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1 Introduction

The lithosphere, earth's rigid outer shell comprising crust and upper mantle rock, is broken into about 14 tectonic plates (Christopherson 2009) that move a few centimeters per year over superheated, pliable rock underneath. Forces within earth's interior push, pull and twist the plates in different directions, producing three types of plate boundaries: convergent (colliding with one another), divergent (moving away from one another) and transform (sliding past one another). Earthquakes occur when plates become locked together, building strain between and within them that is suddenly released, sending a burst of seismic waves that cause shaking and displacement of the surface. Nearly 95% of earthquakes are due to movement along plate boundaries, particularly convergent boundaries surrounding the Pacific Ocean and a mix of transform and convergent boundaries extending southeast from the Mediterranean region of Europe to Indonesia (Wicander and Monroe 2009) (Fig. 1). However, faults can also develop within plates, and intraplate earthquakes strong enough to affect humans and to be recorded in tree rings have occurred (e.g. Sheppard and White 1995; VanArsdale et al. 1998; Carrara 2002; Bekker 2004).

Plate boundaries can occur between any combination of dense oceanic or less dense continental crust, producing six potential combinations of crust type and plate boundary (Table 1). Subduction zones develop when dense oceanic crust collides with and is forced underneath less dense continental crust or another plate comprised of oceanic crust. The plates are in contact with each other from the surface to a depth of several hundred kilometers, thus earthquakes can be centered near the

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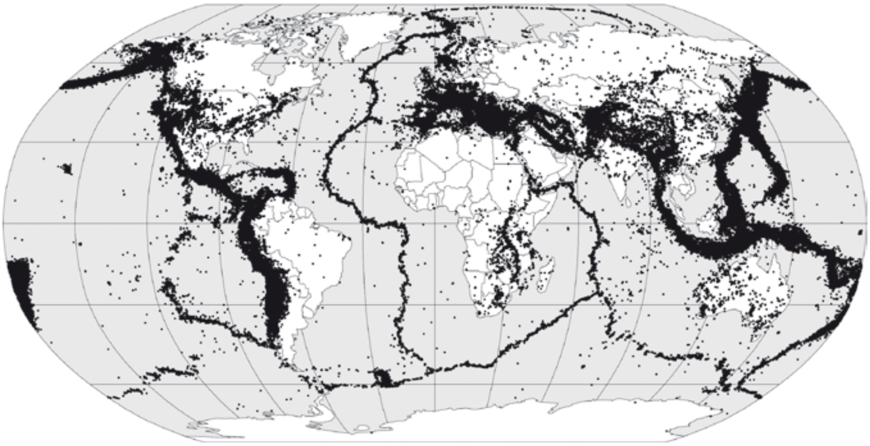

Fig. 1 Location of epicenters for all earthquakes recorded between 1963 and 1998. Lowman et al. 1999. Public domain

Table 1 Seismic features and hazards associated with tectonic plate boundaries

Boundary type	Crust type	Features and seismic activity
Convergent	Continental–continental	Mostly shallow-focus earthquakes; e.g. Himalayas
–	Continental–oceanic	Subduction zones; shallow and deep-focus earthquakes; e.g. NW USA; western S. America
–	Oceanic–oceanic	Subduction zones; shallow and deep-focus earthquakes; e.g. western Pacific Ocean
Divergent	Continental–continental	Shallow-focus earthquakes from offsetting transform faults; e.g. Iceland; E. Africa
–	Continental–oceanic	Nonexistent or short-lived (quickly becomes oceanic-oceanic)
–	Oceanic–oceanic	Shallow-focus earthquakes from offsetting transform faults; e.g. middle Atlantic Ocean
Transform	All	Shallow-focus earthquakes; e.g. southern California, USA, southern Mediterranean; western India

surface (shallow-focus) or deeper underground (deep-focus). In contrast, earthquakes along transform plate boundaries always occur near the surface (shallow-focus). A shallow-focus earthquake typically causes more damage than a deep-focus earthquake of the same magnitude because the energy is less dissipated when it reaches the surface (Wicander and Monroe 2009). At divergent boundaries the plates are not actually in contact with each other, but new crust is being formed between them as they spread apart. Earthquakes occur near these boundaries because of small, offsetting transform faults and thus are also shallow-focus.

Although millions of earthquakes occur annually, about 98% of them have a magnitude less than 3 on the Richter scale (Smith and Petley 2009), too small to be felt by humans or to be recorded in tree rings. The modified Mercalli scale measures earthquake intensity indirectly by assessing the impact on various structures, including trees, on a scale ranging from I to XII. At level V trees are ‘shaken slightly,’ at VI ‘slightly to moderately,’ at VII ‘moderately to strongly’ and at VIII ‘strongly,’ including broken branches or trunks. For comparison, at level VIII shaking is strong enough to overturn very heavy furniture, break stone walls, and do “considerable” damage to unreinforced buildings, including wooden homes (Wood and Newman 1931, 279–280).

