NASA-CR-191319

137056
P.16

Plate Tectonics from VLBI and SLR Global Data

Final Report:
May 1992.
Grant: NAG 5–741

Christopher G. A. Harrison,
Principal Investigator

Stefano Robaudo,
Investigator

Rosenstiel School of Marine and
Atmospheric Science
University of Miami

Rickenbacker Causeway
Miami, Fl 33149
(305) 361-4662

N93-14913

(NASA-CR-191319) PLATE TECTONICS
FROM VLBI AND SLR GLOBAL DATA Final
Report (Miami Univ.) 16 p

Unclas

G3/46 0137056

NSTIF

Introduction

This study is based on data derived from fifteen years of observations of the SLR network and six years of the VLBI network. In order to use all available information VLBI and SLR global data sets were combined in a least squares fashion to calculate station horizontal velocities (Ward, 1991; Robaudo and Harrison 1990). All significant data pertaining to a single site contribute to the station horizontal motion. The only constraint on the solution is that no vertical motion is allowed. This restriction does not greatly affect the precision of the overall solution given the fact that the expected vertical motion for most stations, even those experiencing post glacial uplift, is well under 1 cm/yr. Since the average baseline is under 4,000 km., only a small fraction of the station vertical velocity is translated into baseline rates so that the error introduced in the solution by restricting up-down station movement is minimal. As a reference, station velocities were then compared to the ones predicted by the NUVEL-1 geological model of DeMets et al. (1990).

The focus of the study is on analysing these discrepancies for global plate tectonics as well as regional tectonic settings. The method used also allows us not only to derive horizontal motion for individual stations but also to calculate Euler vectors for those plates that have enough stations located on the stable interior like North America, Pacific, Eurasia, and Australia.

Results

The approach used in this study of combining and integrating both VLBI and SLR data sets to calculate individual station horizontal velocities made it possible to look at some new aspects of global and regional plate tectonic processes. Because of the particular method of data analysis it was possible to calculate, exclusively using space-based data, some of the relative Euler vectors between several major plates. The results indicate a discrepancy between space-based and geologically derived rotational rates for the relative Euler poles analyzed. While the rate difference in the case of the North American-Pacific is only 3%, for the North America-Australian and the North American-Eurasian poles this difference is over 10%. Furthermore the North American-Eurasian relative pole as calculated from SLR-VLBI data lies much closer to the Mid Atlantic Ridge than the pole given by the NUVEL-1 model (DeMets et al., 1990) resulting in a total opening across the mid-Atlantic ridge which is slower by 15%. The indication is that space-based data are recording a slower extensional rate across spreading ridges than the one used by the geological model. An additional piece of evidence that this may be the case is given by the analysis of horizontal motion for the station of Easter Island which lies on the Nazca plate, about 200 km east of the East Pacific Rise spreading ridge. This site shows a horizontal velocity with respect the the Pacific plate which is 19±2.8 mm/yr slower than the one predicted by the NUVEL-1 model.

By using space-based data it was also possible to obtain a complete relative rotation vector between Eurasia and the Adriatic block, a separate microplate in the complicated tectonic setting of the Mediterranean region. The space-based pole location (45°N, 5°E) agrees well with the position derived from purely geological data (46°N, 10.2°E) but here it was also possible to calculate the magnitude of the vector.

Individual station horizontal velocities have also been analyzed. Particular attention has been placed on those stations behind island arcs (Arequipa, Simosato, Kashima, Shanghai, and Yakataga). These sites all show abnormal velocities, that is the space-based velocity is quite different from the one predicted by the geological model. The analysis indicates that their additional motions are in the same direction as the vector representing the relative subduction rate between the overriding plate where the station lies, and the oceanward subducting plate. What the results suggest is that strain in a subduction environment is not completely taken up at the trench but is carried over, at least in part, onto the overriding plate. The inter-relation between the station additional velocity and the subduction vector can be used to determine on what plate a station belongs. As in the case of the station of Kashima the results of this study indicate that the site is more influenced by a Eurasia-Pacific plate interaction than a North America-Pacific interaction suggesting that Kashima is more likely to belong to the Eurasian plate.

Finally, the influence of the subducting plate is not only limited to the areas close to the trench axis but, as in the case of the results to the station of Shanghai, can extend to 800 kilometers in the plate interior. A direct consequence of this phenomenon is the failure of the *rigid plate* assumption in such sensitive areas which raises the question of how far from the trench it is safe to assume such a *rigid* behavior.

References

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, 1990. Current plate motions. *Geophys. J. Int.*, 101, 425–478.

C. G. A. Harrison, S. Robaudo, 1990. SLR and VLBI results from back arc stations, *EOS*, 71, 860

Ward Steven, 1991. Pacific-North America plate motion; new results from very long baseline interferometry. *J. Geophys. Res.*, 95, 21965–21981.

Presentations, Talks, and Publications

C. G. A. Harrison, S. Robaudo, 1990. SLR and VLBI results from back arc stations, *EOS*, 71, 860

S. Robaudo and C. G. A. Harrison, 1990. New methods of precise positioning for plate tectonics. *International Symposium on Marine Positioning proceedings, ed. G. Maul,* 93-104.

S. Robaudo and C. G. A. Harrison, 1990. Plate tectonics from SLR and VLBI results, *EOS*, 71, 1278.

S. Robaudo, 1992. Plate tectonics from SLR and VLBI results. *Master Thesis. University of Miami.*

S. Robaudo and C. G. A. Harrison, 1992. Are there discrepancies between space based and geological observations of spreading rates? *EOS* 73 suplement, 80.

S. Robaudo and C. G. A. Harrison, 1992. New results from space based geodetic techniques on deformation close to plate boundaries. *IGC*, Kyoto, August abstracts.

