Determining the Sula block kinematics in the triple junction area in Indonesia by GPS

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Abstract. The point of convergence of the Eurasian, Philippine, and Australian Plates, is situated adjacent to the island of Sulawesi, Indonesia. The relative plate velocities are estimated by NUVEL1 to be 7 to 9 cm/yr. The complex tectonic mechanism of the triple junction has been studied over a two year period in the course of the GEODYSSEA South-East Asian Project. The GPS investigations concentrate on both, measurements of the Sulawesi (Eastern Indonesia) part of the inter-regional GEODYSSEA network, and on a local sub-network on Sulawesi. Motions derived using data from the sub-network confirm what the results of the inter-regional GEODYSSEA network have suggested: that current deformation is high and includes distinct deformation domains in the study area on Sulawesi. The tectonic mechanism of the triple junction has been analyzed using a rigid micro-block model. The triple junction area can be best interpreted as headland of the Australian Plate deflected by its collision with the Philippine Plate, hereby identifying the driving forces of the current deformations. The northern part is dominated by the Sula domain displaying clockwise rotation. To the South, it is connected to the Australian Plate by an ensemble of micro-blocks in counter clockwise rotation. In addition to the above stated, our tectonic model permits the determination of the local influence of two large earthquakes (on 1 January 1996 with M=7.8 and 22 July 1996 with M=7.0) on the motion of the Tomini station (North Sulawesi). Intensified observations and densification of the GPS network are planned in order to study the behaviour of the Palu-Koro Fault, the main fault on the Sula block's western limit.

Key words: Tectonics, GPS, Sulawesi, Triple junction, Indonesia

1. Introduction

The GEODYSSEA network in South East Asia covers the area adjoining the conjunction of the Eurasian, the Philippine and the Australian plates. The rigid plate kinematic model NUVEL1-A [*DeMets et al.*, 1994] predicts very high relative velocities of 7.5 to 9.0 cm/yr between the major plates, and a derived apparent triple junction in Eastern Indonesia (Fig. 1).

About 40 GEODYSSEA GPS stations have been installed and measured during two observation campaigns in December 1994 and April 1996, as a part of the international project between the European Union and the ASEAN countries: Indonesia, Malaysia, Singapore, the Philippines, Thailand, Vietnam and Brunei [*Wilson and Rais*, 1998]. Comparing the solutions produced by 4 independent data processing centres, *Angermann et al.* [1998] showed that the observations are precise to about 5 mm/yr on 1000 km baselines. In this paper those results from the GPS observations are presented that cover what is known as the most highly deforming area of the GEODYSSEA network: the triple junction region between Sulawesi and the Moluccas in Eastern Indonesia (Fig. 1).

According to NUVEL1A, the triple junction is of a Trench-Trench-(transform) Fault (TTF) type, with the Australian and the Philippine plate subducted underneath the Eurasian plate, and the Australian-Philippine boundary displaying left lateral strike slip faulting (with a small reverse component). A closer look at the tectonic features in the triple junction area (Fig. 1) shows that its mechanism is more complicated than the intersection of three simplified plate boundaries described above may imply.

In the following, the tectonic mechanism is analyzed by a model in terms of rigid block rotations, based on the observed velocities. The model uses those rotation poles that fit best to the observed tectonic configuration and kinematics, and evaluates the rates of rigid rotation. By examining the residuals between model and measured velocities, actively deforming areas are identified in detail. Furthermore, the model permits the estimation of the continuous secular motion of a station affected by earthquakes, hereby separating the co-seismic displacements which help to constrain the earthquake mechanisms.

2. Tectonic settings

The triple junction area between the island of Sulawesi and the Moluccas in Eastern Indonesia shows a very complex tectonic scenario. Fig. 1 displays a compilation of tectonic features which are acknowledged to be active, based on *Rangin et al.* [1998], *Rangin* [1989], *Hall et al.* [1991], *Silver et al.* [1983] and *Moore and Silver* [1983]. Instead of a simple intersection of three plate boundaries, one sees, for example, that the collision of the Philippine and the Eurasian plate is absorbed by the double subduction zone in the Molucca Sea (features 4 and 5 in Fig. 1). The Philippine and the Australian plates are separated by the Sula Sorong fault (feature 6) and the subduction zone north of Seram (7). The Sula block collides north-west of Sulawesi with the Eurasian plate under the constraints of the Australian and Philippine plate motions. This

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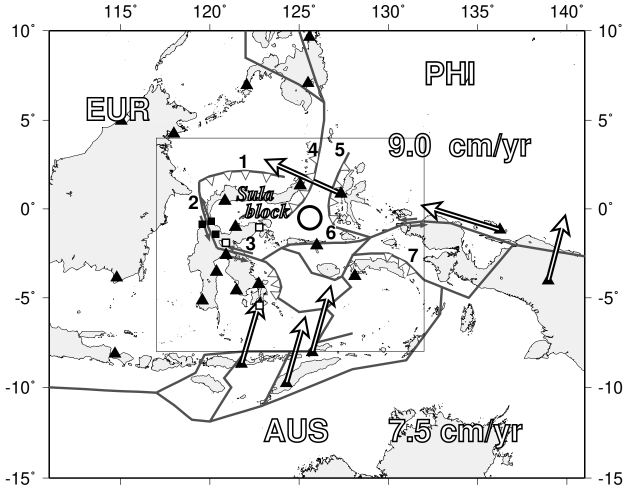

