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IV. EXPERIMENTAL RESULTS

IV.2 DIRECT MEASUREMENT OF PLATE MOTION

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ABSTRACT

Geodetic VLBI experiments have been performed by international cooperation since the mid 1980's using K-3 (Japan) and Mark-III (USA and all other countries) VLBI data acquisition terminals capable of determining delays with an accuracy better than 0.1 nanosecond. These experiments have revealed that current movements of the tectonic plates are almost the same as the average motion for the last few millions of years. They are also providing evidence of plate "deformation", which is of several different types: (l) deformation of island and continental arcs associated with compressional and tensional stress fields applied by subducting plates, (2) deformation of a continental plate near a transform fault and (3) earth deformation on a global scale. Future VLBI activity should concentrate on expanding the networks to the southern hemisphere and on the development of more compact and transportable data acquisition terminals to enable easier and less expensive VLBI operations.

1. Introduction

The basic concept of "plate tectonics" is that several lithospheric "plates" which cover the earth's surface are moving without significant deformation, and their mutual interaction accounts for various geophysical and geological phenomena on earth. Only a few years ago, however, this was nothing more than a hypothesis because nobody had ever directly measured the present-day movement of the plates, the most important assumption underlying the theory.

In order to directly measure plate movement of a few cm/yr, we must determine the distances between "reference points" on different plates with centimeter accuracies. It is preferable that these points are located on land and are well separated from plate boundaries where crustal deformation occurs. These conditions force us to measure distances of a few thousands of kilometers with an accuracy of a few centimeters. Two factors then become important: (1) new geodetic techniques more accurate than conventional "ground survey", and (2) geodetic experiments performed through international cooperation.

New geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) became known as "space geodesy". Among

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these, only VLBI and SLR can measure such long baselines with sufficient accuracies. International space geodetic experiments started as the Crustal Dynamics Project (CDP) conducted by the National Aeronautics and Space Administration (NASA) of USA. This project has scheduled a good number of international VLBI experiments with various station configurations. Although starting out with only American (main land and Pacific), European and Japanese stations, new VLBI stations in other regions such as Australia and China have lately been incorporated to make the networks more global.

2. First Successful Plate Motion Detected by VLBI

Japanese activity on geodetic VLBI began with development of the K-3 data acquisition system by Radio Research Laboratory (renamed to Communications Research Laboratory in 1988). This system is compatible with the Mark-III VLBI system, the worldwide standard for geodetic VLBI. Kashima Space Research Center (Kashima, Ibaraki) started to participate in international geodetic VLBI observations in 1984 as the first station equipped with a K-3 system.

Kashima is located at an important position in the Pacific portion of the international VLBI networks (Fig. 1). Because of the high plate-convergence rate at the Japan Trench, changes in distance between Kashima and Pacific stations, i.e., Kauai (Hawaii) and Kwajalein (Marshall islands), were expected to be detected easily. It was in 1985, one year after start up, that significant contraction of

