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The epicentral areas of volcanic earthquakes and their volcanotectonic significance

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RESUMEN

Los sismos volcánicos ocurren como enjambres en los alrededores del volcán. En este artículo se analiza el tamaño de la zona epicentral de los sismos volcánicos así como la posición del evento máximo. Se eligen para el estudio las ocho erupciones más grandes de todo el mundo. El área de la zona epicentral puede variar mucho para diferentes volcanes. Los sismos máximos pueden ocurrir lejos (hasta 10-15 km) del centro eruptivo. El área de la zona epicentral y la distancia entre el sismo máximo y el centro eruptivo se correlacionan inversamente con el espesor de la corteza. Se propone que la zona de fracturamiento entre la cámara magmática y la superficie es mayor en la dimensión vertical que en la horizontal para los volcanes continentales y lo contrario para los volcanes oceánicos.

PALABRES CLAVE: Volcán, sismos volcánicos, zona epicentral, espesor de la corteza.

ABSTRACT

Volcanic earthquakes occur in swarms and their foci are distributed around the volcanic edifice. The size of the epicentral area and the position of the largest volcanic earthquakes in the eruptive sequences are studied. Eight large volcanic eruptions from different parts of the world were chosen for study. The area of occurrence of small volcanic earthquakes varies strongly for different volcanoes, and the largest volcanic earthquakes occur up to 10-15 km from the eruptive center. Both area and distance between the eruptive center and the position of the largest earthquake are inversely correlated with crustal thickness. The area of fractured rocks between the magma chamber and the surface may be larger in the vertical than the horizontal dimension for continental volcanoes, and conversely for oceanic volcanoes.

KEY WORDS: Volcano, volcanic earthquakes, epicentral zone, crustal thickness.

INTRODUCTION

Volcanic earthquakes occur near volcanoes or within the volcanic edifice. They give us much information about the stress regime within a volcanic region. They can occur before or during an eruption, and are widely used for the prediction of volcanic eruptions (Minakami, 1960; Tokarev, 1976; Okada, 1983).

The magnitudes of volcanic earthquakes are generally rather small. During this century the only event of magnitude 7.0 interpreted as a volcanic earthquake was related to the eruption of Sakurajima Volcano on January 12, 1914 (Abe, 1979). Volcanic earthquakes of magnitude 5 to 6 are as rare as magnitude 8 tectonic earthquakes worldwide. A large volcanic earthquake may mark a turning point in a volcanic eruption. Magnitude 5 events occurred immediately before the explosions of Bezymianny (1956) and Sheveluch (1964) in Kamchatka, and St. Helens (1980) in the Cascade Range, USA. The Tolbachik fissure eruption (1975, Kamchatka) was preceded by two large earthquakes located at the site of the forthcoming eruption. The caldera collapse of Fernandina (1968, Galapagos Islands) was accompanied by several events of magnitude 5 and greater.

A review of volcanic earthquakes was given by Gorelchik, Zobin and Tokarev (1990). Volcanic earthquakes can be divided into two main groups: (1) earthquakes with depths of 0-40 km generated by stresses due to magma migration under volcanoes, and (2) earthquakes directly connected with the eruptions (volcanic tremor, explosion earthquakes). This paper deals with volcanic earthquakes of the first group. We discuss the size of the epicentral area of volcanic earthquake swarms and the position of the largest volcanic earthquakes during the eruptive sequence.

DATA

Eight large eruptions during the last 30 years with well recorded seismic activity were selected (Table 1, Figure 1). Additional factors for selection were the quality of earthquake locations and the presence of large earthquakes (M>4) in the volcanic earthquake sequence. Epicenters were taken from the local data published in the Bulletin of International Seismological Centre (ISC), from local bulletins, and from the Earthquake Data Reports (EDR) of the US Geological Survey. The precision of epicentral location is different for different events but is within 3 km.

EPICENTRAL AREA OF VOLCANIC EARTHQUAKES

The epicentral area is defined as the area of earthquake epicenters (magnitude 1-2 and greater) during eruptive ac–

