GPS compared to long-term geologic motion of the north arm of Sulawesi

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Abstract. Geodetic data acquired in the north arm of Sulawesi are compared with geologic and paleomagnetic data from North Sulawesi and the Celebes Sea. The objective of this study is to assess whether the long-term motion deduced from paleomagnetic and geological studies is coherent with the extrapolation of the current motions measured by GPS. Paleomagnetic data that have been collected in the north arm of Sulawesi indicates that since 5 Myr about 20 to 25° of semi-rigid rotation occurred about a pole located north of Manado. This suggests 200 to 250 km of left lateral displacement along the Palu-Koro Fault with a displacement rate of 4 cm/yr. A rather similar displacement on the Palu Fault is derived using the distribution of the asymmetric magnetic anomalies of the Celebes sea floor. The distribution implies that 200 to 250 km of oceanic crust was subducted at the North Sulawesi Trench. Another marker for the rotation is derived from the opening of the gulf of Tomini and the NW-migration of the calc-alkaline subduction related volcanism. The far-field observation by GPS of 4 cm/yr of left-lateral strike-slip motion over 17 months and the 5 year average of 3.4 ± 0.3 cm/yr on a transect across the Palu Fault fit well with the geological observations that indicate a motion of 4 to 5 cm/yr of the north arm. We therefore conclude that the current rates deduced from GPS measurements approximate the long-term rates and may hence be extrapolated over a few million years.

Key words: Tectonics, Kinematic, Sulawesi, Indonesia, Geodesy
Word count: 3200

1. Introduction

Recent deformation of the eastern Indonesian region is the result of the convergence between the Eurasian, India-Australian, and Philippine Sea Plates (Fig. 1). Under the influence of the northward moving Australian Plate and the westward motion of the Philippine Plate, the Sula domain is colliding with the Eurasian Plate [1, 2]. This collision is both accommodated by motions along the Matano and Palu-Koro Faults at the southern and south-western domain limits, and by subduction at the North Sulawesi Trench. The latter forms the southern margin of the Celebes Sea.

According to geodynamic reconstructions [3, 4], prior to the Neogene collision, the Indian Ocean was subducted beneath North and East Sulawesi along a northward dipping slab. The Celebes Sea Basin opened in a back-arc position [3]. Presently, the Celebes Sea Basin is subducting along the North Sulawesi Trench, which is apparently "pinned" to the East [5]. This subduction is rather young as attested by the lack of subduction related volcanism. The north arm of Sulawesi has been welded to the Sula domain since 15 Myr. By its clockwise rotation, it is now causing subduction in the Celebes Sea Basin. Using paleomagnetic studies Otofuji et al. [6] estimated a rotation of 90° of the North Sulawesi arm. In contrast we will show that to date rotation since the last 5 Myr is less than 25°. This smaller rotation has been derived from geological reconstruction [5], paleomagnetic data [7], the distribution of calc-alkaline volcanism in North Sulawesi [8], and the amount of Celebes Sea oceanic crust subducted along the North Sulawesi Trench [9], attested by seismic observations. The value obtained for the finite rotation is then compared with observations of the current motion of the north arm, determined from GPS observations of the South-East Asian GEODYSSEA network and a supplementary densification network on Sulawesi [2].

