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Island Arcs of Southeast Asia

Contraction of northeastern Japan: evidence from horizontal displacement of a Japanese station in global very long baseline interferometry networks

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ABSTRACT

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Kashima very long baseline interferometry (VLBI) station is situated on the outer arc of the northeast Honshu Arc and its position has been monitored in international geodetic VLBI networks since 1984. Kashima station is found to be moving with respect to the stations on the stable North American craton by about 1.4 cm y^{-1}, which is inconsistent with the general concepts that the Japanese eastern half belongs to the North American plate and that plates are rigid. The direction of the movement (N60°W) is almost the same as the subducting Pacific plate which creates the compressional stress field in the island arc. This suggests that the east–west intraplate contraction of the arc under this stress field is responsible for the movement of Kashima.

Introduction

Kashima VLBI station, Communications Research Laboratory, is the only Japanese station in international VLBI networks and is characterized by its proximity to the active convergent plate margin known as the Japan Trench. From the standpoint that the complicated intraplate deformation in an island arc may contaminate the baseline length changing rates, Kashima station has been pointed out to be unsuitable for the accurate measurements of global plate motions. Recent VLBI measurements, however, have been providing evidence that the contemporary movements of the tectonic plates are almost identical to those averaged over geologic time scales (e.g., Herring et al., 1986; Heki et al., 1987). This enables us to interpret the differences between the observed station movements and the predictions by plate motion models as the component which indicates the plate deformation and to use VLBI as a new device to measure the on-going strain accumulation in the region of an active plate interaction.

Velocity of Kashima station—predictions

Plate boundaries in and around Japan

In order to detect the deformation of an island arc with VLBI, it is important to know on which plate the arc resides. The northeast Honshu Arc has been regarded to be on the Eurasian plate (Chapman and Solomon, 1976) until the following two different possibilities were proposed: it formed part (1) of the North American plate, and (2) of the Okhotsk plate (Fig. 1). These new models assume that a plate boundary extends from Sakhalin, along the Japanese coast of the Japan Sea, down to the Fossa Magna, central Japan. Model (1) considers this boundary to be that of

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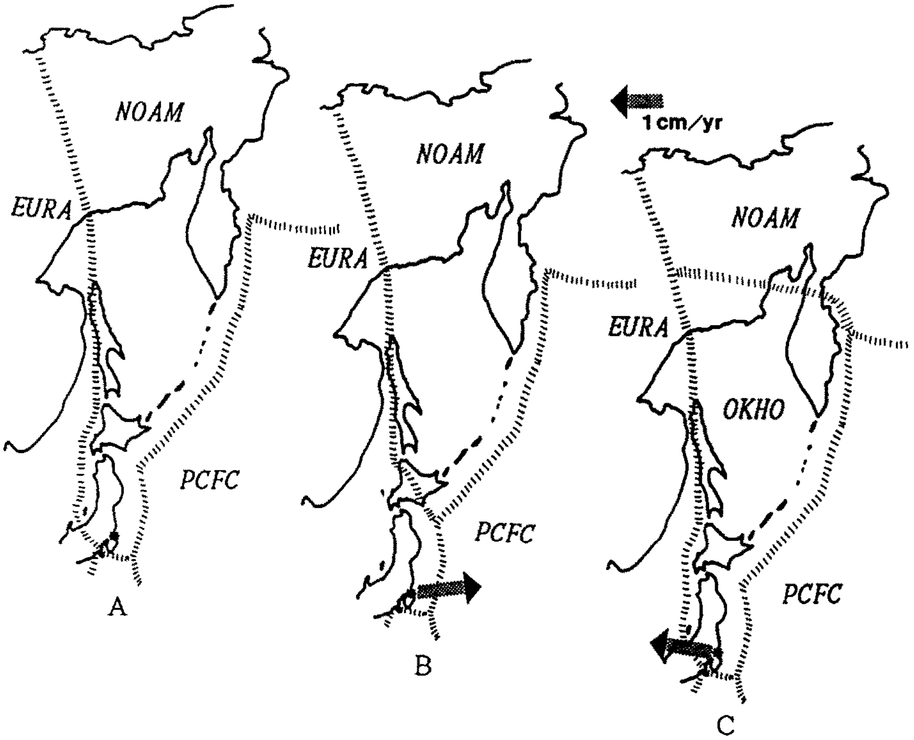

