Time dependent model of magma intrusion in and around Miyake and Kozu Islands, Central Japan in June–August, 2000

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Received 24 May 2004; accepted 2 February 2005
Available online 13 September 2005

Abstract

A time-dependent model of magma intrusion is presented for the Miyake–Kozu Island area in central Japan based on global positioning system (GPS) measurements at 28 sites recorded between June 27 and August 27, 2000. A model derived from a precise hypocenter distribution map indicates the presence of three dikes between Miyake and Kozu Islands. Other dike intrusion models, including a dike with aseismic creep and a dike associated with a deep deflation source are also discussed. The optimal parameters for each model are estimated using a genetic algorithm (GA) approach. Using Akaike’s information criteria (AIC), the three-dike model is shown to provide the best solution for the observed deformation. Volume changes in spherical inflation and deflation sources, as well as three dikes, are calculated for seven discretized periods after GA optimization of the dike geometry. The optimization suggests a concentration of dike expansion near Miyake Island in the period from June 27 to July 1 associated with large deflation at a depth of about 7 km below Miyake volcano, indicating magma supply from depth below Miyake Island. In the period from July 9 to August 10, a huge dike intrusion near Kozu Island is inferred, accompanied by expansion of the lower parts of a central dike, suggesting magma supply from depth in the region between Miyake and Kozu Islands.

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Keywords: time-dependent model; dike intrusion; spherical deflation source; Miyake–Kozu Islands; GPS measurement; genetic algorithm

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1. Introduction

Miyake, Kozu and Nijima Islands are located in the Izu–Bonin arc on the Philippine Sea Plate (Fig. 1). Preceding the 2000 eruption of Miyake volcano, an earthquake swarm beginning on June 26, 2000 was detected, with an aerial extent that encompassed both Miyake Island and a large area of sea between Miyake and Kozu Islands (JMA, 2000) (Fig. 2). This activity was accompanied by significant crustal deformation on Miyake and surrounding islands, with up to 70 cm deformation observed over two months at Kozu Island. The first eruption on Miyake Island was accompanied by caldera collapse on July 8, followed by large-scale magmatic eruptions on July 14 and August 18.

Based on the crustal deformation determined from JMA hypocenter distribution and the daily global position system (GPS) solution of the nation wide dense GPS network (GEONET) deployed by the Geographical Survey Institute (GSI), a number of dike intrusion models have been proposed (Nishimura et al., 2001; Ito and Yoshioka, 2002; Yamaoka et al., 2005). Furuya et al. (2003) considered magma migration based on gravity changes at Miyake and Kozu Islands, and Nishimura et al. (2002) and Furuya et al. (2003) recently proposed a huge dike intrusion with a length of about 20 km and a volume of 1–2 km$^3$ in the earthquake swarm area between Miyake and Kozu Islands in combination with an aseismic fault creep of about 10 m near Kozu Island. Yamaoka et al. (2005) also suggested a single large intrusion, but in association with a spherical deflation source. Ito and Yoshioka (2002) proposed a time-dependent deformation model, but were unable to remove coseismic displacement from the raw GPS solutions.

Recent research on the earthquake swarms observed during the 2000 event has given rise to many valuable suggestions related to dike intrusion models. Sakai et al. (2003) presented epicenter distributions determined from an ocean-bottom seismometer network, and suggested the existence of an aseismic zone within the epicentral area of the swarm. While previous studies have assumed a single long dike, the results of Sakai et al. (2003) suggest the existence of a number of dikes in the swarm area. To
examine this hypothesis in more detail, three dike-complex models are investigated in the present study.

Regardless of geometry, dike intrusion requires a huge magma supply and it is important to determine the origin of the magma. Two models of magma supply have been proposed, from beneath Miyake Island (Nishimura et al., 2001), and from a broader area beneath Miyake Island and the dike itself (Furuya et al., 2003; Yamaoka et al., 2005). The spatio–temporal change in the dike intrusion should be sensitive to the geometry of the magma supply.

Based on petrologic observation, Geshi et al. (2002) suggested that the magma sources beneath Miyake Island shifted from shallow levels to deeper levels around early August. Such a shift is also an important consideration and can be detected by GPS measurements.

In this paper, a time-dependent model for magmatic intrusion between Miyake and Kozu Islands, and inflation and deflation of spherical sources beneath Miyake Island is proposed. The model makes use of detailed GPS measurements and hypocenter distributions. The dike intrusion process is discussed based on the proposed model and considering magma supply and the shift of the magma source beneath Miyake Island.

Fig. 2. Observed deformation and seismic activity (JMA, 2000) during June 27 to August 18, 2000. Stars indicate the locations of five M6 earthquakes. Black and white arrows denote displacements at single and dual frequency GPS stations, respectively. The estimated locations of dikes are shown as solid lines for comparison with seismic activity. Confidence ellipses are $1\sigma$. 

