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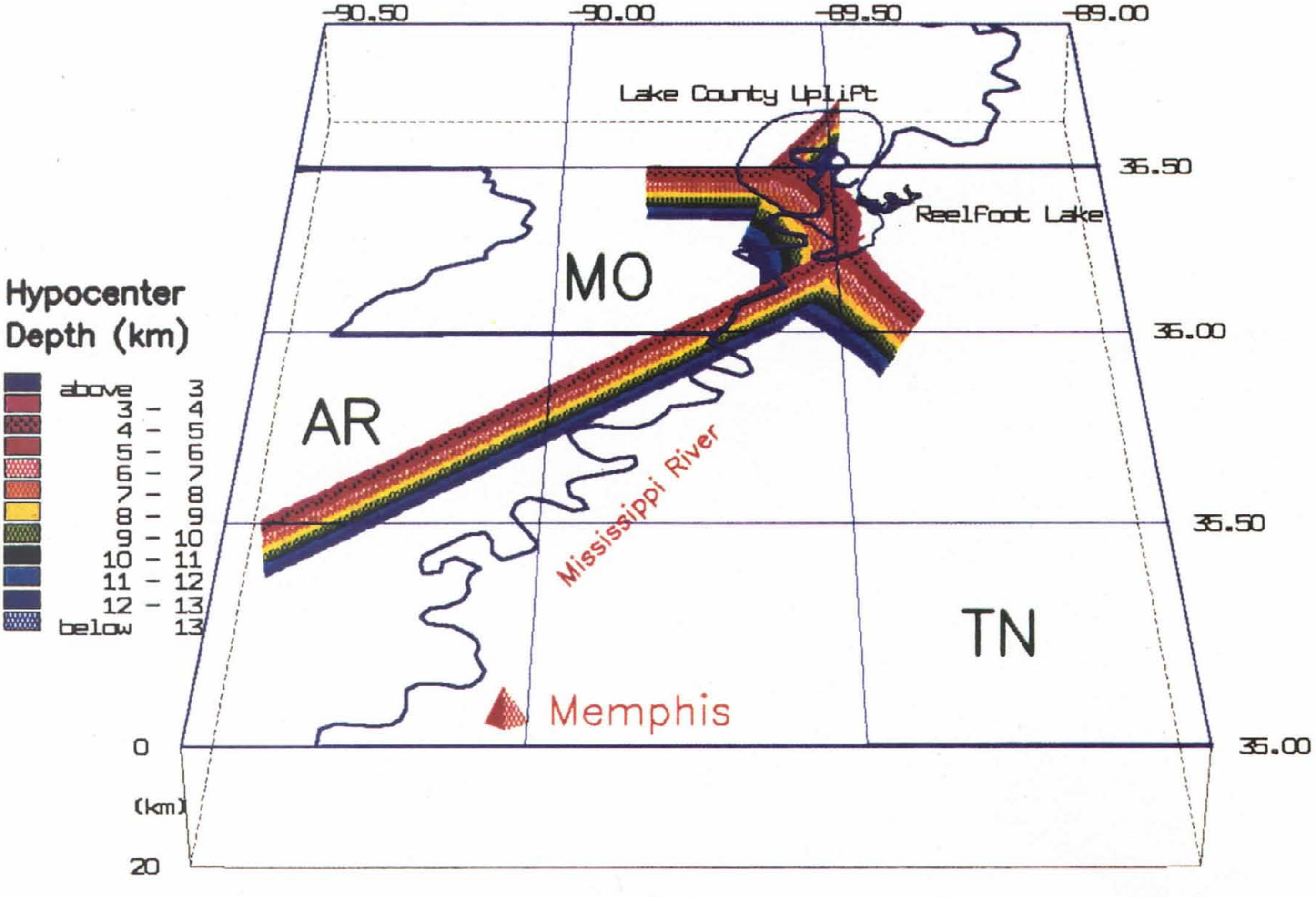

3D Active Fault Zone Geometry of the NMSZ

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TECTONIC SIGNAL IN BALDCYPRESS TREES AT REELFOOT LAKE, TENNESSEE

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ABSTRACT

Tree-ring analyses of baldcypress (*Taxodium distichum*) from Reelfoot Lake, Tennessee, support historical accounts that the lake formed during the great New Madrid earthquakes of 1811-1812. Due to ground subsidence and permanent flooding all of the bottomland hardwood trees within the impounded area were killed. However, many water tolerant baldcypress survived, and hundreds of 200 to 800 year old baldcypress outline the positions of former stream channels drowned by the subsidence. Dendrochronological analyses of multiple cores from 21 baldcypress in the lake reveal several pronounced growth responses to the 1811-1812 earthquakes. These responses include a great surge in radial growth during the decade following the earthquakes and a permanent reduction in wood density beginning in 1812. These and other growth responses to the 1811-1812 earthquakes may allow detection and dating of other large earthquakes in the Reelfoot basin during the late Holocene and may help date the formation of other suspected sunk lands in the New Madrid seismic zone.