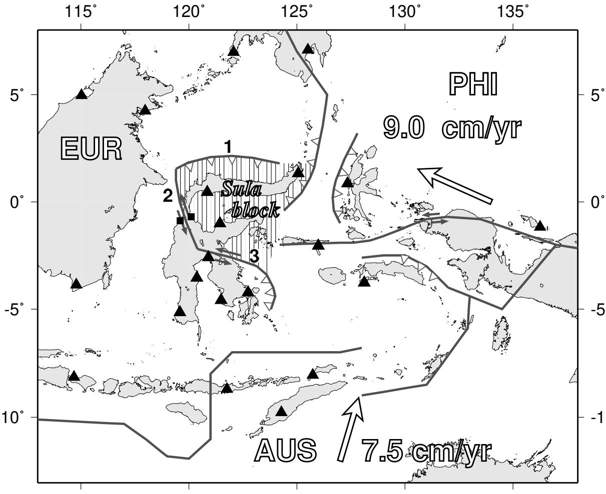

Figure 1. The area of convergence of the Eurasian, Philippine and Australian plate (velocity vectors indicated with respect to Eurasia after NUVEL1A) is characterized presently by the intrusion of the Sula block (dashed area) north-east wards into the Eurasian plate. This motion is absorbed by the North Sulawesi Trench (1) at the northern block boundary, and transfered at its western and southwestern limits by the Palu-Koro (2) and Matano (3) faults.

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2. Geodynamic reconstruction of Sulawesi

Silver et al. [5] proposed a geodynamic reconstruction model of the island of Sulawesi using geophysical and seismotectonic data, in particular from the North Sulawesi Trench and the Tolo Thrust. They gave strong evidence for a clockwise rotation of the north arm of Sulawesi with respect to a pole situated northeast of Sulawesi. Hamilton [10] showed that the increase in width of the accretionary wedge along the arm's northern margin is a result of its rotation about a pivot located at its eastern end. The Palu-Koro and Matano Fault System in central Sulawesi forms a small circle around the proposed rotation pole. Cumulative left-lateral displacement as indicated by displaced features along the southern splays of the Palu-Koro Fault suggest a total displacement of about 250 km along the fault. This implies a clockwise rotation of the north arm of 20° [5]. According to Silver, motion along the fault system took place during the last 5 Myr, leading to an average rotation rate of about 4°/Myr and an average rate of left-lateral displacement of 5 cm/yr on the Palu-Koro Fault. Silver suggests that the discrepancy between his conclusions and that of Otofuji, who suggested a rotation of 90°, might be a result of the longer time period considered by Otofuji in his study of volcanic rocks or of small-scale block rotation within fault zones.

3. Subducted Celebes Sea crust

The Celebes Sea is characterized by a NE-SW magnetic trend, as shown by K. Hinz (personal communication, 1997). Weissel [11] showed that the magnetic anomalies 18 – 20 are arranged asymmetrically in the southern part of the Celebes Sea Basin. Assuming that the Celebes Sea was created by symmetrical spreading with respect to a NE-SW oriented central ridge, it implies that only one half of the original basin is preserved. The present geometry, with the youngest anomaly 18 close to the North Sulawesi trench, might hence be a result of subduction of the other half of the oceanic basin due to the clockwise rotation of the northern arm of Sulawesi. The amount of rotation may be assessed by estimating the length of the subducted crust. The magnetic anomalies 18 – 20 are spread over about 100 km. Furthermore, there is probably more oceanic crust present north of the oldest identified magnetic anomaly. The trend of the preserved magnetic anomalies is oblique to the northern passive margin of the basin along the Sulu archipelago (Fig. 3). Hinz and Block [12] documented the nature of this margin using multichannel seismic data. The obliquity could reflect the former presence of an Early Paleogene spreading centre that propagated to the SW towards the Makassar Strait [9].

This means that more oceanic crust has probably been created north of the oldest identified magnetic anomaly proceeding eastward along the Sulu archipelago. According to the magnetic data, about 150 km of additional intermediate crust is present between the Sulu archipelago and the identified magnetic anomalies. Assuming that the Celebes Sea Basin originated with symmetric anomaly patterns, the present day state would have been reached by a total subduction of up to 250 km of oceanic and intermediate crust in the North Sulawesi Trench. The reconstruction by Rangin et al. [9] suggests a 25° clockwise rotation of the north arm needed to restore the SW termination of the Celebes Sea before the onset of its subduction along the North Sulawesi Trench. This rotation about the eastern extension of the North arm is coherent with the proposed amount of marginal basin Celebes crust subducted along the nascent North Sulawesi trench. It is furthermore in good agreement with the estimation made by Silver (about 20°), as mentioned above.