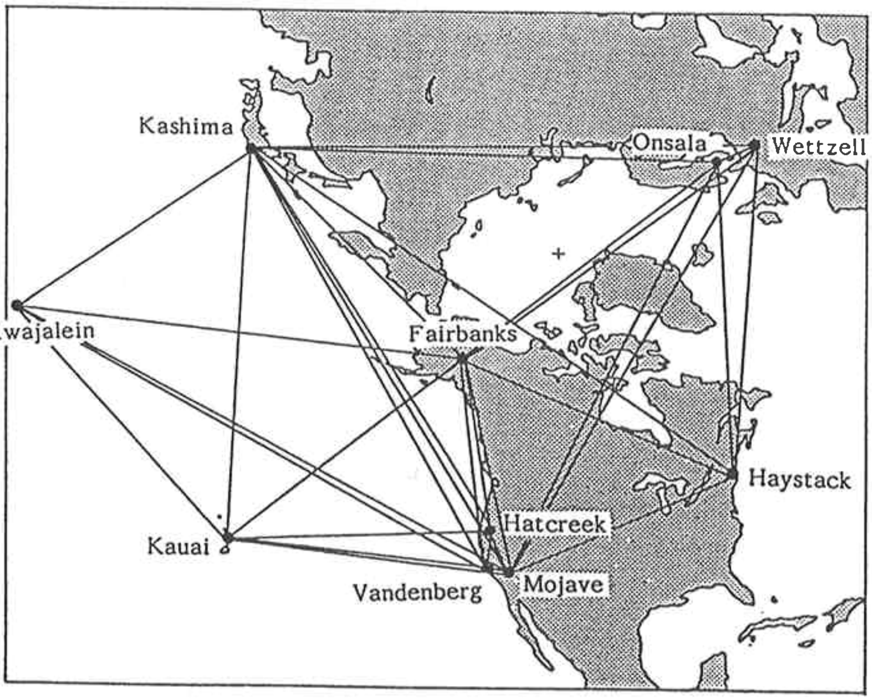


Fig. 1 VLBI stations and baselines for international experiments conducted as the Crustal Dynamics Project (CDP). This shows baselines of the experiments which Kashima VLBI station participated in.

Kashima-Kauai and Kashima-Kwajalein baselines was detected(Heki *et al.*, 1987).(1) This was one of the earliest detections of actual plate motion along with the detection of Eurasian-North American relative plate motion in terms of increasing distances between North American and European VLBI stations (Herring *et al.*,1986).(2)

Once we succeeded at detecting plate motion, our concern shifted from simple "detection" to accurate "measurement" of plate velocity. In standard plate motion models such as RM2 (Minster & Jordan, 1978)(3) and NUVEL-l (DeMets *et al.* 1985)(4) plate motion parameters are determined to best explain three kinds of observed data: ocean magnetic anomalies, slip-directions of interplate earthquakes and the stress of transform faults. Such geologic models representing the average motion over a geologic time scale (actually the last few Ma) are well established. In order to confirm not only known plate motion but also to detect differences, if any, between different time scales and to evaluate plate deformation, VLBI should at least be as precise as geological measurements of past plate motion.

3. Discussion of Changes in Baseline Length

Figure 2 shows how the lengths of several baselines have changed since 1984. The error in these rates of change, 1–2 mm/year, are small enough so that the following topics can be seriously discussed; how well these rates of change agree with geological "predictions", and how rigid can we consider the plates to be. The first question will be answered by the baselines connecting "stable" VLBI stations located on plate interiors. The second question will be answered by contrasting these stable stations to the movement of "unstable" stations located on plate boundaries.

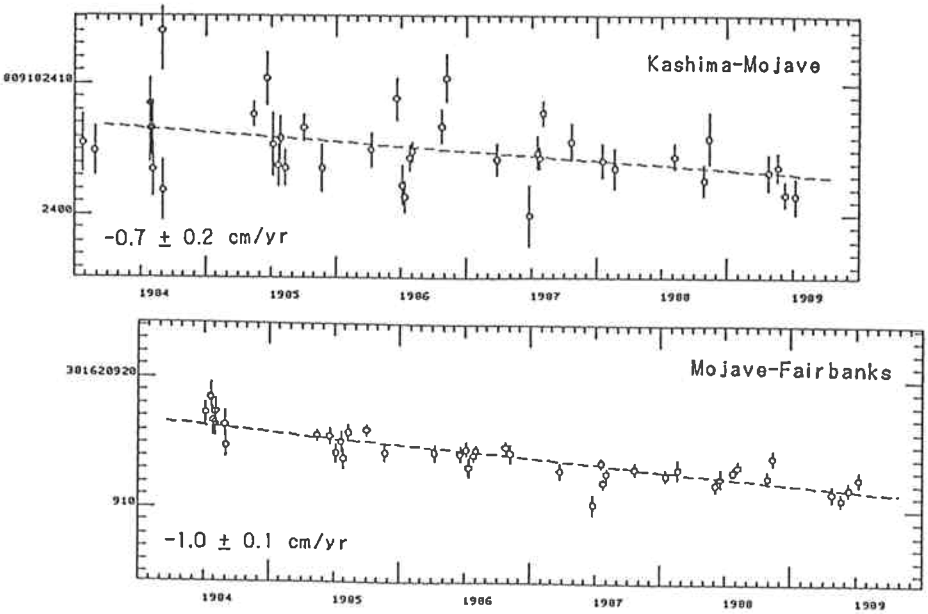
3.1. North America-Europe Baselines

American (except western USA) and European (except southern Europe) stations are free from local crustal deformation and the baselines connecting them are suitable for comparing expected and observed changes in length. These baselines are also characterized by very frequent VLBI observations performed for earth rotation monitoring as well as for crustal dynamics.