2. Recent activity at Miyake Island and surrounding islands and the 2000 Miyake–Kozu event

In the region of Miyake Island, the Philippine Sea Plate is subducting northwestward beneath the Eurasian plate at a rate of 4–5 cm/a (Seno et al., 1993; Kotake et al., 1998), and the Pacific Plate is subducting westward at the Izu Bonin arc on the Philippine Sea Plate (Fig. 1). The convergence motion between the Philippine Sea Plate and the Eurasian Plate produces compressive strain in the NW–SE direction and tensile strain in the NE–SW direction around Miyake Island (Nakamura, 1984). The Izu–Bonin arc constitutes a volcanic front stretching in the NNW–SSE direction. Basaltic volcanism occurs in the Izu Peninsula, at Izu-Ohshima Island and at Miyake Island, whereas rhyolitic volcanism occurs in Kozu, including Niijima and Shikine Islands, which are located behind the main volcanic front (Tsukuda et al., 2000).

Volcanic eruptions at Miyake Island have occurred every 20 to 40 years in recent history, and most of the activity has been characterized by the formation of eruptive fissures on the mountainside. Before 2000, Miyake volcano last erupted on October 3, 1983, forming fire fountains along a 4.5 km-long fissure (Aramaki and Hayakawa, 1984). The cumulative volume of eruption products from that activity is estimated to be $12.1 \times 10^6$ m$^3$. These eruptions persisted for about 15 h and followed crustal uplift of 16 cm in the preceding year, as determined by leveling on Miyake Island (Nagaoka et al., 1984). Recently, a spherical inflation source located at a depth of 9.5 km beneath the Miyake volcano has been inferred from GPS measurements based on observations between June 1997 and June 1999 (Nishimura et al., 2002).

In contrast, no eruptions have been recorded at Kozu or Niijima Islands in the last 1000 years (Sugihara et al., 2001). However, horizontal displacement of up to 2 cm/a and uplift of about 1 cm/a over the last several years have been detected at Kozu Island based on tide level and GPS measurements (Kimata et al., 2000). Compared to the 1983 event, the 2000 Miyake–Kozu activity was quite different in terms of eruption style and time-scale. An earthquake swarm beneath Miyake Island began on June 26, 2000 (JMA, 2000), accompanied by crustal deformation detected by tilt and GPS measurements (Ukawa et al., 2000; Kaidzu et al., 2000). The hypocenters of the earthquakes migrated 20 km northward from Miyake Island toward Kozu Island between June 26 and July 1 (JMA, 2000). Five M6 earthquakes occurred around Miyake, Niijima and Kozu Islands area during this 2000 activity. Sakai et al. (2003) determined the epicenter distribution based on records from an ocean-bottom seismometer network. The distribution suggests the existence of an aseismic zone within the epicentral area of the swarm, and shows intermittent bursts of swarm activity moving from deep to shallow levels over short periods. This swarm activity persisted for about two months. Simultaneously with the migration of the earthquake swarm, large crustal deformation was also detected on Kozu and Niijima Islands by GPS measurements. The crustal deformation suggesting an opening of dike-like crack in the southeast of Shikine Island continued for two months, reaching a total displacement of 70 cm at Kozu Island (Kaidzu et al., 2000).

Crustal deformation detected by continuous measurement of ground tilt and GPS at the Miyake volcano (Irwan et al., 2003; Ueda et al., 2004) suggested a rapid intrusion of magma, and was accompanied by a small ocean-bottom eruption on June 27. The first volcanic eruption on Miyake Island itself, involving a caldera collapse, occurred on July 8, and large-scale magmatic eruptions were observed on July 14–15 and August 18. Geshi et al. (2002) suggested that two kinds of magma were erupted during this event; basaltic-andesite lava in the eruption on July 14–15, and basaltic lava in the eruption on August 18. The emission of sulfur dioxide gas began at the end of August 2000, and the discharge of gas continues to the present day (January 2005).

Based on a detailed interpretation of bathymetry charts, Morita et al. (2000) suggested that many dike intrusions have occurred in the area between Miyake and Kozu islands in prehistoric time. Two caldera formations have been revealed by geological studies, the most recent of which was formed about 2500 years ago (Tsukui et al., 2001). A detailed analysis of the 2000 event is therefore important for considering the long-term future of the Miyake volcano.

