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Fossil forest reveals sunspot activity in the early Permian

Ludwig Luthardt[1,2]* and Ronny Rößler[1,2]
[1]Museum für Naturkunde Chemnitz, Moritzstraße 20, D-09111 Chemnitz, Germany
[2]Geological Institute, Technische Universität Bergakademie Freiberg, Bernhard-von-Cotta-Straße 2, D-09599 Freiberg, Germany

ABSTRACT

Modern-day periodic climate pattern variations related to solar activity are well known. High-resolution records such as varves, ice cores, and tree-ring sequences are commonly used for reconstructing climatic variations in the younger geological history. For the first time we apply dendrochronological methods to Paleozoic trees in order to recognize annual variations. Large woody tree trunks from the early Permian Fossil Forest of Chemnitz, southeast Germany, show a regular cyclicity in tree-ring formation. The mean ring curve reveals a 10.62 yr cyclicity, the duration of which is almost identical to the modern 11 yr solar cycle. Therefore, we speculate and further discuss that, like today, sunspot activity caused fluctuations of cosmic radiation input to the atmosphere, affecting cloud formation and annual rates of precipitation, which are reflected in the tree-ring archive. This is the earliest record of sunspot cyclicity and simultaneously demonstrates its long-term stable periodicity for at least 300 m.y.

INTRODUCTION

Solar cyclicity has been documented in high resolution in the present and the youngest geological past of the Quaternary as affecting global climate to a measurable scale (Sonett and Suess, 1984; Usoskin et al., 2004). Various solar cycles have been shown in natural data archives such as ice cores, varves, or tree rings, differing in their rhythmic scales from decades to millennia (Vasiliev and Dergachev, 2002; Prasad et al., 2004). The 11 yr solar cycle, also known as Schwabe cycle, represents the smallest-scaled solar cyclicity and is traced back to sunspot activity (Douglass, 1928; Lean, 2000), which has a measurable effect on the Earth's climate, as indicated by the Maunder minimum (Usoskin et al., 2015). Global climate feedback reactions to solar irradiance variations caused by sunspots are complex and hypothesized to be triggered by (1) variation in total energy input (Cubasch and Voss, 2000), (2) the influence of ultraviolet light intensity variation on composition of the stratosphere (Lean and Rind, 2001), (3) the effect of cosmic rays on cloud formation (Marsh and Svensmark, 2000; Sun and Bradley, 2002), and/or (4) the effect of high-energy particles on the strato- and mesosphere (Jackman et al., 2005). Documentation of sunspot activity for the past 1 m.y. by ^{10}Be and ^{13}C isotopes in ice cores and tree rings suggests an average periodicity of 11.12 yr (Usoskin et al., 2015).

However, evidence of solar cycles in deep geological time is exceedingly rare (Raspopov et al., 2011). Until now, the oldest record of solar cyclicity was in evaporitic varves from the Delaware Basin, USA, at ca. 255 Ma (Anderson, 1982). Evidence of the 11 yr solar cycle in the geological past comes from tree-ring sequences from the Cenozoic (Kurths et al., 1993; Raspopov et al., 2011) and the Triassic-Jurassic boundary (Prestes et al., 2013). These examples show that tree-ring analysis seems to offer a high potential to study solar cycles in the geological history, although periodicity and effects on paleoclimate were not discussed. We hypothesize that the 11 yr solar cycle has been affecting Earth's climate over hundreds of million years by holding its stable periodicity over time.

Modern and fossil woody trees have been shown as excellent data sources for even small-scale climatic variations (Douglass, 1928; Rigozo et al., 2007). The application of modern dendrochronological methods to fossil wood is still in the early stages as an investigative technique (Falcon-Lang, 2005; Gulbranson and Ryberg, 2013), but it can provide an untapped wealth of information from Paleozoic wood-producing arborescent plants. However, preservation of trees in autochthonous fossil forests is rare. We present new tree-ring data from an early Permian *in situ* preserved fossil forest in Chemnitz, southeast Germany, which enables dendrochronological inferences to be made from trees within the same forest stand. The data presented herein provides results on the occurrence of the 11 yr solar cycle, its impact on paleoclimate, and its periodicity in the early Permian.

GEOLOGICAL CONTEXT, LOCALITY, AND AGE

The research area is located in the city of Chemnitz, southeast Germany, in the eastern part of the Chemnitz Basin, which represents a post-Variscan intramontaneous trough (Fig. 1A; Schneider et al., 2012). The sedimentary column of the Chemnitz Basin consists of alluvial wet red-bed deposits (*sensu* Schneider et al., 2010) of early to late Permian age.