SLR and VLBI results for back arc stations

C G A Harrison and Stefano Robaudo (Rosenstiel School of Marine & Atmospheric Science, Univ. of Miami, Miami, FL 33149)

We have previously found that Satellite Laser Ranging to Lageos gives very accurate relative positions of the SLR stations, such that useful comparisons may be made between SLR results and plate tectonics results. Overall there is very good agreement between the two data sets. However, we have found discrepancies between the two data sets, especially for stations located behind island arcs. In several cases we have found that these stations are influenced by the motion of the oceanic plate on the other side of the trench. In other words, if the motion of these stations is calculated relative to the continental plate on the landward side of the trench, their motion is in the direction of the relative motion between the two plates on either side of the trench. The amount of motion relative to the plate behind the island arc is usually a few cm/yr, or a few percent of the rate of convergence between the two plates on either side of the trench.

Since the number of SLR stations which lie close to trenches is limited, we have expanded our analysis to include VLBI data. These new data will be discussed and compared to geological evidence for back arc strain indications.

1. 1990 WPGM
2. 000577525(AGU)
3. (a) Chris Harrison
   U of Miami, RSMAS/MGG
   4600 Rickenbacker Cswy.
   Miami, FL 33149
   (b) 305-361-4610
4. G
5. G01 Space Geodetic and Observatory Measurements for Earthquake and Tectonic Studies
6. 30%
7. Charge $50 to C G A Harrison
   Southeast Bank
   MC 5239 0000 0490 5305
   Exp 05/91
8. C
9. None

Plate Tectonics from SLR and VLBI Results

Stefano Robaudo and Chris Harrison (Rosenstiel School of Marine & Atmospheric Science, Univ. of Miami, Miami, FL 33149)

By combining VLBI and SLR observations, we can obtain better estimates of plate tectonic motions than by using either method separately. Because the number of stations is limited on most of the plates it is only possible to determine relative motions between the Pacific, North American and Eurasian plates. When performing the analysis, we have used information from stations on other plates because this can help constrain the motion of these three plates, provided that the other stations have significant numbers of observations to them. Each additional station added to the analysis requires two more velocity estimates, so that if the number of observations to this station exceeds two, additional information is given for the motions of the three plates under consideration. In determining the relative motions between the three plates we use rotation poles which best describe the individual motions of those stations which are located far from the plate boundaries or which show no evidence of non-rigid plate behavior.

We have compared our results with those determined by DeMets et al. (1990) from sea floor spreading, fracture zones and earthquakes (the NUVEL-1 model). We find that in the case of North American - Eurasian motion, the space based techniques give a pole which is significantly different than that in the NUVEL-1 model. The actual amount of the discrepancy is fairly small (about 10%). In the case of the North American - Pacific motion, the space based techniques give results which are marginally different from those in the NUVEL-1 model. Possible reasons for these discrepancies will be discussed.

1. 1990 Fall Meeting
2. 000577525(AGU)
3. (a) Chris Harrison
   U of Miami, RSMAS/MGG
   4600 Rickenbacker Cswy.
   Miami, FL 33149
   (b) 305-361-4610
   (b) 305-361-4632 (Fax)
4. G
5. (b) 1209 Crustal movements
   (b) 8155 Plate motions, past and present
6. Oral
7. 30% at 1990 WPGM
8. Charge $30 to C G A Harrison
   Southeast Bank
   MC 5239 0000 0490 5305
   Exp 05/91
9. C
10. None
11. Yes

Are There Discrepancies Between Space Based and Geological Observations of Spreading Rate?

Stefano Robaudo and Chris Harrison (Rosenstiel School of Marine & Atmospheric Science, Univ. of Miami, Miami, FL 33149)

Results for horizontal velocities based on combining information from SLR and VLBI techniques show a tendency for the rate of motion between plate pairs to be smaller than the one given by the NUVEL–1 geological model. In order to study this, we looked at the North American-Eurasian relative motion, since both plates have a reasonable number of SLR and VLBI stations with a good tracking history. The space-based data for this plate pair indicate a slower spreading rate across the Mid-Atlantic ridge compared to the one given by the geologic model. To further investigate the problem we then looked at individual SLR chords separately from the VLBI baseline and transverse rates for those station pairs which lie in the stable plate interior. The SLR data showed a generally slower rate of motion across the plate boundary, but this was found to be due to a few chords with very small formal errors, and with significantly slower rates than the other data. The very small errors meant that these data were given very large weights in the inversion process. On removal of these outliers, the SLR individual rates, connecting three North American stations to seven Eurasian sites show good agreement with the rates predicted by NUVEL–1. On the other hand the VLBI rates between four North American and two Eurasian stations are significantly slower than those given by the geological model.

Because the error associated with the two space-based techniques is comparable, and the station horizontal velocities are obtained from a weighted least squares inversion of the combined data set, the North American-Eurasian Euler pole results are a reflection of the slower VLBI rates.

1. 1992 Spring Meeting
2. 000577525
3. (a) Chris Harrison
   U of Miami, RSMAS/MGG
   4600 Rickenbacker Cswy.
   Miami, FL 33149
   (b) 305-361-4610
   (b) 305-361-4632 (Fax)
4. G
5. (a)
   (b) 1209 Crustal Movements
6. Oral if possible
7. 0%
8. Charge $50 to C G A Harrison
   Southeast Bank
   MC 5239 0000 0490 5305
   Exp 05/93
9. C
10. None
11. No

New Results from Space Based Geodetic Techniques on Deformation Close to Plate Boundaries

Stefano Robaudo and Chris Harrison (Rosenstiel School of Marine & Atmospheric Science, Univ. of Miami, Miami, FL 33149)

We have used Very Long Baseline Interferometry and Satellite Laser Ranging techniques to study deformation associated with plate boundaries. It has been noticed that space geodetic stations located behind island arcs show movement relative to the plate interior. This has been quantified in five different places, Kashima and Simosato in Japan, Arequipa in Peru, Yakataga in Alaska and Shanghai in China. The results show that the relative horizontal deformation, which is defined as the rate of movement of the station with respect to the plate interior divided by the rate of movement of the subducting plate with respect to the overriding plate, is dependent on the distance from the trench axis. A length scale can be defined, but the results depend greatly on the rather sparse data from the VLBI station in Shanghai. If these data are used then the length scale for deformation is about 590 km. If the Shanghai data are omitted, then the length scale becomes about 174 km.