Fig. 1. Three different models for plate boundaries in and around Japan. Kashima station (denoted by the asterisk) is on the North American plate (NOAM), Eurasian (EURA) plate and Okhotsk (OKHO) plate in models A (Kobayashi, 1983; Nakamura, 1983), B (Chapman and Solomon, 1976) and C (Seno et al., 1987), respectively. The Pacific plate (PCFC) is subducting at the Japan Trench under the northeast Honshu Arc. The arrows are the predicted velocity vectors of Kashima station with respect to the North American plate. Plate motion parameters are after Minster and Jordan (1978) for model B and after Seno et al. (1987) for model C. If Kashima is on the North American plate (model A), the velocity of Kashima is predicted to be zero. Plate deformation is not taken into account.

the Eurasian–North American plates and northeastern Japan to be a part of the North American plate (Kobayashi, 1983; Nakamura, 1983). Model (2) hypothesizes that the block (Okhotsk plate) containing the Okhotsk Sea and northeastern Japan is independent from the North American plate (Seno et al.,1987).

Also shown in Fig. 1 are the displacement vectors of the Kashima VLBI station with respect to the North American plate predicted by these models. The movement of Kashima station is predicted to be the vector sum of the movement of a rigid plate and the "additional movement" due to intraplate deformation of the island arc. In this context, the existence of several different plate boundary models may be an unfortunate situation which will turn out to be an ambiguity in isolating the intraplate deformation component from the observed motion of Kashima.

Crustal deformation estimates in Japan

The idea of "rigid plates" where substantial deformation occurs only along distinct plate boundaries is no more valid in an island arc. Not only are active convergent margins generally associated with stronger tectonic stress fields than the plate interiors, but also the thickness of the plate itself is considered to be quite small, especially in a back-arc region, due to its high temperature gradient. Consequently, a considerable amount of intraplate deformation may occur over the relatively wide zones making the displacement of an island arc station a mixture of the rigid plate

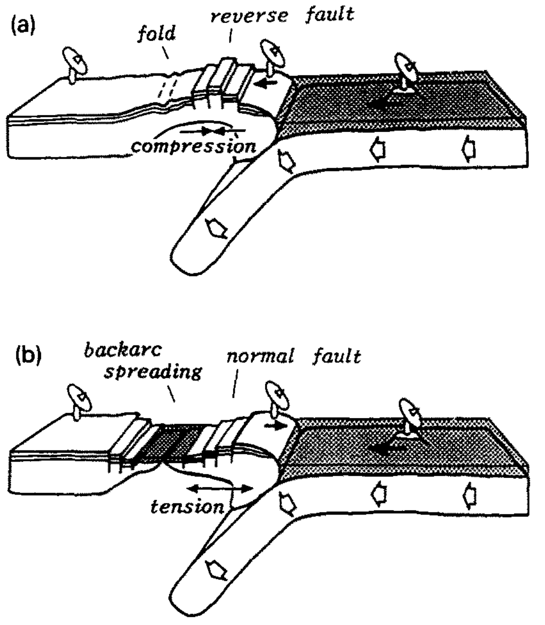

Fig. 2. The movements of the VLBI stations on the subducting oceanic plate (A), on the landward plate near the trench (B) and on the stable platform (C). If the arc is under the compressional fields (a) created by the subducting oceanic plate, the arc is considered to contract in the direction of the stress fields being accompanied by active faulting and folding. In this case, when viewed from C, B is expected to move in the same direction as A. If the arc is under the tensional fields (b), B moves oceanward being accompanied by normal faults and/or back-arc spreading.

motion and that coming from the plastic deformation of the island arc.

