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Interpretation of the Miyakejima 2000 eruption and dike emplacement using time animations of earthquakes

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Abstract

The seismic sequence of over 12,000 earthquakes accompanying the 2000 eruption of Miyakejima volcano has been studied by viewing time animations of the earthquakes beneath transparent topography. Seismic activity began on the evening of June 26 extending southwest from Miyakejima's summit. A few hours later the seismicity abruptly shifted to the WNW and a submarine eruption occurred off the West Coast of Miyakejima on the morning of June 27. Phreatic eruptions at Miyakejima's summit in July were accompanied by the formation of a new caldera. Following caldera formation explosive eruptions occurred in August. The eruption ended with minor explosions in September. The seismic activity that began with a low-magnitude swarm beneath Miyakejima grew to a major swarm with hundreds of events of M > 4 extending more than 40 km WNW from Miyakejima. Lesser numbers of earthquakes occurred on two N-S trending lines extending south and north of the main seismic trend. The seismicity has been interpreted as evidence for emplacement of a massive dike on the main trend that triggered additional earthquakes on the two cross trends. Our interpretation involves more restricted dike emplacement west of Miyakejima, including the possibility of additional submarine eruption, following cracking of the Philippine Sea plate.

The seismic activity associated with explosive eruptions in August helps to define Miyakejima's magma plumbing. A shallow reservoir beneath the southwest slope is defined by concentrations of earthquakes at 4-6 km depth, and a deeper source is suggested by a smaller number of earthquakes extending to 10 km vertically beneath the shallow source. Seismic activity preceding and accompanying eruptions at Miyakejima's summit are defined by seismic swarms extending from 4 km depth to the surface along a path connecting the summit with the shallow reservoir.

Away from Miyakejima shallow (< 1 km) earthquake swarms at minimum rates of 1 event per hour extending over several hours occur within restricted areas of diameter less than 3 km and define possible additional sites of undersea eruption or intrusion. Beneath sites west of Miyakejima the seismicity at depths of less than 4 km occurs earlier and toward Miyakejima, consistent with magma transport from Miyakejima's shallow reservoir. Shallow swarms extending 15 km to the WNW strongly suggest that additional intrusion and possibly eruption may have occurred on June 27-28.

Between June 27 and July 1, along the main seismic trend, and beneath the shallow sites, progressively deeper earthquake swarms occur at progressively later times, a pattern inconsistent with magma transport and interpreted here as the Philippine Sea plate cracking downward. The initial shallow cracking guided magma to the June 27 undersea eruption site. Subsequent cracking to the west allowed very rapid lateral withdrawal of magma from the Miyakejima reservoir allowing a new caldera to form. The deep cracking of the plate may have triggered additional magma sources, including a deep source suggested by the modeling of regional ground deformation data.

Key words: caldera, magma transport, earthquake swarm, Miyakejima

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Introduction

Miyakejima is an island basaltic stratovolcano located about 170 km south of Tokyo, Japan in the Izu-Bonin arc (fig. 1; (Ida, 1991)). In historical time eruptions have occurred about every 20 years (Tsukui and Suzuki, 1998). The eruption that began with a seismic swarm on the evening of June 26, 2000, evolved differently from other historical eruptions in that a submarine eruption near the west coast of Miyakejima occurred soon after the beginning of seismic activity, a new caldera was formed during subsequent eruptive activity at Miyakejima's summit, magma composition changed during the eruption, and the eruptive activity was accompanied by a seismic swarm of over 12,000 events extending WNW of Miyakejima (Nakada *et al.,* 2001 and references therein). Following Nakada and others (2001) we define several stages of eruption as shown in table 1. Eruptions are fed from a shallower magma and are resupplied from a deeper magma chamber, both located beneath the southwest flank of Miyakejima at depths ranging from 3–10 km (Amma-Miyasaka and Nakagawa, 2002; Fujita *et al.,* 2002; Kumagai *et al.,* 2001; Nishimura *et al.,* 2002).

Sakai and colleagues (Sakai *et al.,* 2001) made a comprehensive study of the well-located earthquakes. Data for the entire seismic swarm from June 26 through December 31, 2000 are shown in his figure 1, reproduced here as figure 1. The seismic trends are numbered on figure 1 and described in table 2.

- 1. Earthquake concentrations beneath Miyakejima volcano extending from the summit to about one km offshore in a southwest direction. Such swarms occurred at the beginning of the seismic activity on June 26 at about 6:30 pm to the morning of June 27, and recurred before, between and after eruptions at Miyakejima's summit in July and August.
- 2. Shallow seismic activity extending WNW from Miyakejima's summit a distance of about 15 km, occurring from about 10 pm June 26 to 12 pm June 29. The site of the June 27 undersea eruption is located on this trend.
- 3. The principal trend of deeper (6–20 km)

Table 1. Documented eruption timeline at Miyakejima

Stage	No.[1]	Location[2]	Begin	End	Petrology	comment
		summit/sw flank	6/26 1820	-	-	Seismic swarm begins
I	1	Site s1	6/27 0430?	6/27 0810	basaltic andesite	submarine eruption
II	2	summit	7/8 2000	7/8 2010	basaltic andesite	small eruption accompanies beginning of caldera collapse
	3a	do	7/14 0414	7/14 0714	do	phreatomagmatic (small quantity of juvenile material)
	3b	do	7/14 1550	7/14 2300	do	
	3c	do	7/15 0150	7/15 0320	do	do
	3d	do	7/15 0634	7/15 1300	do	do
III	4	summit	8/10 0650	8/101333	basalt	explosive: small; intermittent probable end of gravitational caldera collapse
	5	do	8/11 1300	8/14 1600	do	explosive; small; intermittent caldera continues to enlarge laterally by landsliding
III	6	summit	8/18 1704	8/18 2030	basalt	explosive: large
	7	do	8/24 0633	8/24 0754	do	explosive: small
	8	do	8/29 0430	8/29 1746	do	explosive: large
III	9	summit	8/30 1200	8/30 1500	basalt	explosive: small
IV	10	summit	9/03 0842	9/03 1800	degassing	Explosion
	11	do	9/09 0530	9/10 1845	do	do
	12	do	9/10 0445	9/11 1650	do	do
	13	do	9/11 0636	9/11 2010	do	do

[1] Numbers and specific times given for the eruption history of Nakada *et al,* 2001 ; S. Nakada, pers. comm. 2003.
[2] Sites shown on Figure 3