3. GPS measurements and data

The GPS measurements analyzed here for the period June 27 to August 27, 2000 were recorded by 28
stations on Miyake, Izu-Ohshima, Niijima, Shikine and Kozu Islands, installed by the Geographical Survey Institute, the National Research Institute for Earth Science and Disaster Prevention (NIED), the University of Tokyo and Nagoya University. The observed deformation is shown in Fig. 2. The displacements at single-frequency stations (11 in total) were determined relative to the nearest dual-frequency stations. As the line length between single-frequency and dual-frequency stations was generally less than 5 km, it is presumed that ionospheric error has been cancelled out.

The time series of the coordinates at Kaeshihama station located in the north of Kozu Island and Miyake 2 station in the southeast of Miyake Island is shown in Fig. 3. As the GPS measurements at Kaeshihama were recorded by a single-frequency receiver, the station coordinates were determined relative to the dual-frequency receiver at Kozu station and are shown as the sum of the Kozu and relative Kaeshihama coordinates.

We obtained the displacements relative to the Tsukuba IGS (International GPS service) station as the first step in our analysis. These were converted to displacements relative to the Eurasian plate using Heki’s Kinematic reference frame (Heki, 1996). The motion of Tsukuba relative to the Eurasian Plate over this two-month period is considered to have been about 3.5 mm. We used the deformation related to the Eurasian plate via Tsukuba IGS site in the next analysis. The deformation caused by the 2000 event at the Tsukuba IGS station was also estimated using the present results, indicating a deformation of about 8 mm over these two months. This deformation is sufficiently small to allow the Tsukuba IGS station to be used as a fixed reference station.

Coseismic displacements were also detected by GPS measurements for five large M6 earthquakes

![Fig. 3. GPS displacements at the Kaeshihama (Kozu Island, north, single frequency) and Miyake 2 (Kozu Island, southeast, dual frequency) GPS stations. (Left) Daily solutions from GPS measurements, showing the five M6 earthquake events with magnitudes provided by JMA (2000). (Right) Deformation after removal of coseismic and PHP motion (approximation curves are shown). These time series are relative to the Eurasian plate through the Tsukuba IGS site.](image-url)
over this period (Fig. 3). We divided time series data into the two periods before and after occurrences of each of the earthquakes and estimated the station coordinates on the occurrence days of the earthquakes by fitting the data to linear curves. We inferred that the difference between coordinate values is the coseismic

Table 1

<table>
<thead>
<tr>
<th>Day</th>
<th>M(JMA)</th>
<th>Lat (°N)</th>
<th>Lon (°E)</th>
<th>Depth (km)</th>
<th>Length (km)</th>
<th>Width (km)</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
<th>Strike-slip (m)</th>
<th>Dip-slip (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000/7/1</td>
<td>6.4</td>
<td>34.215</td>
<td>139.274</td>
<td>1.1</td>
<td>20.5</td>
<td>8.0</td>
<td>115</td>
<td>64</td>
<td>0.00</td>
<td>0.68</td>
</tr>
<tr>
<td>2000/7/9</td>
<td>6.1</td>
<td>34.224</td>
<td>139.241</td>
<td>0.1</td>
<td>15.0</td>
<td>1.0</td>
<td>75</td>
<td>66</td>
<td>0.32</td>
<td>0.41</td>
</tr>
<tr>
<td>2000/7/15</td>
<td>6.3</td>
<td>34.395</td>
<td>139.237</td>
<td>2.0</td>
<td>9.0</td>
<td>2.0</td>
<td>300</td>
<td>55</td>
<td>−0.08</td>
<td>1.55</td>
</tr>
<tr>
<td>2000/7/30</td>
<td>6.4</td>
<td>33.974</td>
<td>139.441</td>
<td>1.5</td>
<td>19.0</td>
<td>5.0</td>
<td>177</td>
<td>65</td>
<td>1.32</td>
<td>1.31</td>
</tr>
<tr>
<td>2000/8/18</td>
<td>6</td>
<td>34.278</td>
<td>139.218</td>
<td>3.6</td>
<td>6.0</td>
<td>8.5</td>
<td>80</td>
<td>89</td>
<td>0.53</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The coordinates (Latitude and Longitude) at the middle of the top edge of the fault. The strike is clockwise from north. The dip is clockwise from a horizontal.

Fig. 4. Modeled faults for five M6 earthquakes and calculated coseismic deformation for each station. The rectangles are the fault planes. The heavy lines on the rectangles are the upper sides of the model faults.
displacement. The fault parameters for the five earthquakes were then estimated using a genetic algorithm (GA) as described later. The parameters for five M6 earthquakes are given in Table 1 and the locations of the model faults are shown in Fig. 4. The cumulative coseismic deformation for all 5 earthquakes at the two stations is estimated to be about 10 cm (Fig. 4).