The active convergent plate boundaries are under either compressional or tensional tectonic stress fields in the direction of the plate convergence (Nakamura and Uyeda, 1980; Uyeda, 1982). In these two situations, additional velocity caused by plate deformation is anticipated to be landward and oceanward, respectively, with respect to the landward plate (Fig. 2a, b). Northeast Honshu arc has been under a compressional stress field for the last 6–8 Ma (Tsunakawa and Takeuchi, 1983) caused by the subducting Pacific plate (Huzita, 1980) and the movement of Kashima (with respect to the plate to which Kashima belongs) is thought to be in the same direction as the Pacific plate.

Shimamoto (1989) suggests from rheological studies of the rocks that the thickness of the lithosphere under the back arc and volcanic arc of the northeast Honshu Arc is only about 20 km which is thinner than the crust. The outer arc, however, is expected to behave as a rigid body due to the underlying cold and strong fore-arc wedge. It is characteristic of the tectonics in Japan that the compressive force from the trench side to the arc once accommodated by the fore-arc wedge, subsequently deforms the thin-skinned volcanic arc and back arc through this rigid fore-arc. Kashima is located on the outer arc and crustal strain rates are smaller than the typical values in Japan by an order of magnitude in this region (Fujii et al, 1985). Accordingly, the movement of Kashima, to some extent, can be regarded to represent the east–west contraction rate of the arc.

Such a contraction rate can be estimated as the spatial integration of the compressional strain accumulation rate in the direction of the maximum horizontal stress field. Presently available estimates of the crustal strain rates and the shortening rates of the northeast Honshu Arc differ considerably between the various estimation methods. Repeated geodetic survey results give the largest values (e.g., Nakane, 1973, gives values of a few times 10^{-7} y^{-1} in terms of maximum shear strain rates). On the other hand, Wesnousky et al. (1982) converted the recent seismic moment release rate of Quaternary faults in intraplate Japan into strain rates which are smaller by almost an order of magnitude than those obtained geodetically. Sato (1989) reports strain rates which are intermediate between these two values from the degree of deformation of late Cenozoic strata. Although VLBI data give only the sum of the rigid plate motion and the plate deformation, the constraint given by them will be important considering the present situation that neither of the components are well established in the northeast Honshu Arc.

Velocity of Kashima station—an observation

We used the data of 82 international VLBI observing sessions from January 1984 to October 1988 in order to obtain the movement of Kashima station with respect to the North American VLBI stations. 63 of them are experiments of the Crustal Dynamics Project (Coates et al., 1985) and the others are those of the Pacific network of Interna-

