The 2006 Eruption of Augustine Volcano, Alaska
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Chapter 7

A Two-Step Procedure for Calculating Earthquake Hypocenters at Augustine Volcano

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Abstract

This chapter describes a two-step technique for determining earthquake hypocenters at Augustine Volcano. The algorithm, which was originally developed in the mid-1970s, was designed both to overcome limitations in the standard earthquake-location programs available at the time and to take advantage of the detailed seismic-velocity information obtained at Augustine Volcano. Hypocenters are calculated on the basis of a two-dimensional (2D) ray-tracing procedure that accounts for in plane lateral discontinuities within the seismic velocity structure. This algorithm calculates the minimum P- and S-wave travel time between theoretical grid points embedded in the velocity structure to each station in the seismic network. Station corrections that account for the differences between the model and actual velocity structure are derived from a time-term analysis of the 1975 active-source seismic experiment. Each relocated hypocenter is assigned to the grid point with the lowest rms residual between observed and calculated arrival times. Statistical techniques are used to assess the effect of random errors in P-wave-arrival determination on hypocentral location. These tests suggest that the 2D ray-tracing procedure presented here is able to resolve earthquake hypocenter depths to within 0.25 km between the volcano's summit and sea level and within 0.5 km from sea level to depths of 2 km below sea level.

Introduction

Augustine Volcano is a 1,200-m-high stratovolcano on a small (8 by 11 km) island southeast of Anchorage, Alaska (fig. 1). The volcano consists of a complex of summit lava domes and flows surrounded by an apron of pyroclastic, lahar, avalanche, and ash deposits. The volcano is frequently active, with major eruptions recorded in 1883, 1935, 1963–64, 1976, 1986, and 2006 and minor eruptive events reported in 1812, 1885, 1908, 1944, and 1971. Because of its frequent eruptive activity and associated hazards and proximity to communities in south-central Alaska, Augustine Volcano has been continuously seismically monitored since 1970 (see Power and Lalla, this volume).

Earthquake activity at Augustine is dominated by volcano-tectonic earthquakes that occur within 1 km of sea level with local magnitudes (M_L) generally smaller than 1.2 (see Power and Lalla, this volume). During inter-eruptive periods, the Alaska Volcano Observatory (AVO) typically locates 100 to 200 small earthquakes each year at Augustine (Dixon and others, 2008). These small earthquakes generally have well-defined to emergent P-wave arrivals and poorly formed to emergent S-wave arrivals. Most earthquakes have P- and S-wave arrivals that are best defined at stations higher on the volcanic edifice, located on the central lava domes and flows, and degrade quickly at stations located closer to the coast on the apron of unconsolidated sedimentary deposits. Additionally, stations close to the island's shoreline are subject to large microseismic noise caused by ocean surf. A representative volcano-tectonic waveform is shown in figure 2. By the time of the 1976, 1986, and 2006 eruptions the volcano was monitored by networks of five, four, and eight permanent short-period seismometers, respectively (fig. 3).

Augustine Volcano was the target of an extensive active-source seismic experiment in 1975 that involved the detonation of 10 chemical explosions which were recorded at 14 temporary seismic stations, as well as at the five permanent stations operating on the island at the time. Data from this experiment were combined with the results from an earlier seismic refraction survey along the north shore of Augustine Island (Kienle and others, 1979) and with seismic-velocity

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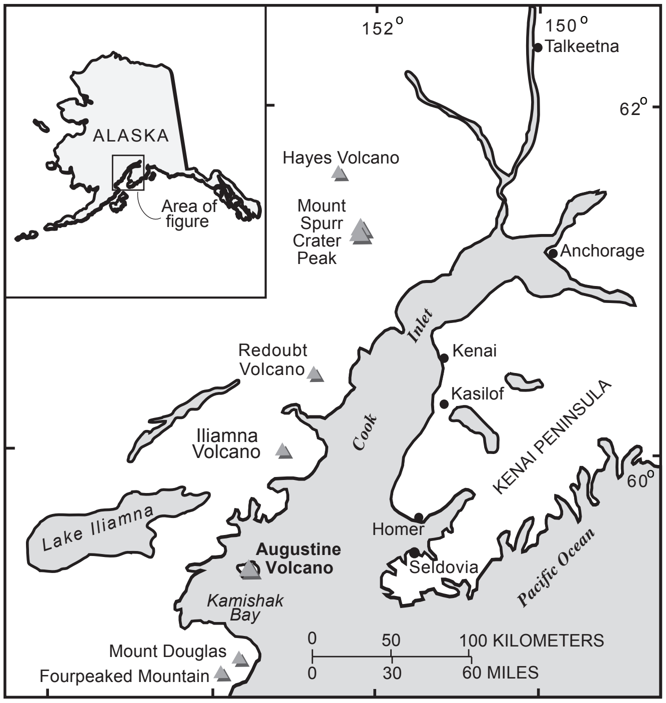

Figure 1. Map showing the Cook Inlet region of Alaska, location of Augustine Volcano, other nearby volcanoes and communities.

data from exploratory oil wells drilled in southern Cook Inlet to determine a three-dimensional (3D) seismic-velocity model of the volcano (fig. 4; Kienle and others, 1979).

Accurate calculation of earthquake hypocenters at Augustine Volcano is unusually difficult because of the high relative topography, the resulting large differences in the elevations of seismic stations, and the heterogeneity of Augustine's seismic-velocity structure. Early computerized earthquake-location algorithms such as HYPO71 (Lee and Lahr, 1971), HYPOINVERSE (Klein, 1978), and HYPOELLIPSE (Lahr, 1989), accounted for station elevations and horizontal changes in seismic-velocity structure through station corrections. Each of these algorithms assumed that the hypocenter was below the elevation of the lowest station. At such stratovolcanoes, as Augustine, this approach presented a serious limitation because topography dictates that many seismic stations are located near sea level and many earthquakes occur in the upper portions of the cone. To overcome this problem, more recent earthquake-location algorithms such as HYPOCENTER (Lienert and others, 1986) and HYPOELLIPSE (Lahr and others, 1994) allow a flat-layered seismic velocity model wherein the highest station can match the highest local topography and stations at lower elevation are embedded within the model. In these algorithms, raypaths and traveltimes are computed for the relative locations of source and receiver.