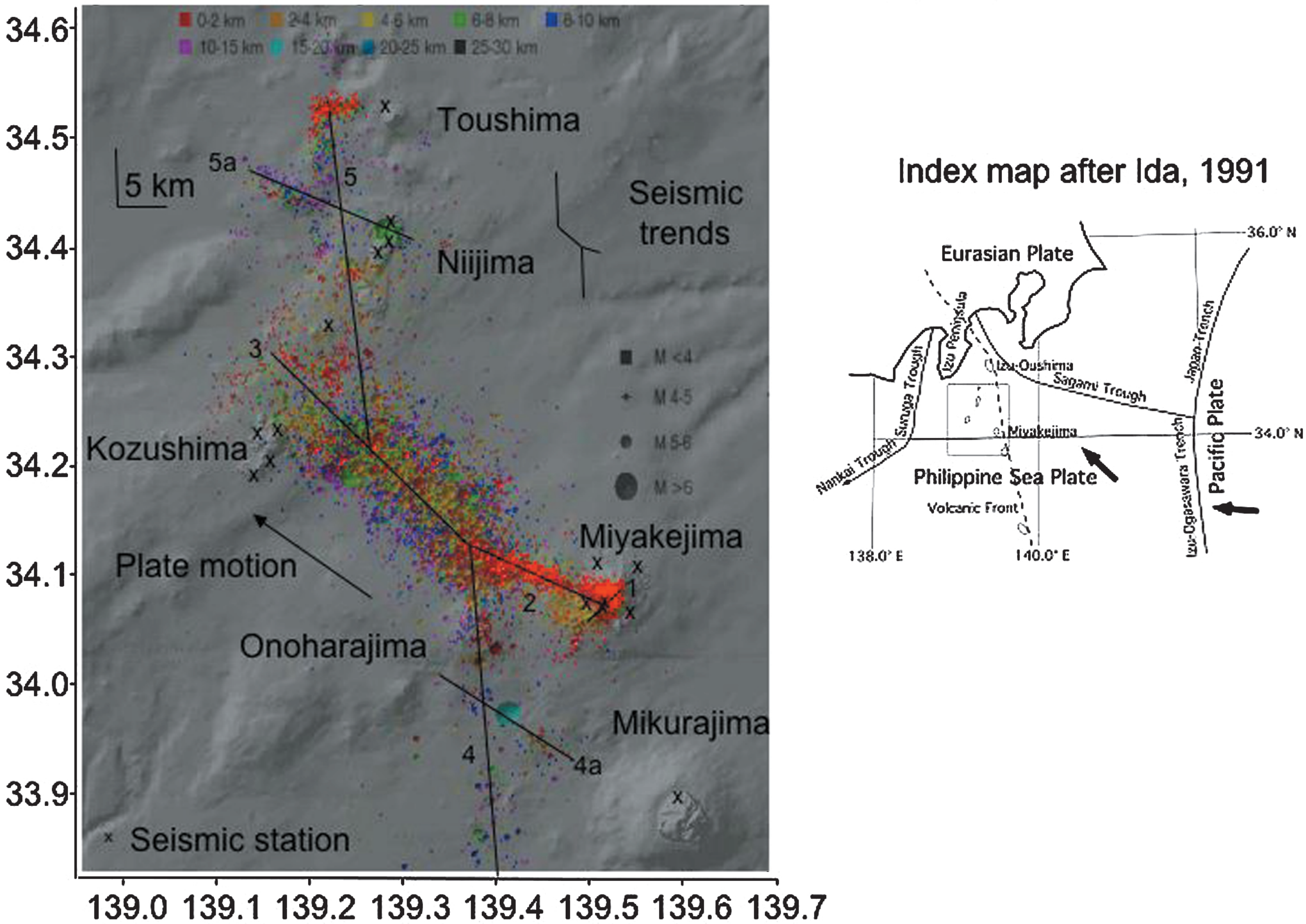

Fig. 1. Index map showing Miyakejima seismic swarm June 26-Dec. 31, 2000. Information for numbered seismic trends is given in table 2. Data shown are located from arrivals at 3-component seismometers ("x" symbol); modified from Sakai and others, 2001, fig. 2.

Table 2. Seismic trends defined by the Miyakejima 2000 earthquake swarm

Trend	Longitude	Latitude	Azimuth	Range#	comment
	139.534 139.50357	34.082 34. 06385			Miyakejima summit Magma chamber*
1	139.47-139.54	34.04-34.10	63.4	± 3 km	1.7 km southwest of magma chamber to Miyakejima's summit
2	139.54-139.34	34.16-34.04	108.051	± 3 km	From Miyakejima to sites of offshore 0-1 km depth earthquake swarms (s1-s5)
3	139.19-139.36	34.30-34.14	124.026	±5 km	From site s5 past site s12
4	139.38-139.4	34.1-33.8	174.8	± 5 km	south trend beginning north of Onoharajima
4a	139.33-139.5	34.02-33.94	117.3	±3 km	Cross trend defined by aftershocks of M 6.5 earthquake on 7/30
5	139.21-139.26	34.6-34.22	170.5	± 5 km	North trend beginning between sites s11 and s12
5a	139.12-139.35	34.47-34.40	105.7	± 3 km	Cross trend defined by aftershocks of M 6.3 earthquake on 7/15

Distance perpendicular to the trend. To eliminate outliers only earthquakes within the distance specified are projected onto plotted sections or used in animations

* Average longitude and latitude of 87 earthquakes associated with the August eruptions whose depth range is 4-6 km and which fall within 1 km on either side of trend 1.

seismicity extending farther to the northwest from the western end of trend 2. This seismicity began about 6 pm on June 27 and continued throughout the period. Three earthquakes of M≥6 occur south of the western end of this trend.

- 4. The western end of trend 2 is connected to seismicity oriented approximately N-S extending south from the main swarm in the vicinity of Onoharashima. In the center of the N-S segment there is a NW-SE cross trend (4 a) defined by aftershocks of a M6.4 earthquake that occurred on July 30.
- 5. A second N-S trend extends from about 2 km east of Kozushima to 2 km west of Toshima. About 8 km south of Toshima there is another NW-SE cross trend (5 a) defined by aftershocks of a M 6.3 earthquake that occurred on July 15.

Previous studies have made the assumption that the principal cause of the seismic activity was the emplacement of a dike originating from Miyakejima. Table 3 shows the seismic energy released over a period of three months compared to thirty years of seismic release at Kilauea, one of the world's most active volcanoes. The rate of energy released by the earthquake swarm shown in figure 1 is several orders of magnitude greater than released at Kilauea and is equivalent to the energy release associated with a large plate boundary earthquake (M 7.6). In this paper we assume that such energy release is too great to be purely magmatically driven and we propose tectonic failure of the Philippine Sea plate as a process that took place during the eruptive activity.

We pose the following questions with regard to the mechanics of eruption and propagation of the seismicity.

- What is the relationship between tectonically induced seismicity ("plate failure") and seismicity associated with intrusion and/or eruption ?
- Why did the caldera form at this time ?
- Can magma source(s) be identified from the seismic data ?

Answers to these questions allow us to locate magma sources, explain the rare formation of a new caldera and provide evidence for location and timing of possible additional seafloor eruption.

Data sources and methods of analysis

Seismic data covering the entire time period are from a set of well-located earthquakes provided by Shin'ichi Sakai (cf. Sakai *et al.,* 2001). Locations are derived from the on-land network only, comprising 3-component seismometers located on Miyakejima, Mikurajima, Kozushima, Shikinejima, Niijima and Toshima (plotted on fig. 1, Sakai *et al.,* 2001, figure 2, pers. comm., 2003). Stations on the Izu peninsula were not used in the locations.

Subsequent to preparation of the original earthquake catalog an Ocean Bottom Seismometer (OBS) network was established on July 1. Earthquakes

Table 3. Seismicity at Kilauea and Miyakejima

Volcano time period	M	No.	Seismic moment ($x 10^{21}$ dyne-cm)	Comment
Miyakejima	6-7	5	1662	Rate of moment release per month: **3158**
6/26-9/26/2000	5-6	83	1485	
3 months	4-5	1607	3992	
	3-4	9021	2336	
	Total	10716	9474*	
Kilauea	>7	1	2236	rate of moment release per month: **4.58**
1971-2000	6-7	1	257	
30 years	5-6	8	307	
	4-5	136	315	
	3-4	1502	302	
	Total	1648	3417	

* M 7.6 (comparable to a single plate boundary event)

that occurred after the OBS network was installed are relocated and being studied by S. Sakai. Earthquakes that occurred before installation of the OBS network have been relocated after determining a new velocity structure and calculating new station corrections. New catalog data for earthquakes from the beginning of the swarm on June 26 through the end of June 28 are used in figures 2–5. The average location errors for the relocated seismicity are as follows:

Longitude: 0.29 km
Latitude: 0.21 km
Depth: 0.56 km

Earthquake data are read from a spreadsheet saved as an ASCII text file. Trend orientations are taken from figure 1 and distances parallel and perpendicular to the trend axes are calculated. The principal concentrations of seismic data are within 3–5 km on either side of the trend axes.