Figure 1. Tectonic settings in the South East Asian triple junction region and predicted motions of the major tectonic plates with respect to Eurasia according to NUVEL1-A [*DeMets et al.*, 1994]. Stations of the GEODYSSEA network are indicated by triangles. Densification stations are shown by squares. All of these stations except those marked by open squares have been measured twice. The most important active tectonic features close to the triple junction area (inside the box) are: 1) North Sulawesi Trench; 2) Palu-Koro fault; 3) Matano fault; 4) East Sangihe fault; 5) West Halmahera Trough; 6) Sula-Sorong fault; 7) Seram Trough. Faults with teeth represent subduction zones (teeth on upper plate). The Sula block, a mainly rigid tectonic domain, is limited by features 1 - 3 to the North, West and South-West, whereas the eastern and south-eastern boundaries are still uncertain. The intersection of the three major plates after these observations is indicated by the circle in the Molucca Sea.

movement is transformed by the Matano fault (3) and the Palu-Koro fault (2) in central Sulawesi, and by the North Sulawesi Trench (1). A simplified best fitting location of an assumed triple junction is indicated by the circle located in the Molucca Sea (Fig. 1). The analysis of the observed velocities below shows that the Sula domain and its current behaviour is the dominating tectonic feature in the triple junction area.

3. GPS observations

The GEODYSSEA network, marked by triangles on Fig. 1, has been observed during two 5 day campaigns of continuous simultaneous measurements, from 28 Nov. to 2 Dec. 1994, and one and a half years later, from 18 to 22 April 1996. Six densification stations (indicated by open and filled squares on Fig. 1) have been measured during an additional session after the second GEODYSSEA campaign in April 1996. The receivers operated in this part of the GEODYSSEA network were Trimble SSE with SST and SSE antennas. Additionally, data from a local network in the Palu region at the end of Sept. 1995 and in mid Dec. 1996 were used. In these campaigns a couple of densification sites in the Palu region were re-occupied (filled squares in Fig. 1), and in the later one also the TOMI GEODYSSEA site in North-West Sulawesi. These two campaigns have been carried out in collaboration with the Indonesian Survey and Mapping Agency (BAKOSURTANAL), Java, using their Ashtech Z12 receivers. We were able to derive the displacement of the densification station TOBO using the result of an even longer observation period of the local Palu network [*Walpersdorf et al.*, 1998].

In the following, we will refer to the 4 measurement epochs Nov. to Dec. 1994, Sept. 1995, April 1996 and Dec. 1996 as epochs 94, 95, 96.1 and 96.2.

In the analysis of the GPS data of the described measurement campaigns we included data of the 5 closest IGS stations KIT3, TAIW, TIDB, TSKB and YAR1 and, when available, of the AUSLIG stations COCO, KARR, XMAS, DARW. The data acquired at a measurement interval of 30 s have not been decimated during the whole processing procedure. Precise IGS combined orbits were employed simultaneously with IERS Bulletin B Earth orientation parameters.

The processing software used are the MIT software packages GAMIT 9.4, GLOBK 4.0 and FONDA 1.1. The processing strategy applied for the ENS GEODYSSEA solution is explained in detail in *Angermann et al.* [1998]. The same approach was used for the processing of the two local measurement campaigns in the Palu region. In summary, the data processing was executed as following :

- First, for each of the measurement campaigns daily solutions were calculated in 24-hour sessions using GAMIT [*King and Bock*, 1993]. The observables were examined in the ionosphere-free combination (LC) and clock errors were eliminated by forming double differences. Tropospheric parameters were estimated every 3 hours for each station. The antenna phase center variations were modeled using the tables recommended by IGS [*Rothacher and Mader*, 1996]. In the solution for each individual session the IGS orbits were kept fixed. Phase ambiguity resolution was attempted by a routine provided in *Dong and Bock* [1989].
- The scatter of independent results of the 24-hour sessions for each baseline component represented the repeatability of the measurement and gave an evaluation of its uncertainty.

During the first GEODYSSEA campaign in 1994 (epoch 94), 11 stations in the local triple junction network have been measured, most of them continuously, in 5 sessions of 24 hours. During GEODYSSEA '96 (epoch 96.1), 17 stations were observed in a sequence of three sessions of 5, 3 and 4 days. We obtained a mean repeatability of the solutions on this local part of the GEODYSSEA network of 4 to 6 mm on the North, 5 to 7 mm on the East, and 15 to 17 mm on the vertical baseline component. The local Palu network measured in Sept. 1995 (epoch 95) and Dec. 1996 (epoch 96.2) includes two stations of the triple junction network in 1995 and 4 stations in 1996. The mean repeatabilities on these baselines are comparable to those of the main GEODYSSEA results.

- As the next step, global campaign solutions were established using GLOBK, which is a Kalman filter applied to the analysis of solution vectors and associated covariance matrices generated during daily GAMIT solutions [*Herring et al.*, 1990]. The GAMIT solutions passed to GLOBK are those with unconstrained station coordinates. The fixed orbit parameters in the daily solution are not re-estimated in the global solution.

The velocity solution is obtained by combining the different epochs. The displacements over the interval of 17 months between the two GEODYSSEA measurement campaigns is attributed to a linear velocity of each of the GEODYSSEA stations. The combination of the measurement epochs 95, 96.1 (GEODYSSEA '96) and 96.2 establishes the velocities on three densification stations (WATA, TOBO, WUAS) and a second displacement rate for the TOMI station which has already been observed in both of the GEODYSSEA campaigns.

- The network adjustment program FONDA developed at MIT and JPL [*Dong*, 1993] is used to calculate the distribution of strain and spin in the network [*Feigl et al.*, 1990]. Input data for this was the station coordinates and velocities from the free network GLOBK solution. The representation in terms of deformation is independent of the reference frame chosen for the velocities. The TOMI station clearly showed co-seismic displacements and was excluded from the study of the continuous strain and spin field. The limit of strain resolution in the GEODYSSEA network is estimated to be 6 mm/yr on 1000 km baseline lengths (6 ppb/yr) by comparing individual and the combined GEODYSSEA solution. This value is in good agreement with the estimation from *Angermann et al.* [1998] (see above), and can be considered as a realistic value for the velocity uncertainties.