The estimated fault parameters differ from the focal mechanisms estimated by JMA (2000). There were large postseismic displacements after these earthquakes at some stations (Fig. 3). Our estimation of coseismic deformation is influenced by the large postseismic component. However, fault geometries are consistent with aftershock distribution, suggesting that our estimation gives a good solution for the fault geometries. The coseismic displacements at all stations are removed from the daily solutions using the displacements calculated from fault parameters to account for missing data at a few sites.

As these islands are located on the Philippine Sea Plate, the rate of plate convergence, calculated from the daily solutions using the Philippine Sea Plate model of Kotake et al. (1998), was removed in data processing. The convergence in this period was less than 10 mm, representing less than a few percent of the displacement detected during the 2000 events.

4. Model and method of analysis

4.1. Three dike-complex models and existing dike intrusion model

Previous studies have assumed a single long dike to explain the observed deformation. However, a single dike does not explain the data completely. Nishimura et al. (2001) and Furuya et al. (2003) assumed an aseismic creep fault on the east side of Kozu Island, with a slip of 10 m estimated by Nishimura et al. (2001).

Hill (1977) proposed that strike-slip faults exist like a mesh connecting with the ends of dikes to explain earthquake swarms in volcanic areas. The dike with aseismic creep fault model is consistent with Hill’s hypothesis.

However, the observed deformation does not fit that calculated from this model at north Kozu Island. Furthermore, the largest earthquake to occur in or around the predicted creep area was an M6.4 event (July 1), involving an estimated slip of only 0.68 m (Table 1). Thus, the 10 m aseismic slip estimated by Nishimura et al. (2001) is very large compared to the known earthquakes in this area. Yamaoka et al. (2005) assumed a spherical deflation source below the dike intrusion to explain horizontal displacements greater than 10 mm detected by GENONET in the Tokai area 200 km from Miyake–Kozu Island. However, the result was not a vast improvement on previous models.

Sakai et al. (2003) has pointed out the possible existence of a single huge dike with three or more aseismic zones based on detailed analyses of the hypocenter distribution. Hayashi and Morita (2003) considered the hypocenter distribution of the earthquake swarm in the Ito area on the Izu Peninsula in 1998, and through detailed analysis predicted a dike intrusion as the cause of the earthquake swarm based on ground tilt and GPS measurements. They pointed out that the central part of the presumed dike represents an aseismic zone surrounded by seismic activity. Adapting that model to the 2000 Miyake–Kozu event and considering the prediction of three or more aseismic zones in the earthquake swarm area by Sakai et al. (2003), the single huge dike may in fact consist of three or more separate dikes.

In this study, a dike complex model involving several dikes is considered. The single long dike is divided into two, three and four dikes, and the parameters of the dike complex model are optimized using a genetic algorithm (GA) to match the GPS data. The optimal parameters for a huge dike intrusion with an aseismic fault (Nishimura et al., 2001) and for a huge dike intrusion with a deep spherical deflation source (Yamaoka et al., 2005) are calculated for comparison with the proposed dike complex model. The goodness of fit for the five models examined is determined based on Akaike’s information criteria (AIC) (Akaike, 1973). The residual between the calculated and observed deformation for each model was also calculated, but the lowest residual can only be used to determine the best model if all models have the same number of parameters, which is not the case for the present set of models. Therefore, the AIC index was used for comparison of these models, where the model with lowest AIC (assuming a difference of 1 or more) is defined as the best.
For Miyake Island, crustal deformation suggesting contraction of the island was detected by GPS and ground tilt measurements associated with inflation immediately prior to the large eruption. Thus, two sources of pressure with contraction and expansion below the island were assumed, similar to Nishimura et al. (2002).

4.2. Genetic algorithm

The parameters for the three models were estimated using a genetic algorithm, which is an attractive global search tool that is suitable for an irregular, multimodal fitness function such as those commonly encountered in nonlinear optimization problems. The geometry parameters estimated by GA are latitude, longitude, depth, length, width and strike for each dike, and latitude, longitude and depth for each spherical source. The openings of each dike and volume change of each spherical source are calculated by a least squares method using the geometry estimated by GA, because the opening and volume change are linear parameters when geometric parameters are fixed. Sakai et al. (2001, 2003) suggest that the swarm was distributed over the form of a vertical rectangular plane. To simplify the estimation procedure, the dip of the dike intrusion was fixed at 90°, and the same width and depth were assumed for each dike in accordance with the hypocenter distribution (Sakai et al., 2001, 2003). The deformation at each station was calculated using the formulations of Okada (1985, 1992). Briefly, the genetic algorithm proceeds as follows:

1. We give the maximum value, minimum value and interval of search for each geometric parameter (Table 3). A random number generator produces 300 potential values for each model parameter.
2. We estimate the openings and volume changes of these potential values using the weighted least squares method, and then we calculate the deformation at each observation site. The inverse numbers of variances of each station were used as weight for the least squares method. These potential values are ranked, from best to worst, according to a fitness function.
3. A set of 50 potential values are taken at random, and the best value (highest rank) is selected. This “tournament” process is repeated 300 times and results in the next generation.
4. Crossover and mutation take place at each generation. Crossover is the random exchange of information among two potential values, while mutation is the random change of a potential value. The event probabilities of crossover and mutation are set as 95% and 5%, respectively.

