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Tree-ring response to the 1995 M_w 7.2 Kobe earthquake, southwest Japan

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Abstract

The 1995 M_w 7.2 Kobe earthquake produced an ~18 km-long surface rupture zone with a maximum right-lateral displacement of ~1.8 m along the pre-existing active Nojima Fault in southwest Japan. Field investigations showed that the co-seismic surface ruptures caused severe damage to trees, some of which survived the disaster during the past twenty years along the co-seismic fault scarp. Analysis of tree-rings from the trunk of a 46-year-old Beech tree (Fagus crenata Blume) revealed that the tree was cracked by earthquake-induced damage and that the tree-rings grown during the five-year period after the 1995 earthquake become sharply narrower in width compared to those grown before the earthquake. Our findings indicate that the earthquake damaged trees along the co-seismic fault scarp and hindered the growth of tree-rings by severing the roots. Thus, the results support the idea that older trees growing along or around fault zones can be used for identifying seismic fault events and for dendrochronological studies related to geomorphological processes.

Keywords: tree-rings, Fagus crenata Blume, 1995 M_w 7.2 Kobe earthquake, Nojima Fault, co-seismic fault scarp

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1 Introduction

Tree-rings often record co-seismic surface fault events along or around seismic faults since the strong seismic shocks can severely damage the trees, tearing the roots from the soil, and therefore stunting growth due to damage that prevents the efficient uptake of water or nutrients (e.g., Lin and Lin, 1998; Hamilton, 2010). A large inland earthquake, which can cause ground deformation and change the topographic morphology, may well dislodge branches and damage trees along co-seismic surface rupture zones. The damage can be seen in the tree-rings grown after the earthquake; in the case of trees that may be killed outright, fossil stumps will display a ring set that terminates at the coinciding time of the earthquake. Therefore, the study of earthquake-induced damage on tree-rings could provide new insights about the fault activity of a region for the assessment of recent activity and also seismic hazards. Our previous study showed that trees were torn in half and horizontally displaced 14.8 m along the co-seismic surface rupture from the 1931 M 8.0 Fuyun earthquake in northwest China (Lin and Lin, 1998). The main mechanism of tree-ring responses to earthquakes are generally thought to be caused by direct damage to the main stems or roots, as with trees that were snapped by the 1812

San Andreas earthquake (Jacoby et al., 1989) and the 1931 Fuyun earthquake (Lin and Lin, 1998). However, due to the lack of study examples, the details of how and why tree-ring growth responds to large earthquakes along active fault scarps is not well understood. In order to understand the tree-ring associated record of earthquakes, an ideal method is to study the effects of a well-known large earthquake on tree-ring growth.

On January 17, 1995, the M_w 7.2 Kobe earthquake struck the Awaji Island, resulting in extensive damage including ~6500 deaths throughout the city of Kobe in southwest Japan. To re-reassess the recent activity of the Nojima Fault and the seismic hazards present in the densely-populated region around the city of Kobe, a new project entitled *Drilling into Fault Damage Zones* is being conducted by Kyoto University on the Nojima Fault after the two decades since the 1995 Kobe earthquake occurred (Lin, 2016; Miyawaki and Uchida, 2016). In this study, we report an example of trees damaged by the co-seismic surface rupturing during the1995 M_w 6.9 Kobe earthquake and the tree-ring growths that have been strongly affected by earthquake-damage during the past two decades.

2 The Nojima Fault and earthquake-damaged trees

The study area is located on the northwestern side of the Awaji Island, in the marginal zone of the Eurasian plate and in the inner zone of southwest Japan (Fig. 1a). Several active faults are found in this area; the Nojima, Asano, Kusumoto, and the Higashiura faults strike in the northeast–southwest direction, whereas the Ikuha and Shizuki faults show a northwest–southeast trend (Fig. 1; Research Group for Active Faults of Japan 1991). The Nojima Fault dextrally offsets the late Quaternary alluvial fans and terraces a few meters to a few tens of meters both dextrally and vertically, which has shown a right-lateral strike-slip tectonic history since the late Quaternary (Mizuno et al., 1990; Lin, 2001; Lin et al., 2001; Murata et al., 2001).