The high quality of these GPS measurements is further supported by a) the careful choice of GEODYSSEA GPS sites (mainly in outcrops of substratum), and b) the monumentation with screw markers, where the antennas are directly screwed on (no error source by inadequately installed tripod, in this way the re-measurement of exactly the same point is guaranteed). This means that the observed displacements are not due to operation errors or local site instabilities, but are caused by tectonics and minor error sources (*e.g.* errors by varying weather conditions).

However, we cannot account for possible effects of time-correlated errors on the accuracy of our velocity field. Since their amplitude is small enough compared to the tectonical signal obtained here, we assume that time-correlated errors will not affect our main conclusions.

4. The velocity field

The velocity field in the triple junction region obtained by the two GEODYSSEA measurement campaigns is presented in Fig. 2. In the chosen reference frame the South China Sea is held fixed by minimizing the velocities of three GEODYSSEA stations situated adjacent to South China Sea (Tanjung Bajau (West Kalimantan), Non Nuoc (Vietnam), Kuala Trengganu (Malaysia)). The mean residual velocity for these three stations is 1.7 mm/yr, far below the measurement uncertainties, so that the representation of the velocities is realized in a coherent way. The choice of the South China Sea as reference frame is appropriate since this region forms the approximated centre of a large rigid block called Sundaland. This rigid block has been newly detected and its independent and slightly different movement from Eurasia has been deduced from the observations on the GEODYSSEA network [*Chamot-Rooke et al.*, 1998]. Its rigidity is demonstrated by the low residuals (1–2 mm/yr) of the velocity observations with respect to modelled velocity according to rigid rotation around the best fitting rotation pole (situated south of Australia in an Eurasian reference frame). *Tregoning et al.* [1994] has presented first geodetic observations showing for Sundaland's southern part already that its motion with respect to Australia is different from the Eurasian plate motion according to NUVEL1-A.

The south-westernmost part of Sulawesi is included in Sundaland. Therefore, in the chosen reference frame, the southern part of Sulawesi has a very slow motion (the residuals resulting from small deformation in the Makassar strait, or from elastic strain accumulated along the Palu-Matano Fault Zone), so that differential velocities in the local network can easily be observed. The numerical values of the velocities in this reference frame are given in Tab. 1.

Two stations in the triple junction region, TOMI and BIAK (light grey vectors, BIAK exceeding the figure limits) suffered a large earthquake close to the site between the two GEODYSSEA measurement campaigns. Their displacement rates include apparent co- and post-seismic displacements, so that they are not representative of secular tectonic velocities. Estimations of the seis-

Table 1. Horizontal Site Velocities with 1-σ Uncertainties and North to East Correlation Coefficients Derived from GPS Campaigns GEODYSSEA 1994 and 1996

Site Code	Latitude °N	Longitude °E	Velocities (mm/yr) North	Velocities (mm/yr) East	N-E Correlation
AMBO	-3.7500	128.1169	43 ± 4	-8 ± 3	0.46
AMPA	-1.0032	121.4362	28 ± 3	-36 ± 3	0.34
BALI	-8.0936	114.6800	-3 ± 3	-5 ± 4	0.40
BATU	-3.8414	114.7912	-2 ± 3	-2 ± 3	0.36
BRUN	4.9332	115.0309	0 ± 3	-7 ± 2	0.09
DAVA	7.0372	125.5081	12 ± 4	-53 ± 3	0.08
ENDE	-8.6496	121.7657	35 ± 4	8 ± 4	0.51
KAPA	-9.7121	124.2804	49 ± 4	12 ± 4	0.54
KEND	-4.1985	122.7362	12 ± 4	-7 ± 5	0.23
LIRA	-8.0058	125.7387	50 ± 4	16 ± 4	0.52
MALI	-2.5776	120.9048	6 ± 3	-14 ± 3	0.41
MANA	1.3220	125.0637	8 ± 4	-13 ± 3	0.32
REDO	-3.5158	120.3674	3 ± 3	-11 ± 3	0.43
SANA	-2.0347	125.9910	35 ± 4	-39 ± 3	0.42
TAWA	4.2230	117.9786	-6 ± 3	-10 ± 2	0.16
TERN	0.8546	127.3417	29 ± 4	-85 ± 3	0.34
TOAR	-4.5513	121.4895	10 ± 3	-4 ± 3	0.46
UJPD	-5.1194	119.5810	2 ± 3	-2 ± 3	0.45
WAME	-4.0149	138.9521	77 ± 6	13 ± 4	0.42
ZAMB	6.9264	122.0728	3 ± 3	-24 ± 2	0.06
KUAL[1]	5.2835	103.1392	2 ± 1	0 ± 2	0.02
NONN[1]	15.9020	108.2634	-4 ± 2	-1 ± 1	0.25
TABA[1]	0.8570	108.8909	-2 ± 2	1 ± 1	-0.15
BIAK[2]	-1.1596	136.2483	916 ± 5	437 ± 3	0.37
TOMI[2]	0.4501	120.8499	65 ± 3	-54 ± 3	0.34

