A RESEARCH REPORT TO THE CITY OF BOULDER OPEN SPACE:

FIRE ECOLOGY IN THE WILDLAND/URBAN INTERFACE OF BOULDER COUNTY

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ABSTRACT

The objective of this study was to quantify the occurrence of fire in the montane zone (1830-2740 m) of Boulder County over the past several centuries and to relate changes in fire regimes to human settlement and short-term (i.e. 1 to 6 year) climatic variation. The methodology consisted of tree-ring dating of fire scars and reconstruction of past climatic conditions from variations in tree-ring widths. Forty-one areas of approximately 1 to 3 km^2, widely distributed throughout Boulder County, were sampled for fire-scarred trees. Partial cross-sections of 526 fire-scarred trees yielded 909 cross-dated fire-scar dates.

Analyses of the fire dates and fire intervals derived from these fire-scar samples support the following principal conclusions:

(1) Fire frequencies have been greater in open woodlands of Ponderosa pine near the Plains grassland than in denser Ponderosa pine forests at higher elevations.

(2) In comparison with the Native American period (pre-1851), fire frequencies were substantially higher during the Euro-American settlement and mining period (1851-1920).

(3) Fire suppression since approximately 1920, has dramatically reduced fire frequency in comparison with both the Native American and Euro-American settlement periods; the magnitude of this reduction has been greatest for sites near the Plains grasslands and is associated with the previously documented increase in density of Ponderosa pine stands in the lower montane zone.

(4) Analyses of spring and annual precipitation since the 1500s (as reconstructed from tree rings) reveal that years of widespread fire occurrence in the montane zone of Boulder County are associated with above-average precipitation two to three years prior to the fire year, followed by drought during the year of fire occurrence.

1552-1808
1746

(1) NATIVE AMERICAN ? → 1851 (ca 105 yrs)

(2) SETTLEMENT, MINING 1851- 1920 (69 yrs)

(3) CURRENT FIRE SUPPRESSION 1920- 1996 (76 yrs)

INTRODUCTION: OBJECTIVES AND RESEARCH QUESTIONS

The objective of this project was the development of a fire history record covering at least the last 250 years in the lower montane forests of Boulder County. The overall goals were to describe the occurrence of fire and to determine how humans have influenced fire occurrence over the past several centuries in the area which today is the wildland/urban interface of Boulder County. These research objectives were defined in order to provide data on fire history pertinent to resource management issues on City of Boulder Open Space and other properties in the wildland/urban interface of Boulder County.

Specific questions to which this research is addressed include:

To what extent has fire suppression during the present century changed the occurrence of fire in the montane zone?

How did the late-nineteenth century period of Euro-American settlement affect fire regimes in the montane zone?

How different is the current fire regime from the fire regime that characterized these ecosystems prior to settlement of the area by Euro-Americans in the mid-nineteenth century?

Concurrent with the development of this project for the City of Boulder Open Space Department we conducted research on the effects of climatic variation on fire regimes in the northern Front Range under a grant from the National Biological Service. Consequently, in this report we include our preliminary findings on the effects of climatic variation on fire occurrence in montane forests in Boulder County.

STUDY AREA

The focus of this study is the montane zone (c. 1830-2740 m) of Boulder County, characterized mainly by forests and open woodlands dominated by Ponderosa pine (*Pinus ponderosa*). Priority was given to locating sample sites on City Open Space land, but sample locations were determined primarily by the availability of relatively old fire-scarred trees. Consequently, the majority of the sample sites are located on land of the Roosevelt National Forest, and a few sites are located just across county boundaries with Larimer and Gilpin Counties.

According to Marr's (1961) classification of the vegetation of the eastern slope of the Front Range, the area sampled in this study includes both the lower montane (1830-2350 m) and upper montane (c. 2440-2740 m) vegetation zones. The vegetation of the lower montane zone consists of open forest with broad-crowned Ponderosa pine frequently interrupted by grasslands. Moist ravines and some northern-facing slopes are characterized by somewhat denser stands of trees in which Douglas fir (*Pseudotsuga menziesii*) is typically abundant. With increasing elevation into Marr's upper montane zone there is a gradual increase in stand densities and in the importance of Douglas fir, aspen (*Populus tremuloides*), limber pine (*Pinus flexilis*) and lodgepole pine (*Pinus contorta*). These elevation- and moisture-related changes in stand composition and density create substantially different fuel conditions between the lower and upper montane zones. In the lower montane zone, characterized by open woodlands of Ponderosa pine near the ecotone with the Plains Grassland, fires are typically low-intensity surface fires. In contrast, in the dense stands of the upper montane zone, woody fuels are sufficiently continuous to support intense crown or "stand-replacing" fires. In both elevational zones, however, the heterogeneity of the vegetation creates a mixed fire regime of both surface and stand-replacing fires. Thus, over relatively short distances changes in fuel conditions, related mainly to topographic position, result in surface fires transforming to stand-replacing fires and vice-versa.

METHODS

Field Sampling

Forty-one sites were sampled for fire scars during the summers of 1993-1995. The main criterion for site selection was the presence of apparently old fire-scarred trees on public lands. Given the history of extensive nineteenth-century logging and the loss of old trees to recent insect outbreaks (mortality caused both by the insects and by pest-control logging), trees older than c. 200 years are relatively rare in the montane zone of Boulder County. Consequently, sampling had to focus on subjectively located stands of older trees. Although an objective location of sample sites was not possible for this reason, in addition to limited access to private lands, the sample sites were located to cover as wide a range of north-south and elevational variation as possible. Given the high density and spatial distribution of the 41 sample sites (Fig. 1), the results of this study are believed to be generally valid for the montane zone of Boulder County. To evaluate this assumption, sites were grouped into clusters of nearby sites and their fire histories are compared in the Results section.

Each area sampled was of similar size (c. 1 to 3 km^2) and all were characterized by presence of Ponderosa pine. The sampled areas range in elevation from 1853 to 2792 m (Table 1) and vegetation types range from open woodlands of Ponderosa pine to dense forests of mainly Douglas fir and/or lodgepole pine. Each sample area was systematically searched for fire-scarred trees. Care was taken to avoid confusing fire scars with animal-caused scars (e.g. porcupine or bear damage). Fire scars are generally triangular in shape and located at the base of the tree on the uphill side (McBride 1983). In contrast, scars produced by a lightning strike that did not ignite more than a single tree are usually not triangular in shape and are located higher on the tree bole. Fire scars were sampled non-destructively by cutting partial cross sections (i.e. "wedges") following the techniques of McBride and Laven (1976). Wherever possible, samples were collected in clusters because it is unlikely that individual trees record every scar that burns in the vicinity (Arno and Sneck 1977). The number of sections per site ranged from 6 to 37 depending on the availability of fire-scarred trees. A total of over 700 fire-scarred trees were sampled from which 526 sections yielded precise fire dates. As far as we know, this is the largest sample size ever taken for a fire history study in Colorado. More than 90% of the 526 wedges used were from Ponderosa pine and include dead as well as living trees.

Sample Processing

Standard methods were used to prepare cross sections for dating of fire scars (Arno and Sneck 1977, McBride 1983). The transverse surfaces of the cross sections were prepared and polished using a belt sander and successively finer grits of sandpaper down to 400 grit. The annual ring series on each cross section were crossdated against master tree-ring chronologies from nearby sites in the Front Range (Drew 1974, International Tree-Ring Data Bank). From these tree-ring chronologies "marker rings" (years of exceptionally narrow or wide rings, generally characteristic of trees in the lower montane zone) were identified and used to graphically crossdate rings on the fire-scar sections. This graphical technique of comparing ringwidth patterns allowed the identification of any missing or false rings and the assignment of precise dates to each year. On samples taken from dead trees and on samples where marker rings were not visually obvious, ring widths on the cross sections were measured to the nearest 0.01 mm using a computer-compatible incremental measuring machine. The computer program COFECHA (Holmes 1983) was used to quantitatively cross-date these samples. COFECHA was used to correlate 50-year segments (overlapped by 25 years) of the undated series against a master chronology derived from several nearby Ponderosa pine chronologies. Samples that could not be conclusively and accurately dated were not included in the analyses.

Although historical fire records indicate that the majority of fires occur during mid-summer to early fall (i.e. July-Sept), the seasonal pattern of fires could have been different prior to the beginning of records in c. 1920 due either to climatic variation or human activities. To determine the season of fire occurrence, the position of scars within the annual ring was determined whenever possible (Dieterich and Swetnam 1984). Annual tree rings on conifers in our study area consist of a light-colored band of relatively large, thin-walled cells that result from rapid tree growth during the spring (earlywood) and a darker-colored band of small cells that reflect declining growth rates as moisture becomes limiting during the summer (latewood). By determining the approximate time of initiation of ring growth, period of earlywood formation, period of latewood formation, and time of cessation of ring growth, it is possible to estimate the month of fire occurrence based on where a fire scar tip occurs within an annual ring. Six categories were used for describing the position of scars within annual rings: D, dormant season (appearing between growth rings); E, early earlywood (first one third of earlywood); M, middle earlywood (second one third), L, late earlywood (third one third), A, latewood; and U, undetermined. Based on our experience of coring trees during different months and on dendrometer measurements of diameter growth of permanently marked trees taken at two-week intervals from May through September (unpublished data), months of fire occurrence were estimated from relative scar positions. E is interpreted as late April through May, M as June, and L as late June or July, and A as July to early August. Our dendrometer measurements indicated a general pattern of later growth initiation with increasing elevation. Because of the inter-tree variability in the timing of tree growth, these estimates of seasonality of fire occurrence must be interpreted cautiously. For example, adjacent periods within the growing season cannot be reliably distinguished but placement of scars in non-adjacent periods probably indicates real differences in seasonality. Consequently, in the interpretation of the results we emphasize differences between dormant *versus* growing-season fires rather than differences within the growing season.

One of the reasons for estimating the seasonality of fire occurrence was to assign dormant season fire scars to the correct calendar year. The dormant season extends from approximately early September through April, and consequently spans two calendar years. Where a dormant season fire scar is associated with some early earlywood scars on nearby trees, it is assumed that the fire occurred in the spring. Where a dormant season fire scar is associated with some latewood scars, it is assumed that the fire occurred in the late summer or early fall. However, many dormant season fire scars are not clearly associated with scars of either adjacent season. In those cases, we assumed that the fire occurred during late summer or autumn because modern fire records for the Front Range indicate fires are more likely to occur during the autumn than during winter or early spring. For example, in Rocky Mountain National Park between 1916 and 1992 ony 4.4% of all recorded fires occurred in January through May, whereas 19.9% occurred in September through December (n = 136 fires; unpublished data from Rocky Mountain National Park).

Data analyses

Fire Interval Analyses

A fire interval is simply the time period between two consecutive fires affecting the same area (composite interval) or the same tree (point interval). Composite intervals are used in this study. The computer program FHX2 (Grissino-Mayer 1995), an integrated software package for analysis of fire history information from tree rings, was used to analyze the fire-interval data. For each site, the number and percentage of trees scarred in a given year was determined. A tree is considered "fire-scar susceptible" once it has been initially scarred by fire (Romme 1980). Hypothetically, following the creation of an initial scar that exposes the wood of the tree, a tree is more likely to be scarred by subsequent fires. Thus, in our analysis trees are considered "recorder" trees only once they have been scarred. Within a site, for a particular year, more widespread fires are indicated by larger percentages of recorder trees (Swetnam 1990, Grissino-Mayer 1995). Years of different types of "fire events" (i.e. different areas burned) were determined by defining fire event years according to numbers, percentages, and locations of fire-scarred trees. For example, in this study the least area burned is implied by defining fire event years to include the occurrence of at least one fire-scarred tree at any site, whereas a large area burned is implied by defining fire event years to include only those years where a minimum of 25% of the recorder trees were scarred in 2 or more distant sites. In different studies, different indices of fire extent have been used in accordance with the type of fire regime (e.g. high frequency parkland type fire regime versus low frequency fire regime typical of mesic forests) and the spatial features of the sampling design.

FHX2 was used to graphically describe fire regimes by creating composite fire interval charts (Dieterich 1980) for each of the 41 sample sites (Fig. 2). The composite fire interval chart, also known as a composite master fire chart or composite fire chronology, shows the dates of all fire scars on each tree. The composite line at the bottom of each chart gives the dates of all fire events (e.g. all fire scars or some specified minimum number or percentage of fire-scarred trees) which have occurred in the sample area. Composite fire chronologies are used for describing the fire regime of an area because it is unlikely that a single tree will record all fires that burn in the area. The relative scarcity of trees with multiple fire scars in many of the sample areas clearly indicates this is the case for the Colorado Front Range where many of the sampled trees only recorded single scars. This is an important contrast with Ponderosa pine in other parts of the western U.S. where multiple-scarred trees are much more abundant (Dieterich and Swetnam 1984).

A variety measures of central tendencies have been used to describe fire return intervals. The fire return interval is the number of years between two successive fires documented in a designated area and a specified time period. Mean fire interval (MFI) is simply the arithmetic average of all fire intervals determined in a specified area during a designated time. It is the inverse of mean fire frequency. Although MFI is the most often reported measure of the central tendency of fire interval data, it is not always an appropriate descriptor because of the tendency of fire interval data to be positively skewed (Baker 1992). In many fire regimes the fire interval data are not symmetrically distributed because there is no upper limit to the maximum interval between fires whereas the lowest possible fire interval is one year (Grissino-Mayer 1995). Thus, other measures of central tendency of fire interval data used in this study are the median and Weibull Median Probability Interval (Johnson and Van Wagner 1985, Johnson 1992). The Weibull distribution is a highly flexible statistical distribution that can used for modeling fire interval frequency distributions. The FHX2 program fits observed fire interval data to the Weibull distribution from which the probability of having fire intervals greater than a specified length can be estimated (i.e. the exceedance probability). It also compares the goodness-of-fit between the fire interval data and both the empirical (i.e. normal) distribution and the Weibull distribution using a one-sample Kolmogorov-Smirnov (K-S) test (Grissino-Mayer 1995). The fire interval associated with the 50% exceedance probability is known as the Weibull Median Probability Interval (WMPI) which is an unbiased measure of the central tendency in fire interval distributions. The Weibull Fire Frequency Probability (WFFP), the reciprocal of WMPI, indicates the probability of fire occurring in any given year. The FHX2 program also computes the 95% and 5% exceedance probability levels which delimit, respectively, significantly short or long fire intervals. The Weibull shape parameter, *c*, is used to describe the overall shape of a fire interval distribution. A value of 1.0 indicates a negative exponential distribution and values that approach 3.6 indicate distributions that approximate normality. Other descriptive statistics used in this study are the standard deviation and coefficient of variation of the MFI.

To obtain sufficiently large sample sizes for some statistical analyses, nearby sites were combined into groups of 2 to 9 sites (Table 2). In particular, these groups were necessary to obtain large enough numbers of fire intervals to detect trends in fire occurrence over time. These groupings were based on proximity of sample sites and include areas of similar habitat, human history and fire history.

Time Periods of Analyses

There are important limitations on the reliability of fire interval data which vary according to the time period considered. For example, prior to the occurrence of the first fire hot enough to scar a tree, less intense fires will obviously not be recorded. Once fire-scar susceptible trees are present, the time period over which the fire history data are considered reliable will be constrained by the survival of those trees to the date of sampling. The mortality and decay of old trees means that evidence of old fires gradually disappears. This introduces a bias towards underestimating fire intervals for older time periods. One way, used in this study, to account for this bias is to consider the percentage of fire-scar susceptible trees scarred rather than the absolute number. Another method is to estimate the "period of minimum reliability," which is the range of years regarded as appropriate for statistical analyses and is determined by the minimum number of fire-scarred samples (Grissino-Mayer 1995). The intent is to include only the range of years for which there is a high probability that trees with fire scars survived to the date of sampling. In this study, the period of minimum reliability starts with the year in which a sample area has accumulated at least three fire-scarred trees. The use of the three-tree criterion for determining the period of minimum reliability is arbitrary, but is relatively conservative compared to most fire history studies.

To detect possible temporal changes in fire occurrence associated with human activities we analyzed fire intervals for the following four periods:

1. *The Full Native American Period* spans from the first year of three accumulated fire scars until 1850. For the eight groups of sample sites, the initiation of the Full Native American Period ranged from 1567 to 1703.

2. *The Recent Native American Period* (1781-1850) includes only the most recent 70 years of the Native American Period. Consequently, it greatly diminishes the bias towards longer fire intervals due to the death and decay of old trees. It was set at 70 years to allow better comparison with the following period.

3. *The Euro-American Settlement Period* (1851-1920) spans the period of intensive mineral prospecting and initial Euro-American permanent settlement.

4. *The Fire Suppression Period* (1921-1995) begins after the creation of the precursors to the Roosevelt National Forest and the adoption of a fire suppression policy.

Analyzing Relationships of Fire to Climatic Variation

Possible influences of short-term climatic variation on fire occurrence were investigated with superposed epoch analysis (SEA) which has been used extensively for the same purpose in the Southwestern U.S. and the Sierra Nevada (Baisan and Swetnam 1990, Swetnam and Betancourt 1992, Swetnam 1993, and Grissino-Mayer 1995). SEA tests the null hypothesis that there is no relationship between occurrence of fire and climatic conditions in the years preceding and during fire years. In SEA all fire event years are superposed (i.e. set at year 0) and mean climatic conditions are computed for years prior to and during the fire year.

SEA was used to compare precipitation during fire years and for six years prior to the fire event. Three Ponderosa pine tree-ring chronologies provided by D.A. Graybill and G.

Funkhauser of the Laboratory of Tree-Ring Research of the University of Arizona were used to reconstruct spring (March - June) and annual precipitation (August-July) over the period 1549 to 1987. These three tree-ring series were selected after extensive testing of the chronology characteristics and relationships to climatic variation of approximately 20 Ponderosa pine chronologies for the northern Front Range obtained from Graybill and Funkhauser, the International Tree-Ring Data Bank (NOAA, Boulder), and from our own data collection. Starting dates of the three selected chronologies were 1547, 1622, and 1681; collection sites included one site just west of Estes Park at 2560 m and two sites west of Denver at 1920 and 1966 m elevation. The three chronologies included a minimum of 25 tree-ring series for each site. Standard dendrochronological techniques were used to produce residual tree-ring chronologies which were averaged and calibrated with averaged climatic data from the Fort Collins, Boulder and Denver climate stations. Tree-ring widths were highly correlated with spring and annual precipitation (correlation coefficients of .63 and .73, respectively). Details of the site and chronology characteristics and are given in Graybill (1989, 1992). Since the Ponderosa pine chronologies did not yield reliable reconstructions of temperatures, SEA was also conducted using reconstructed July temperature based on averages from three temperature-sensitive Engelmann spruce (*Picea engelmannii*) chronologies from the northern Front Range and calibrated with climatic data from the same three climate stations. These chronologies were derived from tree-ring samples at sites near the University of Colorado Mountain Research Station, Long Lake and the upper Poudre River in Rocky Mountain National Park. Site and chronology details are given in Villalba *et al.* (1994; chronologies MR5e, Lle, and PRNe).

The program FHEVENT (Grissino-Mayer 1995) was used to conduct the Superposed

Epoch Analysis of fire events and reconstructed spring and annual precipitation. Climatic conditions were averaged for all fire event years, and then for each year up to six years prior to the fire event year. Statistical significance was determined with a bootstrapping technique that compares actual and simulated climatic conditions. The simulated climatic conditions were derived from 1000 iterations of random selections of "windows" (i.e. series of years preceding and including the fire event year) from the actual data. Separate analyses were conducted for different types of fire events ranging from the occurrence of any fire at any of the 41 sites to occurrence of fire scars on at least 25% of fire-scar susceptible trees at two or more sites.

RESULTS

Composite Master Fire Charts for Individual Sites

The total of 526 sections yielded 909 cross-dated fire-scar dates with the earliest recorded occurrence dated in 1474 and the most recent in 1982 (Table 1). Composite master fire charts (Fig. 2) show all fires in each sample area, but on the composite line fire years are only plotted for years in which at least two fire scars occurred. By emphasizing years in which at least 2 scars occurred, the influence of extremely small fires (e.g. campfires or lightning ignitions that do not spread beyond a single tree) is diminished. The focus on years of 2 scars also reduces the possible influence of slight errors in crossdating fire scars.

Although the numbers of fire years at most sites were too small to justify statistical analysis of fire interval data for individual sites, some patterns are qualitatively evident. There is a tendency for fire frequency to be greater at low elevations. For example, sites 14 and 15, located close to the Plains grassland, recorded the highest frequency of fires among all sites. The large percentages of multiple fire-scarred trees at these two sites are also indicative of both high point fire frequencies (i.e. recurrence of fire at the same point) and also of low intensity fires. The fire records of these two low elevation sites are believed to be typical of the high frequency, low intensity fire regime at the ecotone with the Plains grassland. In contrast, high elevation sites (i.e. above c. 2300 m) record relatively few fire years (e.g. sites 17-20 and 30) and at many sites multiple-scarred trees are scarce (e.g. 30, 37, 40). These traits of the master fire charts of the upper montane stands plus the even-aged character of these stands (Veblen and Lorenz 1986) indicate a predominance of stand-replacing fires towards higher elevation.

Fire Intervals for Groups of Sites

To obtain sufficently large numbers of fire intervals for statistical analyses, nearby sites were combined into eight groups (Table 2). The numbers of samples (trees) in these groups ranged from 45 to 98, and the number of different fire years from 15 to 60. Fire interval distributions were computed based on intervals determined by all fire scars, $\geq$ 2 scars per group, and $\geq$ 25 percent of fire-scar susceptible trees scarred (minimum 2 scars) per group. These fire interval distributions were modelled with the Weibull function and compared to normal distributions to identify the most appropriate descriptor of central tendency. In all cases, the fit to the Weibull distribution was better (i.e. smaller *d*-statistic in Table 3). In the case of fire intervals based on all scars, most fire interval distributions differ significantly ($P < 0.05$) from a normal distribution but only differ from a Weibull distribution in two of eight groups. For intervals based on a minimum of two scars, none of the observed distributions differed significantly from a Weibull distribution. Likewise, distributions of intervals based on $\geq$ 25% of trees scarred, all fit the Weibull distribution, but in two groups, fire events of this type were two few to compute the statistical test. Consequently, it is more appropriate to emphasize fire interval distributions based on a minimum of two scars and to use the Weibull Median Probability Interval (WMPI) as the measure of central tendency in these distributions.

Descriptive fire interval statistics were calculated for the period of reliability (i.e. from the year of a cumulative total of ≥ 3 scars) for each group for years of ≥ 2 scars and ≥ 25% of fire-scar susceptible trees scarred (Tables 4 and 5, respecively). The highly skewed nature of most of the ≥ 2 scars-fire interval distributions is reflected by the substantial differences between the mean and the other two measures of central tendency, median and WMPI, which tend to be similar. In every case, the median and WMPI are less than the MFI. Measures of central tendency are more similar for the ≥ 25 percent scarred class (Table 5) because of the elimination of a large number of less widespread fires which contribute to the skewing of the distribution.

In interpreting the descriptive statistics given in Tables 4 and 5, it is important to consider the number of sites included and their locations. Groups which include more sites, theoretically, would be expected to show more fire scars simply because of the increased probability of finding fire-scarred trees as the search area is increased. For example, fire intervals for Lower South Boulder Creek group, which includes only two sites, should not be directly compared with the other groups which include 5 or more sites. The other seven groups, however, vary from only 5 to 9 sites which makes them much more comparable in area.

The minimum interval for ≥ 2 scars was 1 to 3 years for all groups (Table 4). At a few sites, 1 to 3 year intervals were often observed on different trees within the same site (e.g. sites 9, 14, 15, 31-41) and occasionally on the same tree (e.g. sites 15, 31, 35, 36 and 38). Maximum intervals for ≥ 2 scars ranged from 29 years for the lowest elevation group (Lower South Boulder Creek) to 162 years for one of the higher elevation groups (Upper Left Hand Canyon). Despite the much smaller sample area for the Lower South Boulder Creek group, it has the shortest maximum interval for ≥ 2 scars and the second shortest interval for $\geq 25\%$ samples scarred (Tables 4 and 5). It also has the smallest median and WMPI value for $\geq 25\%$ samples scarred (Table 5). Among the groups of comparable sample areas, James Creek, also a relatively low elevation group, has the lowest median and WMPI value for $\geq 25\%$ samples scarred. Thus, the frequency of extensive fires tends to increase with decreasing elevation.

Given the good fits to the Weibull distribution, exceedance probability levels provide a statistical basis for identifying unusually long or short fire intervals. For example, for the North St. Vrain Creek group, 95% of all intervals for ≥ 2 scars can be expected to exceed 2.1 years (Table 4). Conversely, for the same group only 5% of all intervals for ≥ 2 scars can be expected to exceed 51.9 years. The Weibull-derived fire frequency probability (WFFP) indicates the probability of a fire event occurring in any given year. Among the groups of comparable areas, Upper Left Hand Canyon had the highest probability (18%) of occurrence of ≥ 2 fire scars in any given year and South St. Vrain and North St. Vrain Creeks the lowest probability (6%; Table 4). For fire years resulting in $\geq 25\%$ samples scarred, all groups of similar size had 2 to 4% probabilities of occcurence in a given year (Table 5).

Changes Over Time

Maximum fire intervals for different fire events reflect a decline in fire occurrence during the fire suppression period (1921 to present) (Table 6). The maximum fire interval occurs during the fire suppression period in only 3 of eight groups. Five of the groups have maximum fire intervals terminating during the Native American period which probably reflects the much longer span of this period. For both types of more widespread fire events, however, five groups have maximum intervals terminating during the fire suppression era (Table 6). Considering that maximum intervals were arbitrarily terminated in 1995, these results demonstrate that the period since 1921 has been characterized by unusually long fire intervals.

When years of any fire occurrence are plotted for each of the eight groups and then summarized as a composite for all 41 sites, there is an obvious increase in the number of fire events over time (Fig. 3). All groups show an increase in the number of fire events beginning about 1850, coincident with the beginning of prospecting and permanent settlement by Euro-Americans. The group which shows the sharpest increase in the number of fire events is Upper Left Hand Canyon which was an area of heavy mid- to late-nineteenth century mining activity. Conversely, the group showing the most moderate increase in number of fire years is North Saint Vrain which is an area with little history of mining. For all 41 sites, a decline in the number of fires is apparent following the first two decades of the present century (Fig. 3). For the Middle South Boulder Creek and Lower Middle Boulder Creek groups, this decline is relatively moderate, but for the other groups it is conspicuous.

When years recording ≥ 2 scars per group are considered, fire years also increase in the mid-nineteenth century but less dramatically so than for all fire years (Fig. 4). However, for these more widespread fires the decline during the twentieth century is much more marked. Fire events of both these types, are interpreted as reflecting primarily changes in the numbers of human-set fires in Boulder County which has been previously documented qualitatively (Veblen and Lorenz

1986, 1991).

Fire events defined as ≥ 25% samples scarred in at least one group (Fig. 5) or in ≥ 2 groups (Fig. 6) indicate exceptionally widespread fires during the same year. Fire events of both these types peak during the Euro-American settlement period and are absent from the Fire Suppression period. Similarly, when number of fires (2 scar minimum) per fifty-year period for all 41 sites combined is plotted beginning in 1600, the association of peak fire occurrence with the mid- to late-nineteenth century Euro-American settlement period is obvious (Fig. 7). Comparison of fire interval statistics for fire years with ≥ 2 scars also shows that the Euro-American settlement period was a time of consistently higher fire frequency compared to both the Native American and Fire Suppression periods (Table 7).

Fire Seasonality

Of the 909 fires dated from all 41 sites, it was possible to estimate season of fire occurrence based on intra-annual position of the scar in the tree ring in 529 cases (Table 8). With the exception of James Creek, fires occur primarily during the growing season. In five of the eight groups, seasonal fire occurrence peaks during late summer, which is consistent with historical records from Rocky Mountain National Park where July, August and September fires account for 33.1%, 23.5% and 14.7% of all fires, respectively.

Climatic Influences

During some years, high percentages of sample sites dispersed over large distances, recorded fire scars (Figs. 8-17). For example, in 1654 and 1786 the percentages of sample sites recording fires were 50 and 53%, respectively (Figs. 8 and 10). For the combined years 1859-1860, 66% of the 38 sites with fire-scar susceptible trees recorded fire scars (Fig. 14). Given the conspicuous occurrence of widespread burning in a relatively small number of specific years, the possible influence of short-term climatic conditions on fire occurrence was investigated.

Superposed epoch analysis (SEA) was conducted over the full record of fires for fire event types ranging from 1 or more fire at any site to at least 25% samples scarred in two or more groups (Fig. 18). Years of any fire occurrence have significantly ($P < 0.001$) below average expected spring and annual precipitation. Years of a minimum of 2 fire scars have average spring and annual precipitation that are 10.5 and 7.3%, respectively, below the expected values. As the fire event type changes to the indicator of the most widespread fires, the severity of spring and annual drought increases up to 21.1 and 14.5%, respectively, below the expected values. The SEA results show that occurrence of fire is generally more dependent on spring drought than on below expected annual precipitation. Years one year prior to fire occurrence also exhibit below average expected spring and annual precipitation (Fig. 18.).

There is an analogous, but reversed, pattern of fire occurrence and precipitation two and three years prior to the fire event (Fig. 18). For fire events of 2 mininum scars and all the more severe fire event types, spring and annual precipitation are above the expected values 2 and 3 years prior to fire years. Again, the deviation from expected values is greater for years with more widespread fires. Thus, two years of above average precipitation followed by two years of below average precipitation are conducive to the occurrence of widespread fires. The above average precipitation may promote fire occurrence by increasing the growth of herbaceous plants, creating more abundant fine fuels that become desiccated in droughts two to three years later.

Although the results of SEA explain the occurrence of many years of exceptionally widespread fire, they do not fully describe the range of climatic variations under which widespread fire occurs. Climatic conditions associated with the 10 years of most widespread fire show substantial variation (Table 9) which serves as a reminder that individual years can deviate from the average pattern described by the SEA. The years 1624, 1654, 1709, 1859, 1863, and 1880 all fit the general pattern of above average precipitation two or three years prior to a major fire year which coincides with severe drought (Table 9). However, other major fire years deviate from this pattern. The years 1786, 1813, 1860 and 1871 are not characterized by severe spring or annual drought. However, reconstructed July temperature is above average for all of those years, except 1860, and would have contributed to summer drought. The year 1860 followed a year of below average spring and annual precipitation. It also, along with 1859, occurred during a period of peak prospecting activity. The year 1786, the single year of most widespead fire, does not stand out as being a climatically unusual year. Seasonal drought may have occurred during that year when tree-ring reconstruction could not be made (e.g. late summer or fall drought) or the widespread fires could be attributed to an unusual abundance of fires set by native Americans.

DISCUSSION AND CONCLUSIONS

There are important limitations on the interpretation of the results of any study of fire history based on long-term tree-ring records. Fire scars provide only a minimum estimate of past fire occurrence--not a total record of all past fires. Even where fire-scar susceptible trees are present, some surface fires may not leave any fire scars due to variable fire behavior. For example, if fuel accumulations are low beneath scattered trees on rocky sites in open grasslands, fires in the grassland may not leave fire scars on the tree boles. Thus, fire scars are an indicator of the minimum number of fire events but may be substantially less than the actual number of fires. Consequently, a quantitative reconstruction of past fire intervals should not be used as a management target for re-creating a "natural" fire regime. Summary fire statistics should be regarded as indices of fire activity rather than indicators of exact numbers of fires affecting the designated areas.

The fire dates in the composite interval chronologies indicate occurrence of fire in the sample area during that year, but they do not necessarily indicate that the entire sample area burned during that year. Some of these fires may have affected only a small part of a sample area whereas others may have burned the entire area. Obviously, the occurrence of fire scars on several trees in the same year is an indicator of more extensive burning. In interpreting composite fire interval chronologies, it is also important to consider the influence of the size of sample area on fire intervals. As the size of the area searched for fire-scarred trees increases, so does the likelihood of recording more fires. Consequently, composite fire intervals should only be compared for sample areas of similar size. These limitations require that the trends in fire intervals be interpreted rather than their specific numerical values.

In the montane zone of Boulder County fires have been more frequent in the lower elevation areas (e.g 1900-2100 m) of scattered Ponderosa pine than they have been in denser forests dominated by a mixture of Ponderosa pine with other conifers at higher elevation (e.g 2500-2700 m). At sites of open Ponderosa pine woodland near the ecotone with the Plains grassland, prior to the twentieth century low-intensity surface fires recurred at intervals of approximately 8 to 12 years in areas of 2 to 3 km^2 (e.g. at sites 14 and 15). In contrast, the denser forests towards higher elevations were characterized by a mixture of stand-replacing crown fires and low intensity surface fires. Given the heterogeneous nature of stand densities (and hence fuel loads) in the Ponderosa pine-dominated forests of the montane zone, fire behavior can differ over relatively short distances.

Fire-scar data from the individual sample sites with more abundant fire events and from combined data for sites with fewer fire events, clearly indicate that fire frequency has been much lower during the fire suppression period (1921-1995) than during the pre-1921 period. This probably reflects both the effects of suppressing lightning-ignited fires and a decline in the number of human-set fires. The interpretation that many of the pre-1921 fires were set by humans is based on the observation that during the historical period of fire-record keeping, lightning-caused fires have been relatively infrequent on the eastern slope of the Front Range. For example, during the 73-year period from 1915 to 1988 over the entire eastern slope of the Front Range in Rocky Mountain National Park only 28 lightning-ignited fires were reported (Rocky Mountain National Park, unpublished data). Given the extreme difference in the size of the area for which these fires are reported in Rocky Mountain National Park and the area sampled in this study, it is likely that most of the pre-1921 fires were set by humans.

The results of this study clearly demonstrate that in the montane zone of Boulder County fire frequencies increased from the Native American period to the Euro-American settlement period. This is believed to be due to an increase in fires set accidentally or intentionally by prospectors and settlers (Veblen and Lorenz 1991). The same trend towards greater fire frequencies has been found in similar Ponderosa pine-dominated forests in the Poudre Canyon

(Laven *et al.* 1980) and in an earlier study of fire history in Fourmile Canyon (Goldblum and Veblen 1992). In Boulder County, it appears that the relative influence of Euro-American settlers on changing fire frequencies was less pronounced near the ecotone with the Plains grassland than it was in Ponderosa pine forests at 1000 to 2000 m greater elevation. This reflects the fact that during the Native American period, the lowest elevation sites were characterized by higher fire frequencies than were higher elevation sites. Thus, the relative impact of Euro-American settlers in increasing fire frequencies between 1851 and 1920 was less at the lowest elevation site. In contrast, the relative importance of fire suppression in decreasing the former fire frequency has been greater at low elevation sites near the Plains grassland.

