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Change of Strain Rate in Thailand after the 26 December 2004 and 28 March 2005 Earthquakes Using GPS Measurements

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Abstract

During the period 1994-2004, before the Mw 9.3 Sumatra-Andaman earthquake of 26 December 2004, Thailand was moving horizontally constantly eastward with an average rate of approximately 33.2±1.1 millimeters per year in ITRF2000. The magnitude of the horizontal strain rate was less than 30 nanostrain per year, which was considered small but significant. After the occurrence of the mega thrust earthquake, a horizontal movement to the southwest direction is evident at different rates all over the Thai region. Large co-seismic horizontal displacements were observed in the southern part of Thailand, while moderate and small displacements were seen in the central and northern parts of Thailand. The Royal Thai Survey Department (RTSD) carried out multiple Global Positioning System (GPS) field campaigns to monitor the post-seismic displacements. However, their efforts were complicated by the second mega thrust (Mw8.7) earthquake, which occurred at Nias, Sumatra on 28 March 2005. This study focuses on the use of GPS data, collected between 1994 and 2006, gathered from six GPS stations located at Phuket, Chumporn, Chonburi, Uthaitani, Srisaket and Lampang in Thailand and an additional station located in the northern part of Malaysia to derive changes in the strain rate. Here we find that today's deformation in Thailand is dominated by SW-NE trending extension. This feature is in agreement with post-seismic relaxation occurring on the Sumatran trench.

Keywords: *strain rate, GPS, Sumatra-Andaman earthquake, Nias earthquake, Thailand*

1. Introduction

Since the 1990s, GPS sites located in Southeast Asia have been observed by several campaign-style projects such as GEODYSSEA (GEODYnamics of South and South-East Asia), GAME-T (GEWEX Asia Monsoon Experiment Tropics) and SEAMERGES (South-East Asia Mastering Environmental Research with GEodetic Space techniques). Several field campaigns and experiments using the GPS measurements started before the occurrence of the 2004 great Sumatra-Andaman earthquake (e.g., Chamot-Rooke and Le Pichon, 1999; Michel *et al*., 2000; Michel *et al*., 2001; Vigny *et al*., 2003). These studies revealed that a large piece of continental lithosphere comprising the Indochina peninsula, Sunda shelf and part of Indonesia behaves as a rigid 'Sundaland' platelet. In addition, it was found that the Sundaland platelet is moving eastward with respect to Eurasia at a velocity of 123 millimeters per year (Socquet *et al*., 2006; Simons *et al*., 2007). Within Sundaland, deformation is very small, but Iwakuni *et al.* (2004) confirmed that small but significant strain rates of the order of 10 nanostrain per year existed in Thailand. These deformations can be related to different mechanisms. In the southern part of Thailand, they are probably due to accumulation of elastic deformation due to the locking of plate tectonics on the Sumatran trench. In the northern part of Thailand, they most probably relate to North-South diffuse convergence, as attested by the crustal seismicity in this area.

After the 26 December 2004 Sumatra-Andaman earthquake, many studies reported large co-seismic displacements all over Southeast Asia (e.g., Vigny *et al*., 2005; Hashimoto *et al*., 2006; Satirapod *et al*., 2007a; Simons *et al*., 2007). In Thailand, Satirapod *et al.* (2007a) found that the earthquake had resulted in horizontal displacements approximately ranging from 33 cm in the south and 9 cm in the center to about 3 cm in the north and east of Thailand. The Nias earthquake also generated small horizontal displacements in the central and the southern parts of Thailand (Satirapod *et al*., 2007b). This study focuses on the use of GPS data, collected between 1994 and 2006, gathered from six GPS stations located at Phuket, Chumporn, Chonburi, Uthaitani, Srisaket and Lampang in Thailand, and an additional station located in the northern part of Malaysia to derive the changes in

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strain rate during this 12 year period. It covers the 3 critical phases of the seismic cycle: inter-seismic steady state deformation before December 2004, co-seismic offsets at the time of the earthquake(s), and post-seismic decay since then.