2 Application of Tree-Ring Research to Earthquakes

Earthquakes can produce a variety of tree-ring responses in trees (see Jacoby 2010, this volume). Previous studies have used tree rings to date known modern or historical earthquakes, most of them from sites at tectonic plate boundaries, including convergent (e.g. Jacoby and Ulan 1983; Veblen et al. 1992; Yadav and Kulieshius 1992; Kitzberger et al. 1995; Allen et al. 1999; Vittoz et al. 2001), and transform boundaries (e.g. Page 1970; LaMarche and Wallace 1972; Meisling and Sieh 1980). Others have found evidence for known earthquakes from intraplate faults (Ruzhich et al. 1982; Stahle et al. 1992; Sheppard and White 1995; Van Arsdale et al. 1998; Lin and Lin 1998, 2010, this volume; Carrara 2002; Carrara and O’Neill 2003, 2010, this volume; Bekker 2004).

Tree rings can contribute to a better understanding of earthquake hazards and the reduction of their impacts by identifying unknown events, and by clarifying the magnitude, epicenter location, timing, or amount of displacement for known but poorly-understood historical events (Jacoby et al. 1988; Jacoby 1997, 2010, this volume). Such “paleoseismic” studies are rare, but a prominent example is the identification of a previously unknown, major earthquake and associated tsunami along the Cascadia Fault in northwestern North America in AD 1700 (Atwater et al. 2005). This quake induced coastal subsidence and produced a tsunami that struck both the Pacific coast of North America and Japan. This discovery required a combination of: (1) tree-ring data, including death dates, growth rates prior to death, and ring-width changes (Atwater and Yamaguchi 1991; Jacoby et al. 1995; 1997; Yamaguchi et al. 1997); (2) geologic evidence, including radiocarbon dates and the preservation of plants in growth position in North America. (e.g. Atwater and Yamaguchi 1991; Atwater et al. 1991); and (3) historical, written evidence of a tsunami in Japan (Satake et al. 1996). This work demonstrated the potential for very large earthquakes, probably greater than Richter magnitude 9 (Yamaguchi et al. 1997; Atwater et al. 2005) to occur in the region, for which no information was available through historical records.

In another paleoseismic study, Wells et al. (1999) used ^{14}C to date several prehistoric earthquakes along a transform plate boundary in New Zealand. The most recent event was dated between 1665 and 1840. Tree-ring data showed strong and synchronous ring-width suppressions at several sites along the fault that were initiated between AD 1717 and 1719. Noting that 1–2 year delays between the timing of damage and physiological response are not uncommon, they suggested that the most recent earthquake occurred after the 1716 growing season but before the end of the 1717 growing season.

3 Future Research Needs and Challenges

One of the principal challenges in using tree rings to identify earthquakes is finding trees that have recorded the event. Many studies have focused on "event-response" trees, which exhibit obvious damage and are located within a few meters of a fault scarp. This technique may increase the probability of finding a response in a given tree, and certainly makes it easier to attribute the response to an earthquake rather than some other factor. However, Bekker (2004) studied spatial variation in tree-ring responses to the 1959 Hebgen Lake (Montana) earthquake and found that: (1) trees that recorded a response in their rings did not always show external damage; (2) distance from the fault scarp, up to 58 m, had little effect on the proportion of trees recording a response; (3) trees below the scarp, on the downthrown block, were much more likely to record a response than those on the stationary block above the scarp; and (4) larger (mean 74 cm DBH) and older (mean 259 year) trees were more likely to record a response regardless of their position above or below the scarp (Fig. 2). These results suggest that dendroseismological studies can benefit from a research design that includes sampling over broader areas (at least tens of meters from a scarp), recording the position of trees relative to scarps, and sampling a range of tree sizes and ages. Such a design would require greater care to identify control trees, but would increase the likelihood of finding trees with a response and may reveal details about block movement for an unknown quake.

Another potential way to expand the identification of earthquakes through tree-ring analysis is by examining the effects of seismologically-induced landslides (Carrara and O'Neill 2003, 2010, this volume). Landslides can be triggered hundreds of kilometers from an earthquake's epicenter, and can damage trees over a much more extensive area than that produced by shaking alone. This method does, however, require independent evidence of a synchronous earthquake, and care to rule out climatic or other potential triggers of landslides.