INTRODUCTION

Reelfoot Lake of western Tennessee is reported to have formed during the great New Madrid earthquakes of 1811-1812 (Figure 1) (Fuller, 1912). Tectonic uplift of the Tiptonville dome and probable concurrent subsidence of the Reelfoot basin are believed to have occurred during the 1811-1812 earthquakes (Fuller, 1912; Crone and Brockman, 1982; Russ, 1982), and these deformations apparently impounded the west-flowing Reel Foot River to create the 36 km^2 lake. Reelfoot scarp marks the surface flexure and overlies the Reelfoot bedrock fault (Hamilton and Zoback, 1982) that separates the Lake County uplift from the Reelfoot Lake basin (Russ, 1982; Crone and Brockman, 1982). A map of Tennessee published in 1795 (Figure 2) reveals that the Reel Foot River flowed through the area that is now Reelfoot Lake and entered the Mississippi River west of Tiptonville, Tennessee. This map indicates that Reelfoot Lake did not exist in 1795 (Figure 2). A land survey conducted by Henry Rutherford in 1785 (Tennessee Historical Society, Nashville) defined the boundaries of the Doherty Grants. As discussed in Rutherford's survey notes and illustrated in Figure 3 the Grant boundaries were surveyed when the area was the Reel Foot River (creek) basin, prior to the formation of Reelfoot Lake (Glenn, 1933).

As a consequence of severe ground shaking and flooding of the Reel Foot River basin, most of the hardwood trees within the newly formed Reelfoot Lake were killed (Fuller, 1912). However, baldcypress (*Taxodium distichum*) can tolerate partial inundation and many 200 to 800 year old baldcypress trees survive today in Reelfoot Lake.

The principal objective of this study is to identify a tree growth response to the formation of Reelfoot Lake preserved in the annual growth rings of old baldcypress trees still living in Reelfoot

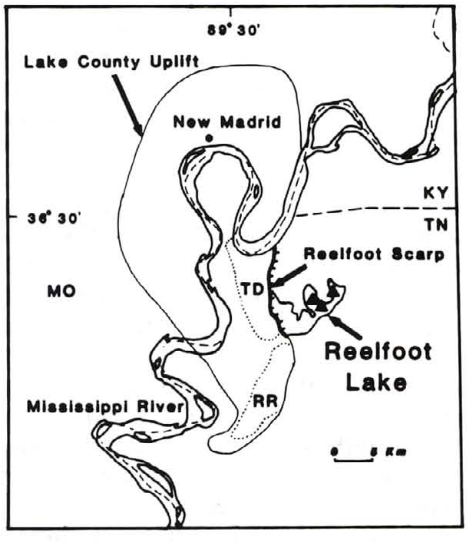

Fig. 1. Reelfoot Lake area of Tennessee and Missouri. TD = Tiptonville dome, RR = Ridgely ridge, triangles = baldcypress sample site. Modified from Russ (1982).