The earthquake sequence was originally studied using programs written or modified by the senior author using the IDL programming language. One program displays a single frame of an earthquake dataset under topography rendered transparent to the earthquakes. Topography is variously represented by a Digital Elevation Model (DEM) of Miyakejima, obtained from a password-protected site on the worldwide web, or from an image of the Izu area in the vicinity of Miyakejima (see cover image, Toda *et al.,* 2002, modified image provided by Serkan Bozkurt). The model containing both topography and earthquakes can be rotated with the mouse to find a useful perspective from which to view the earthquakes. Either the entire dataset or a part of it specified by beginning and ending times can be viewed.

A second program creates time animations produced at the chosen perspective (including map views or vertical sections where relevant) over time intervals (starting time, ending time and elapsed time for each frame) specified by the user. Frames may either be chosen as non-overlapping or as overlapping. In the latter case, two parameters are given. The first specifies the time interval shown in one frame (e.g., one day) and the second parameter specifies the time increment by which the frames progress (e.g., one hour). The resulting time animation shows one day of earthquakes in which successive frames are incremented ahead and decremented behind by one hour.

Earthquakes used in the animations are color-coded (in the present instance by depth) for easy distinction. Earthquakes whose magnitude is less than 4 are shown by small square symbols. Earthquakes whose magnitudes are greater than or equal to 4 are shown as solid spheres of the appropriate color whose size is proportional to magnitude. The entire dataset used for the animations is shown in figure 1.

After viewing animation sequences, we used the spreadsheet to identify earthquake sequences that occur as swarms. The distance parallel to and perpendicular to the trend axis are calculated for every earthquake. Criteria for identifying swarms are given below.

frequency of events--≥1 event/hour with no gap of greater than one hour. Within such swarms there are some instances of more intense activity with rates of over 6 events/hr with no gap of greater than 10 minutes. These are referred to in the figures, tables and text as intense earthquake swarms.

number of events--minimum of 10 events in a normal swarm and 5 events in an intense swarm falling within a region.

size of region--approximately 3 km by 3 km.

Sites were identified at which earthquake swarms occurred at the shallowest depths (0–1.0 km). Site locations, swarm times and number and depth of events used to define the location are given in table 4 and shown in figure 3, which shows the location of trends 1 and 2 and sites 1–5 in relation to an expanded view of Miyakejima before formation of its caldera. We associate magma transport with seismic sequences that propagate with time from a magma source to shallower depths. We associate plate failure with seismic swarms that propagate laterally parallel to the main seismic trend and downward. The latter are assumed to have a broader distribution in both time and space.

Results

Seismic data is inherently difficult to represent on two-dimensional plots as there are four variables of importance, i.e., distance, depth, time and magnitude. We have used the animations to identify criti-

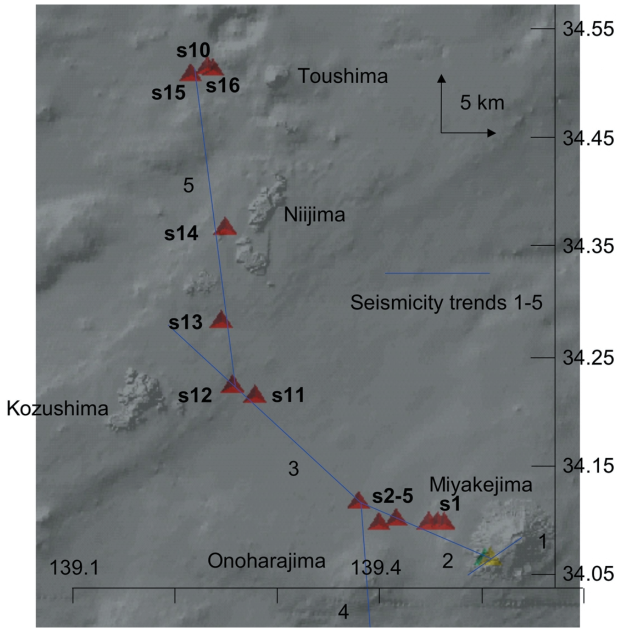

Fig. 2. Sites of earthquake swarms shallower than 1 km (s-designations). Sites 1–5 are defined using relocated data (S. Sakai, pers. comm., 2004) and are shown in detail in figure 3. Sites 10–16 are located from the original catalog and may be changed after relocations are finished. All sites are numbered according to the earliest earthquake swarm activity.

cal time periods. Earthquakes are then plotted on time-distance plots with the depth coded by color. We have chosen to use the symbol size to identify swarm activity. Variation of magnitude with distance and time is described below.

Seismic activity beneath Miyakejima (trend 1)

Strong swarm activity began at about 6:30 pm on June 26 and continued to the time of undersea eruption on the morning of June 27 (fig. 4 a), then markedly slackened (fig. 4 b). Seismicity picked up again on July 4, precursory to the beginning of eruption and caldera collapse on July 8, slacked off after the last of the July eruptions (fig. 4 b) and picked up again during the period of eruptions in August (fig. 4 c). Magnitudes are mostly less than 3 with some events in the range 3–3.5 and no events exceeding M 4. At the beginning swarms occur mostly shallower than 3 km. Swarm activity during the July eruptions is confined to depths shallower than 3 km, and earthquakes deeper than 4 km are significantly absent.

Location of Miyakejima's magma reservoir

Earthquakes deeper than 4 km during the August eruptions do not occur in swarms, but occur

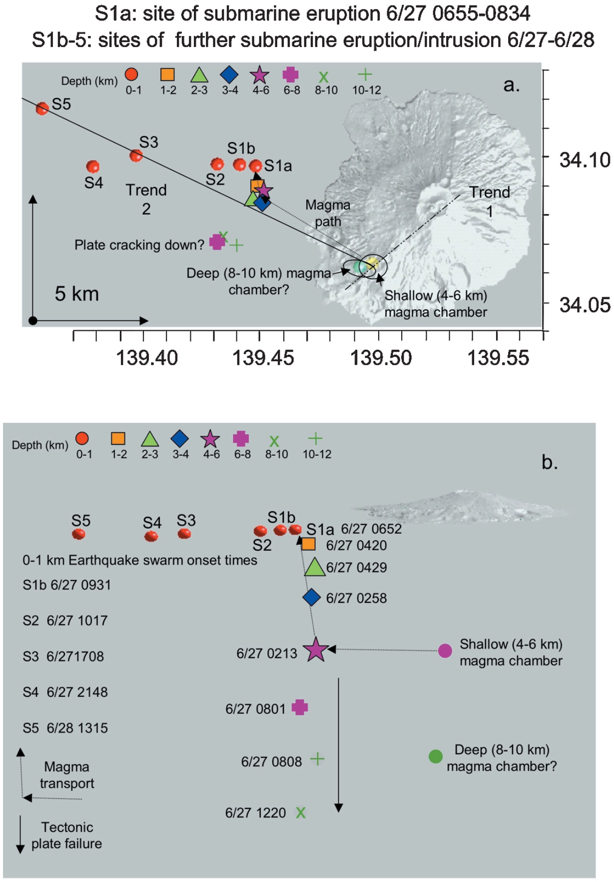

Fig. 3. Sites of eruption and/or shallow intrusion along trend 2 that are inferred to be fed from a shallow magma reservoir beneath the SW flank of Miyakejima. Magma chamber locations are inferred from seismicity associated with explosive eruptions at Miyakejima's summit in August 2000. See text for further explanation.

a. plan view

b. cross-section

within a restricted area beneath the southwest flank of Miyakejima and these are used to define possible locations for two magma reservoirs, one at 4–6 km depth and the other at 8–10 km depth. These are not well-determined, but are consistent with the views of other authors for the existence of two reservoirs (Amma-Miyasaka and Nakagawa, 2002; Fujita *et al.*, 2002; Kumagai *et al.*, 2001; Nishimura *et al.*, 2002). Earthquakes deeper than 4 km are more numerous at the times of the intense shallow swarms. Deep earthquakes are particularly abundant following the eruption on August 18, the most explosive eruption of the series (fig. 4 c).

