The 2006 Eruption of Augustine Volcano, Alaska
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Chapter 6

Distal Volcano-Tectonic Seismicity Near Augustine Volcano

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Abstract

Clustered earthquakes located 25 km northeast of Augustine Volcano occurred more frequently beginning about 8 months before the volcano's explosive eruption in 2006. This increase in distal seismicity was contemporaneous with an increase in seismicity directly below the volcano's vent. Furthermore, the distal seismicity intensified penecontemporaneously with signals in geodetic data that appear to reveal a transition from magmatic inflation of the volcano to dike injection. Focal mechanisms for five events within the distal cluster show strike-slip-fault movement. Directly above the earthquake cluster, shallow (<5 km deep) folds and faults mapped using multichannel seismic-reflection data strike northeast, parallel to the regional structural grain. About 10 km northeast of Augustine Volcano, however, the Augustine-Seldovia arch, an important trans-basin feature, strikes west and intersects the northeast-striking structural zone. We propose that the fault causing the distal earthquake cluster strikes northwest, subparallel to the arch, and is a right-lateral strike-slip fault. Future earthquake monitoring might show whether increasing activity in the remote cluster can aid in making eruption forecasts.

Introduction

Augustine Volcano most recently erupted explosively during 2006, and intense shallow seismicity directly below the volcano's vent of the volcano preceded and accompanied this eruption (Cervelli and others, 2006, and this volume; Power and others, 2006). Contemporaneously with this volcanic and earthquake activity, seismicity occurred in a cluster located 25 km northeast of the volcano (figs. 1, 2). This distal seismicity ceased about 9 months after the eruption ended. On a worldwide basis, similar distal seismicity has occurred before many explosive eruptions (for example, White and Rowe, 2006). Thus, a future increase in distal seismicity near Augustine Volcano might help predict an eruption.

Regional Setting and Basin Structure

Augustine Volcano is part of the active magmatic arc associated with plate convergence at the Alaska-Aleutian subduction zone. The volcano lies within the southwestern part of the Cook Inlet forearc basin (fig. 1) and rests on a thick section of sedimentary and volcanic rocks that indicate protracted near-trench tectonics, including Late Triassic rocks that signal a transition from reef building far from volcanic sources to proximal magmatic-arc sedimentation (Wang and others, 1988), and thick Early Jurassic volcaniclastic rocks that record a vigorous volcanic arc near the Cook Inlet basin (Detterman and Hartsock, 1966; Fisher and Magoon, 1978). The Jurassic and Cretaceous batholiths exposed extensively along the northwest side of the Cook Inlet basin indicate active subduction during that period.

These plutonic rocks likely form the basement complex beneath the Cook Inlet basin, especially near Augustine Volcano. The basement complex might also include early Mesozoic oceanic crust, following from a tectonic analogy we draw between the Cook Inlet basin and the Great Valley of California, both of which are Mesozoic forearc basins. The Great Valley appears to be floored by oceanic crust, the distribution and structure of which is much debated (see summary cross sections in Constenius and others, 2000). The point is that the basement under Cook Inlet might have a complex structure.

We determined the upper-crustal structure near Augustine Volcano from a grid of multichannel seismic-reflection (MCS) lines collected by Western Geophysical, Inc., in 1975 (fig. 1). The data were obtained with an Aquapulse source, an array of six sleeve exploders in which propane and oxygen

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were detonated to produce an acoustic pulse with reduced bubble oscillation. The survey ship employed two streamers—one 2,380 m long with 72 recording channels, and the other 184 m long with 12 channels designed to achieve a high spatial resolution.

MCS data reveal that the Iniskin structural zone strikes northeast through lower Cook Inlet (fig. 1). The structural zone is made up of reverse faults and faulted anticlines (fig. 3). The vertical component of offset along some faults amounts to 500 m. The total along-strike length of this zone is unknown but is at least 70 km. The MCS section in figure 3*C* shows the Iniskin structural zone extending southwestward to within about 10 km of Augustine Volcano (fig. 1). However, this zone's total southwestward extent remains unknown because the zone is not evident in Mesozoic rocks exposed on the northern part of the Alaska Peninsula, southwest of Augustine Volcano.