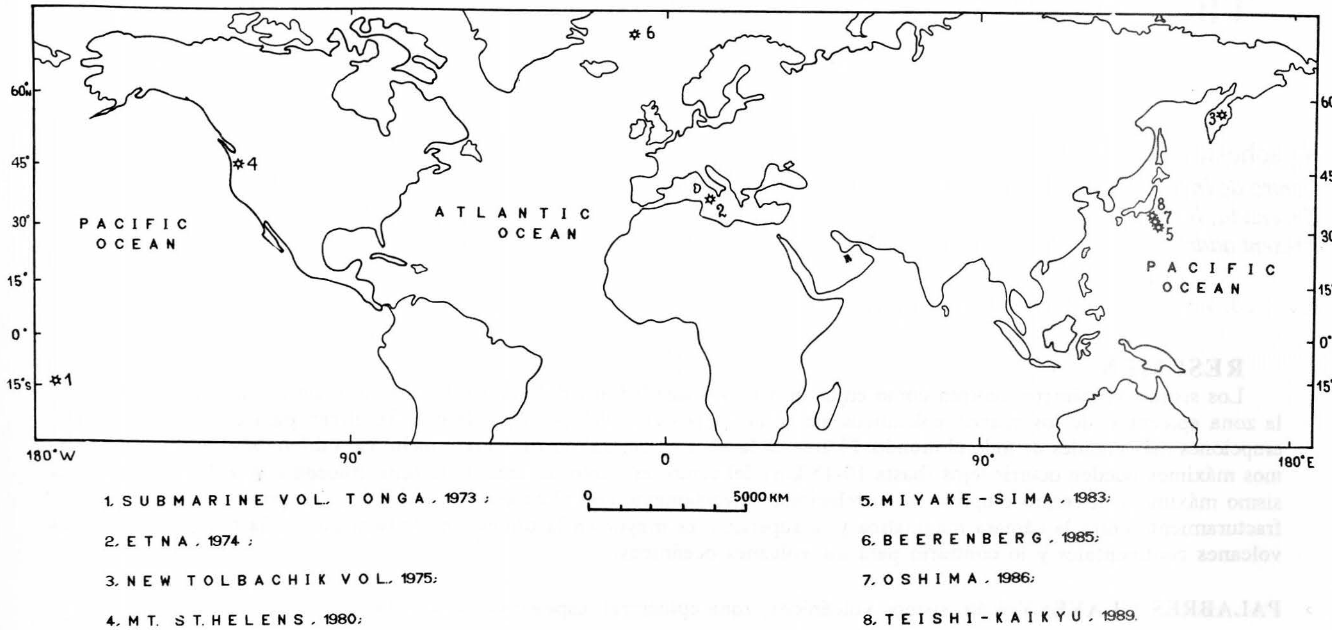

Fig. 1. Geographical location of the studied volcanoes.

Table 1

Parameters of eruptions

Volcano, region, date	Type of eruption	Period of eruption	Period of seismic activity	Volume of erupted material	Magnitude of the largest quake	Reference
Northern Tonga, 1973	Submarine	July	2 days before eruption		ML 5.1	1
Etna, Sicily, 1974	Lateral	30.01.- 29.03	27.01.- 28.03.		M 4.3	2
Tolbachik, Kamchatka, 1975	Fissure	06.07- August	27.06.- 01.08.	2.2 km³	MLH 5.0	3
Mt. St. Helens, Cascades, 1980	Central, blast	March- May	20.03.- 18.05.	~2 km³	Ms 5.2	4
Miyake-sima, Izu, 1983	Central+ lateral	3-4.11.	3-11.11.		Ms 6.2	5
Beerenberg, Jan Mayen, 1985	Lateral	6-9.01.	5-10.01.	0.01 km³	mb 4.9	6
Oshima, Izu, 1986	Lateral	15-22.11.	21-30.11.	0.05 km³	Ms 5.9	7
Teishi- kaikyu, Izu, 1989	Submarine	13-26.07.	03.07.- 15.07.		Ms 5.0	8

References. 1, Gibowicz *et al.*, 1974; 2, Bottari *et al.*, 1975; Scarpa *et al.*, 1983; 3, Fedotov, 1984; 4, Lipman and Mullineaux, 1981; 5, Tada and Nakamura, 1988; 6, Andersen, 1987; 7, Earthquake Research Institute, 1988; Yamaoka *et al.*, 1988; 8, Ida and Mizoue, 1991.

tivity (see, e.g., Figures 2 and 3). We determined the area defined by the distribution of magnitude 1-2 events, and the position of large events (magnitude 4-6) within this area. An example is shown in Figure 3.

Epicentral area of volcanic earthquakes as a stable characteristic of the volcano: Beerenberg Volcano, Jan Mayen.

The Beerenberg volcano on Jan Mayen Island had three large eruptions accompanied by intense seismic activity during 1970-1985. The best location of events was done during the 1985 eruption when a local digital 3-station network was in operation (Andersen, 1987).

The epicentral area of the Beerenberg volcanic earthquakes was defined using the spatial distribution of the