2. GPS Data Used

The primary GPS data used in this research were kindly provided by the Royal Thai Survey Department (RTSD) and the International GNSS Service (IGS). The RTSD survey sites (Phuket (PHUK), Chumporn (BANH), Chonburi (CHON), Uthaitani (UTHA), Srisaket (SRIS), and Lampang (OTRI)) have been regularly occupied (every six months) since 1994. Therefore, the continuous tectonic motions in Thailand, which prevailed before the mega-thrust earthquake, are well known with uncertainties below 1 mm/yr. They correspond to the tectonic motion of the Sundaland platelet. After the mega-thrust earthquake, the network was intensively surveyed (up to 4 times in 2005). The latest allow to monitor closely the co- and post-seismic motions generated by the earthquakes. Details of the Thai GPS data sets can be found in Satirapod *et al*. (2008). In addition, the GETI station as a part of IGS network was used to fill the gap in the southern part of Thailand and lead to a more comprehensive study of deformation over the Thailand region.

3. GPS Data Processing

To determine the magnitude of displacement of each GPS station, the absolute GPS positioning technique needs to be employed rather than the relative GPS positioning technique. This is due to the fact that the relative GPS positioning technique will not give a real picture of the displacement if the positions of both stations are moved (Satirapod *et al*., 2005). Therefore, the absolute GPS positioning technique or so-called Precise Point Positioning (PPP) technique is chosen as a processing strategy in this study. By using the PPP technique, the users can expect a daily repeatability of a few millimeters in the horizontal components, and about a centimeter in the vertical component, for data from a static site occupied by a geodetic-quality receiver (Zumberge *et al*., 1997). However, it should be noted that for a calculation of strain rate, the relative GPS positioning technique can also be used since the calculation of strain rate only requires the relative displacement information.

The GIPSY-OASIS II (GPS Inferred Positioning System–Orbit Analysis and Simulation Software) was used to process the GPS data sets described in the previous section to produce daily fiducial-free network solutions by employing the PPP strategy. For more details on the PPP processing steps, see Simons *et al*., 2007. To fit coordinate time series of data before the 2004 earthquake (1994-2004), these can be estimated by computing a linear fit through all ITRF2000 mapped station coordinates and checking the coordinate residuals at each point of the time series. On the contrary, time series of data after the mega thrust earthquake cannot be fit by linear trends. Satirapod *et al.* (2008) found that a Logarithmic decay function presented by Marone *et al.* (1991) can fit the post-seismic time series due to the 2004 and 2005 earthquakes better. Therefore, a logarithmic decay function was used to fit the displacements of each GPS site, which can be described as:

$$u(t) = c + a\ln\left(1 + \frac{t}{\tau_{\log}}\right) \tag{1}$$

where: t is time since Sumatra–Andaman earthquake
$u(t)$ is the displacement in each component (i.e. east, north, and up)
c is the co-seismic offset
a is the amplitude associated with the decay
$\tau_{\log}$ is the logarithmic decay time

In order to determine velocities after the mega earthquake, an instantaneous velocity at each station can be obtained from a partial derivative of Eq. (1) with respect to t. Then, the instantaneous velocity can be expressed as:

$$velocity = \frac{a}{\tau_{\log} + t} \tag{2}$$

4. Strain Rate Calculation

The surface of the Earth is continually being strained by tectonic processes, which are often a consequence of large-scale forces. Hence, the measurement of surface strain can provide important information on fundamental geodynamic processes. Because surface strains are generally very small, sophisticated distance-measuring techniques are required to determine them. Strain rates can be determined by measuring changes in distances between several points, usually arranged in triangles or quadrilaterals, over time (Janssen *et al.*, 2009). Thus geodetic techniques, especially GPS, can measure these changes. By using geodetic networks, a triangle is the minimum polygon required to compute strain. For a long-term analysis, strain rates per year are usually determined.

To calculate the strain rate in this study, a triangular network is formed using the three nearest GPS stations (e.g. OTRI, UTHA and SRIS forming triangle 1) in which the area inside of each triangle is assumed to be homogeneous. Fig. 1 shows how the triangle network is formed. In this study, the strain rates at different periods were calculated using the following equations (Cai and Grafarend, 2007).

$$\begin{bmatrix} V_{E_1} \\ V_{N_1} \\ V_{E_2} \\ V_{N_2} \\ V_{E_3} \\ V_{N_3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Delta E_1 & \Delta N_1 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta E_1 & \Delta N_1 \\ 1 & 0 & \Delta E_2 & \Delta N_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta E_2 & \Delta N_2 \\ 1 & 0 & \Delta E_3 & \Delta N_3 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta E_3 & \Delta N_3 \end{bmatrix} \begin{bmatrix} V_{E_B} \\ V_{N_B} \\ \frac{\partial V_E}{\partial E} \\ \frac{\partial V_E}{\partial N} \\ \frac{\partial V_N}{\partial E} \\ \frac{\partial V_N}{\partial N} \end{bmatrix} \tag{3}$$

