ELSEVIER

Earth and Planetary Science Letters 187 (2001) 239–244

EPSL

www.elsevier.com/locate/epsl

Crustal motion and block behaviour in SE-Asia from GPS measurements

Gero W. Michel [a,*], Yue Qui Yu [a], Sheng Yuan Zhu [a], Christoph Reigber [a], Matthias Becker [b,1], Ewald Reinhart [b], Wim Simons [c], Boudewijn Ambrosius [c], Christophe Vigny [d], Nicolas Chamot-Rooke [d], Xavier Le Pichon [d], Peter Morgan [e], Saskia Matheussen [e]

[a] *GeoForschungsZentrum Potsdam, Division 1, Telegrafenberg, 14473 Potsdam, Germany*
[b] *Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany*
[c] *Delft Institute for Earth-Oriented Space Research, Delft, The Netherlands*
[d] *École Normale Supérieure, Paris, France*
[e] *University of Canberra, Canberra, Australia*

Received 8 January 2001; accepted 6 March 2001

Abstract

Results acquired using global positioning system (GPS) data taken over a large part of SE-Asia, indicate that Sundaland, i.e. Indochina along with the western and central part of Indonesia, constitutes a stable tectonic block moving approximately east with respect to Eurasia at a velocity of 12 ± 3 mm yr^{-1}. With respect to India and Australia this block moves due south. Significant motion has not been detected along the northern boundary to South China i.e. along the Red River Fault, whereas nearly 50 mm yr^{-1} of right lateral motion has to be accommodated between India and Sundaland in the Andaman–Burma region.

Keywords: geodynamics; plate tectonics; Global Positioning System; Southeast Asia

1. Introduction

The south-eastern margin of Eurasia, from North China to Indonesia, has been considered as rigidly attached to Eurasia [1], continuously deforming [2], or formed by a mosaic of blocks deforming mainly at their boundaries [3,4]. Recent global positioning system (GPS) results indicate that North and South China are decoupled from Eurasia [5–7] and move eastward with a velocity of 4–13 mm yr^{-1}. Further south, previous geodetic results obtained from across Sundaland (i.e. Indochina, the Sunda Shelf, Borneo, Sumatra, and Java) suffered from a less well defined global reference system [8], restricted areal extension of networks [9,10], or concentrated on seismically active boundaries [9,11]. This paper deals with results of repeated measurements that were made of a GPS network extending over an area of 4000 by 4000 km (Fig. 1), covering Brunei, Indo-

* Corresponding author.

[1] Present address: University of the Bundeswehr, Munich, Germany.

0012-821X/01/$ – see front matter
PII: S0012-821X(01)00298-9

nesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. These results indicate that a large part of SE-Asia is best described by motion of a 'rigid' block that is moving east with respect to Eurasia.

2. GPS measurements and data processing

The GEODYSSEA (i.e. **GEODY**namics of **S**- and **SE**-Asia) GPS network was measured in 1994, 1996, and 1998. The data sets were analysed independently by five different groups and combined to reach the final solution mapped into ITRF97 [12]. GPS observations were conducted simultaneously at 42 stations and included data from the Australian Survey and Land Information Group (AUSLIG) and the International GPS Service for Geodynamics (IGS). Five analysis groups (BKG, DEOS, ENS, GFZ, and UC) used the latest version of one of four GPS software packages (BERNESE v4.0 [13], EPOS v3.0 [14], GAMIT v9.9 [15], and GIPSY-OASIS II v2.5 [16]) and applied their favoured analysis strategy [9]. Processing included: fiducial-free network solutions, ionosphere-free linear combinations of GPS data, tropospheric modelling, and the use of IGS antenna phase centre tables. This solution differs from earlier solutions [9] by virtue of the additional epoch and the use of additional global IGS stations. Additionally precise GPS satellite orbits/clocks and corresponding earth rotation parameters from the IGS, GFZ, the Jet Propulsion Laboratory (JPL), and UC were applied. For the 1994 and 1996 campaigns the data were re-computed using the ITRF97 reference frame. The daily solutions from each group were combined into multi-day averaged solutions and averaged coordinate solutions for the individual campaigns.