This study and others (Laven *et al.* 1980; Goldblum and Veblen 1992) show a dramatic decline in fire frequencies during the 20th century period of fire suppression in Ponderosa pine-dominated forests on the eastern slope of the Front Range. However, direct comparison of fire intervals for the Native American and suppression periods can be misleading because of the likelihood that the extensive burning during the settlement period destroyed some of the evidence of prior fires. Consequently, for the forested sites characterized by stand-replacing fires it is likely that fire frequencies for the Native American period are underestimates. For example, in some sites in the upper montane zone, few pre-nineteenth century fire scars were found in stands of mostly young trees. This clearly does not indicate a lack of earlier fires, but more likely is the result of the destruction of older fire-scar bearing trees by nineteenth century fires. Thus, for the areas of denser forests, fire frequencies during the Native American period and the suppression period cannot be directly compared. For areas of scattered Ponderosa pine, such as sites 14 and 15, the unlikelihood of stand-replacing fires decreases the probability of destruction of fire-scar bearing trees by more recent fires. Nevertheless, even at these sites the mortality of old trees (due to natural causes or cutting) means that some evidence of earlier fires has disappeared and that the fire frequencies during the Native American period are underestimates.

The changes in fire regimes quantified in this study are consistent with vegetational changes previously documented in the montane zone of Boulder County. For example, in the upper montane zone, the peak of fire occurrence during the mid- and late-nineteenth century corresponds with the abundance of dense stands of Douglas fir, Ponderosa pine and Lodgepole pine that are typically 90 to 140 years old today (Veblen and Lorenz 1986). These are post-fire cohorts (i.e. even-aged tree populations) which established following the stand-replacing fires typical of the higher elevations. The abundance of similarly aged stands dating from a relatively brief period of high fire occurrence creates an upper montane landscape which is probably more homogeneous than the landscape of the Native American period. As these even-aged stands develop under the fire suppression regime, they take on stand structures that are highly susceptible to both insect outbreaks and wildfire. Beneath the original post-fire cohorts, young populations of Douglas fir have established and two-tiered stand structures have developed. The understory populations of Douglas fir are typically slow growing, stagnant trees that are highly susceptible to outbreaks of the western spruce budworm (*Choristoneura occidentalis*). Severe budworm outbreaks affected much of Boulder County beginning about 1980 (Hadley and Veblen 1993). Mortality of Douglas fir caused by the budworms, as well as mortality caused by outbreaks of Douglas fir bark beetles (*Dendroctonus pseudotsugae*), which typically follow budworm outbreaks by a few years, creates an abundance of fuels. Even in the absence of insect-caused tree mortality, these even-aged post-fire stands pose an extreme wildfire hazard due to the abundance of self-thinning at stand ages of c. 100 years and the continuity of these fuels over large areas.

A second vegetational change which has been previously documented by historical photographs taken near 1900, historical aerial photographs from c. 1940, and by studies of tree population age structure, is the dramatic increase in density of Ponderosa pine woodlands in the lower montane zone over the past approximately 100 years (Veblen and Lorenz 1991, Mast 1993). Photographic comparisons of sites in the lower montane zone show marked increases in densities of Ponderosa pine woodlands and tree invasions into former grasslands during this century. Peaks of tree ages in these invading tree populations appear to correlate with 2 to 10 year periods of above average precipitation (Mast 1993). It has also been suggested that severe overgrazing during the late 19th century created bare areas which may have favored tree establishment in competition with grasses (Marr 1961). Although the timing and rates of these tree invasions have probably been influenced by short-term climatic variation and changes in livestock pressure, the most obvious change in environmental constraints on tree seedling survival over the past century has been fire. Prior to the present century, relatively frequent fires in grasslands and open woodlands of Ponderosa pine allowed only infrequent tree seedling establishment, and, therefore, maintained low densities of mature trees. The increase in Ponderosa pine stand-densities in the lower montane zone of Boulder County, associated with modern fire suppression, constitutes a fundamental change in habitat, with important implications for wildlife, landscape aesthetics, and especially fire hazard. The fire history data from this study clearly establish that the frequency of fire during the Native American period was relatively high in these low elevation, open Ponderosa pine woodlands. The recent, approximately 80 years of fire suppression has created a fire regime of rare fires which is a radical departure from the fire regime that maintained these open habitats in the eighteenth and nineteenth centuries.

The occurrence of fires, especially widespread fires, in the montane zone is associated with particular climatic conditions as demonstrated by Superposed Epoch Analysis of spring and annual precipitation reconstructed from tree rings for the period 1549 to 1987. Drought during the fire year and one year prior to the fire year is increasingly severe over the range of fire events from the occurrence of 1 or more fire scars at any site to years in which large percentages of trees were scarred at disjunct sites. Similarly, the association of above-average precipitation two to three years prior to the fire year is stronger for years of more widespread fire. Above-average precipitation is believed to promote fire by enhancing the growth of herbaceous plants which increases the quantity of fine fuels during the subsequent dry years. The occurrence of pre-historic fires at large percentages of the sample sites scattered throughout Boulder County during a single year (e.g. Figs. 8-16) is without precedent during the twentieth century. Such widespread pre-historic fire occurrence during years that are climatically predisposed to fire clearly establishes the severity of the fire hazard in the montane zone of Boulder County. Evidence of such extensive burning in single years is strong support for current fire hazard mitigation efforts.

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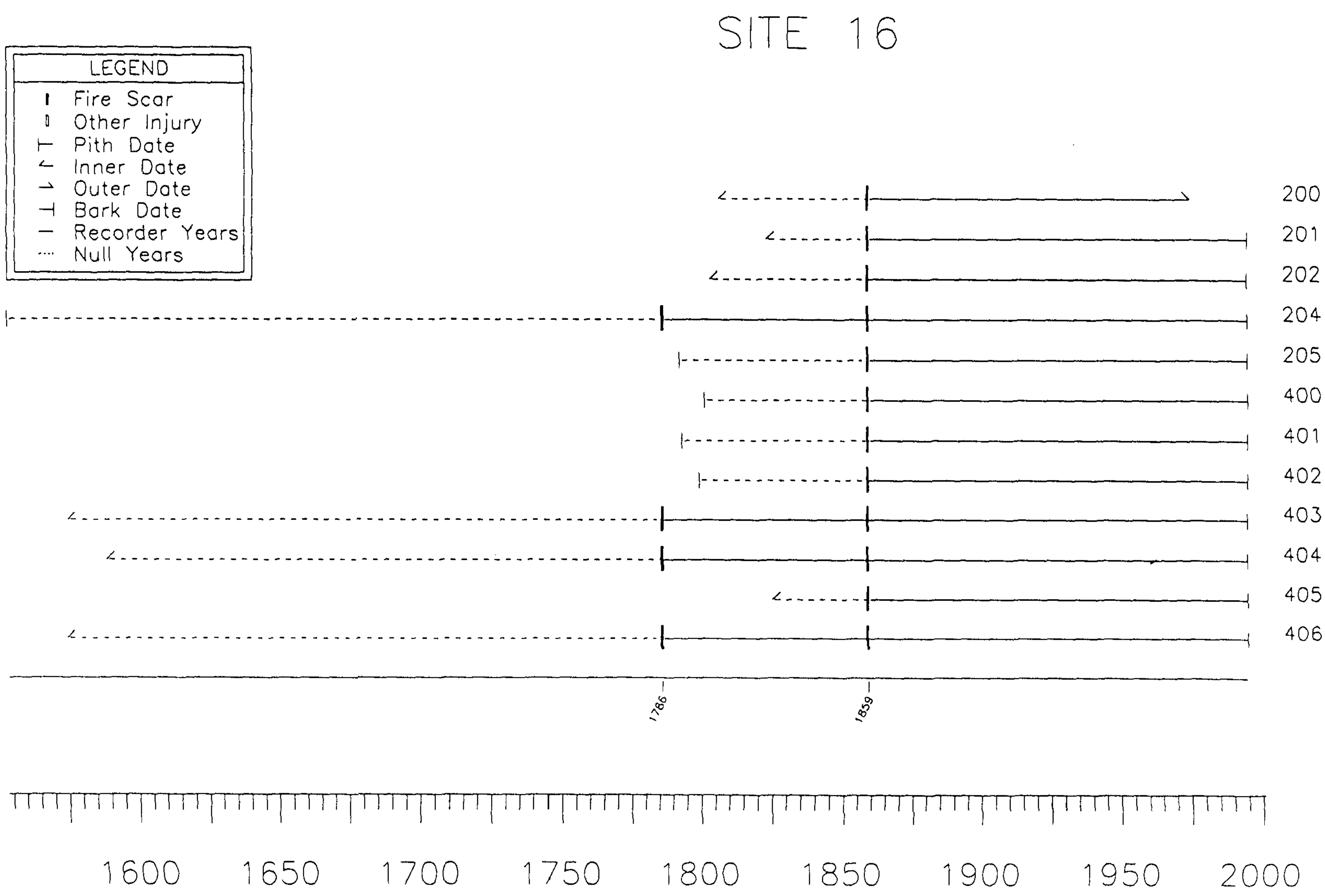


SITE 16
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
200
201
202
204
205
400
401
402
403
404
405
406
1786
1859
1600
1650
1700
1750
1800
1850
1900
1950
2000

Table 1. Summary information on sample sites and on fire scars over the full record for each site. For site location see Fig. 1.

Site No.	Elevation m	Dominant Tree Species*	No. of Sample Trees	No. Fire Years	Earliest Fire	Latest Fire
1	2371-2493	Pp	11	7	1654	1976
2	2377-2524	Pp	20	9	1859	1977
3	2414-2536	Pp, Pm, Pc	6	4	1786	1900
4	2646-2771	Pp, Pm, Pf	13	14	1552	1915
5	2377-2502	Pp	11	3	1624	1859
6	2573-2658	Pp	11	6	1474	1859
7	2597-2679	Pp, Pc	3	2	1863	1893
8	1926-1975	Pp, Pm	7	8	1513	1866
9	1951-2073	Pm, Pp	13	11	1567	1925
10	2048-2292	Pp	7	6	1667	1867
11	2146-2207	Pp, Pm	10	5	1684	1902
12	2036-2280	Pp, Pm	29	9	1707	1930
13	2121-2256	Pp	10	9	1597	1921
14	1853-1914	Pp	18	14	1763	1915
15	1847-1999	Pp	37	30	1679	1916
16	2414-2621	Pp	12	2	1786	1859
17	2484-2585	Pp	9	5	1595	1885
18	2414-2554	Pp	21	7	1601	1880
19	2566-2682	Pp	11	5	1541	1859
20	2463-2505	Pp, Pm	11	5	1584	1859
21	2195-2475	Pp	14	6	1685	1900
22	2182-2374	Pp	11	5	1709	1922
23	2060-2170	Pp	12	7	1723	1896
24	2003-1926	Pp	10	6	1630	1880
25	2341-2597	Pp	15	5	1709	1925
26	2243-2487	Pp	16	7	1813	1925
27	2225-2515	Pp	7	4	1696	1871
28	2073-2097	Pp	4	5	1595	1846
29	2079-2091	Pp	3	1	1877	1877
30	2316-2438	Pp	4	1	1859	1859
31	1829-1945	Pp	12	22	1791	1956
32	2036-2059	Pp	7	18	1634	1913
33	2463-2536	Pp, Pc	16	22	1785	1986
34	2560-2682	Pp	20	21	1820	1972
35	2627-2713	Pp, Pc	27	23	1833	1983
36	2676-2743	Pp, Pc	19	28	1656	1953
37	2451-2524	Pc, Pp, Pt	10	8	1849	1886
38	2612-2647	Pc, Pp, Pt	14	15	1802	1982
39	2609-2676	Pp, Pm	8	11	1693	1980
40	2515-2583	Pc, Pp, Pt	12	11	1904	1982
41	2743-2792	Pp, Pc, Pm	15	10	1754	1884

* Species codes: Pc, *Pinus contorta*; Pf, *Pinus flexilis*; Pm, *Pseudotsuga menziesii*; Pp, *Pinus ponderosa*; Pt, *Populus tremuloides*

Table 2. Summary information on groups of sample sites and on fire scars over the full record for each group.

Group Name (code)	Sites Included	No. of Samples (trees)	No. of Fire Years	Earliest Fire	Latest Fire
1. Lower South Boulder Creek (Losobo)	14, 15	55	35	1703	1916
2. Middle South Boulder Creek (Midsob)	3, 12, 13, 38, 40	71	42	1597	1982
3. Lower Middle Boulder Creek (Lomidb)	1, 2, 11, 31, 37, 39	76	60	1684	1951
4. Fourmile Canyon (Fourmi)	4, 35, 36	59	58	1809	1978
5. Upper Left Hand Canyon (Uplh)	5-7, 33 34, 41	77	50	1624	1897
6. James Creek (Jamsal)	8-10, 16, 30	43	20	1786	1868
7. South St. Vrain Creek (Sosv)	17-24, 32	98	45	1601	1880
8. North St. Vrain Creek (Norths)	25-29	45	15	1786	1925

Table 3. Comparison between fits provided by the empirical (i.e. normal distribution) and Weibull distributions to fire-interval data as measured by the Kolmogorov-Smirnov *d*-statistic. Small values of *d* indicate a better fit. Fits that are significantly different from either theoretical model are indicated by asterisks. Fire events for which the number of intervals were too few to perform the Kolmogorov-Smirnov test are indicated by n.d.

	Type of Fire Event					
Group	All Scarred		≥ 2 Scarred		≥ 25% Scarred	
	Empirical	Weibull	Empirical	Weibull	Empirical	Weibull
Losobo	0.531*	0.086	0.321*	0.156	0.443	0.184
Midsob	0.647*	0.182	0.440*	0.181	0.326	0.260
Lomidb	0.822*	0.221*	0.622*	0.110	0.333	0.204
Fourmi	0.538*	0.183	0.537*	0.332	n.d.	n.d.
Uplh	0.717*	0.276*	0.771*	0.258	0.333	0.285
Jamsal	0.263	0.113	0.454	0.302	0.461	0.221
Sosv	0.542*	0.168	0.274	0.144	0.458	0.200
Norths	0.495*	0.260	0.259	0.220	n.d.	n.d.

Table 4. Fire interval statistics over the period of reliability (i.e. cumulative of ≥ 3 scars) for each group of sample sites for years in which ≥ 2 samples recorded fire in the same group.

Group (period)	Intervals (yrs) Mean	Median	WMPI[1]	Min-Max	95 EI[2]	5 EI[3]	WFFP[4]	S.D.[5]	C.V.[6]	Shape[7]
Losobo (1703-1995)	11.2	9.0	9.5	1-29	1.5	26.3	0.11	8.4	0.8	1.43
Midsob (1654-1995)	23.4	9.5	11.1	1-73	0.4	76.3	0.09	28.3	1.2	0.76
Lomidb (1684-1995)	19.0	10.5	11.4	1-102	0.8	52.1	0.09	26.6	1.4	0.96
Fourmi (1581-1995)	16.9	2.5	6.5	1-63	0.2	51.0	0.15	23.0	1.4	0.71
Uplh (1624-1995)	19.5	3.0	5.5	1-162	0.2	36.8	0.18	44.0	2.3	0.77
Jamsal (1567-1995)	11.7	4.0	8.1	2-34	0.8	29.3	0.12	13.2	1.1	1.13
Sosv (1595-1995)	19.9	16.0	15.6	2-53	1.9	51.6	0.06	16.2	0.8	1.22
Norths (1696-1995)	19.9	23.0	16.4	3-38	2.1	51.9	0.06	14.7	0.7	1.27

[1] WMPI is the Weibull median probability interval.
[2] 95 EI is the Weibull-derived interval exceeded by 95% of all other intervals.
[3] 5 EI is the Weibull-derived interval exceeded by 5% of all other intervals.
[4] WFFP is the Weibull-derived fire frequency probability (i.e. the probability of fire occurring in any given year).
[5] S.D. is the standard deviation of the mean fire interval.
[6] C.V. is the coefficient of variation of the mean fire interval.
[7] Shape is the Weibull shape parameter *c*.

Table 5. Fire interval statistics over the period of reliability for each group of sample sites for years in which ≥ 25% of samples (with a minimum of 2 samples) were scarred in the same group. Groups not included had fewer than 3 fire events.

Group (period)	Intervals (yrs) Mean	Median	WMPI[1]	Min-Max	95 EI[2]	5 EI[3]	WFFP[4]	S.D.[5]	C.V.[6]	Shape[7]
Losobo (1703-1995)	23.7	23.0	21.5	7-65	5.5	46.5	0.05	17.4	0.73	1.90
Midsob (1654-1995)	41.2	53.0	28.0	1-73	0.7	218.1	0.04	31.1	0.76	0.71
Lomidb (1684-1995)	58.3	56.0	53.4	17-102	8.4	151.2	0.02	42.5	0.73	1.41
Uplh (1624-1995)	78.7	73.0	35.7	1-162	0.1	811.1	0.03	80.6	1.03	0.47
Jamsal (1567-1995)	24.3	27.0	24.3	12-34	8.0	45.5	0.04	11.2	0.46	2.35
Sosv (1595-1995)	51.6	37.0	32.5	4-155	1.7	170.5	0.03	61.2	1.2	0.88

[1] WMPI is the Weibull median probability interval.
[2] 95 EI is the Weibull-derived interval exceeded by 95% of all other intervals.
[3] 5 EI is the Weibull-derived interval exceeded by 5% of all other intervals.
[4] WFFP is the Weibull-derived fire frequency probability (i.e. the probability of fire occurring in any given year).
[5] S.D. is the standard deviation of the mean fire interval.
[6] C.V. is the coefficient of variation of the mean fire interval.
[7] Shape is the Weibull shape parameter *c*.

Table 6. Maximum fire intervals for different fire events in each of the eight groups of combined sites. In this table only the date of sampling (1995) is regarded as closing a fire interval. Events with ≤ 2 intervals are indicated by n.d.

Group (period)	Types of Fire Event		
	All fires	≥ 2 Scars	≥ 25% Scarred with Minimum of 2 Scars
Losobo (1703-1995)	1916-1995	1916-1995	1916-1995
Midsob (1654-1995)	1654-1707	1786-1859	1860-1995
Lomidb (1684-1995)	1684-1786	1684-1786	1859-1995
Fourmi (1581-1995)	1772-1809	1915-1978	n.d.
Uplh (1624-1995)	1654-1754	1624-1786	1624-1786
Jamsal (1567-1995)	1925-1995	1868-1995	1859-1995
Sosv (1595-1995)	1913-1995	1880-1995	1654-1809
Norths (1696-1995)	1786-1809	1925-1995	1871-1995

Table 7. Weibull median probability intervals (yrs) for years with ≥ 2 scars in a group according to time periods. The full Native American period starts when ≥ 3 trees are scarred in the same group. The recent Native American period is the same length as the Euro-American settlement period. Periods with ≤ 3 fire events are indicated by n.d.

	Time Periods			
Group	Full Native American (pre-1850)	Recent Native American (1781-1850)	Euro-American Settlement (1851-1920)	Fire Suppression (1921-1995)
Losobo	14.4	15.7	6.0	n.d.
Midsob	42.6	n.d.	3.9	n.d.
Lomidb	45.1	n.d.	5.3	n.d.
Fourmi	n.d.	n.d.	3.8	n.d.
Uplh	23	n.d.	2.5	n.d.
Jamsal	n.d.	n.d.	3.1	n.d.
Sosv	20.9	11.9	9.5	n.d.
Norths	n.d.	n.d.	5.4	n.d.

Table 8. Seasonality of fires for the eight groups of sampled sites.

Group	No. of Fire Scars	Percent with Season Determined	Percent by Season				
			Dormant	Early Earlywood	Middle Earlywood	Late Earlywood	Latewood
Losobo	154	61.0	19.1	29.8	4.3	4.3	42.6
Midsob	129	58.9	31.6	36.8	11.8	1.3	18.4
Lomidb	120	58.3	11.4	28.6	18.6	2.9	38.6
Fourmi	97	51.5	16.0	22.0	28.0	6.0	28.0
Uplh	125	48.8	0.0	62.3	18.0	1.6	18.0
Jamsal	65	60.0	56.4	17.9	15.4	2.6	7.7
Sosv	166	60.2	22.0	20.0	12.0	11.0	35.0
Norths	62	62.9	12.8	28.8	15.4	5.1	38.5

Dormant Sept - March
EE April, May
EM June
LE Late June/July
L July → Early August

Table 9. Deviations (%) from reconstructed mean precipitation and mean temperatures associated with years of major fire occurrence. Years are included in which ≥ 15% of the 41 sample sites recorded fire scars with a minimum of 10 sites with fire-scar susceptible trees. Locations of sites recording scars in these years are given in Figures 8 - 17.

	Year									
Years Before Fire Year	1624	1654	1709	1786	1813	1859	1860	1863	1871	1880
Spring Precipitation (March - June)										
-5	+24	-21	+4	-2	+26	+5	-26	+18	+16	-10
-4	-42	-19	+21	+1	-22	-26	-6	-12	+5	+3
-3	+43	+19	+10	+15	+5	-6	+7	+18	+22	-13
-2	-14	+18	-36	+12	-6	+7	+18	-20	+26	+24
-1	-29	-44	-16	+2	-3	+18	-12	-14	-23	-14
0	-28	-54	-40	-4	-6	-12	+18	-34	0	-59
Annual Precipitation (Aug. - July)										
-5	+28	-15	+3	-1	+18	-3	-18	-4	+11	-7
-4	+17	-13	+15	0	-15	-18	-4	+5	+3	+2
-3	-29	+13	+7	+10	+3	-4	+5	+12	+15	-9
-2	+30	+12	-25	+8	-4	+5	+12	-14	+18	+17
-1	-20	-30	-11	+2	-2	+12	-8	-10	-16	-9
0	-19	-37	-28	-2	-4	-8	+12	-24	0	-41
July Temperature										
-5	+3	0	-1	0	+3	0	0	-2	0	-2
-4	+3	-1	-2	+2	-1	0	+3	+4	0	+3
-3	+2	0	-2	+1	-3	+3	0	0	-1	+1
-2	+2	0	-4	0	-2	+0	-2	+4	+1	+2
-1	+2	-2	-1	+2	+4	-2	+4	0	+2	+2
0	+4	-1	-1	+2	+1	+4	0	+2	+4	-2

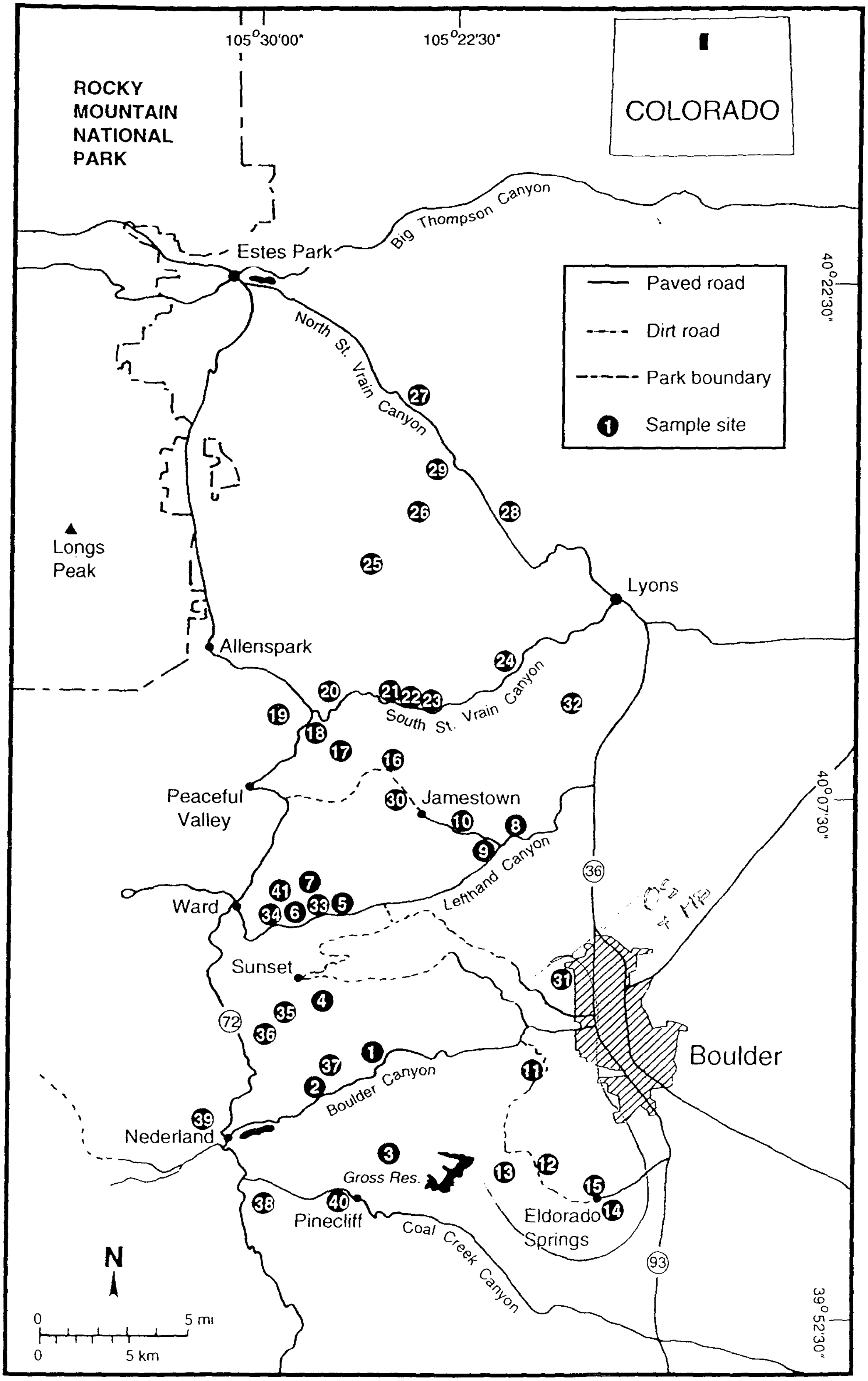
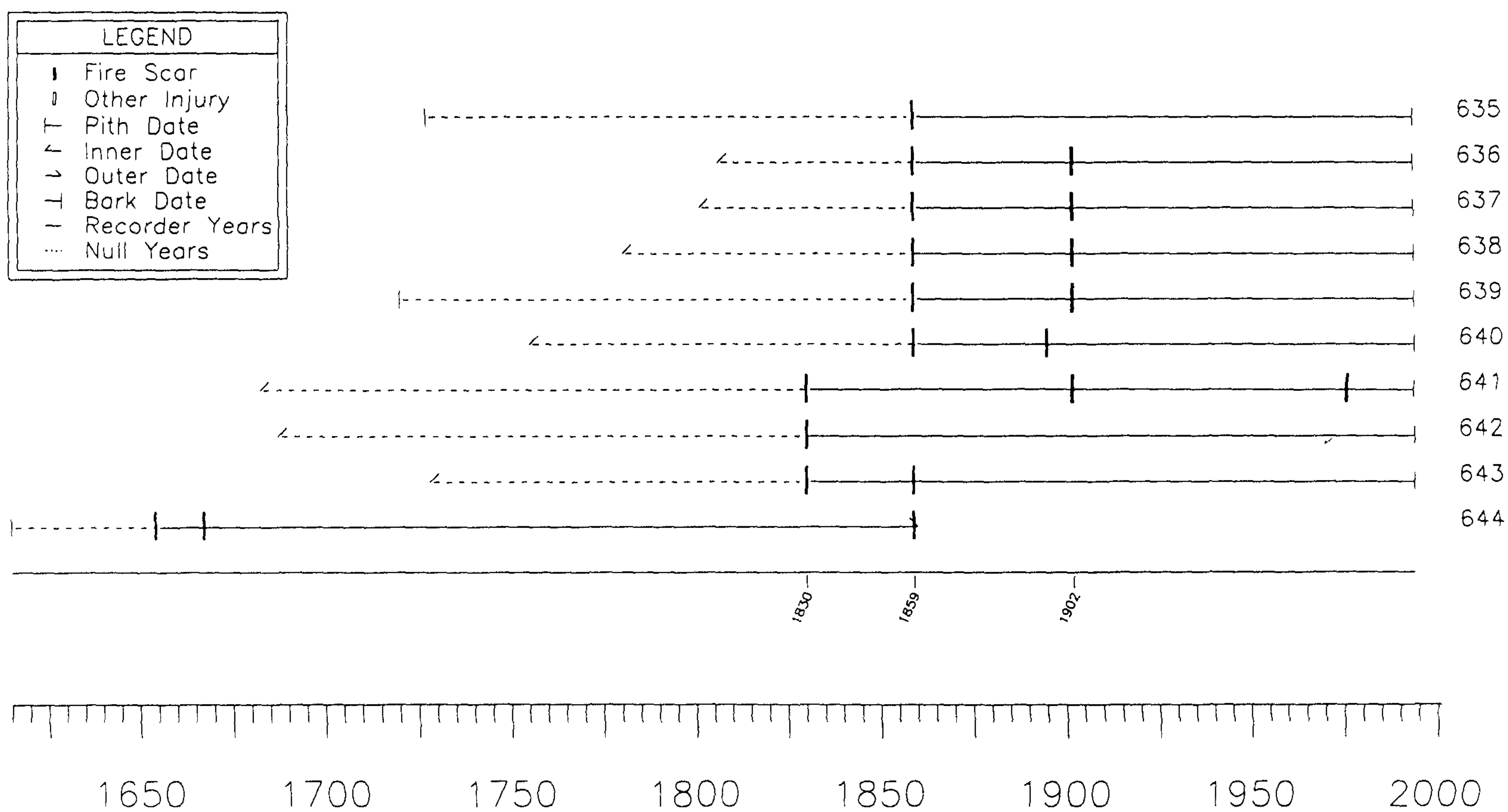


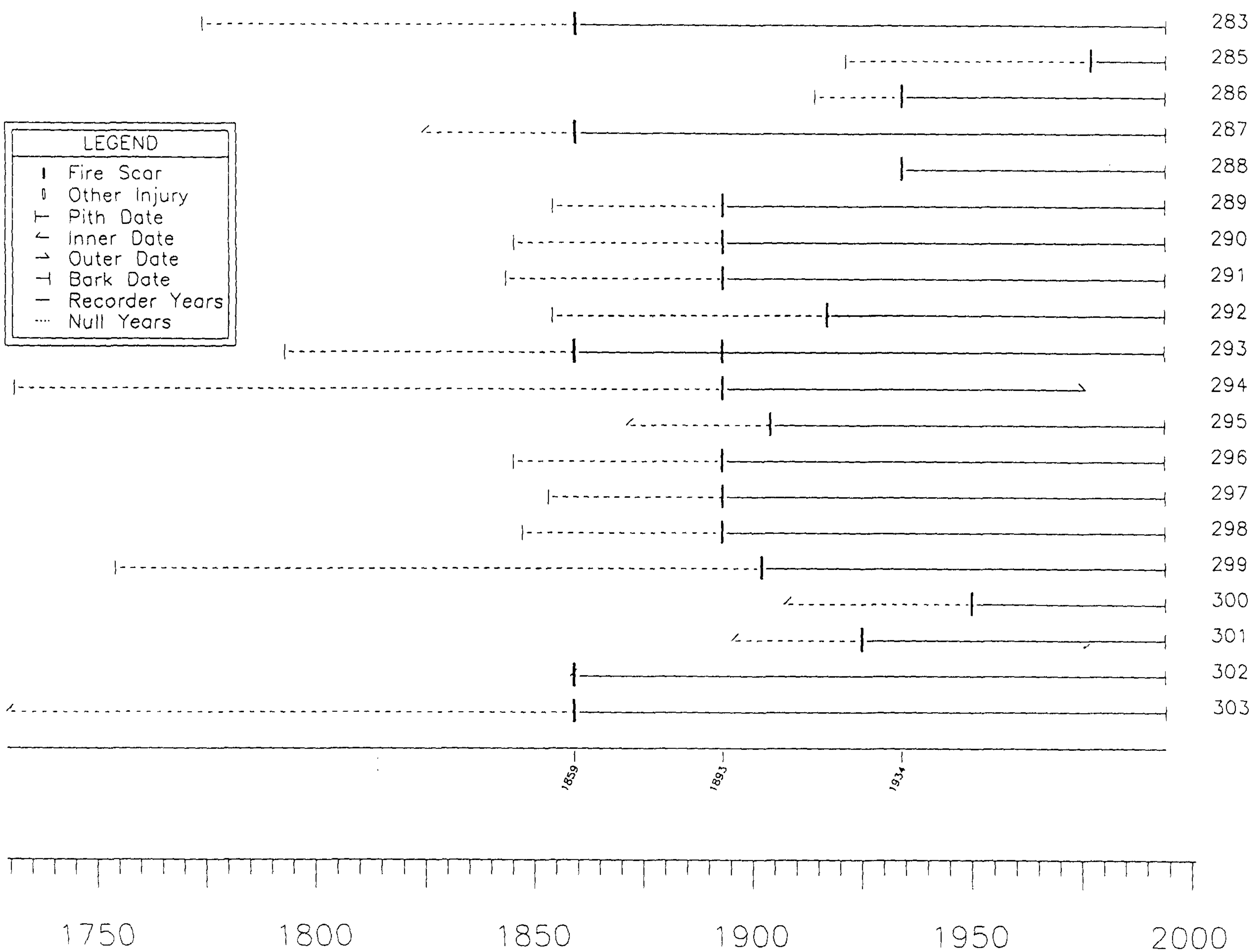
Fig. 1 Map showing locations of sites sampled for fire scars.

Fig. 2. Composite master fire charts (following 41 pages) for each of the 41 sites sampled for fire scars. Site locations are given in Figure 1 and site information in Table 1. Each numbered line represents a fire-scarred tree. Symbols in the legends indicate dates of the pith, innermost ring, outermost ring, ring adjacent to the bark, recorder years (years following the initial fire scar on a tree), and null years (years prior to the initial fire scar on a tree). Years on the composite line indicate occurrence of at least two fire scars during that year.