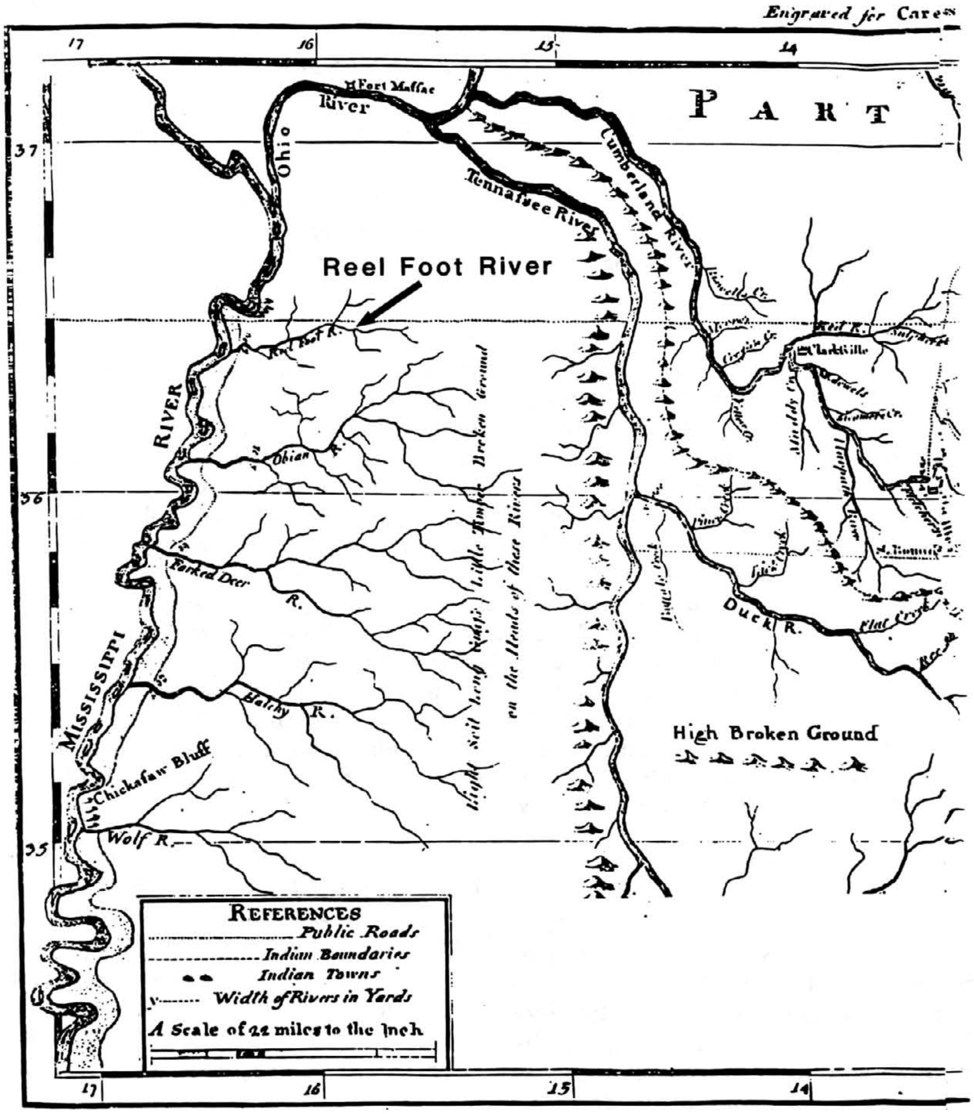

Fig. 2. Western portion of a map of Tennessee entitled "Map of the Tennassee Government formerly part of North Carolina taken Chiefly from Surveys by Gen. D. Smith & others", published in 1795. A copy of the map was obtained from the Tennessee State Library and Archives in Nashville, TN.

Lake. An exactly dated growth response should help confirm the formation of Reelfoot Lake in 1811-1812. The spatial distribution of a distinctive baldcypress growth response to the 1811-1812 earthquakes might help identify the regional impact of these great quakes and this information could provide useful constraints on the magnitude of these events. The past occurrence of a distinctive growth response similar to the 1811-1812 response in long baldcypress tree growth records from Reelfoot Lake, and perhaps in other suggested sunkenlands elsewhere in the vicinity, might also provide evidence concerning the previous occurrence of similar large magnitude earthquakes in the New Madrid seismic zone (NMSZ). For these purposes, a baldcypress tree growth response is defined as a large, statistically significant, radial growth anomaly in the Reelfoot Lake tree-ring chronology when compared with other baldcypress growth chronologies in the region (Figure 4). Baldcypress tree-ring chronologies (i.e. exactly dated estimates of annual tree growth) in the lower Mississippi Valley of Missouri, Arkansas, Tennessee, and northern Mississippi are highly and significantly correlated because the radial growth of these swamp-grown trees is strongly influenced by the regional climate, particularly the history of wet and dry years (Stahle *et al.*, 1985a,b; Stahle *et al.*, 1991). Because a large growth response to the 1811-1812 earthquakes should be present in trees at Reelfoot Lake, but not in baldcypress trees located some distance away from the

NMSZ, the growth differences between the Reelfoot tree-ring chronology and unaffected chronologies elsewhere in the region should allow the exact dating and quantitative measurement of the Reelfoot growth response to the 1811-1812 earthquakes. This growth response might then be useful for further temporal and spatial investigations of large magnitude seismicity in the NMSZ.

Bowers (1975) pioneered the tree-ring analysis of baldcypress and first suggested that radial growth anomalies in cypress trees might help outline the regional impact of the 1811-1812 earthquakes. However, the use of trees to help decipher earthquake impacts in the lower Mississippi Valley is an old idea, and can be traced at least as far back as the visit of Sir Charles Lyell to the NMSZ in 1846 (Lyell, 1849). In fact, Lyell concluded that large convulsions similar to the 1811-1812 earthquakes were not likely to have occurred for "many centuries previous to 1811", due to the absence of surficial features and absence of dead trees older than those associated with the 1811-1812 events (Lyell, 1849: 238-239).