The Chemnitz Fossil Forest has an absolute age of 290.6 ± 1.8 Ma that is constrained by U-Pb isotopes of magmatic zircon. This age dates a series of volcanic eruptions that entombed a locally restricted hygrophilous forest ecosystem instantaneously by a succession of pyroclastic surges, flows, and fallout (Fig. 1C). This diverse well-preserved plant fossil assemblage consists of arborescent plants at different ontogenetic stages and fauna such as amphibians, reptiles, and various arthropods (Rößler et al., 2012; Dunlop et al., 2016). Trees are commonly found broken or still standing upright in growth position (Fig. 2C), petrified by silica and fluorite, and thus anatomically preserved (Rößler et al., 2014).

The regional paleoclimate during the early Permian was characterized by monsoonal seasonality under semi-arid conditions (Parrish, 1993; Schneider et al., 2012), whereas dry phases were probably prolonged and severe (Luthardt et al., 2016). The Chemnitz forest ecosystem likely developed within a semi-arid alluvial plain setting with sparse vegetation cover, there representing a "wet spot" (*sensu* DiMichele et al., 2006), which was characterized by a sub-humid local paleoclimate and supported by a high groundwater table (Luthardt et al., 2016).

METHODS

Selected from several thousand fossil stems and branches, tree-ring sequences were measured on the 43 best-preserved specimens from the Museum für Naturkunde Chemnitz collection and from *in situ* material from a scientific excavation in Chemnitz-Hilbersdorf (50°51′58.69″N, 12°57′32.54″E). Among the specimens are different gymnosperms (*Agathoxylon* sp., $n = 26$; *Cordaixylon* sp., $n = 2$; *Medullosa stellata* var. *lignosa*, $n = 7$) and calamitaleans (*Arthropitys bistriata*, *Arthropitys sterzelii*, $n = 8$). Measurment was performed by microscopic software (NIS-Elements D version 3.2) under a Nikon SMZ 1500 microscope. The data set comprises 1917 ring width measurements, whereas individual ring sequences exhibit up to 77 rings (sample list provided in the GSA Data Repository[1]).

*E-mail: luthardt@mailserver.tu-freiberg.de

[1]GSA Data Repository item 2017073, data table of investigated samples and correlation scheme of ring sequences, is available online at www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.