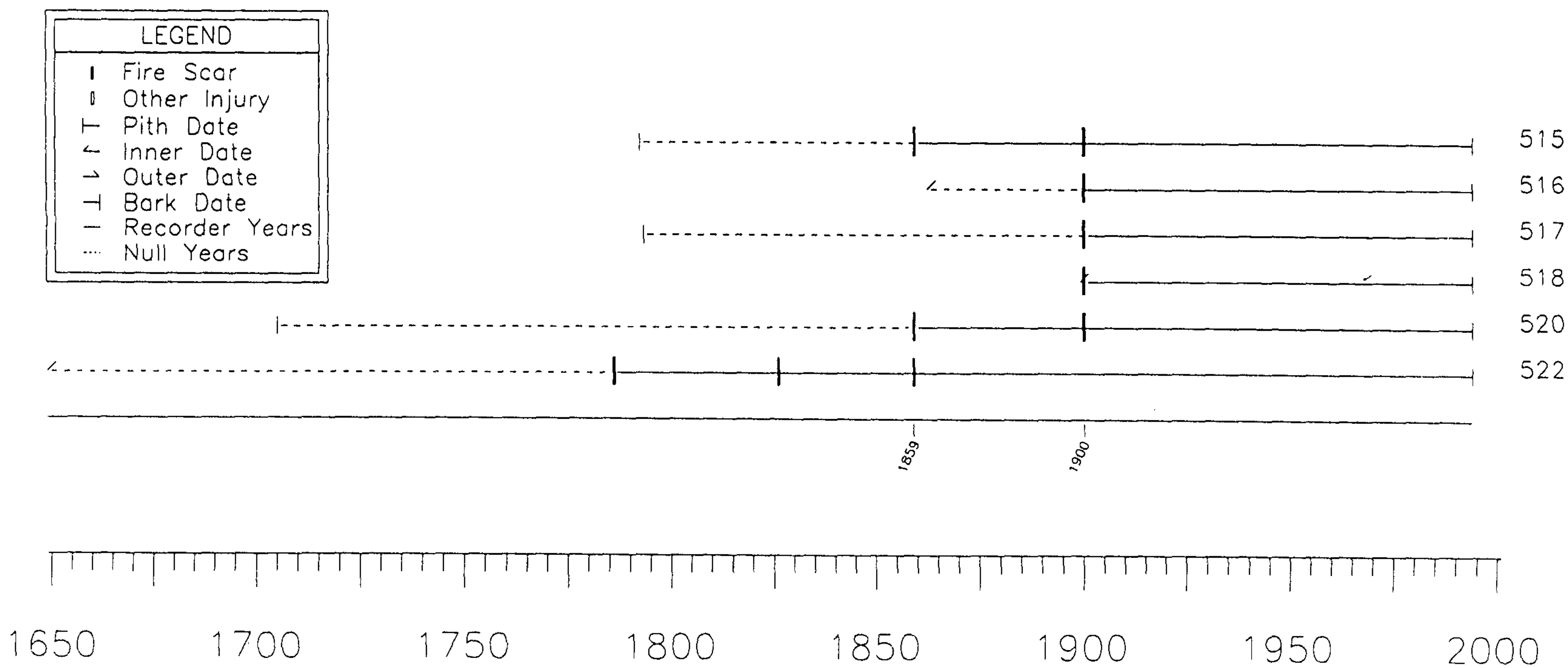
SITE 1


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
635
636
637
638
639
640
641
642
643
644
1830
1859
1902
1650
1700
1750
1800
1850
1900
1950
2000

SITE 2

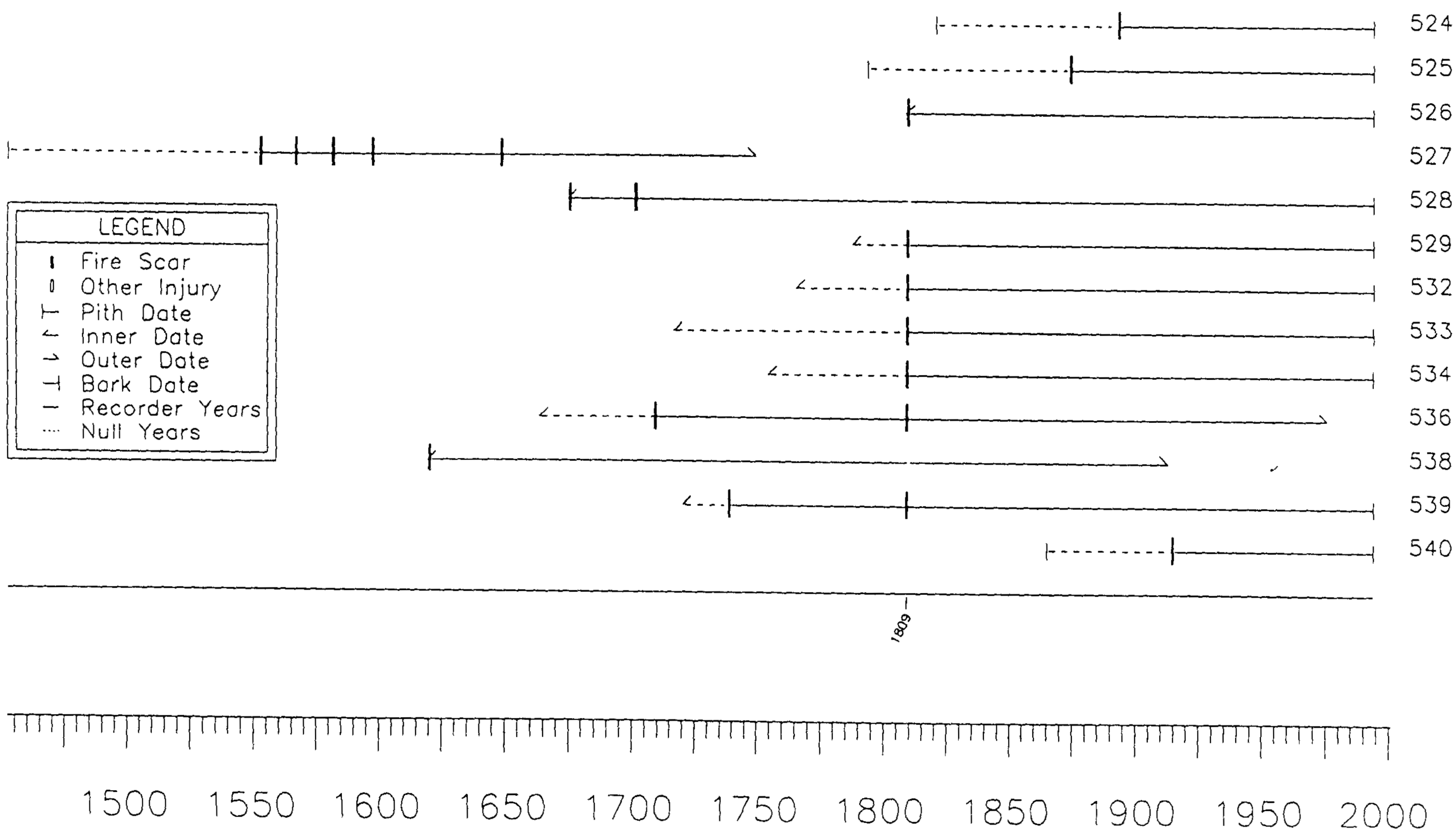

LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
283
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
1859
1893
1934
1750
1800
1850
1900
1950
2000

SITE 3



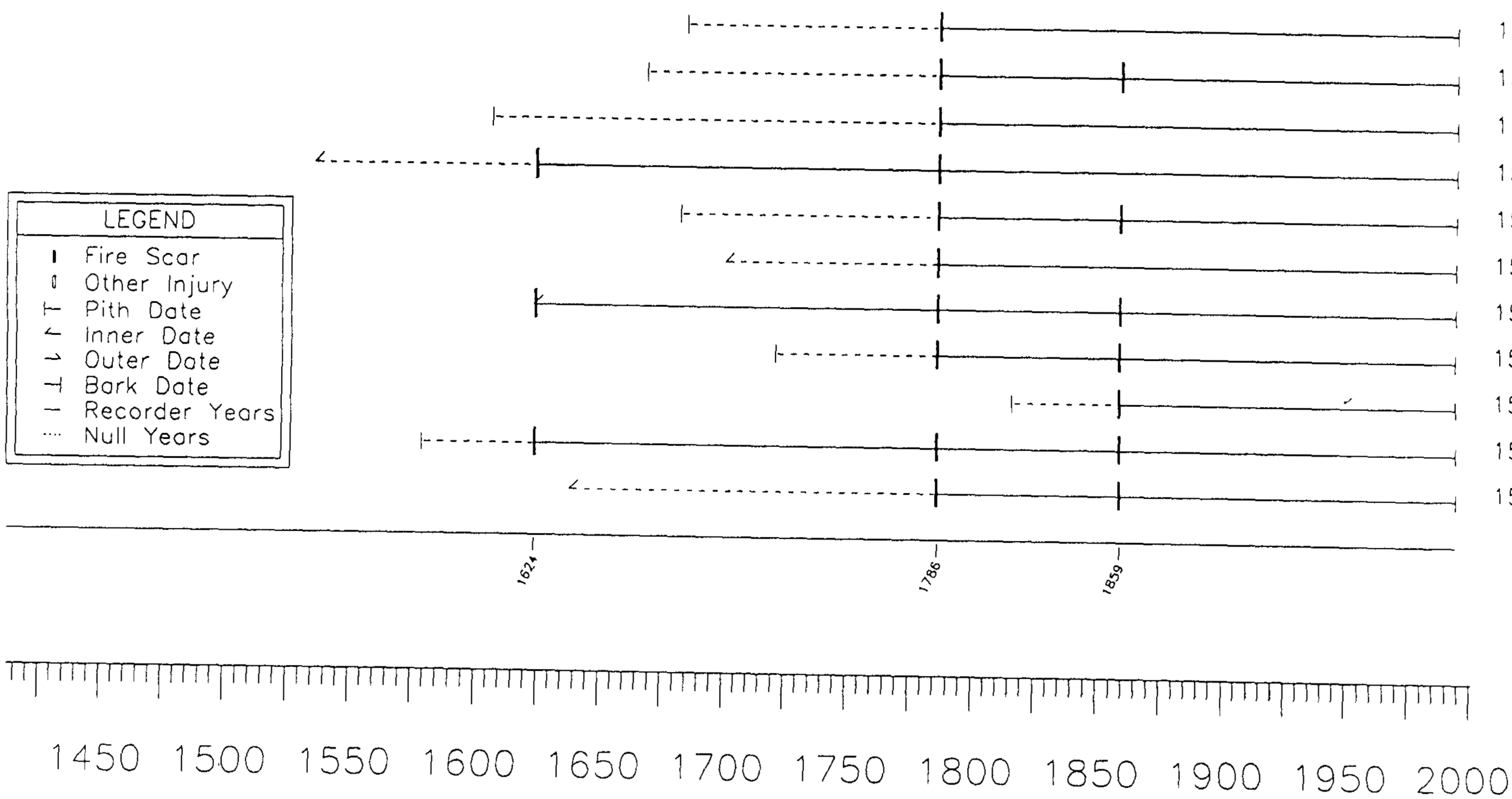
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
515
516
517
518
520
522
1859
1900
1650
1700
1750
1800
1850
1900
1950
2000

SITE 4

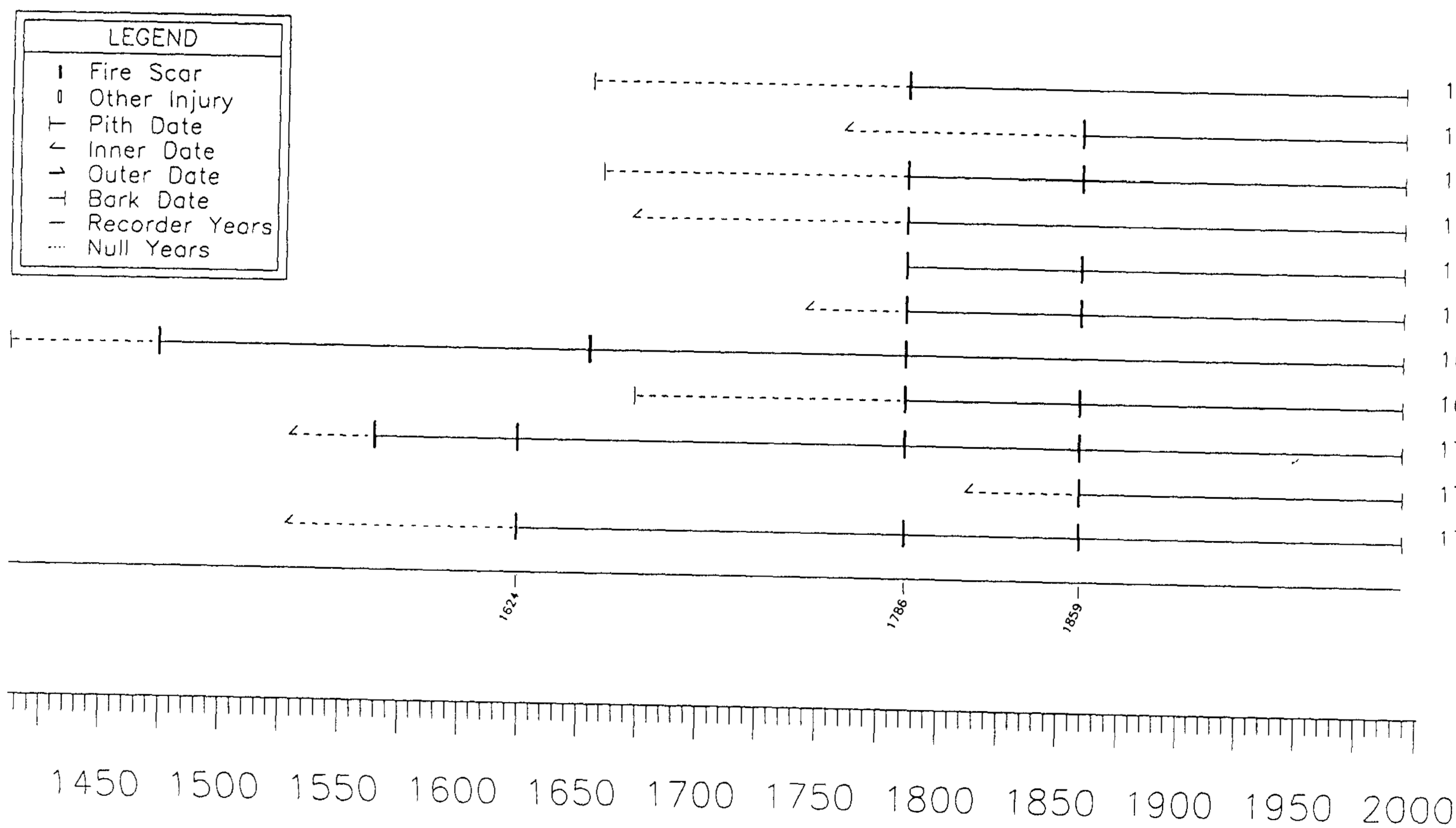


524
525
526
527
528
529
532
533
534
536
538
539
540
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1809
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

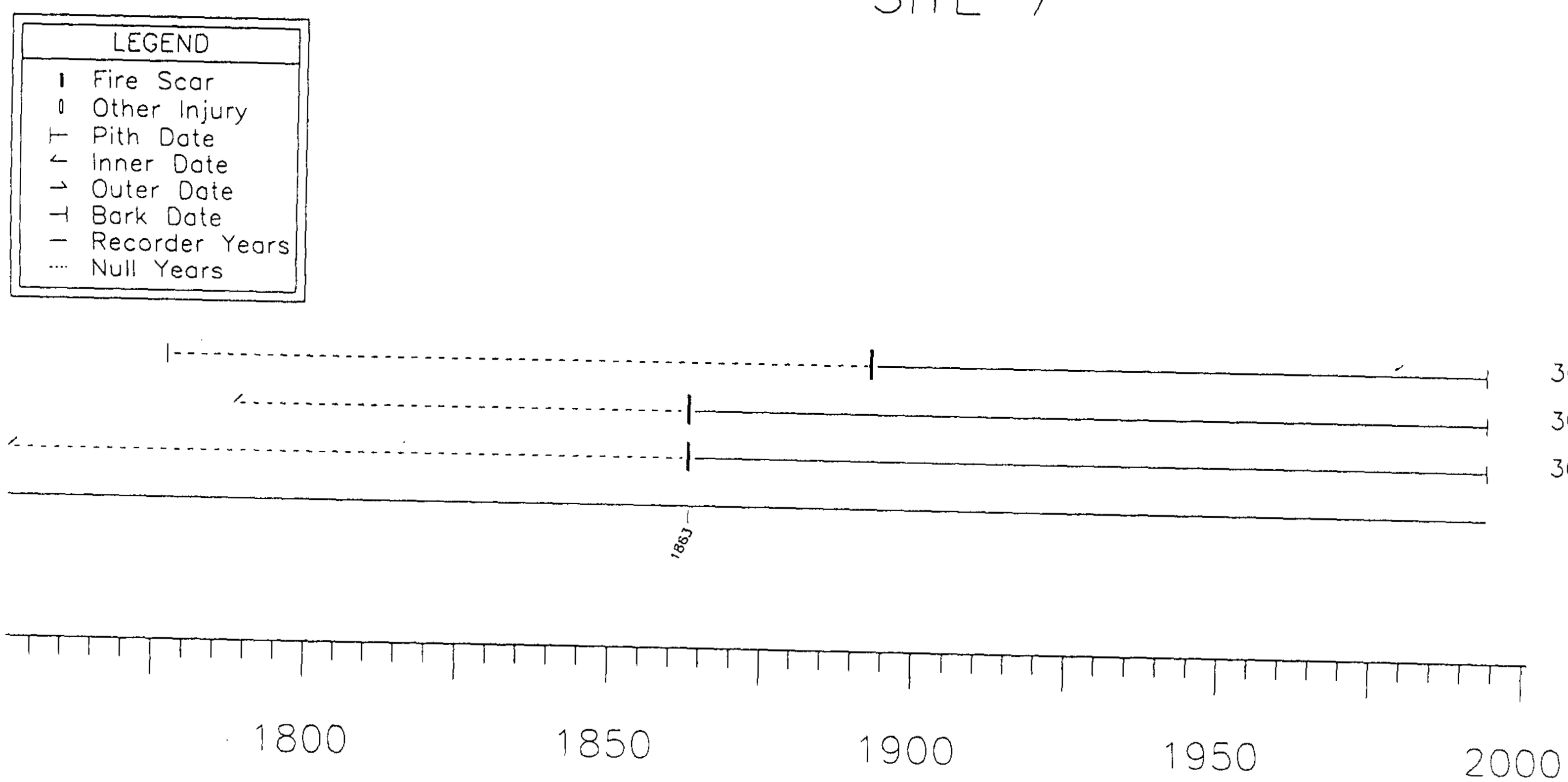
SITE 5

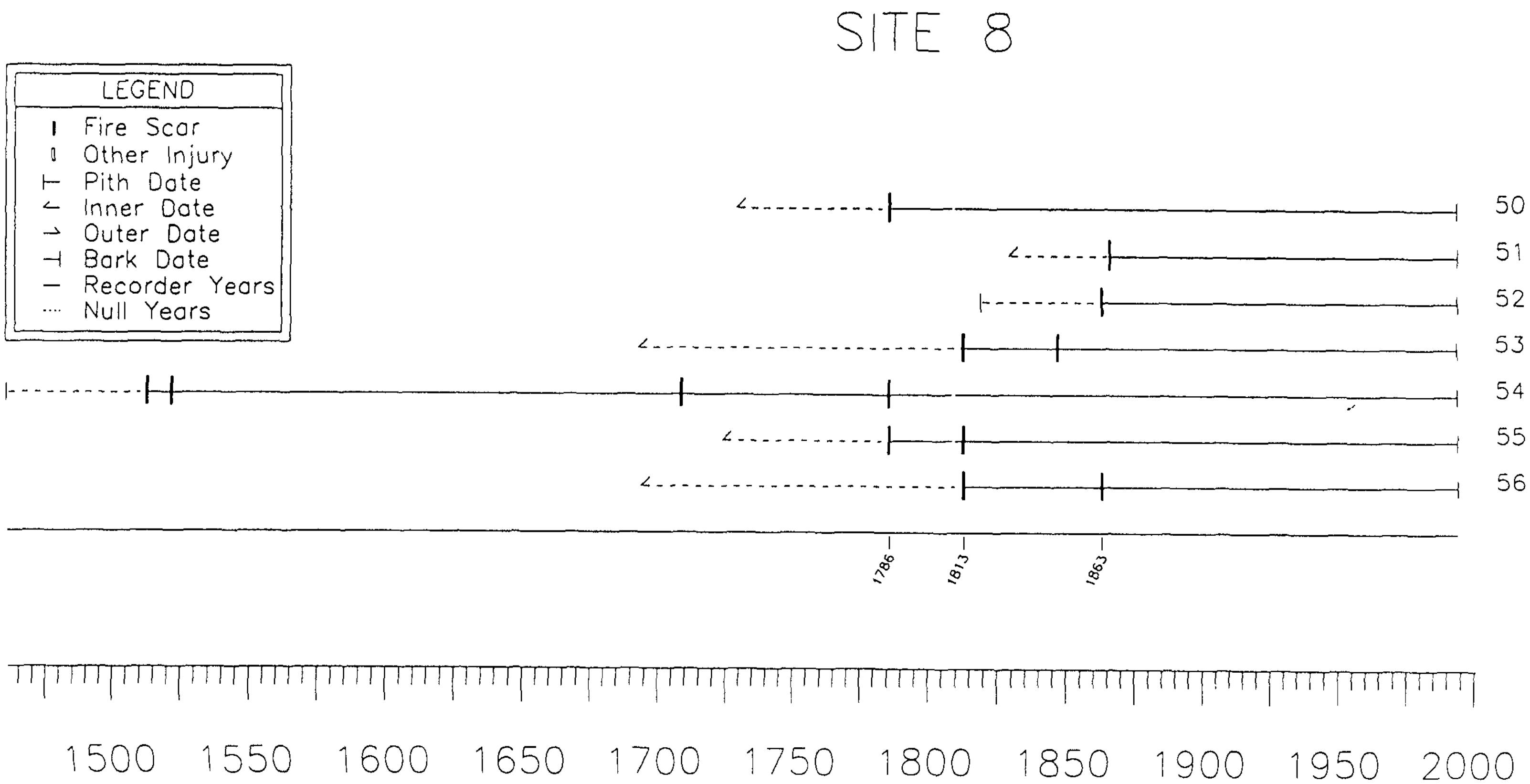

LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
149
150
151
152
153
154
155
156
157
158
159
1624
1786
1859
1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000

SITE 6

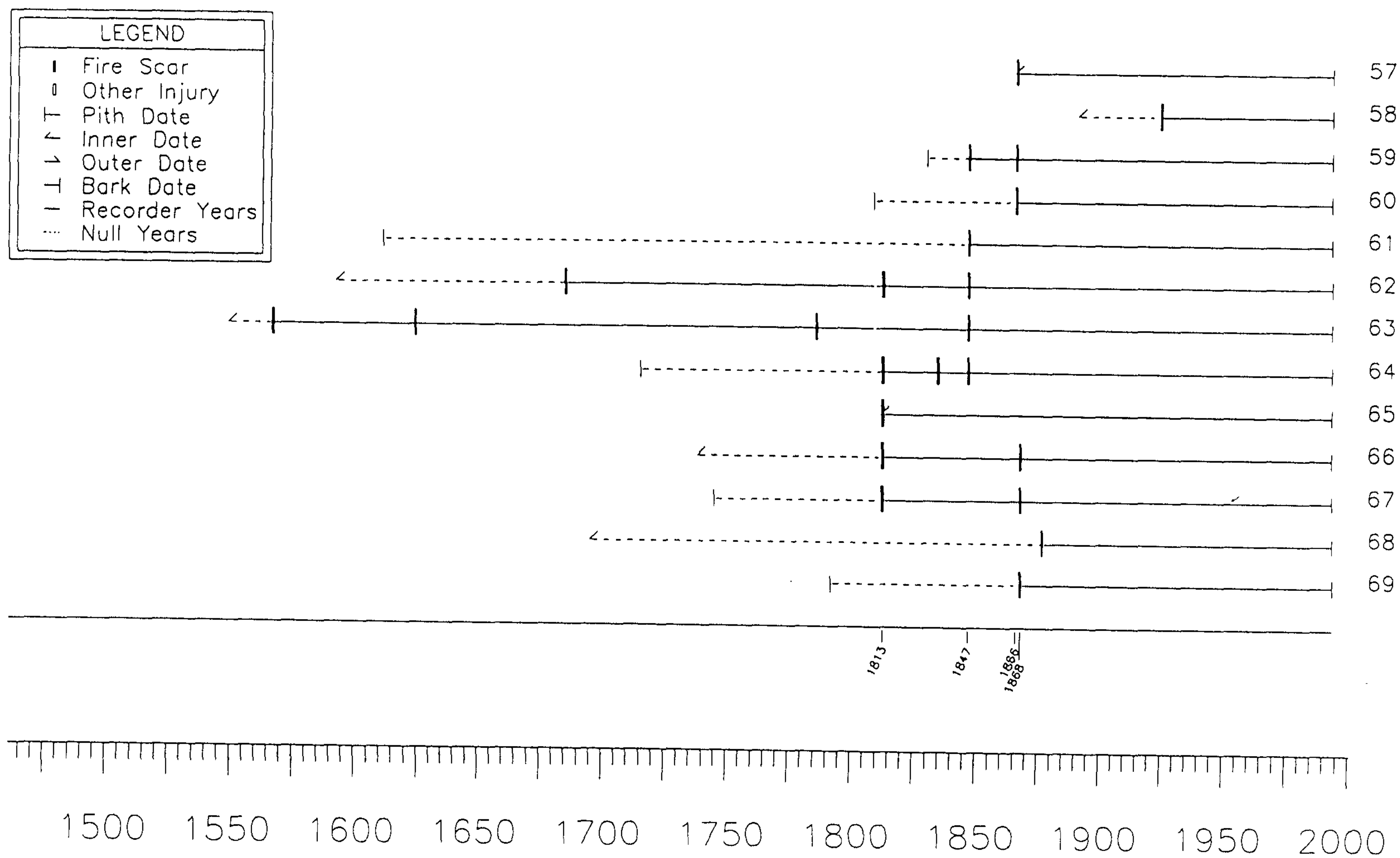

LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
162
163
164
165
166
167
168
169
170
171
172
1624
1786
1859
1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000

SITE 7


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
304
307
309
1863
1800
1850
1900
1950
2000


SITE 8
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
50
51
52
53
54
55
56
1786
1813
1863
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 9


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
57
58
59
60
61
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65
66
67
68
69
1813
1847
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1500
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1600
1650
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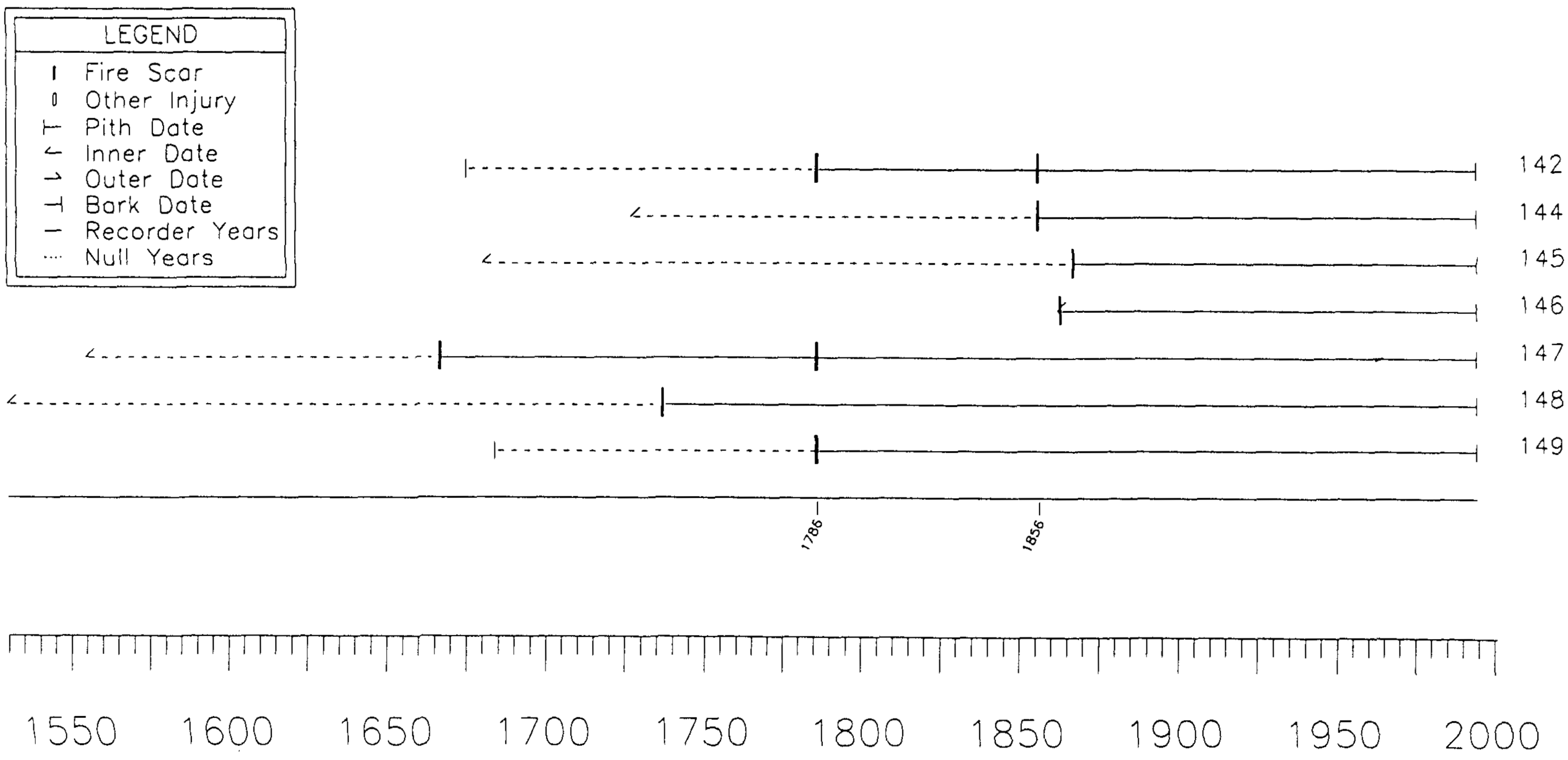
1750
1800
1850
1900
1950
2000

SITE 10


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
142
144
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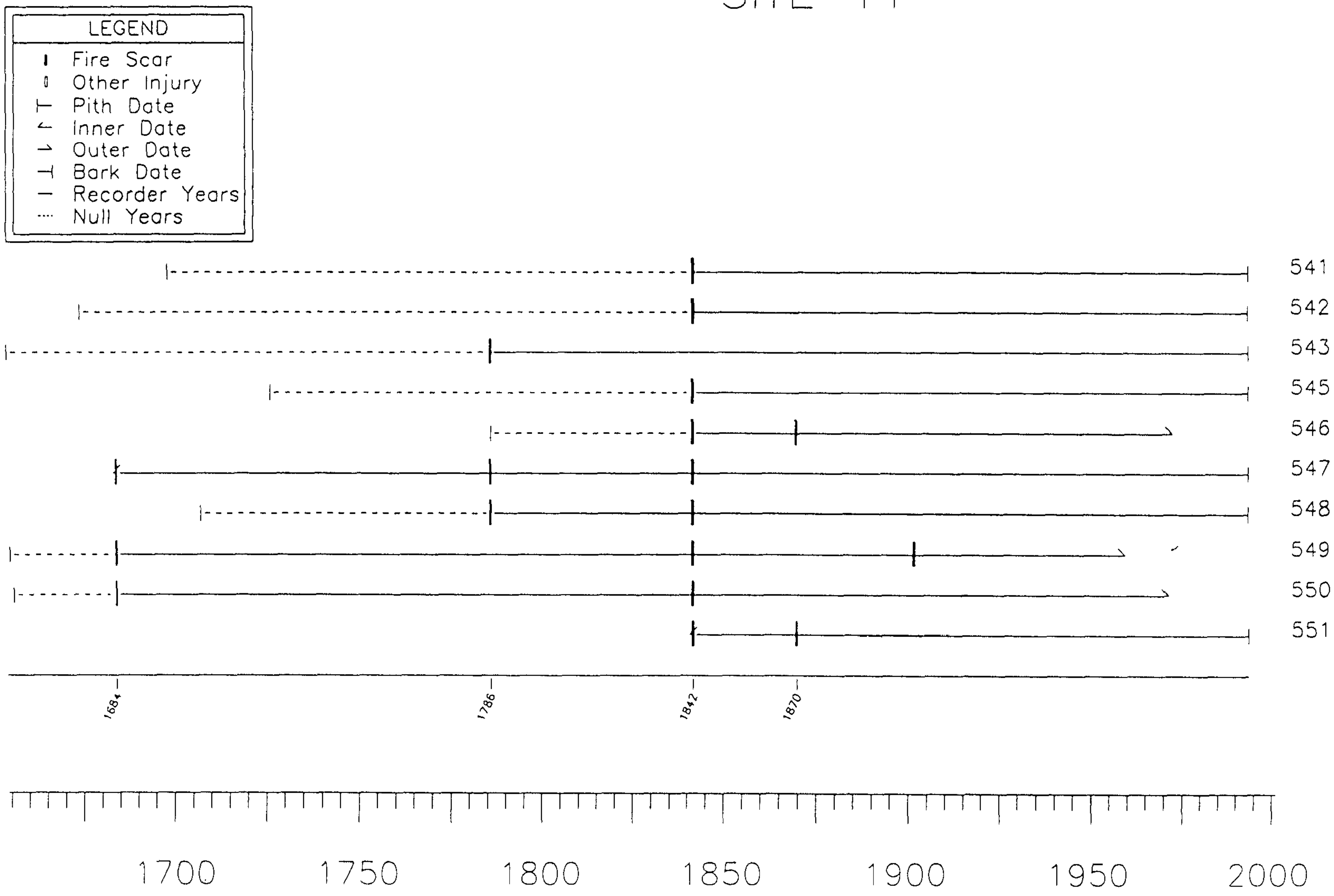
1786
1856
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 11