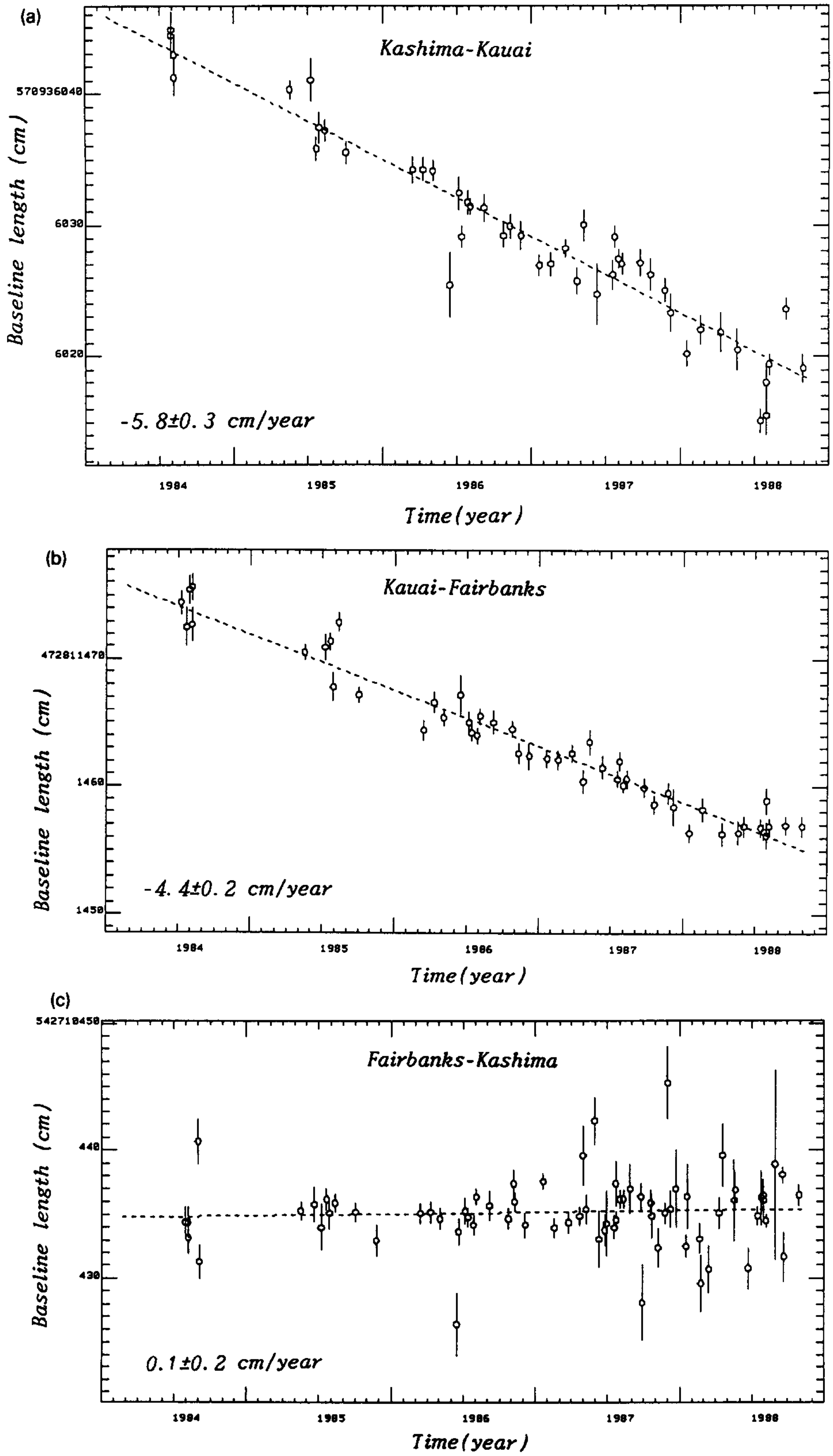

Fig. 3. Baseline length evolution for Kashima–Kauai (a), Kauai–Fairbanks (b) and Fairbanks–Kashima (c) baselines in 1984–1988 observed by VLBI experiments. Error bars are the 1σ formal errors of the individual baseline length data. The broken line is the best-fit line obtained by the least-squares method, whose slope including its 1σ formal error are also shown in the figure.

tional Radio Interferometric Surveying (Carter et al., 1985). According to the procedures described in Heki (1989), we distilled from the VLBI raw data the velocity vectors of the individual stations.

Each VLBI observing session gives a set of relative station positions in terms of their three components with respect to geocentric Cartesian coordinates. These station positions are converted into the baseline lengths (i.e., inter-station distances), which are free from error due to inaccurate information on the earth orientation in a celestial reference frame and are also independent from the selection of the reference station in individual observing sessions. The changing rates of these baseline lengths obtained by linear regression (Fig. 3) are the most basic data in the studies of crustal dynamics.

The horizontal velocity of the VLBI stations are adjusted with a least-squares procedure so that they best explain the observed baseline length changing rates. Generally speaking, conversion of the distance changes into the station's velocity requires a number of fixed reference stations. For the determination of the horizontal velocity vectors of Kashima in this study, three Pacific plate stations (Vandenberg, California; Kauai, Hawaii; and Kwajalein, Marshall Islands) and two Eurasian plate stations (Wettzell, West Germany; and Onsala, Sweden) are estimated while the vectors of four stations on the North American plate (Fairbanks, Alaska; Haystack, Massachusetts; Mojave and Hatcreek, California) are fixed.