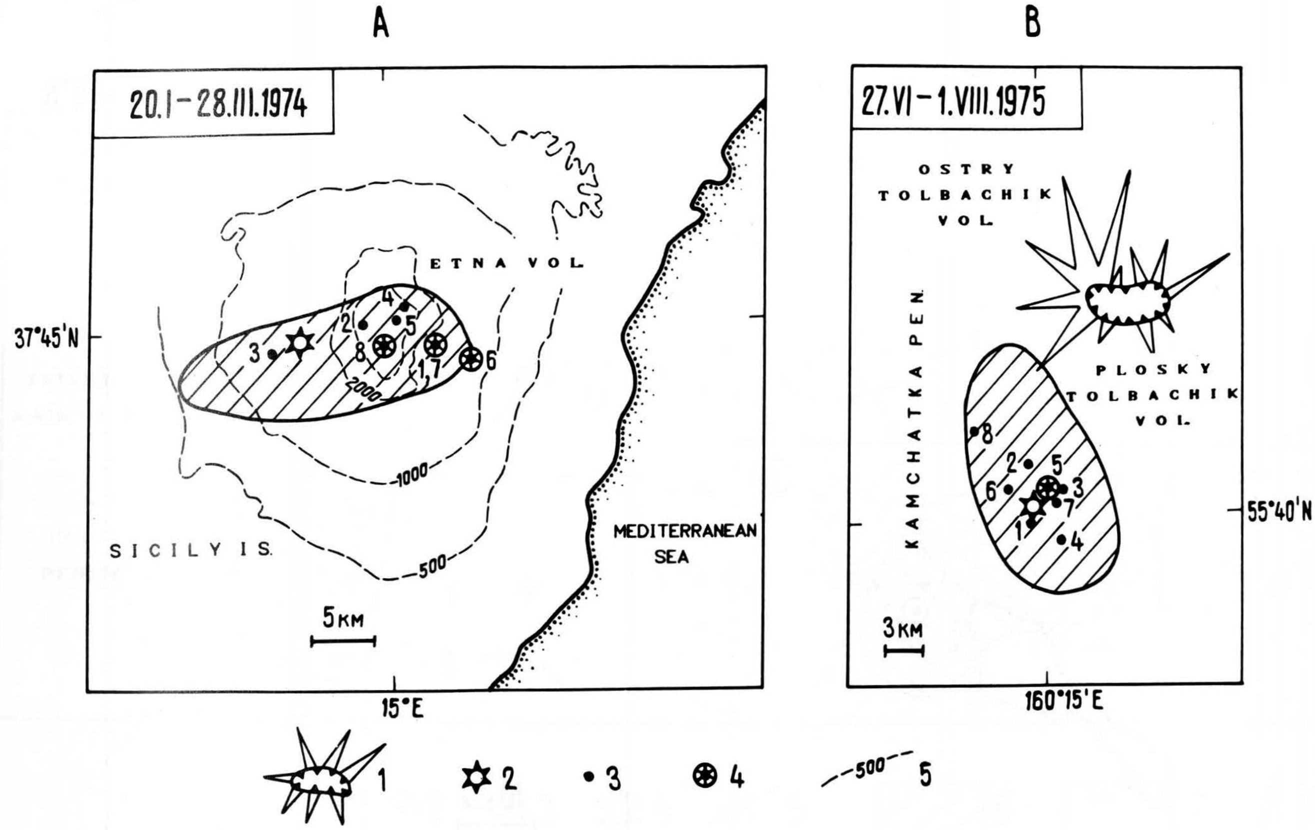

Fig. 2. Epicentral areas of volcanic earthquakes for the Etna, Sicily (A) and Tolbachik, Kamchatka (B) eruptions. 1, passive volcanic center; 2, active volcanic center; 3, epicenter of large volcanic earthquake; 4, epicenter of the largest volcanic earthquake; 5, topographic contour, m. The Etna epicenters are shown according to the list from Bottari *et al.*, 1975; the Tolbachik epicenters were taken from the local Kamchatka catalogue.

11985 events, January 5 to 26. Figure 3 (a) shows the position of 44 epicenters from ISC (magnitude 1.3-4.9) and 32 additional events for January 5 and 6 from the Jan Mayen local survey (JM). A comparison of the epicenters of the arger events determined by ISC with those determined by JM showed a good coincidence. This suggests that the accuracy of epicenter locations by ISC was comparable to those by JM, which accuracy was of ±3 km (Andersen, 1987).

The epicentral area of the 1985 events is an ellipse-shaped area of 760 km^2 with a long axis of 40 km. The eruptive center is within this zone. The positions of large volcanic earthquakes (mb ≥ 4.0) are shown in Figure 3 (b). All are in the central and NE part of the area, clustered in a linear trend. Two events of magnitude 4.9 (Nos 4, 7 in Figure 3 b) are near the eastern end of the area. The western epicentral zone is represented by events of magnitude less than 4.0. The area may be divided into three subzones according to the maximum magnitude of events: the eastern subzone for the largest events, the western subzone for small events and the central subzone for medium-size events.

The 1985 swarm practically included nearly all of the epicentral zones of the 1970 and 1973 events. I plotted all larger events of the 1970 and 1973 swarms located by ISC (Figure 3 c). Two magnitude mb ≥ 4.0 events of 1970 and 6 events of the same magnitude range in 1973 occurred within the 1985 epicentral zone. Figure 3 (c) suggests some stability of the structure of the epicentral area from swarm to swarm. In every case the largest events are in the eastern part of the area between the 2 000 m isobaths. There were no events of magnitude 4.0 or greater in the western part of the zone.

Development of epicentral area of volcanic earthquakes in the course of the eruption: the Izu Island Arc volcanoes

The evolution of the epicentral area of volcanic earthquakes in time may be illustrated by three large eruptions in the Izu Island Arc in 1983-1989 (Figure 4). Three volcanoes (Miyake-sima, Oshima and Teishi-kaikyu) were active in 1983-1989. Their eruptions were accompanied by intense seismic activity.

Miyake-sima. The lateral eruption began on October 3, 1983 at 15 h (Local time) and ended the next day (Tada and Nakamura, 1988). Eruptive centers formed along a 5 km fissure on the southwestern slope of the volcano. A swarm of earthquakes began a few hours after the eruption and ended with the end of the eruption. The epicenters (Figure 5 c) were mainly on the southern slope of the volcano. The central crater of the volcano and the eruptive fissure were