In the present analysis, the evolution is halted after 50 repetitions of Steps 2–4, giving the optimum parameters.

The potential models are ranked based on the minimization of the fitness function $F$, as given by

$$
F = \sum_{n=1}^{28} \left( \frac{\text{Obs NS}_n - \text{Cal NS}_n}{\sigma_{\text{NS}_n}} \right)^2 + \sum_{n=1}^{28} \left( \frac{\text{Obs EW}_n - \text{Cal EW}_n}{\sigma_{\text{EW}_n}} \right)^2 + \sum_{n=1}^{28} \left( \frac{\text{Obs UD}_n - \text{Cal UD}_n}{\sigma_{\text{UD}_n}} \right)^2 
$$

where Obs NS, Obs EW and Obs UD are the observed deformations in the north–south, east–west and up–down directions, Cal NS, Cal EW and Cal UD are calculated deformations, $n$ denotes the number of observation points, and $\sigma_{\text{NS}}$, $\sigma_{\text{EW}}$ and $\sigma_{\text{UD}}$ are variances at each station. For further details on the genetic algorithm, refer to Tiampo et al. (2000) and Irwan et al. (2003).

4.3. Time-dependent model

Although Ito and Yoshioka (2002) have also considered a time-dependent model for dike intrusion to explain the 2000 Miyake–Kozu event based on GPS data, they were unable to remove the coseismic displacement from the raw solutions. They estimated parameters of dike, fault and sill-like sources under Miyake Island simultaneously, which is difficult because the coseismic deformation has a strong resemblance to surface displacements caused by dike intrusion (Fig. 4). We removed the coseismic displacements from raw GPS data by estimating fault parameters using the GA above.
In the present analysis, the period from June 27 to August 27 was divided into seven stages related to seismic or volcanic activity (Nakada et al., 2001), with boundaries at July 1, July 9, July 15, July 30, August 10, and August 18, corresponding to the onset of caldera collapse at the Miyake volcano (July 8), magma eruption (July 14–15), and largest eruption (August 18).

Each of the three dikes was divided into upper and lower sub-dikes in order to estimate the spatial variation in the horizontal and vertical directions. The GA was used to determine the geometries of two spherical sources beneath Miyake Island. The spherical sources are required to explain the deflation observed during all periods and the inflation during the period from July 10 to July 15 (Fig. 7). We assumed the same model in all periods to prevent parameter changes, as opposed to using models that are different for every period. The geometric parameters of the six sub-dikes were fixed to values estimated from the data for the period from June 26 to August 18, 2000, and openings of the six sub-dikes and volume changes of two spherical sources were estimated using weighted least squares method in each stage. These time-dependent models were calculated independently for each time period and each sub-dike.

The resolution of the estimated parameters was checked using synthetic data (Fig. 5). Random numbers of ± 1 cm in the horizontal direction and ± 3 cm in the vertical direction were added as error in the resolution check. The present GA process provides a good estimate of the opening of the six sub-dikes and the parameters of the two spherical sources (Fig. 5). Division of the dikes into a larger number of sub-dikes (9 and 24) was also attempted, but did not result in increased resolution of model parameters.

5. Results and discussion

5.1. Model selection

The $F$ and AIC values for the five models (three kinds of dike-complex model, single dike with aseismic fault model, and single dike with deep deflation source model) were calculated and are given in Table 2. The optimal parameters for these models were estimated for the period from June 27 to August 18, 2000, and the models were compared based on the AIC. Of these models, the dike-complex model with three dikes provides the best fit for the observed data, supporting the existence of several dikes as suggested by Sakai et al. (2003). The optimized parameters for the three-dike model and the location of the dikes are estimated (Table 3) and corresponding seismic activity

![Fig. 5. Resolution check, showing (left) the synthetic model and (right) the estimated parameters for this model. (Upper) Location of spherical inflation and deflation sources, and (lower) expansion of dikes and volume changes of spherical sources. Circle size indicates the magnitude of the volume change. Open and filled circles represent inflating and deflating sources, respectively.](image-url)
is shown in Fig. 2. Observed and calculated deformation with locations of model dikes and faults are given in Fig. 6.

The strikes of the dikes are aligned almost uniformly at about 132°, which is parallel to the direction of maximum compressive stress in this area (Nakamura, 1984). Moreover, the five model faults locate at the ends of the dikes, consistent with the hypothesis of Hill (1977).