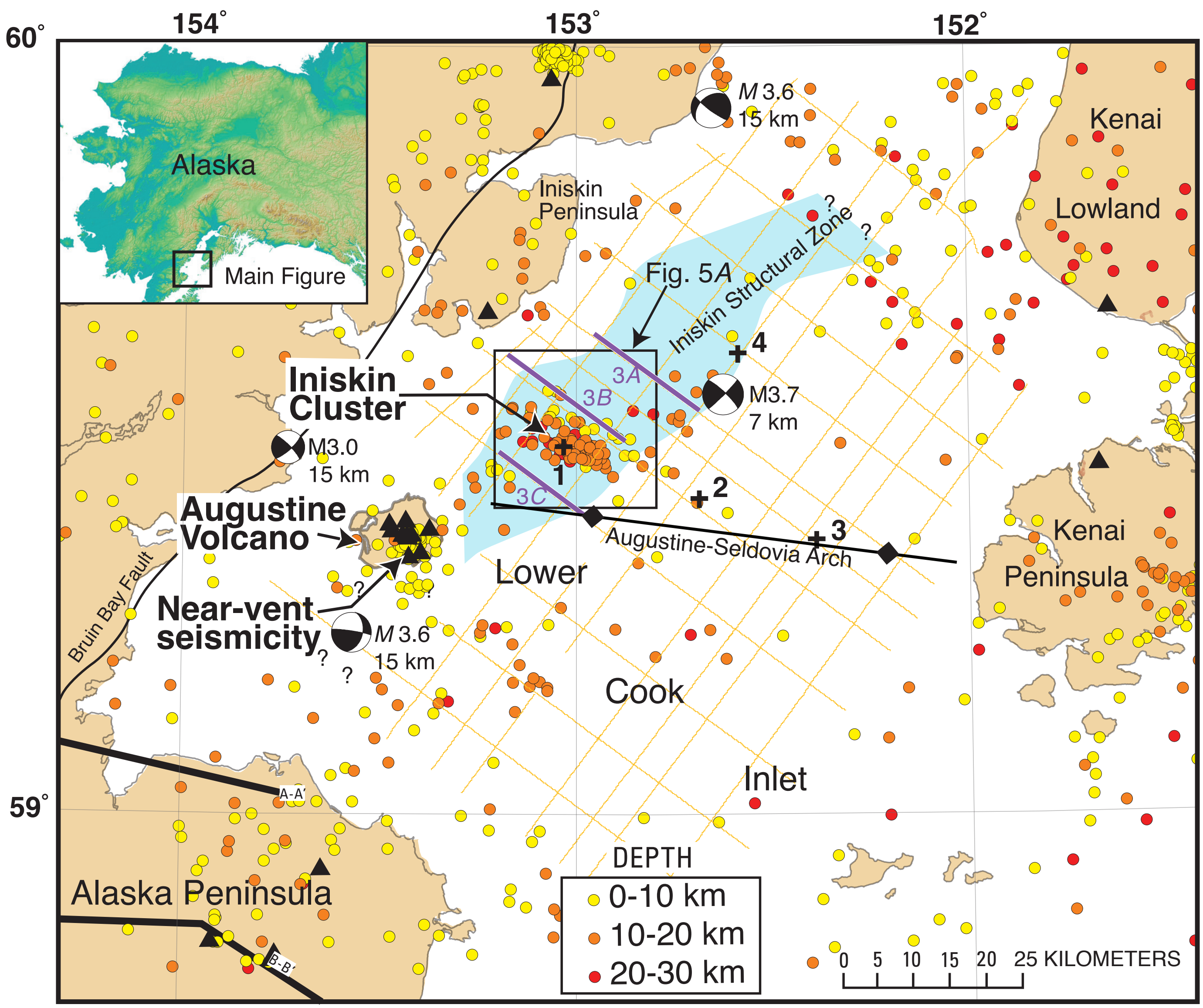

Figure 1. Map of Lower Cook Inlet, Alaska, showing the location of Augustine Volcano, the Iniskin earthquake cluster, and the Iniskin structural zone (blue area). Seismic events (colored dots) have not been relocated. Black rectangle on index map denotes area of relocated events in figure 5. Orange lines, show track lines of 1975 Western Geophysical, Inc., seismic-reflection survey; purple lines, multichannel seismic reflection sections shown in figure 3; Black lines labeled A-A′ and B-B′ indicate geologic cross sections by Detterman and Reed (1980) and Riehle and others (1993), respectively. Numbered black crosses show oil wells near Augustine Volcano: 1, Hawk #1; 2, Ibis #1; 3, South Arch #1; 4, COST #1. Earthquake epicenters are from the Alaska Earthquake Information Center (AEIC) catalog (1971-2006); earthquake focal mechanisms are lower-hemispheric projections. Black triangles show seismograph stations.

Geologic cross sections (A–A’, B–B’, fig. 1) from there show little-deformed, mainly flat lying rocks (Detterman and Reed, 1980; Riehle and others, 1993).

Folds and faults within the Cook Inlet basin strike consistently northeast (fig. 4). Northwest-striking structures are not evident in offshore areas, nor do such structures deform the major faults, such as the Bruin Bay Fault, that bound the basin on the northwest and southeast. The Iniskin structural zone strikes northeast, conforming to the regional structural grain.

The prime exception to the consistent northeastward strike is the westward strike of the Augustine-Seldovia arch, which extends across the basin to near Augustine Volcano (figs. 1 and 4). This arch is a fundamental feature of the Cook Inlet basin because it forms the south flank of the thick (7 km) accumulation of Cenozoic rocks north of the arch (for example Kirschner and Lyon, 1973). South of the arch, Cenozoic rocks are thin (<1 km thick) or absent (Fisher and Magoon, 1978). Evidently, the arch forms a trans-basin hinge that enabled rapid Cenozoic deepening of the northern part of the basin.