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
541
542
543
545
546
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551
1684
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1842
1870
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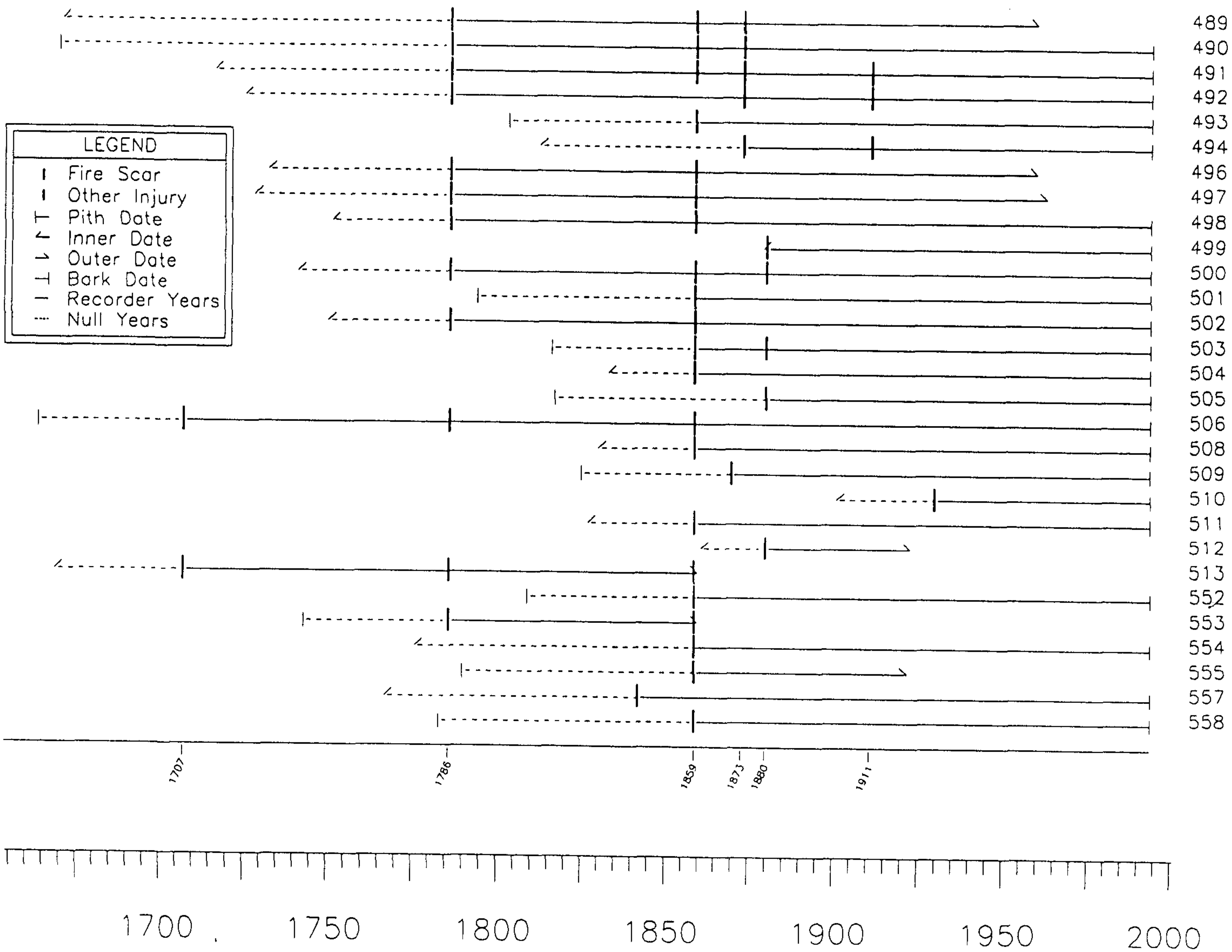
1800
1850
1900
1950
2000

SITE 12



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
489
490
491
492
493
494
496
497
498
499
500
501
502
503
504
505
506
508
509
510
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512
513
552
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1950
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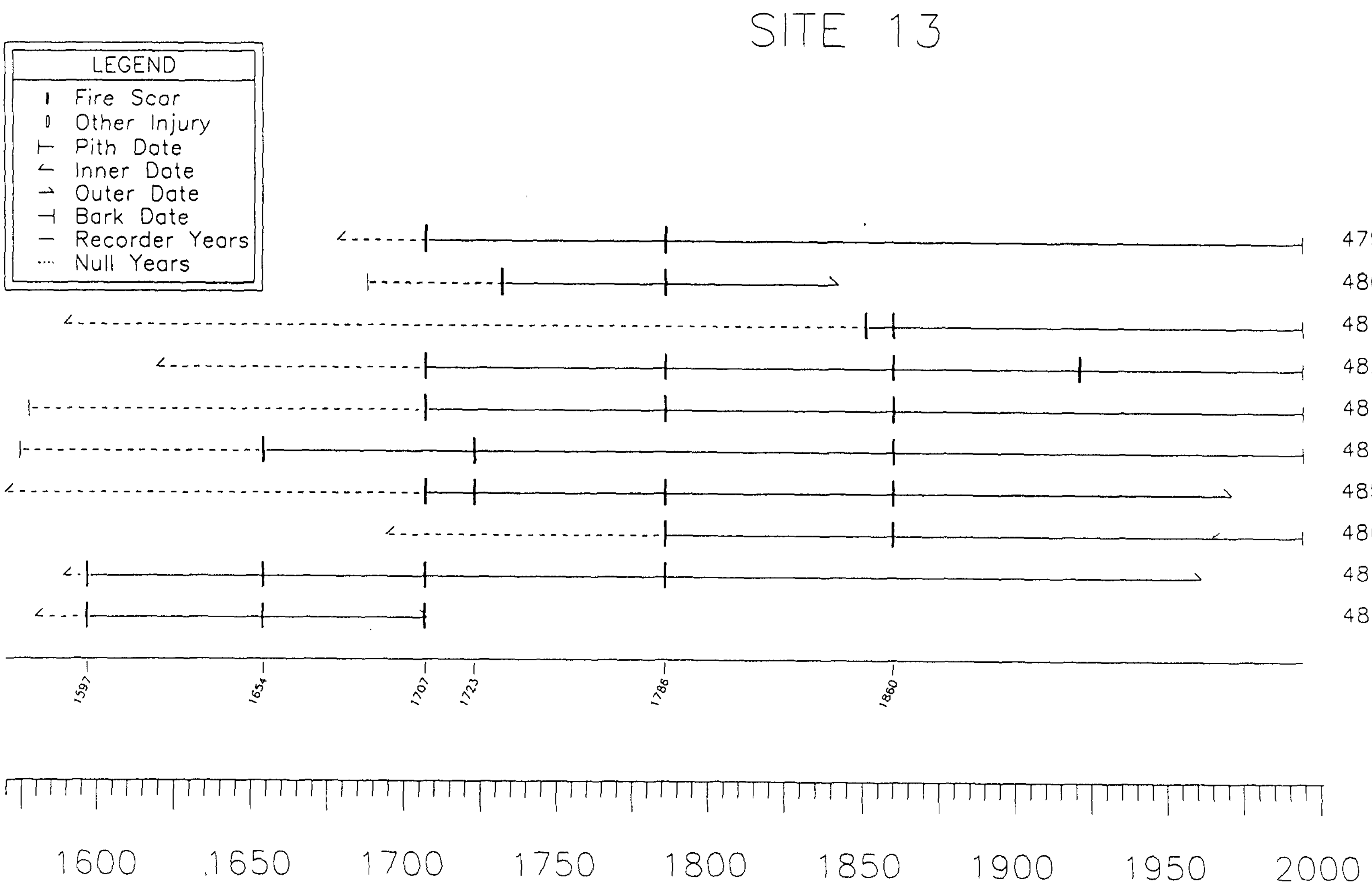

SITE 13
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
479
480
481
482
483
484
485
486
487
488
1597
1654
1707
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1786
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1600
1650
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1750
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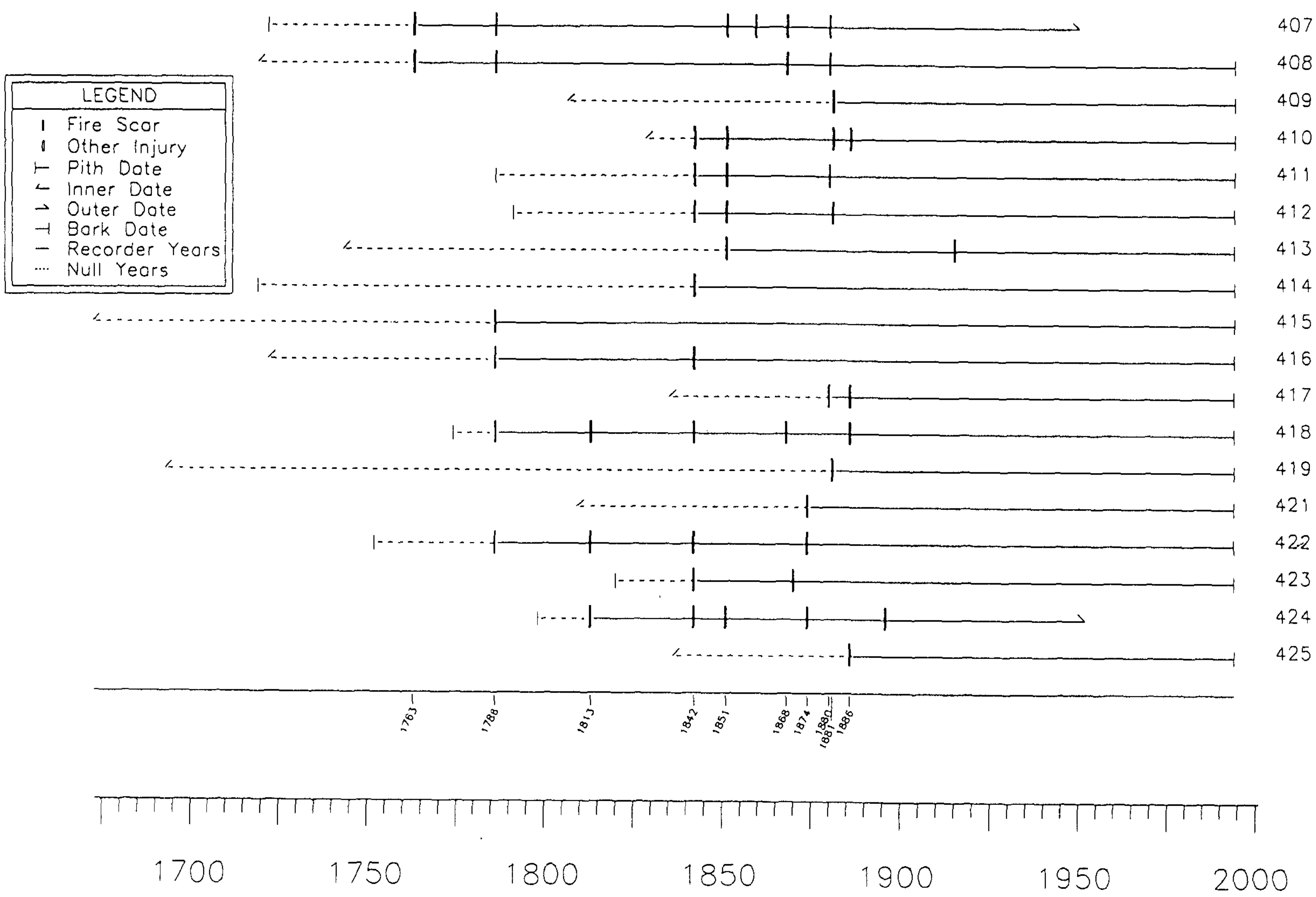
1850
1900
1950
2000

SITE 14



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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408
409
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415
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424
425
1763
1788
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1900
1950
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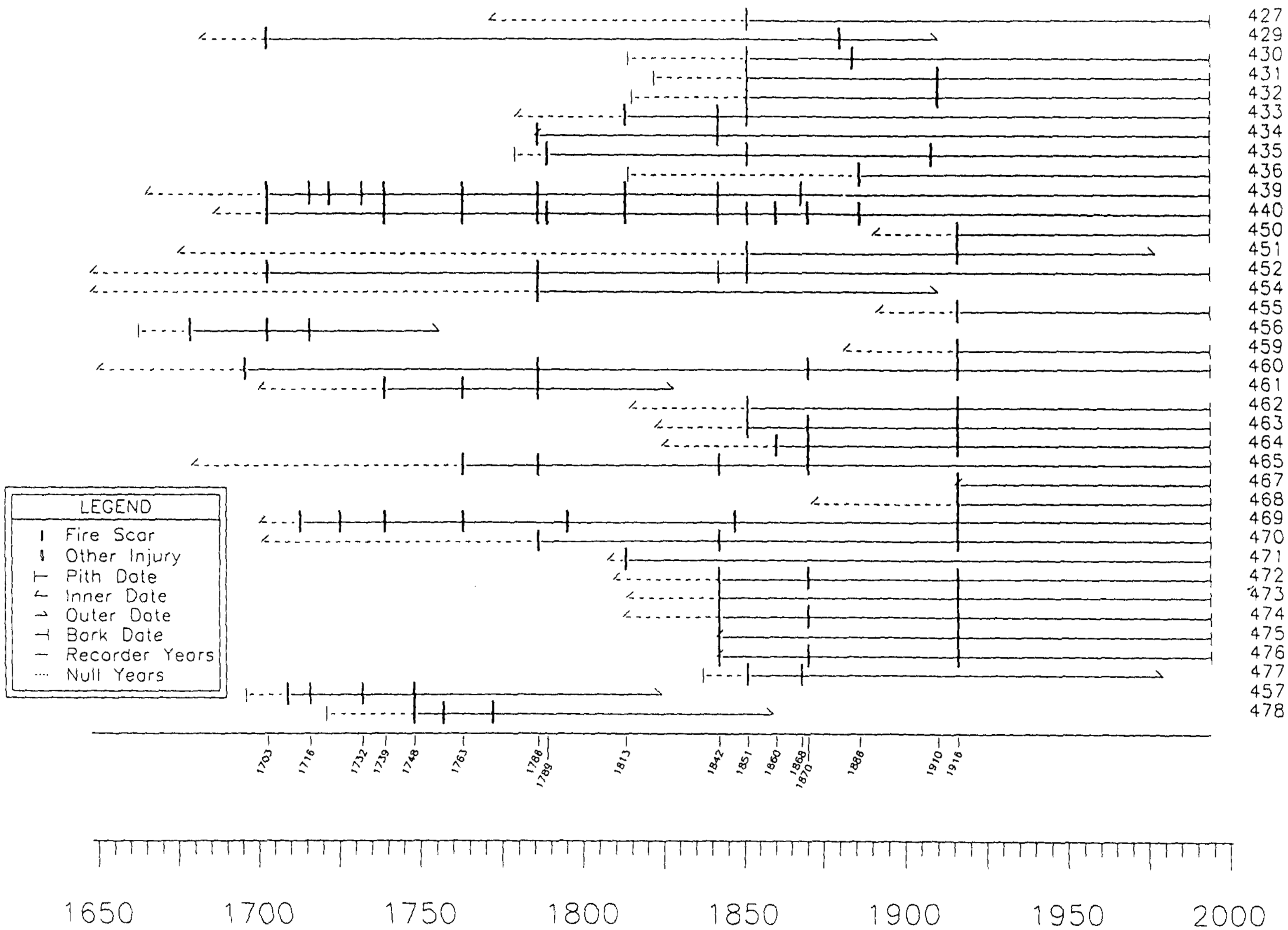
SITE 15



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462
463
464
465
467
468
469
470
471
472
473
474
475
476
477
457
478
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1703
1716
1732
1739
1748
1763
1788
1789
1813
1842
1851
1860
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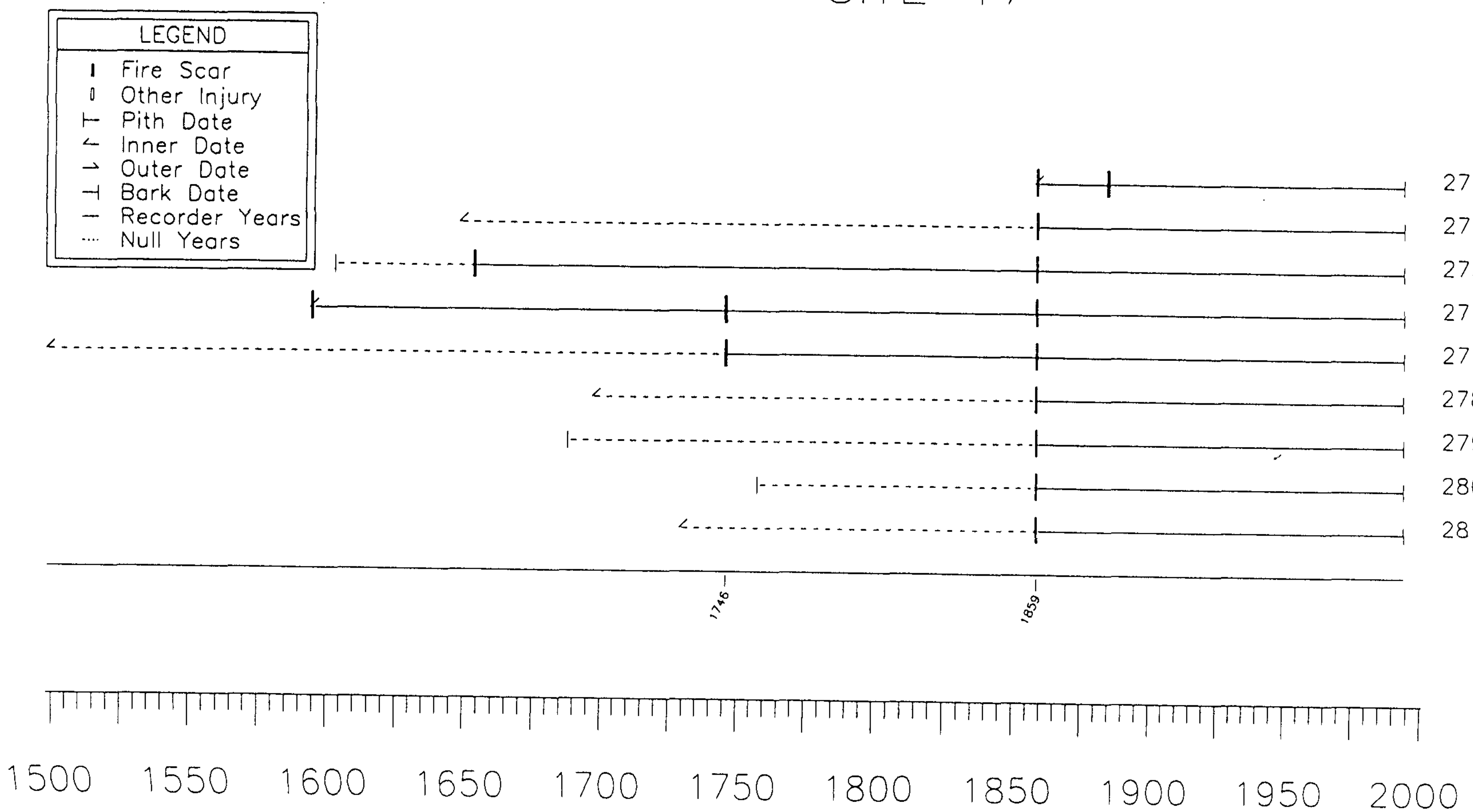
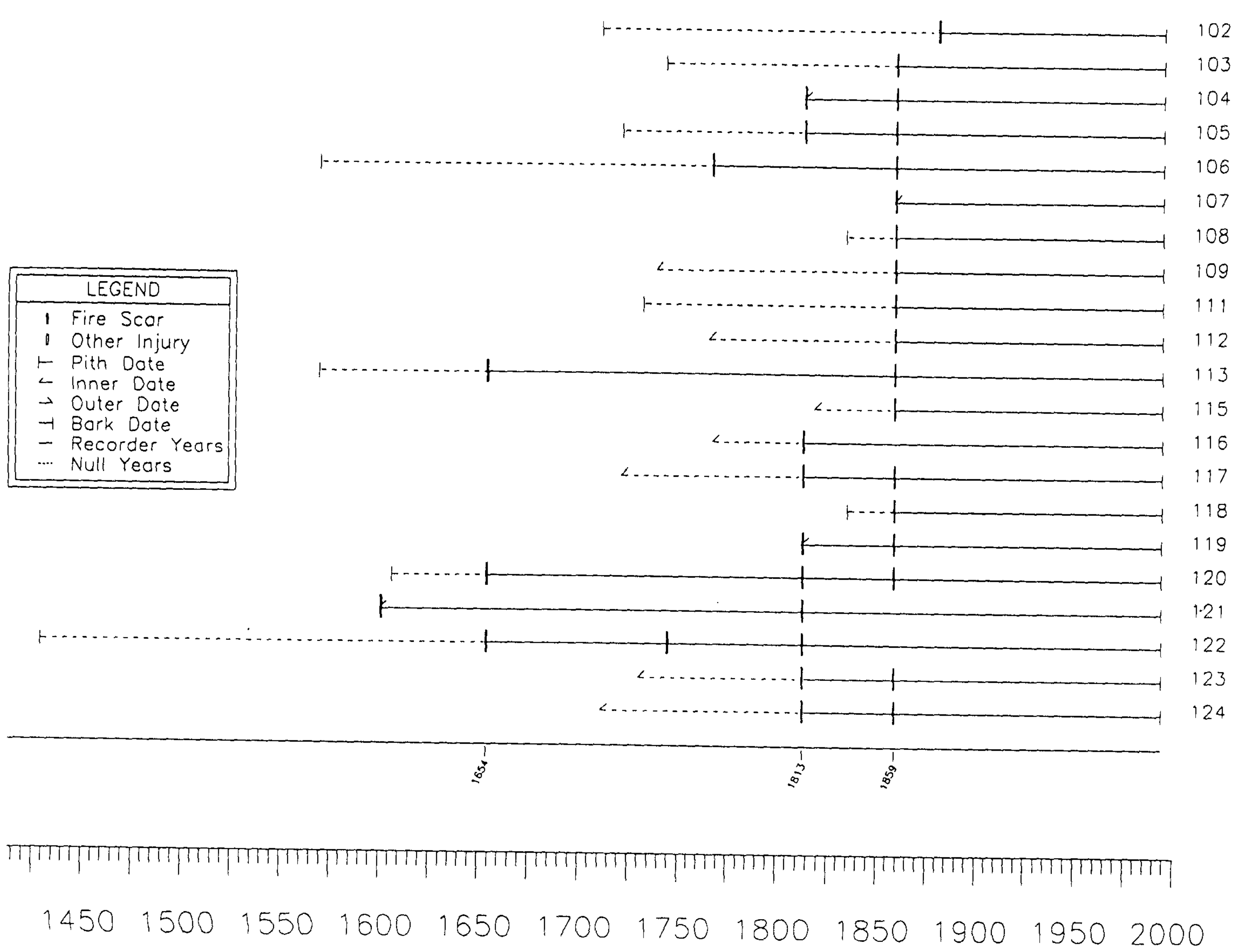
1950
2000

SITE 17



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
273
274
275
276
277
278
279
280
281
1746
1859
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 18



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
102
103
104
105
106
107
108
109
111
112
113
115
116
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120
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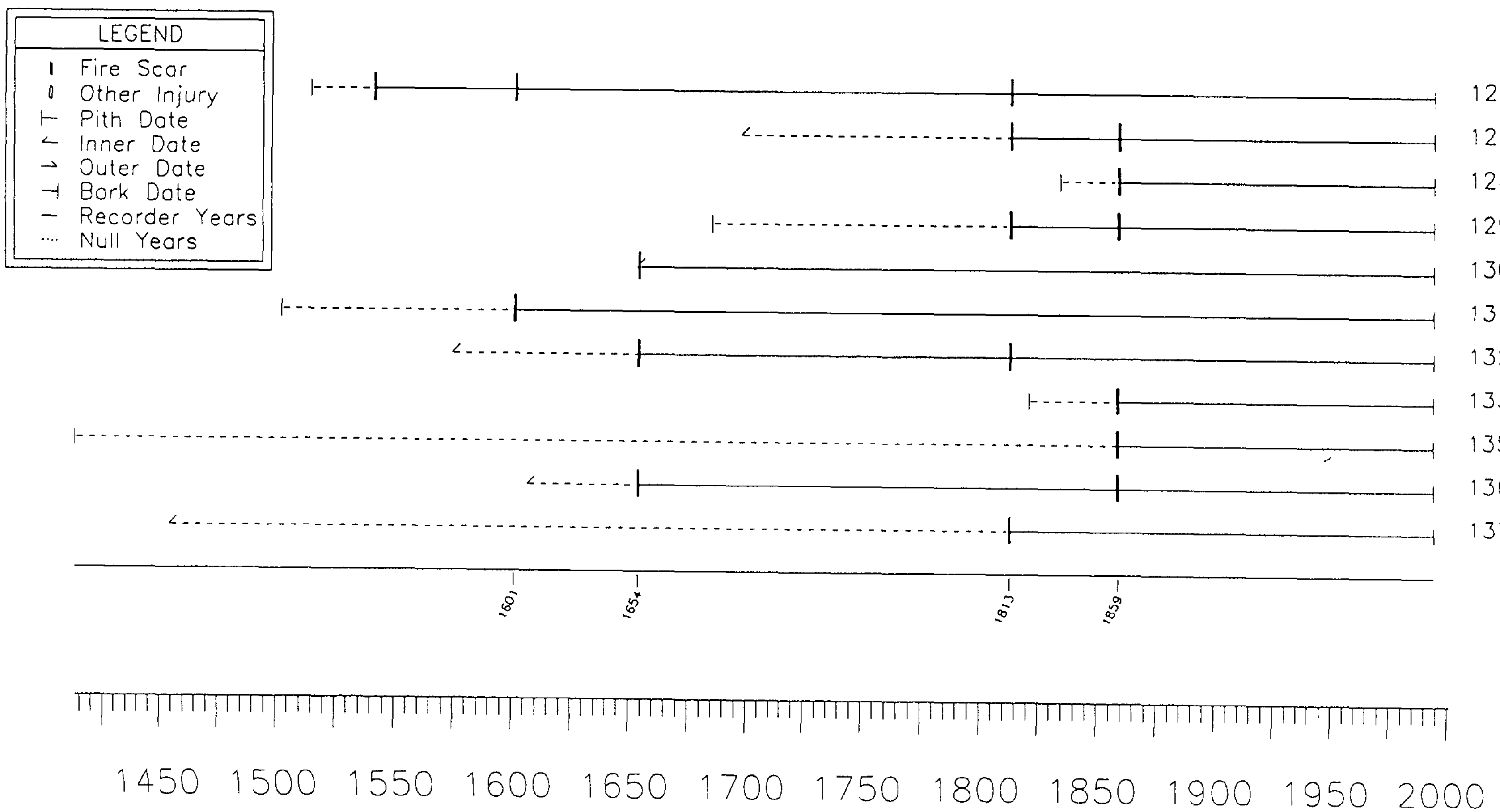
124
1654
1813
1859
1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000

SITE 19



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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127
128
129
130
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133
135
136
137
1601
1654
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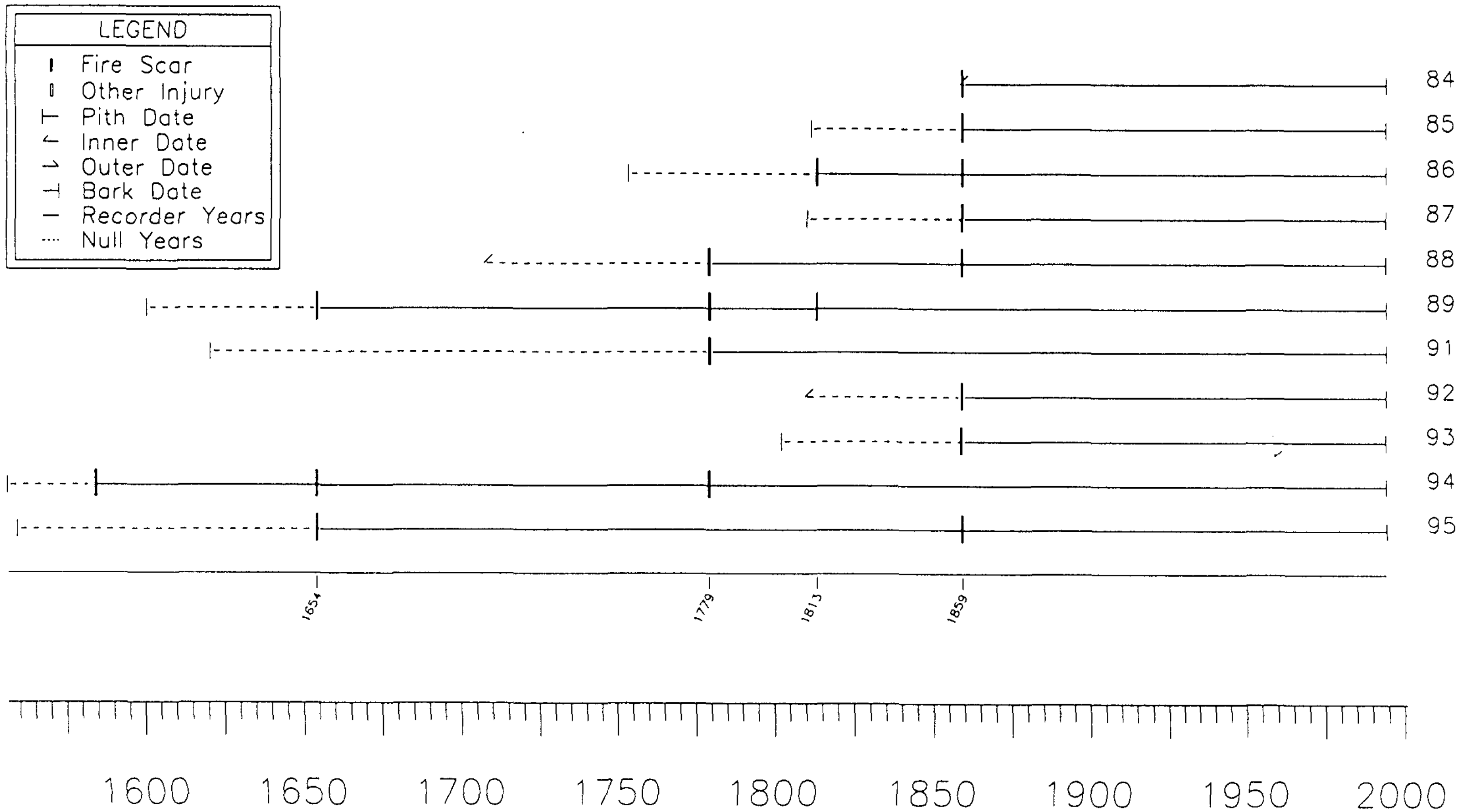
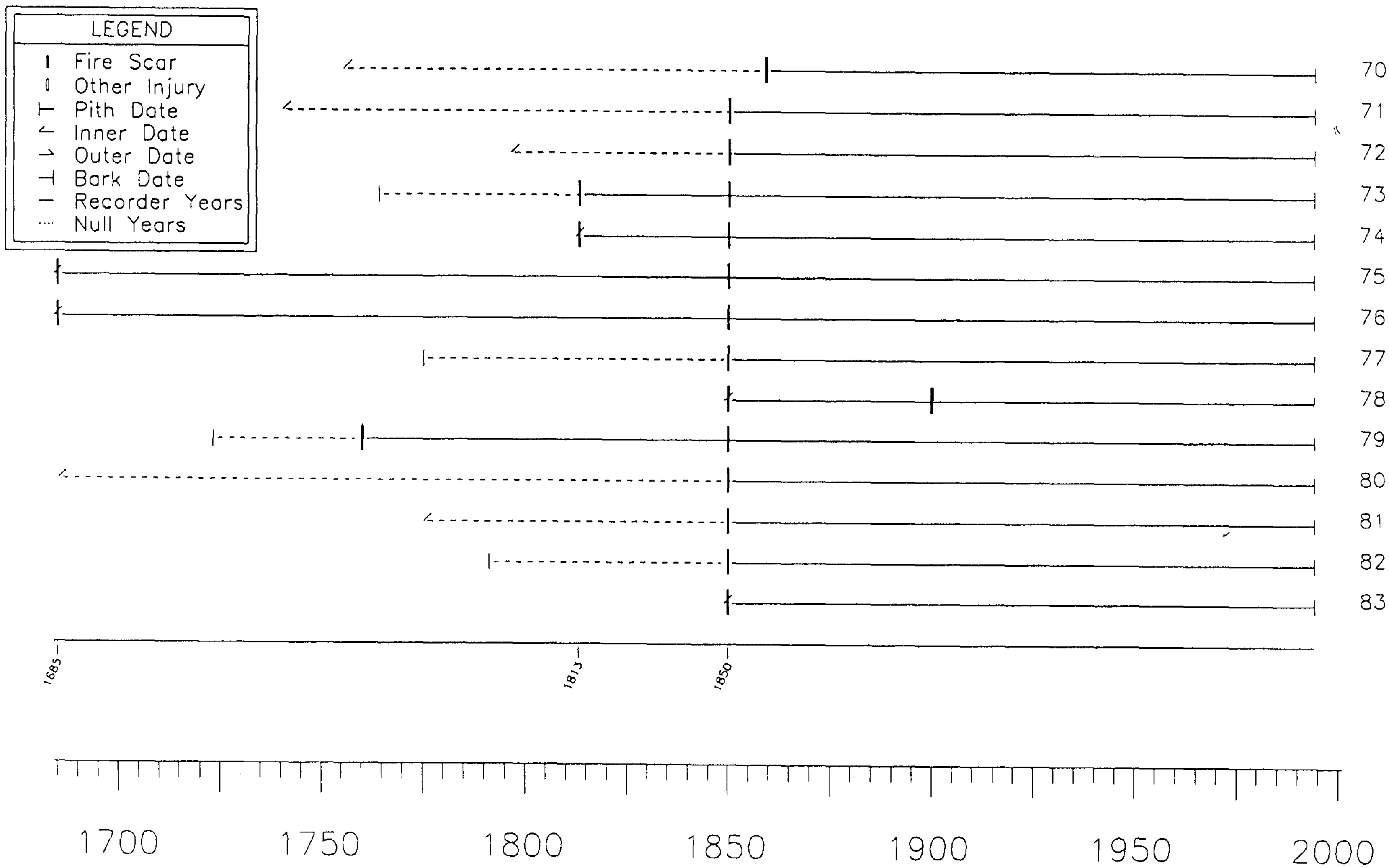
1900
1950
2000