We assumed that Fairbanks and Haystack stations are fixed on the North American plate

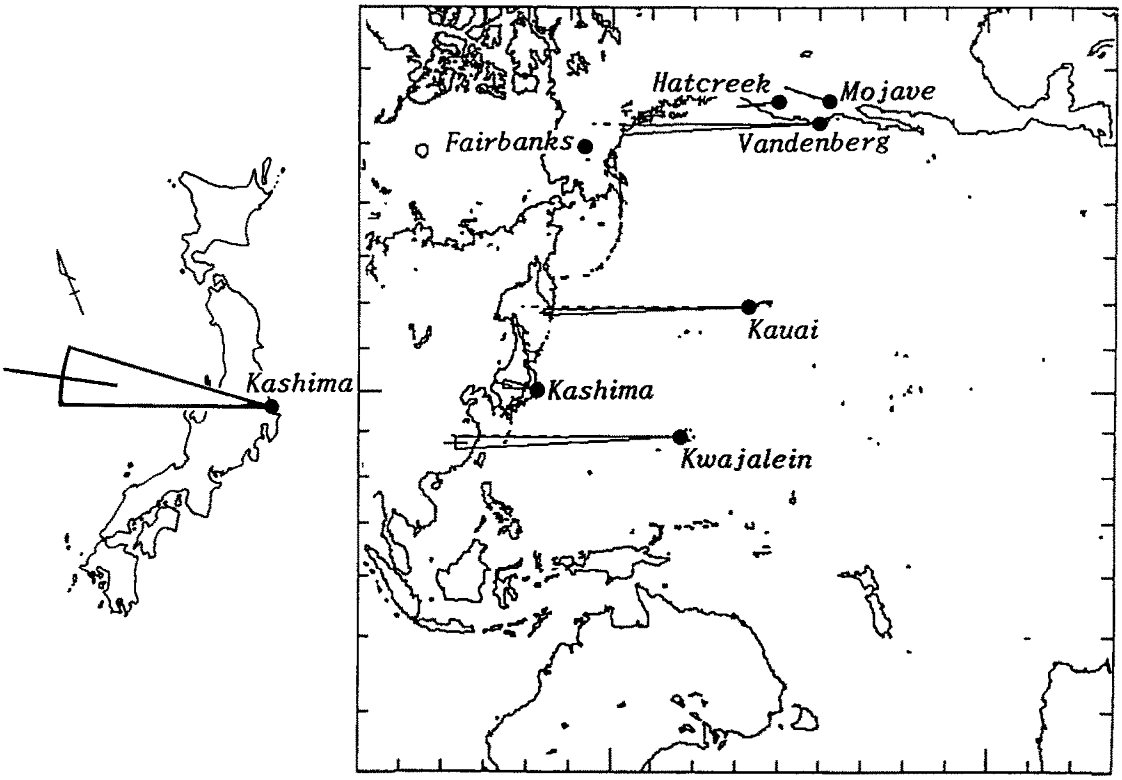

Fig. 4. Estimated horizontal velocity vectors and their formal errors of the VLBI stations with respect to the stations on the North American plate. Fairbanks (Alaska) and Haystack (Massachusetts) are fixed on the North American plate while a-priori vectors are given for Mojave and Hatcreek (both California) considering their movement with respect to the North American craton (Clark et al., 1987). The pole of projection has been shifted to the North American–Pacific Euler pole of the RM-2 plate motion model (Minster and Jordan, 1978). Velocity vectors are exaggerated by the secant of the latitude. The width of the fan and the small line attached to the end of the fan denote the 1σ formal errors of the azimuth and the horizontal velocity, respectively. Broken lines for the three Pacific plate stations are the velocity vectors predicted by the RM-2 model. The separation of the divisions in the frame is 10°. The Japanese part is shown magnified on the left.