[1] South China Sea stations with minimized velocities

[2] Earthquake affected stations

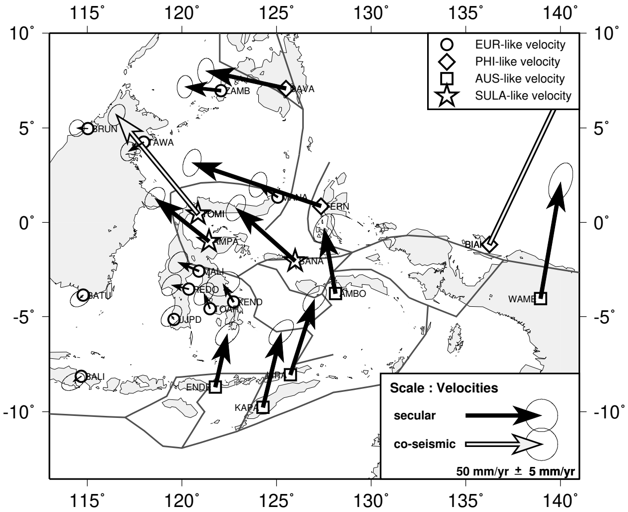

Figure 2. GEODYSSEA velocities in the triple junction area. Reference frame is with respect to South China Sea held fixed. The station velocities are attributed to one of the major tectonic plates as shown by the different symbols at the station locations, except for stations in the Sula domain, with displacements clearly different from EUR-, AUS- or PHI-like velocities. The error ellipses indicate a formal uncertainty of 1-σ. A realistic error for the measured velocities is estimated to about 6 mm/yr.

mic displacement due to the Feb. 1996 earthquake of a GPS station close to GEODYSSEA's BIAK site are given by *McCaffrey et al.* [1996] based on their measurements from 1991 to 1993 of the station velocity. A last occupation in March 1996, following the earthquake, provided these authors with a BIAK displacement that shows the same direction as, but a smaller magnitude than the GEODYSSEA results. We suggest that the GEODYSSEA solution includes post-seismic deformation that was not detected by McCaffrey.

The other observed velocities in the triple junction area coincide in most cases with the NUVEL1-A predictions for one of the three major plates: Low velocities in the western part of Fig. 2 are compatible with the motion of Sundaland (these stations are indicated by circles in Fig. 2), westward velocities in the North-East with the Philippine plate motion (stations shown by diamonds), and north-eastward velocities in the South of the figure coincide with the Australian plate motion, with the stations depicted by squares in Fig. 2. Except for the already mentioned slight differences from the principal motion in South Sulawesi, some other small variations can be observed: An increase from North to South of westward velocity on the Philippine plate (DAVA and TERN on Fig. 2) is related to the rotation of this plate around a pole situated further North and to the absorption of a part of the Philippine plate motion by the Philippine Trench East of DAVA. Still, the observed TERN displacement rate is about 1 cm/yr slower in western direction than the NUVEL1-A prediction of the Philippine plate motion at this location. This difference might be due to accumulated inter-seismic strain close to the subduction zone in the Molucca Sea.

For the Australian plate, the station velocities on Timor and Flores show that a minor fraction of the original motion is absorbed in the Java Trench or by short term elastic strain on transform faults close to for example ENDE. This seems to be confirmed by a comparison with GPS velocities in the Banda arc observed by *Genrich et al.* [1996]. In general, our displacement rates of KAPA, LIRA and ENDE on Timor, Liran Island (south east of Wetar Island), and Flores in South China Sea reference frame are about 1 cm/yr slower on the North component and directed more to the East than observations by *Genrich et al.* [1996] for KUPA (Timor), WETA (Wetar Island) and MAUM (Flores) with respect to Sunda Shelf fixed. An offset from this systematic is presented by ENDE compared to MAUM, where the difference on the north component is more than 2 cm/yr. ENDE is situated closer to the fault zone in central Flores than MAUM, and seems to be affected by the elastic strain field surrounding this active fault. The AMBO motion to NNW instead of NNE like the Australian plate in the same reference frame (Fig. 2) shows interaction with the Philippine motion, although the station is situated south of the Seram Trough and therefore clearly separated from the Philippine plate. Finally, the similar velocities of the AMPA and SANA stations, which are situated in the Sula domain (defined in Fig. 1), are clearly different from any of the major plate velocities. The velocity of AMPA and SANA appears to be a combination of the Australian and Philippine plate velocities. This implies that the Sula domain could be a slightly rotated and slower moving headland of the Philippine plate, or a highly deflected headland of the Australian plate. The major boundary between the Philippine plate and the Australian plate to the East of the triple junction was for a long time considered to be the Sorong fault. But *Puntodewo et al.* [1994] showed that the Sorong fault is not of major activity in Irian Jaya. An interaction of the Philippine plate motion further to the South than the Sorong fault is compatible with the still clearly westward motion of the SANA station situated just South of the Sorong fault's western extension in our triple junction network.

The major issue of this study is to use our GPS observations for determining both the driving forces for the kinematics of the Sula domain, and the location of the block limits with respect to the Philippine and Australian plates.

The assumption that Sula is deflected headland of Australia is emphasized by the equal amplitudes of the Sula block velocities, similar to those on the Australian plate, but with varying directions, implying deflection and distributed deformation in the zone relating the Sula domain to the Australian plate. Geologic and geodetic evidence for this hypothesis could be given *e.g.* by the accretion of southern Banda arc to the Australian plate margin [*Genrich et al.*, 1996], indicating the extension to the North of the zone with characteristic Australian plate motion. Furthermore, a high number of micro blocks (*e.g.* Buru block, North Banda Basin, Banda block) and active faults exist in the Banda Sea region [*Rangin et al.*, 1998], and a deformation zone in the South Banda Sea is suggested by *McCaffrey and Abers* [1991], all of these phenomena accommodating the high deflection of the Sula domain motion with respect to the Australian plate motion.