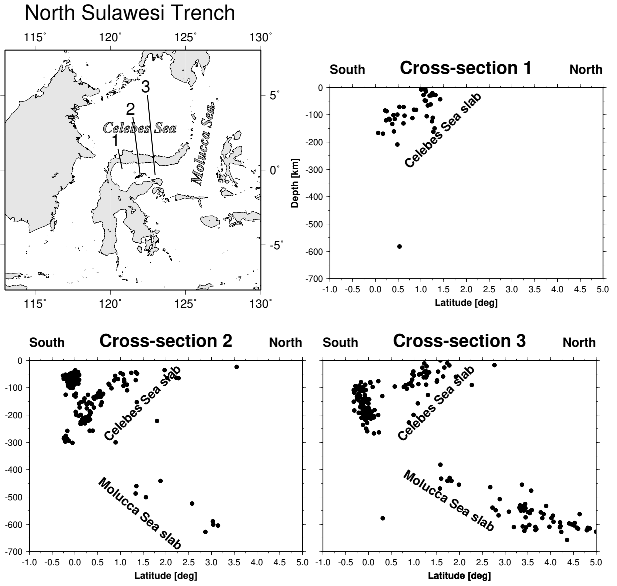

Figure 2. Seismic sections across the North Sulawesi Trench showing NEIC and Harvard locations from 1964-1988. The upper left figure shows three sections as lines. They correspond to the three boxes that include seismic locations. Each section shows data from distances of up to 25 km projected on the profile plane. The sections indicate the apparent position of the south dipping Celebes Sea slab and of the north dipping Molucca Sea slab.

3.1. The south dipping slab in seismic data

In Fig. 2 several cross sections through the trench are presented, showing the projected seismogenic traces of the southward dipping slab that reaches depths of up to 200 km. This suggests that more than 200 km of oceanic crust has been subducted. This evaluation coincides with the estimated length of over 200 km for the south dipping slab below Sulawesi after Cardwell et al. [13]. Moreover, it can be seen that the southward dipping Celebes Sea slab is encountering at depth the northward dipping subduction of the Molucca Sea slab. This suggests that the Celebes Sea slab is blocked at depth in the eastern part of the North Sulawesi subduction zone, so explaining the pinned eastward motion of the north arm of Sulawesi.

3.2. Paleomagnetic observation of the north arm rotation

An extensive paleomagnetic study was carried out in the north arm of Sulawesi by Surmont et al. [7]. Results suggest clockwise rotation of 22° of the north arm and contradict the 90° rotation derived by Otofuji et al. [6]. The results are in good agreement with the amount of rotation (20°) and the location of the rotation pole (north-east of Manado) proposed by Silver et al. [5] based on geological reconstructions. These new paleomagnetic observations imply a displacement of more than 200 km at the intersection between the North Sulawesi trench and the Palu-Koro Fault. The new paleomagnetic results have been obtained from sites situated on the North arm between Ampibabo located at 120° E in the western part of the arm and Bolaanguki at 124° E, northwest of Kotamobagu, in the east. The samples have been taken mainly in Miocene-Pliocene volcanic and volcanoclastic rocks (21 – 5 Myr). The tectonics of the North arm of Sulawesi are characterized by a more stable behaviour in its western part, while the eastern part is dissected by NW-SE dextral strike-slip fault zones (Gorontalo and Kotamobagu Faults) that extend offshore (K. Hinz, personal communication,