It is well known that a tree may respond differently to an earthquake around its circumference, as with the formation of reaction wood when trees are tilted. Hamilton (2010, this volume) notes that trees may also show differing responses vertically on the stem. He found evidence of the 1700 Cascadia and 1959 Hebgen Lake earthquakes by sampling several meters above the ground, where trees are more likely to be directly damaged by acceleration and whiplash. LaMarche and Wallace (1972) also noted that dating leaders on a broken stem could precisely date the timing of such damage from an earthquake. Sampling trees in this way may reveal responses that are not recorded near the ground.

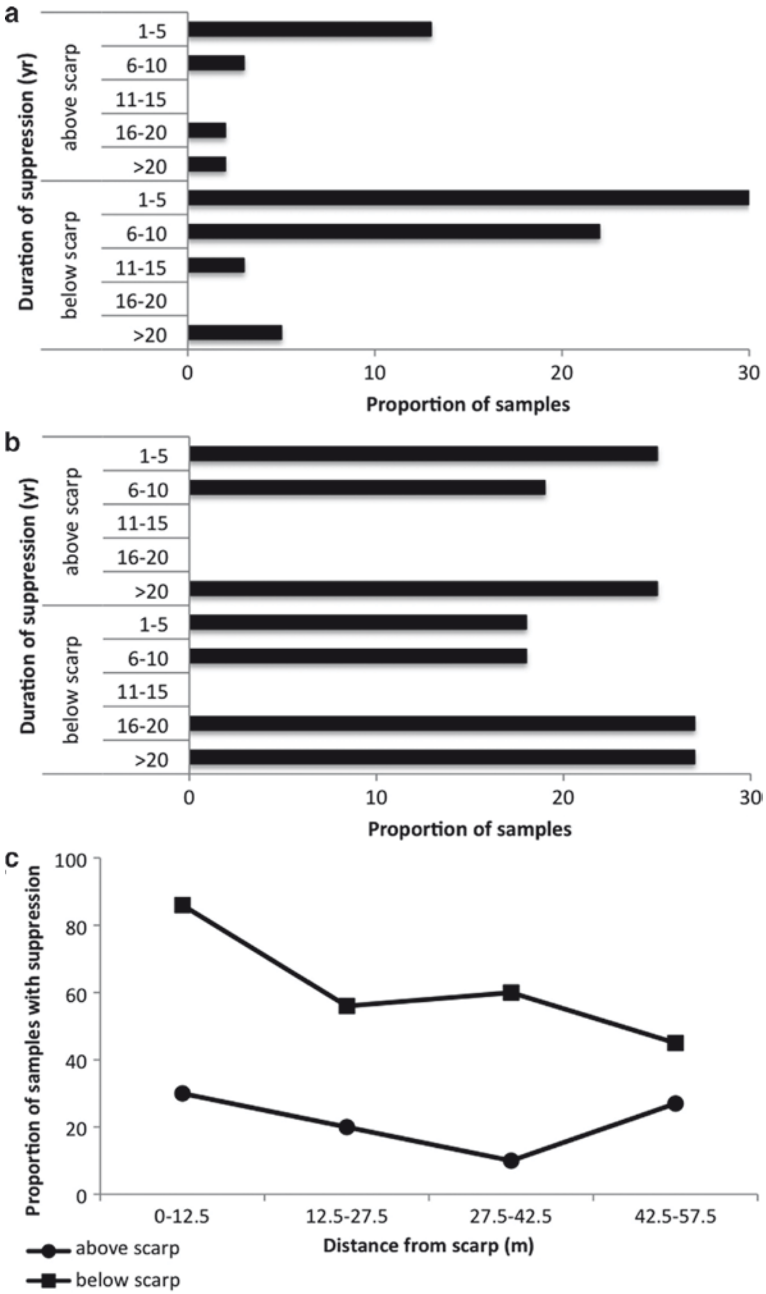

Fig. 2 Data from a dendroseismological study of the 1959 Hebgen Lake, Montana earthquake showing (**a**) higher number of growth suppressions below than above the fault scarp for all tree ages and sizes; (**b**) more even number of suppressions above vs. below the scarp for the largest and oldest trees; and (**c**) weak effect of distance from the scarp (up to 58 m) on the proportion of trees recording a suppression (Redrawn from Bekker 2004)

Most studies of tree-ring responses to earthquakes have appropriately been conducted along plate boundaries, where most earthquakes occur and human population densities are high. However, major intraplate quakes threaten large populations near several faults in China, the Wasatch Fault in Utah, and the New Madrid Fault in the Midwestern U.S. among others. Recurrence probabilities for earthquakes along intraplate faults are also difficult to estimate because the forces behind them are usually poorly understood and movement is less consistent than at plate boundaries. Thus, dendroseismological studies may be particularly valuable in clarifying the behavior of intraplate faults.

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