We have also attempted to look at deformation across a different type of plate boundary, this time a fracture zone. There are quite a few VLBI stations located close to the San Andreas fault, and an attempt has been made to look at deformation length scales in this region as well, using space based data. It is obvious that the deformation length scale is much less for this transform boundary than for the subduction boundary data described above.

1. 1992 Western Pacific
2. 000577525
3. (a) Chris Harrison
   U of Miami, RSMAS/MGG
   4600 Rickenbacker Cswy.
   Miami, FL 33149
   (b) 305-361-4610
   (c) 305-361-4632 (Fax)
   (d) internet cgh@pinet.aip.org
4. G
5. (a)
   (b) 1209 Crustal Movements
6. Oral if possible
7. 10% at 1990 Spring Meeting
8. Charge $50 to C G A Harrison
   Southeast Bank
   MC 5239 0000 0490 5305
   Exp 05/93
9. C
10. None
11. No

1 of 12

New Methods of Precise Positioning for Plate Tectonics

Stefano Robaudo and Christopher G. A. Harrison
Rosenstiel School of Marine and Atmosheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, Florida 33149

Abstract

Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) are two new space based geodetic techniques. Since the time of the last INSMAP Conference (1986) the accuracy of these methods has improved such that repeat measurements of position of individual observatories can be used to determine relative observatory position changes with an accuracy of 1 cm/yr or even less for observatory pairs with good recording and a long history of observation. These relative station movements can be compared with those predicted by geological plate tectonic models. In this paper we describe briefly a comparison of movement for stations located behind subduction zones. It is shown that the three stations with available space based information (Simosato and Kashima in Japan and Arequipa in Peru) all show strain with respect to the plate behind the subduction zone, and that the direction of relative motion of the stations with respect to this plate is close to the direction of relative motion of the subducting plate beneath the plate behind the subduction zone. In the case of Simosato, the amount of motion of this station with respect to Eurasia is almost the same as that of the Philippine plate (the subducting plate), indicating that most of the strain between these two plates in this location is occurring to the west of Simosato.

Introduction

The traditional approach to plate tectonic modeling has been to invert global data sets derived from the geologic record (Chase, 1978; Minster and Jordan, 1978; DeMets et al., 1990). This gives information about plate motion averaged over a period of 3-5 My, depending on the age of the magnetic anomaly used to measure separation rates at ridge crests. A more recent approach has used space-based geodetic data to measure directly plate motion on a three to five years time scale. Several authors (Douglas, 1988; Harrison and Douglas, 1990; Smith et al., 1990) have compared the two approaches and have reported a correlation coefficient on the order of 0.9 or larger. Such a good correlation has helped to establish space-based geodesy as a powerful tool to investigate crustal deformations. These space-based techniques consist of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS).

VLBI uses a network of radio telescopes to observe and record simultaneously signals from distant quasars. A complete treatment of this method can be found in Rogers et al. (1983) and Clark et al. (1985). Measurements derived from VLBI give, among other geodetic information, the rates of change for baseline, transverse, and vertical length (see Figure 1) between pairs of stations. The accuracy reached by this technique is on the order of few mm/yr for frequently observed baselines.

SLR uses a laser station to range to an orbiting target satellite (e.g. LAGEOS) equipped with laser retroreflectors. Ranges from several stations to the same satellite over a period of a few years are integrated to derive a global solution (Coates et al., 1985). How the raw data are reduced and analyzed to produce a global solution is treated in Smith et al. (1985) and, for a more recent solution, in Smith et al. (1990). A typical SLR solution would give the rate of change of the geodetic baseline (see Figure 1) between pairs of stations. The error associated with this type of measurement is close to 1 cm/yr.

The GPS technology has only recently begun to be utilized for crustal deformation studies (Davis et al., 1989). Although repeatability (Bock et al., 1986; Davison et al., 1987) and good agreement with VLBI results (Blewitt, 1989; Larson, 1989; Dong and Bock, 1989) have been achieved for short baseline experiments, there is still much work to be done for longer baselines. In fact the uncertainties associated with long-time experiments covering a widely spaced network of stations do not permit use of this method as a tool to investigate global plate tectonics at this time. Nevertheless GPS shows the potential of becoming a very precise geodetic technique as more studies and data are collected in the forthcoming years.

In this paper we use VLBI baseline and transverse rates of change and SLR geodetic baseline rates to calculate stations velocities. By combining both data sets all available information to one particular station is used so that better velocities are obtained. The results are compared with the NUVEL-1 geological model (DeMets et al., 1990) and some of the discrepancies are then discussed.

Data and Method of Analysis

The data used in this study were obtained from the NASA Crustal Dynamic Data Information System (CDDIS) which stores VLBI and SLR data from the global network of stations. In particular we analyzed VLBI baseline and transverse rates from 1984 to 1990 and SLR arc rates derived from an early version of the SL7.1 solution (Smith et al., 1990) covering the period from 1978 to 1988. Overall a total of 324 rates connecting 54 stations on 7 different plates was used.

