Monitoring of the Palu-Koro Fault (Sulawesi) by GPS

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Abstract. 5 years of GPS measurements across the Palu-Koro fault (Sulawesi, Indonesia) state left lateral strike-slip (3.4 cm/yr) with a small normal component (0.4 cm/yr). The measurements on intermediate points of the transect show that the fault is locked, at a depth estimated around 8–16 km by a very simple model. The best measured baseline linking the two most separate sites (Watatu and Toboli) shows very interestingly a constant rate of 2.6 cm/yr from 1992 to 1995, and an increased rate of 6.3 cm/yr since then. This increase is due to an earthquake on January 1, 1996 in the Minahasa trench, presumably affecting station Toboli's position by 2 cm of co-seismic and 2 cm of post-seismic displacement, which is added to its long term velocity. We interpret this phenomenon as additional stress loading on the Palu fault, driven by the slip during the earthquake 100 km to the North-East.

Introduction

The Palu-Koro fault is a major transform zone in the region of convergence of three major tectonic plates with high relative motions, in Eastern Indonesia. Here, the Australian and the Philippine plates are colliding with velocities as high as 7.5 and 9 cm/yr respectively with the Eurasian plate, or more precisely, the South-East Asian block. For simplification, we consider it in this study to be part of the Eurasian plate. In the triple junction area is situated the Sula block, showing the high residual motion (more than 5 cm/yr) of both the Philippine and the Australian plate with respect to Eurasia. The intrusion of the Sula block [*Rangin*, 1989; *Walpersdorf et al.*, 1998] into the Eurasian plate is transfered at its western and south western limit by the Palu-Koro and the Matano fault (features 2 and 3 in Figure 1), and accommodated at its northern limit by the North Sulawesi trench (feature 1). Long term velocities across the Palu-Koro fault have been estimated by *Silver et al.* [1983] and *Rangin et al.* [1997] to 5 cm/yr left lateral strike-slip motion over 5 Ma. On the other hand, geological field studies based on the datation of uplifted coral terraces show displacement rates on single fault planes of about 2 cm/yr, but each of these estimates has a high uncertainty [*Bellier et al.*, 1998]. This paper presents the observation of the present day activity across the Palu-Koro fault inferred from two years of GPS observations on a transect of 13 stations, and from five years of observation on the main baseline.

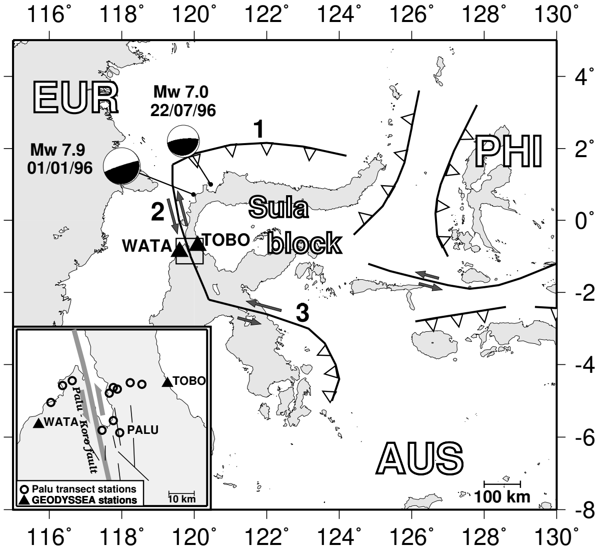

Figure 1. The area of convergence of the Eurasian, Philippine and Australian plate is characterized by the Sula block motion. Active block boundaries are the North Sulawesi trench (1), the Palu-Koro (2) and the Matano (3) faults. The Palu transect is indicated by the box, with a zoom presented in the inset. Furthermore, the two largest earthquakes (CMT) occurring during the observation period are indicated.