The daily coordinate repeatabilities of the GEODYSSEA stations for each campaign range between 2.5 and 6.5 mm for the horizontal components and between 6 and 15 mm in height. The internal consistency of all contributing multi-day averaged group solutions is 2, 4, and 7 mm in the north, east and up components (data are available on request by the first author). A precise estimate of the horizontal station velocities was obtained by mapping each campaign solution into the ITRF97 [12] frame using 16–22 global IGS sites, with long and stable time series (data are available on request by the first author). This was done using linear models for all stations not affected by nearby large earthquakes (i.e. Biak and Tomini in Indonesia). The 1-sigma quality of these models was 2 mm yr^{-1} in north–south and 3 mm yr^{-1} in the east–west direction.

Abundant large earthquakes suggest that transient seismic deformation processes may have significantly influenced some of the observed site motions [17,18]. Dislocation modelling was therefore applied to estimate the influence of seismic loading and release on the site motions [19]. Results indicate that apart from the eastern perimeter of the study area and the fore-arc sliver along Sumatra, the sites appear to be almost unaffected by seismic elastic loading and release phenomena.

3. Strain rates and block behaviour

Geodetic strain and rotation rates (Fig. 2) show that highly strained regions are restricted to the Philippine Mobile Belt to the east and the Sumatra shear zone to the west. The central part of the network covering Sundaland displays a coherent velocity field. A subset of 10 stations defined by small baseline variations (<4 mm yr^{-1}) and small interstation strains ($<2\times10^{-8}$ yr^{-1}) was chosen to define a 'rigid' Sundaland platelet (Fig. 1). Motion of these sites can be modelled to within 3 mm yr^{-1} (data are available on request by the first author) with a single Euler vector (56.0°S, 77.3°E, $-0.339\pm0.007°$ Myr^{-1} in ITRF97) significantly distinct from the Eurasian vector from the NNR-NUVEL-1A frame [20]. Taking into account that the NNR-NUVEL-1A solution for the motion of 'stable' Eurasia may differ from the ITRF97 solution, Sundaland's motion with respect to Eurasia, was further evaluated approximating the solution of [21]. This was done by minimising the adjustment to the horizontal velocities of the stations mentioned in [21] (without the station YAKB) in the ITRF97. Results of this solution coincide in principal with the above so-

