# Deformation related to the 1994 Liwa earthquake derived from Geodetic Measurements

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**Abstract.** The deformation field around the southern Great Sumatran Fault (GSF) in the vicinity of the February 15 1994 Mw = 6.8 Liwa earthquake has been determined by geodetic survey. Geodetic trilateration and Global Positioning System (GPS) measurements were carried out from experiment conducted in July 1991 in the Ranau Lake-Liwa area. A second geodetic survey reoccupied the same stations in September 1994, seven months after the Liwa earthquake. Despite the limited number of benchmarks most of the geodetically measured field displacement appears to be related to the 1994 Liwa earthquake. In addition, we show that most of this co-seismic deformation is localized along a narrow zone corresponding to the GSF segment with a right lateral displacement of about 70 cm along the fault trace.

## Introduction

The Great Sumatran Fault (GSF) is a NW-trending right lateral fault zone that parallels the western Sunda Trench and follows the magmatic arc southward from the Andaman Sea back-arc basin to the Sunda Strait extensional domain (Figure 1). Although several damaging historical earthquakes are known, only 17 seismic events (M > 6 or MMI > VIII) have been reported along the fault since 1835 [e.g., Beaudouin et al., 1995]. This suggests that the GSF exhibits stick-slip behavior, appearing to remain locked between major earthquakes. However, the low ratio of released seismic moment suggests that the GSF has presently a large aseismic component [Zwick and McCaffrey, 1991].

In July and August 1991, we set up both EDM and GPS geodetic networks along the GSF within two zones: the Ranau Lake-Liwa area (5°S) and the Singkarak Lake-Padang area (0°30'S) [Kasser et al., 1994]. The foci of the current study are threefold : (1) to assess the deformation field around the GSF, (2) to observe if there is some creep-slip or only stick-slip behavior along the GSF, (3) to determine if the deformation is distributed across a wide zone or mainly localized along a narrow fault zone. In September 1994, seven months after the February 15 Liwa earthquake, we repeated the Ranau Lake-Liwa area geodetic network measurements. This study reports the geodetic results and presents simple elastic model which shows that most of the observed geodetic displacements are due to the Liwa earthquake.

## Convergence obliquity versus sumatran arc deformation

In subduction areas associated with oblique convergence, relative plate motion may be partitioned between displacements along the subduction plane and deformation within the overriding plate [Fitch, 1972]. This overriding plate deformation corresponds sometimes to a shear component localized on a parallel to the margin, strike-slip fault zone. The N3°-20°E-trending convergence [DeMets et al., 1990; McCaffrey, 1992; Tregoning et al., 1994] of the Sunda trench is oblique off Sumatra. It has to be accommodated mechanically by both subduction and strike-slip deformation in the overriding plate; i.e., mostly along the GSF and the Mentawai Fault (MF) [Diament et al., 1991; Bellier and Sébrier, 1995].

To estimate slip rate, an along-strike survey of the GSF has been conducted from geomorphic feature offsets observed on SPOT images and topographic maps [Bellier and Sébrier, 1995]. These estimates show a southward slip rate decrease along the GSF from about 23±2 mm/yr at 2°N, to 6±4 mm/yr at 5°S, near Ranau lake. SPOT image analysis and structural field studies suggest that the GSF slip-rate variation is chiefly accommodated by transpressional deformation in the back-arc [Bellier and Sébrier, 1995; Detourbet, 1995]. Several dextral-reverse oblique-slip fault zones splay south-eastward from the GSF to reach obliquely the Sumatran back-arc basins. The horizontal slip rate of these faults appears to be about 1 mm/yr. Most of the fore-arc sliver, between the GSF and the MF, should be under compression as suggested by the MF geometry which suggests a dextral movement [Diament et al., 1991; Zen, 1993] with the western block upthrusted [Karig et al., 1980]. This has been supported by field observations that showed an about N40°E-trending shortening [Detourbet, 1995] similar to the compression in the back-arc [Mount and Suppe, 1992]. These remarks suggest that even if the active deformation of Sumatra is mostly localized along the GSF, combination of different modes of deformation throughout the fore-arc platelet to the back-arc domain contribute to accommodate the oblique convergence. The overriding plate being mainly under compression, the margin parallel stretching suggested by thrust earthquake slip vectors of the Sumatran trench [McCaffrey, 1991], it should be mainly located between the trench and the MF [Bellier and Sébrier, 1995].

## The southernmost GSF

The southernmost part of the GSF, between the Ranau Lake and the Semangka Bay, consists of the 60-km-long Ranau-Suwoh and the 70-km-long Semangka fault segments (Figure 1), that are linked by a 7 km wide releasing stepover fault zone, i.e., the Suwoh pull-apart graben. The Ranau-Suwoh segment is formed by only one major strike-slip fault that cross-cuts the Ranau Lake, to the north, and which constitutes the northern border of the Suwoh pull-apart. The northernmost part of this segment ruptured during the 1933 (M~7.5) earthquake which affected the SE region of the Ranau Lake.