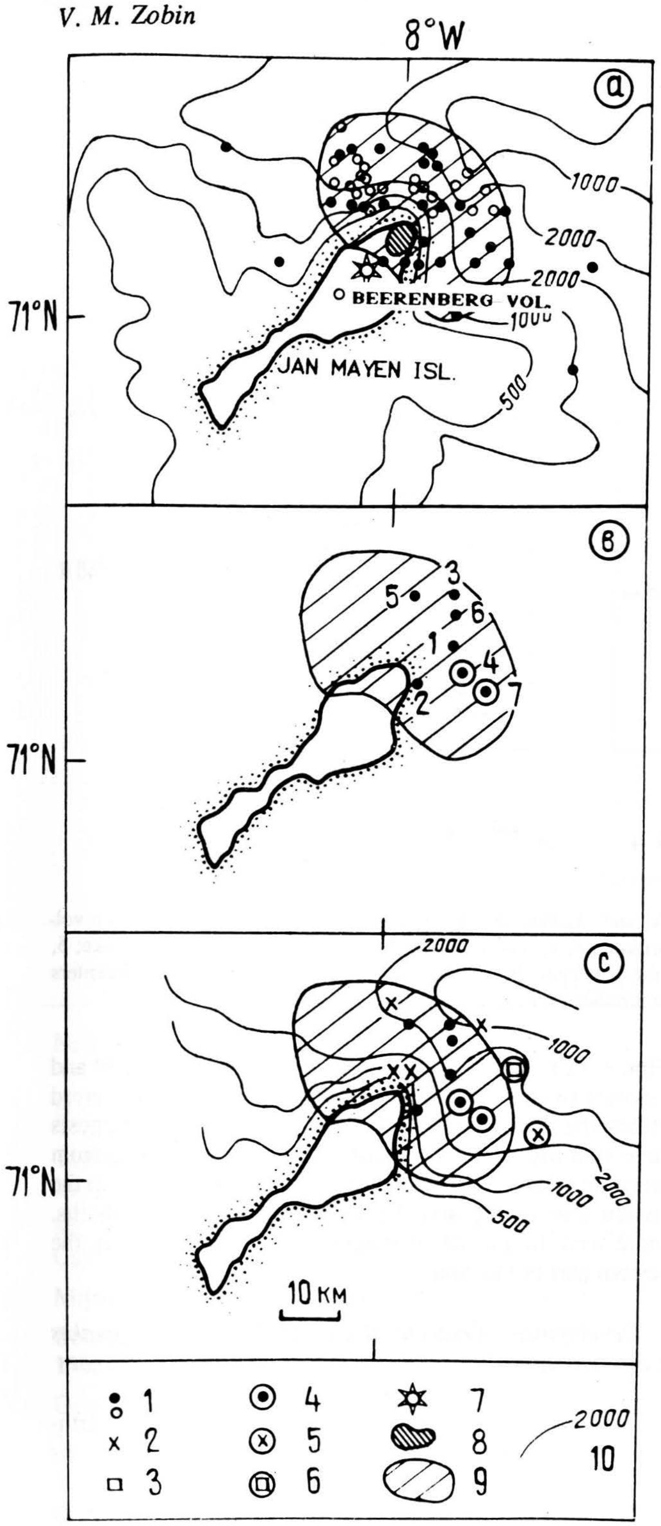

Fig. 3. Epicentral area of the Jan Mayen volcanic earthquakes. a) epicentral area of the 1985 eruption; b) position of the 1985 large events within the area; c) position of the 1970, 1973, and 1985 large events within the 1985 epicentral area. 1-3, earthquake epicenter (1, 1985; 2, 1973; 3, 1970); 4-6, epicenter of the largest event of swarm (4, 1985; 5, 1973; 6, 1970); 7, volcano; 8, area of flank cones; 9, boundary of the epicentral area; 10, isobath of the ocean floor, m. Numbers correspond to the sequence of appearance of the 1985 events. In Figure a) many foci had the same epicenter, and the number of events was larger than shown.

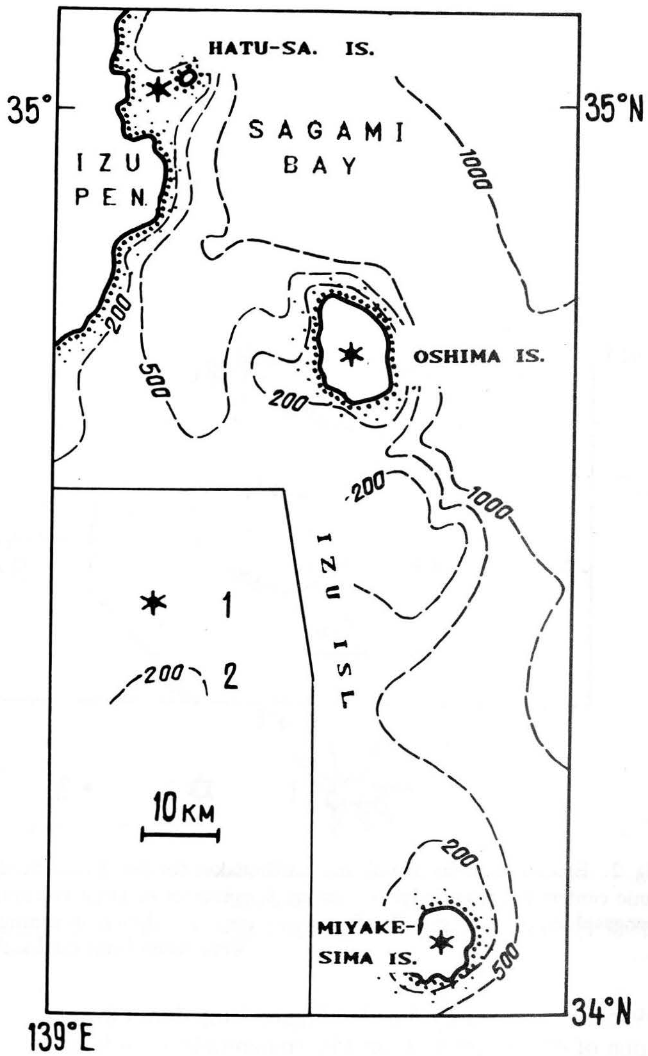

Fig. 4. The position of the Izu Island Arc volcanoes discussed in this paper. 1, volcano; 2, isobath of the ocean floor, m.

within this area. Five large earthquakes clustered off the southern slope of the volcano and three of them (including the Ms=6.2 event) were situated along the eruptive fissure. Epicenters of large events occurred off the eruptive centers. The area was 180 km^2, and the distance between the largest seismic event and the eruptive centers was 6 km. The largest event occurred 7 hours after the beginning of the eruption.