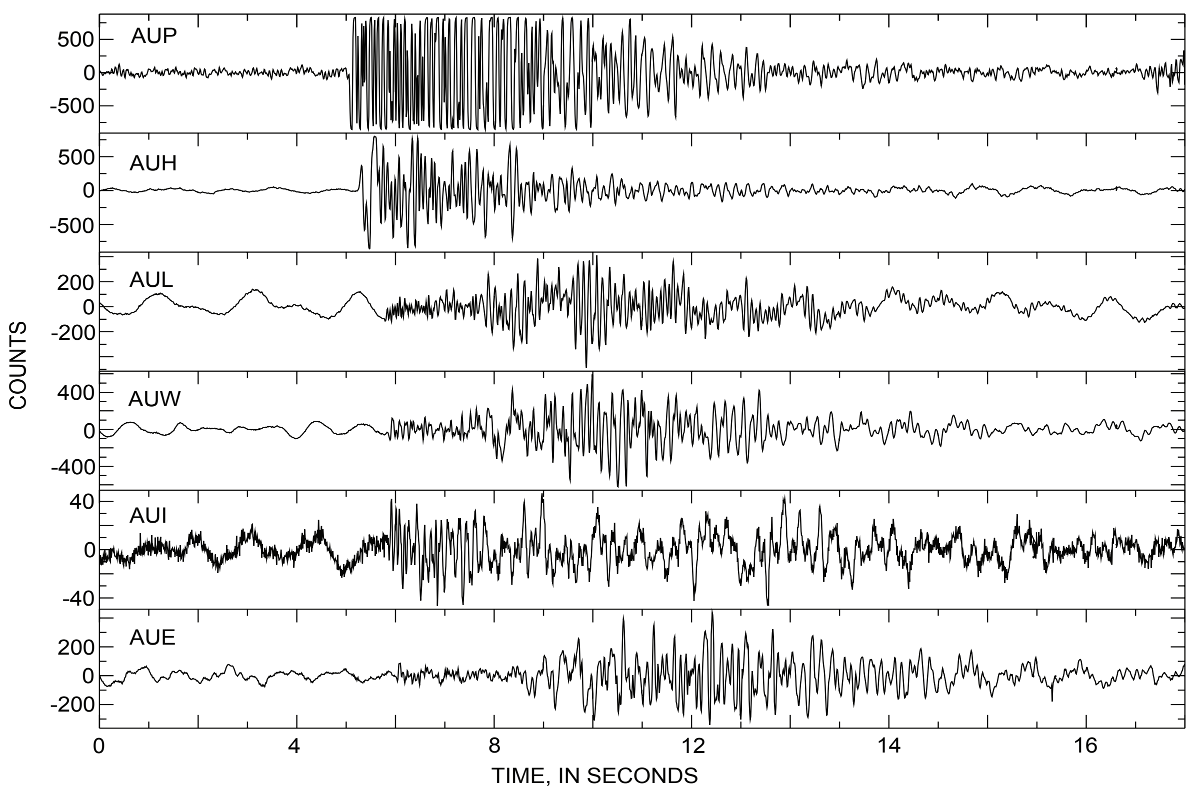

Figure 2. Volcano-Tectonic (VT) earthquake waveforms recorded at Augustine Volcano on January 3, 2006. Hypocenter was at a depth of 0.66 km a.m.s.l. and the local magnitude (M_L) was 0.6. See figure 3 for station locations.

To more accurately locate earthquakes at Augustine, we have developed a two-step procedure to calculate earthquake hypocenters for shocks that occur within a maximum radial distance of 3 km from the volcano's summit and between 1 km above mean sea level (a.m.s.l.) and 8 km below mean sea level (b.m.s.l). This procedure first uses a standard earthquake-location algorithm, such as HYPO71 or HYPOELLIPSE, to determine whether the shocks are occurring beneath the volcano's summit. Earthquakes that meet this criterion are then relocated by using a computer algorithm that calculates hypocenters within the 3D seismic-velocity model of Augustine Volcano shown in figure 4.

This algorithm, which was originally developed in the mid-1970s, was designed both to overcome limitations in the standard earthquake-location programs available at the time and to take advantage of the detailed seismic-velocity information at Augustine Volcano. The algorithm is based on a two-dimensional (2D) ray-tracing procedure that accounts for lateral discontinuities within the seismic-velocity structure. The algorithm calculates the minimum P- and S-wave traveltimes between theoretical grid points embedded in the velocity structure to each station in the seismic network. The grid is a 3 km by 3 km square centered on the summit of the volcano that extends from 1 km a.m.s.l. to 8 km b.m.s.l.; the spacing between grid points is 0.25 km in all three directions. The spatial extent of the grid is shown in figure 5. Station corrections derived from a time-term analysis (Scheidegger and Wilmore, 1957) of the 1975 active-source seismic experiment are applied to calculated traveltimes in order to account for discrepancies between the seismic-velocity model and the measured P-wave traveltime to each station. Each earthquake hypocenter is assigned to the grid point with the lowest residual between observed and calculated arrival times.

In this chapter, we describe details of the two-step hypocenter-relocation procedure and the algorithm that performs the 2D ray tracing and earthquake location within the Volcano's seismic-velocity structure. We also describe calculation of the travel time-terms and station corrections, using data from the 1975 active source seismic experiment. We then evaluate the precision and accuracy with which earthquakes can be located at Augustine with this technique by modeling the known sources of error. Finally, we compare the results of this algorithm with hypocenters calculated with the most recent version of HYPOELLIPSE (Lahr, 1999), using several station configurations.

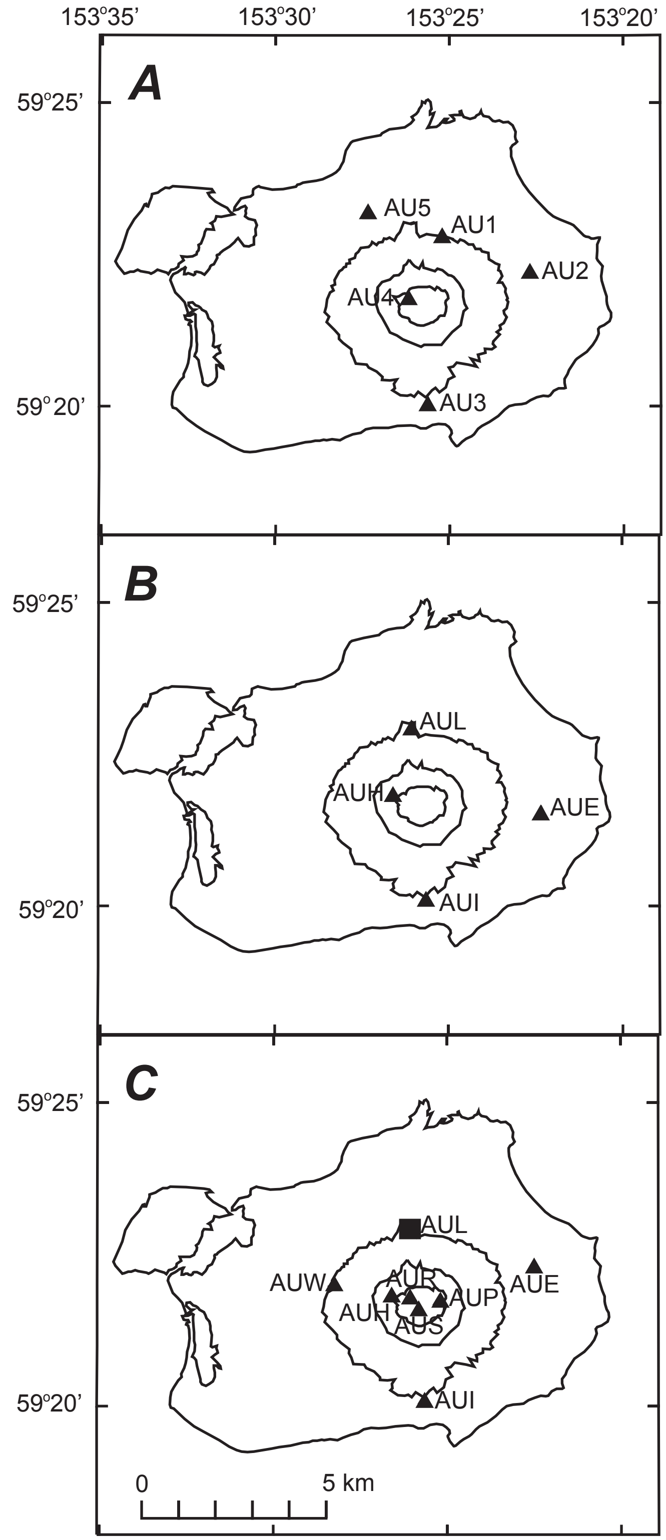

Figure 3. Map of Augustine Island, showing locations of short-period seismic stations on Augustine Volcano in *A*, 1975, *B*, 1985, and *C*, 2005. Triangles, short-period seismometers; squares broadband seismometers. Sea-level, 1,000-ft, 2,000-ft, and 3,000-ft contours are shown in map view.