SITE 20



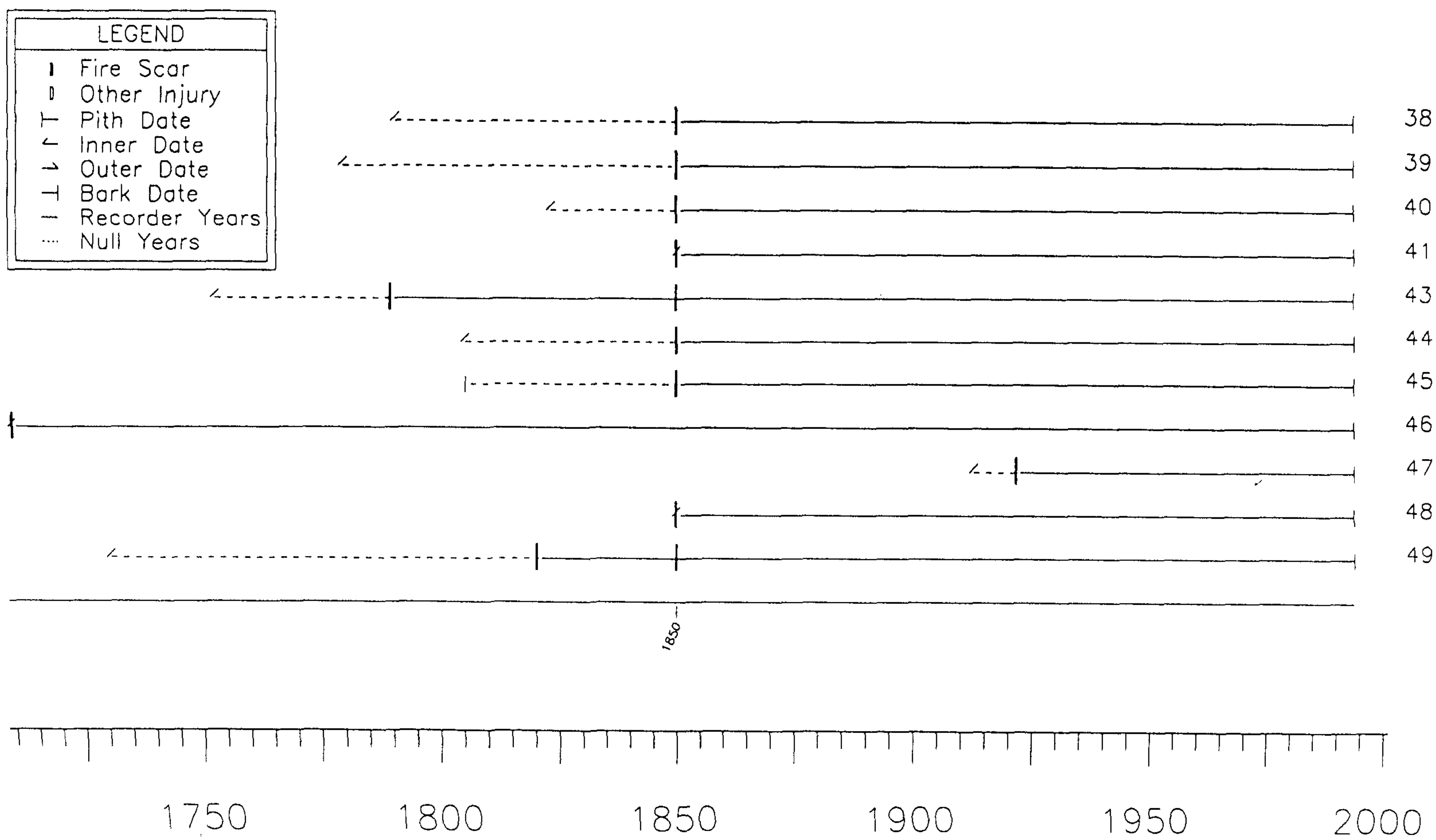
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
84
85
86
87
88
89
91
92
93
94
95
1654
1779
1813
1859
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 21



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
70
71
72
73
74
75
76
77
78
79
80
81
82
83
1685
1813
1850
1700
1750
1800
1850
1900
1950
2000

SITE 22


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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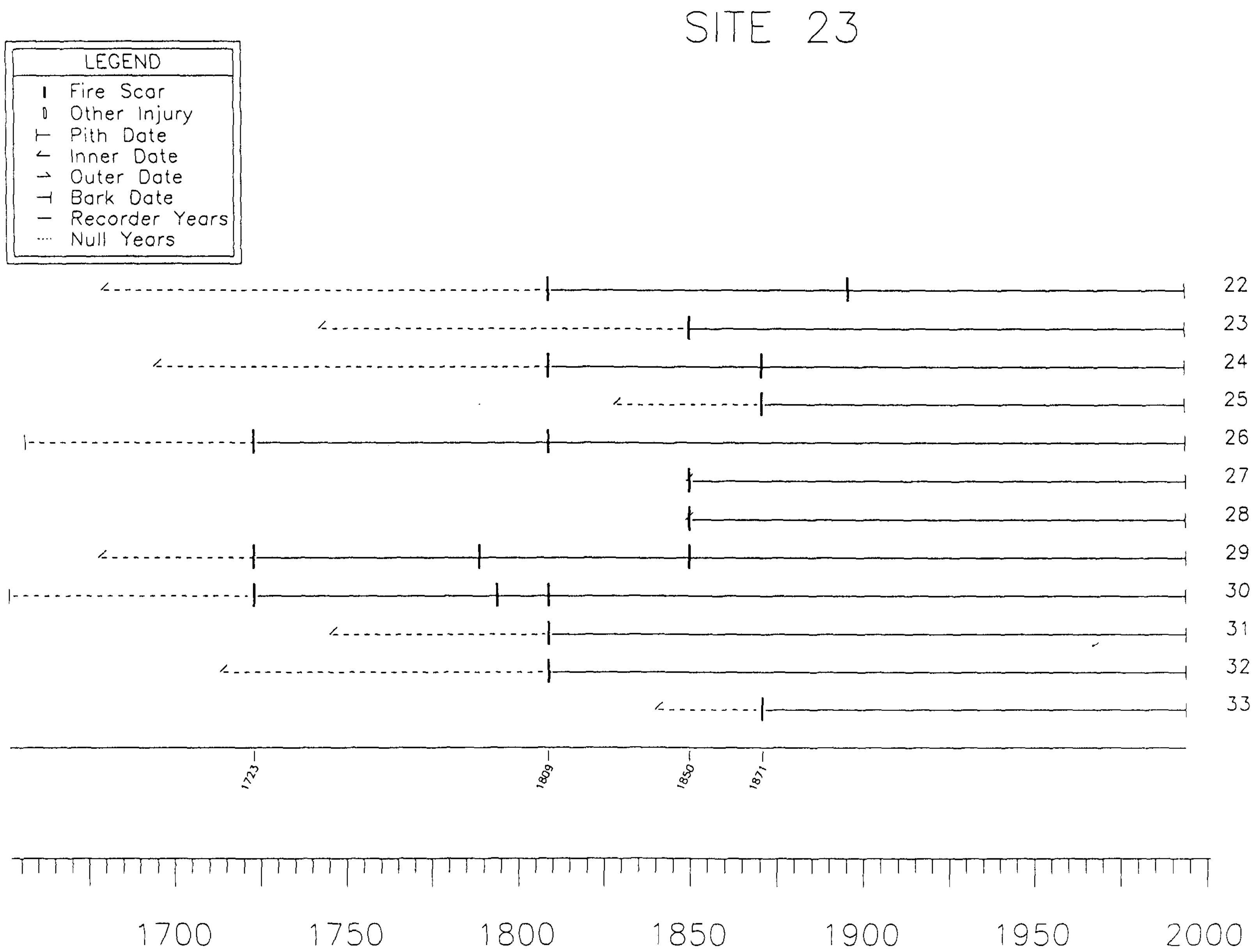
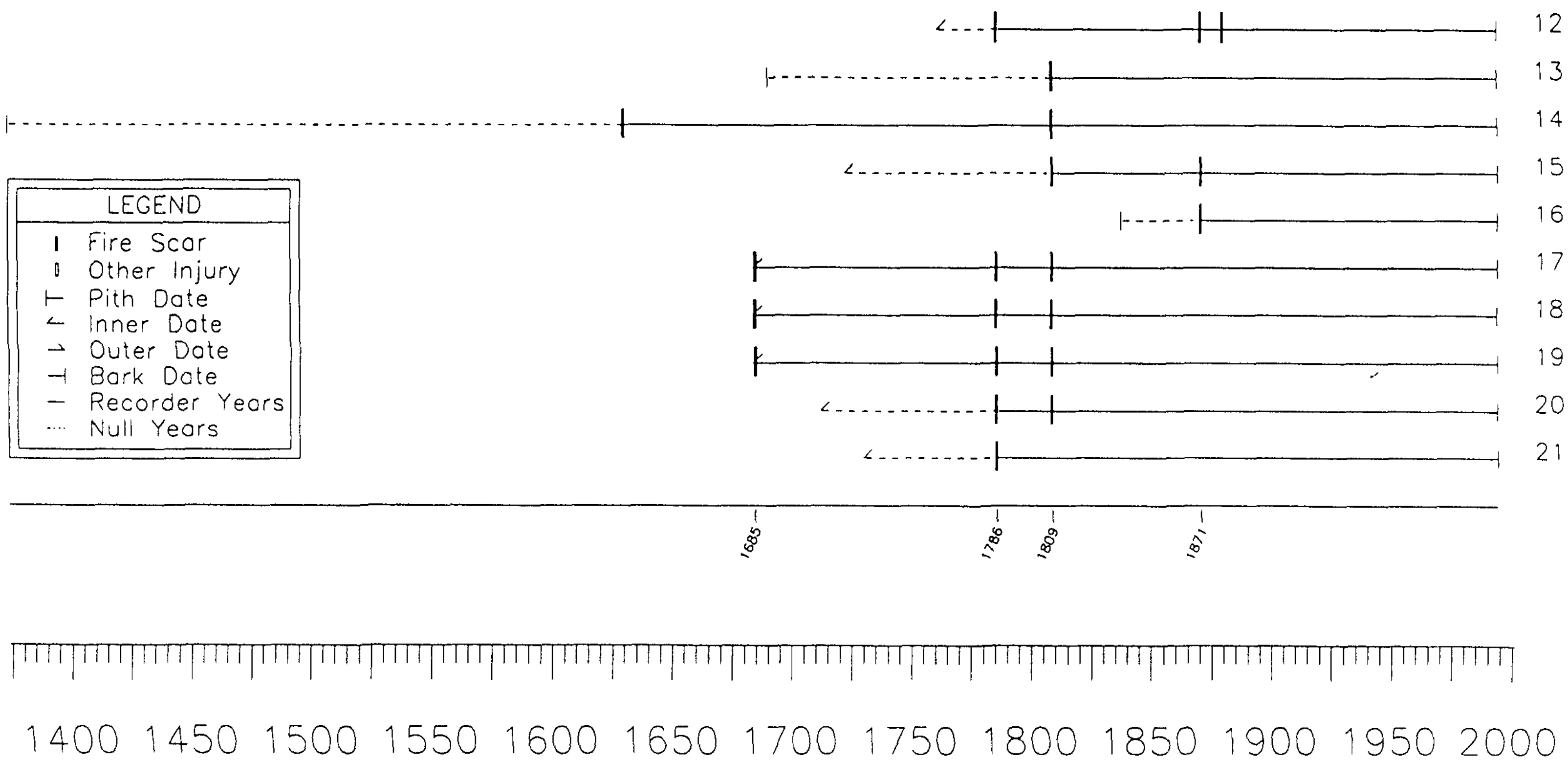
39
40
41
43
44
45
46
47
48
49
1850
1750
1800
1850
1900
1950
2000



SITE 23
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
22
23
24
25
26
27
28
29
30
31
32
33
1723
1809
1850
1871
1700
1750
1800
1850
1900
1950
2000

SITE 24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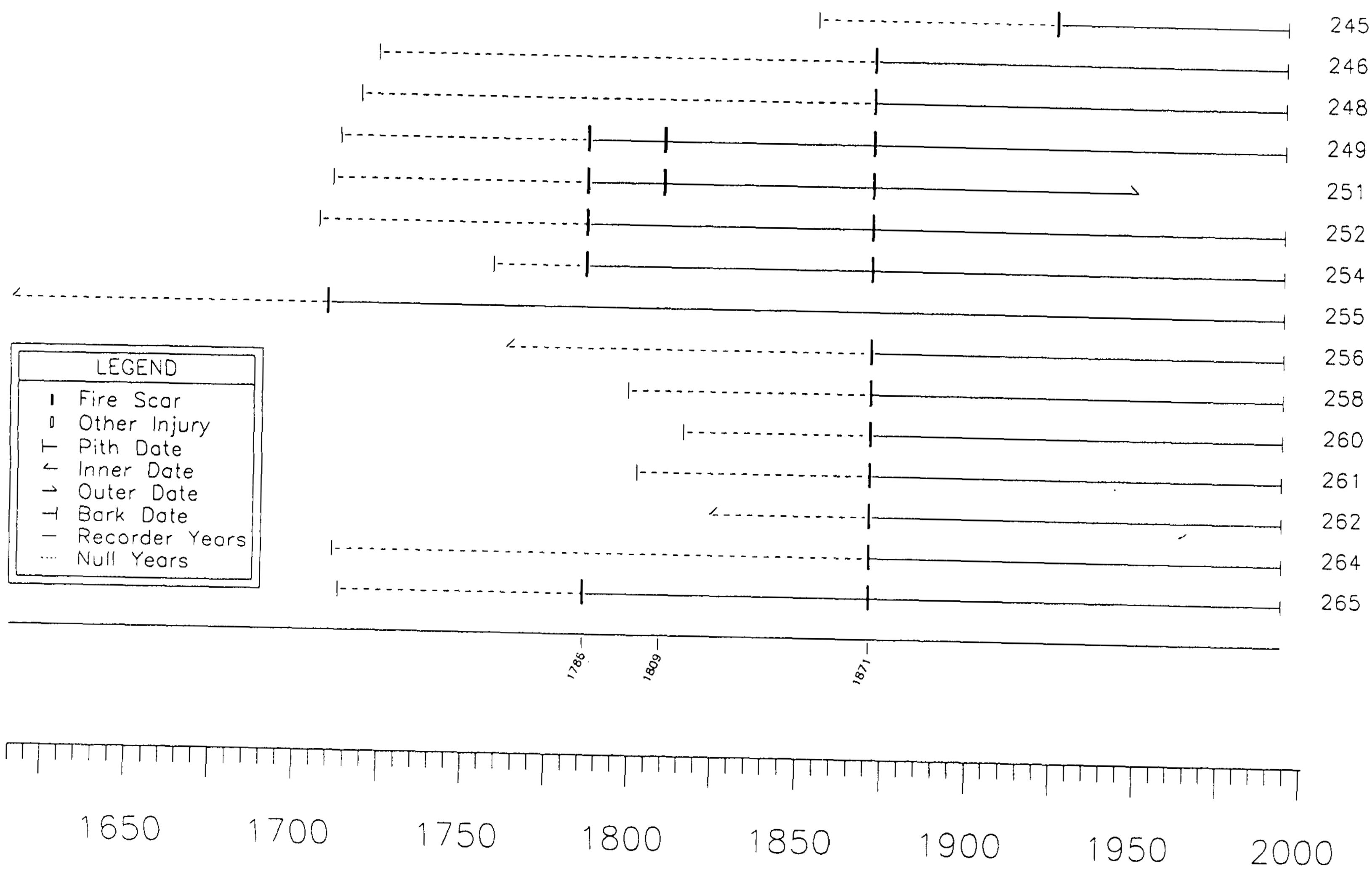
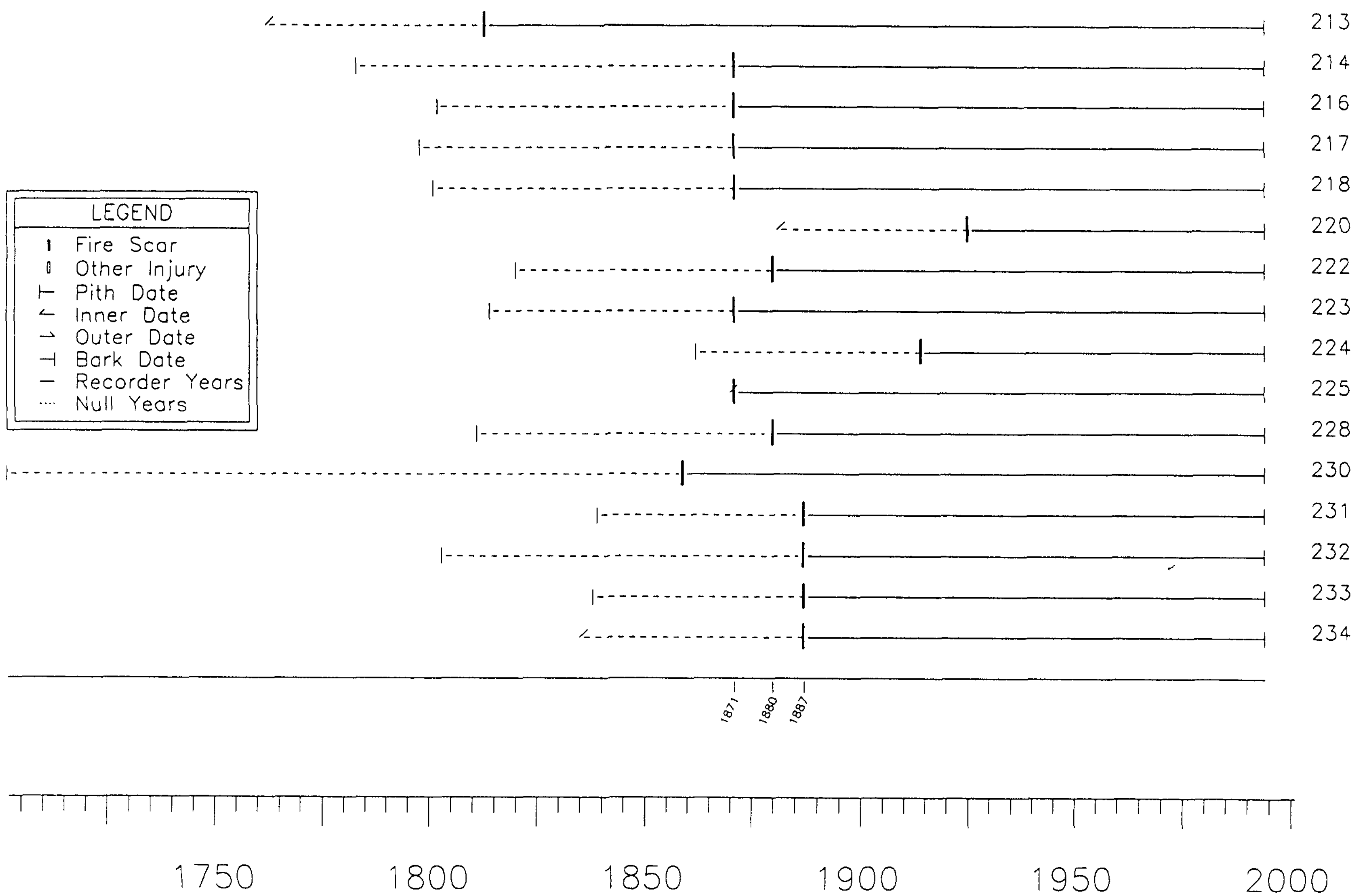
13
14
15
16
17
18
19
20
21
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1685
1786
1809
1871
1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000

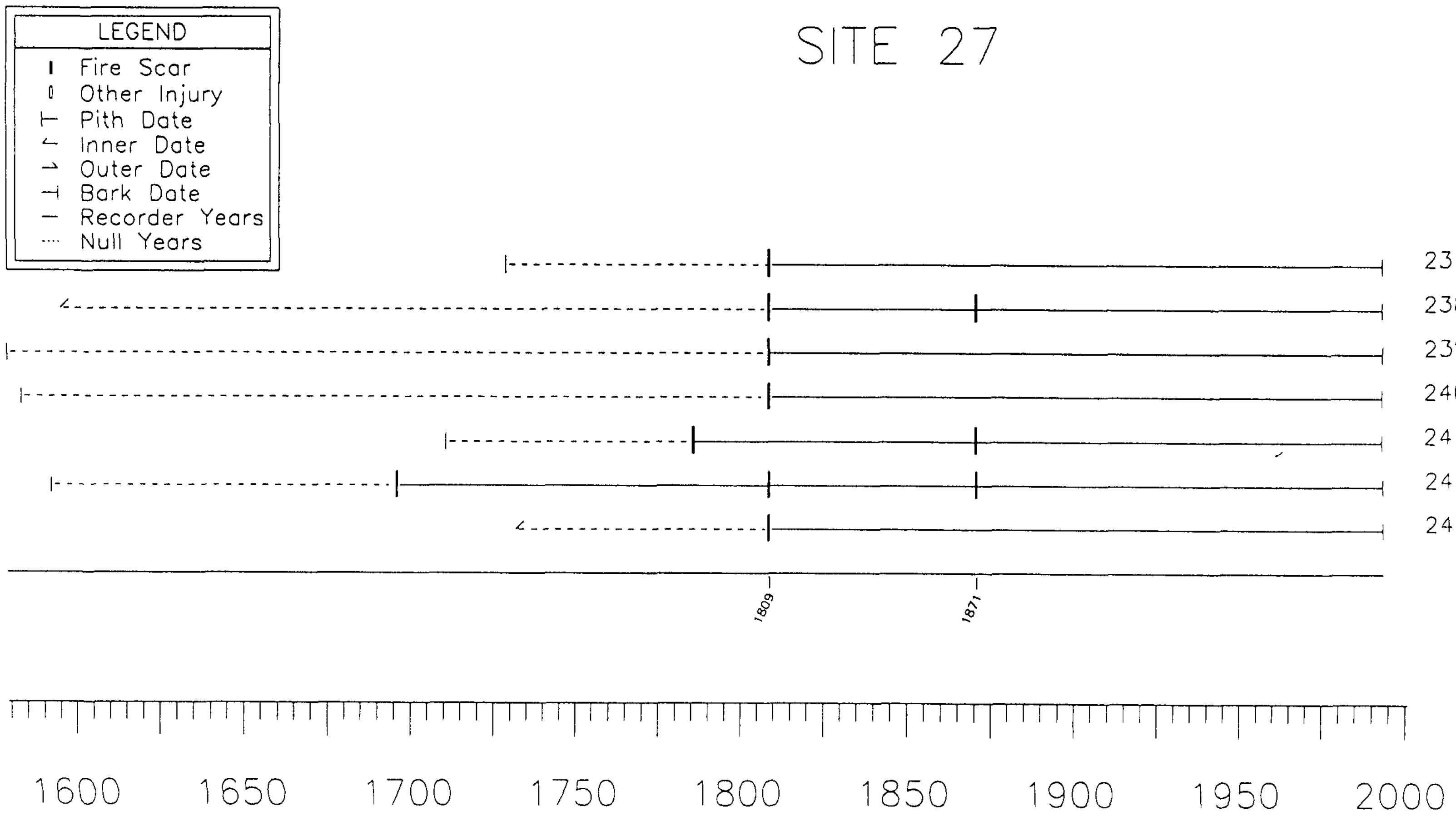
SITE 25



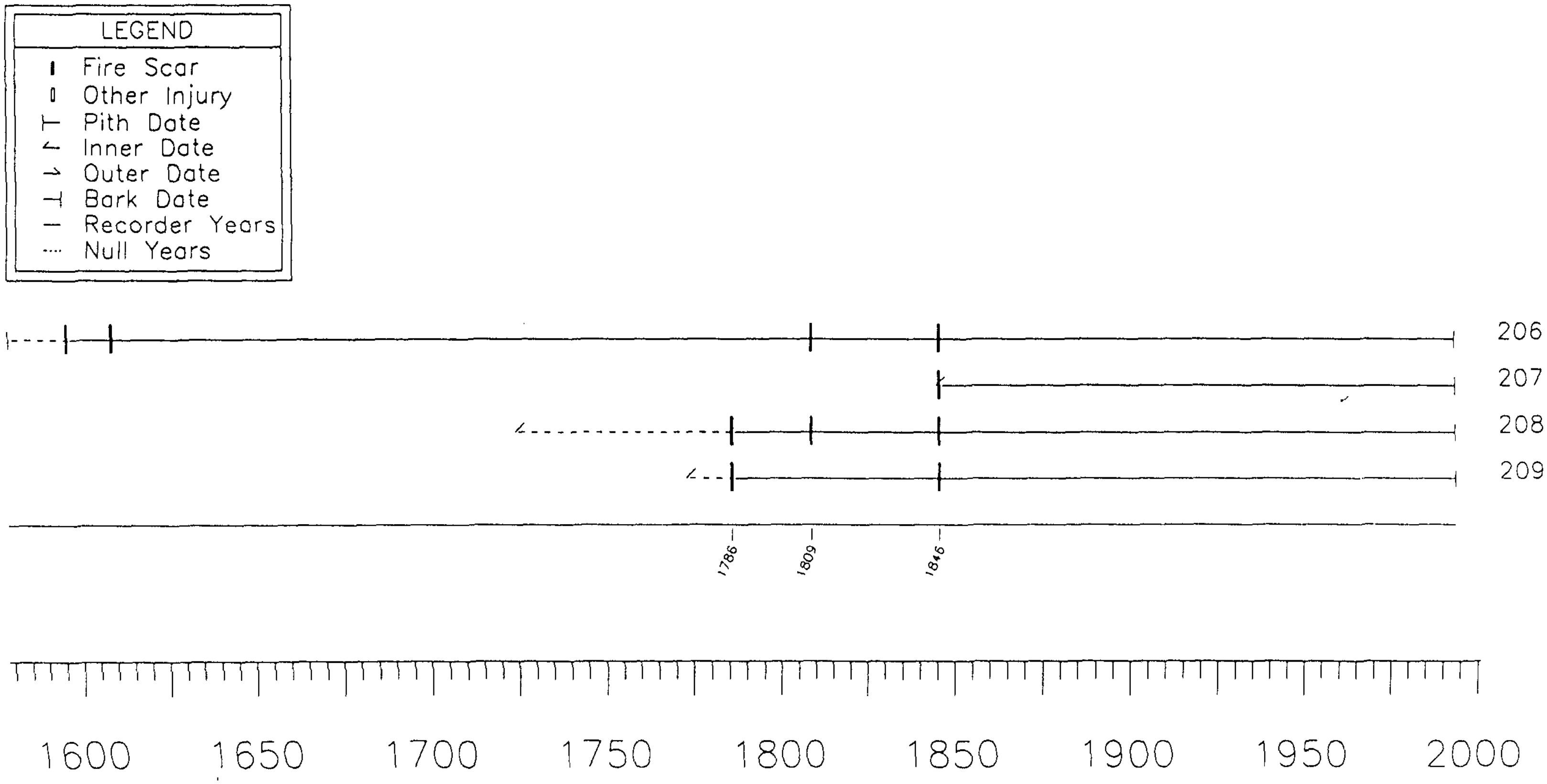
245
246
248
249
251
252
254
255
256
258
260
261
262
264
265
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1786
1809
1871
1650
1700
1750
1800
1850
1900
1950
2000

SITE 26

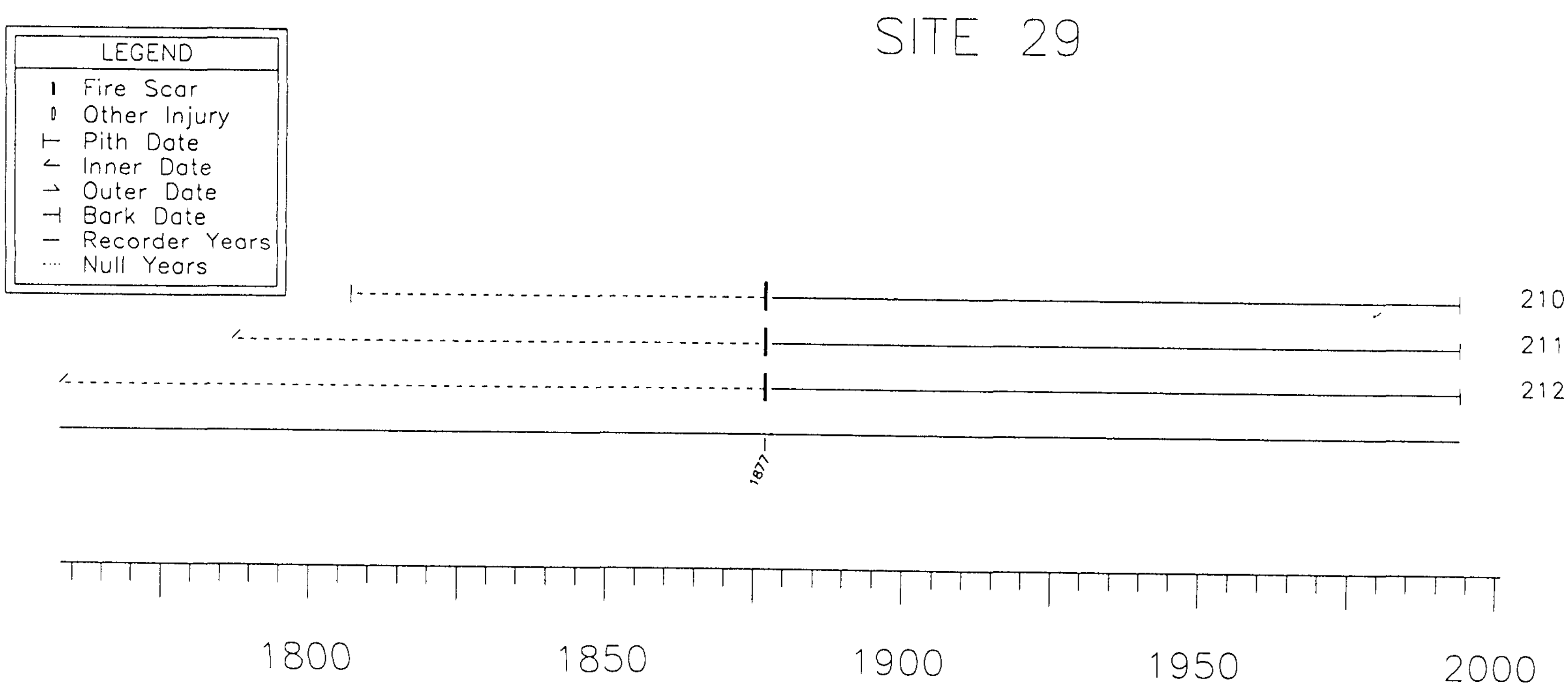

LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
213
214
216
217
218
220
222
223
224
225
228
230
231
232
233
234
1871
1880
1887
1750
1800
1850
1900
1950
2000

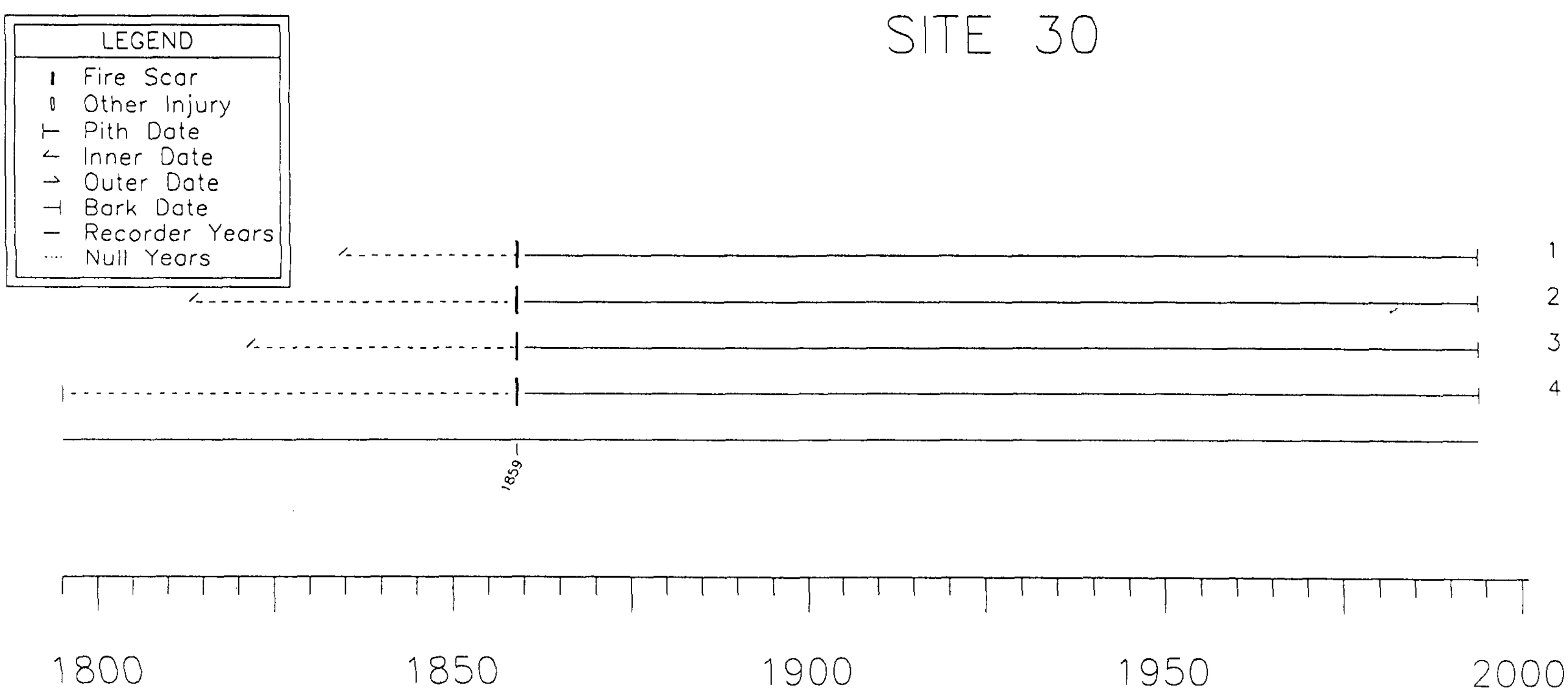

SITE 27
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
237
238
239
240
241
242
243
1809
1871
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 28