The Semangka fault zone includes several minor faults and a NW-trending major fault which marks the southern border of both the Suwoh pull-apart to the north and of the Semangka depression to the south. Other faults of the Semangka fault zone include the North-Semangka NW-trending fault and the Banding WNW-trending fault bounding the Banding triangular basin. The right stepover between the Semangka and the Ranau-Suwoh faults is marked by a complex pull-apart resulting from the coalescence of two basins. In the western part of this stepover fault zone, we observe a cluster of small active calderas that seems to play a major role during the 1994 aftershock sequence [Widiwijayanti et al., this issue]. Geological study and SPOT image analyses along the GSF trace show right-lateral offsets of streams, lineaments, and of the Ranau caldera rim (Figure 1) suggesting that most of the recent deformation is localized along a narrow fault zone. These analyses indicate that the GSF in the Ranau-Suwoh area has an average slip-rate ranging between 2 and 10 mm/yr [Bellier and Sébrier, 1994].

## Liwa earthquake rupture

The 15 February 1994 Liwa earthquake reactivated the southern part of the 60-km-long Ranau-Suwoh segment and caused many deaths and damage. Our field study did not locate any surface rupture showing that co-seismic rupture has not been transmitted up to the surface owing to the rheological characteristics of the Quaternary Ranau Tuff that covers extensively the region. Indeed, these tuffs are poorly compacted clayished volcano-sedimentary deposits which were saturated with water during the Liwa earthquake, i.e., during the wait season, implying a plastic behavior of the uppermost crust. The reactivated segment has a mean seismogenic depth of 15 km and a length of ~30 km according to the aftershock distribution [Widiwijayanti et al., this issue]. Using these values and the estimated moment of $M_0$=2.2 $10^{26}$ dyne.cm [seismological notes, 1994], we infer a mean co-seismic displacement of about 1.5 m.

## Geodetic data

The relative positions of six GPS points covering an area of 40 x 35 $km^2$ were initially measured during July 1991 [Kasser et al., 1994] in the southern part of Sumatra island, i.e., the Ranau Lake-Liwa region (Figure 1). To obtain the best station coverage, we occupied three stations on each side of the fault. Three of these, C, D, and E, are close to the Ranau-Suwoh active segment. Two points, A and B, are along the coast, i.e., on the eastern edge of the forearc. One point, F, is in the back arc domain. Site locations and the number of stations were drastically limited by the conditions in the field: dense vegetation with tropical jungle and few accessible roads. To measure movement along the fault, we added four EDM points, one of which is also a GPS benchmark (D) and three others (G, H, I on the Figure 1). Those four points are located around Ranau lake, i.e., on both sides of the fault trace. In 1991, the GPS data were collected in two daily sessions from 04:30-09:30 UTC and from 16:30-21:30 UTC, with three dual frequency Ashtech LDXII receivers. In September 1994, we measured the network again. The GPS data were collected in four daily sessions from 04:45-10:45 UTC, 11:00-17:00 UTC, 17:00-23:00 UTC and again from 23:15-05:15 UTC with four dual-frequency Ashtech receivers, one "codeless", two "P-code", and one "Z-code".

We analyzed the GPS data using the version 3.5 of the Bernese GPS software [Rothacher et al., 1994]. For the 1991 data, we used the broadcast orbits, but for the 1994 data, we used precise orbits from IGS. To evaluate the precision of the estimated relative position, we calculate the Weighted Root Mean Square (WRMS) scatter [Larson and Agnew, 1991], between multiple session measurements of individual baselines. For 1991, the average WRMS scatter is 5 mm, 7 mm and 48 mm for north, east and vertical components, respectively, while for the 1994 measurements, the values are 7 mm, 11 mm and 20 mm, respectively. The 1991 WRMS probably slightly underestimates the uncertainty because of the small number of repeated baselines. In addition, the quality of the 1994 measurements is affected by the presence of temporary buildings located close to the benchmarks. Moreover, since some main markers were not available, measurements on auxiliary points built in 1991 were performed in order to prevent possible damage of the network. GPS data and EDM measurements were adjusted with AGE software which permits geodetic adjustment on reference ellipsoid system [Ruegg and Bougault, 1992]. We held the position of point F fixed because it is the point farthest from the main shock earthquake epicenter. The relative error on the horizontal component is around 20-30 mm. For the vertical component, the difficulty of modeling the tropospheric delay leads to an error of some 50-100 mm.

## Geodetic results and modelling of the main shock

As no nearby fiducial station was available in 1991, we have only a relative displacement between the network benchmarks. The largest movement with respect to point F fixed, 558 mm on a N63°W direction is measured on the point C, within the Liwa depression. The two points A and B, localized along the coast, have been displaced of about 120 mm and 161 mm in the directions N42°W and N61°W, respectively. Points E and D have N174E°-trending 282 mm and N72°W-trending 63 mm displacements, respectively. We consider that G, H and I benchmarks have no significant displacements because of the uncertainty on EDM measurements.