A modified version of the method developed by Ward (1990) was chosen to combine SLR arc-rates and VLBI baseline and transverse rates. In the analysis a set of linear equations relate the observed rates of change between two stations to unknown east and north velocities at those stations. This relationship is based on geometric functions dependent on the location of each pair of stations i and j on the earth's surface. Equations for the baseline B_{ij} and transverse T_{ij} are of the form

$$B_{ij} = \hat{b}_{ij} \cdot \hat{n}_i \cdot N_i + \hat{b}_{ij} \cdot \hat{e}_i \cdot E_i - \hat{b}_{ij} \cdot \hat{n}_j \cdot N_j - \hat{b}_{ij} \cdot \hat{e}_j \cdot E_j \tag{1}$$

$$T_{ij} = \hat{t}_{ij} \cdot \hat{n}_i \cdot N_i + \hat{t}_{ij} \cdot \hat{e}_i \cdot E_i - \hat{t}_{ij} \cdot \hat{n}_j \cdot N_j - \hat{t}_{ij} \cdot \hat{e}_j \cdot E_j \tag{2}$$

where $\hat{b}$ and $\hat{t}$ are the the unit vectors in the chord and transverse direction while $\hat{n}$ and $\hat{e}$ are the unit vectors in the north and east direction at the stations i and j. N and E are the unknown north and east velocities at each station. For VLBI inversions we have assumed that the vertical motion at each station is zero. Since SLR gives geodetic arc rates equations of the type (1) and (2) change to

$$A_{ij} = \hat{c}_{ij} \cdot \hat{n}_i \cdot N_i + \hat{c}_{ij} \cdot \hat{e}_i \cdot E_i + \hat{c}_{ji} \cdot \hat{n}_j \cdot N_j + \hat{c}_{ji} \cdot \hat{e}_j \cdot E_j \qquad (3)$$

where

$$\hat{c}_{ij} = \frac{(P_i \times P_j) \times P_i}{|(P_i \times P_j) \times P_i|} \qquad (4)$$

$$\hat{c}_{ji} = \frac{(P_j \times P_i) \times P_j}{|(P_j \times P_i) \times P_j|} \qquad (5)$$

The unit vectors $\hat{c}_{ij}$ and $\hat{c}_{ji}$ are necessarily different since the arc vector takes a different direction at each end of the arc.

The total set of equations can be reduced to matrix form as

$$\mathbf{r} = \mathbf{G}.\mathbf{v} \qquad (6)$$

where **r** is the observed rate of change, **G** is the matrix geometric function and **v** is the vector of unknown north and east velocities for each station. The weighted velocity vector, **v**, is calculated by operating a least squares inversion after dividing the **r** and **G** terms in (6) by the respective observational error of the **r** term. In order to compare the space-based model with the NUVEL-1 model we fixed the North American plate and calculated the velocities of the stations relative to this reference plate. First the Euler vector for the North American plate was calculated with a least squares procedure and then this motion was subtracted from the motion of every station. The stations chosen as representative of a stable North American plate are Fort Davis, Yuma, Fairbanks, Greenbelt, and Westford.

Results

A comparison of site velocities obtained from SLR and VLBI data with the NUVEL-1 model shows some significant discrepancies. The focus of the discussion will be only on those stations behind island arcs which show abnormal motion and in particular the two Japanese stations of Simosato and Kashima and the South American site of Arequipa.

Located in the Kii peninsula the SLR station of Simosato belongs on the Eurasian plate (Chapman and Solomon, 1976; Seno, 1985). South of Simosato is the Nankai Trough where the Philippine plate is subducting under the Eurasian plate. The space-based velocity for Simosato shows a motion of 23 ± 4 mm/yr with a bearing of 314°E; a substantial difference from the 12 mm/yr at 89°E velocity predicted by the NUVEL-1 model (see Figure 2). The overall discrepancy between SLR-VLBI data and NUVEL-1 amounts to 33 ± 4 mm/yr at 300°E (this is the motion of Simosato relative to the Eurasian plate) and is significant at the 95% confidence level (see Figure 3). The direction of this velocity is only 10° clockwise from the direction of relative motion beween the Philippine and the Eurasian plates (see Figure 3). Also the amount of motion with respect to Eurasia is very close to that of the subducting Philippine plate (Table 1). The results for Simosato confirm the previous conclusions by Harrison and Douglas (1990) who have this station moving with a velocity of 37 mm/yr at 294°E relative to Eurasia.

The VLBI station of Kashima lies on the East coast of Honshu, north-east of Simosato and west of the Japan Trench. The placing of Kashima on a tectonic plate is still under debate (Heki et al., 1987). Some authors have this site on the North American plate (Chapman and Solomon, 1976) while others place it on the Eurasian tectonic plate (Seno, 1985). For the purpose of our discussion we consider Kashima as belonging to the Eurasian plate. The SLR-VLBI model indicates a motion of 8 ± 2 mm/yr in a direction of 323°E. in net contrast with the 11 mm/yr, 85°E motion predicted by DeMets et al. (1990) (see Figure 4). The vector difference between the SLR-VLBI and NUVEL-1 shows a motion of 16 ± 2 mm/yr at 289°E (i.e. relative to Eurasia) which is significant at the 95% confidence level (see Figure 5). As in the case of Simosato the additional motion of Kashima is remarkably close to the direction of subduction between the Pacific and Eurasian plates which has a 294°E bearing (see Figure 5). .

The Peruvian station of Arequipa is situated in a tectonically active area. To the west of Arequipa the Nazca plate is subducting the South American plate at the Peru-Chile Trench with a bearing of 77°E. The site velocity of 9 ± 3 mm/yr is only 2 mm/yr faster than the one predicted by NUVEL-1, but the difference of 138° in motion direction is clearly noticeable (see Figure 6). Overall the Arequipa velocity is 15 ± 3 mm/yr at 87°E with respect to South America, very close to the direction of relative motion between the two plates (see Figure 7). Even if the north and east velocity errors for this station are bigger than those of the previous two sites, its resultant velocity lies well out of the 95% confidence level. Therefore we are confident in saying that Arequipa has a substantial additional motion toward the East.