(velocity = zero). Two Californian stations (Mojave and Hatcreek) are known to have a certain velocity with respect to the North American craton (Clark et al., 1987) which can be interpreted either by the crustal stretching of the Basin and Range Province (Minster and Jordan, 1987) or by an elastic–plastic megashear along the North America–Pacific plate boundary (Ward, 1988). A-priori velocity vectors of these stations with respect to the stable part of the North American plate are taken after Ma et al. (1989) and are fixed. Therefore the estimated horizontal velocity vectors of other stations can be regarded as those with respect to the stable interior of the North American plate.

The obtained velocity vectors are drawn in Fig. 4 and are summarized in Table 1. In Fig. 4, the pole is shifted to the relative rotation pole of the Pacific and North American plates (pole position is after Minster and Jordan, 1978) so that the expected velocity vectors of the three Pacific plate stations are parallel and of equal length. The coincidence of the estimated velocity vectors of these stations are remarkable indicating that Pacific plate is moving about the Euler pole as a rigid spherical shell, even on a time scale of a few years.

Table 1 and Fig. 4 indicate that the velocity of Kashima with respect to the North American plate is not zero (1.4 cm y^{-1}, N60°W) suggesting the following possibilities: (1) Kashima is not on the North American plate, and/or (2) the island arc plate is not rigid (i.e., intraplate deformation of the northeast Honshu Arc is significant). If Kashima is assumed to be on the North American or Eurasian plate, the rigid plate movement component is zero or eastward respectively and we have to assume some additional movement due to plate deformation to account for the discrepancies between the predictions and the observation. Only if Kashima is on the Okhotsk plate whose rotation vector is given by Seno et al. (1987), the observation coincides within errors with the prediction and plate deformation becomes unnecessary. This point will be discussed in the following section.

Table 2 summarizes the "excess velocity" vectors required by the various plate models based on the assumption that the movement of Kashima is the vector sum of the rigid plate movements and the component due to the plate deformation. Gen-

TABLE 1

Movements of VLBI stations with respect to the North American plate

Station	North (cm y^{-1})	East (cm y^{-1})	Horizontal (cm y^{-1})	Azimuth (°)
North American plate stations				
1. Fairbanks [a]	0.0	0.0	0.0	–
2. Haystack [a]	0.0	0.0	0.0	–
3. Mojave [b]	1.0	−0.3	1.1	17
4. Hat Creek [b]	0.8	−0.6	1.0	36
5. Kashima	0.7 ± 0.3	−1.2 ± 0.3	1.4 ± 0.4	−60 ± 8
Pacific plate stations				
6. Vandenberg	3.8 ± 0.1	−3.1 ± 0.1	5.0 ± 0.1	−39 ± 1
7. Kauai	5.5 ± 0.2	−5.9 ± 0.2	8.1 ± 0.2	−47 ± 1
8. Kwajalein	5.2 ± 0.4	−7.6 ± 0.4	9.2 ± 0.5	−56 ± 2
Eurasia plate stations				
9. Wettzell	−0.5 ± 0.7	1.2 ± 1.2	1.3 ± 1.2	112 ± 34
10. Onsala	−0.7 ± 0.7	2.3 ± 0.8	2.4 ± 0.7	108 ± 18

North, East, Horizontal: components of the estimated velocity vectors; Azimuth: direction of the estimated vectors (from north, clockwise). The errors are 1σ formal errors. Several of these movement vectors are plotted in Fig. 4.

[a] Stations fixed on the North American plate.

[b] A-priori velocity vectors assumed after Ma et al. (1989).