Oshima. The eruption began on November 15, 1986 at 17h local time, from the central crater of the volcano (Figure 5 b). A 1 km fissure opened on November 21 at 16 h within the caldera of the volcano. Another fissure of 1.2 km length opened on November 21 at 17h on the northern slope of the volcano. The eruption ended on November 22 at 12 h. Earthquakes began two hours before the first fissure eruption and lasted until the end of March, 1987 (Earthq. Res. Inst., 1988; Yamaoka, Watanabe and Sakashita, 1988).

The epicentral area of volcanic earthquakes is shown in Figure 5 (b). The area was 1022 km^2. It started from the

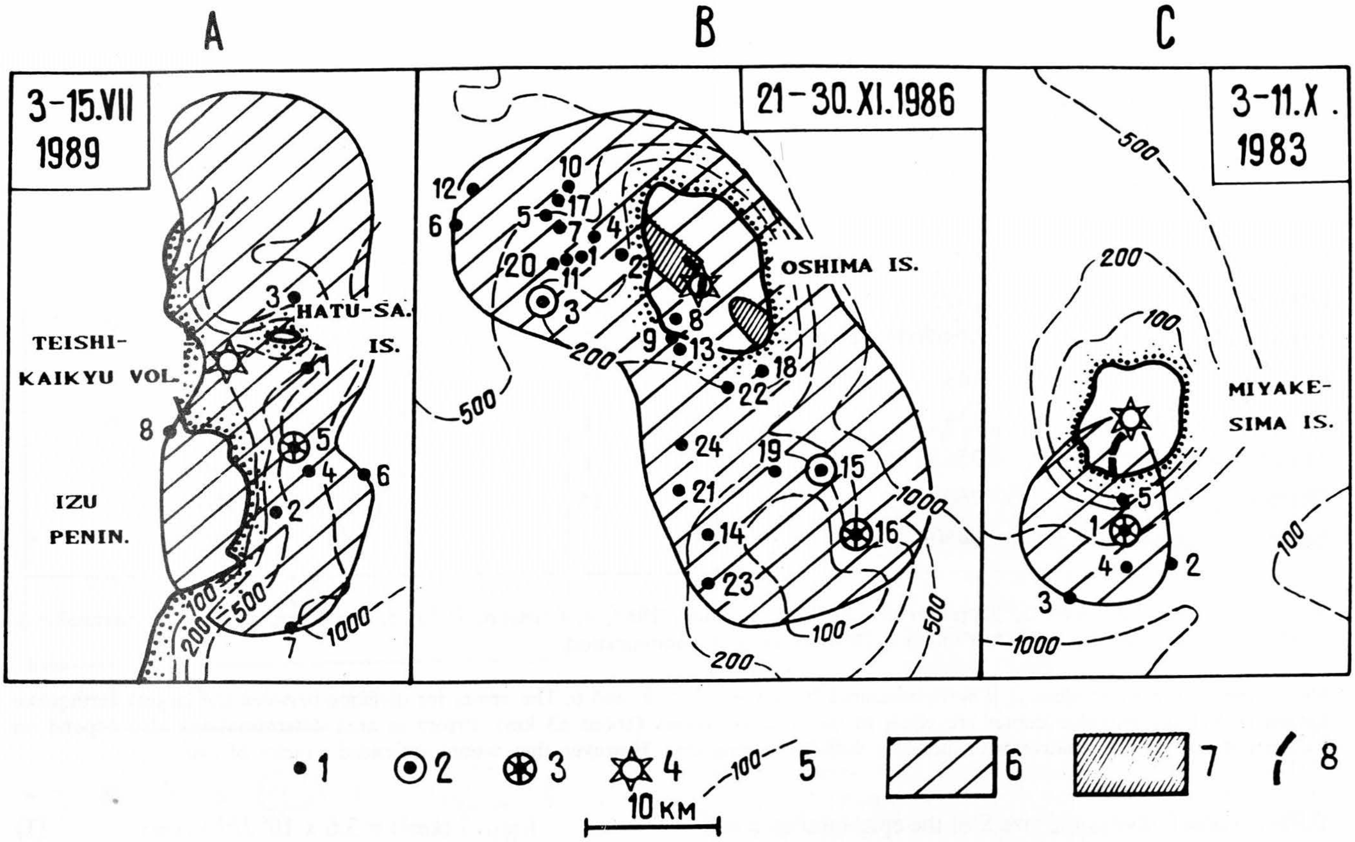

Fig. 5. Epicentral areas of volcanic earthquakes of the Izu Island Arc volcanoes: Teishi-kaikyu (a), Oshima (b) and Miyake-sima (c). 1, epicenter of large earthquake; 2, epicenter of large earthquake of magnitude 5 and greater; 3, epicenter of the largest earthquake of the swarm; 4, central cone; 5, isobath, m; 6, area of volcanic earthquakes (M = 1-2); 7, area of depression formed during the eruption of Oshima; 8, eruptive fissure. The Miyake-sima and Oshima epicenters are from ISC; the Teishi-kaikyu epicenters are from the US Geological Survey Earthquake Data Reports.

NW edge. There were 12 large events in this area, the largest event being of magnitude Ms 5.5. This event occurred one hour after the beginning of the first fissure eruption and was located 10 km from the eruptive centers.

The SE part of the epicentral area became active 6 hours later. There were 12 large events in this area. The largest event (magnitude Ms 5.9) occurred 25 km from the eruptive centers, 18 h after the beginning and two hours before the end of the eruption.

Teishi-kaikyu (or Teisi Knoll). This submarine eruption began on July 13, 1989 13 km off Teishi Island near Izu Peninsula. Visible volcanic manifestations continued until July 26. A swarm of earthquakes began on June 30 and ended July 15 (Ida and Mizone, 1991). The epicentral area was along the steep continental margin of Izu Peninsula (Figure 5 a). Its area, according to locations by EDR, was 618 km^2. The epicentral area from Japanese relocations (K. Yamaoka, personal communication, 1994) is more compact and close to 200 km^2. We use an average value of 410 km^2.