GPS data from the Palu transect

The 50 km long Palu transect was installed in 1992 and measured yearly until 1994 by American RPI (Rensselaer Polytechnic Institute) and SIO (Scripps Institution of Oceanography), and Indonesian BAKOSURTANAL teams [*Stevens et al.*, 1998]. In this paper, data acquired by French ENS (Ecole Normale Supérieure) and BAKOSURTANAL on 13 transect stations (inset of Figure 1) are shown, measured during 6 days in September 1995 and 4 days in December 1996. Four roving Ashtech Z12 receivers were used to occupy the stations in 4 to 12 hour long sessions. The furthermost stations WATA and TOBO, and the central station PALU were occupied during several sessions, the other (intermediate) stations once or twice in each campaign. Additionally, for the main baseline WATA–TOBO, we combined RPI results from 1992 to 1994 [*Stevens et al.*, 1998] with ours from 1995 to 1996. We also included 3 days of continuous observation on WATA, TOBO and PALU in April 1996, executed with Trimble SSE receivers in the framework of the GEODYSSEA '96 campaign [*Wilson and Rais*, 1998; *Walpersdorf et al.*, 1998].

The GPS data have been processed in individual observation session with MIT's GAMIT 9.4 software [*King and Bock*, 1993]. Data from the 5 closest permanent stations of the IGS network have been included in the analysis (YAR1, TIDB, TAIW, TSKB, KIT3). Precise IGS combined orbits were held fixed in the data analysis. The processing strategy applied is described in details by *Walpersdorf et al.* [1998] and *Angermann et al.* [1998].

Since the earlier RPI and ENS solutions are obtained with the same software with only slight differences in strategy, no persistent

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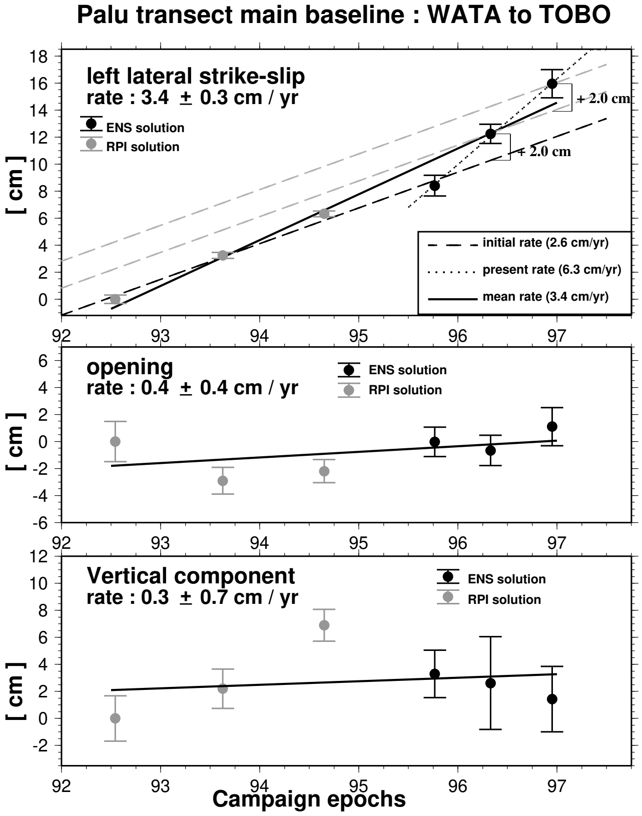

Figure 2. Time evolution of the three WATA-TOBO baseline components. Error bars indicate formal uncertainties. Straight lines represent the mean rates of motion on each component. On the strike-slip component are shown additionally an initial and a present day rate.

biases are expected between the respective solutions, as is verified by an independent analysis of the 1995 data set, showing excellent coherence.

Time evolution of the Palu main baseline

The 5 years average rates of the three baseline components North, East and Vertical obtained in the data processing are 3.4 ± 0.4, -0.5 ± 0.4 and -0.3 ± 0.7 cm/yr, respectively. Assuming a fault's azimuth of 165° at the transect's latitude [*Bellier et al.*, 1998], this yields a strike-slip rate of 3.4 ± 0.3 cm/yr and a rate of opening of 0.4 ± 0.4 cm/yr. The time evolution over the 6 measurement campaigns is shown in Figure 2. The average present day strike-slip rate over the last 5 years is 3.4 cm/yr, well in between the two geological values (2 and 5 cm/yr).