TABLE 2

Two components of the movement of Kashima

Model	Plate motion		Plate deformation			
	north ($cm\ y^{-1}$)	east ($cm\ y^{-1}$)	north ($cm\ y^{-1}$)	east ($cm\ y^{-1}$)	horizontal ($cm\ y^{-1}$)	azimuth (°)
EURA [a]	0.2	1.3	0.6	−2.5	2.6	−78
NOAM [a]	0.0	0.0	0.7	−1.2	1.4	−60
OKHO [b]	0.3	−1.3	0.4	0.0	0.4	4

Model: assumed plate for Kashima station (EURA = Eurasia; NOAM = North America; OKHO = Okhotsk). The velocity vectors are those viewed from the North American plate.

[a] Plate motion parameter after Minster and Jordan (1978).

[b] Plate motion parameter after Seno et al. (1987).

erally speaking, one component in a vector sum cannot be determined without a-priori knowledge of the other. In the following section, we try to compare this sum with other geophysical/geological information so that we can discuss which model(s) is (are) acceptable.

Discussion

The additional velocity which is necessary if Kashima is situated either on the Eurasian or on the North American plate is parallel with that of the Pacific plate (Table 2). This strongly suggests that this "excess velocity" is a consequence of the intraplate contraction of the northeast Honshu Arc under a compressional stress field induced by the subducting Pacific plate. In this section, we discuss the consistency of the various estimates of the strain accumulation rates in Japan with the observed additional velocity of Kashima.

Contraction rate estimates of the arc with conventional methods

Figure 2a shows how the compressional stress field and the island arc contraction result in the small landward movement of the VLBI station located on the outer arc. The compressional stress field induces deformation of the weak island arc crust such as active reverse or strike-slip faulting and/or active folding, both of which is commonly observed in the northeast Honshu Arc. On the other hand, the contraction between Kashima and the trench is considered to be much smaller because Kashima resides on the rigid fore-arc wedge. Hence, the rate of Kashima's landward movement is estimated as a spatial integration of the compressional strain rates in the direction of the plate convergence.

The largest strain rate estimates are those by conventional ground geodetic surveys (Nakane, 1973; Sato, 1973). They show that the typical strain accumulation rate in the last few tens of years is about $1\text{–}3 \times 10^{-7}\ y^{-1}$ in the Japanese Islands. From the horizontal displacement vectors of triangulation points obtained by these repeated geodetic surveys (Harada, 1967; Harada and Isawa, 1969), Mogi (1970) calculated that the cumulative shortening in the recent 60 years between the Pacific coast and the Japan Sea coast in the direction of the Pacific plate subduction is about or a little less than 1 m. This may correspond to an annual contraction rate of about 1–2 $cm\ y^{-1}$.

Wesnousky et al. (1982) surveyed the historical record of large earthquakes and geologically determined rates of slip on Quaternary faults in intraplate Japan and converted the seismic moment release rate to the crustal shortening. They obtained $2.4 \times 10^{-8}\ y^{-1}$ for the average strain rate and about 4.7 $mm\ y^{-1}$ for the east–west contraction of northeastern Japan, which is much smaller than the geodetic estimates. They suggested that this difference is caused by the contribution of strain processes other than active faulting (e.g., on-going folding) to the geodetically measured strain rates. They also criticized that the time span of the geodetic measurements is shorter than the recurrence interval of the great interplate earthquakes and that they are unable to separate the elastic compressive strain which is released coseismically during the earthquakes from the observed strain.

Recently, Sato (1989) surveyed the degree of deformation of late Cenozoic strata in northeastern Japan from geological cross-sections and concluded that the average strain rates of shortening are $2.4\text{–}4.4 \times 10^{-8}$ y^{-1}. In spite of the inaccurate estimation of the onset of deformation, his value is somewhat smaller than those obtained by geodetic methods (Nakane, 1973; Sato, 1973) and somewhat larger than those determined by Wesnousky et al. (1982). He also suggests that his value is a slight underestimate because his method was unable to estimate the "layer parallel shortenings" intrinsically.

In summary, it seems that the shortening rate of the northeast Honshu Arc is at least larger than 5 mm y^{-1} but smaller than a few centimeters per year.