Seismicity

The regional seismicity of lower Cook Inlet, recorded in by the Alaska Earthquake Information Center (AEIC) catalog (1971–2006), is diffuse and reveals few patterns in map view (fig. 1), except in two areas of heightened activity. The first area encompasses abundant shallow earthquakes directly below the volcano’s vent. This seismicity was recorded by seismographs located on the volcano and on nearby parts of

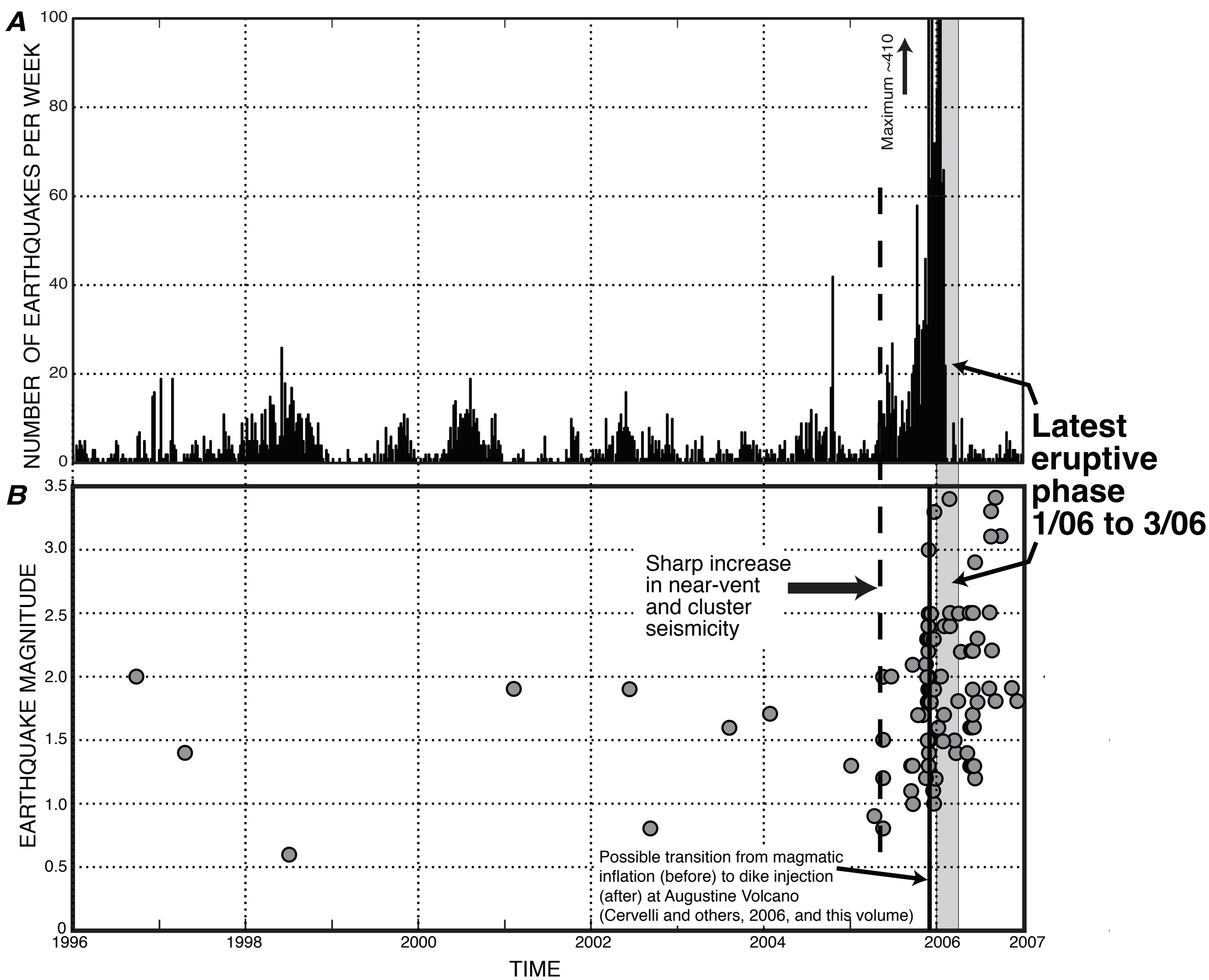

Figure 2. Earthquake activity over time at Augustine Volcano. *A*, near vent seismicity, *B*, seismicity within the Iniskin cluster. Cluster activity began about 8 months before the 2006 eruption and ended about 9 months afterward. Vertical dashed line denotes the abrupt increase in activity in late 2005.

the Alaska mainland. In general, near-vent earthquakes have very small magnitudes (M<=1.2). This activity has been attributed to volcanic processes because it is concentrated near sea level, directly below the volcanic vent. After 1996, near-vent seismicity oscillated between infrequent and moderately frequent until late 2005, when the frequency intensified to more than 100 events per week (fig. 2*A*).