Seismic activity beneath trend 2

Seismic swarm activity along trend 2, to just

Table 4 a. Locations of earthquake swarms on seismic trend 2 WNW of Miyakejima.

Depth	Begin	End	no.	eq/hr	Lon.	Lat.	D#	A*	Comment
4-6 km	na	na	na	na	139.504	34.064	1.62 1	-0.743	magma chamber
0-1 km	**6/27 0652**	**6/27 0834**	10	5.9	139.457	34.097	7.054	0.424	**s1a:** known submarine eruption near this time
1-2 km	6/27 0420	6/27 0540	23	17.3	139.459	34.091	6.603	-0.022	
2-3 km	6/27 0429	6/27 0446	6	21.2	139.461	34.089	6.409	-0.077	
3-4 km	6/27 0258	6/27 0550	10	3.5	139.474	34.081	6.540	-0.434	
4-6 km	6/27 0213	6/27 0443	8	3.2	139.459	34.086	6.374	-0.406	displaced from site 1a
6-8 km	6/27 0801	6/27 1345	37	6.5	139.443	34.071	7.085	-1.975	do
8-10 km	6/27 0808	6/27 1902	5	0.5	139.450	34.070	6.419	-1.841	do
10-12 km	6/27 1220	6/27 1616	5	1.3	139.444	34.073	7.055	-1.833	do
0-1 km	6/27 0931	6/27 1150	10	4.3	139.451	34.098	7.602	0.272	**s1b**
1-2 km	6/27 0701	6/27 0951	82	28.9	139.451	34.094	7.436	-0.050	
2-3 km	6/27 0701	6/27 0802	23	17.3	139.454	34.091	7.047	-0.155	
3-4 km	6/27 0702	6/27 0822	24	22.6	139.451	34.088	7.105	-0.440	
4-6 km	6/27 0456	6/27 0512	5	18.8	139.466	34.085	6.650	-0.240	
6-8 km	6/27 0714	6/27 0727	5	23.1	139.463	34.096	6.555	0.533	displaced from site 1b
8-10 km	6/27 1617	6/27 1626	8	53.3	139.435	34.071	7.212	-2.207	do
0-1 km	6/27 1017	6/27 1225	10	4.7	139.442	34.098	8.347	0.016	**s2**
1-2 km	6/27 0824	6/27 0836	5	25.0	139.443	34.095	8.122	-0.167	
2-3 km	6/27 0800	6/27 0816	5	18.8	139.442	34.095	8.175	-0.359	
3-4 km	6/27 0641	6/27 0653	3	15.0	139.441	34.092	8.167	-0.467	
4-6 km	6/27 0400	6/27 01219	8	1.0	139.438	34.093	8.467	-0.519	
6-8 km	6/27 1235	6/27 1309	8	14.1	139.438	34.095	8.506	-0.334	
8-10 km	6/27 1321	6/27 1333	5	25.0	139.449	34.110	8.354	1.172	displaced from site 2
0-1 km	6/27 1708	6/27 1834	8	5.6	139.410	34.101	11.165	-0.716	**s3**
1-2 km	6/27 1323	6/27 1608	39	14.2	139.417	34.099	10.490	-0.651	
2-3 km	6/27 1233	6/27 1335	7	6.8	139.420	34.099	10.230	-0.547	
3-4 km	6/27 1338	6/27 1542	12	5.8	139.415	34.094	10.382	-1.056	
4-6 km	6/27 1257	6/27 1640	14	3.8	139.411	34.095	10.814	-1.083	
6-8 km	6/27 1358	6/27 1814	34	8.0	139.411	34.099	10.932	-0.936	
8-10 km	6/27 1355	6/27 1724	11	3.2	139.407	34.091	10.930	-1.566	
10-12 km	6/27 1341	6/27 1527	5	2.8	139.414	34.092	10.371	-1.260	
0-1 km	6/27 2148	6/28 0152	6	1.5	139.392	34.097	12.438	-1.500	**s4**: shallow site not tightly constrained
1-2 km	6/27 2029	6/27 2125	7	7.5	139.401	34.112	12.369	-0.119	intense swarm begins at 2142, D=12.418, A=-0.580
2-3 km	6/27 1855	6/27 1951	6	6.4	139.391	34.102	12.792	-0.435	intense swarm begins at 2046, D=12.152, A=-0.569
3-4 km	6/27 2111	6/27 2148	6	9.7	139.400	34.109	12.357	-0.425	
4-6 km	6/28 0222	6/28 0258	9	15.0	139.395	34.105	12.539	-0.819	
6-8 km	6/28 0828	6/27 1301	7	1.5	139.397	34.109	12.587	-0.489	
8-10 km	6/28 1124	6/28 1246	5	3.7	139.392	34.102	12.707	-1.136	
10-12 km	6/28 1334	6/28 1422	3	3.8	139.384	34.115	13.926	-0.374	
0-1 km	6/28 1315	6/28 1555	6	2.3	139.372	34.117	15.018	-0.601	s5 high magnitude 3.5-4.9
1-2 km	6/28 1250	6/28 1359	32	27.8	139.368	34.130	14.806	-0.121	do 3.3-4.4
2-3 km	6/28 1245	6/28 1314	12	24.8	139.376	34.118	14.768	-0.372	
3-4 km	6/28 1242	6/28 1310	10	21.4	139.378	34.120	14.650	-0.230	
4-6 km	6/28 1311	6/28 1334	6	15.7	139.377	34.119	14.701	-0.302	
6-8 km	6/28 1338	6/28 1554	8	3.5	139.375	34.118	14.866	-0.444	
8-10 km	6/28 1309	6/28 1600	10	3.5	139.379	34.121	14.723	0.114	later seismicity at 1733-2159, D=14.973, A=-0.275 closer to site
10-12 km	6/28 1352	6/28 1559	5	2.4	139.374	34.119	14.950	-0.385	

distance (km) measured from Miyakejima's summit projected onto WNW azimuth 108.051° (fig. 1 trend 2)
* distance (km) perpendicular to trend 2

Table 4 b. Locations of Earthquake swarms. b. <1 km depth and away from Miyakejima#

Depth	Begin	End	no.	eq/hr	Lon.	Lat.	D*	Comment
	8/02 1050	8/2 1159	4	3.5	139.222	34.525	8.32	s10
0-1 km	9/11 0802	9/11 1040	7	2.7				
0-1 km	9/20 1939	9/20 2112	8	2.8				
0-2 km	8/03 2216	8/04 0048	5	2.0	139.269	34.217	42.37	s11
0-2 km	8/04 0155	8/04 0422	5	2.0	139.247	34.226	41.08	s12
0-2 km	8/18 1328	8/18 1651	8	2.4	139.236	34.287	34.37	s13
0-1 km	8/18 2233	8/19 0240	6	1.5	139.240	34.374	24.91	s14
0-0.5 km	8/29 1217	8/29 1556	4	1.1				
0-1 km	9/11 0611	9/11 1442	14	1.6	139.205	34.518	8.88	s15
0-1 km	9/11 0854	9/11 1354	7	1.4	139.227	34.523	8.59	s16

#Depths from original catalog (Sakai and others, 2001) subject to re-evaluation using obs network
* arbitrary distance south of Latitude 34.6 along azimuth 170 (trend 5)

past the end of the undersea eruption is shown in figure 5 a. At about 9: 50 pm on June 26, 3 hours after the beginning of the swarm, the seismicity began a clockwise migration to the north and the trend of the seismicity changed from SW to WNW (trend 2 of fig. 1). Seismic swarms between the presumed magma reservoir and Miyakejima's summit are mostly between 1 and 3 km depth. Following the shift in trend, seismic activity became shallower beneath Miyakejima, but deepened again as the seismic swarm moved offshore.