Seismic-Velocity Model

In August 1975, Kienle and others (1979) conducted an active-source seismic experiment that involved the detonation of 10 chemical explosions on Augustine Island. These explosions were recorded by 14 temporary seismometers, as well as at four stations that were operating on the island as part of the permanent seismic network. The locations of shot points and

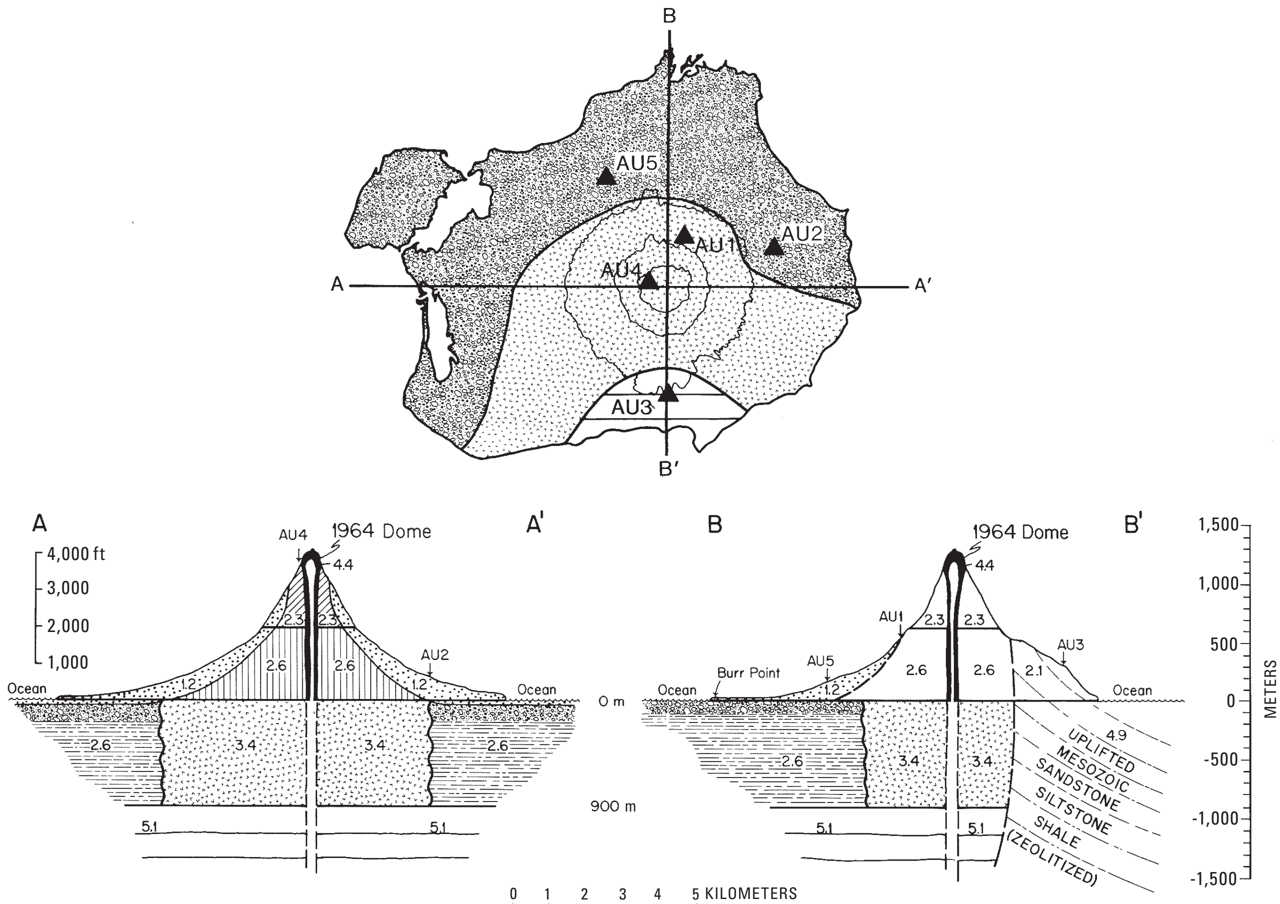

Figure 4. Map view and west-east and north-south cross sections illustrating generalized three-dimensional velocity model of Augustine Island (after Kienle and others, 1979). Map view of island shows velocity boundaries at sea-level (see fig. 3 for explanation of contour lines). Numbers represent seismic velocities in kilometers per second. Triangles note locations of seismic stations that operated in 1975.

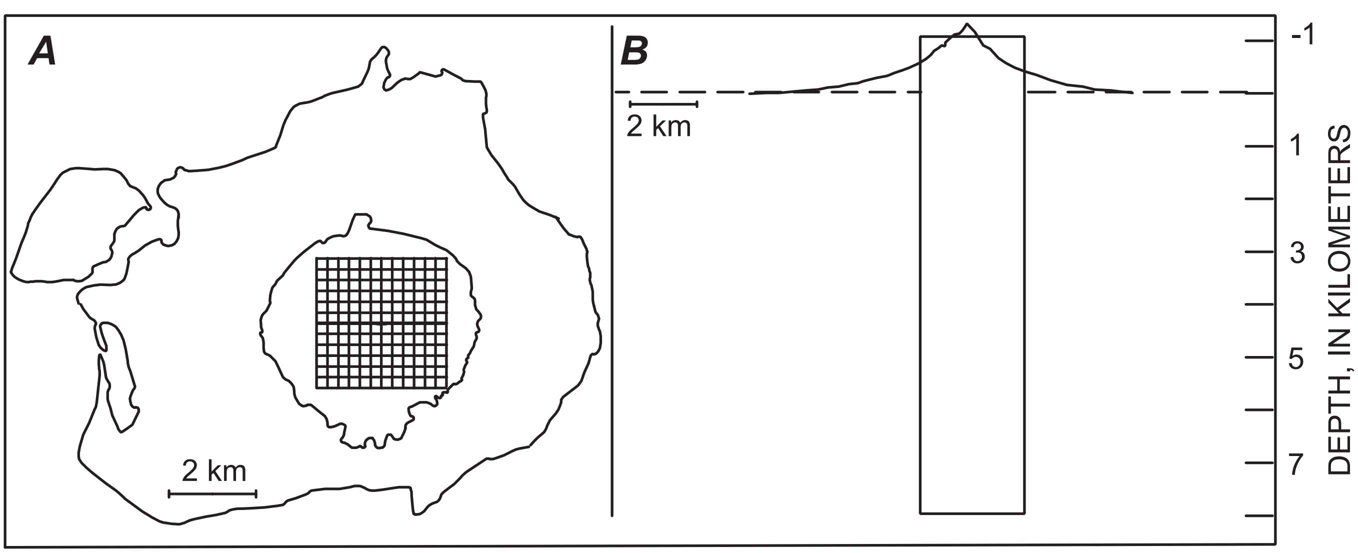

Figure 5. Map view and cross section of Augustine Volcano, showing *A,* the horizontal and *B*, vertical extent of the three-dimensional location grid in relation to volcano. Sea-level and 1,000-ft contour lines are shown in map view.

receivers are shown in figure 6. This combined network measured a total of 66 seismic rays that traversed all parts of the Island and the volcanic cone. These data provided the means to produce the 3D seismic-velocity structure shown in figure 4. An earlier 2D seismic-velocity model of Augustine Volcano was constructed by Pearson (1977), using the 1975 explosion data. A second, smaller active-source seismic experiment constructed in August 1995 measured similar seismic velocities on the volcanic cone (Clippard, 1998).

The major elements of the 3D seismic-velocity model are the cylindrical volcanic cone that comprises the central complex of lava domes and flows and has a P-wave velocity of 2.6 km/s between sea level and 600-m elevation. The seismic velocity decreases outward and upward to 2.3 km/s from 600-m elevation to the summit. The unconsolidated pyroclastic, avalanche, and lahar deposits that surround this central core have a P-wave velocity of 1.2 km/s. The layer between sea level and 0.90-km depth is laterally heterogeneous, increasing in seismic velocity from north to south across the island. The northern part of the island is underlain by a 2.6-km/s velocity layer that was interpreted as non-zeolitized sedimentary deposits. Beneath the central part of the volcano is a layer with a P-wave velocity of 3.4 km/s, perhaps consisting of interlaced volcanic dikes and sills. Near the south shore of the island, the zeolitized sedimentary deposits have been uplifted to near sea level, and in this area the seismic-velocity is 4.85 km/s. The southern part of the volcanic edifice to 600-m elevation is composed of uplifted sedimentary deposits with a P-wave velocity of 2.1 km/s. The stratum of the volcano beneath 0.90 km b.m.s.l. is modeled as a half-space with a P-wave velocity of 5.1 km/s. This layer is believed to represent zeolitized Lower Cretaceous sedimentary deposits (Detterman, 1973). The extent of each of these units is shown in figure 4. A detailed description of this model was presented by Kienle and others (1979).

Earthquake-Location Technique and Methodology

In the first step in calculating an earthquake hypocenter, we determine an initial location for each shock, using a standard algorithm, such as HYPO71 or HYPOELLIPSE with a flat-layered one-dimensional model, similar to the standard processing used to produce the AVO earthquake catalog (Dixon and others, 2008). We then remove earthquakes with hypocenters outside the location grid (fig. 5).