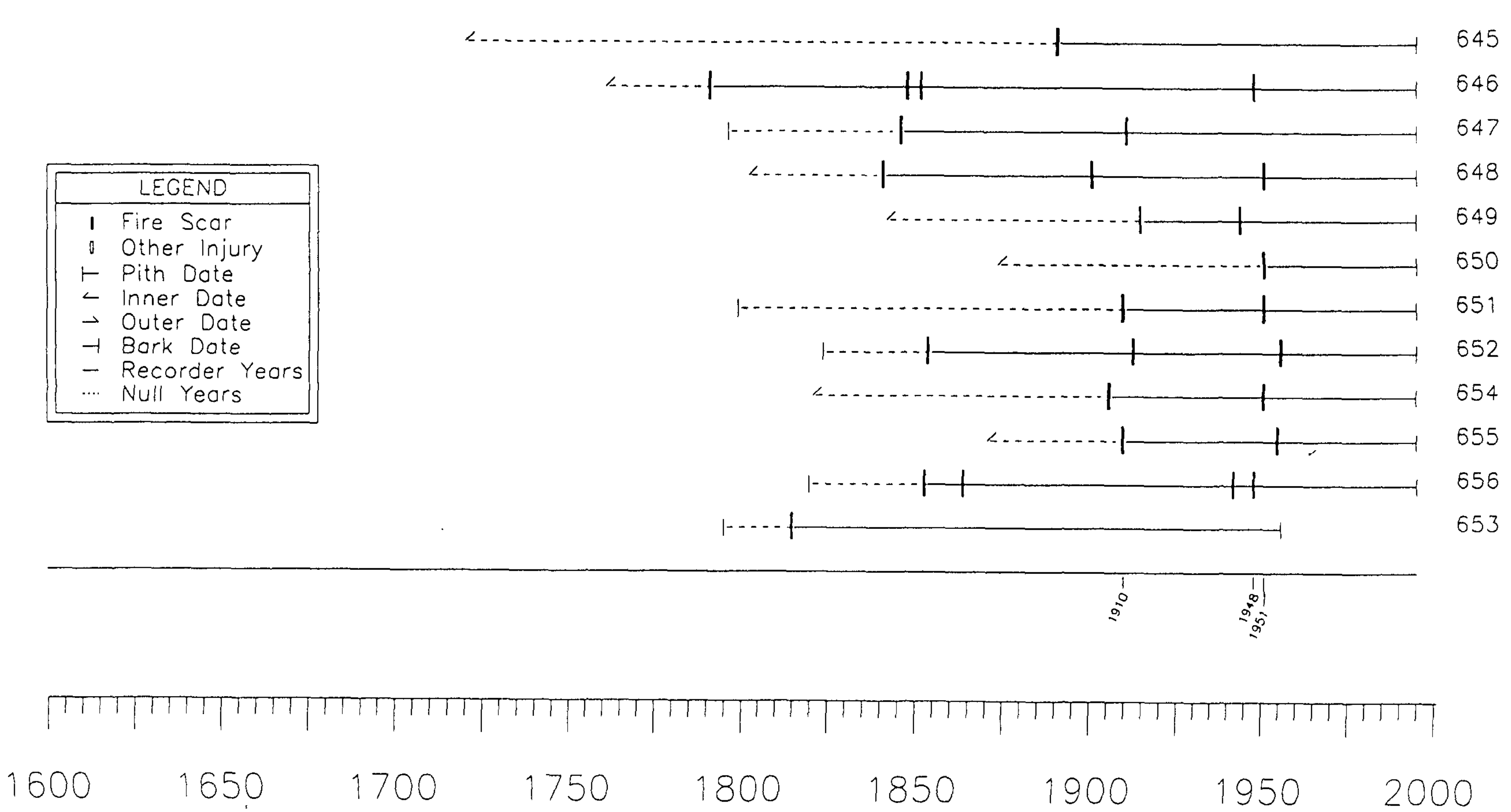
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
206
207
208
209
1786
1809
1846
1600
1650
1700
1750
1800
1850
1900
1950
2000


SITE 29
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
210
211
212
1877
1800
1850
1900
1950
2000



SITE 30
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1
2
3
4
1859
1800
1850
1900
1950
2000

SITE 31



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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646
647
648
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653
1910
1948
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1600
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1950
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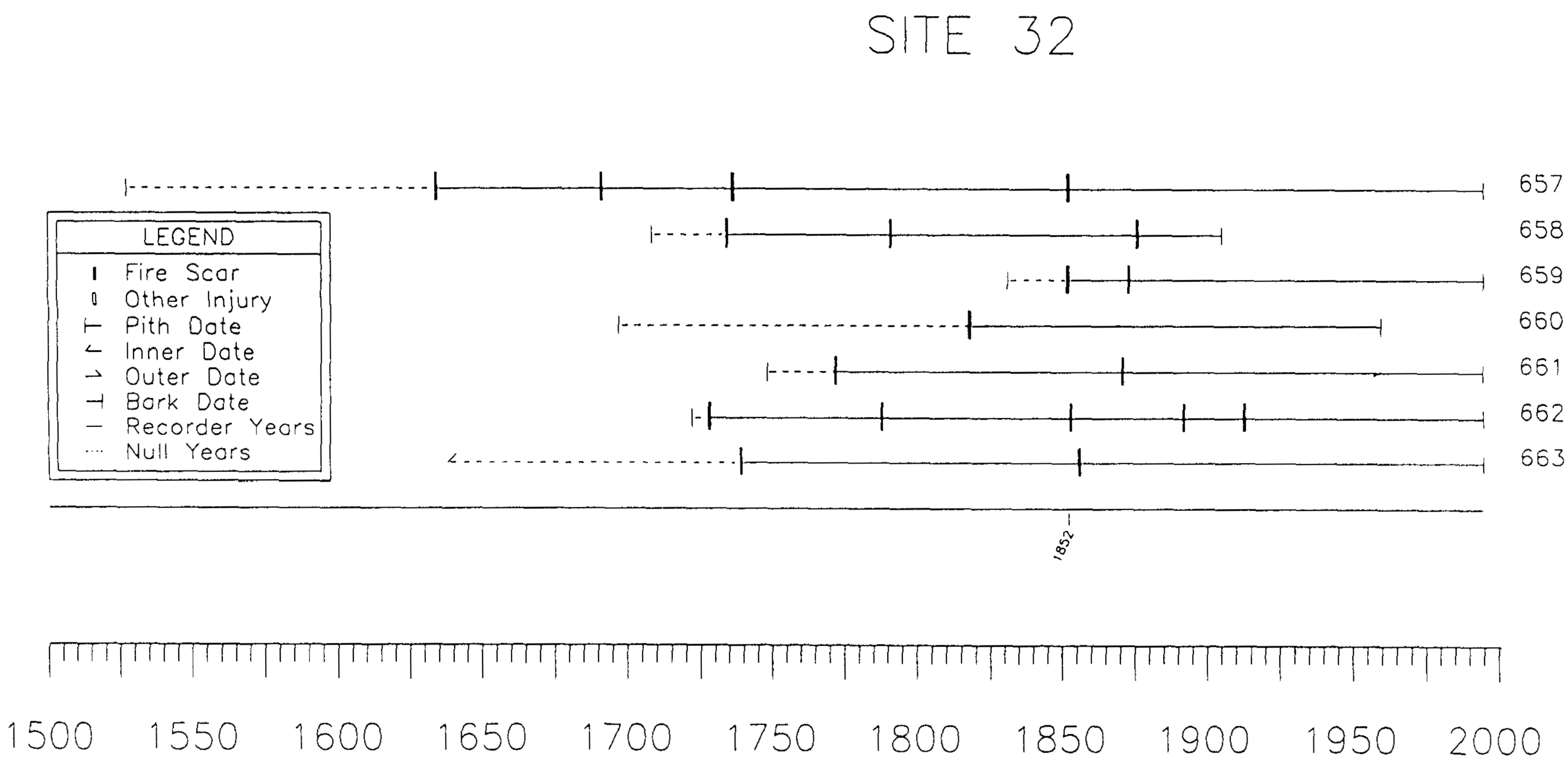
SITE 32
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
657
658
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663
1852
1500
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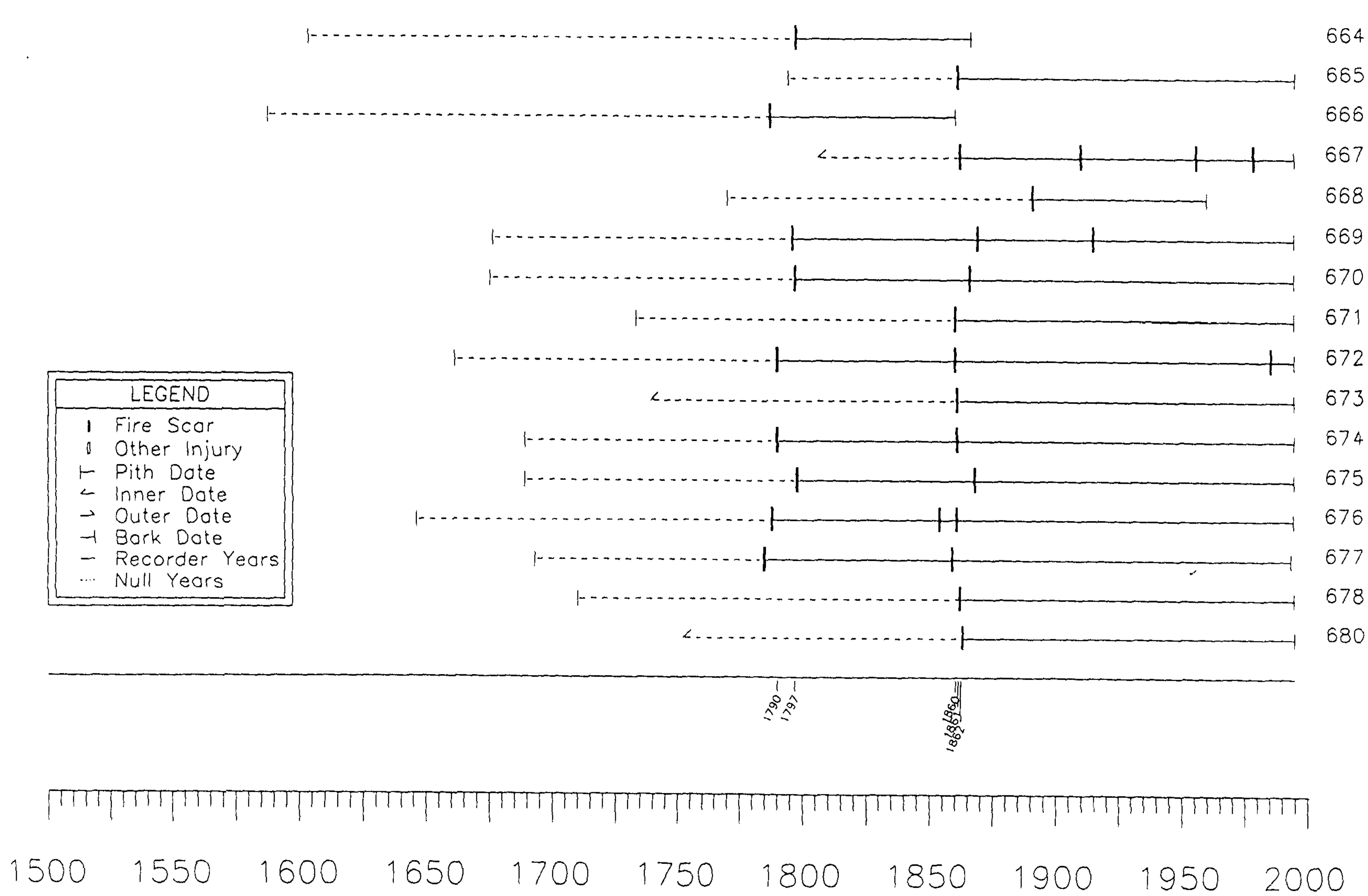
SITE 33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680
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1790
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1861
1862
1500
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1600
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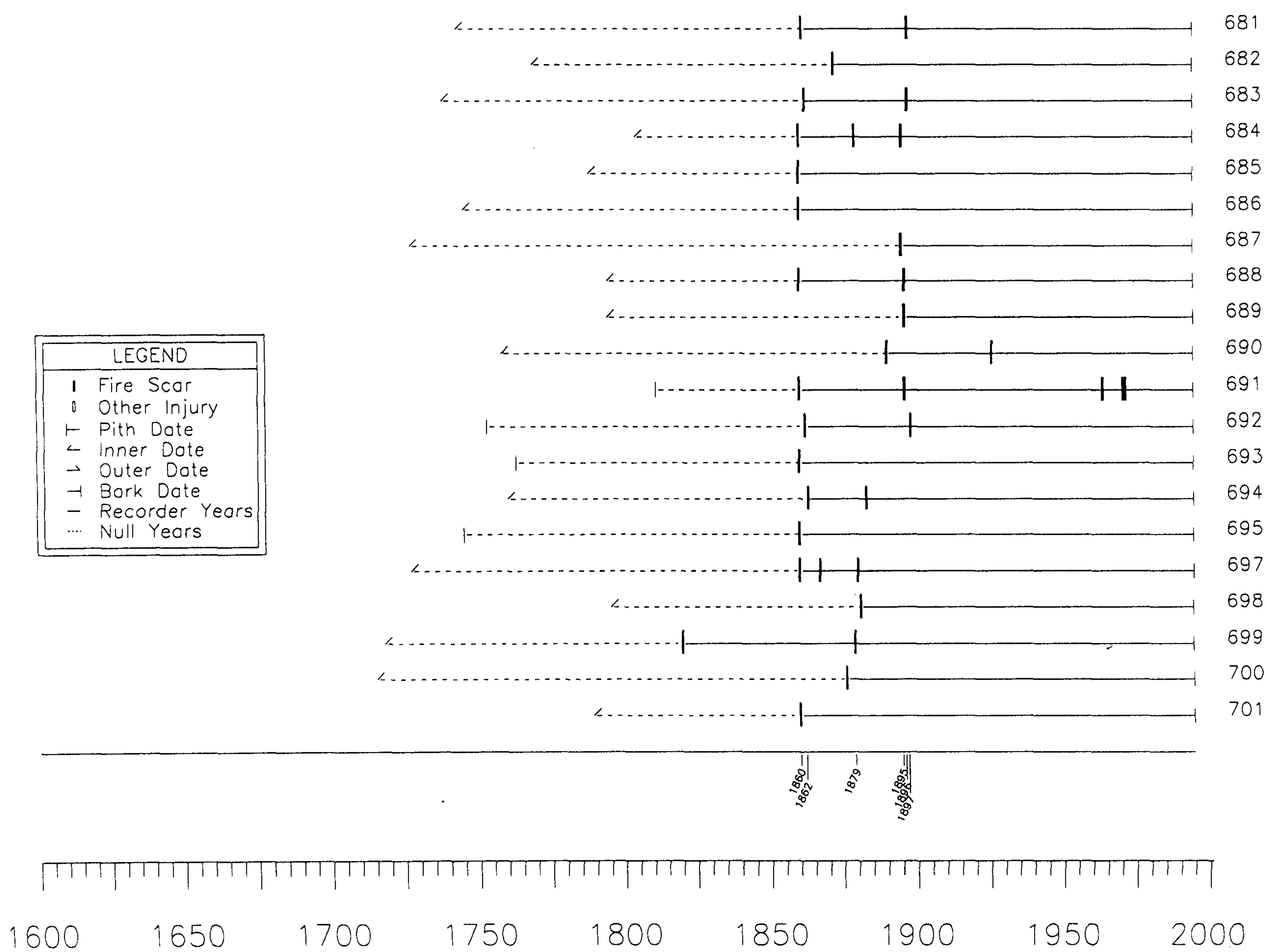
2000

SITE 34



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700
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LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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1862
1879
1600
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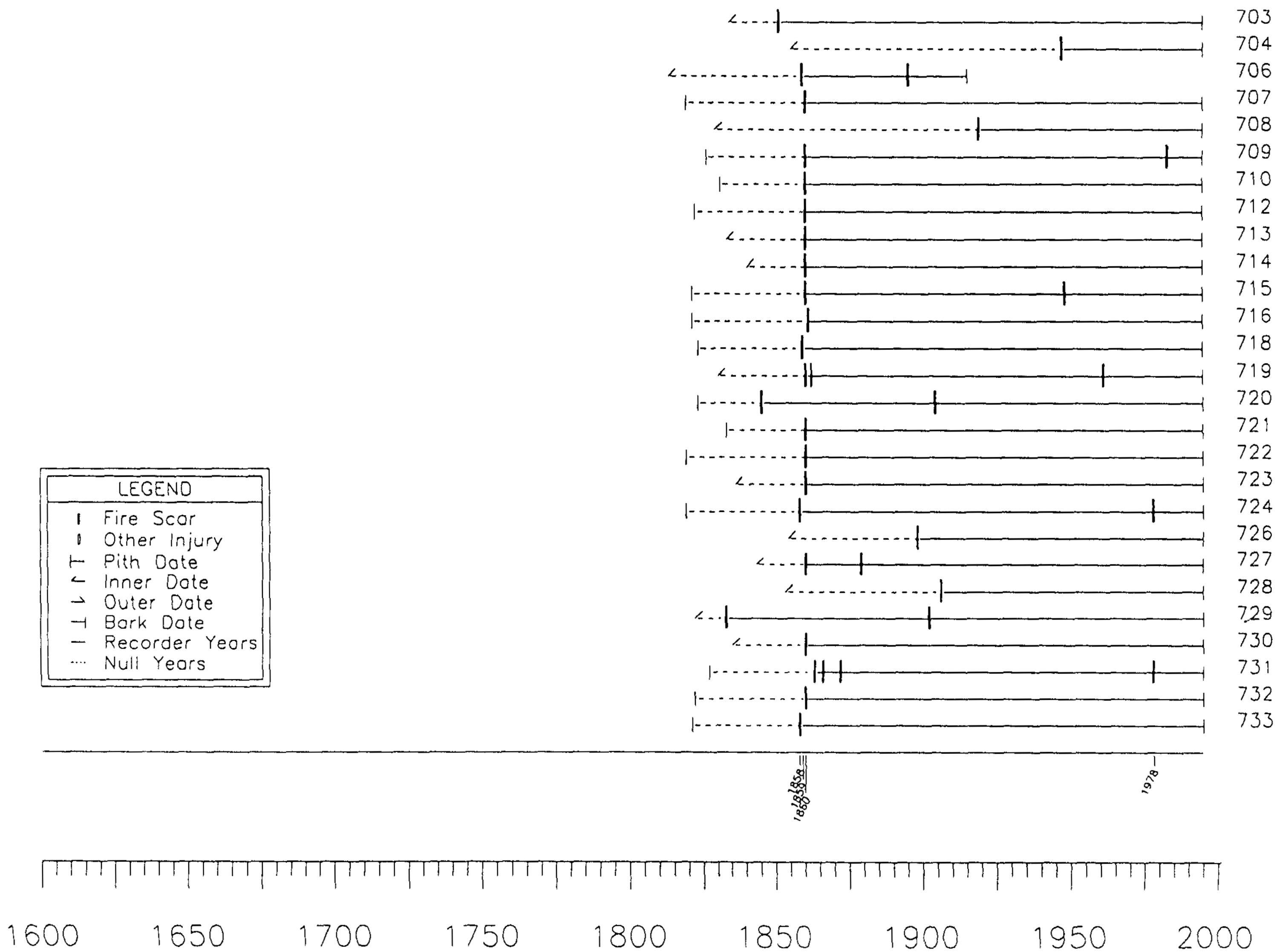
1800
1850
1900
1950
2000

SITE 35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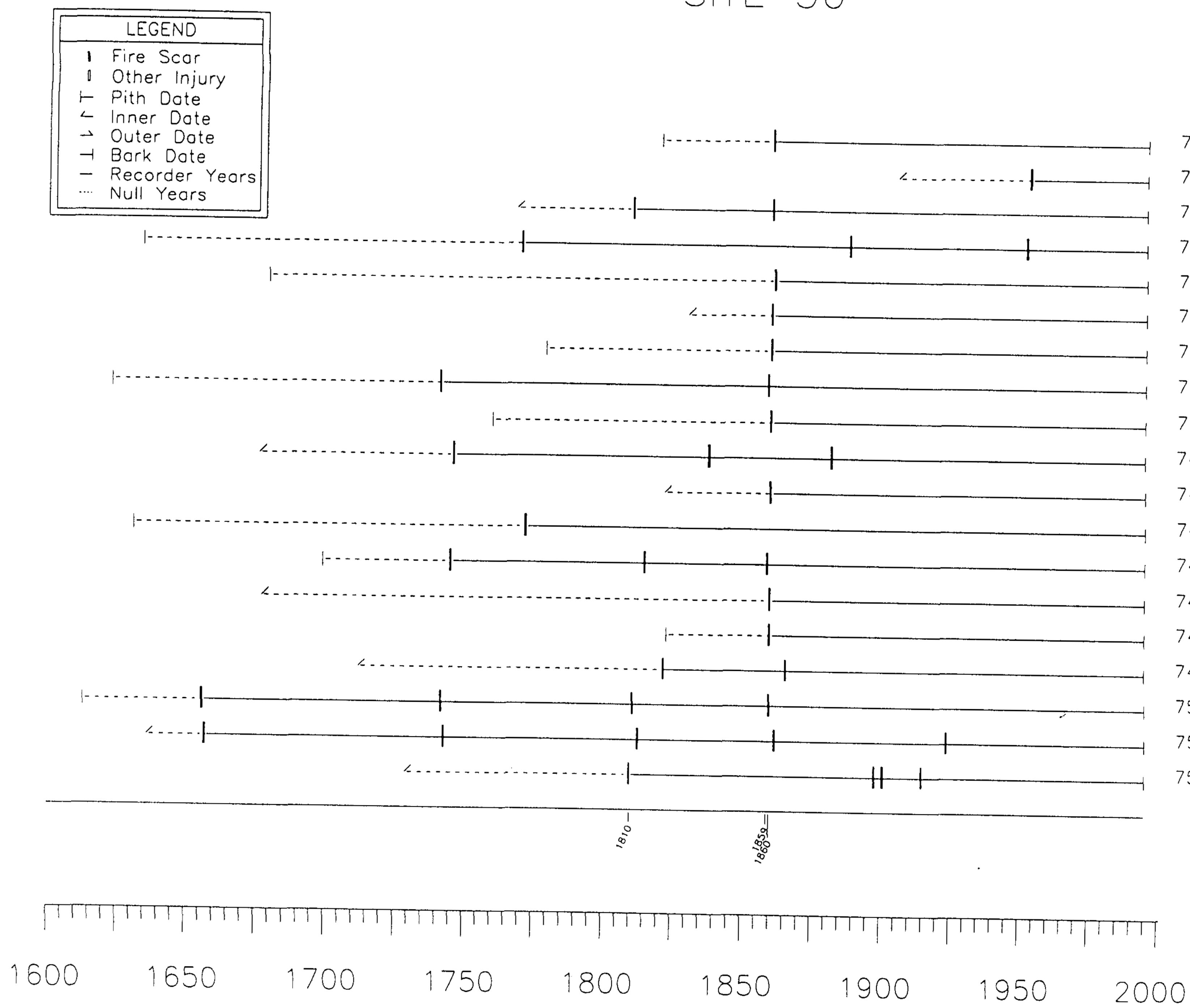
727
728
729
730
731
732
733
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1858
1859
1860
1978
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 36


LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
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735
736
737
738
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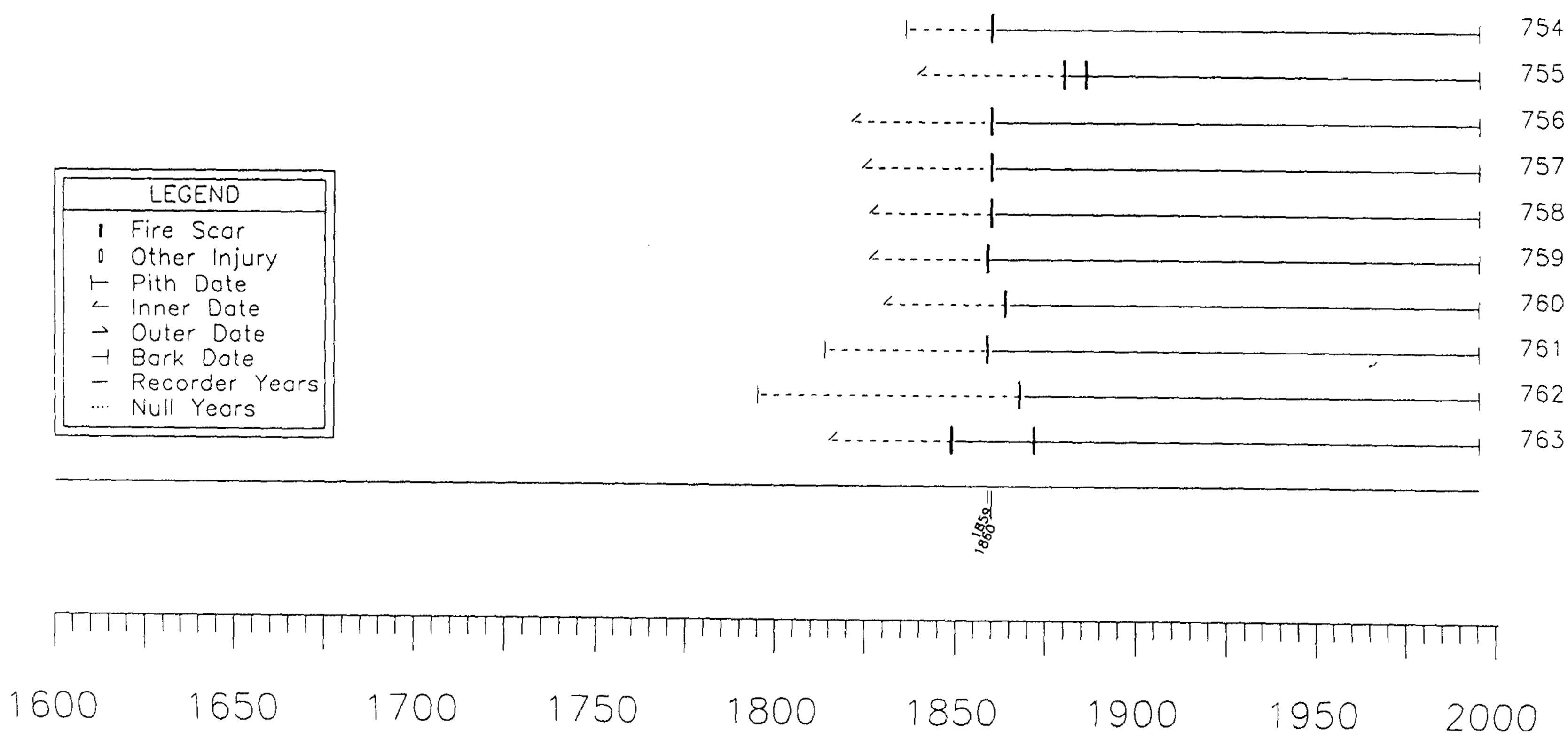
740
741
742
743
744
745
746
747
748
749
751
752
753
1810
1859
1860
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 37



754
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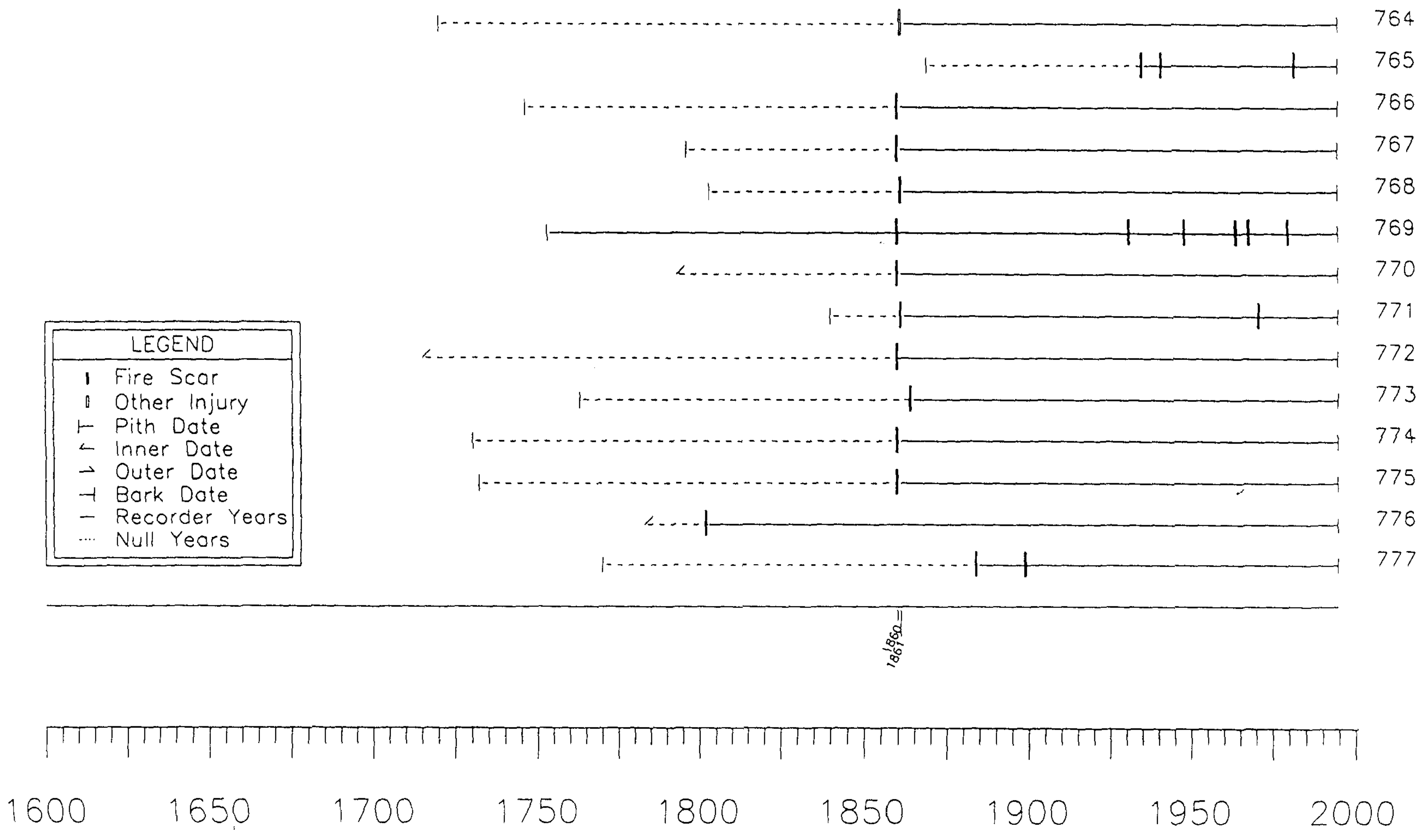
756
757
758
759
760
761
762
763
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1859
1860
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 38



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765
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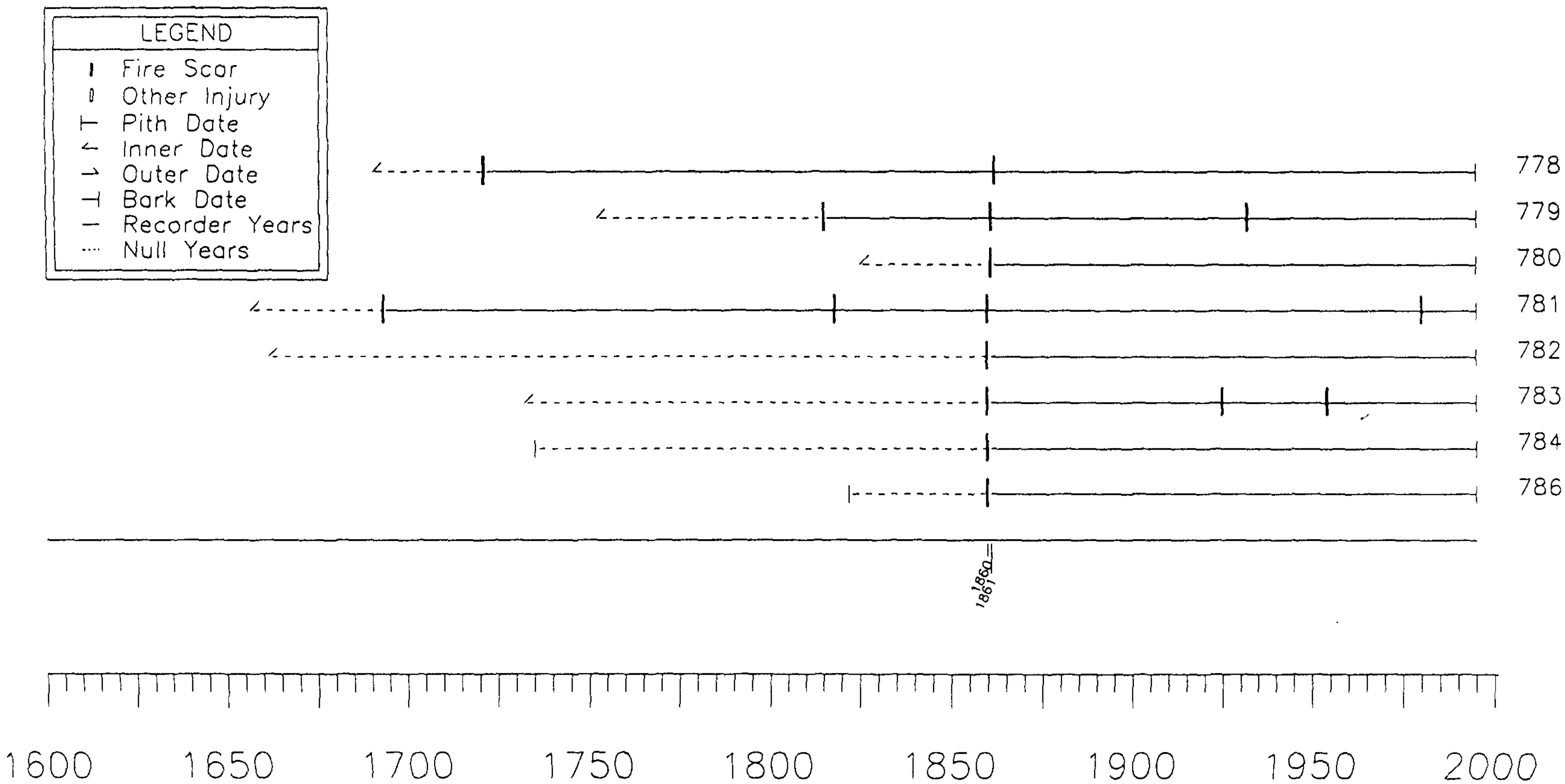
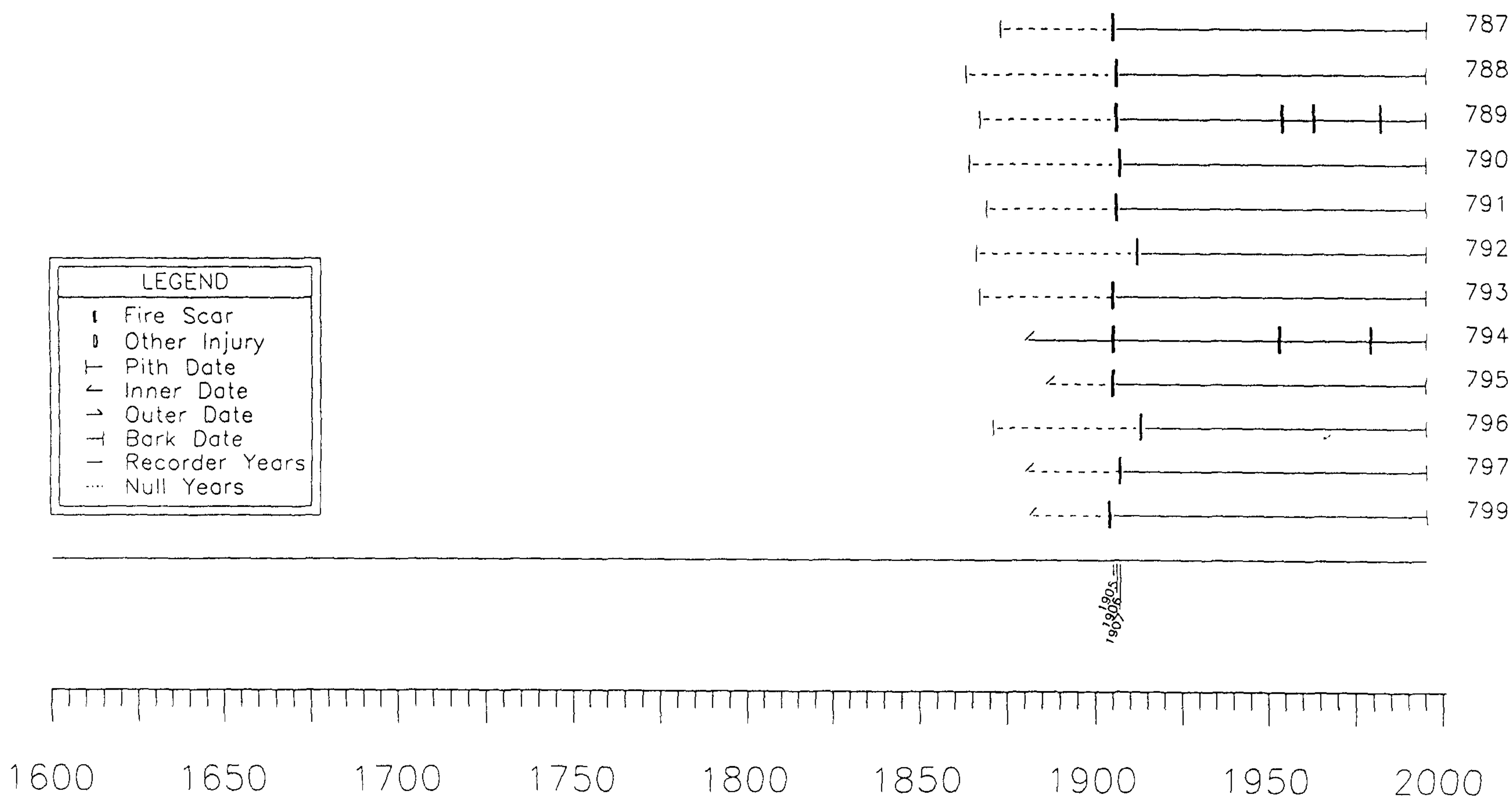
767
768
769
770
771
772
773
774
775
776
777
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1860
1861
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 39