The 1995 Kobe earthquake produced a co-seismic surface rupture zone of ~18 km with a maximum horizontal displacement of ~1.8 m along the pre-existing active Nojima Fault, which developed along the topographical boundary between the mountains and lowlands (Fig. 1; Lin et al., 1995; Lin and Uda, 1996a, b). The co-seismic surface faulting was characterized by right-lateral shearing with a thrusting component, which damaged trees along the co-seismic fault zone, mostly along the fault scarp (Fig. 2; Lin and Uda 1995, 1996 a, b). Along the surface rupture zone, vegetation including bamboos, grasses, and trees were damaged and mostly withered after the earthquake (Fig. 2). The damaged trees were found along the co-seismic surface ruptures during field investigations carried out on January 19, 1995, two days after the 1995 Kobe earthquake, and were re-observed three months after the earthquake, in which some of the observed tree had withered. The trunks of the scrub that survived along the co-seismic fault scarp mostly grew in a tilting and bending pattern due to the collapse of the fault scarp (Fig. 2).

3 Analytical results

To understand whether or not tree-ring growth was affected by the earthquake-induced damage, we selected one large damaged tree, a Beech (Fagus crenata Blume) trunk with a diameter of ~35 cm, which was titled on the fault scarp (Fig. 3). We cut the main trunk into five pieces in December 2016, 21 years after the 1995 Kobe earthquake, and polished two cross-sections to analyze the tree-rings. Individual annual rings were

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characterized by dual-rings showing light-yellow and light-brown colors (Fig. 3), which are used to measure the width of a single ring and to count the ring numbers.

Analytical results showed that the tree was 46 years old, and was planted in 1970. The width of tree-rings grown during the 12-year period before the 1995 Kobe earthquake ranged from 5.0 to 7.5 mm, but sharply changed to rings with a width of 3.0 to 4.5 mm in the five years after the 1995 earthquake (Fig. 4).

4 Discussion and conclusions

Strong earthquakes often cause intensive physical damage to trees such as the severing of roots, tilting, and sometimes even complete destruction. Trees which survive such shocks exhibit certain features in their annual growth rings (e.g., Jacoby et al., 1983, 1989; Lin and Lin, 1998). These features include narrow rings (growth depressions), wood growth eccentricity, the production of reaction wood, and the termination of growth or other morphological changes in the internal wood structures (GFZ German Research Centre for Geosciences (2015). In the vast majority of cases, tree rings will record large earthquakes (Jacoby et al., 1989; Sheppard and White, 1995; Lin and Lin,

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1998) and other natural events such as landslides (Clague, 2010), rockfall (Stoffel, 2006; Stoffel et al., 2010), and volcanic eruptions (e.g., LaMarche and Hirschboeck, 1984; Salzer and Hughes, 2007), because the event in some way interrupts the tree from growing, usually along the ground deformation zone on the seismogenic fault zone. Recently, the 2016 M_w 7.1 Kumamoto earthquake also damaged trees along the co-seismic surface rupture zone, where a maximum right-lateral displacement of ~2.5 m was observed (Fig. 5, Lin et al., 2016; Lin, 2017). Some trees were tilted, but have survived along the co-seismic fault scarp one year after the 2016 Kumamoto earthquake (Fig. 5).

The sample tree analyzed during this study was a Japanese beech (Fagus crenata Blume), which are widely distributed across the Japan archipelago. Previous studies have shown that the geographical variation in the water use patterns of Japanese beeches are determined by the interaction between its physiological and morphological status (Tateishi, et al., 2010). Our results showed that the width of the tree-rings had become sharply narrower during the 5 years after the 1995 earthquake than those that grew during the 12-year period prior to 1995, indicating that a reduction of tree-ring growth occurred after the 1995 Kobe earthquake that depressed the growth of the tree rings for 21 years after the earthquake. Such depressed growth for several years has also been reported following a volcanic eruption event in Hokkaido, Japan (e.g., Hinckly et al., 1984; Briffa et al., 1998; Abrams et al.1999). As documented above, the 1995 Kobe earthquake caused intensive physical damage to trees such as tilting, cracking of trunks, and severing of roots (Figs. 2 and 3), and therefore interrupted the growth of tree-rings along the fault scarp. Our finding confirms the idea that a large earthquake can affect tree-ring growth along the co-seismic topographical deformation zone around the seismogenic fault zone. Therefore, tree-rings can be used as valid indicators of natural events such as earthquakes and landslides to study the magnitude and event timing of topographical changes.

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Data availability. The data are not publically available.

Competing interests. The authors declare that they have no conflict of interest.