Discussion

A summary of the results from the three stations behind subduction zones is shown in Table 1. A fourth station, Mazatlan, is north of the north boundary of the Riviera plate (Johnson and Harrison, 1989). Here, the North American plate stretches westward to the East Pacific Rise, indicating that Mazatlan should be stationary with respect to the North American reference frame, and the SLR results for this station indicate that this is indeed the case. A fifth station, Yakataga, lies behind the Alaska subduction zone. At the present time we do not have enough data to determine accurately whether Yakataga is moving with respect to North America, or its possible direction of motion.

Table 1
Station Motions Behind Trenches

Station/Plate	Subducting Plate	Station Motion		Relative Plate Motion	
		Rate, mm/yr	Direction, °E	Rate, mm/yr	Direction, °E
Simosato/Eurasia	Philippine	33	300	41	310
Kashima/Eurasia	Pacific	16	289	87	294
Arequipa/S. America	Nazca	15	87	81	77

Conclusions

Using satellite geodetic techniques like SLR and VLBI it is now possible to measure crustal deformations with good precision. The results obtained from 4-5 years of observations using these techniques are mostly similar to those derived from seafloor spreading rates and directions and earthquake studies, with some exceptions. SLR and VLBI data from a world-wide network of stations were combined to derive site relative velocities with respect to a fixed North American plate. By comparing these velocities with the NUVEL-1 model, some significant discrepancies were found. In particular three stations, Simosato, Kashima and Arequipa, which are landward of active subduction areas show abnormal motions. The bearing of these abnormal velocities is in the same general direction of motion of the subducting plates with respect to the overriding plates, suggesting that strain is not all taken up at the trench but some of the velocity of the subducting plate is carried over onto the overriding plate. In the case of Simosato, the additional velocity of this site is almost equal to the subducting rate of the Philippine under the Eurasian plate. This is an indication that most of the strain between the Philippine and Eurasian plates is probably occurring to the west of Simosato.

Acknowledgements

We thank David Smith, Nancy Douglas, Carey Noll and other scientists involved with the NASA Crustal Dynamics Project for the excellent data generated by the project. Research supported by NASA grant NAG 5-741. Contribution from the University of Miami, Rosenstiel School of Marine and Atmospheric Science.

References

Blewitt, G., 1989. *Carrier phase ambiguity resolution for the Global Position System applied to geodetic baselines up to 2000 Km.* J. Geophys. Res., 94, 10,187-10,203

Bock, Y., R. I. Abbot, C. C. Counselman III, and R. W. King, 1986. *A demonstration of 1-2 parts in* 10^7 *accuracy using GPS.* Bull. Geod., 90, 241-254

Chapman, M. E., and S. C. Solomon, 1976. *North American-Eurasian plate boundary in north-east Asia.* J. Geophys. Res., 81, 921-930

Chase, C. G., 1978. *Plate Kinematics: the Americas, East Africa, and the rest of the world.* Earth and Planet. Sci. Lett., 37, 353-368

Clark, T. A., et al., 1985. *Precision geodesy using the Mark III very-long-baseline interferometer system.* IEEE Trans. Geosci. Remote Sens., GE-23, 438-449

Coates, R. J., H. Frey, J. Bosworth, and G. D. Mead, 1985. *Space age geodesy: The Nasa Crustal dynamics project.* IEEE Trans. Geosci. Remote Sens., GE-23, 358-368

Davis, J. L., W. H. Prescott, J. L. Svarc, and K. J. Wendt, 1989. *Assesment of Global Positioning System measurements for studies of crustal deformation.* J. Geophys. Res., 94, 13,635-13,650

Davison, J. M. , et al., 1987. *The March 1985 high precision baseline test of the JPL GPS-based geodetic system: A final report.* JPL Publ., 87-35

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, 1990. *Current plate motions.* Geophys. J. Int., 101, 425-478

Dong, D., and Y. Bock, 1989. *GPS network analysis with phase ambiguity resolution applied to crustal deformation studies in California.* J. Geophys. Res., 94, 3949-3966

Douglas, N. B., 1988. *Satellite laser ranging and geologic constraints on plate tectonic motion.* M.S. thesis, University of Miami, FL., 187 pp.

Harrison, C. G. A., and N. B. Douglas, 1990. *Satellite Laser Ranging and geological constraints on plate motion.* Tectonics, 9, 935-952

Heki, K., F. Takahashi, T. Kondo, N. Kawaguchi, F. Takahashi, and N. Kawano, 1987. *The relative movement of the North American and Pacific plates in 1984-1985, detected by the Pacific VLBI network.* Tectonophysics, 144, 151-158

Johnson, C. A., and C. G. A. Harrison, 1989. *Thematic mapper studies of volcanism and tectonism in Central Mexico.* Adv. Space Res., 9, 85-88

Larson, K. M., 1989. *Estimates of crustal deformation in southern and central California from GPS: 1986-1989.* Eos Trans. AGU, 70, 1353

Minster, J. B., and T. H. Jordan, 1978. *Present-day plate motions.* J. Geophys. Res., 83, 5331-5354

Rogers, A. E. E., et al., 1983. *Very-long-baseline radio interferometry: The Mark III system for geodesy, astrometry, and aperture synthesis.* Science, 219, 51-54

Seno, T., 1985. *Is northern Honshu a microplate?.* Tectonophysics, 115, 177-196

Smith, D. E., D. C. Christodoulidis, R. Kolenkiewicz, P. J. Dunn, S. M. Klosko, M. H. Torrence, S. Fricke, and S. Blackwell, 1985. *A global geodetic reference frame from LAGEOS Ranging (SL5.1AP).* J. Geophys. Res., 90, 9221-9233

Smith, D. E., M. H. Torrence, J. W. Robbins, S. M. Klosko, R. G. Williamson, E. C. Pavlis, N. B. Douglas, and S. K. Fricke, 1990 *Tectonic motion and deformation from Satellite Laser Ranging to LAGEOS.* J. Geophys. Res., in press