Tree-ring analyses along the Fairweather fault in Alaska (Page, 1970) and the San Andreas fault in California have demonstrated the effectiveness of dendrochronology in the paleoseismological study of surface faults (LaMarche and Wallace, 1972; Meisling and Sieh, 1980; Jacoby *et al.*, 1988). These authors document a number of ways in which trees have been affected by seismic activity. The most common observations in these studies include the detrimental effects on subsequent tree growth due to lost canopies, tree tilting, and the severing of roots by fault rupture. These detrimental effects resulted in the formation of narrow annual rings, or in some cases the complete cessation of radial growth, in the years immediately following the earthquakes.

As described below, baldcypress trees in Reelfoot Lake have recorded the coseismic impoundment of the Reelfoot Lake basin primarily by the

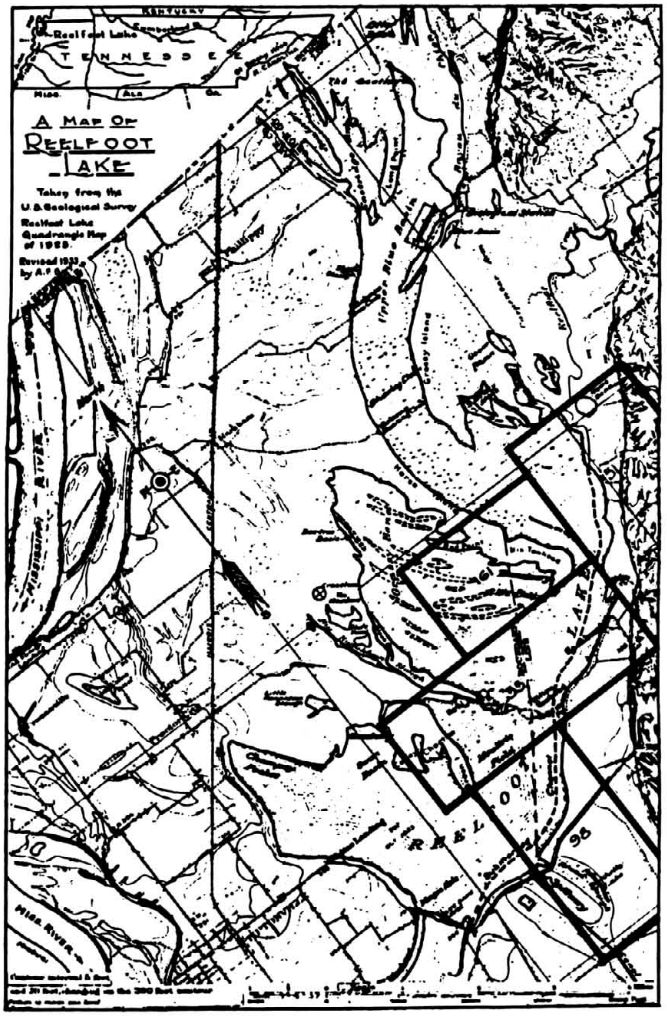

Fig. 3. A map of Reelfoot Lake area from Glenn (1933). The Doherty Grants surveyed by H. Rutherford in 1785 are outlined in heavy rectangular blocks over the present Reelfoot Lake.

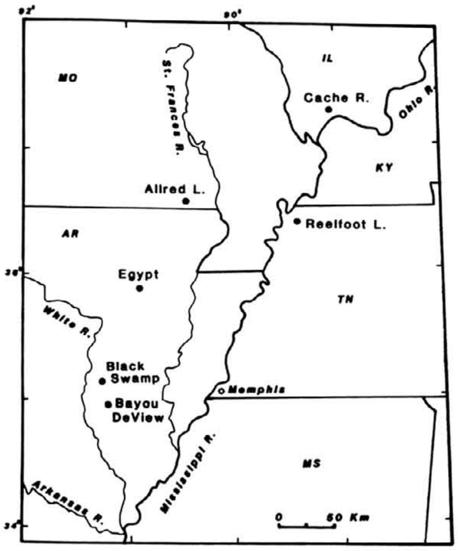

Fig. 4. Baldcypress tree-ring chronology sites in the Mississippi valley.

growth enhancing effects of the radically altered hydrological regime. However, some qualitative growth response and tree damage data associated with the 1811-1812 events are also evident in the tree-ring analyses of these ancient baldcypress trees surviving in Reelfoot Lake. These various data suggest that dendrochronology may prove to be a valuable tool in future New Madrid paleoseismic studies.

BALDCYPRESS TREE-RING CHRONOLOGY DEVELOPMENT AT REELFOOT LAKE

Forty-eight living baldcypress trees were sampled in Reelfoot Lake with one to four cores taken from each tree with a Swedish increment borer (Stokes and Smiley, 1968). Cores were extracted above the hanging buttresses common on these trees (see Kurz and Demaree, 1934, for a discussion of the hanging buttresses of Reelfoot Lake) and the annual rings were dated to their exact year of formation and then measured with a precision of 0.01 mm (Stokes and Smiley, 1968). For quality control a cross-correlation procedure was used to confirm the dating and measurement accuracy of each annually dated ring-width series (Holmes, 1983).