In the second step, we relocate the selected earthquakes, using the 2D ray-tracing procedure implemented by three computer programs written in the FORTRAN4 computer language. The programs are called TRAVEL, NORMAL and FASTM2; copies of them are contained on the DVD-ROM disc included with this volume (see appendix).

The program TRAVEL calculates traveltimes from all points in the three by 3 km by 3 km by 9 km grid to five seismic stations located on Augustine Island. To calculate the minimum traveltime between each grid point and each station, both the critical and refracted wave paths are considered. The minimum travel time from each grid point to each station is stored in a lookup table.

The program TRAVEL was originally coded to calculate traveltimes for the five stations in the 1976 Augustine seismic network. For this discussion, we refer to station names from the 1975 network (fig. 3*A*). To run with later network configurations, TRAVEL was modified with appropriate station coordinates and elevations. The reference elevation for this technique is sea level, with negative depths reflecting height above sea level.

The seismic-velocity model (fig. 4) is approximated as follows:

1. For stations AU5 and AU2, the contact between the 3.4 and the 2.6-km/s velocity zone (stippled area, fig. 4) is approximated by a circular arc with a radius of 2.2 km and a center at the volcano's summit (taken to be 59°21.65'N., 153°25.650' W.). Only within this layer, situated between sea level and 0.9-km depth, is a lateral velocity discontinuity allowed.

2. The volcanic cone is modeled as two bounded plane layers. From sea level to 600-m elevation the P-wave velocity is 2.6 km/s, and above 600-m elevation it is 2.3 km/s.

3. The seismic velocity model for rays traveling to station AU3 is considered to be a simple set of plane layers 2.1 km/s-velocity overlying a 3.4-km/s-velocity layer from sea level to 0.9-km depth.

4. Below 0.9 km b.m.s.l., a half space with a constant velocity of 5.1 km/s is assumed.

5. The central high-seismic-velocity conduit is assumed to affect only station AU4 and is modeled by applying a station correction that is proportional to the depth of the grid point below the station in the region between the summit and sea level. For grid points below sea level, the station correction is fixed at a maximum value of -0.1 s.

For homogenous plane-layered waves, we use the standard expressions to calculate traveltimes derived by many workers, such as Lee and Stewart (1981). For waves that meet a lateral discontinuity, the traveltime path is formulated for the specific ray path and seismic-velocity structure at Augustine.

The program NORMAL applies station corrections to the traveltime table and the calculated traveltimes are then normalized relative to station AU1 or its equivalent and stored in a second lookup table. To decrease the required computational time, this second lookup table is stored in binary rather than ASCII format.

The program FASTM2 performs a direct search of the traveltime lookup table and matches the normalized calculated traveltimes with normalized observed arrival times. Each earthquake hypocenter is then assigned to the grid point with the lowest value between the calculated and observed arrival times. The coordinates of this point are determined by a point to point search over all the grid points. Origin times are determined simultaneously in this process. This procedure considers both P- and S-wave arrival times, although the program is typically run without S-wave phases, which are difficult to determine at the vertical short-period stations on Augustine Island (fig. 2). The S-wave traveltime table is computed by assuming a constant V_p/V_S ratio of 1.78.

Station Corrections and Time-Term Analysis

To account for discrepancies between the actual and modeled traveltimes to individual seismic stations, we have applied traveltime corrections for the individual seismic stations that we use on Augustine Island. Station corrections are calculated by using a time-term analysis (Scheidegger and Wilmore, 1957) with observed traveltimes from the 1975 active-source seismic experiment (Kienle and others, 1979); the time terms are the observed traveltimes between the 5.1-km/s -velocity refractor (fig. 4) at the base of the 3D seismic-velocity model and each seismic station.

The time-term analysis for calculating station corrections relies on the following assumptions (Scheidegger and Wilmore, 1957): 1, the refractor velocity is uniform, 2, the refractor boundary is uniform and has negligible dip, and 3, the seismic-velocity structure of the overburden beneath any station is a function of only the depth normal to the refractor within the cone defined by the critically refracted waves. Under these assumptions, the traveltime between any two points s_i and s_j can be expressed by the following equation:

$$T_{ij} = d_i + d_j + \frac{L_{ij}}{V_r} \ , \qquad (1)$$

where T_{ij} is the traveltime between points s_i and s_j; d_i, d_j are the timeterms for points s_i and s_j, respectively; L_{ij} is the horizontal distance between points s_i and s_j, and V_r is the seismic-velocity of the refracting layer. The time-term is the summation of the total traveltime reduction needed for any number of plane layers above the refractor.

The part of the Augustine seismic-refraction dataset applicable to the time-term analysis consists of 31 critically refracted raypaths (fig. 6) and 15 unknown variables, which 14 are shot point or station time-terms and one is refractor slowness ($1/V_r$). One equation can be written for each shot point/receiver-site pair. Station 8 and shot point 4 occupied the same site in the 1975 active-source seismic experiment (Kienle and others, 1979). This station-shot point position overlap allows the system of equations to be solved uniquely for the unknown variables; without it, the system of equations could be solved only for relative time-terms.

The QR decomposition method of Lawson and Hanson, (1974) was used to solve this problem in a least-squares sense. We chose this method over formulating normal equations for two reasons: 1, solving the normal equations requires n^2 precision, whereas the QR decomposition method requires only n precision, so round-off errors are minimized; and 2, the QR decomposition method solves for a variable only if that column does not cause the condition number of the matrix to fall below the value allowed by consideration of the precision of the data, thus preventing problems associated with the precision of ill-conditioned matrices.

The standard deviation of each variable is estimated from the diagonal terms of the unscaled variance- covariance matrix and the residual solution vector. We assume that errors are additive and uncorrelated and have a consistent variance and that the mean is zero. The results of the time-term analysis are plotted in figure 6 and listed in table 1. The inversion yields a seismic velocity of the underlying refractor of 5.0±0.2 km/s, in agreement with the seismic velocity of 5.1±0.2 km/s calculated from the generalized model of Kienle and others (1979).

The station correction that we apply in the program NORMAL is the difference between the modeled traveltime from the 5.1 km/s -velocity refractor and the traveltime to the station calculated by time-term analysis. The station corrections thus account for discrepancies between the seismic-velocity model and the actual velocity structure beneath each station; we also increase the traveltime to account for the elevation of each station. Station corrections for all the stations used with the 2D earthquake-location algorithm are listed in table 2.

Implementation with 1976, 1986, and 2006 Seismic Networks

The Augustine seismic network has changed somewhat since this hypocenter-relocation procedure was originally formulated to locate earthquakes with the five-station network on the volcano in 1975 (see Power and Lalla, this volume). Some stations have been moved and renamed, and a number of stations were added to the network (fig. 3); stations AU4–AUH, AU3–AUI, AU2–AUE, and AU5–AUL have operated consistently since the early 1970s. This hypocenter- relocation procedure was used to determine earthquake hypocenters before the 1976 (Lalla and Kienle, 1978) and 1986 (Power, 1988) eruptions. During these periods, the Augustine seismic network consisted of five and four stations, respectively. This procedure has also been used to locate earthquakes before the 2006 eruptions of Augustine Volcano (see Power and Lalla, this volume).

Although many of the permanent stations on the island were located at shot-points or receiver sites used in the 1975 active-source seismic experiment (compare figs. 3 and 6), none of the 1975 shot-points and receiver sites was located at the exact position of stations AUI, AUL, or AU1; however, measurements were available for sites with equivalent positions with respect to major features of the seismic-velocity model (fig. 3). The time terms established for stations AU3, AU5, and R5 were used for stations AUI, AUL, and AU1, respectively (fig. 6). Additional travel time to compensate for changes in station elevation were added to each of these station corrections as needed.

For stations AU4 and AUH, a proportional correction was used to account for the effects of the 4.4-km/s-velocity central core of the volcano that extends from the summit to sea level (fig. 4). This correction makes a −0.025-s adjustment to each grid point for every 0.25 km the point is below the top of the model. A total correction of −0.1 s was applied to all grid points at sea level and below.