The second area of heightened activity, which we call the Iniskin cluster, is located 25 km northeast of the volcano (fig. 1). Events making up this cluster were recorded by the Alaska regional seismic network; the nearest seismic stations are located on Augustine Volcano (fig. 1). Before we relocated the cluster events, their average horizontal and vertical location uncertainties were 3.6 and 4.1 km, respectively, at the 67 percent confidence level. In the worst case of the smallest events recorded by only a few stations, such uncertainties were as large as 10 km. Before being relocated, the group of epicenters was elongated northwest-southeast ward (fig. 1), but as we describe below, the relocated epicenters fill a compact area with a poorly expressed elongation.

Since 1996, near-vent earthquakes have numbered nearly 3,000 (Dixon and others, 2007), but only about 100 events have occurred within the Iniskin cluster. Cluster earthquakes were infrequent until mid-2005, when they became more frequent (fig. 2*B*). This increase in frequency occurred contemporaneously with the rapid rise in near-vent seismicity (compare figs. 2*A* and 2*B*), and both increases preceded by about 8 months the latest explosive eruption of Augustine Volcano. The level of earthquake activity within the Iniskin cluster remained relatively high throughout most of 2006, slowing only toward the end of the year. No events occurred in October and November, and only one in December.

An abrupt offset in geodetic data recorded during November 2006 indicates a change in the style of deformation at Augustine Volcano (Cervelli and others, 2006, and this volume). Before this offset, geodetic data most likely reveal magmatic inflation of the volcano, whereas afterward such data point to the onset of dike intrusion. The timing of this change in style of deformation coincides with a sharp increase in seismicity within the Iniskin cluster (fig. 2*B*).

To evaluate the detailed distribution of earthquakes within the Iniskin cluster, we relocated events, using the double-difference algorithm hypoDD (Waldhauser and

