283 (1986).
6. Tapper, M., Fletcher, J. & Walker, F. *Br. archaeol Rep.* (*Int. Ser.*) **51**, 339–342 (1978).
7. Kelly, P. M. & Sear, C. B. in *Proc. 3rd Conf. on Climatic Variations and Symp. on Contemporary Climate: 1850–2100*, 178–179 (American Meteorological Society, 1985).
8. Hammer, C. U. *Jökull* **34**, 51–65 (1984).

The dependence of convection planform on mode of heating

Gregory Houseman*

Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra ACT 2601, Australia

A fundamental property of a convecting fluid is its planform—the distribution in the horizontal plane of hot rising regions and cold sinking regions. For the Earth's mantle the planform might be visualized as a map of subduction zones, hotspots and possibly ocean ridges. Here I report numerical experiments of convection at high Rayleigh number which show a strong dependence of planform on heating mode. When heat generation is distributed uniformly through the box the preferred planform consists of an ensemble of time-dependent cold axial sinkers distributed in a hot diffuse upward flow. When half of the heat is generated within the box and the other half is input through the base, the preferred planform consists of an array of hot axial plumes and elongated cold sheets. In the former case the mean horizontal wavelength is about equal to the layer depth; for the latter it is about twice the layer depth.

Many previous two-dimensional convection calculations have been published[1-7] in which the planform is necessarily prescribed as a series of alternating (often time-dependent) hot and cold sheet-type structures that extend into the third dimension. In general, such a planform is unstable at large Rayleigh numbers[8] and would be replaced by a set of three-dimensional structures[9,10]. The three-dimensional planform is generally also time-dependent; given structures may die out or coalesce with other structures, while new ones may form by instability of the upper or lower thermal boundary layers[11].

An approximate model of convection in the Earth's mantle is defined by the three equations that specify incompressible flow, conservation of momentum (infinite Prandtl number) and conservation of energy[12]:

$$\nabla \cdot v = 0 \tag{1}$$

$$\eta \nabla^2 v + \rho g = \nabla p \tag{2}$$

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \kappa \nabla^2 T + \frac{H}{\rho C} \tag{3}$$

where v is the velocity field, ρ is the density, p is pressure, g is acceleration due to gravity, η is dynamic viscosity, T is temperature, κ is thermal diffusivity, H is heat generation per unit volume and C is heat capacity at constant pressure. The Boussinesq approximation is assumed; the physical properties are constant except that where the density appears in equation (2) it depends linearly on temperature:

$$\rho = \rho_0(1 - \alpha T) \tag{4}$$

where ρ_0 is the density at $T = 0$ and α is the coefficient of thermal expansion.

* Permanent address: Department of Earth Sciences, Monash University, Clayton, Victoria 3168, Australia.