To relocate earthquakes in 2006, we observed that a four-station network provided hypocenters with the lowest average rms values. The four stations used were AUE, AUH, AUI and AUL (fig. 3*C*). We attempted to include stations AUP and AUW, using time-terms and station corrections from receivers

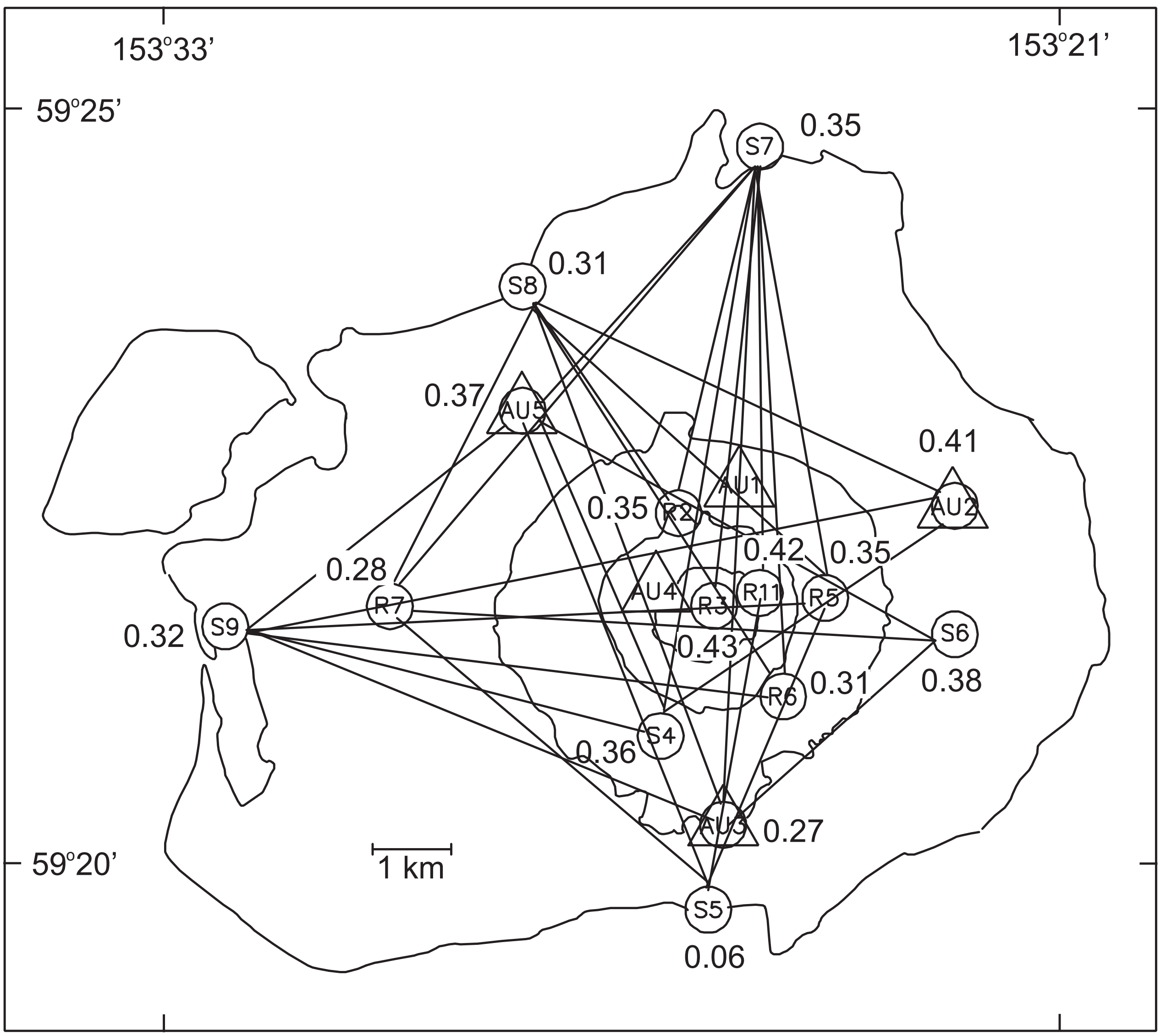

Figure 6. Map of Augustine Island showing locations of shot-points (S) and receiver sites (R) and time terms (numbers) from the 1975 active-source seismic experiment. Straight lines note ray paths used in calculation of time terms and stations corrections. Note that shot point 4 and receiver site 8 were collocated. Permanent short-period stations operating in 1975 are noted by triangles. Contour interval is 1,000 ft. Calculated time-terms are listed in table 1, and station corrections in table 2.

Table 1. Time-terms calculated for shot points and seismic stations.

Station	Time-term (s)	Standard deviation	Station elevation (km)
Shot point 4	0.36	0.04	0.00
Shot point 5	0.06	0.04	0.00
Shot point 6	0.38	0.04	0.17
Shot point 7	0.35	0.04	0.00
Shot point 8	0.31	0.04	0.00
Shot point 9	0.32	0.04	0.00
Station AU2	0.41	0.03	0.20
Station AU3	0.27	0.04	0.29
Station AU5	0.37	0.03	0.15
Station 2	0.35	0.04	0.68
Station 3	0.43	0.05	1.21
Station 5	0.35	0.03	0.50
Station 6	0.31	0.04	0.50
Station 7	0.28	0.04	0.15
Station 11	0.42	0.04	1.03

Table 2. Time-terms and station corrections.

Station	Time term	Model value	Station correction
AU1[1]	0.34	0.49	0.15
AU2	0.40	0.46	-0.06
AU3	0.28	0.21	-0.07
AU5	0.37	0.20	0.17
AUE[2]	0.27	0.31	-0.04
AUI[3]	0.38	0.43	-0.05
AUL	0.28	0.34	-0.06
AUE[4]	0.27	0.31	-0.06

[1] Time term from station S5 assumed, correction adjusted for elevation.

[2] Time term from station AU2 assumed, correction adjusted for elevation.

[3] Time term from station AU3 assumed, correction adjusted for elevation.

[4] Time term from station AU2 assumed, correction adjusted for elevation.

R7 and R11 (fig. 6), but this inclusion produced much greater average errors than in the four-station solutions. We also attempted to include station AUP, using the same proportional correction as for station AUH, but this inclusion also produced greater errors in test runs of the program. These results suggest that the parameterization of the seismic-velocity model by Kinele and others (1979) may not be accurate for stations at these locations. We did not attempt to expand the programs to include the other stations located on Augustine Island in 2005 and 2006 (fig. 3*C*).

Analysis of Error, Precision, and Accuracy

Our ability to determine earthquake hypocenters depends on our knowledge of the seismic-velocity structure of the Earth, the number and distribution of recording stations, and accurate measurement of the arrival times of seismic waves. A review of standard methods of determining earthquake hypocenters was presented by Lee and Stewart (1981). Earthquake-hypocenter determinations contain both systematic and random errors. Systematic errors result from errors in the velocity model, misidentification of phases, or timing errors and affect the accuracy of the hypocenter determination. The effects of systematic errors can be evaluated through controlled experiments, such as locating manmade explosions. Random errors result from errors in determining phase arrivals and affect the precision with which hypocenters can be calculated. The effects of random errors are generally estimated through the use of standard statistical techniques.

To estimate the effect of phase misidentification on the accuracy of earthquake locations at Augustine Volcano with the 2D ray-tracing procedure, we determined the precision with which we can measure P-wave arrivals. We then used a Monte Carlo simulation (Beck and Arnold, 1977) to evaluate our calculated hypocenters. The method consists of generating a population of synthetic arrival times for a given grid point within the location space calculated by the program TRAVEL. The initial arrivals for the "seed" event are taken from the traveltime lookup table, and a set of synthetic arrival times is generated by adding errors with a Gaussian distribution, a zero mean, and a standard deviation that corresponds to the precision with which we can determine P-wave arrivals for local earthquakes at the Augustine seismic stations. This method depends on the characteristics of the earthquakes, the individual stations in the seismic network, and the recording media used at the time of the earthquake.