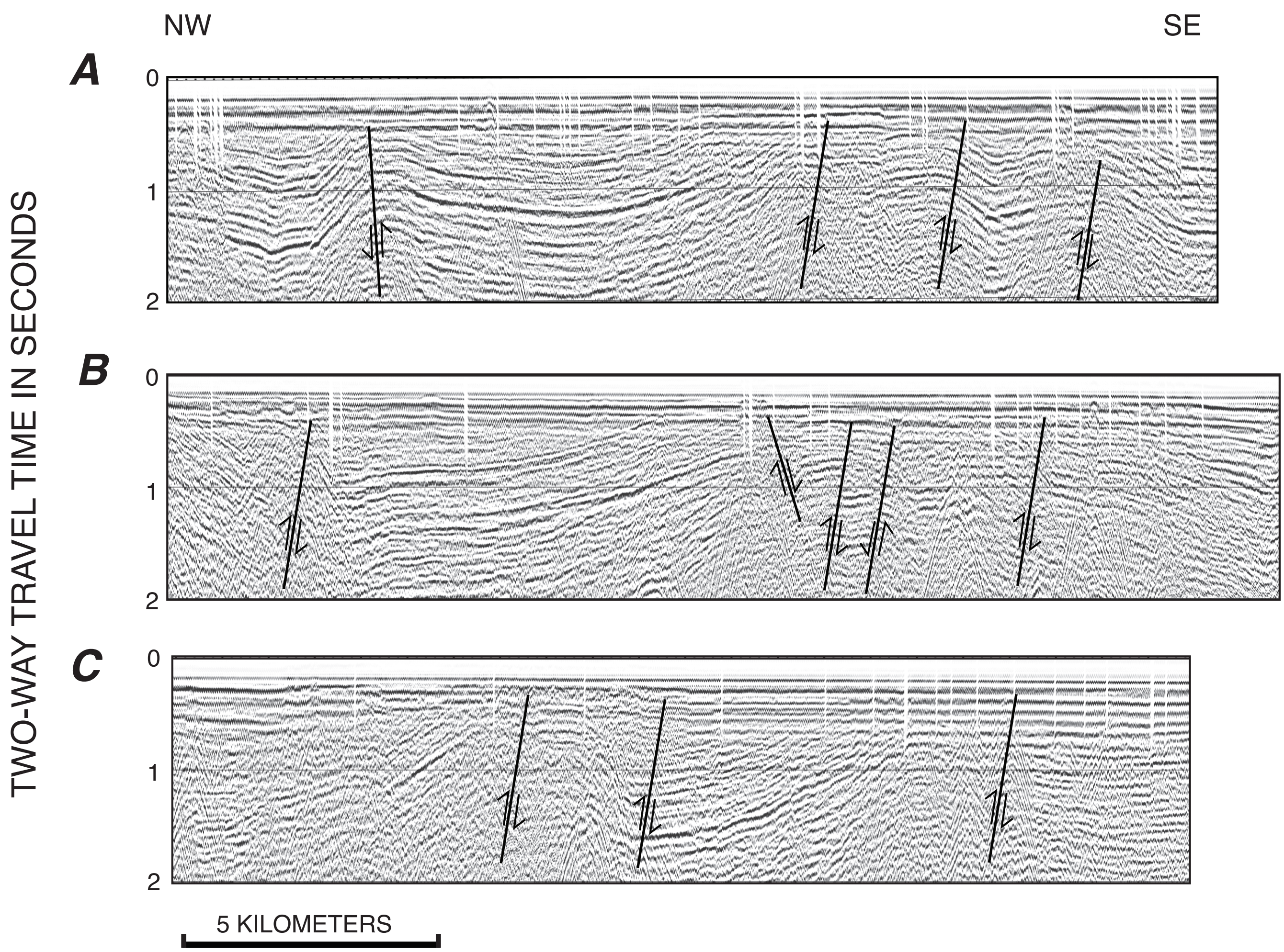

Figure 3. Multichannel seismic-reflection sections in lower Cook Inlet (fig. 1), collected with short survey streamer across the folds and faults of the Iniskin structural zone northeast of Augustine Volcano.

Ellsworth, 2000). Altogether, we relocated 108 events within 20 km of the center of the Iniskin cluster, using the catalog p- and s-wave arrivals and the standard plane-layer velocity model utilized by the AEIC for locating events in the study area (fig. 1). Because the number of events was small, we were able to use the singular-value decomposition approach, which is useful for working with small earthquake groupings because it provides information on the resolvability of hypocentral parameters and adequately represents location errors (Waldhauser, 2001). We allowed a maximum separation of 20 km between linked events and a maximum station distance of 300 km. The average offset between linked events was 4.6 km, and each event pair averaged 11 links.

The relocated events collapsed into a dense cluster less than 5 km across and from 11 to 16 km deep (figs. 5*B*–5*E*). The mean absolute location errors were 0.9 km horizontally and 1.2 km vertically, and the relative location accuracy between events was 32 m horizontally and 47 m vertically.

We calculated focal mechanisms for five events with magnitudes ranging from 3.1 to 3.4, using p-wave first motions and the program FPFIT (fig. 6) (Reasenberg and Oppenheimer, 1985). For all five events, the number of available first-motion picks ranged from 11 to 20; only one event had fewer than 15 picks. Regional stations in Cook Inlet provide good azimuthal coverage of the focal sphere. All mechanisms consistently indicate strike-slip faulting (fig. 5*A*). Although some uncertainity may remain in the focal-plane strike and dip estimates, the overall strike-slip sense of motion inferred from the five focal mechanisms is well constrained. By analyzing p-wave first motions for the events for which focal-mechanism data are available, we noted that earthquakes within the Iniskin cluster are spatially diverse but occupy a small volume and reflect a consistent mode of faulting.

Discussion

Strike of the Seismogenic Fault

Focal mechanisms for five earthquakes within the Iniskin cluster (fig. 5*A*) and for an M 3.7 event, 7 km deep and located northwest of the cluster along the Iniskin structural zone (fig. 1), all indicate that cluster seismicity results from strike-slip faulting. The main unresolved question is which nodal plane reveals the seismogenic fault.

One answer to this question is obtained from correlating nodal planes to the northeastward strike of the Iniskin structural zone (fig. 1). The northeast-striking nodal planes from all focal mechanisms closely parallel the strike of this zone, which, in turn parallels the regional structural grain of the basin (fig. 4). If this correlation is correct, then the cluster seismicity results from left-lateral oblique faulting. An important consideration in this analysis is that MCS data (for example fig. 3*C*), show the Iniskin structural zone extending southwestward from the Iniskin cluster, and so choosing the northeast-striking nodal plane relates the seismicity to a through going structure that connects the cluster with the volcano.

Alternatively, the northwest-striking nodal planes might be associated with one or more faults subparallel to the Augustine-Seldovia arch. About 10 km northeast of Augustine Volcano, this west-striking arch intersects the northeast-striking Iniskin structural zone (figs. 1, 4). As mentioned above in the section entitled “Regional Setting and Basin Structure,” this arch is the primary transverse structure within the southern part of the Cook Inlet basin. Although raw earthquake