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
778
779
780
781
782
783
784
786
1860
1861
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 40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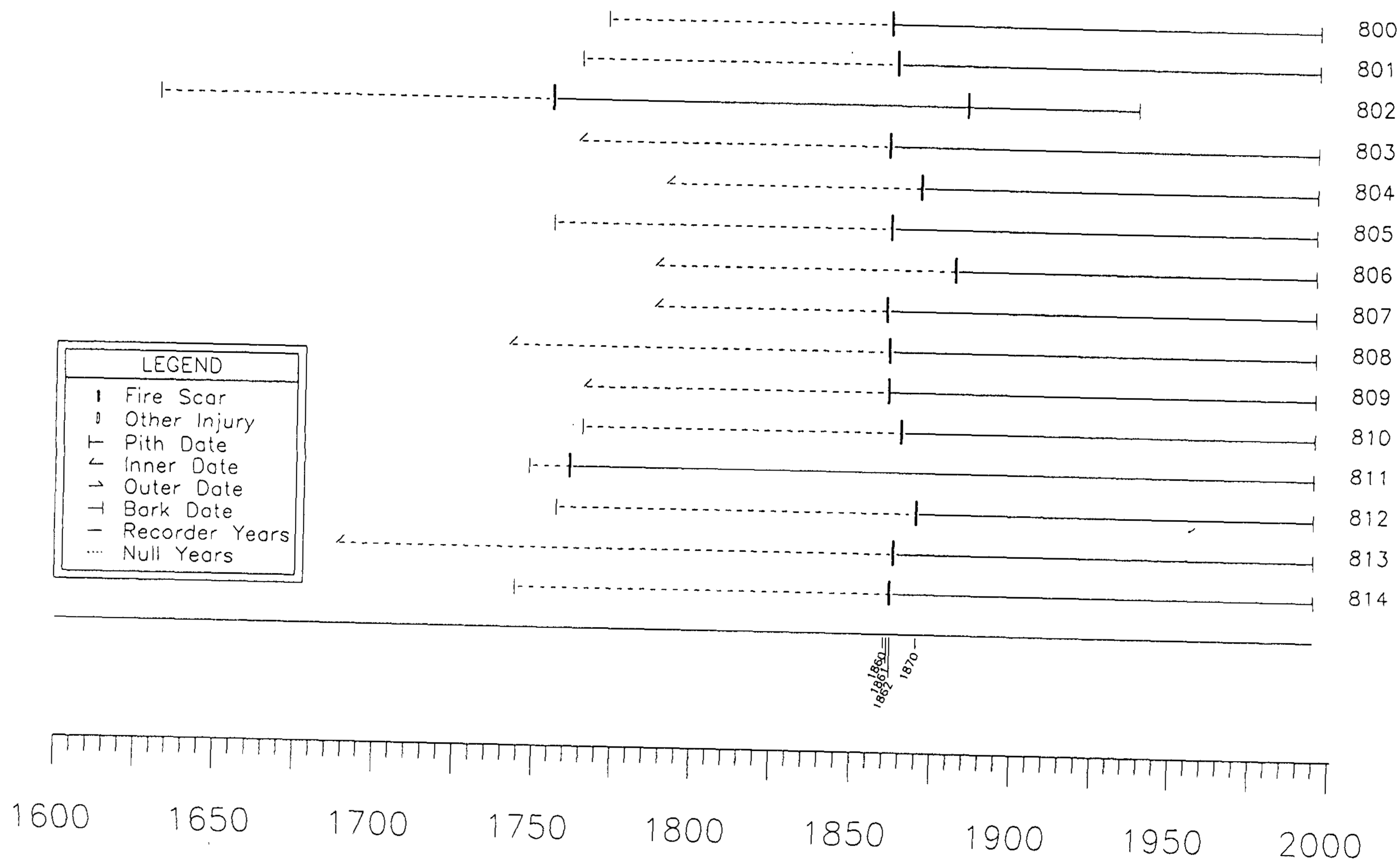
791
792
793
794
795
796
797
799
LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
1600
1650
1700
1750
1800
1850
1900
1950
2000

SITE 41



LEGEND
Fire Scar
Other Injury
Pith Date
Inner Date
Outer Date
Bark Date
Recorder Years
Null Years
800
801
802
803
804
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807
808
809
810
811
812
813
814
1860
1861
1862
1870
1600
1650
1700
1750
1800
1850
1900
1950
2000

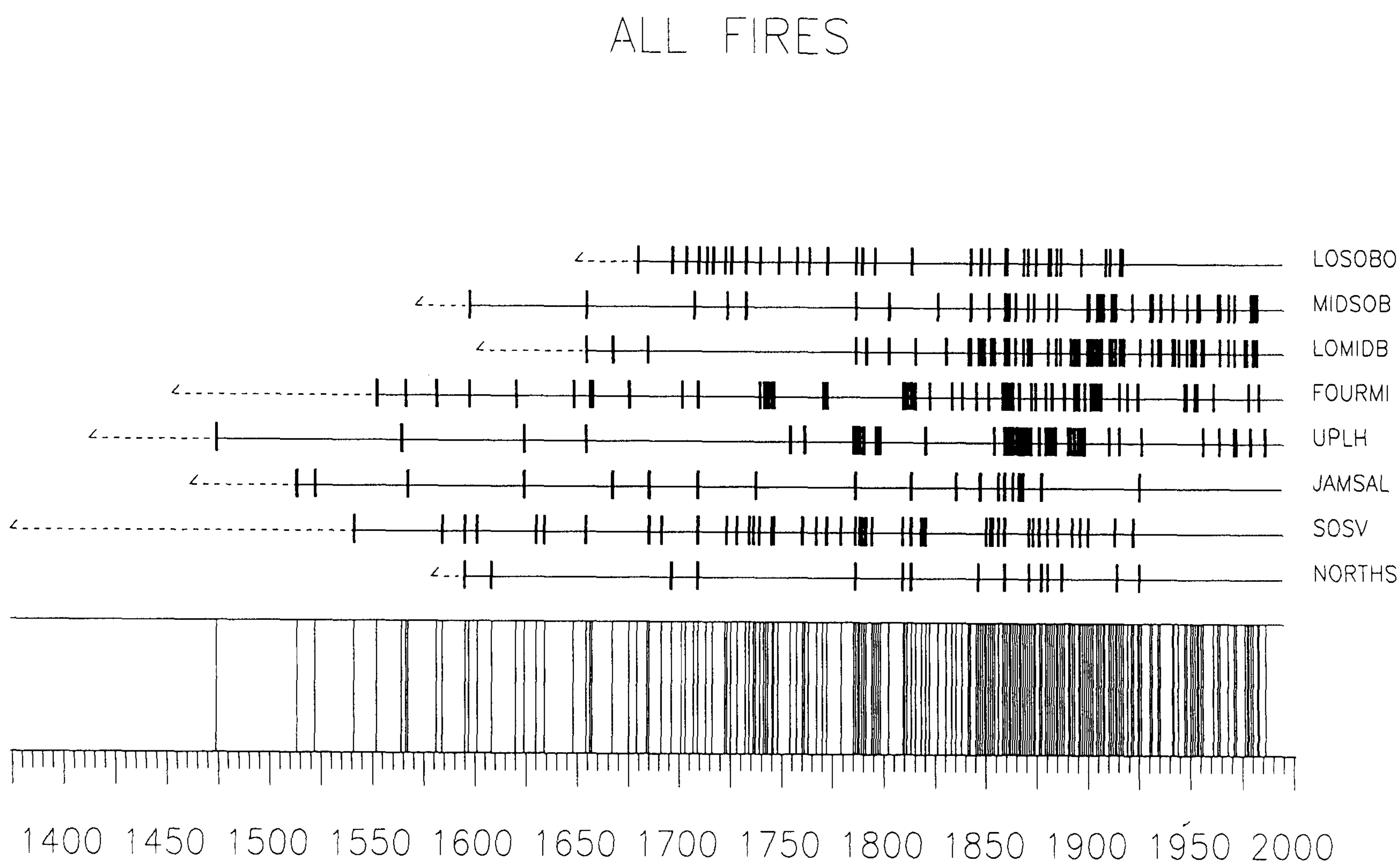

Fig. 3. Composite master fire chart for all sites organized into eight groups of nearby sites. For each group all fires are plotted, and on the composite line all fires are also plotted. For definitions of groups see Table 2.

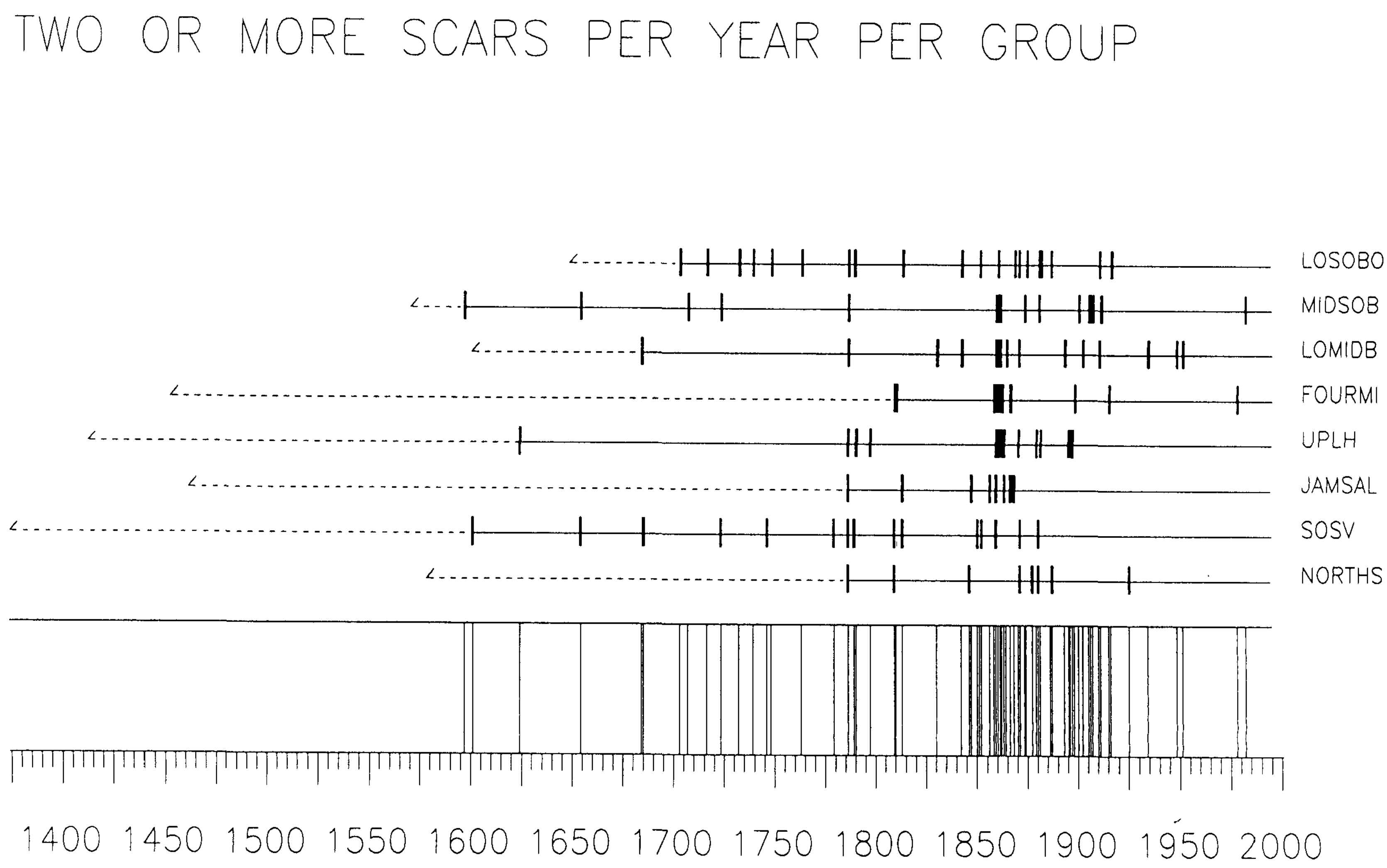

Fig. 4. Composite master fire chart for all sites organized into eight groups of nearby sites. For each group fires are plotted for years in which two or more fire scars are recorded. All these fire years are plotted on the composite line. For definitions of groups see Table 2.

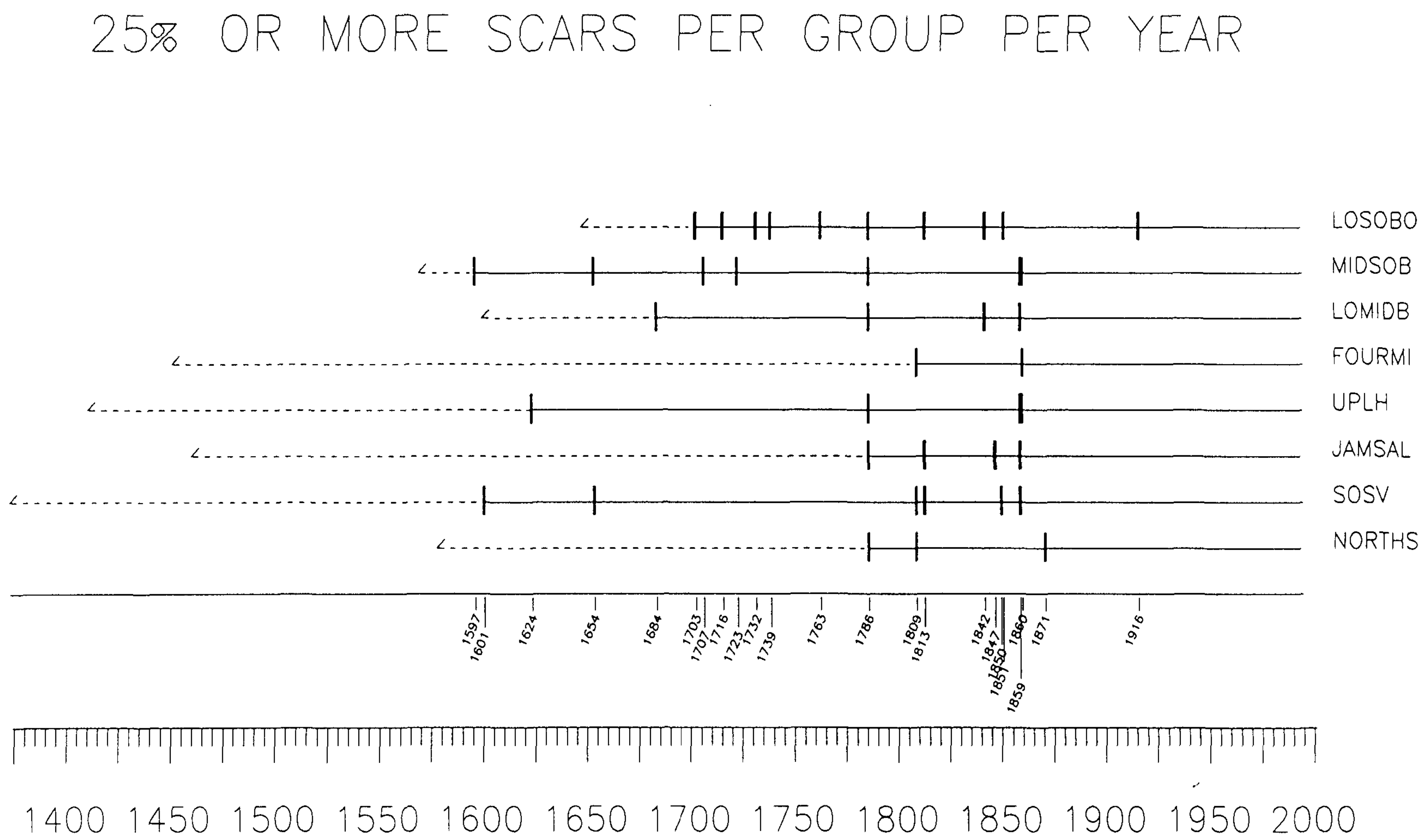

Fig. 5. Composite master fire chart for all sites organized into eight groups of nearby sites. For each group fires are plotted for years in which 25% or more of the fire-scar susceptible trees recorded fire scars and a minimum of at least two trees were scarred. All these fire years are plotted on the composite line. For definitions of groups see Table 2.

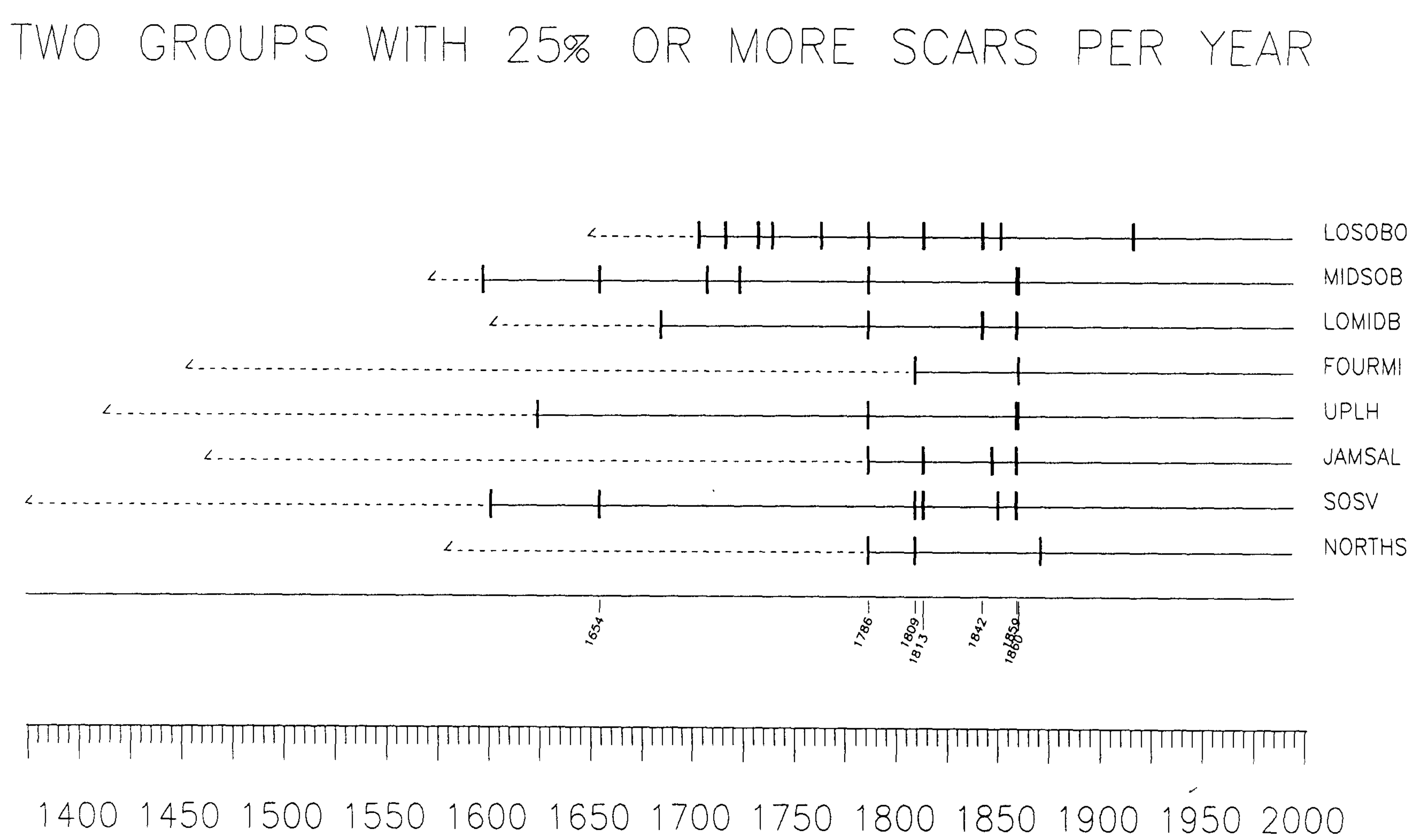

Fig. 6. Composite master fire chart for all sites organized into eight groups of nearby sites. For each group years are plotted in which 25% or more of the fire-scar susceptible trees recorded fire scars and a minimum of at least two trees were scarred. Years in which 2 or more groups recorded these 25%-fire years are plotted on the composite line. For definitions of groups see Table 2.

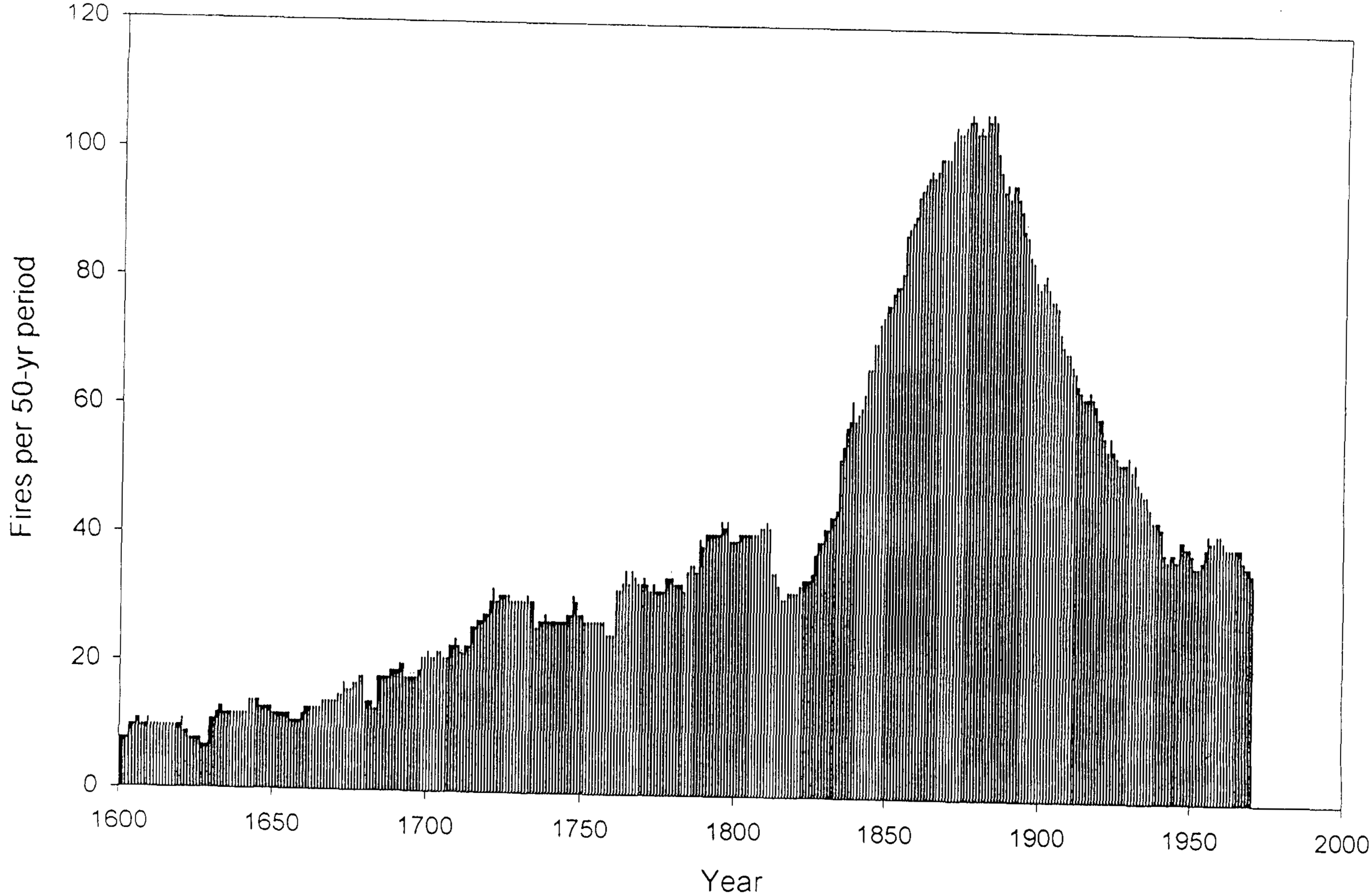

Fig. 7. Number of fires for running 50-yr periods. Fires are only included if they were recorded by at least two trees in one of the eight groups of nearby sites (see Table 2).

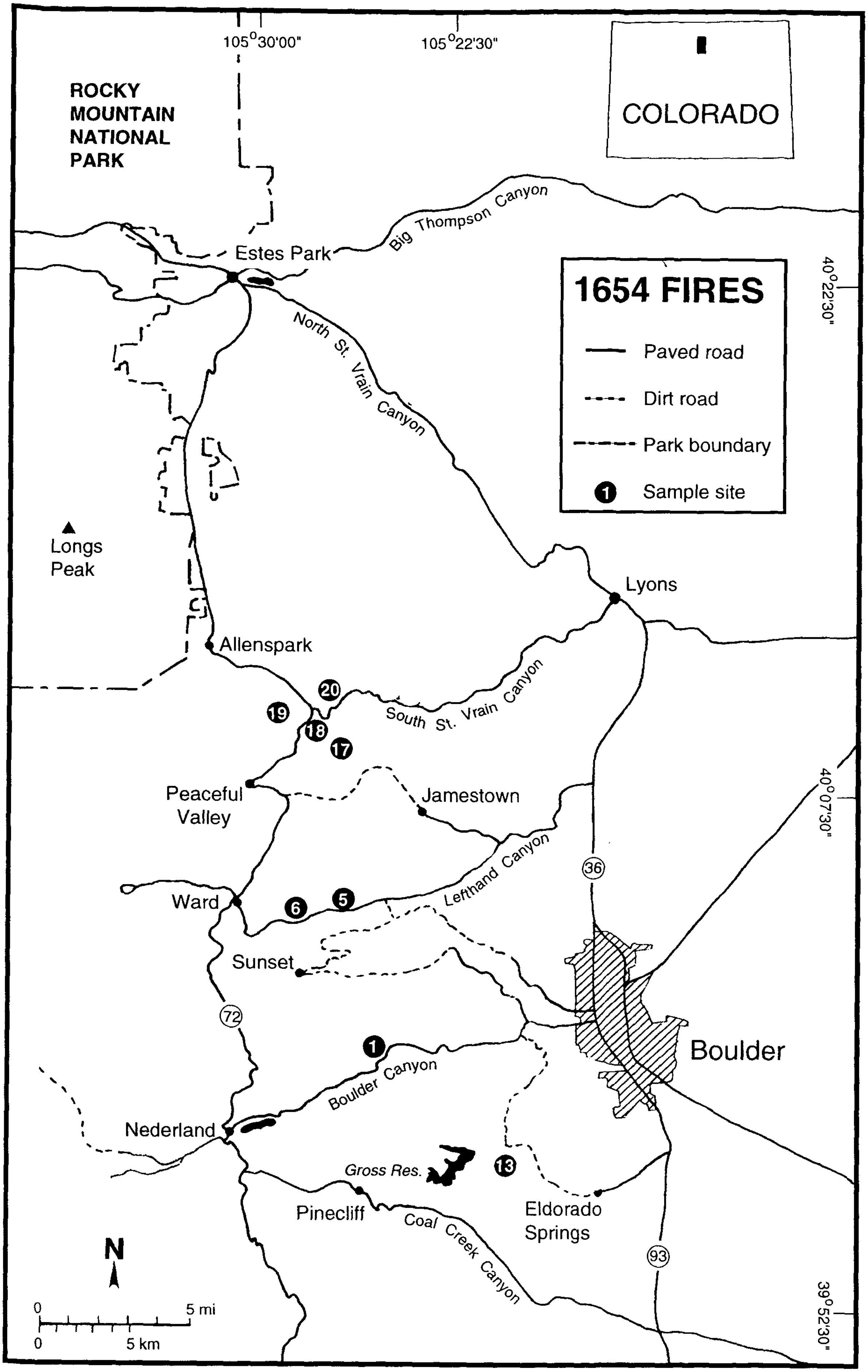

Fig. 8. Locations of sites recording fire in 1654. Among the 14 sites with fire-scar susceptible trees, 50% recorded fire.

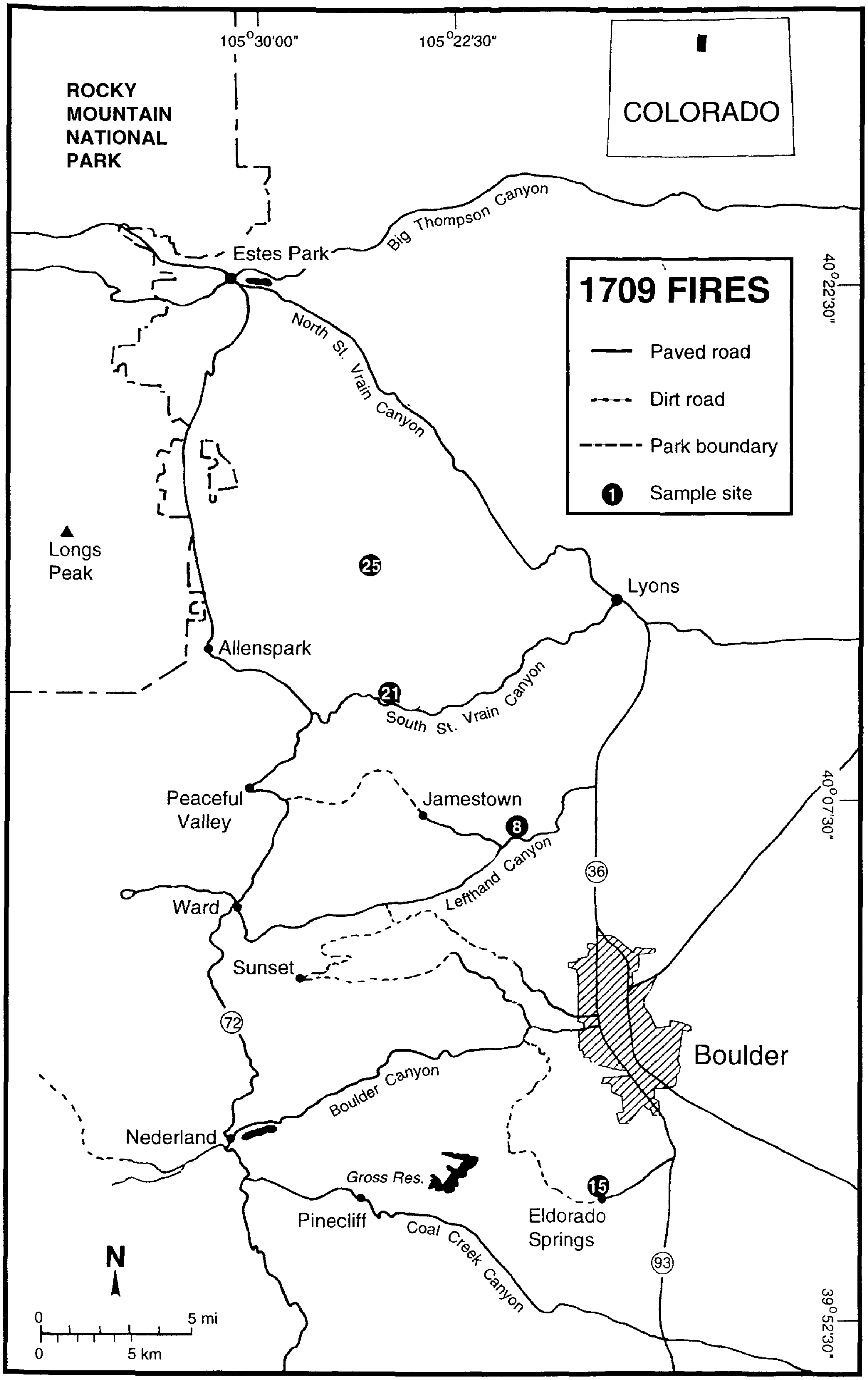

Fig. 9. Locations of sites recording fire in 1709. Among the 24 sites with fire-scar susceptible trees, 17% recorded fire.