Although the overall tendency of observed changes is consistent with predictions (i.e., baselines are getting longer), the actual values are found to be deficient by about "40%" (Carter and Robertson, 1989).(5) For example, the increase in the baseline length between Westford (Massachusetts) and Wettzell (FRG) are only 13.4 ± 0.8 mm/yr (Ma *et al.*, 1989)(6) while NUVEL-l predicts it to be 18.6 mm/yr. Such a difference is not due to chance displacement of a specific station. This tendency is common for every European and American station combination.

A simple interpretation is that instantaneous relative movement parameters of the plates differ from the average over the last few Ma. The instantaneous position of the Euler pole, however, cannot differ greatly from the model because the plate motion is geometrically constrained by its boundaries. Differences in rotation rates might be possible. Changes in baseline length depend on the angular distances of the stations from the pole. If there is rotation rate deficiency, deviations in the rate of change should be proportional to predicted values (i.e., the ratio between observed and predicted rates should be constant). Figure 3a shows this relationship. Unfortunately, the predicted changes do not differ sufficiently (1.5–2.0 cm/yr) and it is not clear whether they are proportional. It has also been found that some intra-USA baselines are contracting slightly but significantly (e.g., -5.6 ± 0.4 mm/yr for Westford-Fort Davis [Texas]). This cannot be explained just by modifying plate motion parameters.

Another conceivable interpretation is the "uniform contraction" of the whole region having



(a)

Fig. 2 Plots of baseline length evolution for several of the baselines in Fig. 1. Vertical axes are baseline lengths in centimeters and horizontal axes are the time in year. Broken lines are the "best-fit" lines and errors denote one-sigma formal errors.

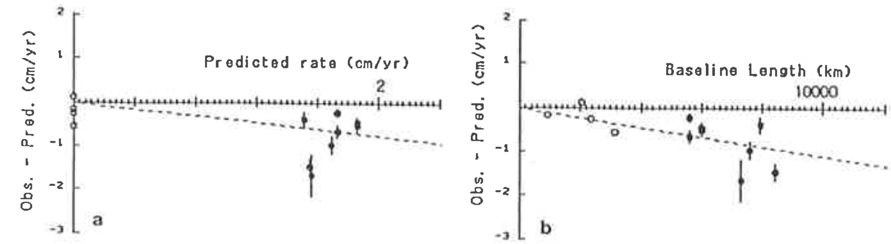


Fig. 3 Vertical axes show the difference between the rates of change in baseline length observed by VLBI and predicted by the NUVEL-1 plate motion model. Baselines are those connecting Westford, Haystack (both in Massachusetts), Richmond (Florida), Fort. Davis (Texas), Wettzell (FRG) and Onsala (Sweden) stations. Horizontal axis is the predicted rate of change in "a" and the baseline lengths in "b". If the differences are due to the plate rotation rate deficiency, they should be proportional to the predicted rates. If they are due to "uniform contraction", they should be proportional to the baseline lengths. Open and solid circles are intra- and inter-plate baselines, respectively.