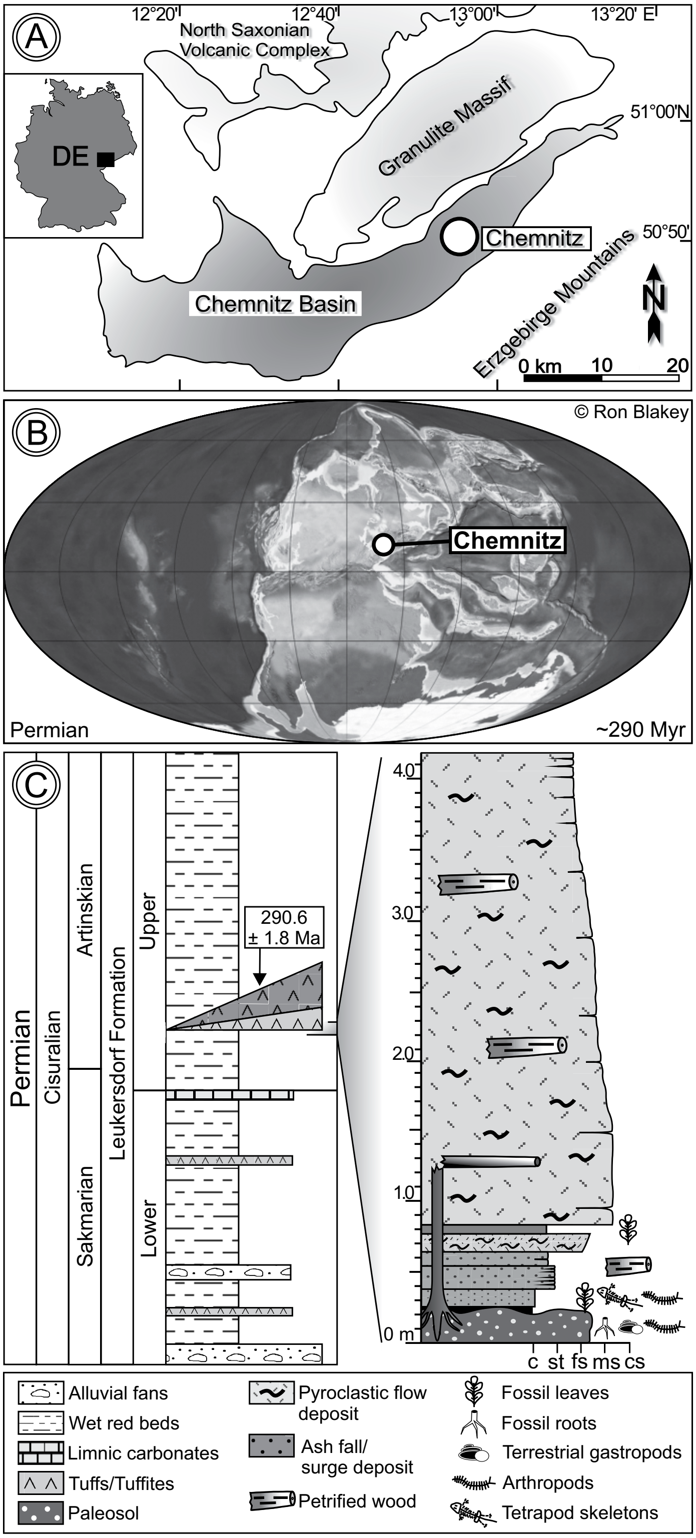

Figure 1. A: Geographical position and geological map (modified from Schneider et al., 2012). Study site is located in town of Chemnitz, southeast Germany. B: Paleogeographical position of Chemnitz within paleotropical belt (~15°N) of Northern Hemisphere on early Permian Pangea (ca. 290 Ma). C: Stratigraphic section of Leukersdorf Formation within Chemnitz Basin and position of geological section at Chemnitz-Hilbersdorf excavation. Profile shows pyroclastic succession, which buried upright-standing trees of fossil forest *in situ*. Grain size abbrevations: c—claystone; st—siltstone; fs—fine sandstone; ms—medium sandstone; cs—coarse sandstone.

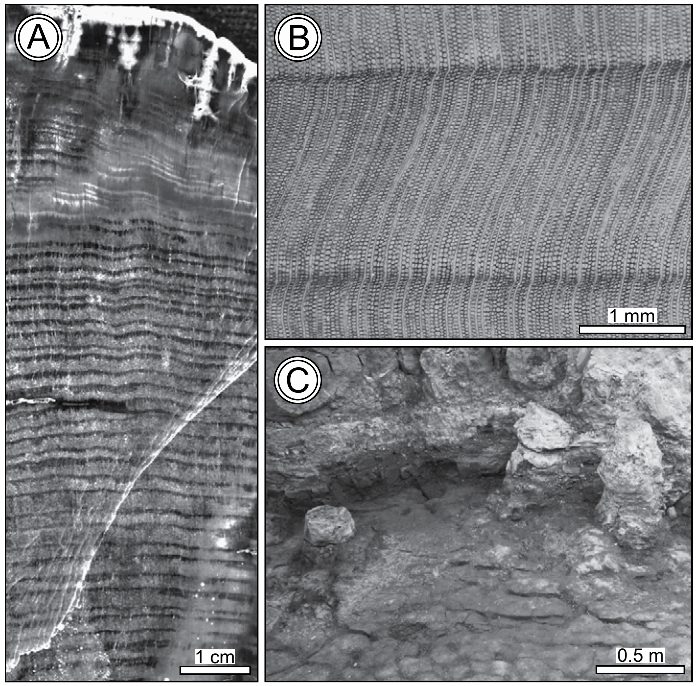

Figure 2. Fossil trees (Chemnitz Fossil Forest, southeast Germany) *in situ* and selected examples with their tree-ring record. A: Regular distinct tree rings in gymnosperm (*Agathoxylon* sp., Museum für Naturkunde Chemnitz specimen K6044). B: Detail of tree ring with small latewood portion and distinct earlywood-latewood boundary (*Agathoxylon* sp., specimen K6043). C: Detail of fossil forest at Chemnitz-Hilbersdorf excavation showing still upright-standing trees rooting in paleosol, entombed in pyroclastics.