To calculate the precision in measuring P-wave arrivals at each station, we measured the P-wave arrival times for groups of earthquakes located at Augustine a second time. The sum of the average difference between the two sets of P-wave arrivals and the associated standard deviation was taken to be an estimate of the precision of P-wave arrival determination at that station. Seismic data at Augustine were recorded on photographic film from 1970 to 1989 and digitally by various computerized acquisition systems after 1989 (see Power and Lalla, this volume). The average precision of P-wave-arrival determination was 0.034 s (Lalla and Kienle, 1980) at stations that operated in 1975 (fig. 3*A*), 0.06 s (Power, 1988) at the stations that operated in 1985 and 1986 (fig. 3*B*) and 0.02 s at the stations that operated in 2005, as determined by picking a set of 25 earthquakes that occurred in December of 2005 a second time. We believe that the improvement in precision in the 2005 data set reflects the higher-quality digitally recorded data and associated computerized analysis techniques.

To evaluate our ability to locate earthquakes at Augustine Volcano with the 2D ray-tracing procedure, we ran the Monte Carlo simulation with the stations used with this technique in the 1975, 1985 and 2005 networks (fig. 3) and allowed the average precision of P-wave-arrival determination to follow a Gaussian distribution centered at 0.02, 0.05, and 0.10 s, with seed events at 0.25-km intervals for grid points directly beneath the volcano's summit to a depth of 7.75 km b.m.s.l.

These simulations allowed us to estimate the standard horizontal and vertical location errors that are typically referred to as ERZ and ERH. We define ERZ as

$$\mathrm{ERZ} = \sqrt{\sum_{1}^{n} \frac{(Z_i - \overline{Z})^2}{n-1}}\,, \tag{2}$$

where Z_i is the hypocentral depth, $\overline{Z}$ is the average hypocentral depth, and n is the number of hypocenters. ERH is calculated in the same way as ERZ, except that the horizontal rather than the vertical position is used. For each grid point, the estimated shift in ERZ and ERH represents the mean value of 100 test events, the results of which are summarized in figures 7 and 8. We also used this technique to estimate the expected shift in hypocentral depth for the networks operating in 1975, 1985–86 and 2005–6 (fig. 9).

We used these simulations to evaluate the shift in hypocenter position as a result of the changing array configuration in 1975. During 1975 five stations were operating on the island, four of which had temporary failures. For this evaluation, we ran these tests without phase readings from one of the stations in the 1975 network to simulate periods when the four stations were operational. Again, we ran these tests with a sample population of 100 test events for each grid point. The results of these simulations, showing the expected shifts in vertical and horizontal errors and in depth are summarized in figure 10.

These tests suggest that the 2D ray-tracing procedure presented here is able to resolve earthquake hypocenter depths to within 0.25 km for shocks located above sea level and within 0.5 km for shocks located between sea level and 2 km b.m.s.l. when the average network P-wave-arrival determination is 0.05 s. This result is similar to the precision estimates calculated for the 1975 (Lalla and Kienle) and 1985–86

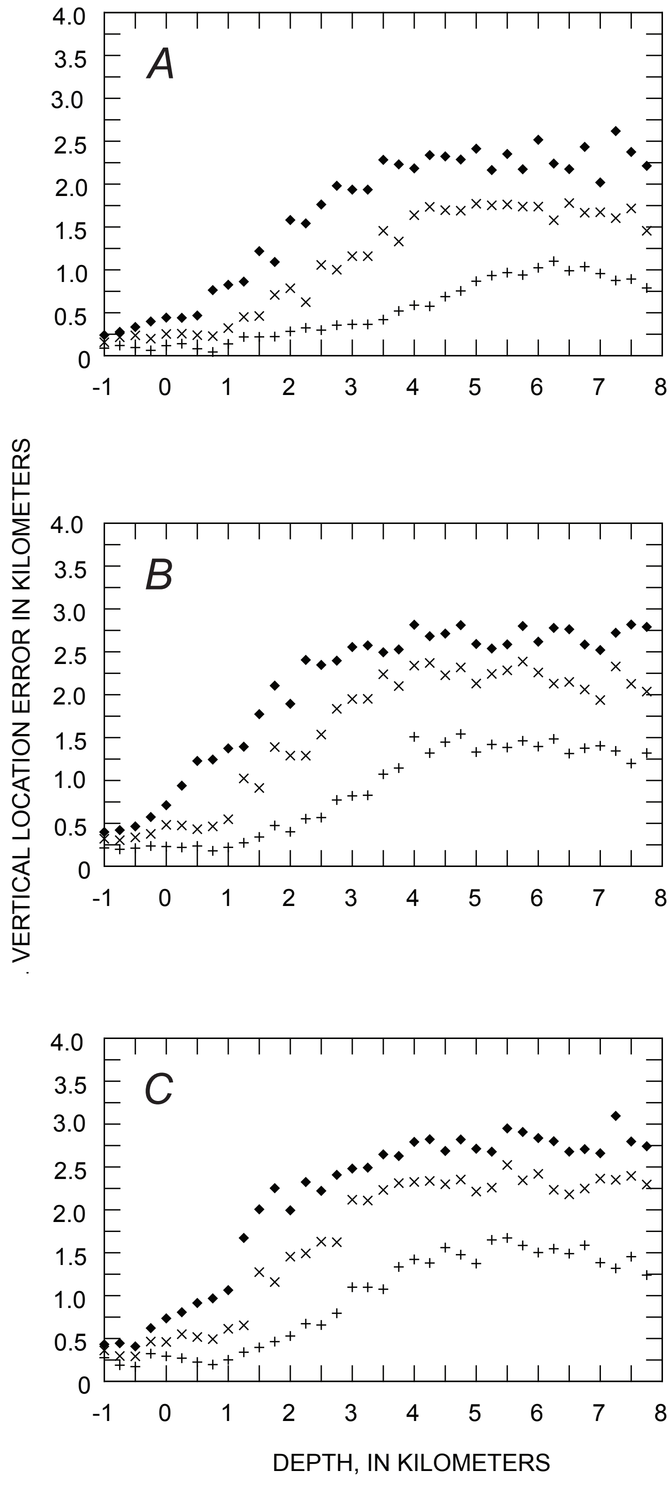

Figure 7. Simulated values of vertical location error (ERZ) based on three error levels of P-wave arrival determination for seismic networks used for the 2D ray tracing procedure in *A*, 1975, *B*, 1985–1986, and *C*, 2005–2006. The pluses, crosses, and diamonds, correspond to the 0.02-, 0.05- and 0.10-second P-wave reading errors, respectively. Each data point represents the mean ERZ for 100 simulated events.