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Figure captions

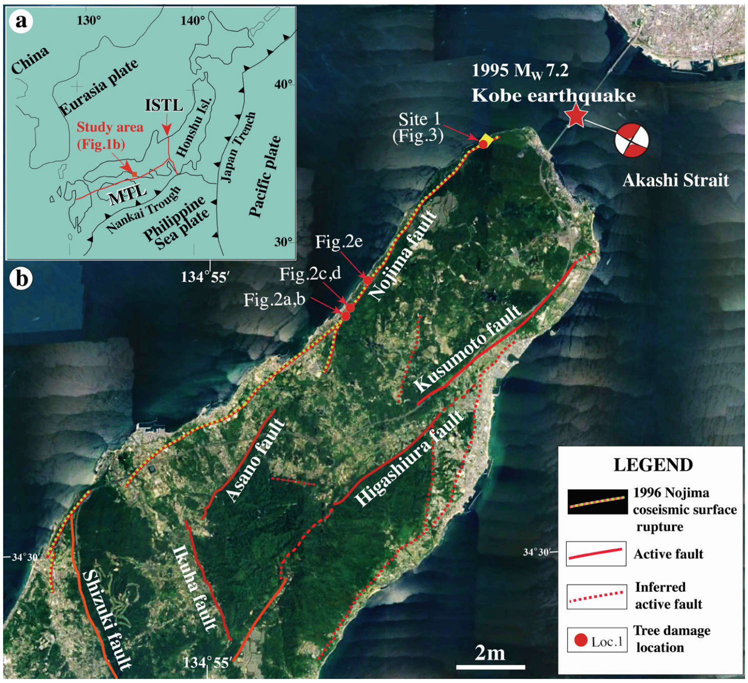

Figure 1. Index maps of the study area showing, (a) the tectonic setting, and (b) the distribution of active faults in the Awaji Island (Google image, active fault data are cited from the Research Group for Active Faults of Japan [RGAFJ], 1991), and the co-seismic surface ruptures are cited from Lin and Uda (1996a, b). MTL: median tectonic line; ISTL: Itoigawa–Shizuoka tectonic line; RAFT: Arima-Takatsuki tectonic line; Honshu Isl.: Honshu Island.

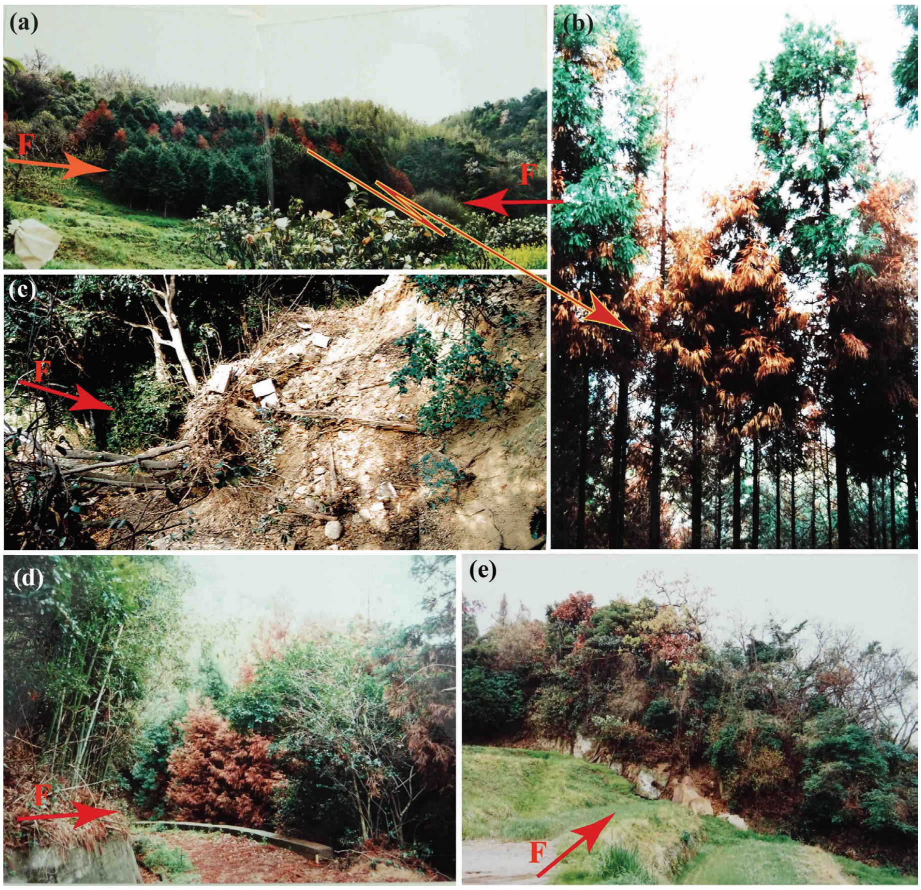

Figure 2. Photographs showing the trees damaged along the 1995 Nojima co-seismic surface rupture zone (see Fig.1b for detailed locations).