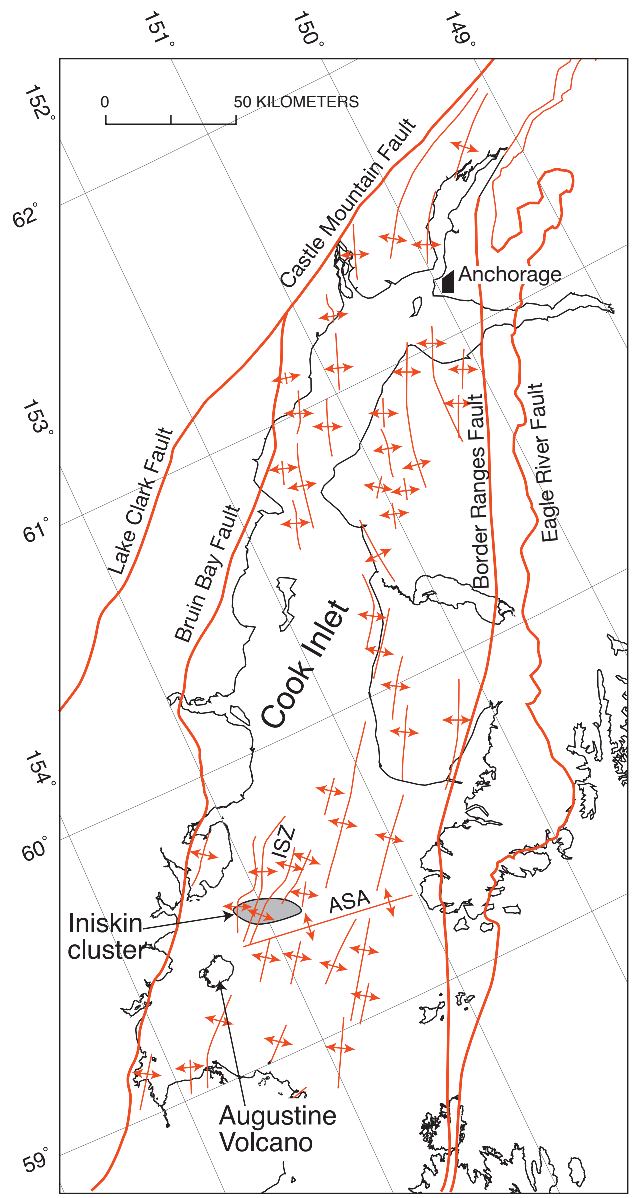

Figure 4. Map of geologic structures and major basin-bounding faults in the Cook Inlet basin. All features share a regional northeastward strike (Kirschner and Lyon, 1973; Magoon and others, 1976; Fisher and Magoon, 1978; Wilson and others, 1999; Haeussler and others, 2000). ISZ, Iniskin Structural Zone; ASA, Augustine-Seldovia Arch.