Although the model dikes are located in the swarm area, the Kozu-side dike is about 3 km north from the center of the swarm axis. If the Kozu-side dike is assumed to be located on the swarm axis, the observed deformation at Shikine Island cannot be explained. It is crucial to study the relationship between the seismicity and dike intrusion to improve this model.

We use the model including a complex of three dikes for the time dependent model below.

### 5.2. Time-dependent model of dike intrusion

After estimating the optimal geometric parameters of the dikes, we determined the opening of the six sub-dikes and the parameters of the spherical sources beneath Miyake Volcano for each period. First, the preceding static model from Section 5.1 and the time-dependent model were compared based on the cumulative volume changes in the period from June 27 to August 18. The static model and time-dependent model volumes are shown in Table 3.

Estimated volume changes of the deflating spherical source are −0.13 km³ in the static model and −0.21 km³ in the time-dependent model. We believe the difference to be caused from estimation of the spatio-temporal change of the spherical source beneath Miyake Volcano, suggesting that this factor is essential for accurately modeling the dike intrusion.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>F-value and AIC-value for each model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model type</td>
<td>Dike complex model</td>
</tr>
<tr>
<td>Two</td>
<td>Three</td>
</tr>
<tr>
<td>F value</td>
<td>0.72</td>
</tr>
<tr>
<td>AIC value</td>
<td>254.63</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>The maximum, minimum and optimal values of the parameters in the search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat (°N)</td>
<td>Lon (°E)</td>
</tr>
<tr>
<td>Searching internal</td>
<td>0.005</td>
</tr>
<tr>
<td>Dike Miyake-side</td>
<td>Lower band</td>
</tr>
<tr>
<td>Upper band</td>
<td>34.150</td>
</tr>
<tr>
<td>Optimal value</td>
<td>34.135</td>
</tr>
<tr>
<td>Lower band</td>
<td>34.133</td>
</tr>
<tr>
<td>Central</td>
<td>Upper band</td>
</tr>
<tr>
<td>Optimal value</td>
<td>34.183</td>
</tr>
<tr>
<td>Lower band</td>
<td>34.175</td>
</tr>
<tr>
<td>Kozu-side</td>
<td>Upper band</td>
</tr>
<tr>
<td>Optimal value</td>
<td>34.270</td>
</tr>
<tr>
<td>Lower band</td>
<td>34.060</td>
</tr>
<tr>
<td>Spherical source</td>
<td>Inflation</td>
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<tr>
<td>Optimal value</td>
<td>34.085</td>
</tr>
<tr>
<td>Lower band</td>
<td>34.060</td>
</tr>
<tr>
<td>Deflation</td>
<td>Upper band</td>
</tr>
<tr>
<td>Optimal value</td>
<td>34.080</td>
</tr>
</tbody>
</table>

\[ F_0.13 \]
The estimated dike expansions are consistent with the seismic activity in each period (Fig. 7, Table 4). We suggest that the two M6 earthquakes of July 1 and July 9 were triggered by expansion of Miyake-side and central dikes, respectively during the period immediately prior to the earthquakes.

The spatio–temporal evolution of the dikes (Figs. 8 and 9) is as follows. In the first stage from June 27 to July 1, opening is rapid at the Miyake-side dike, particularly in the upper portion. The openings accelerated rapidly for the Kozu-side and central dikes on and after July 8, while the intrusion of the Miyake-side dike stagnated. After August 10, the Kozu-side dike intrusion stalled and the Miyake-side dike intrusion accelerated again. The central dike, particularly the lower sub-dike, had a great expansion during the period from July 2 to July 30. The final volume of the three dikes was estimated to be 1.67 km$^3$ (Fig. 8). This is much larger than the total deflation of 0.22 km$^3$ beneath the Miyake volcano. The dike volumes estimated by Nishimura et al. (2001), Ito and Yoshioka (2002) and Yamaoka et al. (2005) are 1.04, 1.09 and 2.00 km$^3$, respectively.

Hgiwara et al. (2004) discussed the spatio–temporal change of the high-Q area calculated by seismic wave tomography. Their result suggests an expansion from 139°139.5°34°34.5°0510 km Observation Calculation 30 cm Observation Calculation 7/15 7/1 7/9 8/18 7/30 7/30 7/1 7/9 8/18 7/15

Fig. 6. Observed and calculated deformation from the dike-complex model in the (a) horizontal and (b) vertical directions including modeled faults for the five M6 earthquakes. Black and white arrows denote observations and calculations, respectively. Confidence ellipses are 1σ.
of the high-Q area not only beneath Miyake Island but also around Kozu Island after July 1. Sakai et al. (2003) suggest that the intermittent bursts of the swarm migrated from deep to shallow in a short period of time at the same part of the swarm area.