The other hypothesis, that the Sula domain is a headland of the Philippine plate, is supported by the common direction of motions of the AMPA and SANA velocities and the Philippine plate. In this case the Sula domain should be clearly limited to the South by an active block boundary, and its rotation should be related to the Philippine plate's own rotation. However, according to our data, the Sula block moves more slowly to the NW than the Philippine Plate. This relative motion must be accommodated by an active block limit between the Philippine plate and the Sula domain, which could be realized in this case of parallel displacements by strike–slip along *e.g.* the North Sula Sorong fault, or by continuous deformation in a larger transition area. An argument in favor of this hypothesis is provided by *Puntodewo et al.* [1994]. They show that at the same latitude as the Sula domain, but to the East, the forces driving the deformation are related to the motion of the Pacific plate (which is similar to the Philippine plate motion), and not to the motion of the Australian plate. Puntodewo shows typical Pacific-like motions for a station south of the Sorong fault, and suggests that the major active limit with the Australian plate is found in the Birds Neck Belt rather than in the Sorong fault, as commonly suggested.

The two hypotheses have different consequences for the location of the intersection of the three simplified plate boundaries between the Eurasian, Philippine and Australian plate: For the Australian plate extending on the Sula domain, this assumed triple junction is found in the Molucca Sea, coherent with the tectonic observations (Fig. 1). The plate limits in case of the Sula domain being kinematically part of the Philippine plate show an intersection in the Banda Sea south-east of Sulawesi, which would result in a location of a triple junction about 800 km south of the location described in the foregoing model. Furthermore, the kinematic relation of the Sula domain to one or the other major tectonic plate determines the present day status of the time history of the triple junction zone. Geologically, North Banda Sea and the Sula Islands are of Australian origin and a part of East Sulawesi has Australian affinities [*Rangin et al.*, 1990]. Evaluating how much the Sula domain motion is currently constrained by the Philippine plate or by the Australian plate will indicate the progress of accretion and the state of tectonical evolution of the triple junction area.

According to the existing velocity observations, either of these Sula domain behaviours (the direction of motion coherent with the Philippine Plate or the deflection on the Sula block relating it to the Australian Plate) might be a consequence of deflection of the Australian Plate as a result of its collision with the Philippine

Plate.

5. Strain and spin distribution

One approach to regional kinematics has been to emphasize the major faults or boundaries and approximate the behaviour of the area between the faults as rigid [*Peltzer and Saucier*, 1996]. This has been done in the rigid micro-block model applied in the next chapter. Another approach is to treat the deformation as being continuous although heterogeneous. Both approaches have their drawbacks. Neither is the studied area between faults free of deformation, nor are the investigated faults and boundaries of considerably smaller dimensions than the deformed region. A main part of the deformation is accommodated along boundary faults.

The continuous approach has been applied for the study area using Delaunay triangles and triplets of nearest stations [*Feigl et al.*, 1990]. Results are 2-dimensional principal strain or stretching axes and a specific amount of spin for each of the triangles. Thanks to the localizations of the GEODYSSEA GPS stations with roughly one station per tectonic (micro-) block, we obtained significant strain and spin in nearly each Delaunay triangle in the triple junction area. The numerical values are strongly dependent of the triangles' geometry and should be considered relative to each other.

The major features of the distribution of horizontal deformation in the triple junction area are represented in Fig. 3*a*. The major principal strains calculated from the Delaunay triangles indicate that the stations AMPA and SANA on the Sula block, as well as the southern part of the Philippine Plate are under compression, whereas extension dominates to the South. Figure 3 shows these two zones as belts. Typical values are –0.29 μstrain/yr for the observed compression in the Molucca Sea, and 0.07 μstrain/yr of extension in the southern belt. This strain distribution suggests that the Sula domain deformation belongs to that of the southern Philippine plate. A zone of extension separates the Sula domain - Southern Philippine assembly from Australia.

Derived spin rates in the triple junction area (Fig. 3*b*) indicate counter clockwise rotation in South Sulawesi, and clockwise rotation in the northern part of Sulawesi. Typical values for the rotations within the chosen triangles are 3–4 μrad/yr for the clockwise rotation in North Sulawesi and 5–10 μrad/yr for the counter clockwise rotation in South Sulawesi.