To explain the coseismic surface displacement field, we use a simple dislocation model in an elastic half space [Okada, 1985] as for another earthquake [Ruegg et al., 1996]. Having few points around the rupture zone, we chose a simple elastic model constituted by a single rupture. Taking into account the strike, dip, rake, and magnitude parameters of the main shock [Seismological notes, 1994], and the 30 km-long and 15 km-depth seismogenic rupture deduced from the aftershocks study [Widiwijayanti et al., this issue] (Figure 2; column 2 on Table 1 ), we obtained an acceptable fit to the measured horizontal displacement vectors except for point E. Indeed, the other displacement discrepancies between the observed and calculated vectors are included within the uncertainties of the measurements and to the modelling. Point E is localized on a flat topped river terrace overlooking a valley parallel to thr GSF some 9 km NNE from the Ranau-Suwoh segment. Field observations and the peculiar topography lead us to assume that E displacement may include some settling component. This seems confirmed by our geodetic data showing a displacement vector that may result both from a coseismic displacement and a settling component toward the SW, i.e., normal to the fault component of the E point vector. Neglecting this component, we infer the minimum cumulative strike-slip displacement along the GSF can be deduced summing the parallel to the fault displacement components of the points C and E. This cumulative displacement is about 70 cm. The modelling of vertical motions fits well the general trend; however, we get a slight discrepancy in the mean amplitude of point C; indeed, the calculated vertical displacement is about 15 cm lower than the observed one ( Table 1).

## Conclusion

Despite a limited number of benchmarks, we show that the observed displacements between July 1991 and September 1994 may be mostly explained by the 15 February 1994 Liwa earthquake. Surface deformation is mainly localized along a narrow 10 km-wide zone (between points C and E) along a major GSF segment and corresponds to a right-lateral strike-slip displacement of about 70 cm. Although, we infer that most of the measured displacements are related to the 1994 earthquake; however, we cannot quantify the aseismic slips because we did not measure the network just before and after earthquake.

The last destructive earthquake on the Ranau-Suwoh Segment occurred close to Ranau Lake in 1933. Thus, about 70 cm of displacement that should be related to the 1994 earthquake suggests that the part of the fault segment ruptured both in 1933 and 1994 agrees with an average slip-rate of about 10 mm/yr similar to the long-term slip-rate estimated by geological observations [Bellier and Sébrier, 1994]. This leads us to propose a mainly stick-slip mechanical behavior for the Ranau-Suwoh Segment of the GSF. The EDM network localized around the Ranau Lake section of the GSF major fault trace did not provide evidence for significant motions confirming the locked behavior of the southern GSF between major earthquakes. In addition, seismometers deployed around the southern GSF zones did not record any microseismic activity that might indicate some creeping process in this area [Harjono et al., 1991; Zen, 1993].

In conclusion, our study gives evidence for co-seismic right-lateral deformation within the arc domain in relation with the GSF strike-slip displacement. Next experiments will be required to constrain the role of interseismic deformation and strain accumulation within the Sumatran Arc, and the aseismic behavior of the GSF. In addition, it will be necessary to better assess with a dense network the back-arc and fore-arc deformation which contributes to accommodate the oblique convergence.

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**Figure 1.** Structural map of the studied region after Bellier and Sébrier [1994]. Steppled areas represent depression zones; double hatchures bounded the Ranau Caldera and the Suwoh caldera cluster. Letters are location of geodetic benchmarks. Star is the CMT location of the mainshock after Harvard University, with the preferred Moment Tensor solution [Seismological Notes, 1994].
Inset right present the geodynamic framework of the Sumatran Arc where we represent the GSF and MF. Arrow indicate the plate convergence. Inset "A" depicts a sketch showing offsets of the Ranau caldera rim, a lineament and streams.

**Figure 2**. Uniform slip model based on GPS measurements. Observed (solid lines) and modelled value (dashed lines) relative to point F. S1 is the USGS point Source.Dashed rectangular is the fault plane. Error ellipses are drawn at 95% confidence level.

Table 1 - Observed (1) and modelled (2) relative displacement components to point F (East, North, vertical) in centimeters.

| Point | (1) | | | (2) | | |
|---|---|---|---|---|---|---|
| A | -8 | 9 | 9 | -7 | 7 | 0 |
| B | -14 | 8 | 9 | -6 | 9 | 0 |
| C | -47 | 24 | 19 | -31 | 30 | 3 |
| D | -6 | 2 | 3 | 1 | -5 | -2 |
| E | 3 | -28 | -4 | 19 | -13 | -2 |
| F | 0 | 0 | 0 | 0 | 0 | 0 |
| G | -11 | 2 | 3 | 0 | -2 | -2 |
| H | -8 | 6 | 3 | -2 | 1 | -1 |
| I | -9 | 9 | 3 | -1 | -1 | -2 |