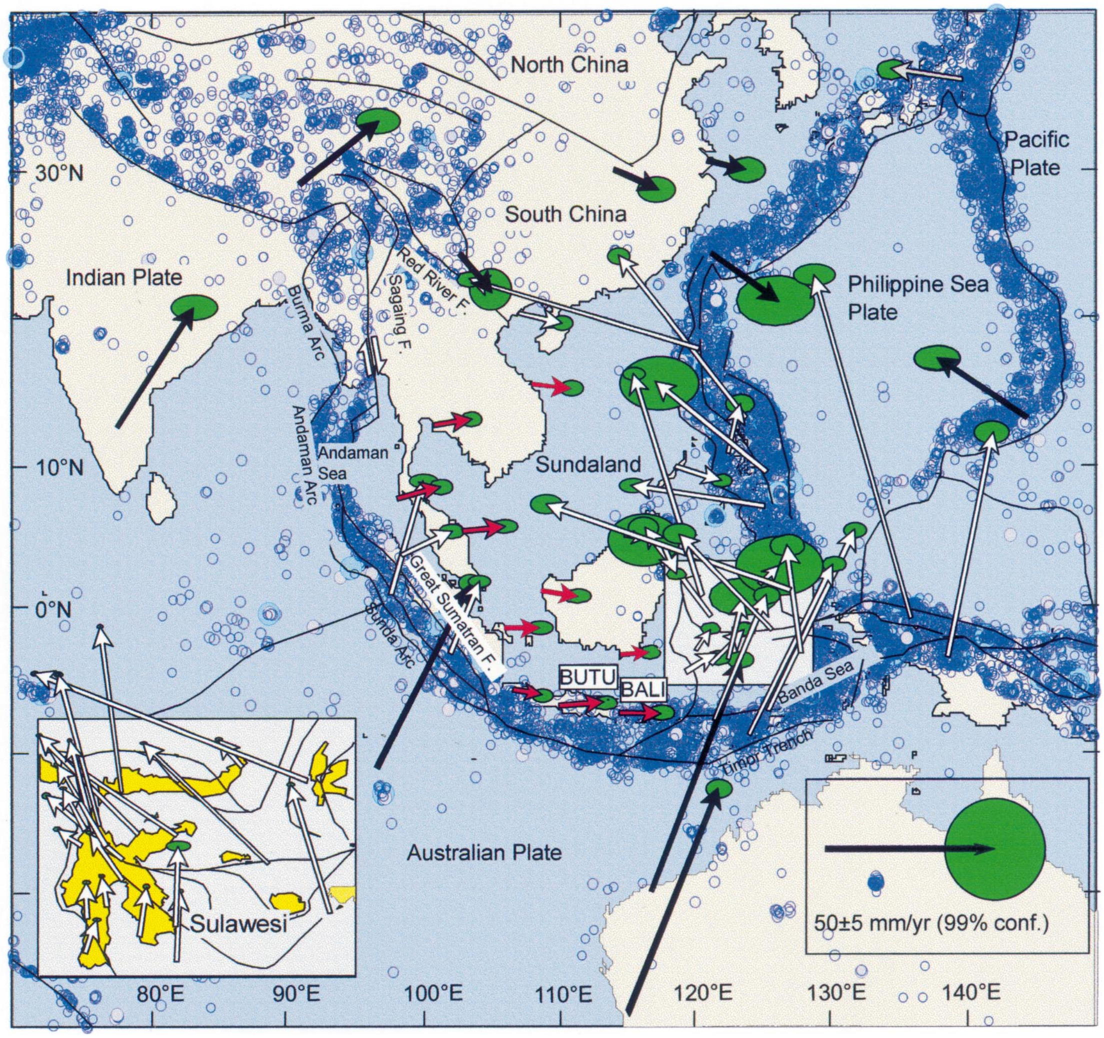

Fig. 1. GPS velocity vectors in a Eurasian (NUVEL-1A) reference frame. Black arrows: permanent stations from the IGS and AUSLIG, red and white arrows: velocities derived in this study (red: 'stable' Sundaland). Inset map (marked rectangle in main figure): triple junction densification network (vectors relative to Sundaland). Error ellipses represent 99% confidence limits. Black lines denote major faults. Black/grey dots denote epicentres of crustal earthquakes from the USGS catalogue (1973–2001).

lution, whereas relative velocities of Sundaland with respect to Eurasian are diminished by roughly one third.

Residuals of the individual solutions to the average solution (Fig. 3) suggest that, although the average east component of the Sundaland motion with respect to Eurasia is distinct at 10–14 mm yr^{-1} (NNR-NUVEL-1A, Fig. 3), a small and systematic variation of this component with latitude cannot be ruled out. This implies two interpretations: the Sundaland platelet escapes due east with respect to Eurasia at an average rate of 12 ± 3 mm yr^{-1}, or Sundaland rotates clockwise with respect to Eurasia at a velocity increasing from 10 mm yr^{-1} in the south to 14 mm yr^{-1} in the north. The use of ITRF97-velocities for the definition of Eurasia as a reference diminishes the escape velocity to ~ 8 mm yr^{-1}. The range covered by the individual group solutions represents the uncertainty of the combined solution in terms