By applying standard methods (Cook and Kairiukstis, 1990), ring width measurements were standardized by detrending and power transformation (Box-Cox transformation) to minimize individual growth trends. Sequences of the resulting ring indices were smoothed by using a three-point moving average smoother. Correlation of ring sequences was performed manually and verified by the more-or-less concurrent termination of the correlated ring sequences, which shows the distinct point of death caused by the entombing volcanic eruptions (correlation scheme provided in the Data Repository). By reflecting ring width variation from year to year within a ring sequence, mean sensitivity was calculated for every ring sequence to assess whether a plant reacted as sensitive or complacent to environmental impact (Douglass, 1928). Best-fitting ring sequences (n = 11) were selected to calculate the mean curve. Cyclicity was statistically analyzed by Fourier transformation–based periodogram to calculate precise periodicity and visualized in a Morlet wavelet diagram, which is based on the continuous wavelet transform analysis method (Fig. 3B).

RESULTS

Ancient arborescent plants in the Chemnitz fossil assemblage such as cordaitalean gymnosperms, medullosan seed ferns, and calamitaleans have striking secondary growth that is similar to that of the modern conifer-like gymnosperms. Tree rings occur either as regular and clearly differentiated growth increments with characteristically minor latewood portions (in *Agathoxylon* sp.; Figs. 2A and 2B) or as more irregular and indistinct with diffuse boundaries as in *M. stellata* var. *lignosa*, *A. bistriata*, and *A. sterzelii*. Mean ring width varies among all specimens in a range of 1.34–8.30 mm, with an average of 2.96 mm. By showing an overall mean sensitivity value of 0.389, the plants as a whole reacted as sensitive (>0.3).

Ring sequences exhibit similar distinct cyclic patterns of ring widths, which were used to cross-date specimens within the fossil assemblage

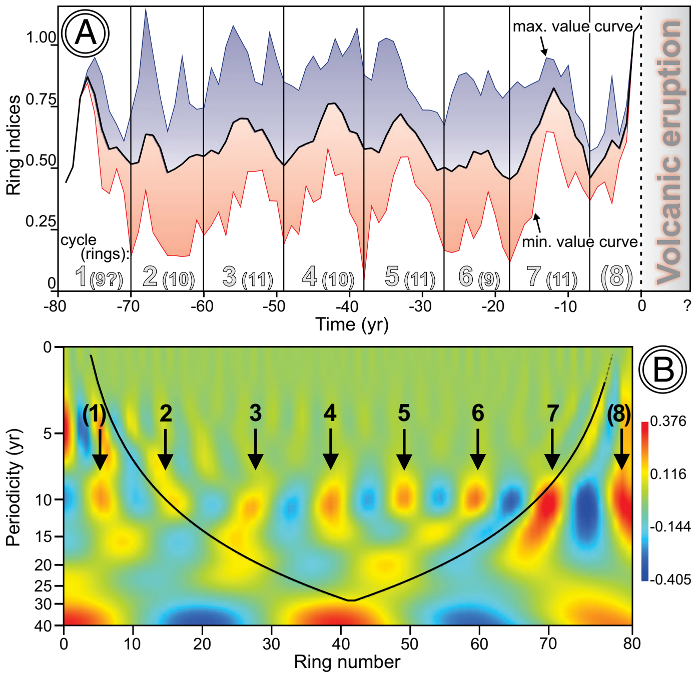

Figure 3. Statistical analysis of mean tree-ring curve assembled from correlated ring sequences of 11 selected specimens (Chemnitz Fossil Forest, southeast Germany). Ring width pattern reveals 10.62 yr cyclicity interpreted as 11 yr solar cycle. A: Mean tree-ring curve showing at least six complete cycles extending 79 yr back in time from entombing volcanic eruption; maximum and minimum value curves (red and blue lines) reflect cyclic pattern of mean tree-ring curve, supporting its statistical significance. B: Morlet wavelet diagram based on spectral analysis showing about eight sunspot cycles of high regularity with periodicity of ~11 yr. Vertical axis is in logarithmic size scale (base 2). Black line represents cone of influence distinguishing regions of statistically verified cycles 2–7 and of occurring boundary effects (cycles 1 and 8). Colors show signal power in time domain of statistically valuable cyclicity (warm colors show high signal power, cold colors show low signal power).