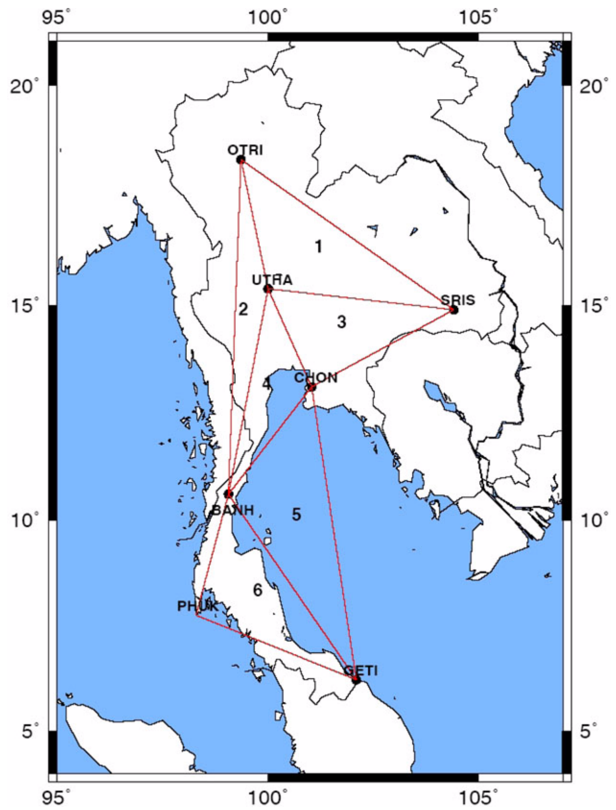

Fig. 1. The Triangle Network in Thailand

where V_{E_i} and V_{N_i} are velocities of stations, $i = 1, 2, 3$. V_{E_B} and V_{N_B} are velocities at centroid. ΔE_i and ΔN_i are coordinate difference at stations, $i = 1, 2, 3$.

From calculated velocity gradient tensors, a two-dimensional symmetric strain tensor can be computed from (Cai and Grafarend, 2007):

$$\mathbf{E} = \begin{bmatrix} \dot{\varepsilon}_{xx} & \dot{\varepsilon}_{xy} \\ \dot{\varepsilon}_{yx} & \dot{\varepsilon}_{yy} \end{bmatrix} \tag{4}$$

Each component of the matrix E can be expressed as:

$$\dot{\varepsilon}_{xx} = \frac{\partial V_E}{\partial E} \tag{5}$$

$$\dot{\varepsilon}_{yy} = \frac{\partial V_N}{\partial N} \tag{6}$$

$$\dot{\varepsilon}_{xy} = \dot{\varepsilon}_{yx} = \frac{1}{2}\left(\frac{\partial V_E}{\partial N} + \frac{\partial V_N}{\partial E}\right) \tag{7}$$

The matrix E has two Eigen values:

$$\dot{\varepsilon}_1 = \frac{\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy}}{2} + \sqrt{\frac{\left(\dot{\varepsilon}_{xx}\dot{\varepsilon}_{yy}\right)^2}{4} + \dot{\varepsilon}_{xy}^2} \tag{8}$$

$$\dot{\varepsilon}_2 = \frac{\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy}}{2} + \sqrt{\frac{\left(\dot{\varepsilon}_{xx}\dot{\varepsilon}_{yy}\right)^2}{4} + \dot{\varepsilon}_{xy}^2} \tag{9}$$

where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are strains in the direction of compression and extension, respectively.

In the principal strain axis coordinate system, shear strain components are zero. The direction of one of the principal axes of strain can be computed using:

$$\tan 2\theta = \frac{2\dot{\varepsilon}_{xy}}{\dot{\varepsilon}_{xx} - \dot{\varepsilon}_{yy}} \tag{10}$$

where θ is the angle between the direction of maximum variance and the eastern direction.

5. Results

The crustal deformation was studied using the representative principal strain rate within a triangle formed by the three nearest GPS stations. The analysis was divided into 3 periods – the first period is between 1994 and 2004 (before the mega earthquake), the second period is between 26 December 2004 and 28 March 2005 (after the mega earthquake but before the Nias earthquake) and the third period is after 28 March 2005 (after the Nias earthquake). Table 1 shows an example of the value of principal strain rate ($\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$), and θ during the period of 1994-2004. It should be noted that a positive value of principal strain rate is considered as extension while a negative value is compression. Fig. 2-4 illustrates the derived strain rates at different times (where $t = 0$ indicates the epoch of the mega earthquake). The red-crossed arrow denotes extension.