To develop the tree-ring chronology for Reelfoot Lake, all ring width measurements for each core were first "standardized" using the ARSTAN program (Cook and Holmes, 1984). This detrending procedure involves fitting an expected growth curve to the ring width measurements and then dividing the measurements by the corresponding curve value at each available year. The expected growth curves fit to the ring-width data were typically negative exponentials, inflexible smoothing splines, or straight lines of negative slope (Cook and Holmes, 1984). The tree-ring indices thus derived for each core are dimensionless with a mean of 1.0. This standardization procedure is

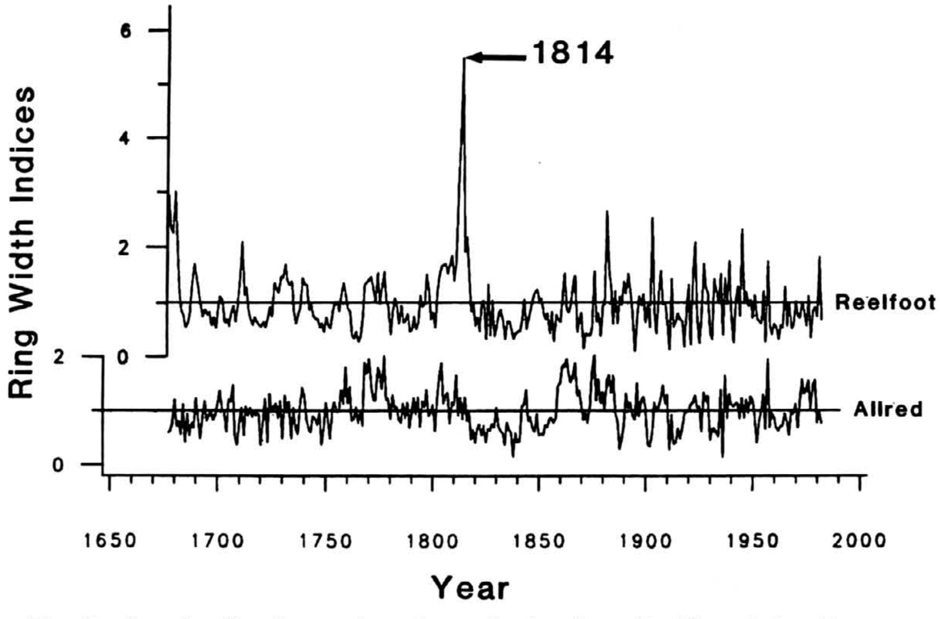

Fig. 5. Standardized tree-ring chronologies from Reelfoot Lake, Tennessee, and Allred Lake, Missouri. These mean ring-width index chronologies are dimensionless indices of growth for each year. Biological or age-related growth trends were removed and each core series was indexed before averaging into the chronology. Growth trend was not entirely removed from two cores that comprise the first 5 years of the Reelfoot Lake chronology.

necessary to remove age-related growth trend typically present in ring-width data, and also to minimize the influence of different mean growth rates on the computation of the final site chronology.

An enormous growth surge after 1811 is found in the middle of most Reelfoot Lake ring-width time series and presents particular difficulties for proper standardization. In fact, the periods of below average growth noted at Reelfoot from ca. 1750 to 1800 and ca. 1820 to 1880 (Figures 5 and 7 below) may partly represent artifacts of standardization. Additional ring width data from the centuries prior to 1800, and additional analyses will be needed to overcome these potential curve-fitting problems. It is clear, however, that the curve fitting has nothing to do with the huge and unprecedented growth surge in the few years after 1811.

Once the ring width indices were derived for each core, all available indices for each year from 1677 to 1990 were averaged to complete the standard chronology for Reelfoot Lake (Figure 5, top). The indices were averaged using a robust mean value function which discounts the influence of