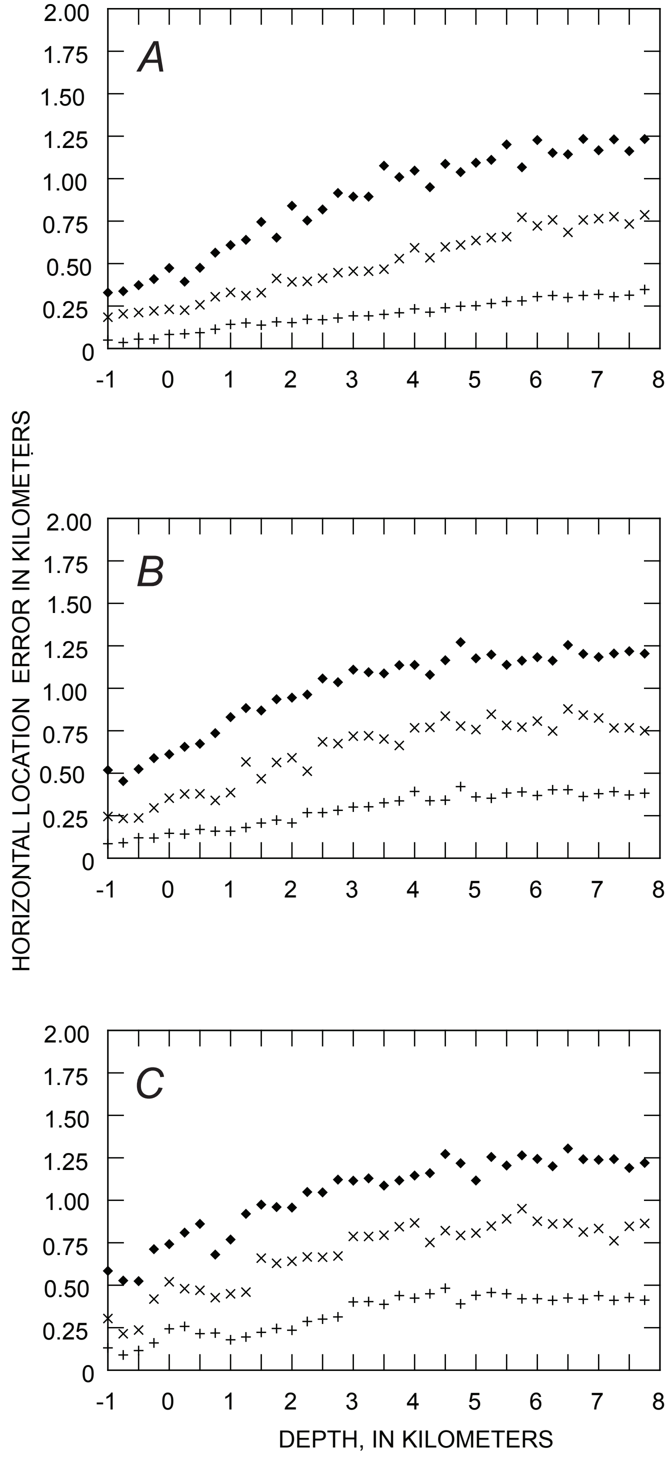

Figure 8. Simulated values of horizontal location error (ERH) based on three error levels of P-wave-arrival determination for seismic networks used for the 2D ray-tracing procedure in *A*, 1975, *B*, 1985–1986, and *C*, 2005–2006. The pluses, crosses, and diamonds, correspond to the 0.02-, 0.05-, and 0.10-second P-wave reading errors, respectively. Each data point represents the mean ERH for 100 simulated events.

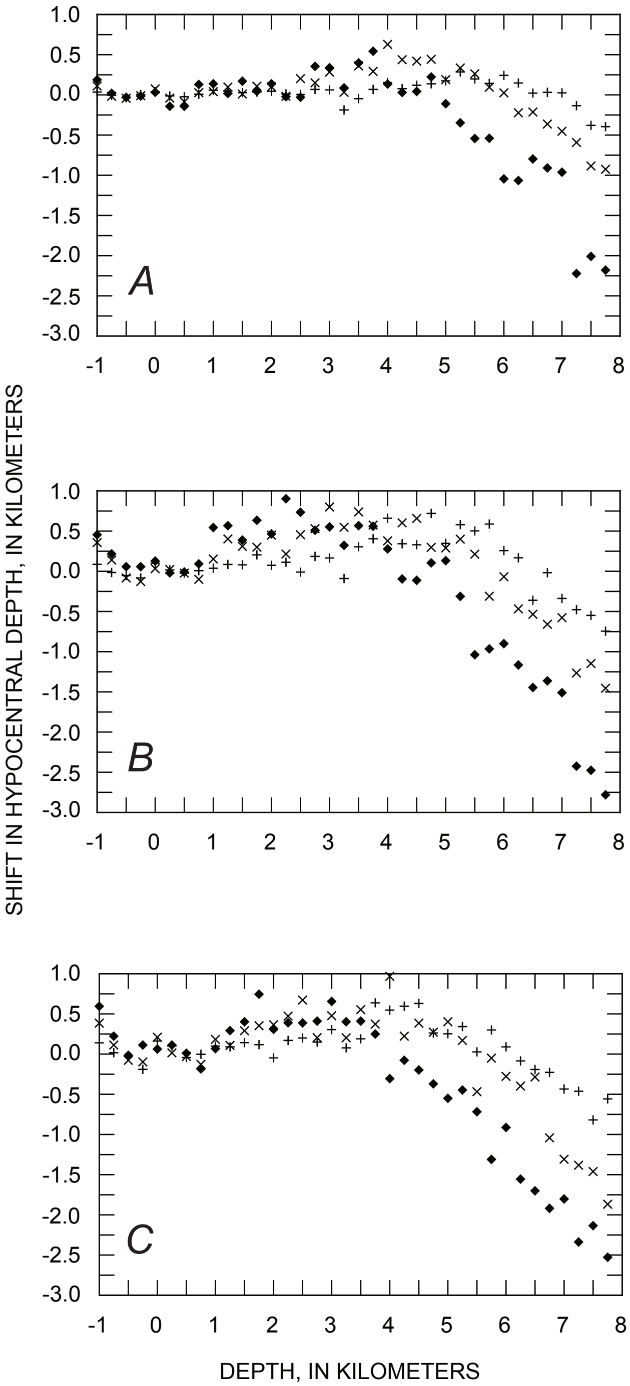

Figure 9. Simulated shifts in hypocentral depth based on three error levels of P-wave-arrival determination for seismic networks used for the 2D ray-tracing procedure in *A,* 1975, *B,* 1985–1986, and *C,* 2005–2006. The pluses, crosses, and diamonds correspond to the 0.02-, 0.05- and 0.10-second P-wave reading errors respectively. Every point represents the mean value of the shift in depth of 100 synthetic earthquake hypocenters.

(Power, 1988) networks, using the same statistical approach. These simulations also suggest that after 1993, when digital data allows us to determine P-wave-arrivals to within 0.02 s, that hypocentral depths can be determined to less than 0.25 km above sea level and less than 0.5 km above 2 km b.m.s.l. using a four-station network (figs. 7, 9, 10). The simulations for various four-station networks in 1975 plotted in figure 10 also indicate that a station high on the volcanic cone, such as station AU4 (fig. 3*A*) is critical for determining hypocentral depth. Changes in horizontal position for the same set of tests fig. 8) indicate an even smaller shift in calculated epicenter position as a result of our ability to determine P-wave arrivals. However, our ability to accurately determine earthquake depths rapidly diminishes below 3 km b.m.s.l.

The use of S-wave-phases was not considered in these simulations. We note that these uncertainties apply only for reading errors with a Gaussian shape.

Comparison with the Program HYPOELLIPSE

To further evaluate the accuracy of earthquake locations calculated with the 2D ray-tracing procedure, we located a subset of 30 well-recorded earthquakes that occurred between May 20 and December 10, 2005, with this technique and the program HYPOELLIPSE (Lahr, 1999), using two separate station configurations. For HYPOELLIPSE, we used a one-dimensional seismic-velocity model consisting of six horizontal layers with boundaries at depths of −1.2, −0.7, 0.0, 1.0, 9.0, and 44.0 km. The top of the model at 1.2 km a.m.s.l. corresponds approximately to the summit of the volcano. The respective P-wave velocities for each layer are 2.3, 2.6, 3.4, 5.1, 6.3, and 8.0 km/s. These layer boundaries and velocities, which were determined by using the results of the 1975 active-source seismic experiment (Kienle and others, 1979), were observed to minimize residuals in several test runs of HYPOELLIPSE. The station configurations used for HYPOELLIPSE were the entire permanent network in 2005 and a four-station network with only stations AUE, AUH, AUI, and AUL (fig. 3*C*), the same four stations used with the 2D ray-tracing procedure.

The average hypocentral depth and standard deviation for the 30 earthquakes sampled for each earthquake-location technique are listed in table 3, and calculated depths are compared in figure 11. These results suggest that hypocenters calculated with the 2D ray tracing procedure presented here yield earthquake depths by using P-wave-arrivals from four stations that are comparable to those calculated with HYPOELLIPSE by using the eight available stations of the 2005 network. The 2D relocations of our sample have a slightly higher standard deviation, indicating a greater scatter in depth. The run of HYPOELLIPSE with only four stations returns a deeper average depth and a higher standard deviation, suggesting that these hypocenters are not so reliable. These results indicate that the 2D relocations are preferable for periods when only