(Cook and Kairiukstis, 1990). In the result, ~75% of the 43 ring sequences show high conformity. The calculated mean curve offers statistically significant information on plant-environment interaction by minimizing individual growth phenomena. The entire record of 79 consecutive years shows a regular cyclic pattern of alternating wide and narrow rings (Fig. 3A); six complete cycles were determined, and each cycle consisted of 9–11 consecutive rings. Narrow tree rings exhibit a large range of variation in ring width, suggesting increased annual sensitivity. Curves of maximum and minimum values for each data point support the statistical significance of the mean curve (Fig. 3A). The high regularity of cyclicity is well expressed in the wavelet diagram of Figure 3B. Variations among the cycles occur with regard to their amplitude (Fig. 3A). Fourier analysis provides a periodicity of 10.62 rings with a high statistical significance within the 99% confidence level.

TREE-RING FORMATION UNDER MONSOONAL PALEOCLIMATE

In general, modern tree-ring formation results from seasonally fluctuating growth conditions, e.g., summer-winter seasons in the temperate latitudes or dry-wet seasons in subtropical and tropical regions (Schweingruber, 1996; Worbes et al., 2013), where growth interruptions are formed during dry seasons demonstrating the stress response of the plant to water deficiency. In turn, plant growth rates are triggered by the amount of available water during the wet season. Seasonality of alternating distinct dry and wet seasons was suggested for the Chemnitz Fossil Forest (see Fig. 1C; Luthardt et al., 2016). High mean sensitivity in the majority of investigated fossil specimens reflects unfavorable paleo-environmental conditions, most probably induced by generally increased moisture stress.

Annual formation of tree rings is an essential precondition in assessing the nature of solar cycles. Paleoclimate models predict monsoonal seasonality in the tropical belt of Pangea during the early Permian (Fig. 1B; Parrish, 1993). Modern and ancient monsoonal climate regions can be characterized by several dry seasons per year causing the formation of up to four tree rings, which are irregularly shaped, indistinct, discontinuous, and usually narrow with ring widths <1 mm (Ash, 1983, 1985; Falcon-Lang, 1999). In the current study, however, *Agathoxylon* sp. specimens show a "normal" growth pattern characterized by regular, continuous, and clearly distinctive tree rings with a sharp latewood-earlywood boundary (Figs. 2A and 2B) and a mean ring width of 2.96 mm. These ring morphology characteristics suggest that tree-ring formation in woody plants from Chemnitz was in fact annual and, in turn, that monsoonal paleoclimate was characterized by only two seasons per year.

CORRELATION AND DECADAL CYCLICITY

The correlation of ~75% of all tree-ring sequences studied represents the first application of dendrochronological principles to trees of a Paleozoic forest. The distinct cyclicity in the ring sequences results from wide and narrow tree rings reflecting phases of increased and reduced growth rates, respectively. Water as a limited resource was likely one of the major determining growth factors in the ancient forest ecosystem. Thus, reduced growth rates are attributed to phases of unfavorable environmental conditions due to water deficiency, which is further expressed by an increased annual sensitivity in the tree rings. Water deficiency was most likely caused by lower annual precipitation rates; in contrast, phases of increased growth rates were the result of increased annual precipitation rates.

Assuming the annual formation of tree rings, the cyclicity demonstrated in the current study exhibits a periodicity of 10.62 yr. Due to the high regularity, we suggest that tree-ring sequences reflect an environmental signal induced by the 11 yr solar cycle. Hence, tree-ring sequences reflect a sensitive feedback reaction of early Permian monsoonal paleoclimate to variations of solar irradiance. We hypothesize that the impact of cosmic rays on cloud formation (Marsh and Svensmark, 2000; Sun and Bradley, 2002) triggered the amount of precipitation during monsoonal wet seasons in the continental, sub-humid to semi-arid paleoclimate of tropical Pangea.

This study on trees of the Chemnitz Fossil Forest (290.6 ± 1.8 Ma) provides (1) the oldest evidence of sunspot activity known as the 11 yr solar cycle, (2) details on resulting paleoclimate feedback reactions, and (3) the first statistical evidence of sunspot periodicity in deep geological time. This periodicity of 10.62 yr during a time frame of ~80 yr shows a slightly higher frequency of sunspot activity in the early Permian compared to the modern-day average periodicity of 11.12 yr. However, during the last four centuries, solar periodicity has fluctuated slightly in a range of 10.44–11.16 yr (Kane, 2002; Keijun et al., 2004). As it falls in this range, the calculated 10.62 yr periodicity more likely emphasizes the continuity of sunspot periodicity through geological time than an overall increased frequency.

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