The spatial change of the Miyake-side dike and other dikes differ widely. The pattern of volume change of the Miyake-side dike is negatively correlated with that of the spherical sources beneath Miyake Island (Fig. 9). A volume of 0.8 km$^3$, obtained when adding the deflation source and the caldera collapse of 0.6 km$^3$ as estimated by Nakada et al. (2001), migrated from Miyake Island to the dike. The volume of the magma supply from Miyake Island is equal to the volume of the Miyake-side dike, suggesting that magma is supplied to that dike from below Miyake Island. However, the large expansion of the lower part of both the central dike and the Kozu-side dike without change in the Miyake-side dike after July 8 suggest a second magma supply source from an area below the central dike rather than below Miyake Island. As the volume of the four segments of the central and Kozu-sub dikes is very much larger than the total volume of the two spherical sources (Fig. 9), other magma supplies are required to maintain a balance between the dike and source volumes.

The cumulative expansion of the lower part of the central dike is about 0.45 km$^3$ and is the largest of all
Fig. 7. (Left) Estimated expansion of dikes and volume changes of spherical sources in each period. Open and filled circles note inflation and contraction, respectively, of point sources beneath Miyake Island. Source strength scales with circle size. (Central) The observed and calculated horizontal deformation compared with the seismic activity during each period. (Right) The observed and calculated vertical deformation. Confidence ellipses are $1\sigma$. 
sub-dikes. The temporal change of the central dike is almost the same as that of the Kozu-side dike. A small opening (0.3 m) of the Kozu-side dike is estimated for the period from June 27 to July 1. This expansion is not significant as it only causes a few mm deformation at some stations. There is no swarm near the Kozu-side dike during the period from June 27 to July 1. As a result, we believe that the Kozu-side dike did not open until after that time, and the expansion of the central dike preceded that of the Kozu-side dike. This
suggests that a magma supply must be located beneath the central dike and intruded toward Kozu Island. Based on these observations, we suggest that the primary magma supply switched from a source below Miyake Island to a source below the central dike sometime during the July 1 to July 15 period.

5.3. Spatio–temporal variation of the spherical sources below Miyake Island

The spatio–temporal variation of the spherical sources below Miyake Island associated with dike opening was also calculated. Although there is disagreement between observations and calculations at some measurement sites, we believe that our models can explain the overall displacement pattern (Fig. 7).

In particular, the calculated deformation is inconsistent with that which was observed for two periods (June 27 to July 1; July 9 to July 15) at Miyake island, attributable to the simplified assumption of a two spherical sources (one inflating and the other deflating) below Miyake Island. Irwan et al. (2003) suggested the existence of two shallow dikes beneath the Miyake volcano on June 26. The observed deformation would therefore include the effects of these dike intrusions. The Miyake volcano erupted on July 14 and July 15. We propose that migration of magma to shallow depths during this time caused the complex deformation pattern.

The present estimation gives depths of 11.5 km for the deflation source during the August 11 to August 18 time period, although it was located at a depth of

Table 4
Estimated expansion of dikes and volume changes of spherical sources during each period

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</thead>
<tbody>
<tr>
<td>Miyake-side Dike (m)</td>
<td>Upper</td>
<td>9.60</td>
<td>0.19</td>
<td>0</td>
<td>0.51</td>
<td>0.40</td>
<td>0.93</td>
<td>1.13</td>
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<td></td>
<td>Lower</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>1.35</td>
<td>1.64</td>
<td>4.97</td>
<td>2.73</td>
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<tr>
<td>Central Dike (m)</td>
<td>Upper</td>
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<td>2.08</td>
<td>0</td>
<td>0</td>
<td>1.41</td>
<td>1.69</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0</td>
<td>4.16</td>
<td>5.32</td>
<td>7.31</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Kozu-side Dike (m)</td>
<td>Upper</td>
<td>0.30</td>
<td>0</td>
<td>2.24</td>
<td>3.74</td>
<td>4.18</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>0</td>
<td>0</td>
<td>0.16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.52</td>
</tr>
<tr>
<td>Spherical Sources (*10^7 m^3)</td>
<td>Inflation</td>
<td>1.60</td>
<td>0.02</td>
<td>5.96</td>
<td>0.27</td>
<td>0.07</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Deflation</td>
<td>12.06</td>
<td>1.31</td>
<td>6.57</td>
<td>1.86</td>
<td>1.32</td>
<td>6.10</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Fig. 8. Cumulative expansion of dikes and volume changes of spherical sources. Symbols and conventions are the same as in Fig. 7.
about 5 km in other periods. Eruptions occurred at Miyake volcano on August 18, just after the time in which the development of a deep source is indicated by the present analysis. Through examination of the basaltic-andesite lava of the July 14–15 eruption and the basaltic lava of the August 18 eruption, Geshi et al. (2002) suggested that the basaltic-andesite magma moved from a shallow reservoir to the dikes until the beginning of August, and basaltic magma was supplied from greater depth leading to the eruption on August 18. The deflation source at a depth of 11.5 km depth is therefore considered to represent the deeper supply of basalt magma. The huge volume changes estimated beneath the Miyake volcano on June 27 to July 1 and August 10 to August 18 correspond to periods of accelerated expansion of the Miyake-side dikes. This suggests that the source beneath the Miyake volcano is related to both the eruption of the volcano and the activity of the Miyake-side dike.