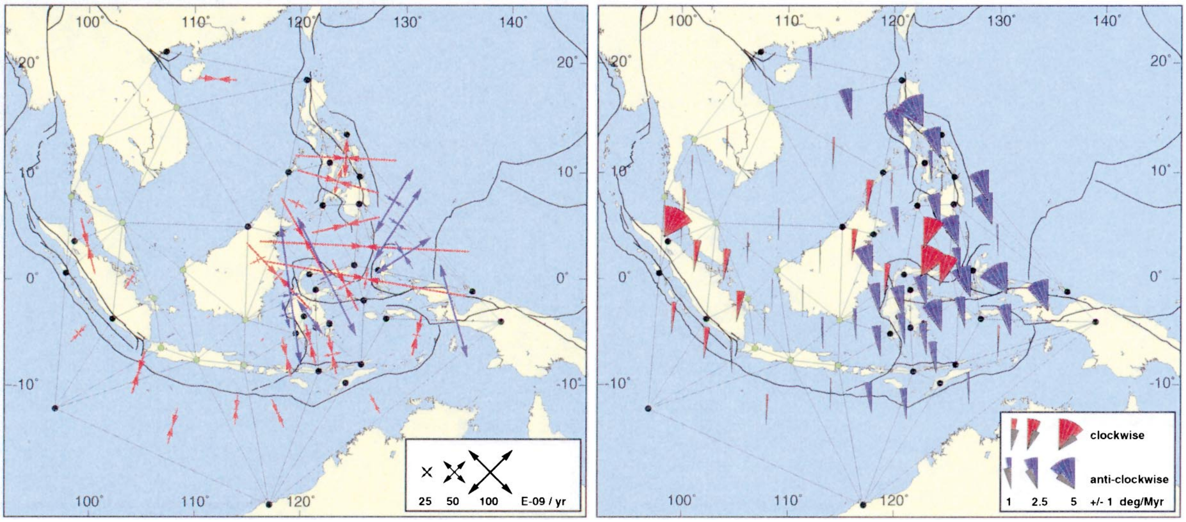

Fig. 2. Strain and rotation rates derived within the GEODYSSEA network. (Left panel) Strain rates, horizontal principal axis of the deformation tensor (red for compression and blue for extension). (Right panel) Rotation rates (red wedges for clockwise rotation and blue for anti-clockwise rotation) with associated uncertainties (grey wedges). Green dots show sites on rigid Sundaland.

of both the reduction of GPS measurements and the realisation of the reference frame in this area of the world, where ionospheric noise is high and fiducial stations are scarce. Some part of these uncertainties may originate from apparent transient effects, indicated by the time series for the station velocities at BALI and BUTU (Fig. 1), where velocities are lower (1994–1996) and higher (1996–1998) than predicted by the other eight stations of the Sundaland block. Further studies are necessary to explain these effects.

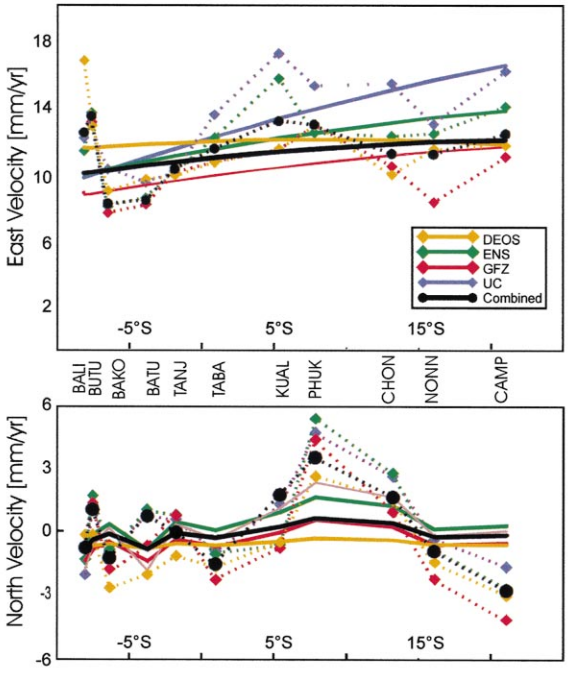

Fig. 3. (Upper panel) East velocity components of Sundaland stations sorted by latitude. Group solutions: GFZ (red), ENS (green), DEOS (orange) and UC (violet), combined solution (black). For each solution, actual values (symbols) and trends (solid lines) are computed using the individual Sundaland/Eurasia poles. (Lower panel) North velocity components sorted by latitude.

4. Results and conclusions

This new geodetic solution demonstrates that a large piece of the eastern Eurasian margin behaves to first order as a single block, as suggested previously by the results of the first two rounds of measurements [8,17,22]. To the north, the relationship of this Sundaland block to the adjacent South China block is still to be established, but in any case, differential motion is small and at the detection limit of current data. Predicted rates on the assumed boundary, the Red River Fault, are below 5 mm yr^{-1}. To the south, the Sundaland block is bounded by the Great Sumatran Fault and the Sunda Arc. Relative motion between Sundaland and Australia is directed northwards suggesting similar eastward components of motion for both plates along this boundary. The apparent difference between the NUVEL-1A convergence direction and earthquake slip directions discussed in the literature [23] thus appears to have been resolved. Convergence rates between Australia and Sundaland reach values between 66 and 72 mm yr^{-1} (see also [1]). Relative velocities of sites on the fore-arc sliver on Sumatra with respect to Sundaland suggest strike-slip motion of between 20 and 30 mm yr^{-1} along the Great Sumatran Fault. Along the Banda Arc, collision occurs between the Australian continental lithosphere and a complex block assemblage in the area of the triple junction between the Pacific/Philippine Sea plate, the Australian plate, and Sundaland. Here deformation is transferred from the Timor Trench to the north where it is concentrated on the back-arc thrust system [11], as well as influencing motion of sites within the Banda Sea and Sulawesi area. In this region, a large portion of the deformation is accommodated by small-scale block rotations at rates of up to 4° Myr^{-1}. To the east, convergence between the Philippine Sea plate and Sundaland partitions within the complex Philippine Mobile Belt [19]. To the west, motion of India with respect to Sundaland is roughly north at a rate of 45–52 mm yr^{-1}. Relative motion is accommodated by opening of the Andaman Sea, strike-slip motion on the Sagaing fault system, oblique shortening along the Andaman and Burma subduction arc, and rotation about the eastern syntaxis of India.