Ward, S. N., 1990. *Pacific-North American plate motions: new results from Very Long Baseline Interferometry.* J. Geophys. Res., in press

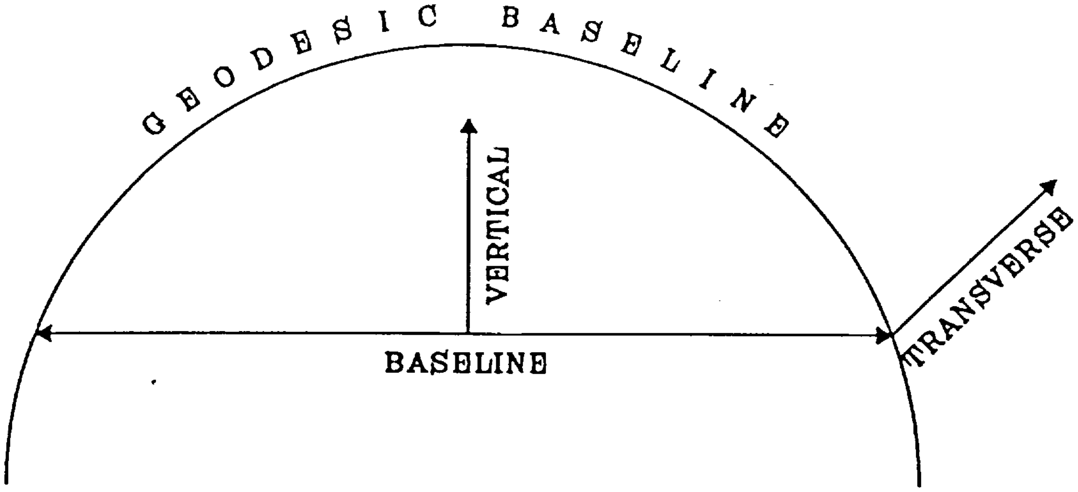

Figure 1: Geometry of the VLBI baseline, transverse, vertical, and SLR geodetic cord. The VLBI transverse is in a horizontal direction, perpendicular to the baseline

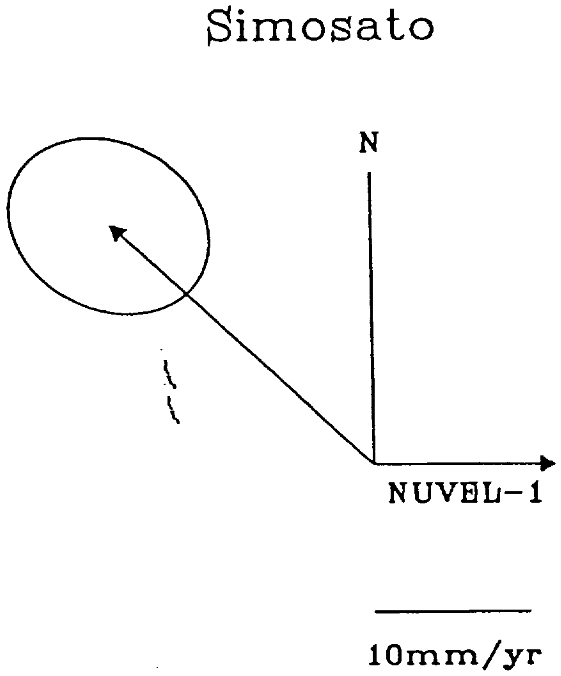

Figure 2: Motion of Simosato measured by SLR-VLBI data surrounded by a 2-sigma ellipse of confidence. NUVEL-1 shows the motion of this station as predicted by DeMets et al. (1990). Both motions are with respect to North America