The submarine volcanic center was within this area. There was a cluster of 7 large events 5-7 km from the eruptive centers. The largest event (Ms 5.0) occurred 4 days before the eruption at a distance of 8 km from the eruptive center.

These three examples illustrate the process of development of the epicentral area of volcanic earthquakes. Areas of epicentral zones may vary for different volcanoes. The largest earthquakes may occur at different stages of the eruption, and their epicenters may be situated at different distances from volcanic centers for different eruptions.

Some regularities of the epicentral area parameters

The preceding results show that within any tectonic province the size of the epicentral area of volcanic earthquakes and the distance between the eruptive center and the largest volcanic earthquake epicenter may vary. However, there are regularities for volcanoes from five different parts of the world.

Figures 2, 3, 5, and 6 show the epicentral areas for seven out of eight selected volcanoes. A catalogue of events for the submarine eruption in northern Tonga was not available; instead we used estimates by Gibowicz *et al.*

Table 2

Characteristics of the epicentral areas of volcanic earthquakes

Volcano, date	Area, km^2	Distance from the largest quake epicenter to eruptive center, km	Thickness of the Earth's crust, km/[Reference]
Miyake-sima, 1983	180	9	15-17/[1]
Oshima, 1986	1022	10	15-17/[1]
Teishi-kaikyu, 1989	618/200* (410)	8	15-17/[1]
Etna, 1974	143	15	27/[2]
Tolbachik, 1975	134	1	35/[3]
Mt. St. Helens, 1980	25	1	41/[4]
Beerenberg,1985	760	15	18/[5]
Submarine volcano, 1973	9450/[7]		5-10/[6]

References: 1, Hotta, 1970; 2, Scarpa *et al.*, 1983; 3, Fedotov, 1984; 4, Crosson, 1976; 5, Andersen, 1987; 6, Demenitskaya, 1967; 7, Gibowicz *et al.*, 1974. * Yamaoka, 1994, personal communication.

Note: Dimensions in columns 2, 3 were measured from Figs. 2, 3, 5, and 6. The errors for distance between the largest earthquake epicenter and the volcanic center are equal to the location errors (about ±3 km). Errors in area determinations also depend on location errors, and the relative error increases with decreasing area. However, they would not exeed a factor of two.

(1974). Table 2 shows the size S of the epicentral area and the distance Δ of the largest events to the active volcanic centers for the eight selected eruptions.

The epicentral area varies between 25 km^2 for Mount St. Helens (Figure 6) to 9450 km^2 for northern Tonga (Gibowicz *et al.*, 1974). Table 2 indicates that the areas are larger for volcanoes on small islands and smaller for volcanoes on large islands or on continents.

Generally, oceanic volcanoes are more mafic and the magma is less viscous than for continental volcanoes. Fluid magma is more mobile and may spread over a larger fractured area under volcanoes. However, there are examples of low-viscosity magma for continental volcanoes (e.g., the last stage of the Tolbachik eruption, Kamchatka).

A more stable parameter is crustal thickness under a volcano. The crust is thinner for the oceanic volcanoes than for the continental volcanoes. There is a significant negative correlation between the epicentral areas of volcanic earthquakes S and the crustal thickness H under the volcanoes (Table 2, Figure 7 a). The coefficient of correlation r is -0.92 which is significant at the 95% confidence level. The critical value of $r_{95\%}$ is 0.70 for 8 parameters. If we omit the data for the Tonga eruption, as being the largest and least significant, we find r = -0.83 which is also significant. Critical value of $r_{95\%}$ is 0.75 for 7 parameters.

A regression analysis shows that the best fit is obtained by

$$log_{10}\, S\ (km^2) = 3.6 \times 10^5\, H^{-3.1}\ (km) \qquad (1)$$

shown in Figure 7 (a).

The position and time of occurrence of the largest volcanic earthquakes in an eruption sequence have been widely discussed (e.g., Okada, 1983). For our sample of eruptions, the largest earthquakes occurred either before the eruption (Tonga, 1973; Etna, 1974; Tolbachik, 1975; Teishi-kaikyu, 1989), just before the main explosion (Mt. St. Helens, 1980) or during the eruption (Miyake-sima, 1983; Beerenberg, 1985; Oshima, 1986). The distance D of the largest earthquake from the active volcanic center varies between 1 km and 15 km (Table 2). No regularity in the temporal appearance of these events can be detected. However, the distance D of the largest earthquake from the active volcanic center (Figure 7 b) correlates with the crustal thickness at the 95% confidence level (r = -0.84):

$$log_{10}\, D\ (km) = 1.8 - 0.04\ (\pm 0.01)\ H\ (km). \qquad (2)$$

Equations (1) and (2) may be used for preliminary estimates of seismic hazard in volcanic eruptions. Their accuracy is small, but they may be useful as preliminary estimates of the eventual location of largest volcanic earthquakes and areas of seismic activity.