During the Tertiary [24] the Sundaland region was divided into a number of distinct provinces each with distinct boundaries and motion. The apparent change from this regime to one of relative homogeneity that accommodates the eastward component of the motion of the Indian and Australian plates is remarkable. One plausible explanation is the general change in the boundary conditions of E- and SE-Asia with the onset of subduction and subsequent roll-back along the Philippine trench in the late Miocene [24]. The alternative is that Sundaland's eastward directed motion relates to the onset of the eastward motion of India at about 8.5–10 Ma [25], when the Indian equatorial zone of deformation was initiated and the Indian plate was detached from the Australian plate. In any case, this new evidence for a rather homogeneous motion of E- and SE-Asia rejects any model that includes either intense deformation within blocks or large differential motion between them.

Acknowledgements

We are especially grateful to Peter Wilson, J. Rais, M. Kasser, P. Suharto, J. Klotz, Dato'Abdul Majid, Dato' Paduka Awang Haji Othman Bin Haji Yaakub, R. Almeda, C. Boonphakdee, and Cecep. The Project was supported by the European Commission (first two rounds of measurements) and was financed by the BKG, GFZ and individual partners in SE-Asia (third campaign). Thanks are extended further to the ASEAN and the hosting agencies, to AUSLIG, the Australian Research Committee, and the Department of Land: Queensland.*[AC]*

References

[1] P. Tregoning, F.K. Brunner, Y. Bock, S.S.O. Puntodewo, R. McCaffrey, J.F. Genrich, E. Calais, J. Rais, C. Subaraya, First geodetic measurement of convergence across the Java Trench, Geophys. Res. Lett. 21 (1994) 2135–2138.

[2] C. Kreemer, W.E. Holt, S. Goes, R. Govers, Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data, J. Geophys. Res. 105 (2000) 663–680.

[3] G. Peltzer, G.F. Saucier, Present-day kinematics of Asia derived from geologic fault rates, J. Geophys. Res. 101 (1996) 27943–27956.

[4] J.-P. Avouac, P. Tapponier, Kinematic model of active deformation in central Asia, Geophys. Res. Lett. 20 (1993) 895–898.

[5] K. Heki, S. Miyazaki, H. Takahashi, M. Kasahara, F. Kimata, S. Miura, N.F. Vasilenko, A. Ivashchenko, K.D. An, The Amurian Plate motion and current plate kinematics in eastern Asia, J. Geophys. Res. 104 (1999) 29147–29155.

[6] Z.-K. Shen, C. Zhao, A. Yin, Y. Li, D.D. Jackson, P. Fang, D. Dong, Contemporary crustal deformation in east Asia constrained by Global Positioning System measurements, J. Geophys. Res. 105 (2000) 5721–5734.

[7] Z. Chen, B.C. Burchfiel, Y. Liu, R.W. King, L.H. Royden, W. Tang, E. Wang, J. Zhao, X. Zhang, Global Positioning System measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation, J. Geophys. Res. 105 (2000) 16215–16227.

[8] W.M.F. Simons, B.A.C. Ambrosius, R. Noomen, D. Angermann, P. Wilson, M. Becker, E. Reinhard, A. Walpersdorf, C. Vigny, Observing plate motions in South East Asia: Geodetic results of the GEODYSSEA Project, Geophys. Res. Lett. 26 (1999) 2081–2084.