Table 1. Results of Principal Strain Rate During the Period of 1994-2004

No.	Triangle Network			Position of Centroid		$\dot{\varepsilon}_1$ (nano strain/yr)	$\dot{\varepsilon}_2$ (nano strain/yr)	θ (deg)
				LON (deg)	LAT (deg)			
1	OTRI	UTHA	SRIS	101.2790	16.2185	7.5	-5.9	61.2627
2	OTRI	UTHA	BANH	99.4847	14.7766	25.9	-7.5	28.2457
3	UTHA	SRIS	CHON	101.8240	14.4763	-1.3	-3.4	-9.6526
4	UTHA	CHON	BANH	100.0418	13.0395	-3.2	-9.1	72.6971
5	CHON	SRIS	BANH	100.7461	9.9877	0.9	-8.2	58.0335
6	BANH	PHUK	GETI	99.8330	8.2014	1.2	-4.7	42.8725

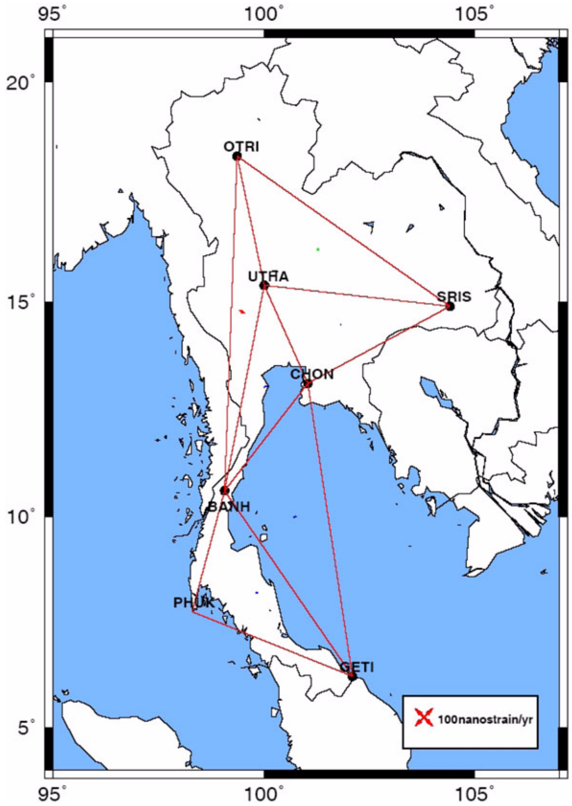

Fig. 2. Strain Rates During 1994-2004

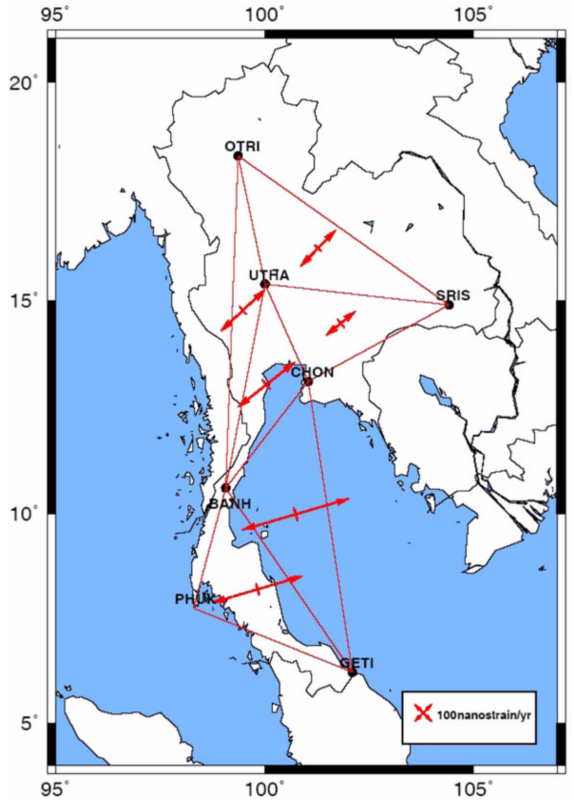

Fig. 3. Strain Rates at 1.5 months after the Mega Earthquake

As shown in Fig. 2, the crustal deformation pattern in Thailand varied from place to place during 1994-2004. The principal strain rate was found to be significant only in the western part of Thailand (see Table 1; Triangle 2). The magnitude is a little less than 30 nanostrain per year. This value very well agrees with the work carried out by Iwakuni *et al.* (2004). However, at 1.5 months after the mega earthquake, the crustal deformation pattern in Thailand was changed throughout the country by showing the extension type of the principal strain rate in the northeast–southwest direction at a magnitude of approximately 300 nanostrain per year (see Fig. 2). It is important to note that the direction of the principal strain rate to the southern area (Triangles 5 and 6) was slightly different from that in the northern part of the country. After the Nias earthquake, the strain rates tend to retain the same characteristics as the period of 1.5 months after the mega earthquake. It can be seen from Fig. 4 that the magnitude of strain rates decreases over time.

6. Discussion