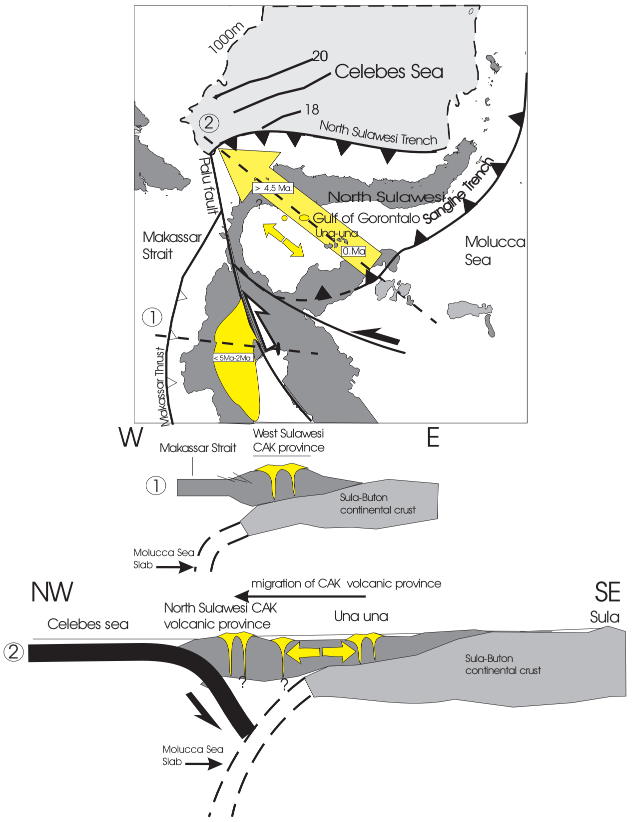

Figure 3. Distribution of the Calk Alcalik Potassic (CAK) volcanism in Sulawesi. In the west arm this volcanism is restricted to the central part of the arm, while east of the Palu-Koro fault zone CAK volcanism is distributed across a NW-SE 200 km wide belt extending from North Sulawesi to Una-Una islands. The two synthetic cross sections illustrate the contrasting distribution of this volcanism on both sides of the Palu-Koro fault zone. Extension of the Sula-Buton/North Sulawesi arc is speculative. The double arrow illustrates extension in the Gulf of Gorontalo. Dashed lines in cross sections indicate the presence at depth of the remnant subducted Tethys oceanic crust.

1997). The discrepancy with Otofuji's [1981] measurements may be the result of sampling: Otofuji took a variety of samples along the dextral Gorontalo strike-slip fault zone where minor blocks are expected to have been rotating in response to transcurrent faulting.

3.3. The Calk Alkalic Potassic igneous provinces of Sulawesi

The calc-alkaline (CAK) volcanism in North-West Sulawesi started in the post-Early Miocene after the collision of the Sula-Banggai Australian promontory with the Sulawesi island arc. CAK volcanism is present at both sides of the Palu-Koro Fault.

Priadi [14] and Polvé et al. [8] interpreted the volcanism as a result of the Sula-Buton continental crust subduction below central and western Sulawesi. The CAK volcanism was dated in Priadi [14] as being not younger than 4.5 Myr at the north arm, while it is still active at the west arm, west of the Palu-Koro Fault. The youngest equivalent of CAK volcanism east of the fault is exposed on the Una-Una island, in the midst of the Tomini gulf SE of Tomini (Fig. 3). Recent submarine volcanoes which are assumed to be part of the same volcanic chain are reported in the GEBCO oceanographic chart of the world. They are distributed over a 200 km wide volcanic province from North Sulawesi to Una-Una. The North Sulawesi volcanism was apparently detached from its source and has migrated northward together with the north arm. This explains why the youngest late Neogene CAK volcanism is absent in North Sulawesi, while Una-Una CAK volcanism is presently the closest to the source and still located at the apex of the melting continental crust as its equivalent in West Sulawesi.

In the north arm, youngest samples of this volcanism showing a 20–25° rotation cited by Surmont et al. [7] have been dated to 5 Myr [14]. Deducing the time when the rotation was initialized enables us to evaluate the finite velocities of the rotation and the displacement on the North Sulawesi Trench (and the related Palu-Koro Fault), based on paleomagnetic observations. It follows that the rotation of 20–25° took place at a minimum rate of 4–5°/Myr, and the average velocity of the left-lateral displacement of about 200 km across the Palu-Koro Fault is estimated to exceed 4 cm/yr.