In detail, however, on the strike-slip component, two different rates have been observed: A low rate of 2.6 cm/yr from 1992 to 1995, and a much higher rate of 6.3 cm/yr since 1995. These different displacement rates seem to be related to the seismic activity in the North Sulawesi region. While no large earthquake is reported in this region since the beginning of the measurements in 1992 until 1995 (after USGS, ISC, CMT data), two major earthquakes took place in 1996 ($M_w = 7.9$ on January 1 and $M_w = 7.0$ on July 22), related to the subduction along the North Sulawesi trench (Figure 1). Modeling of elastic deformation in an infinite half-space shows that the larger January earthquake may have caused an instantaneous differential displacement of about 1.5 cm on the Palu main baseline. The weaker and more distant July earthquake could account for a maximum of 0.2 cm (J.-M. Gomez, personal communication, 1997). To explain the additional motion we propose post-seismic relaxation following the $M_w = 7.9$ earthquake. Post-seismic relaxation over many months as large as the co-seismic displacement have already been observed and reported (e.g.[*Heki et al.*, 1997]). The faster northward propagation of the TOBO station results in an increase of the stress loading on the presently locked Palu-Koro fault.

The weak tendency of opening across the Palu fault becomes recognizable on the perpendicular component since the last epochs of the five year observation period. This is in agreement with clear geomorphological traces. With the related vertical offset observed by geological methods as well, geologists estimate the Palu fault inclination to about 60° - 80° facing east [*Bellier et al.*, 1998]. The expected vertical motion on the WATA-TOBO baseline according to these geologic observations would be a downward movement of TOBO with respect to WATA. With TOBO being situated at a higher altitude than WATA, this corresponds to a decrease of the vertical WATA-TOBO baseline component. However, this decrease of the vertical WATA-TOBO baseline component has only been observed between the last four measurement epochs, while the first epochs suggest an increase above the limits of uncertainty. This could be explained by either systematic errors like monument instability after the installation, or by an underestimation of the real uncertainty by the formal error bars in the first three campaigns.

We can evaluate a prediction for the vertical rate by combining the geologically observed fault inclination of 60°– 80° with the 4 mm/yr of opening, resulting from our observations and coherent with the geologic study. This yields a vertical displacement rate of -7 to -23 mm/yr. Since 1995, we obtain a linear vertical rate of -16 mm/yr. Therefore we would suggest that the first three measurements are less significant than postulated by their formal error bars, and that especially the last three epochs of measurement (because since then precise IGS orbits have been used), are more significant for the vertical movement than the formal errors might indicate. With the change of tendency in the vertical baseline evolution appearing approximatively in the seismic period, one could suggest that the new negative rate is earthquake triggered. However, the modeling of the surface deformation in the Palu region due to the subduction zone earthquake predicts a very small uplift (1 mm) of TOBO with respect to WATA, in opposite sense to the observed vertical motion. Unlike the horizontal displacements, the vertical motion is therefore not significantly influenced by the January 1996 earthquake.

Velocities on the intermediate transect stations

An estimate of the velocities of the intermediate transect stations during the period of increased strike-slip velocity on the main baseline is established by combining the results of the 1995 and 1996 PALU campaigns. The resulting velocities with their uncertainties are shown by the vectors and error ellipses in Figure 3.

The locking of the Palu-Koro fault is demonstrated by the pattern of vanishing parallel velocities when approaching the fault. The high displacement rates on the WATA-TOBO baseline since 1995 are therefore not due to a seismic event on the Palu-Koro fault itself, but rather to a transmission of elastic deformation from seismic slip on the subduction zone along the North Sulawesi trench.

Some large velocity components perpendicular to the fault (PL03 and PL04) contrast with the expected velocity pattern of a simple strike-slip fault. Here, a part of the observed opening across the Palu-Koro fault could take place on a secondary fault. Another possible explanation would be a gravity collapse of the coral reef supporting the sites due to the steep relief. Moreover,

