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The first dating of strong Holocene earthquakes in Gorny Altai using long-term tree-ring chronologies

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Abstract

We present the first results of application of long-term tree-ring chronologies for dating seismically triggered rockfalls and determining the upper age of Holocene rockfalls in southeastern Altai. Based on the results of seismic dendrochronological analysis, dating of penetrating wood injuries is proposed and tested, and the criterion for the distinguishing of seismically triggered rockfalls among slope processes of climatic nature is formulated. An earlier unknown strong earthquake of 1532 has been recognized; its traces are dated by the radiocarbon method. Based on the new data and calibration of earlier radiocarbon dates, the recurrence period of strong earthquakes in the southeastern Altai is refined.

Keywords: dendrochronological analysis; long-term tree-ring chronologies; seismically triggered slope processes; paleoseismicity; Holocene; Altai

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Introduction

One of the main problems in seismic zoning and distinguishing of areas of high seismic activity is to determine the maximum possible magnitude and recurrence period of strong earthquakes, which are the most destructive and dangerous to humans. The duration of seismological observations is short as compared with the recurrence period of strong earthquakes. Therefore, this parameter is calculated using historical data and the estimated age of paleoseismic dislocations revealed in the study area (McCalpin, 2009; Solonenko, 1966).

Today, radiocarbon analysis is most often used among the known methods for absolute dating of paleoseismic dislocations. It permits dating of soils, wood fragments, and other organic materials deformed and buried during earthquakes and/or covering seismically induced faults and rockfall/landslide bodies.

The limit of radiocarbon dating is ~50 kyr (in the case of ^{14}C enrichment, up to ~75 kyr). However, the use of this method for estiming the age of seismic events that took place in the last 2–3 kyr is restricted because of its high relative error in this time interval and the presence of several “plateaus” in the calibration curve, complicating binding of radiocarbon dates to the calendar timescale (Vagner, 2006)[1]. For example, our comparison of dendrochronological and radiocarbon dates for the same wood samples from moraine deposits in the Gorny Altai valleys showed that in the interval of the last 3 kyr, the radiocarbon method can yield an error of up to 300 years for wood, the best material for this type of dating. This error is commensurate with the recurrence period of Holocene strong earthquakes in Gorny Altai determined by the radiocarbon method, 500–900 years (Rogozhin et al., 2007). Moreover, radiocarbon dates for paleosoils give an idea of only the average time of their formation, which also significantly reduces the accuracy of age determination for seismic dislocations.

In seismically active zones with tree vegetation, a dendrochronological analysis can be used as an additional and/or alternative method. It ensures dating of events with an accuracy of up to a year or, sometimes, even up to a season. Up to now, several aspects of dendrochronological analysis have been used in the world seismological practice for dating of earthquakes. The following procedures were performed to determine the time of rupturing: (1) dating of primary

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[1] Note that the decrease in the concentration of atmospheric ^{14}C as a result of the anthropogenic activity started in the middle 19th century (Suess effect) does not permit radiocarbon dating of samples younger than 1850 years (Vagner, 2006).

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dendroseismologic evidence, such as breaks of tree trunks and roots as well as tilt and fall of trees in the zone of surface seismic ruptures and (2) dating of secondary evidence, namely, the beginning of the slower growth and/or death of trees along seismic ruptures because of the total or partial loss of their crown as a result of the ground shaking. Dating of rockfalls and landslides of proven seismic nature is made by the following procedures: study of the wood of marker trees growing directly on the landslide body (the beginning of abnormal wood formation corresponds to the time of seismic event); determination of the minimum age of the rockfall/landslide body (from the age of the oldest tree grown on the rockfall body or on its rupture wall); and determination of the exact date of the rock movement (from the time of death of trees buried under the rockfall/landslide body) (McCalpin, 2009). In Russia, a dendrochronological analysis was successfully applied in study of the seismicity of the Stanovoi upland to date earthquakes based on the time of tree death and abnormal wood formation in marker trees in rupture zones (Ruzhich et al., 1982).

