Journal of Asian Earth Sciences 88 (2014) 218–229

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

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

A comprehensive model of postseismic deformation of the 2004 Sumatra–Andaman earthquake deduced from GPS observations in northern Sumatra

Endra Gunawan [a,*], Takeshi Sagiya [a], Takeo Ito [a], Fumiaki Kimata [b], Takao Tabei [c], Yusaku Ohta [d], Irwan Meilano [e], Hasanuddin Z. Abidin [e], Agustan [f], Irwandi Nurdin [g], Didik Sugiyanto [g]

[a] *Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan*
[b] *Tono Research Institute of Earthquake Science, Mizunami, Japan*
[c] *Department of Applied Science, Kochi University, Akebono-cho, Japan*
[d] *Graduate School of Science, Tohoku University, Sendai, Japan*
[e] *Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Indonesia*
[f] *Agency for Assessment and Application of Technology, Jakarta, Indonesia*
[g] *Department of Physics, Syiah Kuala University, Banda Aceh, Indonesia*

ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form 14 March 2014
Accepted 17 March 2014
Available online 1 April 2014

Keywords:
Postseismic deformation
Viscoelastic relaxation
Afterslip

ABSTRACT

We investigate the postseismic deformation of the 2004 Sumatra–Andaman earthquake (SAE) using 5 years of Global Positioning System (GPS) data located in northern Sumatra. Continuous GPS data from northern Sumatra suggest that the relaxation time in the vertical displacement is longer than horizontal displacements. This implies that there are multiple physical mechanisms that control the postseismic deformation, which refer to afterslip and viscoelastic relaxation. In this study, we introduce an analysis strategy of postseismic deformation to simultaneously calculate multiple mechanisms of afterslip and viscoelastic relaxation. The afterslip inversion results indicate that the distribution of the afterslip and the coseismic slip are compensatory of each other. Also, afterslip has a limited contribution to vertical deformation in northern Sumatra. In our rheology model, we use a gravitational Maxwell viscoelastic response and the result indicates that the elastic layer thickness is 65 ± 5 km and the Maxwell viscosity is $8.0 \pm 1.0 \times 10^{18}$ Pa s. We find that afterslip plus Maxwell viscoelastic relaxation are appropriate to explain the deformation in northern Sumatra. We also find that our rheology model reproduces the long-term features of the GPS time series in Thailand. Applying our rheology model to the data in Andaman Islands our afterslip estimation is located at the down-dip part of the plate boundary. Finally, we showed that our rheology model is applicable to the GPS datasets of postseismic deformation of the 2004 SAE located in northern Sumatra, Thailand, and Andaman–Nicobar, respectively.

1. Introduction

After large earthquakes, in many cases significant postseismic deformation is observed (e.g. Feigl and Thatcher, 2006; Wang, 2007). Postseismic deformation is caused by mechanisms such as a viscous flow in the Earth's upper mantle and/or the lower crust, commonly referred to as viscoelastic relaxation (e.g. Wang et al., 2001; Hu et al., 2004; Bürgmann and Dresen, 2008), and afterslip reflecting the frictional properties of a fault or a plate interface (e.g. Miyazaki et al., 2004; Ozawa et al., 2011). Various studies suggest that multiple mechanisms are responsible for postseismic deformation in many cases (e.g. Pollitz et al., 1998; Sheu and Shieh, 2004; Ryder et al., 2007; Suito and Freymueller, 2009; Wang et al., 2009).

On December 26, 2004, a great megathrust earthquake, the 2004 Sumatra–Andaman earthquake (SAE), occurred in the Sunda subduction zone along the northern Sumatra, Nicobar, and Andaman Islands. This was the first M9 class earthquake recorded by modern global networks of seismic as well as geodetic instruments (Kanamori, 2006). The source fault of this earthquake was as long as ∼1300 km along the Sunda trench (e.g. Lay et al., 2005). The coseismic stress change was large and extensive, causing significant postseismic deformation. Global Positioning System (GPS) data after the 2004 SAE indicate extensive displacements of

* Corresponding author. Tel.: +81 9099354436.
E-mail address: endra@seis.nagoya-u.ac.jp (E. Gunawan).

http://dx.doi.org/10.1016/j.jseaes.2014.03.016
1367-9120/

postseismic deformation, characterized by a trench-ward motion on the continental side of the plate boundary (Fig. 1).

Many studies have investigated postseismic deformation related to the 2004 SAE rupture. In the Andaman Islands, by using GPS data for the first 2 years after the main shock, Paul et al. (2007) concluded that postseismic deformation in this region was dominated by afterslip. Using different GPS data, Gahalaut et al. (2008) came to the same conclusion. Later, using more GPS data for 6 years, Paul et al. (2012) revisited the problem and concluded that a combination of afterslip and viscoelastic relaxation was the major mechanism. Their rheology model consists of a 90 km thick surface elastic layer overlying the upper mantle with a viscosity of 3×10^{17}–10^{18} Pa s.