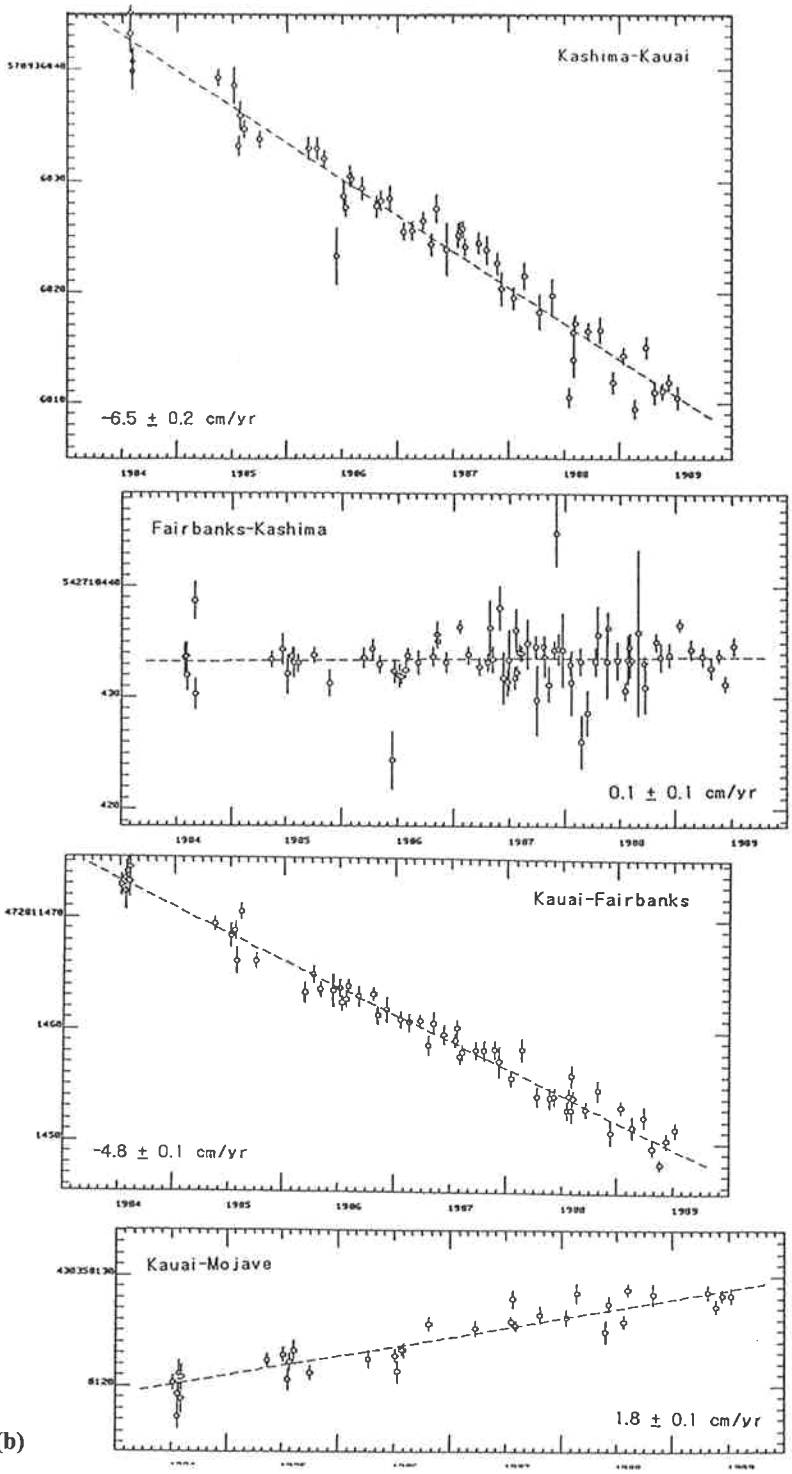

Kashima-Kauai
-6.5 ± 0.2 cm/yr
Fairbanks-Kashima
0.1 ± 0.1 cm/yr
Kauai-Fairbanks
-4.8 ± 0.1 cm/yr
Kauai-Mojave
1.8 ± 0.1 cm/yr

Fig. 2 (b)

nothing to do with plate motion. In this case, the deviations should be proportional only to the distances between the points. Figure 3b shows this relationship, where the correlation seems clearer than that of Fig. 3a. This model also explains the contraction of intra-USA baselines. However, it is not evident, at present, if this relationship is valid in the Pacific region because geologic plate-motion models are not well established there (see next section) nor are the VLBI stations located in the stable interior of the plates.