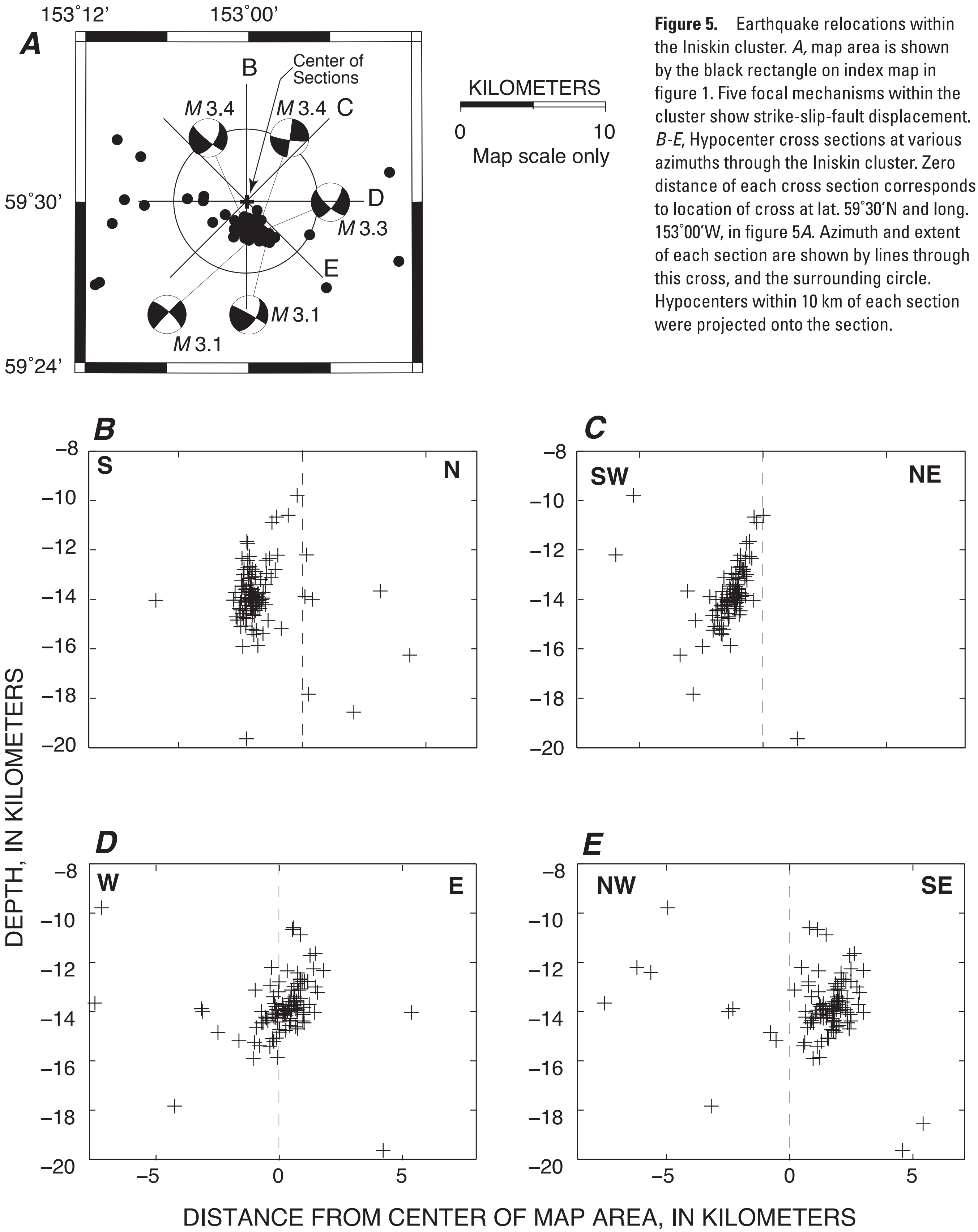

Figure 5. Earthquake relocations within the Iniskin cluster. *A,* map area is shown by the black rectangle on index map in figure 1. Five focal mechanisms within the cluster show strike-slip-fault displacement. *B-E*, Hypocenter cross sections at various azimuths through the Iniskin cluster. Zero distance of each cross section corresponds to location of cross at lat. 59°30'N and long. 153°00'W, in figure 5*A*. Azimuth and extent of each section are shown by lines through this cross, and the surrounding circle. Hypocenters within 10 km of each section were projected onto the section.

epicenters of events within the Iniskin cluster portray the cluster with a strong northwest-southeastward elongation (fig. 1), which seemingly fits this alternative answer, the relocated events form a dense central group with scattered outlying epicenters (fig. 5*A*). Overall, the relocated events show only a weak geographic elongation.

Of the four hypocenter cross sections in figure 5, the northwest-southeast cross section (fig. 5*C*) seems to be most nearly perpendicular to the earthquake cluster, indicating a northwest-striking right-lateral strike-slip fault sub parallel to the Augustine-Seldovia arch and perpendicular to the regional structural grain. Furthermore, regional stress determined from studies of earthquake activity at volcanoes near Augustine, notably Mounts Spurr, Iliamna, and Redoubt, indicate a northwestward direction of maximum principal stress (Jolly and others, 1994; Roman and others, 2004; Sanchez and others, 2004), suggesting that right-lateral strike-slip faults would strike northwest, at an angle of about 30° to the maximum stress direction. This northwestward direction of maximum principal stress agrees with the observations by Ruppert (2008), who used earthquake focal mechanisms from southern Alaska to calculate best-fitting stress tensors. Near Augustine Volcano, west- or northwest-striking strike-slip faults should predominate.

The ambiguity concerning the nodal plane partly arises because MCS data reveal the structure only of shallow (<7 km) crustal levels, because of limited seismic-source strength, whereas the relocated hypocenters in the Iniskin cluster range from 11 km to 16 km in depth. In comparison, near Augustine Volcano, the top of basement is about 10 km deep (see Fisher and Magoon, 1978, fig. 10). Thus, the seismicity appears to have originated within the basement complex below the Cook Inlet basin.

The northwest-striking nodal plane, then, may reveal a basement fault that could have originated as long ago as the early Mesozoic, the likely age of the basement complex. To produce the cluster seismicity, this fault would have been reactivated under the current stress regime as a right-lateral strike-slip fault.

Clearly, Augustine Volcano is situated at a complex structural crossroads. In our opinion, the Iniskin cluster most likely occurred along a northwest-striking right-lateral strike-slip fault associated with the trans basin Augustine-Seldovia arch. The fault might be a reactivated basement structure. The most troublesome aspect of this interpretation is that MCS data do not reveal a right-lateral transverse offset in the Iniskin structural zone directly above the Iniskin cluster.

Connection Between Seismicity and Volcanism

The close temporal association between abrupt increases in near-vent and cluster seismicity (figs. 2) and the fact that both increases preceded an explosive eruptive phase at Augustine Volcano by about 8 months suggest that magma flux and the seismogenic strike-slip fault are closely linked within the crustal stress field, as has been reported for other volcanoes. In fact, numerous studies of volcanic regions detail the close