DISCUSSION

The study suggests the following results. (1) The epicentral area of volcanic earthquakes varies strongly for different volcanoes. (2) The largest volcanic earthquakes may

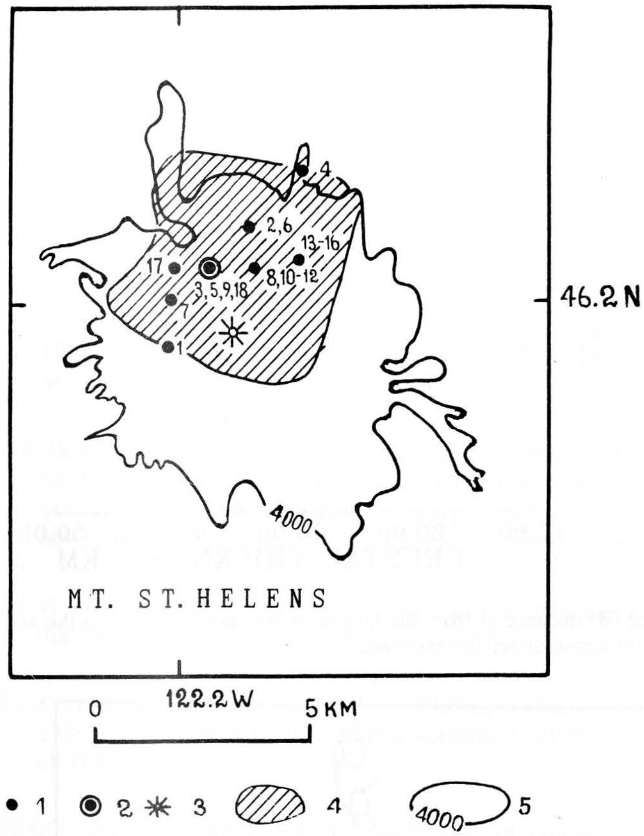

Fig. 6. Epicentral area of volcanic earthquakes preceding the 18 May 1980 eruption of Mount St. Helens. 1, epicenter of large volcanic earthquake (numbers correspond to their time sequence); 2, epicenter of Ms 5.2 event of May 18; 3, crater of volcano; 4, area of epicentral area of volcanic earthquakes, from Weaver *et al.* (1984); 5, 4000 feet topographic contour of volcanic edifice before the 18 May blast. Epicenters 1-18 were taken from Earthquake pickfiles of the Washington University seismic network, provided by Dr. S. Malone.

appear at different stages of the eruption and at different distances from the site of the eruption. (3) The epicentral areas of volcanic earthquakes and the distance of the largest earthquakes from the eruption site are both inversely correlated with crustal thickness under the volcano.

The high correlation level with crustal thickness suggests the key role played by the Earth's crust in magma transport to the surface during an eruption. In Figure 8, two extreme cases are shown: a continental volcano (left), and an oceanic volcano (right). The focal zone of volcanic earthquakes forms due to processes of fracturing around the moving magma during magma transport to the surface (Imsland, 1986). Thus, the epicentral area of volcanic earthquakes is the surface projection of the faulted volume around the magma conduit. For any given amount of erupted material, we would have a narrow vertical faulted volume under the continental volcano and a more widespread and more horizontal faulted volume for the oceanic volcano.

This model does not depend on the focal depth of volcanic earthquakes, but only on the depth of the magma chamber. Most accurate determinations of focal depth for volcanic earthquakes yield a depth of 0 to 10 km independently of the type of crust (e.g., Klein and Koyanagi, 1989, for Hawaii; Moran, 1994, for Mount St. Helens). According to Fedotov (1991), the most likely place for magma collecting is a layer extending from the upper mantle into the crust (or mantle diapir; Hasegawa *et al.*, 1991). If the magma transport begins from the bottom of the crust, which differs in depth for oceanic and continental crust, fracturing due to magma transport should appear only within the upper 5-10 km where rocks are brittle.

This model also accounts for the largest volcanic earthquakes appearing without any regularity in time. They depend only on large faults formed during magma transport. Their distance from the eruptive center should be smaller for continental volcanoes with near-vertical faulted volumes, and more variable for oceanic volcanoes. Larger earthquakes during the eruption of oceanic volcanoes may connect faults in distant parts of the faulted volume with the eruptive centers. Hence these epicenters should occur rather far from the eruptive center.

The relation between epicentral area and crustal thickness suggests a relatively better prediction of the location of a forthcoming eruptions for continental volcanoes than for oceanic volcanoes. When predicting oceanic eruptions one must keep in mind that the area of volcanic earthquakes may be spread too widely to permit locating the forthcoming eruptive center.

These conclusions are based only on a sample of eight events. Additional data are needed. The highly significant level of correlation between crustal thickness and parameters of the epicentral areas of volcanic earthquakes suggests that the proposed model (Figure 8) may be plausible. However, crustal thickness is not the only major parameter which controls the epicentral area of volcanic earthquakes. Multi-parameter correlation analysis should include magma viscosity, chemical composition of magma, type of local stress regime, and other parameters.