The present analysis also indicates a small inflation source at a depth of about 3.5 km beneath Miyake volcano. Furuya et al. (2003) inferred the existence of a low-density area at about 2 km depth based on gravity measurements and suggested the presence of shallow hydrothermal activity. Bando et al. (2005) proposed the emergence of a large temporary inflation source in the period leading up to the eruption on July 10, suggesting that the source represents the emplacement of magma rather than hydrothermal activity. However, the resolution of the our results is not sufficient to discuss the character of these inflation sources in detail.

6. Conclusion

An optimized dike-complex model was derived for the Miyake–Kozu Island area based on GPS measurements recorded at 28 sites during the period from June 27 to August 27, 2000. Dike complexes of two, three and four dikes were considered. Parameter optimization was also performed for two previous models; a
single dike with aseismic creep (Nishimura et al., 2001; Furuya et al., 2003) and a single dike with a deep deflation source (Yamaoka et al., 2005) using the same data. Based on the AIC value, the three-dike model provides the best solution of the dike-complex models examined, supporting existence of several dikes as suggested by Sakai et al. (2003). The geometries of the dikes and five M6 faults are consistent with the hypothesis of Hill (1977) for dike–fault interaction in volcanic regions.

The spatio–temporal change of the three dikes between Miyake–Kozu Islands and the two implied spherical sources beneath the Miyake volcano were also determined for seven discrete periods between June 27 and August 27, 2000. That analysis indicated that the three dikes, Miyake-side, central and Kozu-side, clearly underwent opening during different time periods. In the early stage of the activity, from June 27 to July 1, dike expansion was concentrated at the Miyake-side dike associated with a large deflation source at a depth of 7 km beneath the Miyake Volcano. This result suggests that magma was supplied from depth below Miyake Island. In the next stage, to August 10, a huge dike intrusion was inferred on the Kozu Island side accompanied by expansions of the lower parts of central dike. This indicates that magma was supplied from greater depth somewhere between Miyake and Kozu Islands. In the final stage, August 11 to 27, a huge deflation at an estimated depth of 11.5 km below the Miyake Volcano was inferred, with associated dike expansion in the lower parts of the Miyake-side dike. This final stage corresponds to the period of peak volcanic eruption of the Miyake volcano on August 18.

The dike intrusion processes indicated by the present analysis (Fig. 10) is therefore similar to that proposed by Furuya et al. (2003). Prior to the 2000 activity, basaltic-andesite and basaltic magma accumulated in sources at depths of about 5 and 10 km, respectively (Ueda et al., 2004; Nishimura et al., 2002) (Fig. 10a). Ueda et al. (2004) proposed a dike-like source for the shallow reservoir based on tilt and GPS data, thought our results are not capable of distinguishing such a geometry. The basaltic-andesite magma then rose to shallower levels, and intruded and expanded mainly into the Miyake-side dike between June 27 and July 1 (Fig. 10b). Lateral magma flow from Miyake Island then activated a dormant magma reservoir below the dikes, initiating supply into the lower part of the central dike and upper part of the Kozu-side dike between July 1 and August 10 (Fig. 10c). The existence of a magma source below the central dike is the key to our model. New basaltic magma then migrated from a deep source into the

Fig. 10. Schematic model of dike intrusion processes based on the present results. (a) Prior to the 2000 activity, (b) lateral magma flow from Miyake Island between June 27 and July 1, (c) magma supply from depth below the central dike between July 1 and August 10, (d) activity of a deep source below Miyake Island leading to the eruptive period from August 11 to August 18.
Miyake-side dike between July 30 and August 18, leading to the peak eruption on August 18 (Fig. 10d).

Acknowledgments

We wish to thank Dr. Michael P Poland and two anonymous referees for their careful reading of the manuscript and many constructive suggestions that helped improve this paper. Dr. Takeo Ito also has provided helpful advice and discussion relating to research strategies. We extend our gratitude to the Geographical Survey Institute of Japan for providing GPS data. Some of the Figures were prepared using Generic Mapping Tools (Wessel and Smith, 1995).

References