Undersea eruption on June 27

An offshore concentration of swarms at 2–6 km depth very early on the morning of June 27 are interpreted as being associated with migration of magma precursory to the undersea eruption. Seismic swarms at 4–6 km depth continue beneath the sites of shallow seismicity, suggesting continued magma movement at depth away from the magma reservoir. The confirmed undersea eruption (Kaneko *et al.,* 2004, submitted; Nakada *et al.,* 2001) was first identified by discolored water west of Miyakejima about 9 am on the morning of June 27. The seismic data suggest that eruption occurred between 6: 59 and 8: 34 am at site 1 a, a distance of 7 km from Miyakejima's summit (table 4a, figs. 3 and 5 a, b). The magnitudes of earthquakes during this time are mostly less than 3, with a few events between M3–3.5 and no earthquakes of M > 4.

Seismicity following the undersea eruption

Following the known undersea eruption shallow seismic activity continued to propagate to the WNW beneath sites s1b-s5 (figs. 3 and 5 c, d, table 4 a). Locations of shallow earthquake swarms at several sites WNW of Miyakejima along trend 2 are shown in figure 3, numbered according to the timing of the earliest swarm activity shallower than 1 km (table 4 a). The timing of shallow activity associated with the undersea eruption site s1a is shown on figures 3 b and 5 a, b. The earliest swarm associated with eventual eruption at this site occurs at 4–6 km, 2–3 km closer to Miyakejima. Earthquake swarms both shallower and deeper occur closer to the time of eruption, as shown in figure 5 b. This pattern is repeated at sites 1 b, 2, 3, 4 and 5. Between sites, for a given depth range, earthquakes farther from Miyakejima occur at progressively later times (figs. 5 b, d, 6).

At about 9 am on June 27, large (> M4) earthquakes at depths of 2–4 km began at a distance of 8 km from Miyakejima's summit (site s2) and migrated westward to reach site s5 by 11: 45 on June 28 (fig. 5 c, d). These were succeeded by equally large earthquakes shallower than 2 km that began beneath site s3 at 2 pm June 27 and migrated west to reach site s5 by 1 pm on June 28 (fig. 5 c, d). Shallow swarm activity comparable in intensity to that beneath sites s1 occurred beneath sites s3 on June 27 between 5 and 6: 30 pm (table 4 a). The latest swarm activity at comparable rates occurred beneath site s5 between 12: 50 and 2 pm on June 28. As a background to the most intense activity, nearly 24 hours of westward-progressing, nearly continuous shallow seismic activity, including repetition of shallow swarms beneath sites s1a to s3, occurred from the afternoon of June 27 to the morning of June 28 (fig. 5 c).

Seismic events northwest of site s5, away from Miyakejima (trend 3)

Trend 3 connects shallow sites s5 and s12, yielding a calculated azimuth of 124 degrees, and is located near the center of the main seismic trend. Distances are calculated from site s5. We divided the central part of trend 3 (±2 km from the trend axis) into segments of variable length parallel to the trend (fig. 6). We then looked at the seismic history for each region. West of site s5, seismic swarm activity continued to accelerate and deepen (fig. 1, 6). Figure 6 illustrates the progression using data from the original catalog, not yet relocated. The westward deepening is complete by the early morning of July 1. After that the patterns are more complex.

Seismic events along the N-S trend between Kozushima and Toshima

Earthquake swarms shallower than 1 km depicted in the original catalog are shown on figure 2 as sites s10-s16. There is a particularly intense swarm on September 11, located west of Toshima. These data are flagged for future interpretation when the earthquake relocations using the OBS network are complete.

Interpretation

Earthquake swarms have been envisioned as taking place in a heterogeneous lithosphere, triggered by a concentrated external stress, most commonly a magmatic intrusion (Hill, 1977; Mogi, 1963).

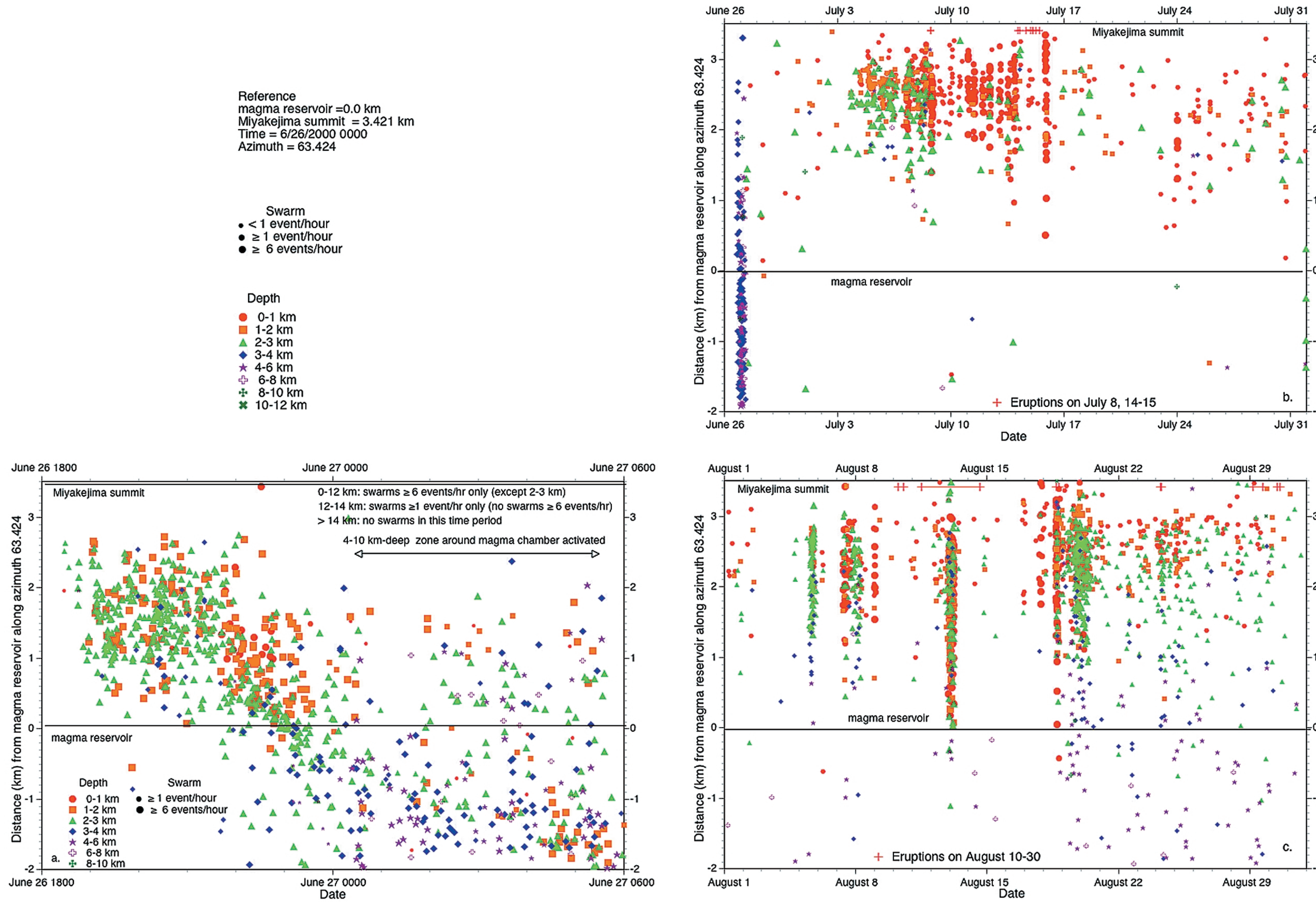

Fig. 4. Time-distance plots showing seismicity between Miyakejima's summit and magma reservoir (trend 1)