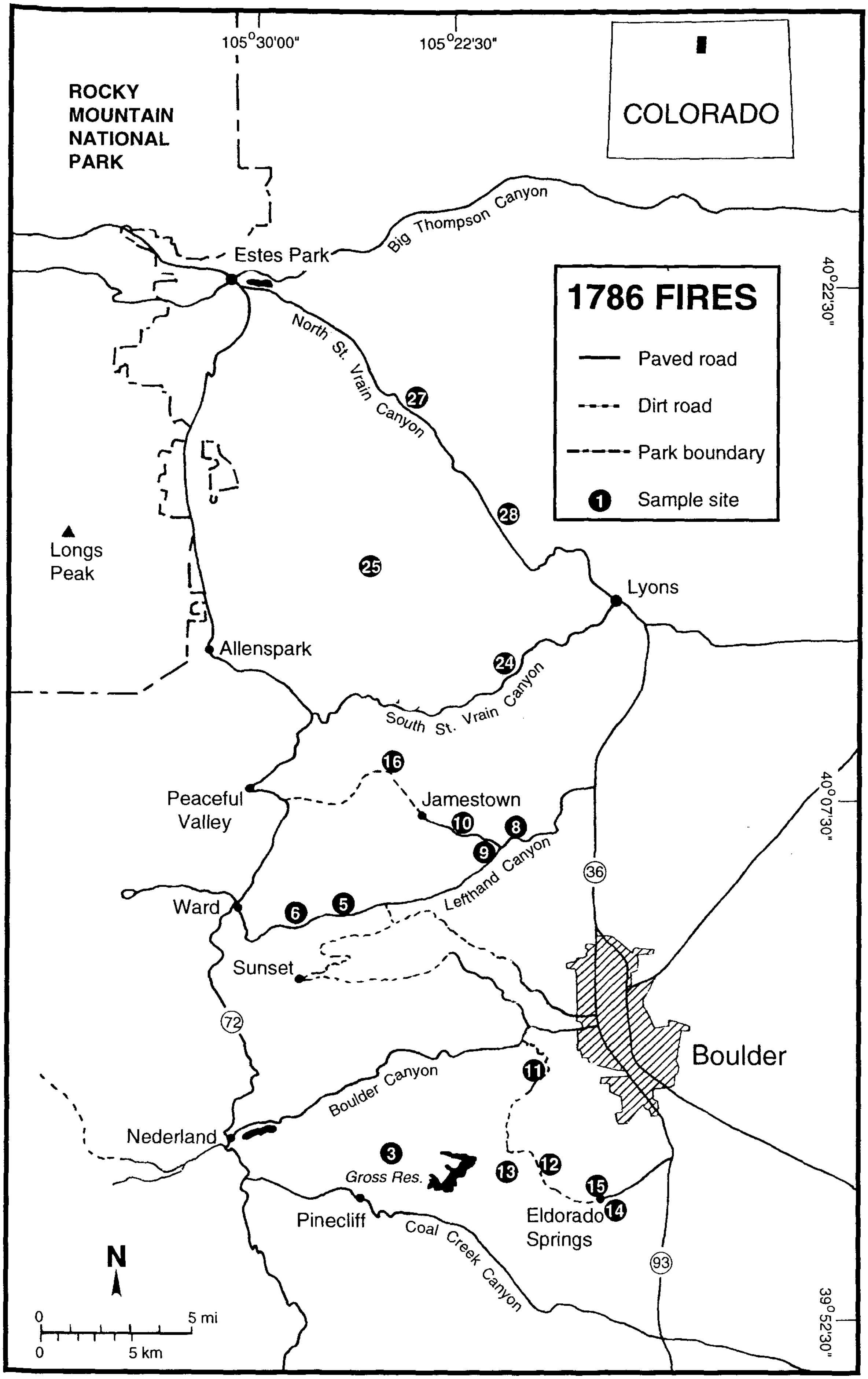

Fig. 10. Locations of sites recording fire in 1786. Among the 30 sites with fire-scar susceptible trees, 53% recorded fire.

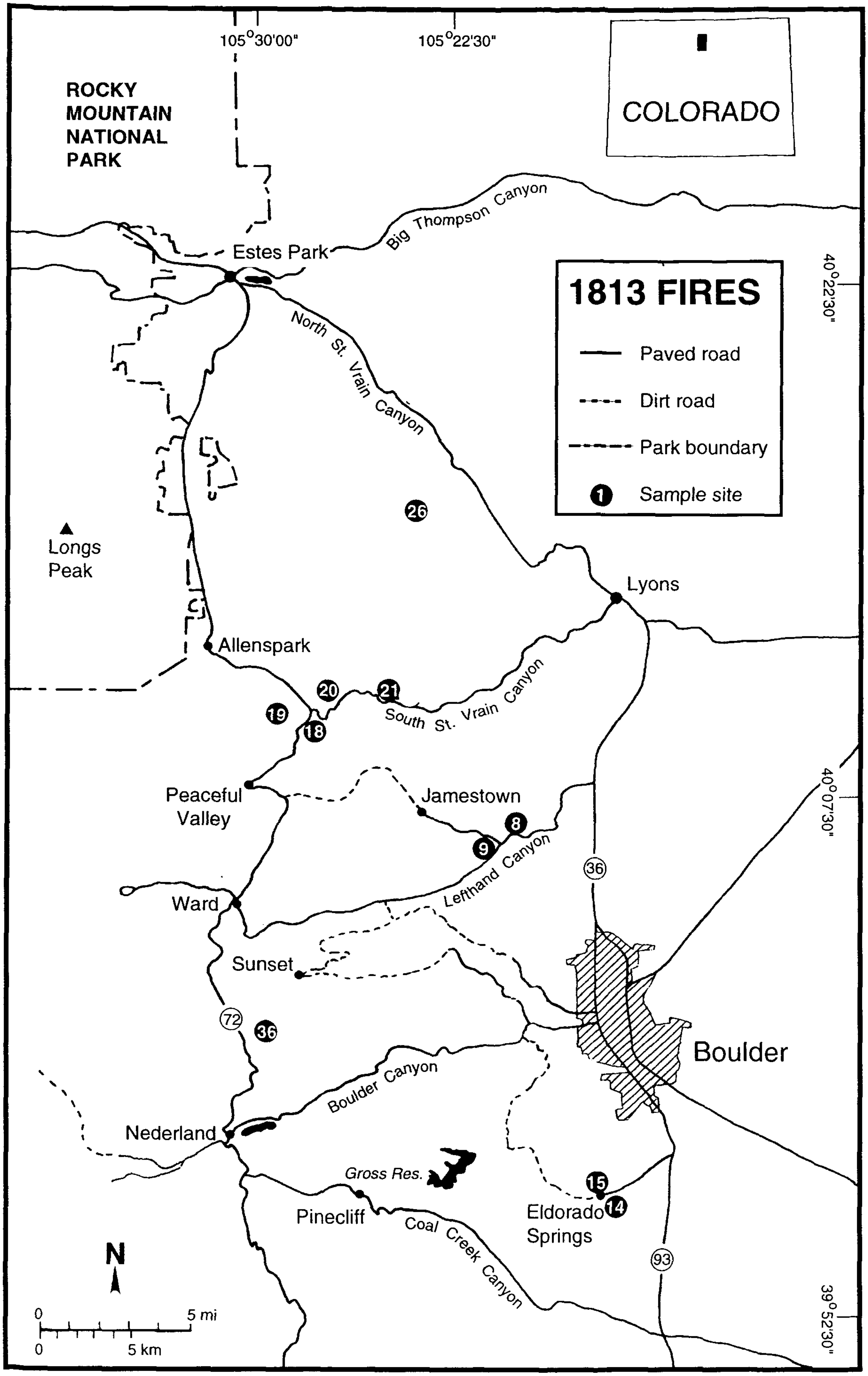

Fig. 11. Locations of sites recording fire in 1813. Among the 33 sites with fire-scar susceptible trees, 30% recorded fire.

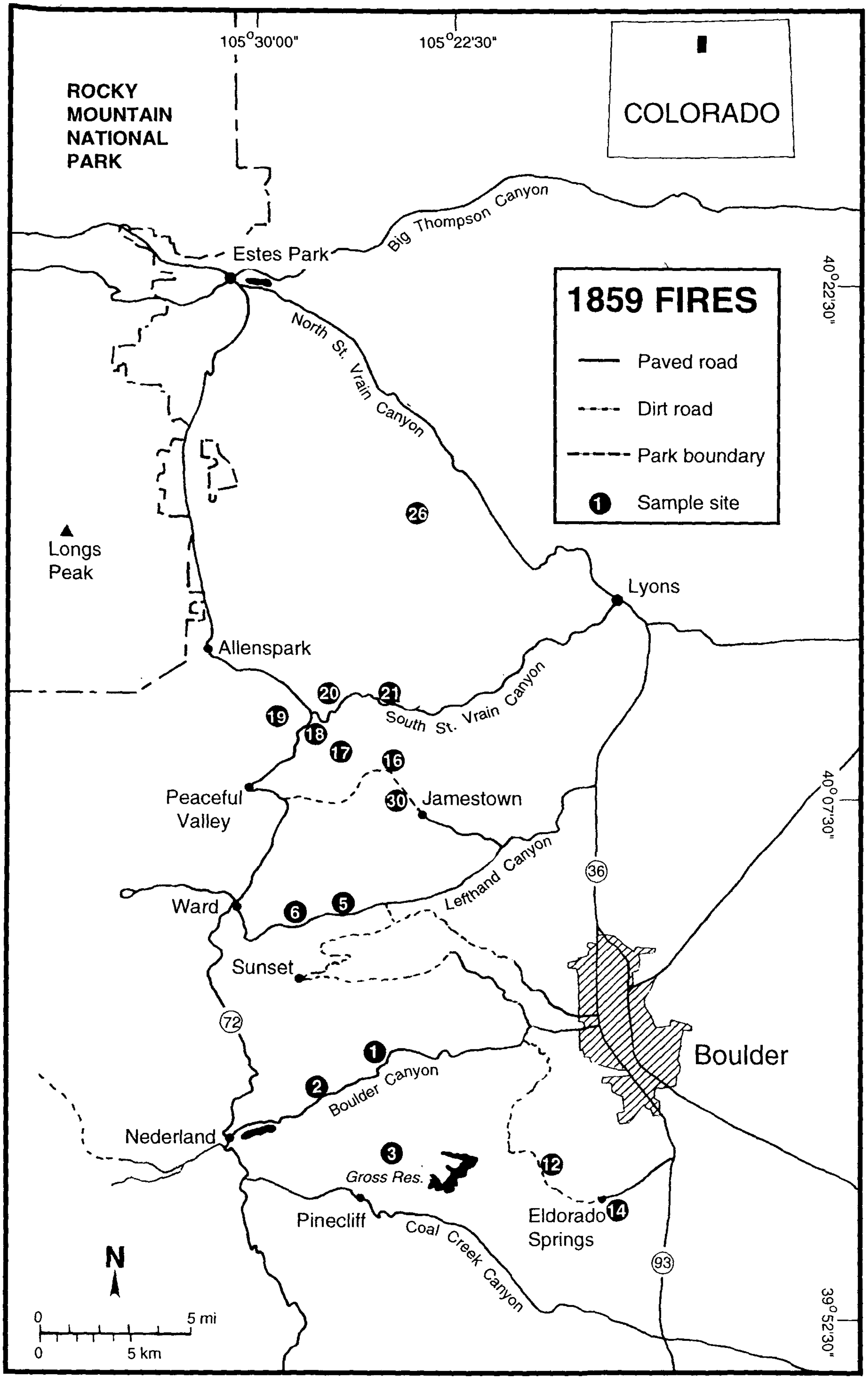

Fig. 12. Locations of sites recording fire in 1859. Among the 38 sites with fire-scar susceptible trees, 47% recorded fire.

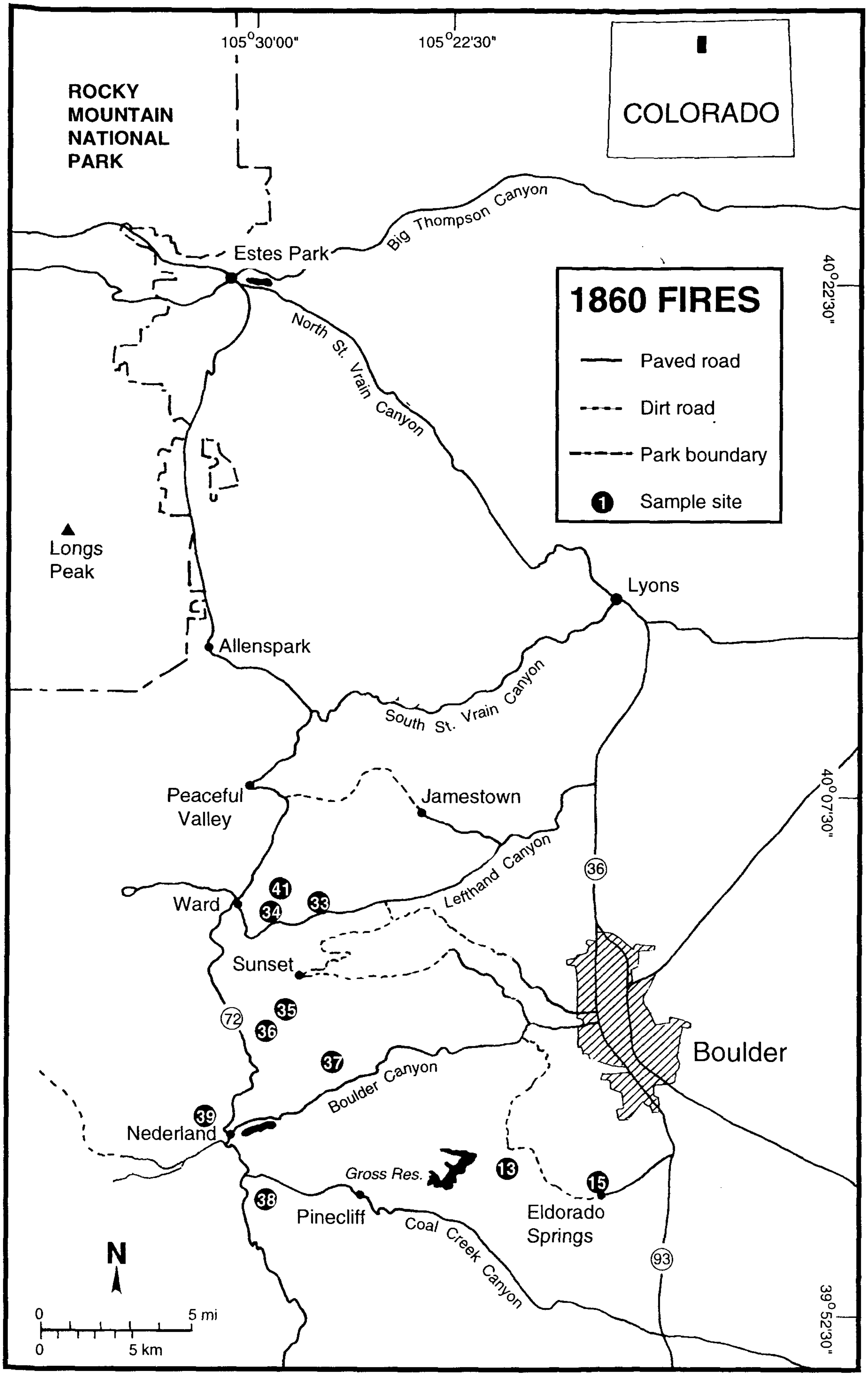

Fig. 13. Locations of sites recording fire in 1860. Among the 38 sites with fire-scar susceptible trees, 26% recorded fire.

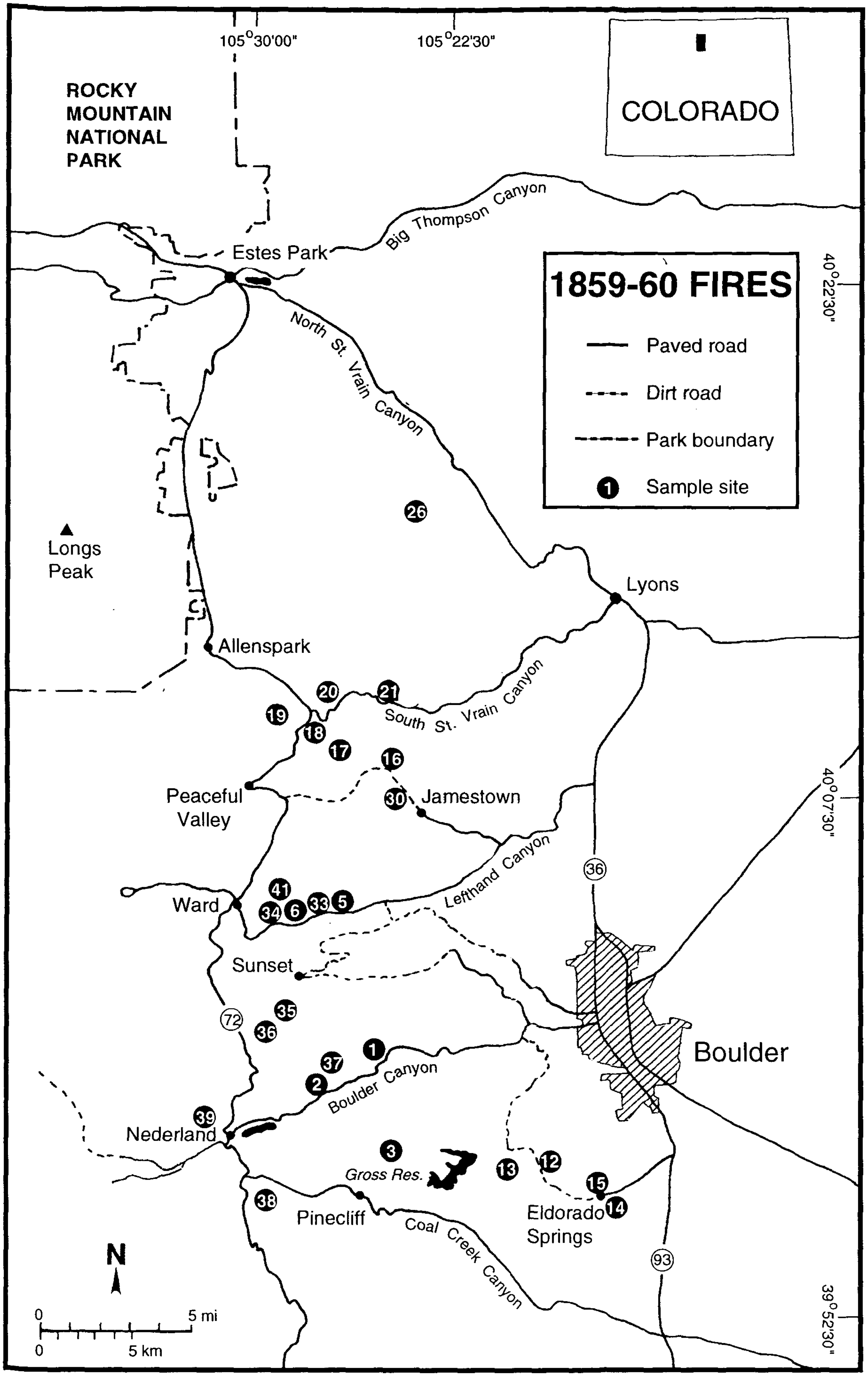

Fig. 14. Locations of sites recording fire in 1859-1860. Among the 38 sites with fire-scar susceptible trees, 66% recorded fire.

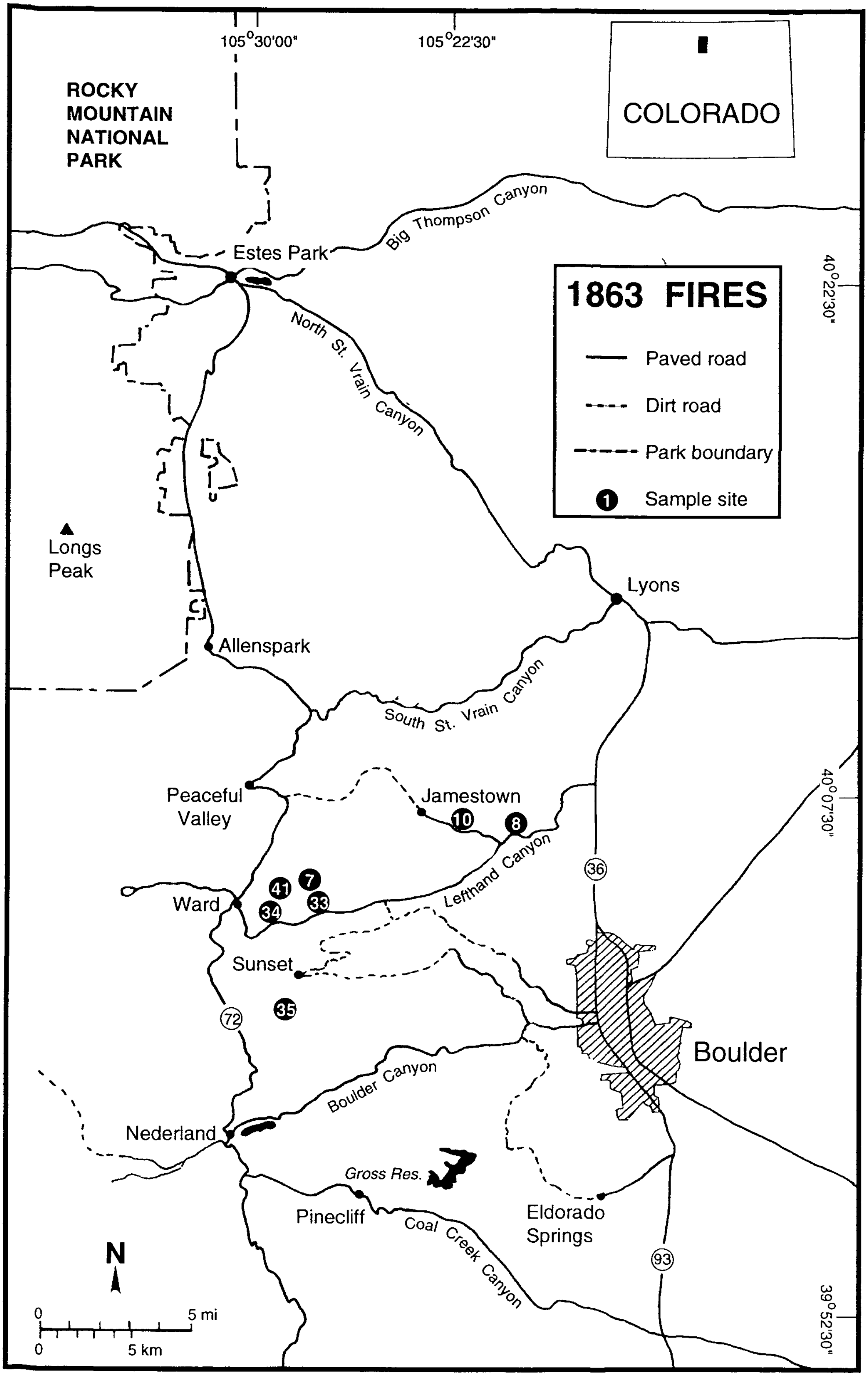

Fig. 15. Locations of sites recording fire in 1863. Among the 39 sites with fire-scar susceptible trees, 18% recorded fire.

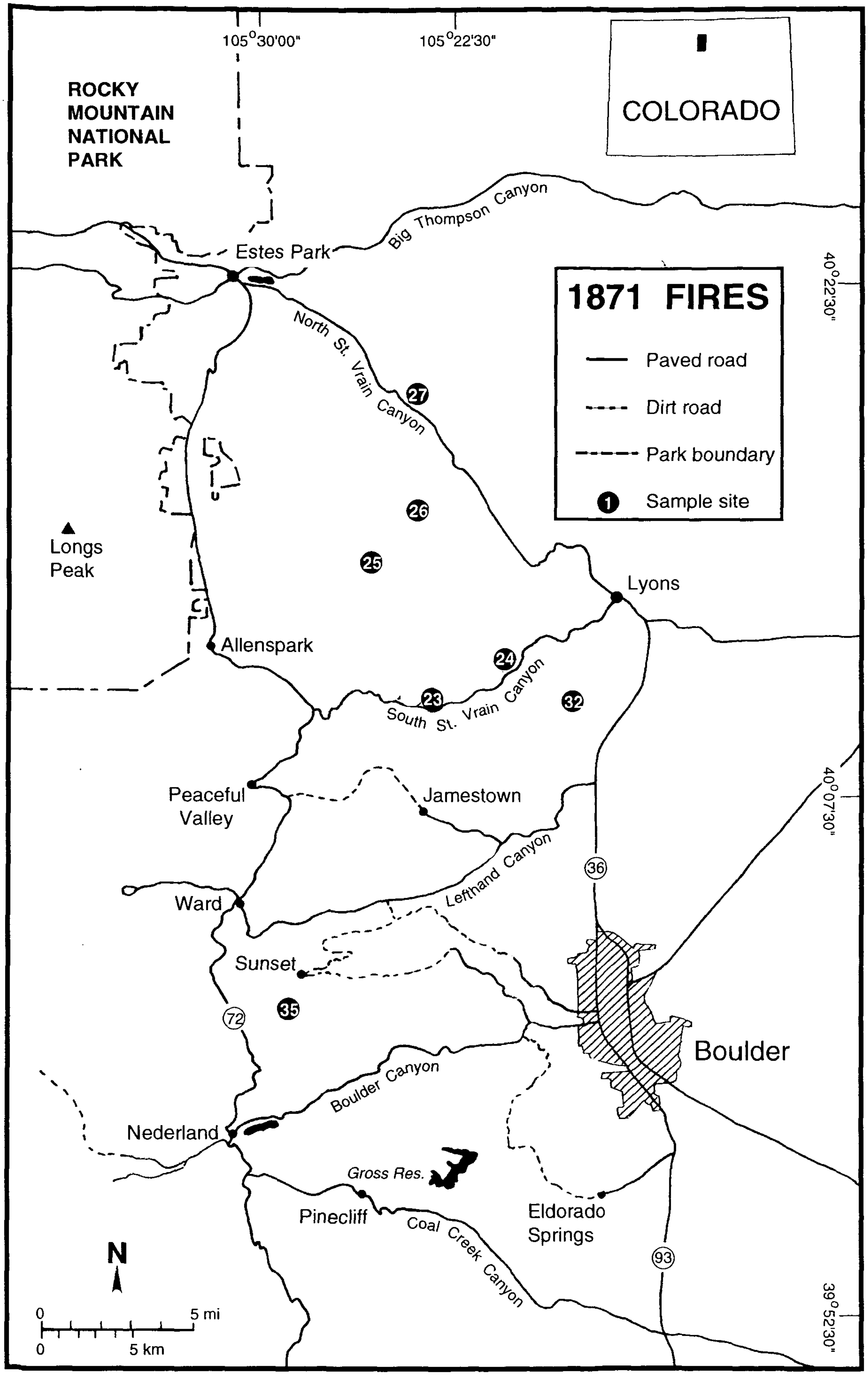

Fig. 16. Locations of sites recording fire in 1871. Among the 39 sites with fire-scar susceptible trees, 18% recorded fire.

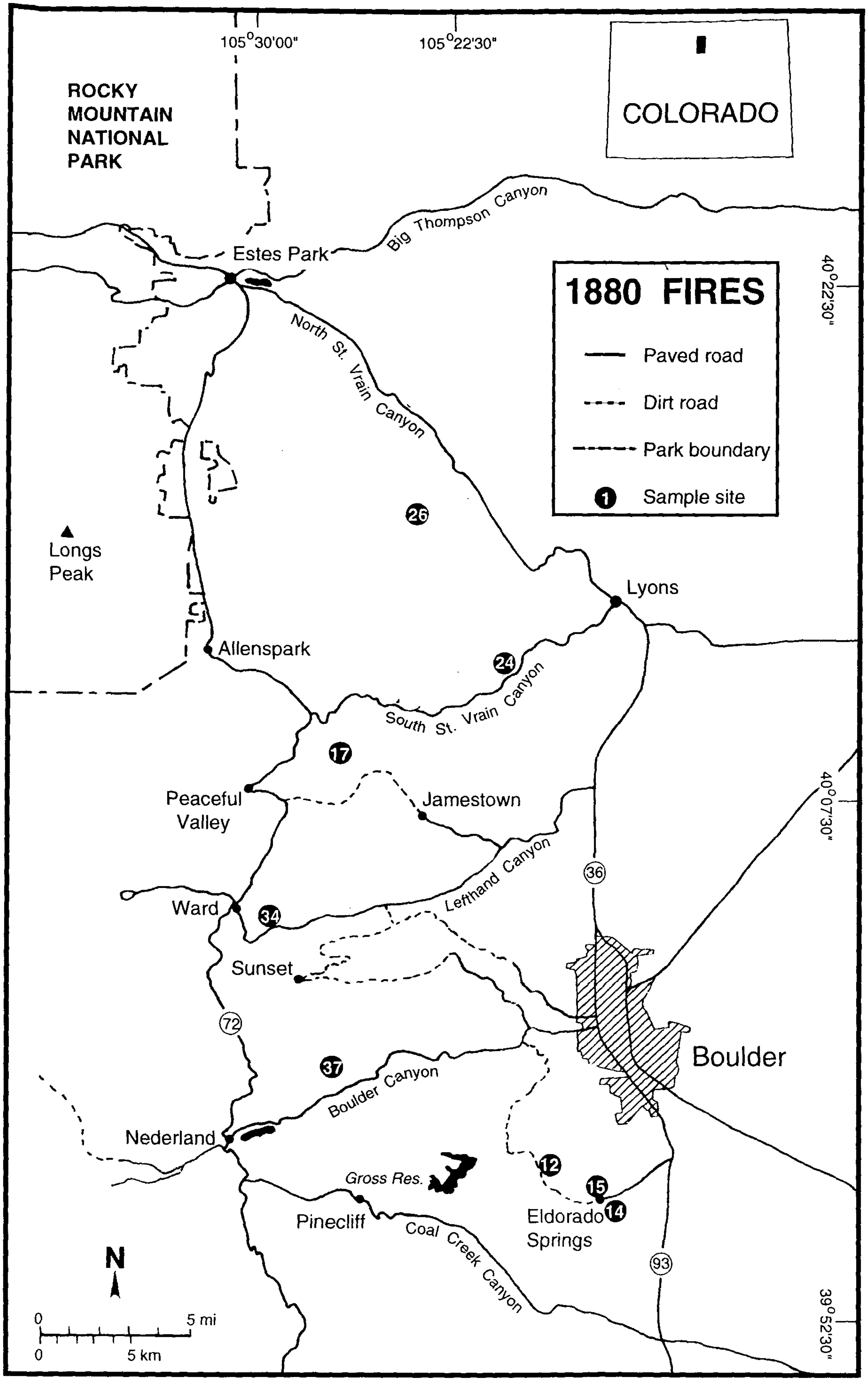

Fig. 17. Locations of sites recording fire in 1880. Among the 40 sites with fire-scar susceptible trees, 20% recorded fire.

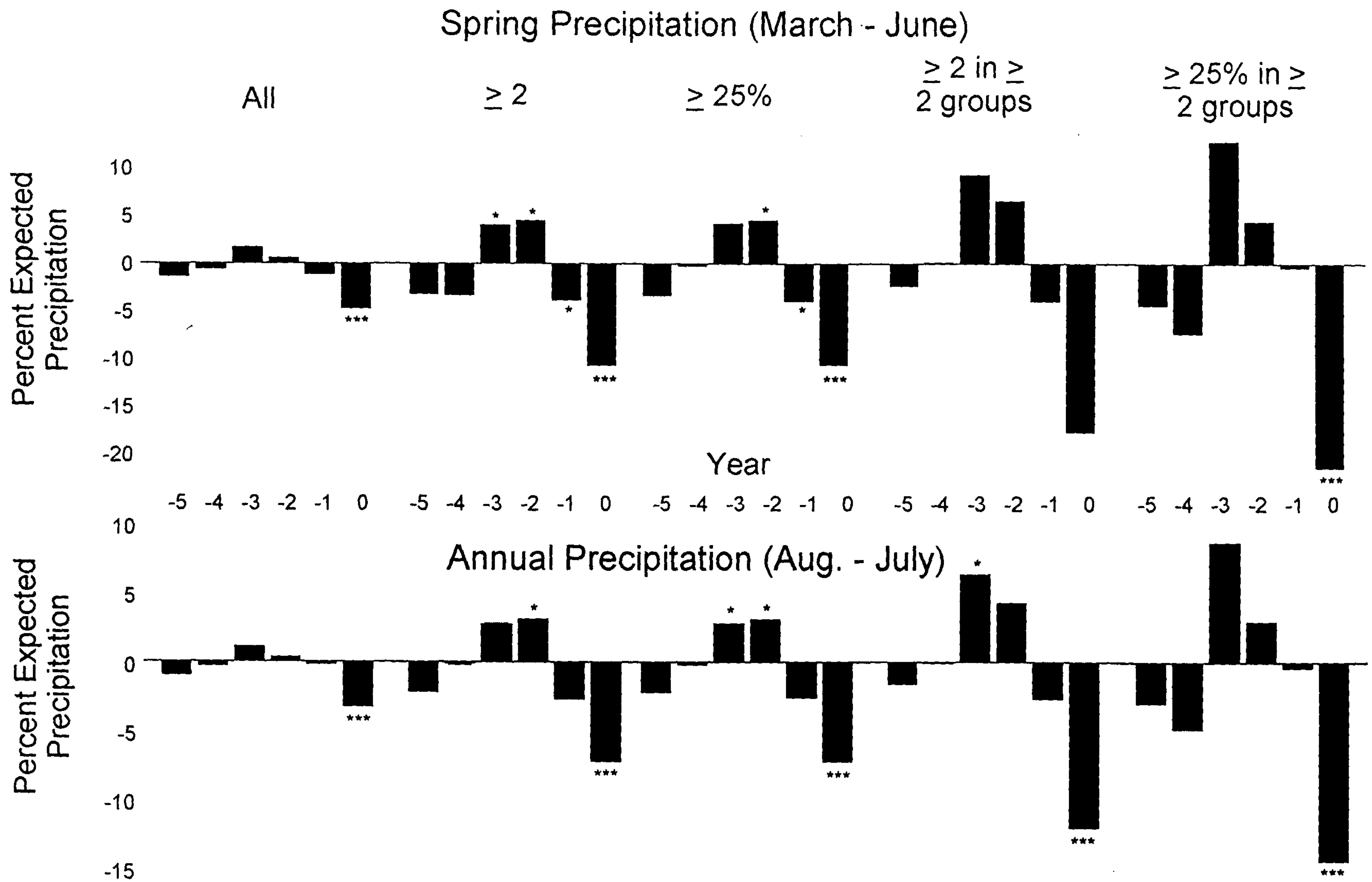

Fig. 18. Deviations (percentage) from expected precipitation during years of different fire events as determined from superposed epoch analyses for the full fire records from all 41 sites combined. Fire events are arranged from least severe (left) to most severe (right). Types of fire events are: all, one or more scars at any site; ≥ 2, two or more scars in any group; ≥ 25%, at least 25% of the fire-scar susceptible trees scarred (minimum two scars) in any group; ≥ 2 in ≥ 2 groups, two or more scars in at least 2 groups; and ≥ 25% in ≥ 2 groups, at least 25% of the fire-scar susceptible trees (minimum 2 scars) scarred in two or more groups. Groups are defined in Table 2. Statistical significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), *** ($P < 0.001$).