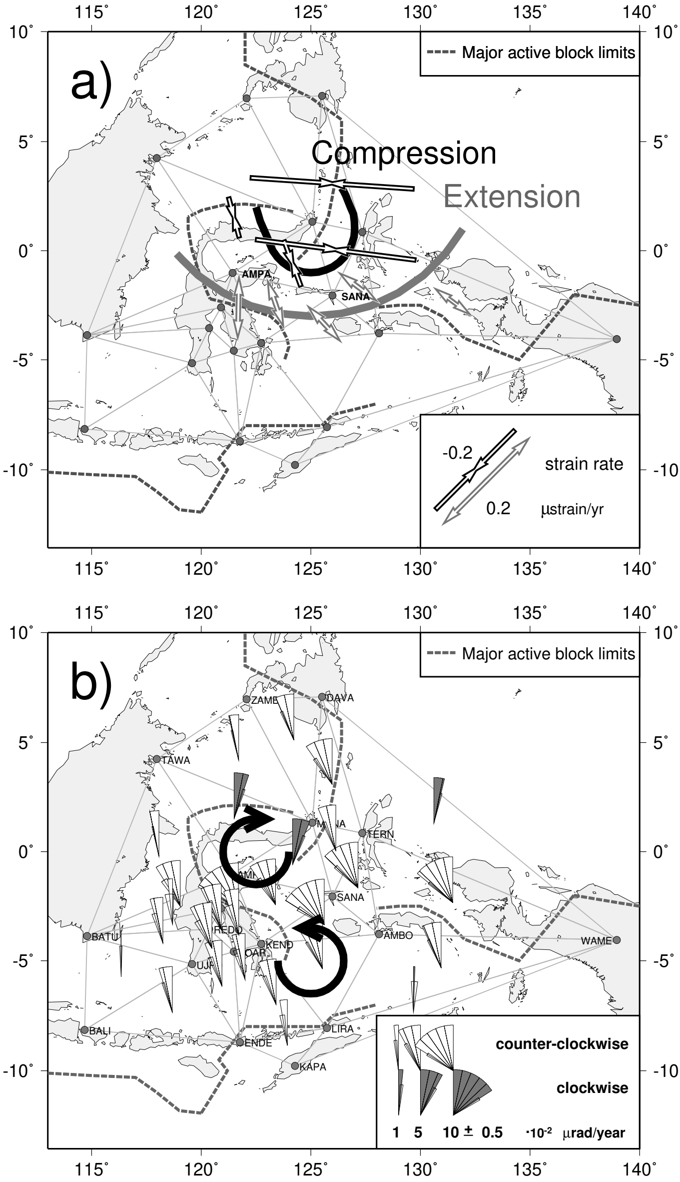

Figure 3. a) Dominant features of the strain distribution in the triple junction area: compression relating the Sula block with the Philippine plate, extension separating the Sula block from the Australian plate. b) Distribution of spin, showing two rotations with opposite signs in North and South Sulawesi.

6. Modelling

Geological evidence for the clockwise apparently rigid micro-block rotation in North Sulawesi, with a rotation pole close to Manado in North-East Sulawesi, is given by *Silver et al.* [1983], *Surmont et al.* [1994], and *Rangin et al.* [1997]. Most of the Sula/Sunda deformation is accommodated along the Palu-Koro and the Matano faults in central Sulawesi. These faults form a small circle around an assumed rotation pole in the area of Manado (Fig. 1).

To obtain quantitative estimates of the rates of clockwise rotation in North Sulawesi from our observations, we apply a model of rigid micro-block rotations in order to describe the measured velocities. This strategy might give further insight into the deformations in the block or plate transition zones or the internal deformation of the tectonic domains themselves by looking at residuals between the rigid block model and the observed displacement rates. The model which best explains the measurements in the triple junction area comprises two rotation poles with opposite signs, as shown in Fig. 4.

The clockwise rotation of the northern part of Sulawesi is constrained best by the MANA, AMPA, WUAS and TOBO velocities, determining the pole P1 north-east of Sulawesi at 2.2°N, 126.2°E with a clockwise rotation rate of 3.4°/Myr in the South China Sea reference frame. The TOMI motion is not included in the estimation, as this station was affected by two large earthquakes. We observe that the rigid block model shows smaller residuals for the MANA and AMPA stations, and larger residuals for TOBO and WUAS. Thus, the first two stations represent the motion of the apparently more rigid part of the tectonic block. The displacement of the latter two sites might be affected by deformation processes along the block boundaries, suggesting that this deformation occurs in an extensive zone of several tens of kilometres.

For the TOBO station two displacement rates were derived. The higher rate was observed from Sept. 1995 to Dec. 1996, and the smaller rate was deduced from a longer observation series on the subnetwork commencing in 1992 [*Stevens et al.*, 1998; *Walpersdorf et al.*, 1998]. The higher observed rate and the direction of deflection of the TOBO motion seems to indicate that TOBO has

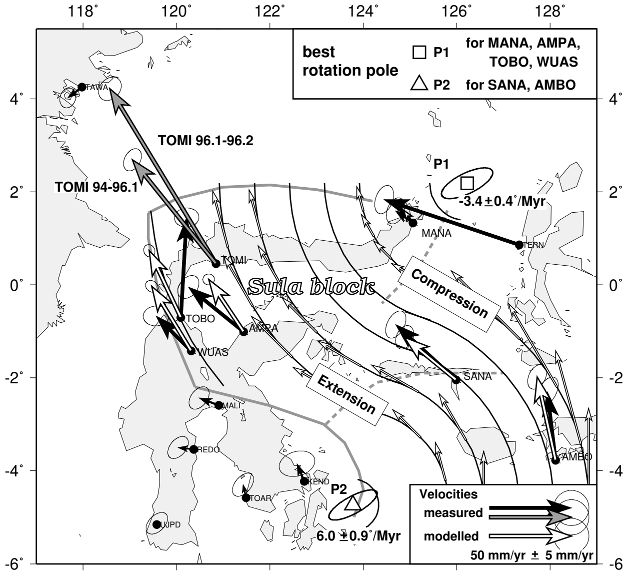

Figure 4. Model of two rotation poles describing the kinematics in the triple junction area. Velocities observed by the two GEODYSSEA campaigns (epochs 94 and 96.1) and by the Dec. 96 campaign (epoch 96.2) constrain the two poles to 3.4°/Myr clockwise rotation for P1 and 6.0°/Myr counter clockwise rotation for P2 with respect to South China Sea fixed. The best pole locations and their 1-σ standard deviations (shown by the ellipses around the best locations) are computed by an iterative linear least squares method. The suggested south-eastern and eastern limits of the Sula block are schematically indicated by the dashed line. The two-pole geometry implies two zones of deformation (compression and extension) where areas of slow velocities close to one pole encounter areas of fast velocities created by the other, more distant pole.

suffered a seismic displacement related to the earthquake of 1 Jan. 1996 northwest of TOMI on the North Sulawesi Trench. The rate trends converge over a longer time-span towards the station velocity predicted by our time invariant model, though the direction of motion is still deflected. The secular displacement rate of WUAS, situated 100 km south of TOBO, is probably affected by the elastic strain caused by the closeby (30 km) locked Palu fault. This suggests that discontinuous deformation occurs adjacent to the Palu Fault and maybe even related over 150 km distance to the North Sulawesi Trench.