a. June 26 1800-June 27 0600, 2000. Relocated data are used

b. June 26-August 1, 2000. Eruptions at Miyakejima's summit are shown as red crosses (+). For June 26–27 only earthquake swarms deeper than 3 km are shown. Depth and intensity of earthquake swarms are coded by color and size (see legend). Original data are used

c. August 1-September 1, 2000. See information given for figure 6 b.

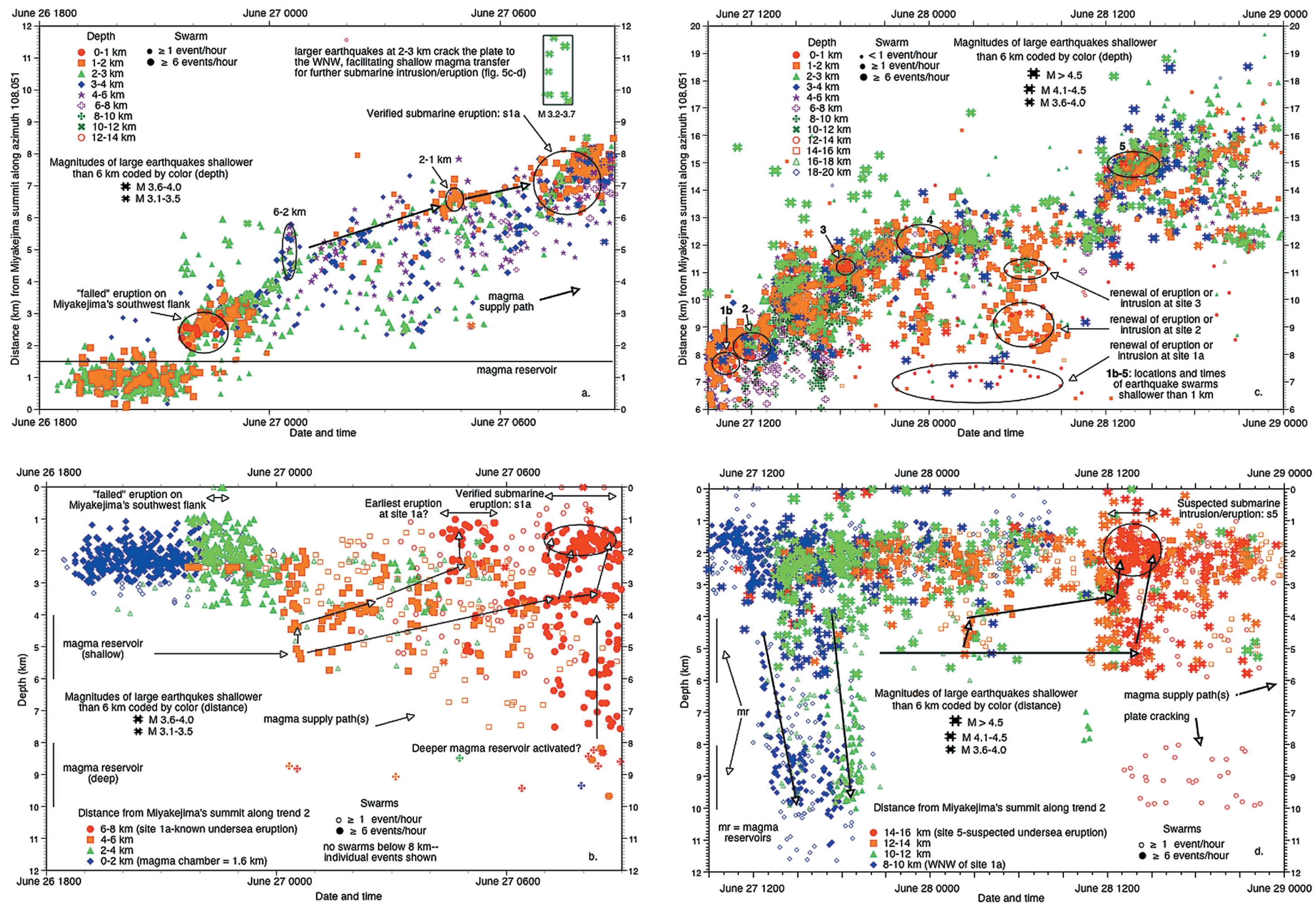

Fig. 5. Time plots showing seismic swarms WNW of Miyakejima (trend 2). Magma transport trends are inferred from the swarm data. Miyakejima's summit is used as reference, distance=0.0. Magma reservoirs at 4-6 and 8-10 km beneath Miyakejima's southwest flank are located at distance=1.62 km. Earthquakes above 6 km with magnitudes greater than 3.5 are shown as special symbols (#-filled) whose size represents intervals of 0.5 M. Colors are consistent with the swarm data. Relocated data are used.

a. Time-distance plot showing earthquake swarms preceding the verified undersea eruption. Depth and intensity of earthquake swarms are coded by color and size (see legend).

b. Time-depth plot showing earthquake swarms preceding the verified undersea eruption. Distance and intensity of earthquake swarms are coded by color and size (see legend).

c. Time-distance plot showing earthquake swarms following the undersea eruption interpreted in the text to be associated with intrusion and/or additional undersea eruption. Depth and intensity of earthquake swarms are coded by color and size (see legend).

c. Time-depth plot showing earthquake swarms following the undersea eruption interpreted in the text to be associated with intrusion and/or additional undersea eruption. Distance and intensity of earthquake swarms are coded by color and size (see legend).

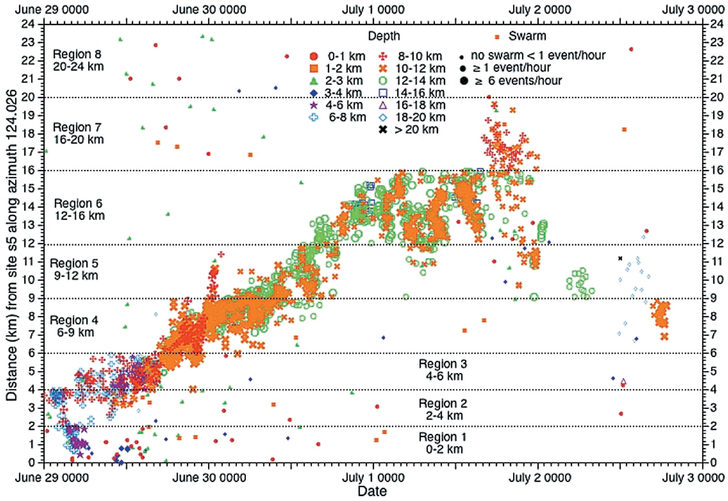

Fig. 6. Time-distance plots from June 29 to July 3 showing WNW migration of earthquake swarms along trend 3. Data are from original catalog. Details of the time-depth relations may change when relocation of the data set is completed.