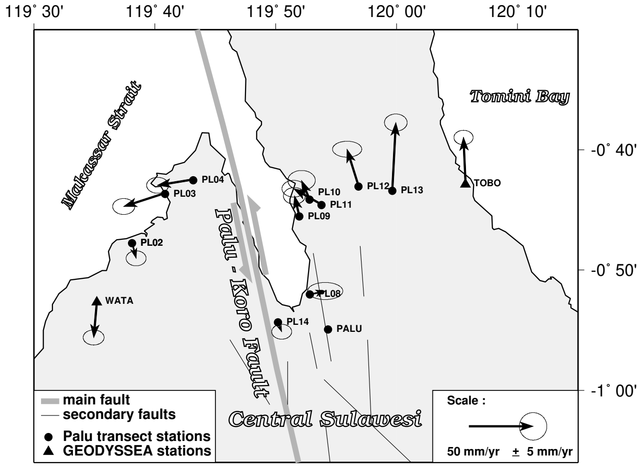

Figure 3. Velocities of the Palu transect stations, with respect to the PALU station. Error ellipses correspond to formal uncertainties of the global solution with a confidence level of 90%.

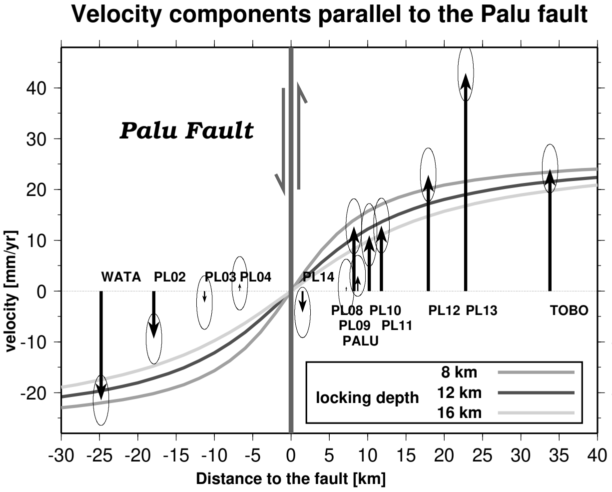

Figure 4. Transect station velocity components parallel to the fault, with the co-seismic deformation due to the Jan. 1996 earthquake removed. They are indicated in function of their distance to the fault. The dark grey line shows best model values (5.5 cm/yr total velocity, 12 km locking depth). Lighter grey lines correspond to locking depths of 8 and 16 km, marking an uncertainty of ± 4 km.

the displacement rates on the intermediate transect stations are only weakly constrained by just two measurement epochs. Only WATA and TOBO have been observed more often. Systematic measurement errors are not taken into account by the formal error ellipses and can only be deduced by repeated measurements.

Nevertheless, a combination of the two ENS epochs of observation (1995 and 1996) with the results of *Stevens et al.* [1998] on the previous three campaigns (1992, 1993, and 1994), to reduce the uncertainties of the station velocities, could only be done at the cost of a precise modeling of the earthquakes effects since the rates before and after these events clearly differ. Precise modeling of the deformation field associated to the earthquakes in this very complex area is currently under process but is complicated by poor localization and recording of the seismic events due to sparse network. In a first attempt, modeled co-seismic displacements of the transect stations due to the January 1996 earthquake on the North Sulawesi trench (J.M. Gomez, personal communication, 1997) have been taken into account in the analysis of the deformation in the fault zone Figure 4.

A simple model for the deformation around a locked fault [*Savage and Burford*, 1973] is applied to analyze the 1995 to 1996 vector field and to detect outliers. A locking depth of 12 km was determined, but some systematic misfits occurred by comparing model and observations. To clarify the origin of these residuals we subtracted in a second study the modeled co-seismic motion mentioned above from the station displacements before comparison with predicted values. The remaining displacement rates agree slightly better with the model, but the deformation pattern in general is not significantly affected by the co-seismic displacements. Therefore also this case evaluates the same locking depth of about 12 km. Figure 4 is based on the motions remaining after correction for the earthquake and shows by the dark grey line theoretical displacement rates parallel to a fault with as model parameters a locking depth of 12 km for a vertical fault plane and 5.5 cm/yr far-field velocity.