[illegible] 八

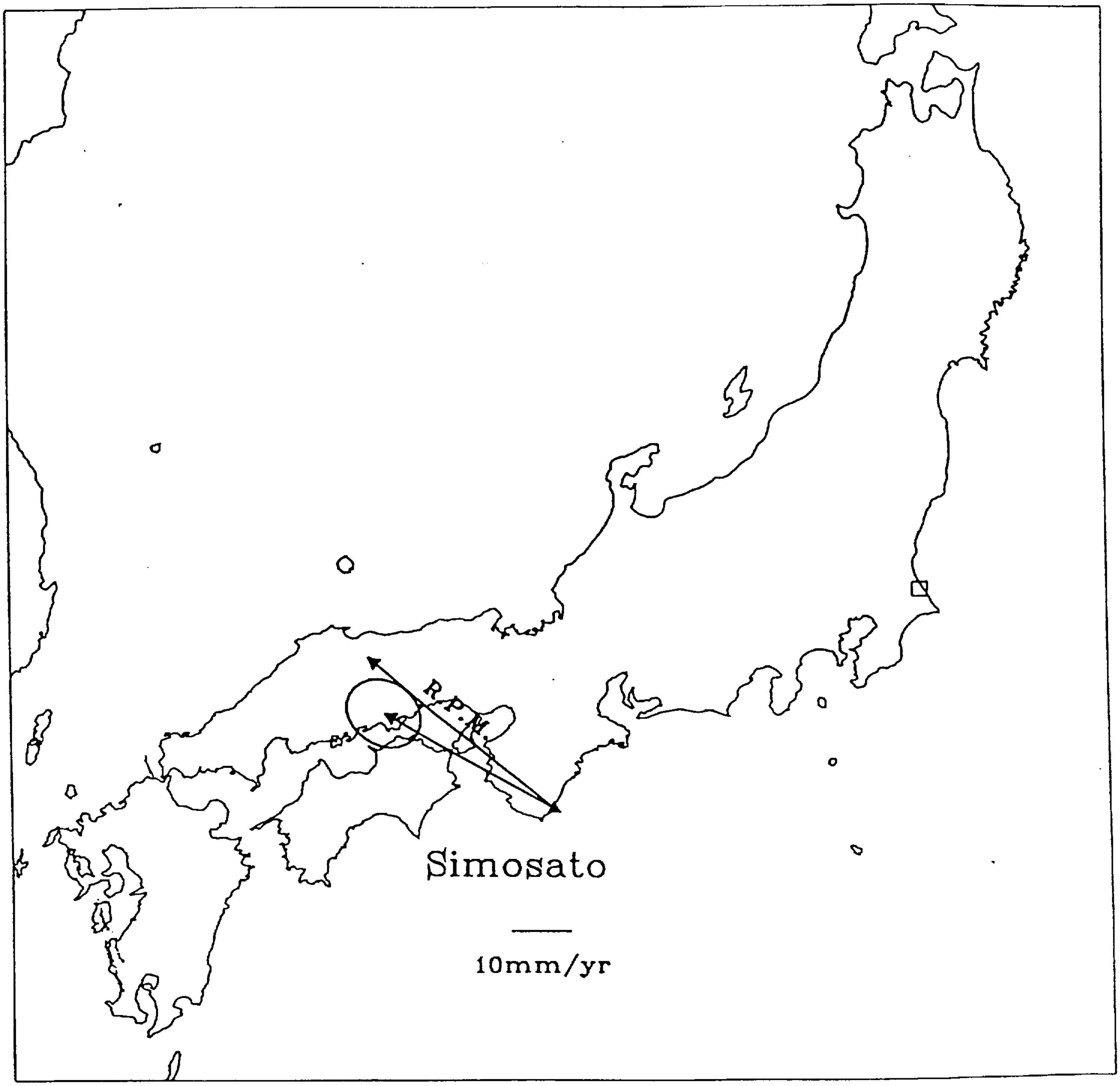

Figure 3: Motion of Simosato measured by SLR-VLBI, with respect to Eurasia. The Relative Plate Motion (R.P.M. vector) between the Philippine and Eurasian plates is also shown