We consider here the implications of a pre-stressed lithosphere, which could add a tectonic component to the resulting swarm, greatly magnifying the effects, including increasing both the number of events and the seismic moment release.

The 2000 Miyakejima sequence is unusual, both in the number of events and the seismic moment release. A purely magmatic process, such as a dike intrusion, would normally be accompanied by a many small magnitude earthquakes whose number should diminish after magma reaches the surface. Using Kilauea volcano as an analog model, intrusion with or without eruption could occur along a linear trend several kilometers in length with possible repetition of shallow seismic activity accompanying reactivation of earlier eruption sites as new pulses of magma are supplied from a magma source. Earthquake hypocenters would be expected to migrate upward and away from the magma source.

The activity in 2000 appears to be an example of a truly tectonomagmatic process, combining features of the two processes listed above, in which both number of seismic events and the moment release exceed by orders of magnitude that associated with a normal magmatic intrusion. We interpret the Miyakejima sequence as consisting of a tectonic component, referred to here as "plate failure", superimposed on a magmatic component that initially consisted of a dike propagating away from Miyakejima along trend 2. The two processes are intimately linked in a feedback loop as interpreted below.

Undersea eruption and plate cracking west of Miyakejima

The northward shift of seismic activity just before 10 pm on June 26 is interpreted as a response to the beginning of cracking of the Philippine Sea plate, marked by isolated seismicity deeper than 6 km beneath Miyakejima. Absent the plate cracking the seismic swarm probably would have led to eruption on Miyakejima's southwest flank, as in the last eruption in 1983. The progressive shallowing with time of earthquakes preceding the undersea eruption shown in figure 3 b is consistent with upward-directed lateral magma transport from the Miyakejima reservoir to the surface. The similar pattern observed beneath the other shallow sites is interpreted as evidence for westward propagation of a dike at depths between 4 and 2 km, periodically feeding additional shallow intrusion and perhaps eruption. Magma originating at Miyakejima is interpreted to have traveled only as far as site s5, the distal extent of seismicity shallower than 1 km depth. Thus the emplacement of a dike west of Miyakejima is interpreted as extending only shallower than 4 km and no more than 13 km from Miyakejima's magma reservoir (fig. 3).

One can speculate as to why this additional undersea activity went undetected. One possibility is that magma did not reach the surface west of site s1 a in spite of the fact that the rates of shallow seismicity beneath sites 2, 3 and 5 are comparable to that associated with the known undersea eruption. If eruption did occur, these sites are in deeper water, 300–400 m estimated from pre-eruption bathymetry, and are located from 1–8 km farther to the northwest. At about 14: 40 on June 27 a helicopter re-visited the area where the discolored water had been seen that morning (Kaneko *et al.,* [2004, submitted]). This would have been between the times of possible eruption at sites 2 and 3, but those sites were more than one km west of the initial sighting and may have been missed. All other activity was later and several km farther west.

The occurrence of larger magnitude earthquakes at 2–3 km both during the eruption (fig. 5 a: M 3.2–3.7, 2–4 km farther west) and following the end of the undersea eruption (fig. 5 b: M > 4, 5–8 km farther west) is interpreted as shallow plate cracking ahead of the propagating dike that allowed the intruding magma to continue to move WNW. It is likely that the subsequent strong (> M 4) earthquakes shallower than 2 km (fig. 5 d) also represent plate cracking toward the surface, as earthquakes of that magnitude were not recorded during eruption at site s1. Once initiated the tectonic earthquake swarm accelerated in number and magnitude of events and also deepened with time resulting in a seismic moment release far exceeding what could be associated with the relatively small magma system beneath Miyakejima (see, for example, arguments in Furuya *et al.,* 2003 a). The downward progression of seismicity deeper than 6 km (table 4 a, fig. 3 b) is inconsistent with upward magma movement and is therefore interpreted as the plate cracking downward below the sites of eruption or shallow intrusion. The resulting tensile fracturing might be analogous to fractures visible in ice beneath the surface of a frozen lake.

The interpretation offered here is most consistent with a model based on gravity and deformation data (Furuya *et al.,* 2003 a). The movement of magma to site 5 approximates the filling of tensile dislocation I (fig. 3 and table 2 of the reference cited). Our interpretation differs from that of other authors (e.g., Ito and Yoshioka, 2002; Nishimura *et al.,* 2001; Ozawa *et al.,* 2004) who suggest that magma from Miyakejima might have traveled the full distance of the earthquake swarm. Their estimates of magma volume, about 1.2 km^3, exceed the volume of caldera collapse, estimated at 0.67 km^3 (table 3). A fundamental question, not addressed in the existing literature, is whether the rather small Miyakejima magma reservoir could provide the overpressures necessary to drive magma all the way to Kozushima. As noted above (table 3), we are skeptical that the large seismic moment release can be attributed solely to long-distance transport of magma from Miyakejima.

The authors cited above, including Furuya *et al.,* mention the possibility of an additional magma source near Kozushima. Lengthening of the GPS baseline between Kozushima and Niijima was underway by June 30 (Kaidzu *et al.,* 2001, fig. 10), timing that is consistent with the westward moving seismic swarm and with either lateral migration of magma from Miyakejima or by filling of Furuya *et al.,*'s tensile crack II from a different source. In the absence of evidence for shallow seismic swarm activity west of site 5, we would favor a second source (see below) to reconcile the difference in magma volumes. The need for a second source could be obviated by partial replenishment beneath Miyakejima of the shallow magma reservoir with material from the deeper basaltic magma reservoir as discussed by Furuya *et al.* (2003a, p. 383), and in the section following.

Magma resupply

Earthquakes below 4 km on trend 1 occur on the morning of June 27, after shallow seismicity had shifted from trend 1 to trend 2, and prior to and following the submarine eruption (fig. 4 a, 5 b). We interpret their occurrence as being associated with removal of magma from the shallow reservoir for eruption along trend 2 and resupply from a deeper basaltic reservoir, magma that eventually was erupted at Miyakejima's summit in August. Earthquakes deeper than 4 km are rare during July, suggesting that most of the magma resupply had taken place in June. The reoccurrence of earthquakes deeper than 4 km following the large explosive eruption on August 18 is correlated with a large increase of SO2 emission (Kazahaya *et al.,* 2001; Uto *et al.,* 2001) that is still continuing as of this writing. The seismic data are consistent with the beginning of convective overturn of the magmatic system, as suggested in these two papers.

Formation of a new caldera

A mechanical model for caldera formation at basaltic volcanoes is given by Takada (2001). He considers both lateral and vertical magma transfer and the properties of the surrounding crust as being of importance. Table 5 compares the rate of magma withdrawal at Miyakejima from initial tilt data (Ukawa *et al.,* 2000) with that at Kilauea during its 3 largest historically observed subsidences. The rate at Miyakejima is nearly one order of magnitude larger than the largest collapse at Kilauea. The data of table 5 show a relationship between the rate of magma withdrawal and the degree of collapse, suggesting that the formation of a basaltic caldera is dependent on a critically high rate of magma withdrawal. This conclusion is supported by a recent study of the gravity changes at Miyakejima before and accompanying the caldera collapse (Furuya *et al.,* 2003 b). Their results show that, in contrast to most gravity studies at active volcanoes, the gravity values decreased as the volcano's summit was subsiding, indicating a large negative mass change. The authors interpreted this to indicate the creation of open space within the volcanic edifice. It was into this space that the caldera collapsed.