3.2. Speed of the Pacific Plate

In the Pacific region, we cannot simply compare the observed and predicted changes because most of the stations are too close to the plate boundaries. Among the circumpacific stations, Fairbanks station in central Alaska is the only station on a stable plate interior. The change in Fairbanks-Kauai baseline length is predicted to be –5.0 cm/yr by RM-2. This is higher by 10% (–4.5 cm/yr) than that of NUVEL-1. The observed slope of the best-fit line for 58 data items from 1984–1989 is -4.77 ± 0.11 cm/yr, which is just halfway between the two predictions. More baselines connecting plate interior stations will need to be measured before we can determine which model better explains instantaneous Pacific plate motion. It was recently reported that Fairbanks station is moving by 1.5 ± 0.5 mm/yr southward with respect to the more stable part of North America (Ma *et al.*, 1990).[(7)] If the contribution of this movement is taken into account, the present data becomes more favorable for the newer NUVEL-1 model.

3.3. Deformation of the Western United States

Plates have been thought to be moving without significant deformation. VLBI has the potential of detecting the displacement of a certain station with respect to a remote station. Even if the strain itself is small, displacement, a spatial integral of the strain, may be larger than the detection threshold. CDP has been measuring the deformation of the western United States by operating transportable VLBI stations at various localities.

We can see this in the Fairbanks-Mojave (southern california) baseline length (Fig. 2). These two stations are significantly approaching one another although both are on the North American plate. Horizontal velocity vectors of VLBI stations (Ma *et al.*, 1989)[(6)] in the western United States with respect to those in North American interiors are shown in Fig. 4. It can be seen that stations on the Pacific plate (west of the San Andreas Fault), which are moving northwest by about 5 cm/yr, are moving in the same direction as stations on the North American plate (east of the fault).

This suggests that mutual movement between these plates occurs not as simple displacement along a distinct boundary but as elastic-plastic "megashear" along a deformation zone as wide as a few hundreds of kilometers. At present, VLBI observation time span is much shorter than the intervals between large earthquakes and it is still unclear how permanent (plastic) or temporary (elastic) is the deformation. NASA and the NGS/NOAA VLBI group (1989)[(8)] reports co-seismic movement of stations associated with the 1989 Loma Prieta earthquake. This suggests that elastic components cannot be neglected near a fault.

3.4. Deformation in a Subduction Zone

Kashima station gives another important example of plate deformation. It is located on the outer arc of northeast Honshu, which is known as a typical island arc. About a hundred kilometers east of the station, at the Japan Trench, the Pacific plate subducts causing vigorous volcanic, seismic and

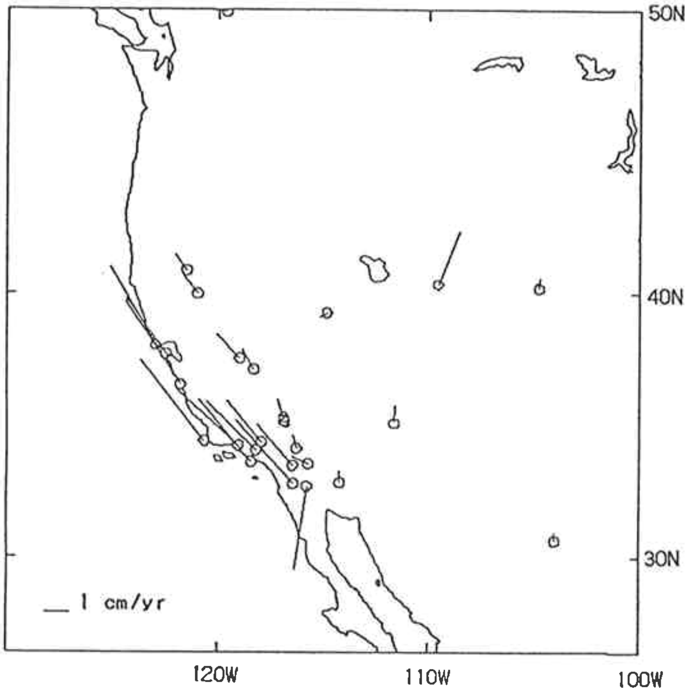


Fig. 4 VLBI stations in western United States (O) and their horizontal movements (Ma *et al.*, 1989)[(6)] with respect to the North American interior.

neotectonic activities in Japan. The subduction is applying compressional east-west stress fields in the arc, which is responsible for the active reverse faulting and folding in northeastern Japan. Such active crustal deformation will induce slow movement of the station on the outer arc in the same direction as the subducting oceanic plate (Fig. 5a), when viewed from the landward plate. Crustal shortening is smaller under the cold/strong forearc and larger under the hot/weak volcanic and back arcs. If we assume that the forearc wedge is rigid, the movement of Kashima would be as large as the rate of island arc contraction.