Comparison with VLBI data

The elastic compressive strain which increases during inter-seismic periods of great interplate earthquakes is considered to contribute to the movement of Kashima to some extent. In this segment of the Japan Trench, however, earthquakes whose magnitudes are larger than 7.4 have not occurred in the historical period (Fujii et al., 1985) and the plate subducts without great earthquakes which largely affect the estimation of the permanent strain accumulation rates. Hence, the interplate earthquake contribution to Kashima's movement observed by VLBI is considered to be relatively small and the additional movement of Kashima will hardly exceed those estimated by conventional methods.

As shown in Table 2, the Kashima–Eurasia model needs about 2.6 cm y^{-1} while the Kashima–North America model needs only 1.4 cm y^{-1} as additional movement coming from plate deformation. The directions of both movements are similar to that of the subducting Pacific plate (N68°W). The difference between 2.6 cm y^{-1} and 1.4 cm y^{-1} is not large enough for us to favor one of the models. At present, both models seem to be acceptable.

If we assume Kashima is on the Okhotsk plate whose rotation vector is given by Seno et al. (1987), neither additional velocity nor east–west contraction of the arc is necessary. This, however, is clearly inconsistent with the evidence that contraction of more than 5 mm y^{-1} does exist. Seno et al. (1987) determines the plate motion parameters only from the interplate earthquake slip vector directions because other geophysical data, such as ocean magnetic lineations and transform fault azimuths, are not available along its boundary. Although they emphasize the statistical significance of the independence of this plate by analyzing the variation of the earthquake slip vectors along the Kuril Trench, these vectors are also well explained as those between North American and Pacific plates. These points suggest that the significance of the Okhotsk plate is marginal (any discussions on Japanese plate boundaries might be meaningless unless we consider plate deformation) and it does not seem probable that the movement of Kashima can be explained only by rigid plate motion.

In order to reveal with VLBI whether the Japanese eastern half is on North American or Eurasian plate, we have to monitor the movement of multiple stations widely distributed in the northeast Honshu Arc. By comparing the velocity vectors of these stations, we will be able to distinguish their movements due to the real deformation of the plate from the movements of the plate resulting from the rigid body rotation about its Euler pole. At the same time, it seems necessary to reexamine the definition of the "plate boundary" in an island arc. The largest difference between the Kashima–North America model and the Kashima–Eurasia model is that the former model supposes that a plate boundary exists along the coast of the Japan Sea and that deformation concentrates along this "plate boundary". It is evident at present that deformation occurs over the wide area of the arc itself, no matter which model is correct. From a geophysical and geological viewpoint we consider that it is not very meaningful to argue to which plate such a weak island arc "plate" belongs.

According to the RM-2 model of Minster and Jordan (1978) the Pacific plate is subducting at the Japan Trench in this region by about 9.5 cm y^{-1} and in a N68°W direction (this speed is about 10% smaller if we assume the NUVEL-1 model of DeMets et al., 1987). On the other hand, it is shown that Kashima moves in the same direction as the subducting plate by about 1.4 cm y^{-1} while the trench itself is considered to be advancing landward with a similar rate (the contraction between Kashima and the trench can be neglected). Accordingly, the difference between these two velocity vectors, i.e., the actual subduction rate, is about 8 cm y^{-1} (this value is slightly smaller for the NUVEL-1 model). Recently, Otsuki (1989) proposed a "law" that back-arc spreading and crustal shortening may account for the deviation of the convergence rate from the "critical value" of 7.2 cm y^{-1} for convergent zones associated with the Wadati–Benioff zone deeper than 200 km. We would like to point out that our result is in good agreement with the prediction of this "law of convergence rate of plates".

New VLBI experiments between Kashima and the mobile stations located on islands such as Okinawa (Ryukyu Arc) and Chichijima (Izu-Bonin Arc) have just been initiated. The changes of these baseline vectors will be clarified within a few years and the results will reveal the intraplate deformation (both contraction and extension) of various island arcs in and around Japan.

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