In the modelling, the parallel AMPA and SANA velocities may not be described as a common rotation around a pole in the MANA region. Therefore, SANA seems to be situated outside the Sula block, whose south-eastern limit passes consequently northwest of SANA, as indicated in Fig. 4. An attempt to model SANA together with the stations further south provided better results indicating a kinematic connection between the Sula block and the Australian Plate. A second pole P2 of counter clockwise rotation for South Sulawesi, at 4.7°S, 123.8°E with a rotation rate of 6.0°/Myr in the South China Sea reference frame, constrained by the SANA and AMBO velocities, shows low residuals. When including the closest stations on the Australian plate in the computation, a coherent counter clockwise rotation with AMBO still results in higher residuals for SANA. This implies a highly deforming zone south of the Sula domain, or the presence of more rigid micro blocks separated by active block limits.

The high residuals are not contradictory to the use of the rigid rotation model, as we have applied this model intentionally for regions which are partially deformed and where only very few velocities are known in the rigid parts. High residuals are to be expected. They provide a means of emphasizing the observation of deformation, rather than a sign of deficiency in the model.

The pole parameters (latitude, longitude, and rotation rate) were evaluated by a least squares method, the 1-sigma standard deviations are indicated by the ellipses around their mean position. The well constrained positions of the two poles show that the model chosen is an appropriate way of describing the kinematics of the area. The corresponding variations of the modelled velocities are indicated by error ellipses around the vector heads.

Other models have been tested, which lead to slightly higher average residuals than those given by the one chosen. With the residuals being only a limited indicator for the choice, independent geological and geodynamic information has been used to determine the most appropriate solution. Moreover, we preferred the model constrained by the highest number of observed velocities. The model with the second lowest residuals was obtained by excluding MANA from constraining the pole P1, under the consideration that MANA might not be situated on the same rigid block as AMPA, TOBO and WUAS. This would invalidate our assumption that the North arm of Sulawesi shows presently no active deformation. The TOBO and WUAS velocities in the deformed Palu fault area get a higher weight in constraining the pole which is found to be significantly closer to the three remaining stations in the model. Until new velocity observations can distinguish between the best and the second best model, the preference is given here to the model including MANA in the determination of P1, as this involves the highest number of velocities. Moreover, the hypothesis that MANA is situated on the same micro-block as AMPA, TOBO and WUAS is well supported by geological studies [*Silver et al.*, 1983; *Surmont et al.*, 1994; *Rangin et al.*, 1997].

The two-pole model with P1 and P2 computed from the displacement rates presently available has a number of characteristic features, and its coherence with geological and geodynamic observations shows that it is an appropriate way of describing the present day tectonics of the triple junction area:

- The clockwise rotation rate with respect to South China Sea obtained for P1 is 3.4 ± 0.4 °/Myr. This value is in good agreement with mean rotation rates of geological models, such as the model of *Silver et al.* [1983], which predicts about 4°/Myr with respect to a pole situated slightly closer to the North Arm than in our model.
- Comparing the Palu-Koro fault system to a circle around the P1 rotation pole, purely strike slip motion is implied in the TOBO region, opening further North and compression further South. Coherently, the observed TOBO velocity from 92 to 96.2 is parallel to the fault with an opening tendency since 1995 (shown by the longer, more northward TOBO vector), whereas the WUAS velocity shows a compressive component with respect to the Palu-Koro fault.
- The AMBO and SANA displacements constrain the pole P2 of counter clockwise rotation, located in South Sulawesi, to a rotation rate of 6.0 ± 0.9 °/Myr with respect to South China Sea fixed.
- The characteristic velocity field resulting from the two rotation poles is shown schematically in Fig. 4. The two-pole geometry implies the existence of a line of continuous displacement at the same velocity from SE to NW (line in Fig. 4 where modelled velocities have equal amplitude). To the NE of this line are lines of continuous motion, where a deceleration takes place when you pass from the domain of motion according to pole P2 into the domain of pole P1. On lines to the SW of the one with equal velocity, an acceleration takes place. Therefore the two-pole geometry implies two special regions of deformation along the boundary between the two

domains: a zone of extension is predicted in the southern part of the region between the two poles, a zone of convergence further north, in the Molucca Sea. The corresponding velocity differences along the lines of continuous displacement can be evaluated at the positions of the "extension" and "compression" boxes in Fig. 4, to an increase of 1 cm/yr in the extension zone, and a decrease of 3–4 cm/yr in the compression zone. Both results are supported by the strain pattern and geological evidence taken in the field. The extension of 1 cm/yr in the South is compatible with the fact that the Matano fault shows a slower left lateral strike-slip motion (about 2 cm/yr [*Silver et al.*, 1983]) than the Palu-Koro fault (over 3 cm/yr according to several studies). The convergence of 3–4 cm/yr in the North is apparently absorbed by the double subduction zone in the Molucca Sea and to some extend by the Seram Trough.

Even with the limited number of velocity observations in the triple junction, this model can evaluate the present day rate of Sula block's clockwise rotation, which is in good agreement with the values obtained by geological studies over intervals of several Myr. According to our model the south-eastern limit of the Sula block seems to pass north of SANA, indicating the Sula-Sorong fault as the block boundary. The suggested, schematical Sula block limits are displayed in Fig. 4. The velocity observations south of this fault (SANA and AMBO) have been described by the rotation pole (P2), which shows the general motion pattern in the southern triple junction region and which predicts a characteristic distribution of deformation along the south-eastern Sula block boundary. Nevertheless, this rotation pole P2 cannot model the kinematics of the different existing micro blocks and therefore it cannot predict the tectonic activity along the limits between these blocks. The entire model will be better constrained by the measurements of densification points planned for the triple junction area.