[9] S.S. Puntodewo, R. McCaffrey, E. Calais, Y. Bock, J. Rais, C. Subaraya, R. Poewariardi, C. Stevens, J. Genrich, Fauzi, P. Zeick, S. Wdowinski, GPS measurements of crustal deformation within the Pacific–Australia plate boundary zone in Irian Jaya, Indonesia, Tectonophysics 237 (1994) 141–153.

[10] S.-B. Yu, L.-C. Kuo, S. Punongbayan, E.G. Ramos, GPS observation of crustal deformation in the Taiwan Luzon region, Geophys. Res. Lett. 26 (1999) 923–926.

[11] J. Genrich, J.Y. Bock, R. McCaffrey, E. Calais, C. Stevenson et al., Accretion of the southern Banda arc to the Australian plate margin determined by Global Positioning System measurements, Tectonics 15 (1996) 288–295.

[12] C. Boucher, Z. Altamimi, P. Sillard, The 1997 International Terrestrial Reference Frame (ITRF97), IERS Technical Note 27, Observatoire de Paris, Paris, 1999.

[13] M. Rothacher, L. Mervart, Bernese GPS Software Version 4.0, Astronomical Institute, University of Bern, Bern, 1996.

[14] D. Angermann, G. Baustert, R. Galas, Z.H. Zhu, EPOS.P.V3 (earth parameter and orbit system), Software user manual for processing of GPS networks, STR. 97/14, GFZ Potsdam, 1997.

[15] R.W. King, Y. Bock, Documentation for the GAMIT GPS software analysis version 9.9, Mass. Inst. Technol., Cambridge, MA, 1999.

[16] G. Blewitt, et al., GPS geodesy with centimeter accuracy, in: E. Groten, R. Strauss, (Eds.), Lecture Notes in Earth Sciences, Springer-Verlag, New York, 1998.

[17] P. Wilson, J. Rais, Ch. Reigber, E. Reinhart, B.A.C. Ambrosius, X. Le Pichon, M. Kasser, P. Suharto, Dato' Abdul Majid, Dato' Paduka Awang Haji Othoman Bin Haji Yaakub, E. Almeda, The GEODYSSEA project: An investigation of the geology and geodynamics of South and South-East Asia, EOS 79 (1998) 548–549.

[18] C. Rangin, X. Le Pichon, S. Mazzotti, M. Pubellier, N. Chamot-Rooke, M. Aurelio, A. Walpersdorf, R. Quebral, Plate convergence measured by GPS across the Sundaland/Philippine Sea plate deformation boundary: Philippines and eastern Indonesia, Geophys. J. Int. 139 (1999) 296–316.

[19] G.W. Michel, M. Becker, D. Angermann, C. Reigber, E. Reinhart, Crustal motion in E- and SE-Asia from GPS measurements, Earth Planets Space 52 (2000) 713–720.

[20] C.R. De Mets, R.G. Gordon, D.F. Argus, S. Stein, Effects of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, Geophys. Res. Lett. 21 (1994) 2191–2194.

[21] M.G. Kogan, G.M. Steblov, R.W. King, T.A. Herring, D.I. Frolov, S.G. Egorov, V.Y. Levin, A. Lerner-Lam, A. Jones, Geodetic constraints on the rigidity and relative motion of Eurasia and North America, Geophys. Res. Lett. 27 (2000) 2041–2044.

[22] N. Chamot-Rooke, X. Le Pichon, GPS determined eastward Sundaland motion with respect to Eurasia confirmed by earthquakes slip vectors at Sunda and Philippine trenches, Earth Planet. Sci. Lett. 173 (1999) 439–455.

[23] R. McCaffrey, Slip vectors and stretching of the Sumatran fore arc, Geology 19 (1991) 881–884.

[24] R. Hall, Reconstructing Cenozoic SE Asia, in: R. Hall, D.J. Blundell (Eds.), Tectonic Evolution of SE Asia, Geol. Soc. Spec. Publ. 106, 1996, pp. 153–184.

[25] J.-Y. Royer, R.G. Gordon, C. De Mets, P.R. Vogt, New limits on the motion between India and Australia since chron 5 (11 Ma) and implications for lithospheric deformation in the Equatorial Indian Ocean, Geophys. J. Int. 129 (1997) 41–74.