We propose that a general principle governing caldera collapse at a basaltic volcano can be formulated as follows: A caldera will form only when the volcano cannot adjust to magma withdrawal by gradual subsidence. If the rate of magma withdrawal exceeds a critical value the edifice will be self-supporting for only a brief period after which collapse is initiated. In the Miyakejima case, the volcano was self-supporting for about 10 days, between the end of intrusion on June 28 (this paper) and the beginning of caldera collapse on July 8 (Furuya *et al.,* 2003b; Nakada *et al.,* 2001).

Timeline of events associated with the Miyakejima magma system

In consideration of the caldera collapse volume of .67 km^3 (Furuya *et al.,* 2003b, table 5) and a maximum intrusion length of 13 km and depth of 4 km, a dike of width of 10 m or less could have supplied the magma for eruption and intrusion beneath sites s1-s5. The seismically estimated magma chamber radius is 1–2 km, yielding a volume of about 4–32 km^3. The amount of magma withdrawn is then 2–16 percent of the chamber volume, a reasonable value for a basaltic magma system. A dike extending the full 40 km length and 20 km depth of the seismic swarm is far greater than what could reasonably be supplied from Miyakejima (Furuya *et al.,* 2003 a). Therefore, we conclude that the activity associated with the Miyakejima magma system consisted of the following events.

Date/time	Activity
6/26 1830	Seismic swarm begins—magma moves up toward SW flank
6/26 2140	Initial plate cracking induces magma path to rotate clockwise to WNW
6/27 0437–0805	Undersea eruption at site s1a
6/27 0830–1700	Accelerated plate cracking at 2.5 km depth beneath sites s1b-s5 creates a condition favorable to further lateral magma transport
6/27 1731–6/29 1513	Undersea eruption/shallow intrusion at sites s1b-s5
6/27 1751–6/28 0359	Continued plate cracking beneath site s3 down to at least 12 km

Table 5. Comparative subsidence rates for Kilauea and Miyakejima

Eruption	Vol (sub)	Time	Rate (sub)	Result (collapse)
Kilauea 1924	.79 km^3	25 d	.032 km^3/day	.21 km^3 pit crater enlarged
Kilauea 1955	.034 km^3	16 d	.002 km^3/day	subsidence only
Kilauea 1960	.13 km^3	21 d	.006 km^3/day	.023 km^3 pit crater enlarged
Miyakejima 2000	.052 km^{3*} .67 km$^{3\#}$	6 hr 2.9 d	**.01 km^3/hr*** **.23 km^3/day#**	**0.67 km^3** **new caldera**

*** From initial tilting (Ukawa et al., 2000) # From caldera volume (Furuya et al, 2003, table A1)**

6/28 0154–6/29 1850	Continued plate cracking beneath sites s4 and 5 down to at least 14 km
7/8–8/15?	Caldera forms—magma remaining in shallow reservoir tapped
7/1–31	Phreatomagmatic eruption of basaltic andesite at Miyakejima's summit
8/1–31	Upward moving magma from the deeper reservoir, beginning on June 27, was tapped following caldera formation, resulting in explosive eruption of basalt. Recurrence of seismic activity at 4–8 km depth is correlated with convective overturn leading to high gas release
9/1＋	Eruption ends with minor explosions

Activity away from Miyakejima

We interpret the seismicity west of site s5 to represent a cascading tectonic plate failure marked by downward cracking of the Philippine sea plate. As noted above plate failure began with very small events near Miyakejima, increased in intensity and deepened beneath sites s1b-s5 and culminated in the deep seismic swarms on June 29 and 30 from region 2 to region 6 , 3–16 km WNW of site s5 (fig. 6). On June 29 seismicity at 2–3 km occurred at distances of 6–24 km from site s5 along trend 3, before seismic swarms deeper than 4 km were recorded. We interpret this sequence as a tectonic plate failure not associated with magma originating beneath Miyakejima. After July 1 the seismic patterns become very complex and many regions affected on June 29–30 show renewed activity, often more than once. It is apparent that there are seismic "rhythms" to be understood. Completion of the relocation of seismicity using the OBS network should make it possible to put together a full understanding of the later seismicity, including answering the questions raised as to whether deeper magma sources were activated as a consequence of tectonic cracking (cf., for example, Furuya *et al.,* 2003 a; Yamaoka *et al.,* 2003).

Finally, we point out two problems suggested from animation of the already published dataset that should be re-evaluated with better control on the location and depth.

1. The occurrence of shallow earthquakes at sites s11 and s12 (fig. 2, 8) above and to the west of the area of the deepest and most intense seismicity needs to be addressed. A deep deflationary (presumably magmatic) source has been suggested by the modeling of regional deformation data (Furuya *et al.,* 2003a; Yamaoka *et al.,* 2003) leading to intrusion (Nishizawa *et al.,* 2002).

2. The occurrence of shallow seismicity west of Niijima on August 29 and west of Toshima on August 2 and September 11. In the animations made using the original dataset each of these episodes of seismicity shallower than 1 km appears to have been preceded within a few hours by swarms of high-magnitude earthquakes at depths of 4–8 km), suggesting a possible magmatic connection. The shallow activity on September 11 is particularly intense, and is followed by another burst on September 20. Such behavior is suggestive of magmatic intrusion or eruption.

Summary

The Miyakejima eruption and seismic swarm is interpreted as a true tectonomagmatic event, that is, magmatic intrusion combined with tectonic failure of the Philippine Sea plate. The two processes are viewed as interdependent, magmatic activity triggering plate cracking and plate cracking facilitating lateral and vertical transport of magma. A broad timeline for these events can be summarized as follows:

Date	Activity
6/26–9/15	Seismic and magmatic activity associated with Miyakejima volcano. The magmatic activity west of Miyakejima extends only to the vicinity of site s5 and occurs only above 4 km depth. Magma sources are located beneath the southwest flank of Miyakejima at 4–6 and 8–10 km depth.
6/27–7/1	Accelerating plate cracking along trend 3, mainly below 4 km, extending WNW about 35 km from Miyakejima. This represents the initiation of a major intraplate failure equivalent in energy release to a large plate boundary earthquake.
7/1–12/31＋	Continued plate cracking at various depths and distances along trend 3, possibly triggering evacuation of deeper magma source (s) required by the modeling of ground deformation data
8/2–9/21	Possible magmatic activity associated with

trend 5

Intra-plate failure probably occurs very infrequently and may be associated with release of residual stress that is unrelieved during large plate boundary earthquakes. In the present instance initiation of the cracking was caused by a swarm of very small magnitude earthquakes beneath the southwest flank of Miyakejima. The cracking developed slowly in the first day, then cascaded into the major failure occurring along trend 3. The principal failure took place in a zone nearly 10 km wide oriented parallel to the direction of regional plate motion (calculated from http: //sps.unavco.org / crustal _ motion / dxdt / nnrcalc /). Secondary seismic swarms also took place on crossing trends oriented approximately parallel to the volcanic front. The lowered lithostatic pressure resulting from plate failure possibly resulted in activation of deep magma reservoirs that normally would not have been active in this time period.

The interpretations presented here are testable. The possible sites of undersea eruption or shallow intrusion can be investigated by seafloor mapping, looking for new topographic anomalies. If such anomalies are seen then submersible or ROV deployment would serve to identify sites of undersea eruption. Sampling of these combined with petrologic and geochemical study could identify magma source compositions. The existence of magma reservoirs in the crust might be investigated through additional geophysical study such as seismic tomography. Finally, the regional deformation modeling should be rechecked using the assumption of a limited dike emplacement west of Miyakejima combined with tensile cracking farther west possibly associated with activation of deep magma sources.

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