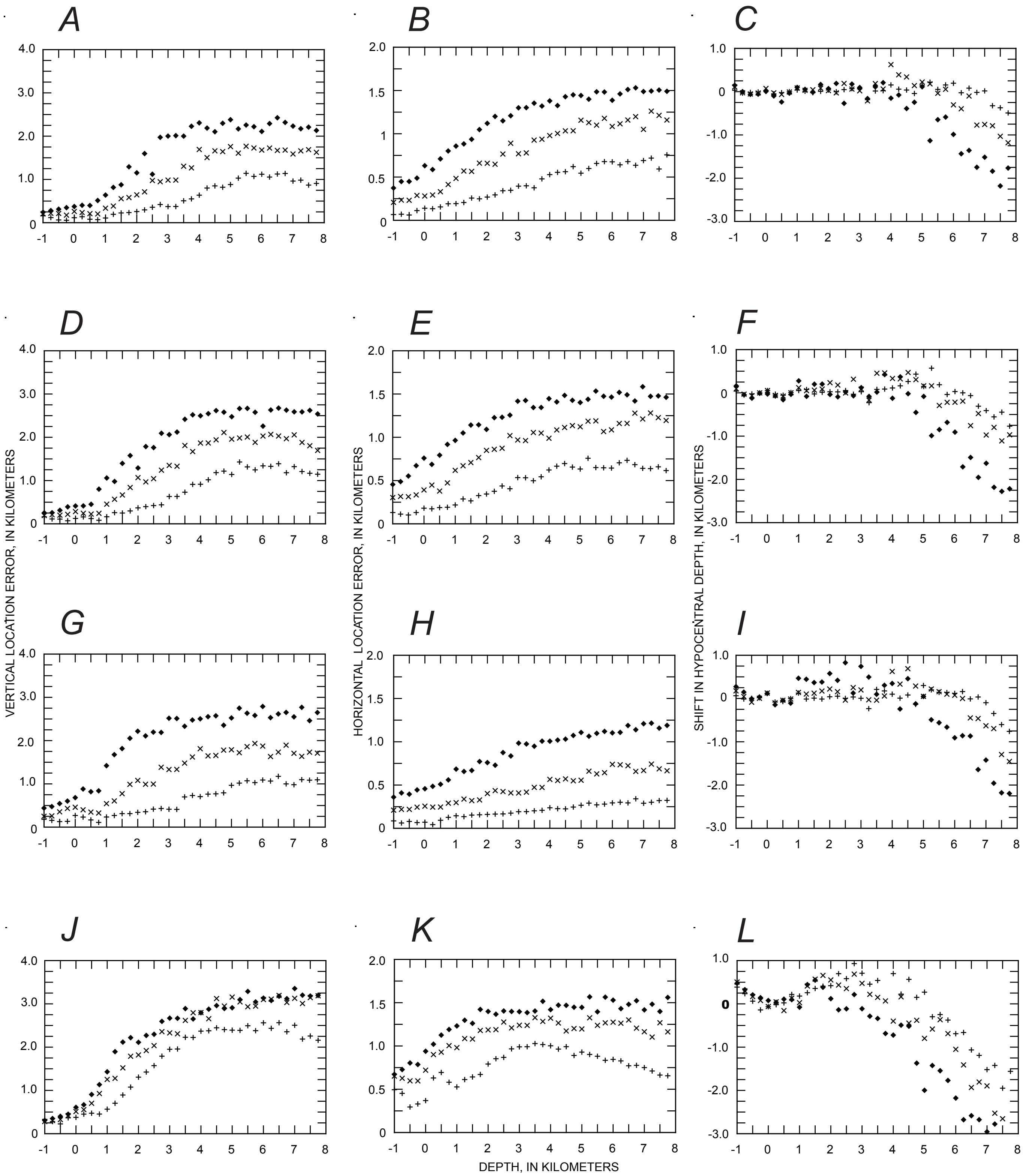

Figure 10. Simulated values of vertical location error (ERZ), horizontal location error (ERH), and shifts in hypocentral depth based on three error levels of P-wave arrival determination for various four station network configurations used to locate earthquakes on Augustine Island in 1975. The pluses, crosses, and diamonds correspond to the 0.02-, 0.05- and 0.10-second P-wave reading errors, respectively. Each data point represents the mean values for 100 synthetic earthquake hypocenters. *A–C*, correspond to hypocenters calculated without station AU2; *D–F,* to hypocenters calculated without station AU3; *G–I*, to hypocenters calculated without station AU4; and *J–L,* to hypocenters calculated without station AU5. See figure 3*A* for station locations.

four stations are operating on the volcano (fig. 11; table 3). The hypocenters calculated from HYPOELLIPSE might be improved further if station corrections were applied as described by Lahr and others (1994), which was not done for this comparison.

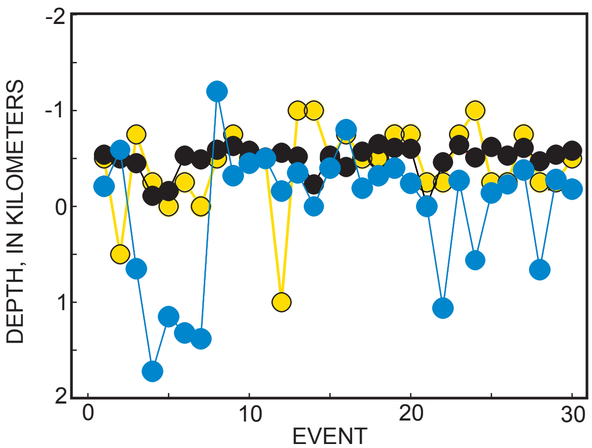

Figure 11. Comparison of earthquake hypocentral depths calculated with the 2D ray-tracing procedure and the program hypoellipse for a set of 30 earthquakes that occurred on Augustine Island in December of 2005. Black dots represent hypocentral depths calculated with the program hypoellipse, using the complete network in 2005; yellow dots represent hypocentral depths calculated with the 2D ray-tracing procedure; blue dots represent hypocentral depths calculated with the program hypoellipse, using only the same four stations used with the 2D ray-tracing procedure.

Summary and Conclusions

The two-step earthquake hypocenter-relocation procedure described here is able to resolve hypocentral depths to within 0.25 km for shocks that occur above sea level and to within 0.5 km for shocks above 2.0 km b.m.s.l. by using the seismic data collected at Augustine Volcano from 1972 to 2007. Hypocenters calculated with this procedure compare favorably with the results from the program HYPOELLIPSE, using the entire eight-station network present on Augustine Island in 2005. These results suggest that the two-step hypocenter-relocation procedure reliably calculates hypocenters at Augustine Volcano during periods when as few as four stations were operating on the island. Augustine Volcano was monitored by four- to five-station networks from 1972 to 1988 (see Power and Lalla, this volume). A study of comparative earthquake hypocenters at Augustine is presented by Power and Lalla (this volume).

Table 3. Hypocentral-depth comparisons.

Location technique	Average depth (km)	Standard deviation
Two-Dimensional ray-tracing procedure	–0.425	0.426
Hypoellipse (all stations)	–0.491	0.159
Hypoellipse (four stations)	0.0733	0.679

Several limitations are inherent in the 2D ray-tracing procedure presented here: 1, it allows for variation of seismic velocity in only two directions, and raypaths are strictly confined to the vertical plane that intersects the station and event location; 2, it takes into account only a simple box discontinuity located between sea level and 0.9 km b.m.s.l. and all other layers are considered to be homogenous and flat laying; 3, locations are not allowed to fall outside the average radius of the volcanic cone at the elevation of consideration; and 4, it can only be used to locate within 2.2 km of the volcano's summit (lat 59°21.65' N., long 153°25.69' W.). Earthquake hypocentral depths at Augustine calculated by using this technique with the seismic-velocity model of Kienle and others (1979) were found to be sensitive to a station located high on the volcanic edifice (fig. 10). Thus, the design of future networks should include several stations high on the Augustine cone, such as AUH, AUP, AUS, and AU4 (fig. 3). Ideally, these stations would have horizontal components, so that reliable S-wave readings could also be included in the hypocenter determination.

If this technique is to be used for future earthquake studies at Augustine, we recommend its expansion to include all available stations in the Augustine seismic network be evaluated. Should additional stations be added to the network, consideration should be given to placing these instruments at shot-points or receiver-sites used in the 1975 active source seismic experiment (fig. 6). Before this technique is used further, we recommend that the relative advantages of other hypocenter-relocation techniques, such as those described by Rowe and others (2004) and Deshon and others (this volume), should be carefully considered.

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Appendix 1. FORTRAN programs TRAVEL, NORMAL, and FAST configured for the 1975, 1985–86 and 2005–06 seismic networks at Augustine Volcano

This appendix contains the FORTRAN programs TRAVEL, NORMAL, and FAST configured for the 1975, 1985–86 and 2005–06 seismic networks at Augustine Volcano. These programs are contained on the DVD-ROM disc included with this volume.