To compare our observations with this simple model, in Figure 4 only the velocity components parallel to the fault are indicated with the Palu fault oriented 165° and located just west of station PL14 [*Bellier et al.*, 1998]. The error ellipses indicate the formal uncertainty in fault parallel direction. The locking depth of 12 km seems to fit best the data, the variation of this model parameter evaluates an uncertainty of about 4 km. The value of 12 km is not unlikely for the continental seismogenic layer in North-West Sulawesi with a slightly thinned lithosphere due to an increased heat flow by magmatic arcs [*Polvé et al.*, 1997]. By geodetic observations in California, *Feigl et al.* [1993] determine locking depths of the San Andreas fault between 10 and 25 km. Here, a similarly thinned lithosphere is found.

Stevens et al. [1998] deduced from the 1992 to 1995 observations a shallower locking depth of 3 to 6 km by adjusting location and orientation of the fault to their velocities. In contrast, in our modeling, we did not want to base the analysis uniquely on our observed displacement rates inferred from only 2 measurement campaigns. We preferred introducing additional information and reducing the number of free parameters by fixing fault location and orientation to their well defined geological values.

Coherently to *Stevens et al.* [1998], the deformed zone is found to extend beyond the furthermost points of the Palu transect. The far-field velocity across the fault evaluated by modeling of the original velocity observations (without subtracting co-seismic motions) reflects with 7.5 cm/yr the increased present day rate on the main baseline WATA-TOBO of 6.3 cm/yr. Deducing the co-seismic displacements, a baseline rate of 4.5 cm/yr remains, and the model evaluates a far-field velocity of 5.5 cm/yr. This rate might still be affected by post-seismic relaxation following the M_w=7.9 event, which could be as large as the co-seismic displacement, as mentionned before. Therefore, the average strike-slip rate over 5 years on the WATA-TOBO baseline, which we believe is the most significant for a long term motion on the Palu fault, is still slower (3.4 cm/yr). A far-field velocity of 4 – 4.5 cm/yr is probably the most realistic estimate, clearly indicating that Palu-Koro is a major fault.

Conclusions and discussion

The GPS measurements on the Palu-Koro transect have shown a displacement rate of 3.4 cm/yr in a 5-year average, with an acceleration in the last two years, which might be interpreted as seismic loading triggered by the increased earthquake activity in North Sulawesi in this time interval.

No seismic activity was observed on the Palu-Koro fault itself, as confirmed by observations of micro seismicity on a local seismic network (Meteorol. and Geophys. Agency, Bandung, and Lab. de Géoph., CEA, Saclay), as well as by the lack of displacements between the inner transect stations close to the fault. From the existing seismicity catalogs (USGS, ISC, CMT,..) it can be inferred that no important earthquake ($M_w > 4.5$) occurred on the Palu-Koro fault since at least 100 years. Until now, no evidence of accommodation of the deformation by aseismic slip or active secondary faults has been found. This means that at present the displacement at the minimum rate of 30 mm/yr is accumulated to at least 3 meters. The magnitude of an earthquake generating a 3 m displacement on a segment of about 50-100 km can be easily estimated to around 7 ! Such an earthquake could have disastrous impact on the neighbouring city of Palu (150,000 inhabitants). From trenches, excavated just 20 km south of Palu we know that at least 2 earthquakes of this magnitude happened around 1000 and 2000 years ago [*Bellier et al.*, 1998]. One could have expected more earthquakes of this kind to have happened in the past, given the high slip rate of the fault. According to present day knowledge, the possibility of an imminent large earthquake occurring in the area cannot be denied, but it is very likely that a part of the large discrepancy between the earthquake recurrence and the high strike-slip rate is caused by still undetected aseismic slip or secondary faults. The assessment of seismic hazards on the Palu-Koro fault is not yet accomplished with the available observations, and its great importance for the nearby city of Palu demands the continuation of the investigations in the future.

Perspectives

Permanent GPS sites would help to acquire the information necessary to understand the process of deformation and seismic loading in North and Central Sulawesi. A good example for the efficiency of permanent GPS networks for this task is given by *Bock et al.* [1997]. A first permanent station is operated in Sulawesi (Pare-Pare) by BAKOSURTANAL, the installation of more sites to monitor the deformation in the Palu-Koro area is already prepared. Then, the relation between the tectonic activity on the North Sulawesi trench and the Palu-Koro fault could be analyzed, allowing to quantify the seismic risk in the Palu region.

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