Han et al. (2008) detected a postseismic transient signal in the first 2 years after the 2004 SAE using Gravity Recovery and Climate Experiment (GRACE) satellite observations. They estimated the rheological structure of biviscous viscoelastic flow with a transient viscosity of 5×10^{17} Pa s and a steady state viscosity of 5×10^{18}–10^{19} Pa s. Similar results were obtained by Hoechner et al. (2011), who analyzed postseismic deformation using GPS data in the Andaman Islands and geoidal change from GRACE during the first 2 years after the main shock. They reported that the surface elastic layer is 40 km thick, and that Burgers transient rheology in the asthenosphere with a transient Kelvin viscosity of 10^{18} Pa s and steady state Maxwell viscosity of 10^{19} Pa s reproduce the observation data very well.

Another study reported a postseismic investigation of 2004 SAE using combination data sets of gravity variations and GPS measurements in Thailand (Panet et al., 2010). They concluded that a combination of viscoelastic relaxation and afterslip at the down-dip portion of the rupture is capable of explaining these data very well. Their rheology structure consists of a 60 km thick elastic layer overlying a Burgers viscoelastic asthenosphere with a transient viscosity and a steady state viscosity equal to 4×10^{17} Pa s and 8×10^{18} Pa s, respectively. In this model, the upper mantle below 220 km depth has a Maxwell rheology with a viscosity of 8×10^{18} Pa s.

Using a spherical-earth finite element model, Hu and Wang (2012) reported a short-term postseismic deformation model using ∼1 year GPS displacements in the Andaman Islands and northern

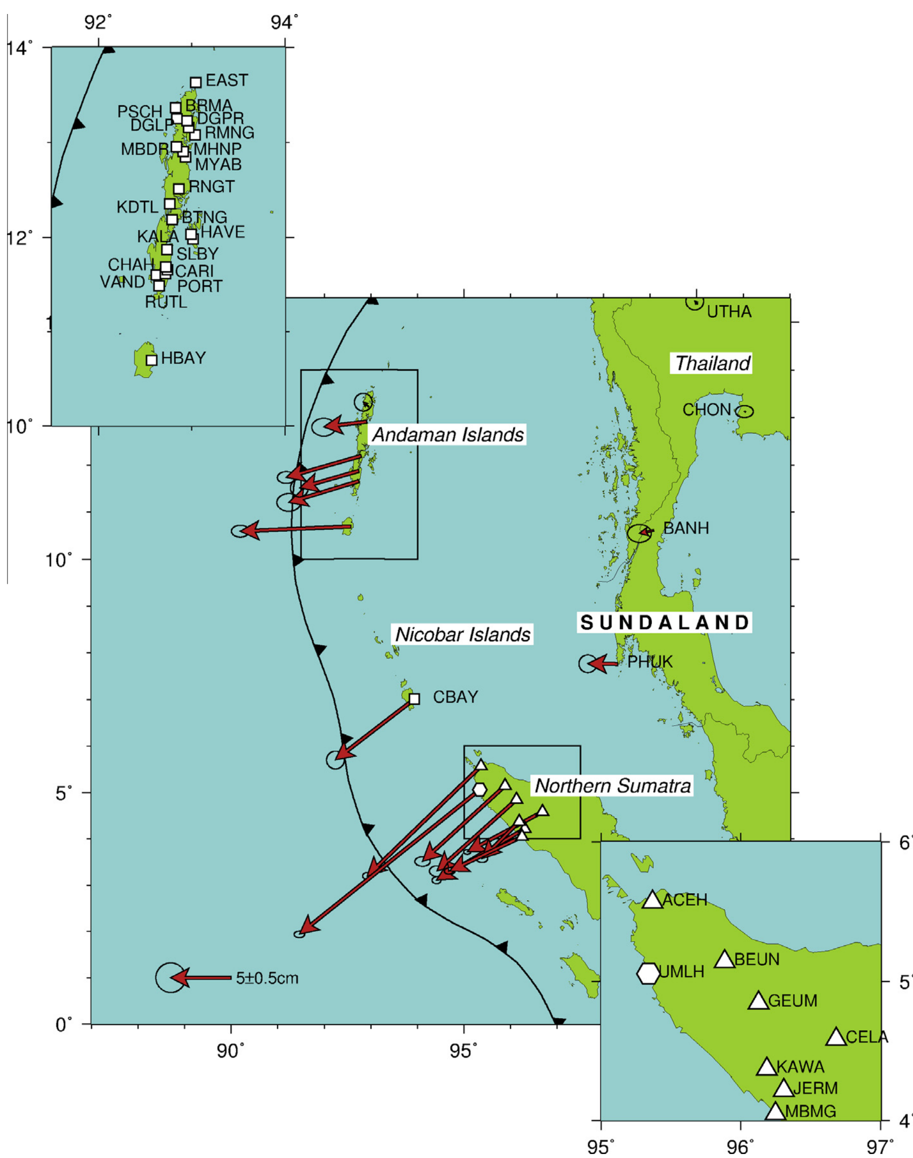

Fig. 1. Cumulative horizontal displacements from 2005.91–2006.90 with reference to the Sundaland block, characterized by trench-ward motion on the continental side of the plate boundary. Arrows scale legend located in bottom left corner of figure. The error ellipsoids of the daily solution indicate the (one sigma) standard deviation. (Top left inset) White square represents Andaman Islands GPS sites (Gahalaut et al., 2008). (Bottom right inset) White triangles denote AGNeSS sites use in this study, and white hexagon identifies SUGaR station in northern Sumatra, respectively.