Tectonophysics 608 (2013) 138–148

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Effects of pore fluid pressure and tectonic stress on diverse seismic activities around the Mt. Ontake volcano, central Japan

Toshiko Terakawa *, Yoshiko Yamanaka, Haruhisa Nakamichi [1], Toshiki Watanabe, Fumihito Yamazaki, Shinichiro Horikawa, Takashi Okuda

Earthquake and Volcano Research Center, Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan

ARTICLE INFO

Article history:
Received 17 May 2013
Received in revised form 30 September 2013
Accepted 8 October 2013
Available online 16 October 2013

Keywords:
Pore fluid pressure
Earthquake swarm
Inland earthquake
Tectonic stress
Volcano

ABSTRACT

To understand the effects of pore fluid pressure and tectonic stress in generating diverse seismicity, we deployed 11 temporary seismic stations around an active volcano, Mt. Ontake, in central Japan during the summers of 2009–2011. We obtained well-constrained focal mechanism solutions from the seismic data recorded at the temporary stations and permanent stations located within 50 km around Mt. Ontake. We estimated the 3-D pore fluid pressure field, taking into consideration spatial changes in the tectonic stress pattern, by applying the method of focal mechanism tomography to the dataset. We found overpressurized fluid reservoirs with a peak of 100–150 MPa at depths between 5 and 12 km in the southeast and east flanks of Mt. Ontake. This region has experienced earthquake swarm activity since 1976. Many seismic events concentrated at the edge of the overpressurized fluid reservoirs, where pore fluid pressure gradients are steep. This indicates that a large amount of fluid flow would trigger seismic events by decreasing fault strength caused by an increase in pore fluid pressures. Many small events ($M < 3$) occurred on pre-existing faults that are unfavorably oriented or severely mis-oriented relative to the tectonic stress pattern, indicating that these events are driven by overpressurized fluids. However, the macroscopic rupture planes of microseismic clouds and larger events ($M \geq 3$) appear to release tectonic stresses produced by steady plate subduction. The critical event magnitude ($M_c = 3$) at which seismic behavior changes would be characterized by a length scale of pore fluid pressure heterogeneity. This quantity might be an indicator of the maximum event magnitude in the region.

1. Introduction

Mt. Ontake, located at the southern end of the Northern Japan Alps in central Japan (Fig. 1), is the second highest stratovolcano in Japan. Around Mt. Ontake, diverse crustal activities are observed, such as large inland earthquakes, microseismic swarms, and volcanic eruptions. In August of 1976 microseismic swarm activity began on the southeast flank of Mt. Ontake, and the activity continued for more than three decades (e.g., Ooida et al., 1989; Yamazaki et al., 1992). During this period the first historic eruptions of Mt. Ontake occurred in 1979, 1991, and 2007 (http://www.seisvol.kishou.go.jp/tokyo/312_Ontakesan/312_history.html, in Japanese). In 1984 the Western Nagano Prefecture (Naganoken-seibu) earthquake with M 6.8 occurred in the earthquake swarm region, triggered debris flows that swept down valleys on the south and east flanks, and 29 people died or disappeared.

Overpressurized fluids in the Earth's crust have been increasingly implicated to play an important role to earthquake generation as well as volcanic activity (e.g., Miller et al., 2004; Terakawa et al., 2010; Yamashita, 1999). In the earthquake swarm region Kimata et al. (2004) revealed 3–6 mm ground uplift during a period from 2002 to 2004 by repeated precise leveling measurements. They estimated, using a Mogi source model (Mogi, 1958) in the center of the maximum ground uplift, a pressure source of volume increase (5×10^5 m^3) at a depth of 2–3 km. This uplift region corresponds to the low resistivity area revealed by the magnetotelluric measurements (Kasaya and Oshiman, 2004; Kasaya et al., 2002; Yoshimura et al., 2009). Geochemical analyses of water and gas samples (e.g., Nishio et al., 2010; Takahata et al., 2003) indicated the existence of fluids from a lower crust and/or upper mantle beneath the region. However, the distribution of pore fluid pressures, or how overpressurized fluids affect seismicity, is not known.

The earthquake is a physical process that releases accumulated tectonic stresses by shear faulting, controlled by the Coulomb failure criterion:

$$\tau_s = \mu\left(\sigma_n - P_f\right), \tag{1}$$

where τ_s and σ_n are the fault strength (shear strength) and normal stress (positive in compression) on a target fault, respectively, P_f is

* Corresponding author at: D2-2 (510), Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan. Tel.: +81 52 789 5054; fax: +81 52 789 3047.
E-mail address: terakawa@seis.nagoya-u.ac.jp (T. Terakawa).
[1] Now at: Sakurajima Volcano Research Center, Disaster Prevention Research Institute, Kyoto University, Kagoshima 891-1419, Japan.