Before the occurrence of the megathrust earthquake, the velocity vectors all over the country have similar magnitudes and were directed to the east, relative to the Eurasian plate. This was caused by the pushing of the Indian plate into Eurasia, which generates the extrusion of SE-Asia to the side. However, after the megathrust earthquake, the direction of the velocity vectors changed to the southwest (Satirapod *et al*., 2007a). This can be explained by the fact that the Myanmar platelet slipped to the west, towards the Indian plate around the earthquake epicenter. Then, the crust connected to the Myanmar platelet, the Sundaland plate on which Thailand sits, was dragged along with it. As the crust is not a rigid body, but rather behaves in a visco-elastic way, the rate of displacement in each part of the crust is different in magnitude. The closer to the epicenter, the faster the rate.

With respect to our strain analysis, before the megathrust earthquake the observed strain rates were relatively small. This implies that the block was moving approximately like a rigid block although there was slow accumulation of small elastic deformations. As the strain accumulation was released suddenly by the earthquake, the strain rates were increased by more than a factor of 10. Fig. 5 illustrates the strain ellipsoid compared with strain calculated after the mega earthquake. It shows normal faulting with a large extension in the SW-NE direction. This is agreeable with the focal mechanism of the earthquake. Since the earthquake was thrusting in this direction, which means the Indian and Sunda plates moved towards each other along this direction, the Sunda plate rebounded towards the Indian plate (the southeast direction).

7. Conclusions

Thailand is part of the Sundaland block, which is considered a rigid plate. However, because of friction along with neighboring plates, Sundaland boundaries deform, slowly accumulating elastic