4. Estimates of instantaneous displacement and rotation rates

The aim of this study is to compare the estimates of finite velocities for the rotation of the north arm of Sulawesi (and in doing so the long term velocity on the Palu-Koro Fault) with observations of the current displacement rates using satellite geodesy over less than 5 years. For this purpose we used the results obtained for the Sulawesi region from the South East Asian GEODYSSEA GPS network [2], and observations of a local GPS network across the Palu-Koro Fault [15, 16].

4.1. Far-field velocity across the Palu-Koro fault

The velocity field measured by the GEODYSSEA GPS campaigns in November/December 1994 and April 1996 is presented in Fig. 4. Detailed descriptions of the GEODYSSEA project are given in [17]. The data processing strategy used to obtain the geodetic results shown in this paper is explained in Walpersdorf et al. [2]. The velocities are shown with error ellipses representing the 90% confidence limits. The accuracy estimated for the relative velocities in the GEODYSSEA network is 5 ppb/yr (5 mm/yr on a baselines of 1000 km), corresponding to the error ellipse in the legend box. For rotation rates inferred from these velocity observations, general uncertainties of 0.3°/Myr can be deduced. The major plate boundaries between the three main tectonic plates (Eurasian, Philippine and Australian) are well resolved, showing that the Palu-Koro Fault and the North Sulawesi Trench are active boundaries between the Eurasian Plate and the Sula domain, which itself has a motion influenced by both the Philippine and the Australian Plates.

An estimate of the relative velocity across the Palu-Koro Fault is given by the motion of the AMPA station in central Sulawesi with respect to stations on Kalimantan (as TAWA and BATU). The TOMI station in North Sulawesi was unfortunately affected by a large earthquake nearby and is hence not representative for the secular velocity of the tectonic block on which it is situated (the Sula domain). In choosing sites on Kalimantan as reference stations for AMPA we show the secular (relative) velocities of the two blocks separated by the Palu Fault, away from the near fault transient effects. Differences in velocities between the stations south of the Palu-Koro and Matano Fault System in South Sulawesi are assumed to reflect this transient behaviour. Therefore the relative motion between AMPA and the closest station MALI is assumed to represent only part of the overall displacement across the fault zone. The velocity of AMPA with respect to the stations on Kalimantan is evaluated by the GEODYSSEA GPS observations to 4.5 ± 0.6 cm/yr oriented 318° ± 4° (AMPA-BATU) and 4.3 ± 0.6 cm/yr oriented 307° ± 4° (AMPA-TAWA). These velocities have been projected on the Palu fault (average orientation 345°) and cor-

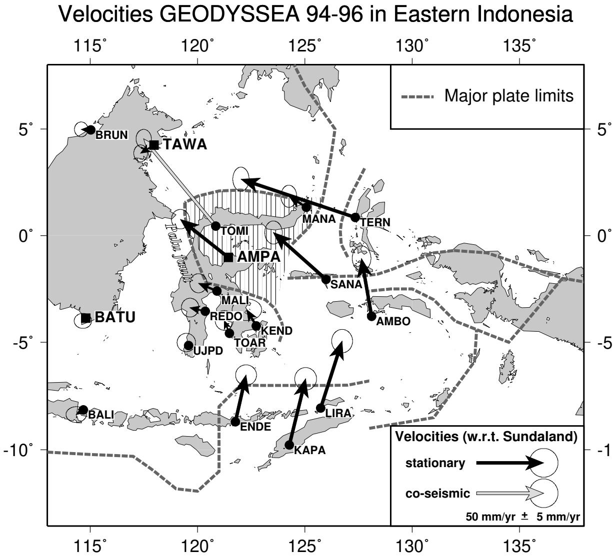

Figure 4. Velocities of the GEODYSSEA stations in Eastern Indonesia relative to Sundaland (see details in Walpersdorf et al. [2]). Velocities are given with formal errors (90% of confidence ellipses). The displacement rate of AMPA with respect to the stations BATU and TAWA on Kalimantan corresponds to a motion of 4 cm/yr parallel to the Palu fault (left lateral strike slip motion).