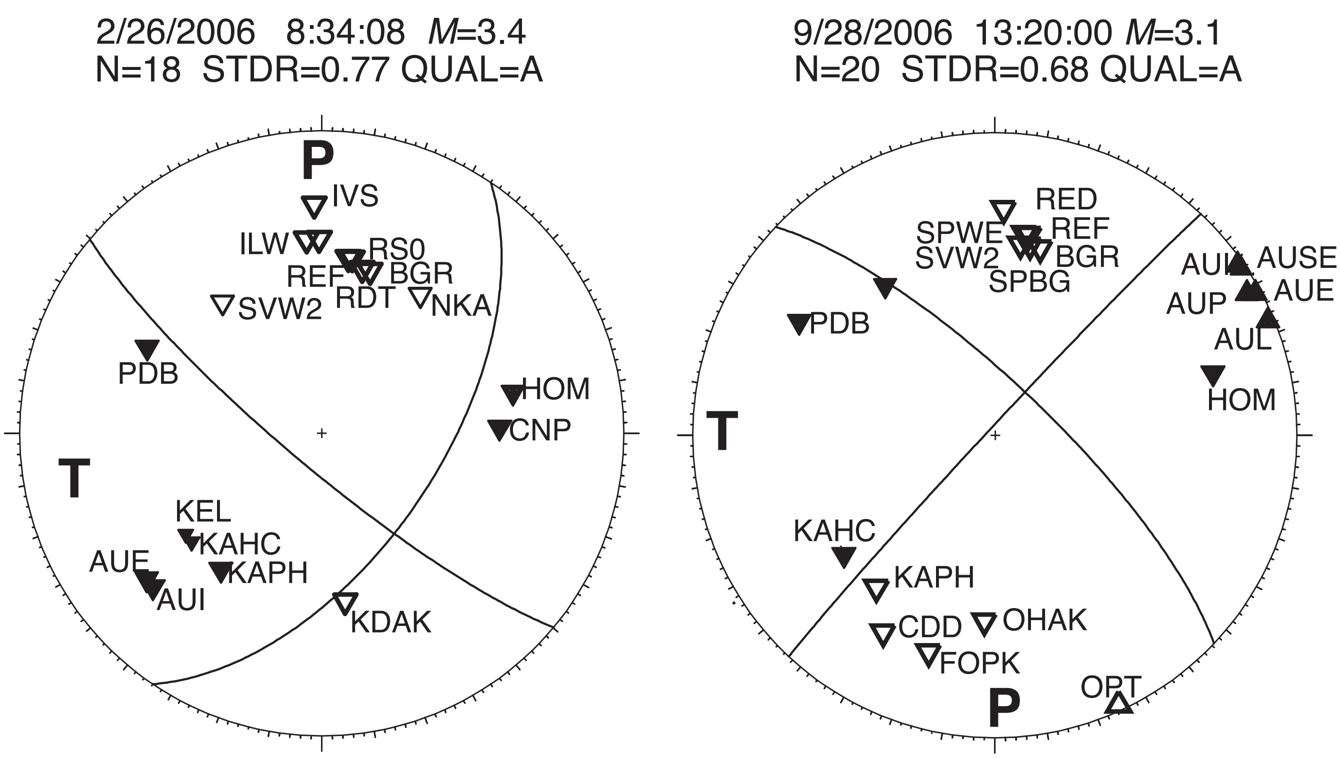

Figure 6. Two examples of p-wave first-motion focal mechanisms for events in the Iniskin cluster, both showing strike-slip motion.

coupling between earthquakes and volcanism and show that magmatic activity can trigger seismicity, and vice versa (Nostro and others, 1998; Hill and others, 2002; Toda and others, 2002; Feuillet and others, 2004; Diez and others, 2005; Manga and Brodsky, 2006; Parsons and others, 2006). Commonly, this triggering requires only subtle changes in Coulomb stress because the volcanic and earthquake systems are poised near critical points. White and Rowe (2006) compiled 25 examples from around the world in which distal earthquake clusters, such as the one we report on here, occurred from 2 to 30 km away from volcanoes just before they erupted. For example, Plinian eruptions of El Chichón (1982; Jimenez and others, 1999) and Mount Pinatubo (1991; Harlow and others, 1996) were preceded by distal earthquake swarms that began 2-26 months before cataclysmic eruptions. The ongoing eruption of South Soufriere Hills Volcano that began in 1995 was preceded by distal seismicity that occurred during the preceding 2 years (Aspinall and others, 1998). Thus, the distal volcano-tectonic seismicity we describe at Augustine Volcano conforms with observations worldwide.

Near Augustine Volcano, the coincident near-vent and distal seismicity appears to have occurred only once because no previous eruption of the volcano is known to have stimulated seismicity in the area of the Iniskin cluster. No candidate events are evident in the AEIC catalog. One possible reason for the dearth of earlier events is poor detection by the dispersed regional seismic network in Alaska before the 1990s. Another possible reason is that before 2005, shear stress within the asperity causing the Iniskin cluster had not attained near-critical values, and so volcanism before the 2006 eruption was an insufficient trigger. If so, then stress in the asperity causing the Iniskin cluster may need to rebuild after the 2006 seismicity. This conclusion bears critically on the use of distal seismicity, like the Iniskin cluster, to predict future eruptions at Augustine Volcano.

Conclusion

Clustered earthquakes located 25 km northeast of Augustine Volcano became more numerous over the 8 months just before the volcano’s 2006 explosive phase, and this seismicity abated within the 9 months after the eruption ceased. Focal mechanisms from events within the cluster reveal strike-slip faulting. We conclude that the earthquake cluster occurred along a northwest-striking right-lateral strike-slip fault because the cluster occurred near the trans-basin Augustine-Seldovia arch. The fault may be a reactivated basement structure. This interpreted fault strikes perpendicularly to a shallow structural zone, interpreted from MCS data, which includes reverse faults and anticlines. These structures, however, reveal no transverse offset. The clustered earthquakes near Augustine Volcano are similar to many examples of preeruption seismicity reported at volcanoes around the world. Recurrence of earthquake activity in or near the Iniskin cluster might be useful in predicting an imminent eruption of Augustine Volcano.

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