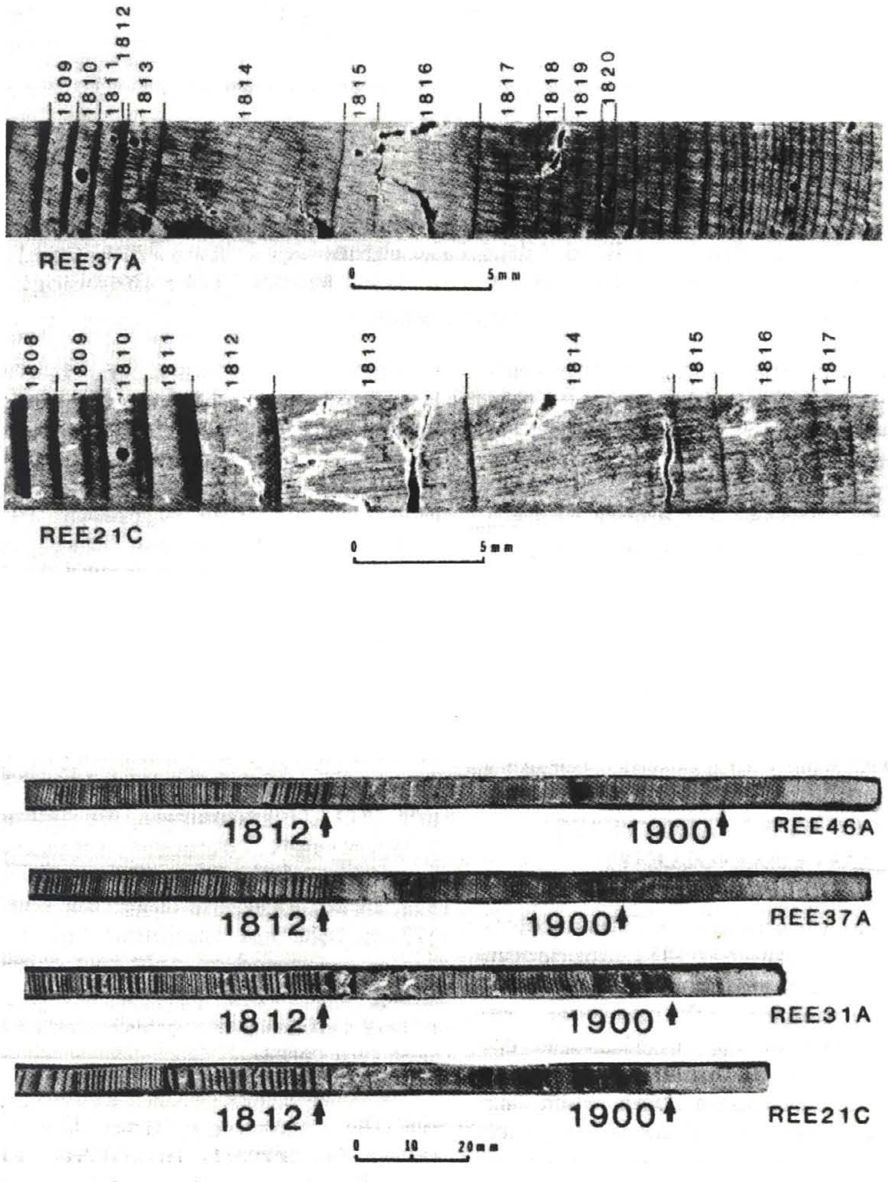

Fig. 6. These photographs of annual growth rings in baldcypress from Reelfoot Lake illustrate the dramatic changes which occurred following the earthquakes of 1811-1812. Note the surge in radial growth centered on 1814 (cores REE 21C and REE 37A, top), and the permanent decline in the density of the dark latewood layer following 1811 (illustrated in these photographs by a decrease in the width and darkness of the latewood, top and bottom).

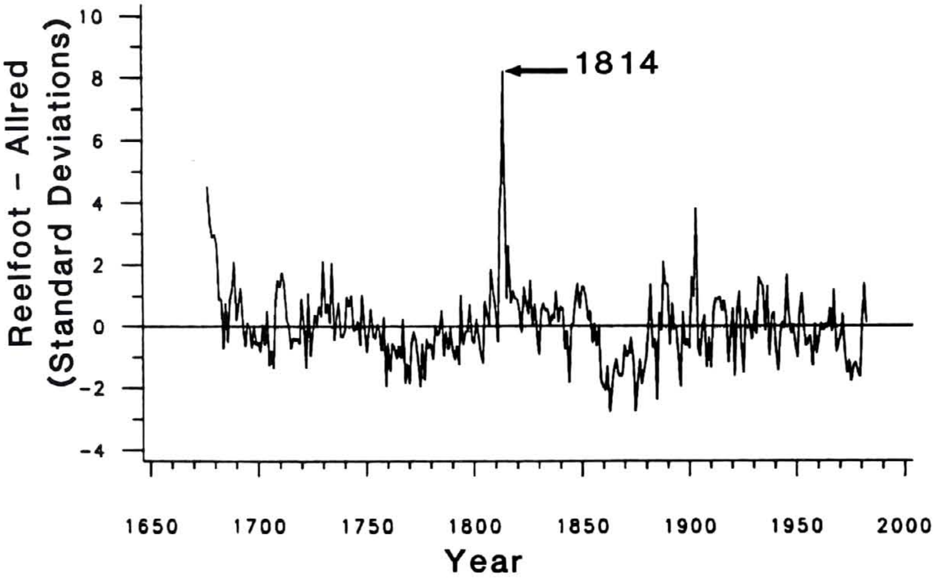

Fig. 7. The Reelfoot Lake chronology after the regional climate signal evident in the normalized Allred Lake chronology (Figure 5, bottom) has been subtracted from the normalized Reelfoot Lake chronology (Figure 5, top).