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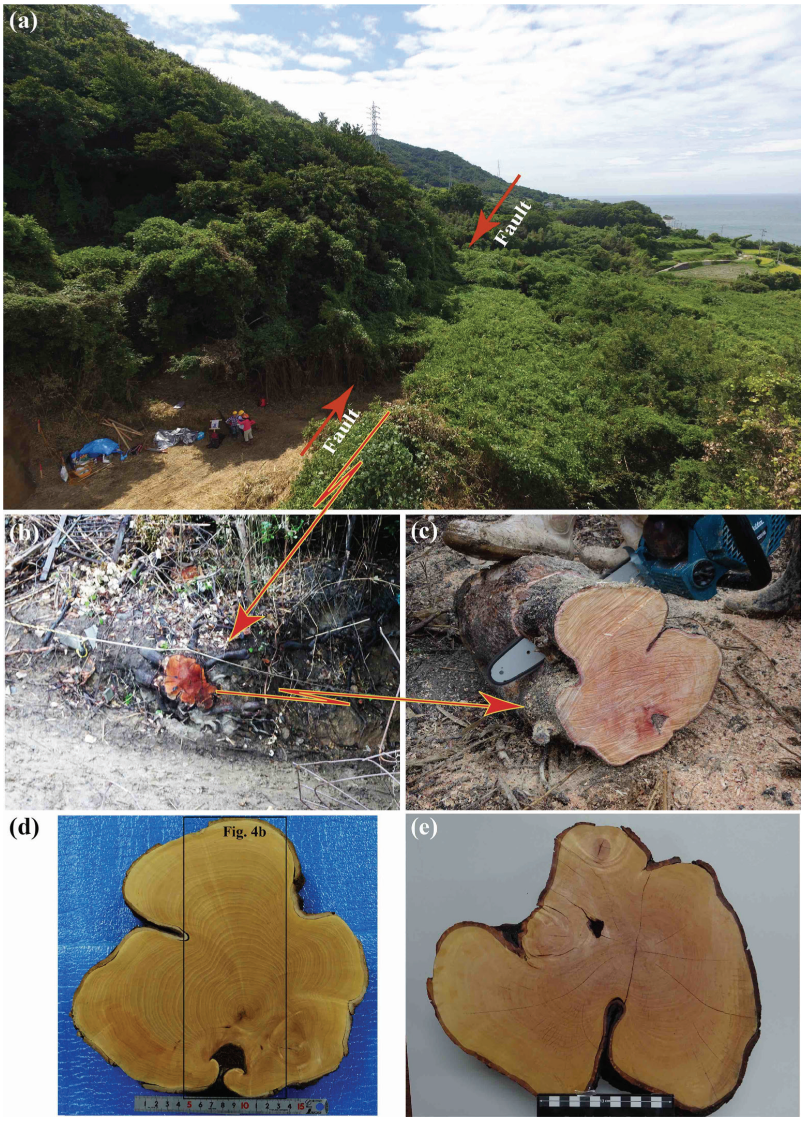

2 Figure 3. Drone image and photographs showing the Nojima fault scarp (a) where the
3 damaged tree was sampled (b-e), Beech (Fagus crenata Blume) trunk cuts (b, c) and the
4 polished sections (d, e).