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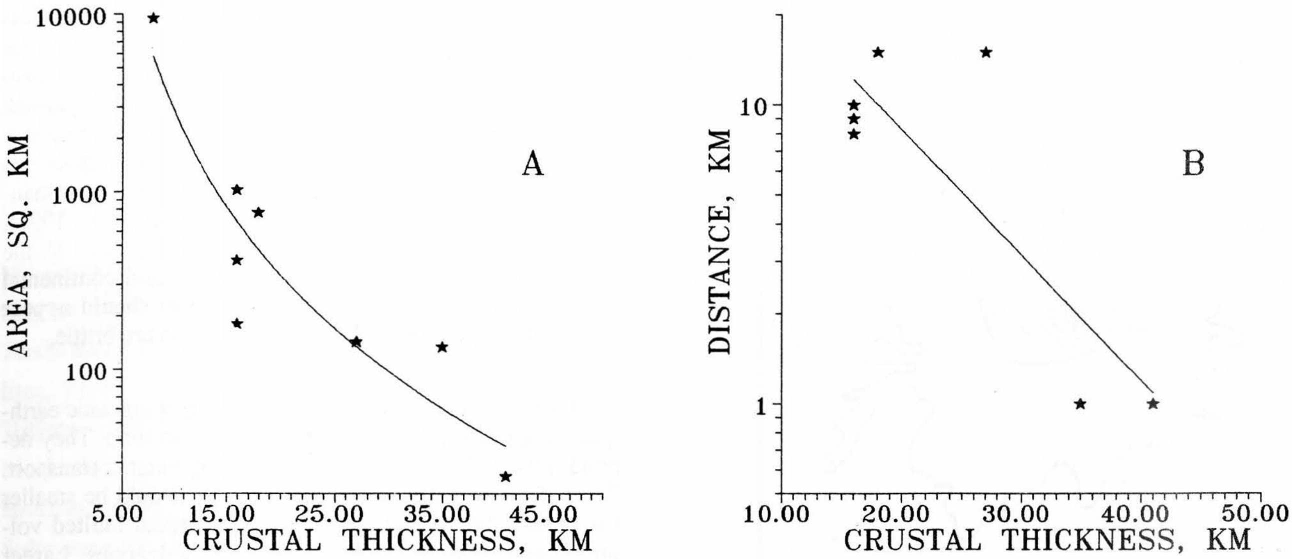

Fig. 7. Relations of (A) epicentral area S of volcanic earthquakes and (B) distance *D* from the largest earthquake epicenter to the active volcanic center, to crustal thickness under the volcano.

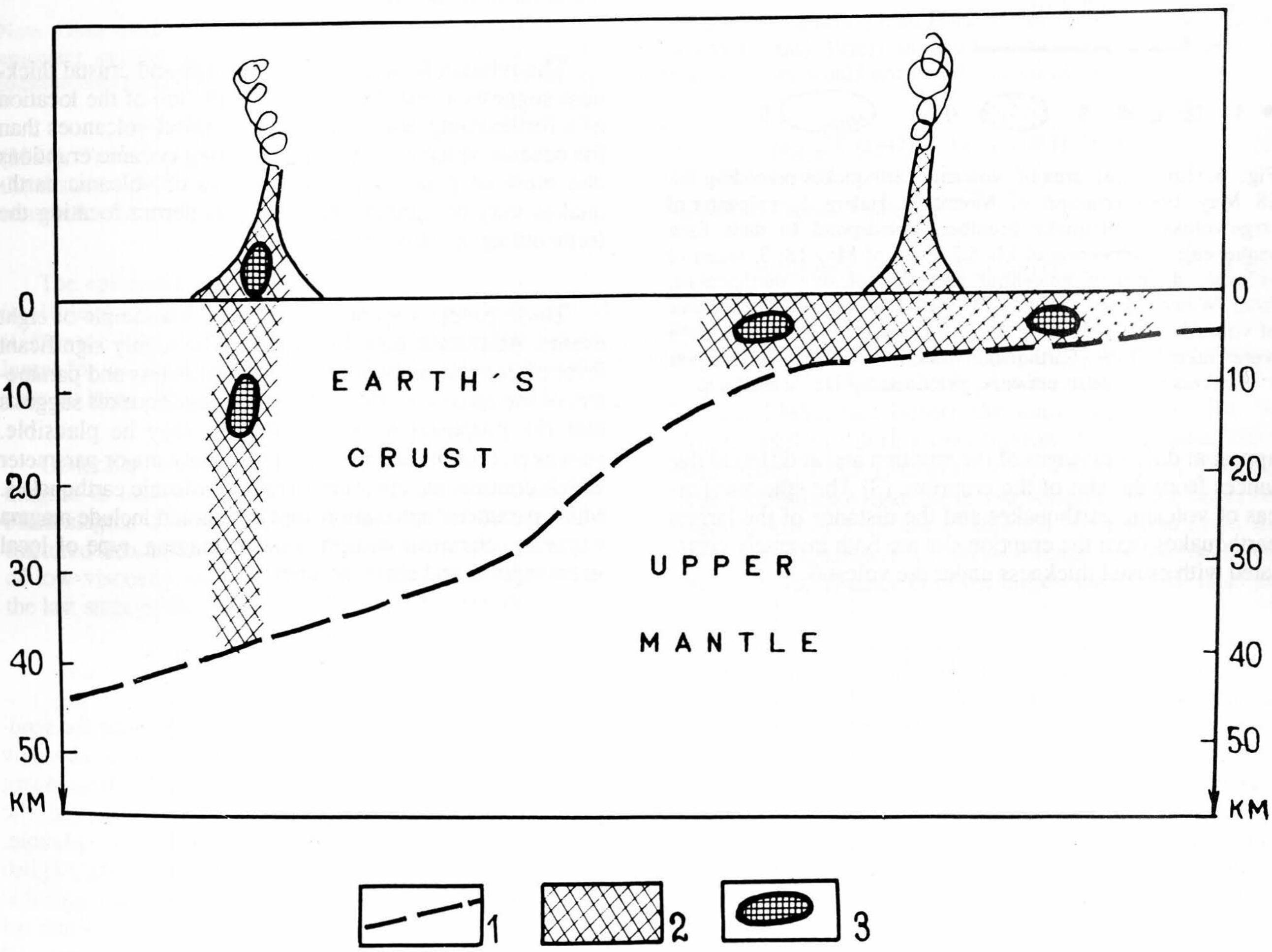

Fig. 8. A model of volcano-tectonic structure of the Earth's crust. 1, "crust-mantle" boundary; 2, magma volume; 3, occurrence of the largest volcanic earthquakes. Fracturing may occur at shallow depths for both type of volcanoes and would not depend on the depth of the magma chamber.

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