statistical outliers on the computation of the index average for each year (Cook and Holmes, 1984). The number of index series (i.e. cores) available for each year increases from 2 in 1677 to 33 in 1989, and the chronology is very well replicated by 1812 with 36 series from 20 trees. A number of trees over 200 years old were not dated primarily because the cores are too broken and the growth rings are too suppressed during the 18th century. Consequently, the Reelfoot chronology prior to 1800 is based primarily on relatively vigorous, fast-growing trees, and does not fully reflect the adverse growing conditions of the late 18th century noted on most cores and partially illustrated in Figures 5 (top) and 7.

DISCUSSION OF THE BALDCYPRESS TREE-RING CHRONOLOGY FROM REELFOOT LAKE

The Reelfoot Lake chronology exhibits an obvious growth response to the 1811-1812 inundation. Ring width indices fluctuate about a value of 1.0 for most of the chronology with one very pronounced growth surge starting in 1812 and continuing until 1819 (Figure 5). Individual 1812 rings are extremely variable with some being much narrower than the 1811 ring and others being much wider (Figure 6). No obvious spatial patterns are apparent in the available ring width variations for 1812 which might reflect depth of inundation, or perhaps degree of tree damage, but the spatial distribution of dated trees at Reelfoot is still rather limited and interesting spatial patterns in tree growth for 1812 (and subsequent years) may indeed emerge given more widespread sampling of old trees. Nevertheless, by 1813 all of the trees have extremely wide rings (Figures 5 and 6), and the mean index value for 1814 is the largest ever observed in any baldcypress tree-ring chronologies yet developed (e.g. Stahle *et al*, 1985a). This enormous growth surge is present in almost every dated core from Reelfoot Lake, and appears to reflect the radically improved water budget of these drought-sensitive trees (c.f. Stahle *et al*, 1985b). This growth surge in fact biases to some extent the ring width indices computed for each core, and thus the average chronology derived from these cores, because the expected growth curves used for the detrending and standardization of each core tend to be raised by the growth surge after 1811. Nevertheless, this standardization bias is conservative because it tends to diminish the magnitude of the growth response from 1812 to 1819. In addition, the large ring width indices from 1677 to 1682 are attributed to the rapid juvenile growth measured on only two cores from one tree during this time period. Detrending failed to entirely remove the growth trend from the first of these two cores.

A comparison of the Reelfoot Lake chronology with the chronology from Allred Lake, Missouri (Figure 4), reveals that Allred Lake baldcypress trees did not experience a similar growth surge from 1812 to 1819 (Figure 5). Allred Lake is a small oxbow lake 85 km west of New Madrid, Missouri, and 100 km west of Reelfoot Lake, and almost certainly was formed centuries prior to the earthquakes of 1811-1812. Reelfoot Lake is the only tree-ring collection site in the mid-continent that shows a growth surge at this time and, in the experience of this research group, this is the largest stand-wide growth surge ever documented in baldcypress.

A second growth anomaly in the Reelfoot Lake data is a major decrease in latewood density beginning in 1812 and continuing through 1990, which is visually apparent as lighter colored wood (Figure 6). (Latewood or summerwood refers to the usually darker, more heavily lignified xylem cells that terminate the annual growth layers of many midlatitude trees.) We have not yet quantified this density change, but have no doubt that the obvious density decrease after 1811 is significant and related to the radically altered hydrological regime following inundation in early 1812.

A third characteristic of the Reelfoot cores is that there are numerous cracks and breaks in the pre-1812 portions of the cores whereas the post-1812 portions of the cores are generally solid. We suspect that the numerous pre-1812 cracks reflect the physical damage sustained by these trees during the 1811-1812 earthquakes.