Until recently, the time interval of application of dendrochronological analysis for dating of seismic dislocations has been limited by the age of the last tree generation. This method was the most effective for dating seismic events no older than 300 years BP. At the same time, dendrochronological analysis, based on a unique combination of the width of annual rings in a particular area, makes it possible to date any events responsible for the damage, death, and burial of trees or for the appearance of a new forest generation on the newly formed surfaces in the time interval significantly exceeding the age of the present-day trees. This interval is determined by the duration of regional absolute tree-ring chronologies, which can be bound with relative tree-ring chronologies (TRCs) made on analysis of paleotrees growing on the studied Holocene seismic dislocations. At present, there are several absolute regional chronologies; however, dating of Holocene earthquakes using these TRCs has not been made in the world dendroseismological practice.

In this paper we present the first results of dating of Holocene strong earthquakes in the southeast of Gorny Altai, the most seismically active zone of the Altai Mountains, based on long-term TRCs (Agatova et al., 2014).

Prospects of dendrochronological dating of seismically induced relief forms in the southeastern Altai

In the new structure of the Altai suture uplift, the southeastern part of Gorny (Russian) Altai (hereafter, SE Altai) is a transpression zone of seismogenic dextral faults stretching from Mongolian Altay (Novikov, 2004; Rebetskii et al., 2013). Within SE Altai, there are a significant crushing of the lithosphere and displacement of large ridge blocks along E–W striking reverse faults and thrusts. This is the most high-altitude (up to 3500–4500 m above sea level) and seismically active area within Russian Altai. It is here that the Chuya earthquake ($M_S = 7.3$) occurred in 2003 (Leskova and Emanov, 2013; Vysotskii et al., 2004) and traces of numerous strong Holocene earthquakes were revealed (Agatova et al, 2006; Butvilovskii, 1993; Rogozhin and Platonova, 2002; Rogozhin et al., 2007). Among them, there are large rockfall and landslide bodies preserved for millennia owing to arid climate and strongly rugged topography. The rainfall at the bottom of intermontane basins within SE Altai does not exceed 200 mm/year, increasing to the ridge crest, and its absolute value decreases from 2000 mm/year in the west to 500 mm/year and less in the east (Narozhnyi and Osipov, 1999). The distribution of forest plants depicts low precipitation and climate aridization toward the east. In the mountain framing of the Kurai basin, a belt of cedar–larch forests stretches on the northern macroslope of the North Chuya Ridge to a height of 2350–2450 m above sea level. In the western part of the Chuya basin, there are only rare larch spots. Old-forest sites are spread here up to heights of 2220–2330 m above sea level; some trees and undergrowth occur up to 2500 m. In the southeastern part of the Chuya basin, within the northern macroslope of the Sailyugem Ridge, forest plants are absent.

The successful use of dendrochronological analysis for dating of seismically triggered ancient rockfalls and landslides in SE Altai is explained by the following factors:

1. Many seismic rockfall and landslide bodies are located at a height close to the tree line. At this level, the climatic signal is best reflected in tree growth, which is necessary for construction of long-term tree-ring chronologies and dating of particular paleotrees that were injured during earthquakes and/or inhabited the newly formed surfaces. Note that during the Holocene, the tree line in SE Altai repeatedly raised above its current position as a result of temperature fluctuations (Nazarov et al., 2012).

2. In arid climate, the wood of dead trees can be preserved on a stone surface for up to 2000 years, which also helps to construct long-term local and regional TRCs.

3. A few years ago, a series of absolute dendrochronologies based on larch (*Larix sibirica* Ledeb) and Siberian pine (*Pinus sibirica* Du Tour) dating was constructed for SE Altai and Tuva, with the Mongun TRC being the oldest (2367 years) (Myglan et al., 2012). For Siberia, this is the fourth chronology longer than 2000 years, after the Yamal, Taimyr, and Indigirka ones. Two years ago, it was joined with the 424 years long "floating" TRC of archaeological wood from the Pazyryk burial grounds of SE Altai (Slyusarenko, 2010). Thus, the dendrochronological method can be used today in SE Altai and Tuva for dating seismic events up to 2720 years old. The uniqueness of the new dating tool is evidenced by the fact that there are only four long-term TRCs: for Central Europe, Ireland, America, and China.

4. The 2003 Chuya earthquake ($M_S = 7.3$) gave a rare opportunity for a comparative analysis of the distribution of seismically induced wood injuries of present-day and ancient trees within SE Altai.

Object of study

We tested dendrochronological dating of paleoearthquakes when studying the earlier unknown complex of seismically