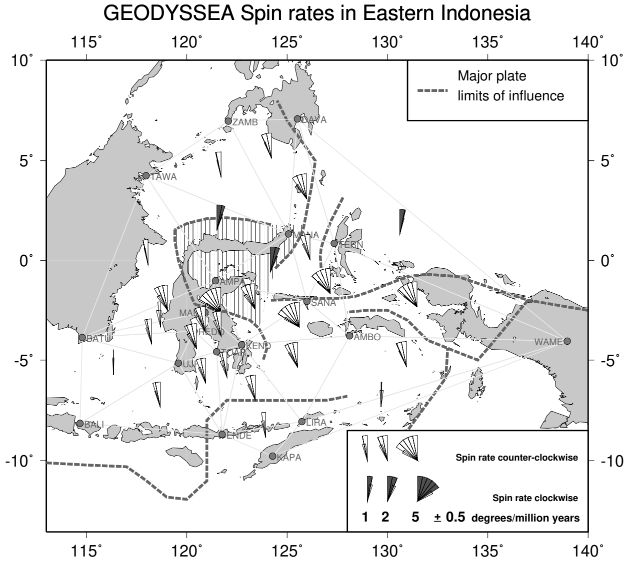

Figure 5. Spin distribution in Delaunay triangles in the East Indonesian part of the GEODYSSEA network according to Walpersdorf et al. [2]. Counter clockwise rotations are indicated in white, clockwise rotation with grey segments. Small segments represent the formal uncertainties, showing significant rotation in nearly all triangles in the presented area. The clockwise rotating Sula block corresponds to the dashed area.

respond to a left-lateral displacement across the Palu-Koro Fault of 3.8 and 4.0 cm/yr respectively. This is the result of only two measurement campaigns with a 17 months interval. The rate is in good agreement with the average displacement rate for the last 5 Myr obtained by geological studies.

4.2. Spin rates in the GEODYSSEA network

An apparent amount of clockwise rotation of the north arm of Sulawesi is estimated using observations of the GEODYSSEA network: Station MANA is located at the eastern extremity of the north arm, close to the rotation poles indicated in Silver et al. [5] and Surmont et al. [7]. Fig. 4 shows a relative velocity of MANA that is similar to that of the Eurasian Plate (i.e. the Sunda Block, [Chamot-Rooke et al., in prep.] and [Le Pichon et al., in prep.]).

The motion of AMPA and SANA westward with regard to MANA corresponds to a clockwise rotation of the Sula domain (with the north arm welded on it), around a pole in the MANA region. The direction of the TOMI motion is also coherent with this rotation, but as TOMI was affected by a seismic displacement, this station has been excluded from the quantitative evaluation.

Fig. 5 shows the distribution of spin in the GEODYSSEA network derived using Delaunay triangles (the most symmetric triangles between nearest stations). Details about this approach can be found in Feigl et al. [18]. For each triangle, a deformation tensor based on the three horizontal station velocities was computed. The deformation matrix is split into a symmetric part and a non-symmetric part. The latter reflects the rotation herein referred to as spin. Fig. 6 shows clockwise spin in two triangles in the northern part of Sulawesi, coinciding with the Sula domain.

A numerical value of the rotation rate in North Sulawesi which is comparable with the geological studies mentioned above was obtained by modelling the rigid rotation of the Sula domain [2] based on GPS velocities in the densified GEODYSSEA network. The area of the clockwise rotating micro block in north Sulawesi is indicated in Fig. 6 by the dashed zone. The northern, western and south western limits are given by the North Sulawesi Trench, the Palu fault and the Matano fault. The south eastern boundary is not yet well determined. The north eastern most extension of Sulawesi's north arm around the MANA station has been included in the Sula domain, inspite of the existence of the active Kotamobagu fault, crossing the north arm just west of MANA [9], (K. Hinz, personal communication, 1997). The amount of motion along this fault is unknown, but we believe it to be minor. A rotation pole with its uncertainties has been established by the least squares adjustment of the pole parameters (latitude and longitude of the pole location and its rotational rate) to the observations of the velocities of four stations situated inside the block boundaries. Slip between the blocks has been handeled as a free parameter. The clockwise rotation rate of 3.4 ± 0.4°/Myr with respect to a pole northeast of Sulawesi (2.1° N, 126.2° E) fits well the overall rotation rates deduced from the paleomagnetic observations.