The movement of Kashima can be seen in the observed rates of change of the baselines between Kashima and Pacific stations. The observed change in Kashima-Kauai baseline length is –6.5 cm/yr (Fig. 2) while the predictions are –8.0 cm/yr by NUVEL-1 and –8.9 cm/yr by RM-2 (Kashima is assumed to lie on the Eurasian plate). This difference suggests deformation like that illustrated in Fig. 5a.

We can generate horizontal velocity vectors from changes in baseline length through a least-squares procedure, although the estimated vectors are dependent on "fixed" stations selected. In Fig. 6, vectors of European, Pacific and Kashima stations are estimated leaving four North American stations fixed on the North American plate; additional a-priori movements (with correspond to the deformation of the western United States, see Fig. 4) are assumed for Mojave and Hatcreek. Since these known vectors are given as viewed from the Eurasian plate, estimated vectors are viewed in the same way. The projection pole in Fig. 6 is shifted to the Eurasia-Pacific Euler pole so that the expected

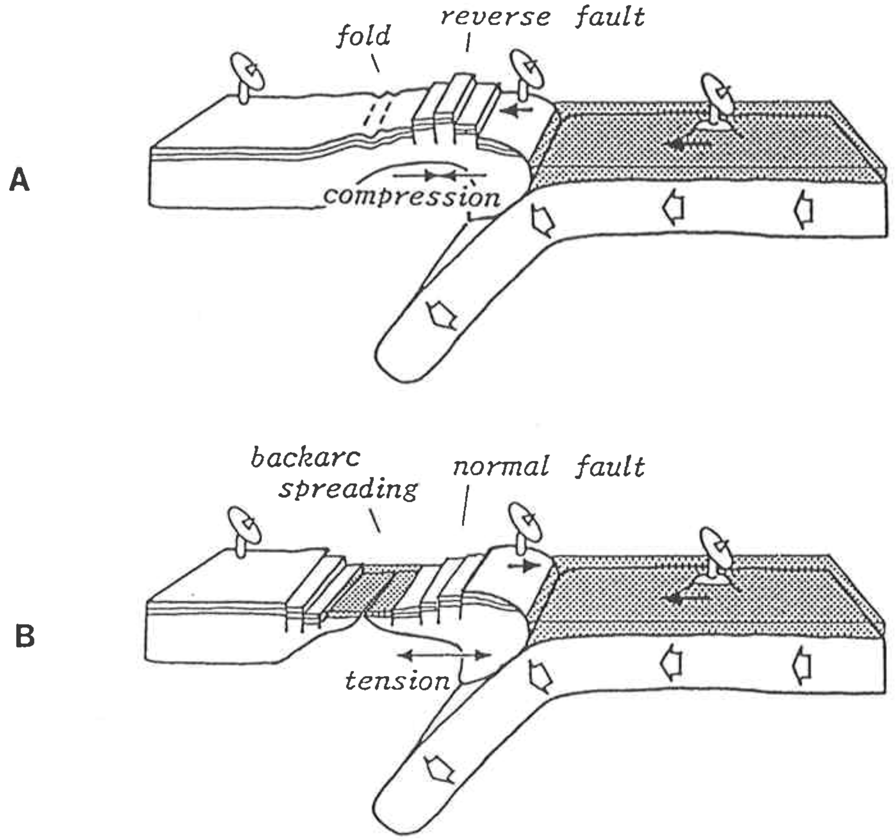


Fig. 5 Schematic of the movements of VLBI stations on the stable interior of a landward plate, on an island arc and on a subducting oceanic plate. The direction of the island arc station is dependent on the tectonic stress status of the island arc.

vectors of Pacific Plate stations are parallel and of equal length. The estimated vectors of these stations, viz., Vandenberg, Kauai, Kwajalein, are well consistent, indicating that the Pacific plate has moved as a rigid body during this period.