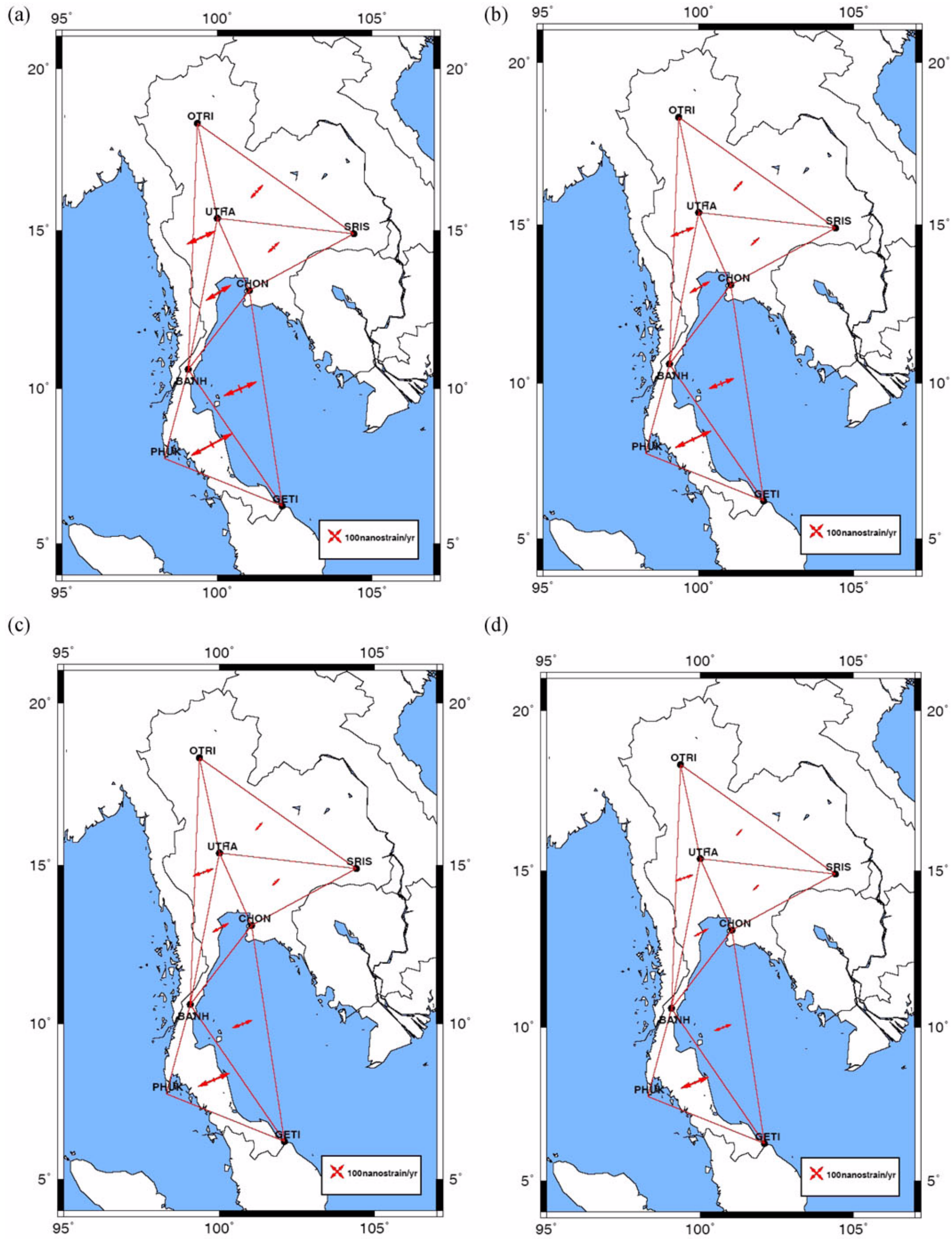

Fig. 4. Strain Rates: (a) 3 months, (b) 6 months, (c) 9 months, and (d) 12 months after the Nias Earthquake

deformation. This deformation was partly released during the occurrence of the mega earthquake on 26 December 2004. Prior to the earthquake, it was thought that the deforming boundaries were only narrow strips of no more than a few hundreds of km in width. The first thing that the earthquake showed was the vast extent of the area affected by co-seismic deformation: there was a large effect all over the Southeast Asia region, and even to China and India. Post-seismic deformations will continue to release the elastic deformation accumulated slowly during the centuries before the earthquake. Only when this phase of the seismic cycle is completed, the plate will return to its original undeformed size and shape, and the compression cycle will resume. But because such large events do not occur very often, we simply guess it will affect roughly the same area as the co-seismic and do not know exactly for how long. This research focuses on the movement of Thailand after the mega earthquake using GPS data from six GPS sites located in Phuket, Chumporn, Chonburi, Uthaithanee, Srisaket and Lampang in Thailand, and one additional GPS station from the northern part of Malaysia. It was found that about 10 years before the mega earthquake, the whole Thai region was moving to the east direction and had small strain rates (less than 30 nanostrain per year). After the mega earth-

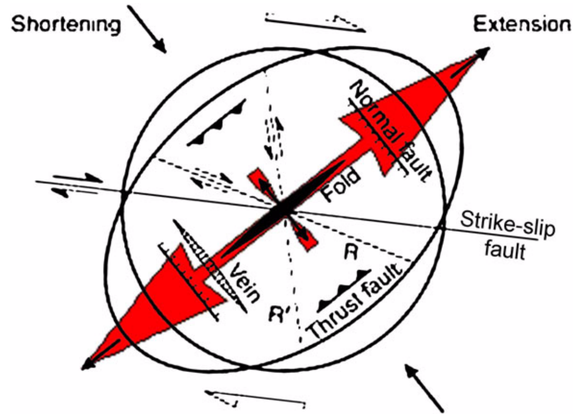

Fig. 5. Strain Ellipsoids Compared to the Strain Calculated from the Period after the Mega Earthquake

quake, Thailand exhibited horizontal movement to the southwest at different rates, higher rates from south to north. The horizontal strain rates are found to be extension along a northeast–southwest direction all over the country and they are in agreement with the movement of the Sumatran trench. The Nias earthquake, occurring further south on the same Sumatra trench with the same mechanisms, simply added more extension, roughly in the same direction. Present day extensional strain rates in Thailand are due to the post-seismic relaxation of the Sunda plate following both earthquakes.

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