4.3. Temporal evolution of the Palu transect main baseline

Finally, we consider the results of GPS observations of a 50 km baseline across the Palu-Koro Fault [16, 15], the location of which is indicated in Fig. 1. The time series of 4.5 years on the main baseline of the Palu transect shows an average strike-slip rate of 34 mm/yr, which is slightly lower than the long term estimates mentioned above. In detail, the strike-slip motion has been observed at two different rates, a low rate of 26 mm/yr from 1992 to 1995, and a much higher rate of 63 mm/yr since 1995. These different displacement rates may be related to the increased seismic activity in the North Sulawesi region in the last years. With the endpoints of the transect probably still situated in the area that suffers transient elastic straining, the relative velocity between these two stations could be less than the total velocity between the two tectonic blocks separated by the fault. Therefore, the average velocity of 3.4 cm/yr might be close to the final rate between the end points of the Palu transect over a longer observation period, and apparently represents a lower limit for the total displacement rate across the Palu Fault.

5. Conclusion

We showed that according to the recent paleomagnetic observations by Surmont et al. [7] the rotation of the north arm of Sulawesi has occurred with an average rate of at least 4°/Myr. This leads to an average minimum rate of 4 cm/yr of sinistral strike-slip motion across the Palu-Koro Fault. The paleomagnetic studies indicating counter clockwise rotation are supported by the apparent amount of subduction of a corresponding slab below North Sulawesi. This coincides with the reconstructions of Silver et al. [5] and Rangin et al. [9] and a rotation of the north arm of Sulawesi of 20–25° in the last 5 Myr about its eastern extremity. This corresponds to at least 200 km of subducted Celebes Sea crust and a displacement of over 200 km across the Palu-Koro Fault.

Current deformation measurements using GPS on the GEODYSSEA network lead to results that are in good agreement with the overall long-term rates. Even on an observation interval of only 17 months the derived rates (a strike-slip rate across the Palu-Koro Fault of 4 cm/yr, and a clockwise rotation rate of North Sulawesi of 3.4°/Myr) can be extrapolated to the estimations of finite motion over several million years. Extrapolation is only reliable if the stations concerned are situated sufficiently distant from active plate boundaries, so that they are not affected by the near fault dynamics and corresponding transient elastic straining but indicate the "steady state" secular velocities of apparently rigid tectonic blocks. A lower limit of the velocity across the fault is given by the displacement rate of 3.4 cm/yr measured on the Palu-Koro transect over a 5 years average, because the endpoints of the transect (at about 30 km from the fault) are apparently situated inside the deformation zone. On the example of the Sulawesi north arm, this study shows the impact of short period GPS observations on the determination of finite kinematics and the understanding of current deformation and tectonics in an area as complex as the one studied.

Acknowledgments.
Many thanks are due to Christophe Monnier, Nantes, for the seismic data on the North Sulawesi Trench. We are grateful to Helmut Beiersdorf and Karl Hinz, Hannover, for the magnetic data acquired on the Sonne cruise in the Celebes basin and our thanks are also extended to Colleen Stevens and Rob McCaffrey (RPI) for the successful collaboration on the Palu-Koro transect. Our gratitude goes to Cecep Subarya and the BAKOSURTANAL team, Cibinong, Java, who carried out the collection of GPS data in Sulawesi. Part of the geodetic data presented was achieved in the framework of the GEODYSSEA Project. The support of the GFZ Potsdam, Germany, has been much appreciated and our thanks go especially to Jürgen Klotz for the support in the field, and to Gero Michel and Peter Wilson for their efforts in revising the text.

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(Received Sep. 25, 1997; revised Sep. 25, 1997; accepted Sep. 25, 1997.)

To appear in the *Earth and Planetary Science Letters*, 1998.