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.10.005

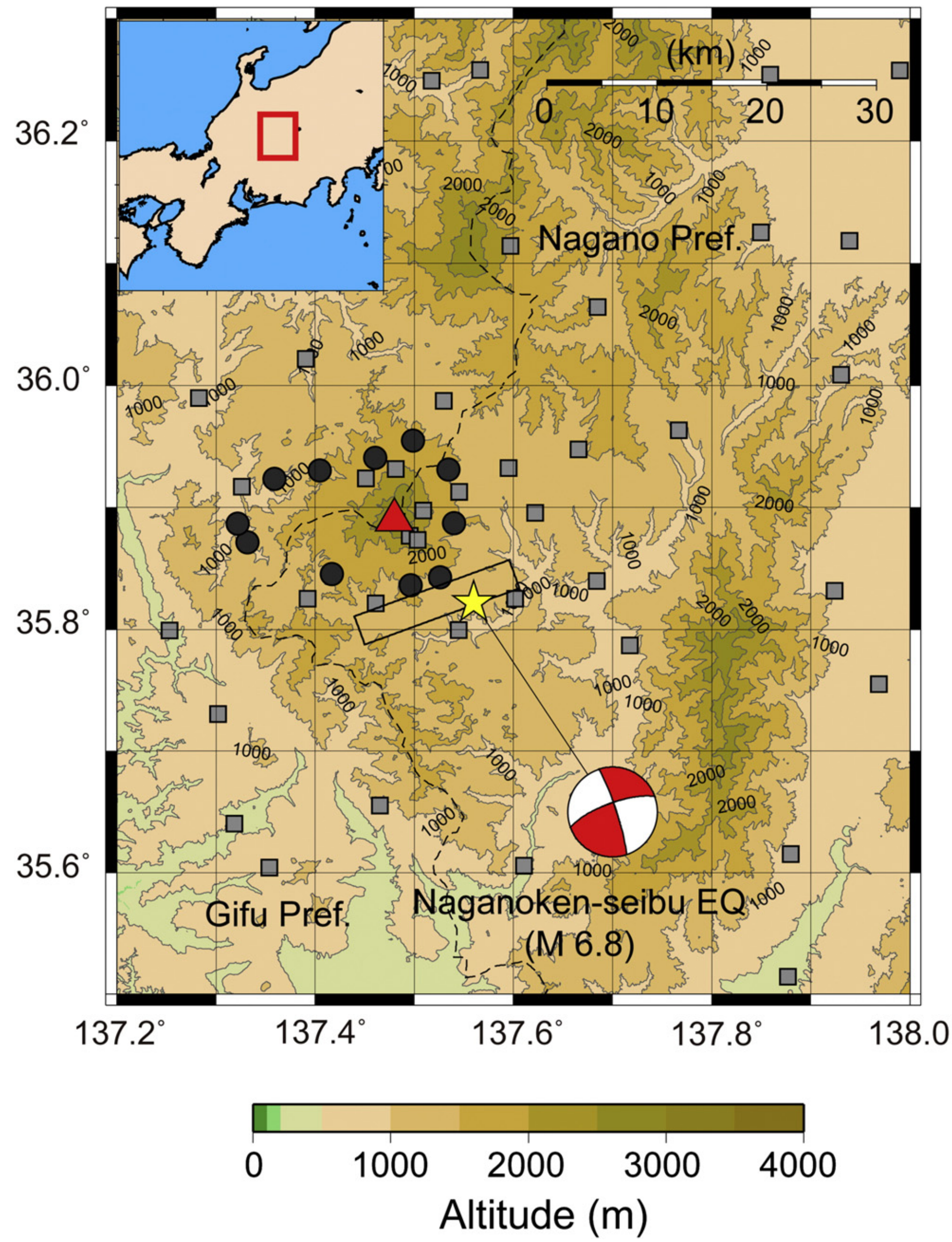

Fig. 1. Map of Mt. Ontake volcano and seismic stations. The red triangle shows Mt. Ontake. The solid circles and squares show temporal and permanent seismic stations, respectively, that contributed data to focal mechanism solutions. The yellow star, the rectangle, and the red focal sphere show the epicenter, the source region, and the focal mechanism of the 1984 Western Nagano Prefecture (Naganoken-seibu) earthquake. The dashed line shows the prefectural boundary between Gifu and Nagano Prefectures.

pore fluid pressure, and μ is the friction coefficient of rocks. Seismic slip occurs when the shear stress reaches fault strength, so, Eq. (1) indicates that shear failure can occur by both a decrease in fault strength (an increase in pore fluid pressure) and/or an increase in shear stress (Hubbert and Rubey, 1959).

Recently, Terakawa et al. (2010) developed a new method to estimate 3-D pore fluid pressure fields by mapping focal mechanism solutions (fault strike, dip angle, and slip angle) of seismic events on the 3-D Mohr diagram for a given tectonic stress field. In this method, termed focal mechanism tomography (FMT) method, the spatial variation in focal mechanisms is attributed to fault strength heterogeneity due to the spatial variation in pore fluid pressures. Application of this technique to the 2009 L'Aquila earthquake in Italy revealed that overpressurized fluid reservoirs at hypocentral depths likely contributed to the intensive foreshock and aftershock activity associated with the main shock. Terakawa et al. (2012) quantitatively demonstrated validity and applicability of the FMT method by analyzing focal mechanism solutions of seismic events induced by fluid injection experiments in the Basel Enhanced Geothermal System, Switzerland. These studies demonstrated that the spatiotemporal change in pore fluid pressures can be estimated from focal mechanisms if the tectonic stress pattern does not change with time.

To understand the roles of overpressurized fluids and tectonic stress in generating diverse seismicity, we deployed 11 temporary seismic stations around Mt. Ontake volcano during the summers of 2009–2011. In this paper we apply the FMT method to focal mechanism solutions obtained through the observations to estimate the 3-D pore fluid pressure field in the Ontake region. In the previous studies on