The estimated movement of Kashima is about 20 mm/yr in the N80W direction. This direction resembles that of the Pacific plate (N69W) suggesting that its origin is the compressional stress fields created by the oceanic plate. If we give a-priori vectors differently, e.g., as those viewed from North American plate, the direction of the estimated Kashima's velocity (N53W) is also close to that of the Pacific plate (N66W), but its amount becomes only about 8 mm/yr. It seems contradictory that the contraction rate of the arc is 8 mm/yr if Kashima is assumed on the North American (NOAM) plate and 20 mm/yr if it is assumed on the Eurasian (EURA) plate. However, this difference comes from the interpretation of the east-west crustal shortening along the back-arc (eastern margin of the Japan Sea); in the Kashima-NOAM assumption, this is regarded as the NOAM-EURA convergence and not a part

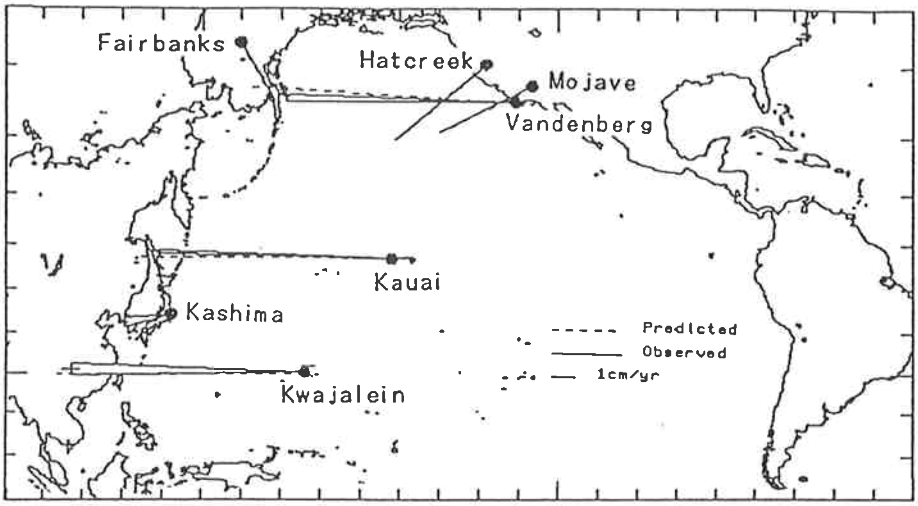


Fig. 6 Horizontal velocity vectors of the stations obtained by fixing those of four stations on the North American continent (Fairbanks, Haystack, Hatcreek and Mojave). Velocity vectors are those viewed from the Eurasian plate and the pole of projection is shifted to the Eurasia-Pacific Euler pole.

of the arc contraction, while in the Kashima-EURA assumption, this is considered as a part of east-west contraction of the arc.

Generally speaking, island/continental arcs are classified into Chilean and Mariana types. In the former type, stress fields are compressional in the direction of plate convergence, while in the latter type, they are tensional (Nakamura & Uyeda, 1980).(9) In these types, the direction of movement of the island arc station with respect to the stable interior is landward (Fig. 5a) and oceanward (Fig. 5b), respectively. Several examples of present-day arc deformation detected by SLR (Watkins *et al.*, 1989; Reigber *et al.*, 1989; Smith *et al.*, 1989)(10)-(12) are as follows. Shimosato SLR station operated by Japan Hydrographic Department (JHD) located on the Kii Peninsula (Southwest Honshu Arc) is found to be moving northwest by a few centimeters per year. This is thought to be due to compression caused by the subducting Philippine Sea plate. Observed velocity of Matera SLR station in southern Italy is found to resemble that of the African plate although the station lies on the Eurasian plate. Arequipa SLR station in the Peruvian Andes is also found to be moving eastward suggesting the east-west contraction of the Central Andes under compressional stress fields applied by the subducting Nazca plate. As an example of the Mariana type, the Aegean SLR network (Reigber *et al.*, 1989) clarified the N-S extension of the network of about 5 cm/yr.

4. Future Plans

Space geodesy made it possible to verify and measure present-day plate motion and revealed that it is consistent with the prediction of geologic models, although minor but important differences are occasionally found which need further study. Such results help us to determine what to concentrate our research on in the next decade. This last section introduces several on-going and future experiments aimed at solving remaining problems.