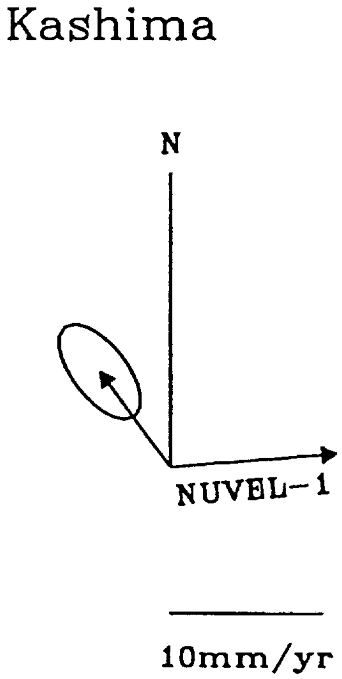

Figure 4: Same as in Figure 2, but for the Kashima station

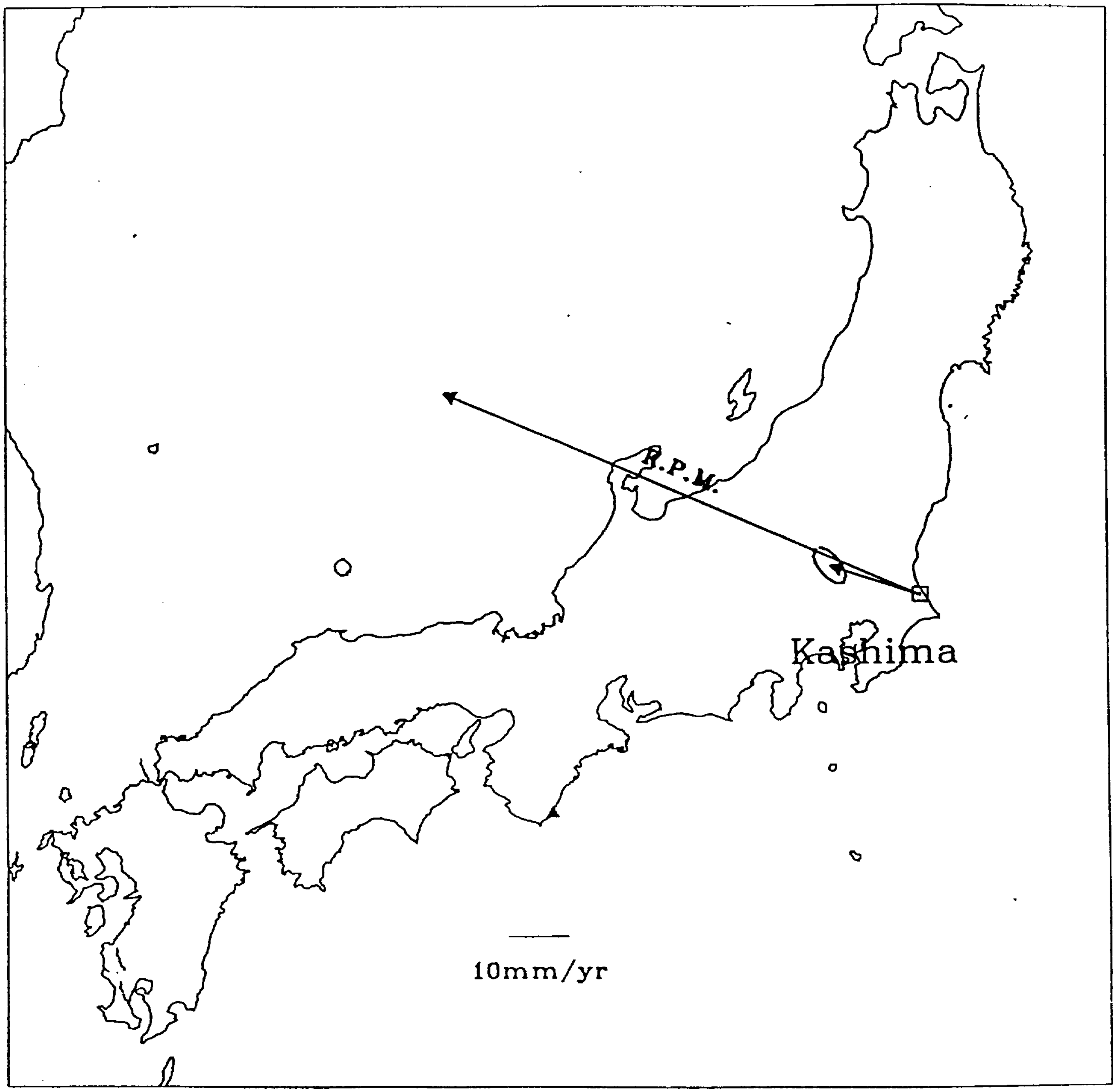

Figure 5: Same as in Figure 3, but for the Kashima station. The R.P.M. vector in this case shows the relative motion between the Pacific and Eurasian plates

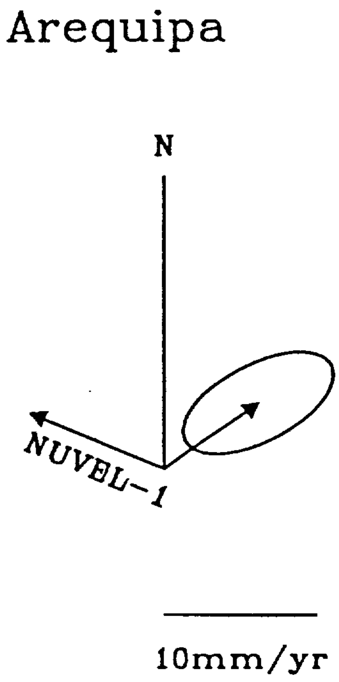

Figure 6: Same as in Figure 2, but for the station of Arequipa (Peru')

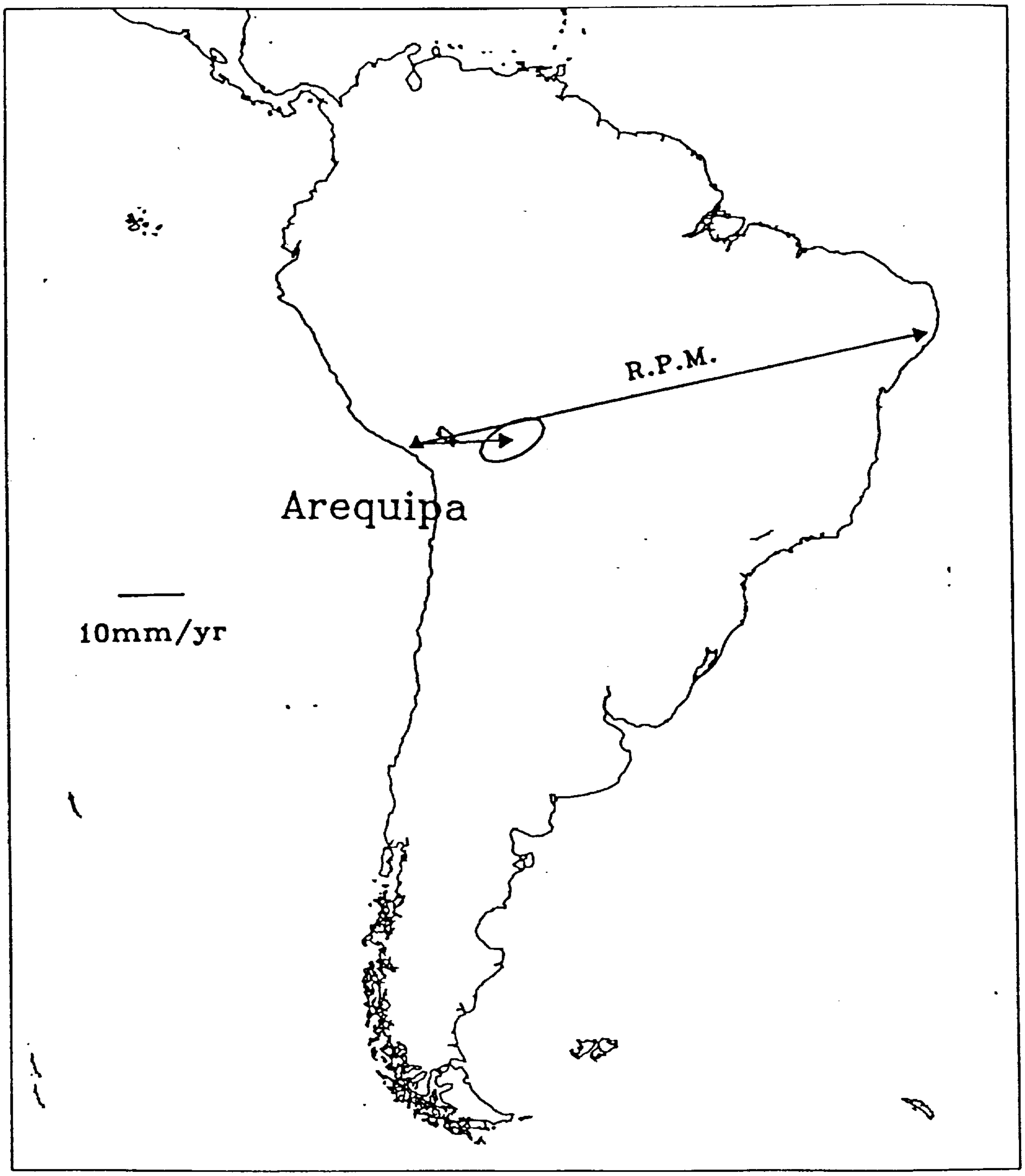

Figure 7: Same as in Figure 3, but for the Arequipa station. The R.P.M. vector indicate the relative motion between the Nazca and South American plates