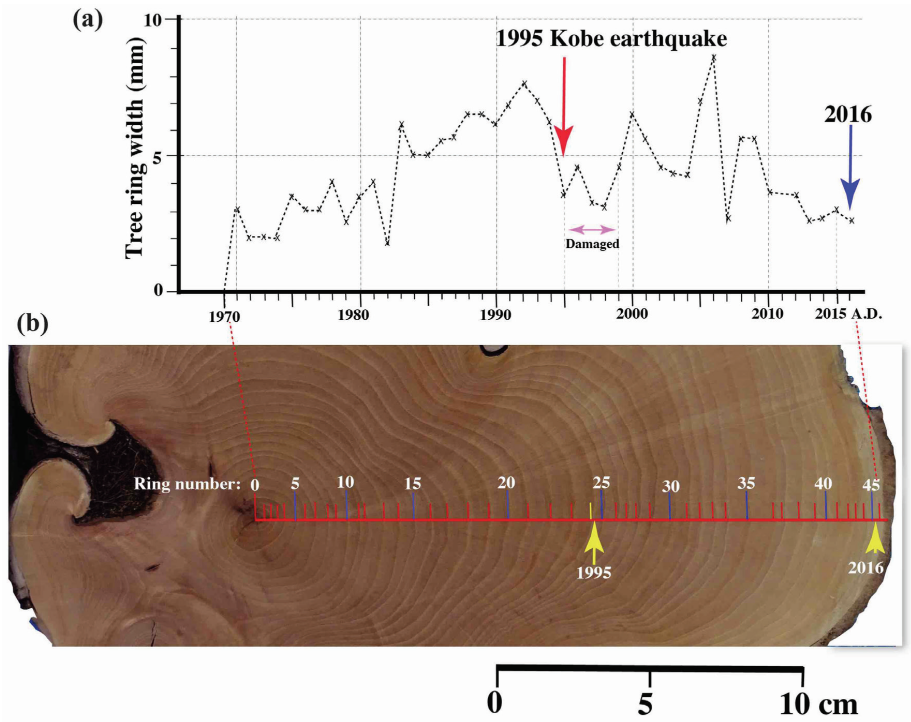

Figure 4. A growth grave for the tree rings (a) and a photograph showing a polished cross section of tree trunk also shown in Fig. 3d (b).

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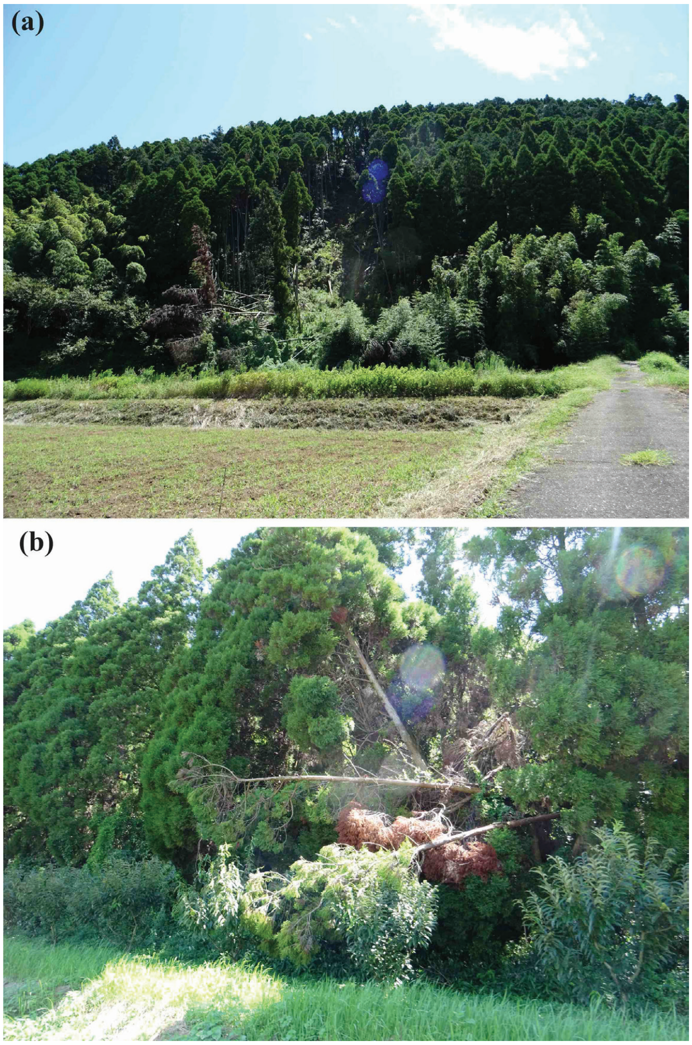

Figure 5. Photographs showing the trees damaged at Kamijin, Mashiki town (Kumamoto prefecture, Japan) along the co-seismic surface rupture zone produced by the 2016 M_w 7.1 Kumamoto earthquake. (a) All view of the fault scarp along which the trees were damaged and (b) the magnified view.