4.1. VLBI in Southern Hemisphere

The concentration of VLBI stations in "developed" countries is reflected by the fact that we have measured only northern hemisphere baselines. Many problems cannot be solved without measuring points far to the south, e.g, those on African, Australian, South American and Antarctic plates. Global VLBI projects including CDP are already extending their networks to stations on African and Australian plates. Their movement will be clarified within a few years. As for the Antarctic plate National Institute for Polar Research (NIPR), in collaboration with Communications Research Laboratory (CRL), hopes to use its multi-purpose parabolic antenna at Syowa Station for regular VLBI experiments in future. Test observations have been successfully carried out between Kashima and Syowa Station in Antarctica in 1990[13].

4.2. Mobile VLBI Stations

It is clear that a few fixed VLBI stations cannot reveal complicated crustal deformation in an area like Japan composed of several different island arcs. Hence, small mobile VLBI stations which can be operated at any desired point can be very useful. Geographical Survey Institute (GSI), using its

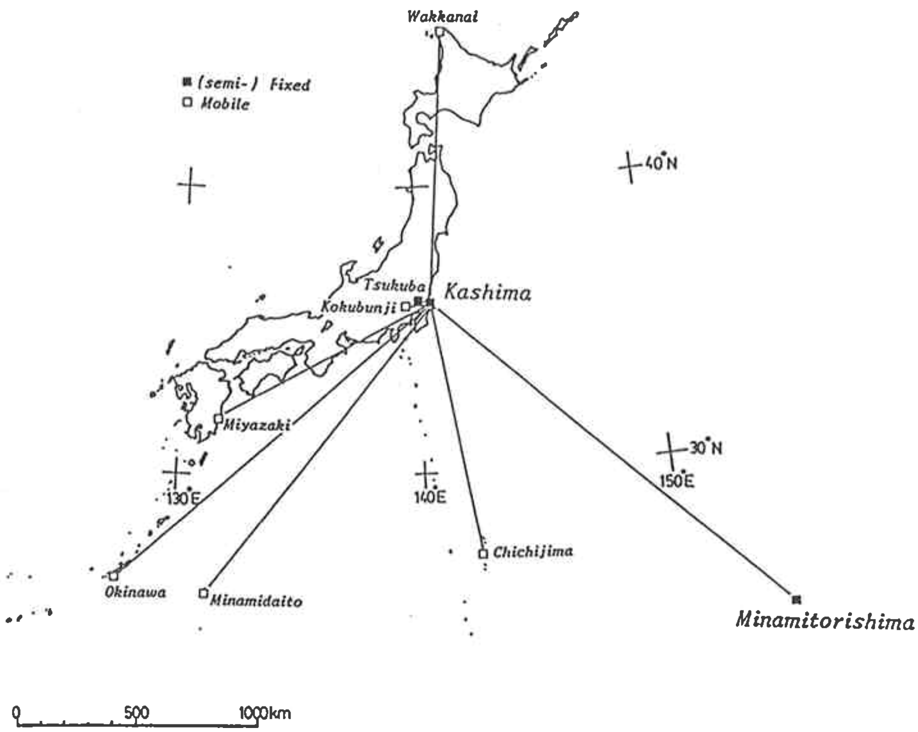


Fig. 7 Fixed geodetic VLBI stations and mobile VLBI sites in Japan.

mobile 5-meter antenna, has successfully conducted VLBI experiments at three sites in Japan (Miyazaki, Kyushu island, Chichijima in the Bonin Islands and Shintotsugawa, Hokkaido island). CRL has developed a smaller VLBI station with a 3-meter antenna and has successfully performed VLBI experiments at several sites such as Okinawa island, the Ryukyu arc and Wakkanai, Hokkaido island. These experiments will provide valuable information on the deformation of other island arcs in Japan (Fig. 7). CRL has also constructed a fixed VLBI station with a 1O-meter antenna on Minamitorishma (Marcus) island, the only Japanese island on the Pacific plate, and it is providing data to measure its movement precisely taking advantage of a short, domestic baseline.

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