The Allred Lake chronology is included in Figure 5 (bottom) for comparison with the Reelfoot chronology. Baldcypress in Reelfoot Lake have experienced essentially the same climate as Allred Lake and therefore they should have very similar chronologies. The baldcypress trees at the Allred Lake site were apparently not immediately affected by the 1811-1812 earthquakes because the chronology shows no anomalous growth departures during the 1812-1820 period, no density changes after 1812, and the cores are not excessively cracked prior to 1812 (Stahle *et al.*, 1985a). However, the Allred Lake chronology does exhibit a period of reduced growth from 1820 to 1860 that might not be entirely climatic in origin. A tree-ring reconstruction of the Palmer drought severity index for June in Arkansas (Stahle *et al.*, 1985b) does indicate several droughts during this period (especially in the 1830's), but the persistent low growth at Allred Lake is not fully matched by the drought reconstruction, and could conceivably be linked to physical injury caused by the earthquakes of 1811-1812 (e.g., loss of canopy or roots due to ground motion). Additional tree-ring chronologies and more detailed analyses will be required to determine whether or not some of the growth reduction from 1820 to 1860 at Allred Lake might be linked to the earthquakes of 1811-1812.

To further compare the climatic signal in the Allred Lake data to the coseismically influenced Reelfoot Lake data both chronologies were normalized and the Allred chronology was subtracted from the Reelfoot chronology (Figure 7). In essence, the climatic variation in the Allred data was subtracted from the Reelfoot data to reveal any residual growth anomaly that might have been seismically or coseismically induced. As revealed in Figure 7, the earthquake spike centered at 1814 is very pronounced, over eight (8) standard deviations from the normalized mean difference.

There are two other large differences between the Reelfoot and Allred Lake chronologies (i.e., in excess of three standard deviations, Fig. 7). The differences in 1677 and 1678 reflect inadequate standardization of the two available cores included in the Reelfoot chronology during this period. The spike in the differenced chronology at 1903 (3.8 standard deviations) reflects accelerated growth at Reelfoot Lake compared with Allred Lake, but cannot presently be explained. Although a magnitude 5.3 earthquake was recorded in 1903 near Reelfoot Lake, the earthquake occurred on November 4, well after the conclusion of the spring-summer growth anomaly in the Reelfoot Lake baldcypress trees. We suspect, but cannot presently demonstrate, that the 1903 anomaly represents climatic or anthropogenic differences between the Reelfoot and Allred Lake sites.

There are also more modest, but prolonged differences between the Reelfoot and Allred Lake chronologies from 1758 to 1770 and from 1854 to 1880. As mentioned, crossdating was not possible through the period 1758-1770 in most of the baldcypress trees from Reelfoot Lake because growth was extremely suppressed and many rings are missing during this time period. Consequently, the growth reduction during this period would probably be more pronounced in Figures 5 and 7 if the undateable cores could be included. Although inadequately quantified, the several potential explanations for this apparent late 18th century growth reduction in the Reelfoot trees would include non-climatic effects perhaps associated with seismic activity along the NMSZ. This hypothesis could be investigated by sampling and dating additional baldcypress collections from sites within, and at increasingly greater distances from the NMSZ.

INTERPRETATIONS AND CONCLUSIONS

A growth response to the formation of Reelfoot Lake is clearly evident in the annual rings of baldcypress trees which survive in Reelfoot Lake, Tennessee (Figures 5 and 6). These trees show a huge increase in radial growth from 1812 to 1819, and the wood density permanently decreased after 1811. This study thus provides field evidence that the Reelfoot basin was inundated during the winter of 1811-1812. After the cypress were flooded to a depth of some 1 to 2 meters they grew lower density wood at a greatly accelerated rate probably because they were not as frequently affected by summer droughts. A third earthquake effect appears to be the extensively broken wood in the pre-1812 portions of the cores.

In addition to the huge growth increase from 1812 to 1819, there are two modest but prolonged growth differences between the Reelfoot and Allred Lake chronologies (growth at Reelfoot was reduced from 1758 to 1770 and from 1855 to 1880 compared with Allred Lake)(Figure 7). There are several possible explanations for these Reelfoot growth reductions, including local climate anomalies, inadequate detrending of the raw ring-width data, seismic effects, or other non-climatic growth disturbances. More detailed analyses of the Reelfoot and other central Mississippi valley baldcypress chronologies will be necessary to explain these two apparent growth reductions at Reelfoot Lake.

This research may have a number of interesting applications. The baldcypress growth response to the 1811-1812 event can be used in a search of older baldcypress trees at Reelfoot Lake for evidence of paleoearthquakes. Trees up to 800 years old have already been discovered at Reelfoot Lake, and it should eventually be possible to extend the exactly dated chronology several hundred years earlier than the current limit of A.D. 1677. This will work, however, only if some portion of the Reelfoot basin was also impounded by earlier uplifts of the Tiptonville dome. In addition, this tree-ring signature could be used to determine whether other "sunk lands" such as the St. Francis Sunk Lands of Arkansas actually formed or were greatly expanded during the 1811-1812 earthquakes as reported by Fuller (1912) but challenged by Saucier (1970). We believe that dendrochronology can provide temporal, spatial, and perhaps ground response information that will be of value to paleoseismological investigations in the New Madrid Seismic Zone.

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