7. The TOMI displacement

The tectonic model could be better constrained by knowledge of a stationary velocity of the TOMI station. Unfortunately, between each of the three measurement campaigns on this site a large earthquake occurred close to the station and superposed an instantaneous seismic displacement onto the secular velocity. The observed displacement rates are indicated in Fig. 4. The first large earthquake occurred at a point 130 km WNW of TOMI on 1 January 1996 with a magnitude of M_s = 7.9. A second earthquake, 70 km distant, took place on 22 July 1996, with M_s = 7.0. The modelling of the seismic displacements caused by these earthquakes has not yet been completed, so that the non-seismic velocity can not yet be retrieved to constrain the modelling of the tectonic mechanism in the triple junction zone. Instead, we can use the model to give an estimation of the stationary velocity of the TOMI station, using the assumption that TOMI is placed on the same rigid block as the stations AMPA, WUAS, TOBO and MANA, and rotates with respect to the same pole north-east of Sulawesi. This velocity is indicated in Fig. 5, and it allows us to decompose the observed displacement rates from Dec. 1994 to Apr. 1996 and from Apr. to Dec. 1996 into the secular part and the two instantaneous displacements caused by the two earthquakes (shown by grey vectors in Fig. 5). The azimuth of the slip vectors obtained by this model is about -50°. This is coherent with the alignment of aftershocks of the Jan. 1996 earthquake (grey dots in Fig. 5) which indicate a trend of the rupture zone azimuth of about 40°. These observations correspond furthermore to a tectonic model established by *Rangin* [1989], where the Sula block is moving in a north-westward direction and colliding with the Sunda block. This motion is transformed at the western boundary of the Sula block by the Palu-Koro left lateral strike slip fault and absorbed to the north at the North Sulawesi trench. At the intersection of these two tectonic features active thrust zones are formed which display an azimuth of 40°. These thrust zones seem to be responsible for the observed earthquakes.

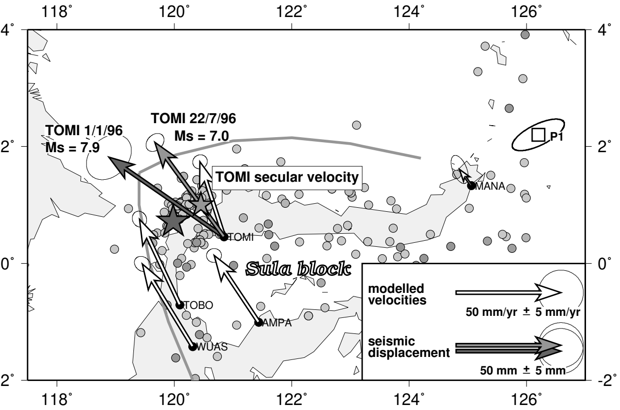

Figure 5. Continuous velocity for the TOMI station, modelled and constrained to a rigid rotation with respect to the rotation pole north-east of Sulawesi. The observed TOMI displacement rates shown in Fig.4 are here decomposed into the secular velocity (in mm/yr), and the two instantaneous seismic displacements indicated, marked by grey vectors (in mm). These are related to the two seismic events shown by the stars. Further earthquakes (IRIS data) are indicated by circles, aligning the rupture zone along an azimuth of about 40° .

8. Conclusions and perspectives

The triple junction is not a simple intersection of three continuous plate boundaries, but consists rather of a transition zone that includes the Sula domain, that both transforms and accommodates the high differential motions of the Australian, Philippine, and Eurasian Plates. The dominant characteristic of this micro-block is a velocity which differs from that of the Philippine and the Australian Plates. It can best be interpreted as a deflection of a headland of the Australian Plate in collision with the Philippine Plate. This identification of the driving forces of the current deformation is one main result of this study. Large deformation at the limits of the Sula domain have been shown by the application of a simple model in terms of rigid rotations. A model consisting of two rotation poles with opposing rotational sense (a clockwise rotation of -3.4°/Myr in North Sulawesi and a counter clockwise rotation of 6°/Myr in South Sulawesi with respect to South China Sea fixed) a) fits well to the observed velocities, b) points out zones of distinct strain, and c) is in good agreement with geologic and tectonic observations in the area. This model has been applied to analyze co-seismic displacements of the North-Sulawesi station TOMI. It helps to constrain the earthquake mechanisms and serves to emphasize local tectonic features. For most of the stations in the triple junction area the velocities are deduced from only two measurement campaigns. A third measurement campaign will show which of the station velocities can finally be approximated by a rigid block model, continuous deformation, or deformation along the major faults and subduction zones.

Precise plans for future measurements have been made to constrain the tectonic mechanism of the triple junction. The most efficient project will be the re-measurement of the LUWU and KAMB stations, which have already been measured once during the GEODYSSEA '96 campaign (open squares in Fig. 1). The next occupation of these sites will establish two new velocity vectors within the Sula domain. This will facilitate the distinction between zones of deformation along block boundaries and rigid micro-block motion in the triple junction area. The western limit of the Sula domain is defined by the Palu-Koro fault, a main transform zone displaying the high relative motions between the three major tectonic plates in the triple junction area. Seismic (elastic) loading is currently inferred for the Palu transect (6.3 cm/yr left lateral strike slip since 1995 instead of a 3.4 cm/yr average over 4.5 years). This can be related to the seismic activity in North Sulawesi [*Walpersdorf et al.*, 1998]. A continuous survey of the Palu fault activity is of utmost importance, and the installation of permanent GPS sites in the Palu region is foreseen. It is planned to install a permanent station close to the earthquake affected TOMI site. With the help of these observations we will be able to distinguish between transient and secular motions and thus constrain the modelling of the Sula block motion.

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