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Seismic and geodetic investigation of the 1996-1998 earthquake swarm at Strandline Lake, Alaska

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Seismic and Geodetic Investigation of the 1996-1998 Earthquake Swarm at Strandline Lake, Alaska

by

Wayne Walter Kilgore

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Geology College of Arts and Sciences University of South Florida

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Microearthquake (< M3.0) swarms occur frequently in volcanic environments, but do not always culminate in an eruption. Such non-eruptive swarms may be caused by stresses induced by magma intrusion, hydrothermal fluid circulation, or regional tectonic processes, such as slow-slip earthquakes. Strandline Lake, located 30 km northeast of Mount Spurr volcano in south-central Alaska, experienced an intense earthquake swarm between August 1996 and August 1998. The Alaska Volcano Observatory (AVO) catalog indicates that a total of 2,999 earthquakes were detected during the swarm period, with a maximum magnitude of M_w 3.1 and a depth range of 0-30 km below sea level (with the majority of catalog hypocenters located between 5-10 km BSL). The cumulative seismic moment of the swarm was 2.03e^{15} N-m, equivalent to a cumulative magnitude of M_w 4.2.

Because of the swarm's distance from the nearest Holocene volcanic vent, seismic monitoring was poor and gas and GPS data do not exist for the swarm period. However, combined waveforms from a dense seismic network on Mount Spurr and from several regional seismic stations allow reanalysis of the swarm earthquakes. I first developed a new 1-D velocity model for the Strandline Lake region by re-picking and inverting precise arrival times for 27 large Strandline Lake earthquakes. The new velocity model reduced the average RMS for these earthquakes from 0.16 to 0.11s, and the average
horizontal and vertical location errors from 3.3 to 2.5 km and 4.7 to 3.0 km, respectively. Depths of the 27 earthquakes ranged from 10.5 to 22.1 km with an average depth of 16.6 km. A moderately high b-value of 1.33 was determined for the swarm period, possibly indicative of magmatic activity. However, a similarly high b-value of 1.25 was calculated for the background period. 28 well-constrained fault plane solutions for both swarm and background earthquakes indicate a diverse mixture of strike-slip, dip-slip, and reverse faulting beneath Strandline Lake. Finally, five Interferometric Synthetic Aperture Radar (InSAR) images spanning the swarm period unambiguously show no evidence of surface deformation. While a shallow volcanic intrusion appears to be an unlikely cause of the Strandline Lake swarm based on the new well-constrained earthquake depths and the absence of strong surface deformation, the depth range of 10.5 to 22.1 km BSL for relocated earthquakes and the high degree of FPS heterogeneity for this swarm are similar to an earthquake swarm beneath Lake Tahoe, California in 2003 caused by a deep intrusion near the base of the crust (Smith et al., 2004). This similarity suggests that a deep crustal magmatic intrusion could have occurred beneath the Strandline Lake area in 1996-1998 and may have been responsible for the resulting microearthquake activity.
Chapter 1

Introduction

Earthquake swarms consist of spatially and temporally clustered micro-earthquakes which lack the typical mainshock/aftershock sequence commonly associated with large crustal earthquakes. The cause of such swarms is a topic of debate within the geologic community (e.g. Vidale and Shearer, 2006). Some swarms are the seismic response to an injection of magmatic material, such as at Lake Tahoe, California in 2003 (Smith et al., 2004) and Upptyppingar, Iceland in 2007 (Jakobsdottir et al., 2008). Other earthquake swarms appear to have non-volcanic origins and that the lack of a mainshock at the onset of the sequence does not necessarily denote the involvement of magma (e.g. Jones and Malone, 2005). Both of these mechanisms are possible, and only by examining multiple pieces of evidence, such as seismic, deformation, and gas emission data, can the specific cause of a swarm be determined.

Strandline Lake is located in south-central Alaska and lies approximately 110 km west-northwest of Anchorage (Figure 1.1). The Strandline Lake area experienced an intense earthquake swarm between mid-1996 and mid-1998. The swarm consisted of approximately 3,000 events with a maximum magnitude of $M_w$ 3.1 and a depth range of approximately 3 to 12 km (McNutt and Marzocchi, 2004) below sea level (BSL).

In the peer-reviewed literature, one study (Jolly and Page, 2004) describes earthquake activity at Strandline Lake as spatially distinct from other, more seismically
**Figure 1.1:** Location map of the Cook Inlet region of Alaska showing Strandline Lake’s (purple star) proximity to and alignment with several volcanoes (red triangles). Black diamonds represent seismic stations and black dots represent population centers.
active areas around the Cook Inlet, but concedes that the Strandline Lake events are poorly located due to sparse network of surrounding seismic monitoring stations. Here, data resulting from a merged seismic network will be analyzed in an attempt to provide well constrained locations and fault-plane solutions for the Strandline Lake events.

It is hypothesized that the earthquake swarm was caused by one of three mechanisms: 1) emplacement of a magma body, such as a dike or sill, 2) microseismicity purely tectonic processes, such as a slow-slip event along the Aleutian Arc, or 3) an increase in (non-magmatic) fluid circulation. In an attempt to determine the cause of the Strandline Lake earthquake swarm, several data sets and analytical methods are employed. First, a b-value is determined for both background and swarm periods. Second, a 1-D velocity model is developed that is specific to the Strandline Lake area. Third, using the new velocity model, the entire Alaska Volcano Observatory (AVO) catalog of earthquakes in the Strandline Lake area is relocated. Fourth, Synthetic Aperture Radar (InSAR) images are analyzed to determine whether any localized uplift in response to an intrusion of a magmatic dike or sill can be detected. Fifth, focal mechanisms of background and swarm earthquakes are examined in an attempt to detect any temporal changes in stress at Strandline Lake. Sixth, the results of the aforementioned analyses are compared to published analyses of several other earthquake swarms that occurred in a non-volcanic setting. From these results, the most logical explanation for the source of the earthquake swarm at Strandline Lake will be determined.
1.1 Motivation

Earthquake swarms are a common occurrence worldwide; however, the swarm at Strandline Lake was chosen for in-depth analyses for several reasons. First, Strandline Lake sits in a unique region at the northern edge of the Aleutian volcanic arc (Figure 1.1), at the point where the North American, Pacific plates, and Yakutat terrane converge (Figure 1.2). Thus, the swarm could be a result of tectonic processes in conjunction with fluid upwelling from the edge of the subducting slab. However, because it is located directly in line with the Aleutian volcanic front, the Strandline Lake area is in the correct location to be a developing “cryptovolcano”. Second, no gas or GPS monitoring was conducted during the swarm period, making analysis of the seismicity the primary investigative tool. A unique velocity model for use in locating earthquakes around the Strandline Lake area did not exist prior to this research. Its development is critical for the seismicity analysis and for future research in the Strandline Lake region. Third, little knowledge currently exists concerning this particular swarm and most explanations of its cause are speculative. Only one study (McNutt and Marzocchi, 2004) attempts to hypothesize a cause for the swarm, but this hypothesis was not rigorously tested.

Because Strandline Lake may reside in a transitional stress regime between the Aleutian Arc and the Alaska Range, understanding the cause of this earthquake swarm may be helpful in understanding the mechanisms that drive similar swarms in non-volcanic regions around the world and Alaskan tectonics in general. An accurate interpretation of the driving process for this earthquake swarm may assist in forecasting future volcanic eruptions and mitigating the associated natural hazards posed to surrounding communities.
Figure 1.2 Tectonic map of southern Alaska. Strandline Lake (dark purple star) sits near the junction of the Pacific Plate, North American Plate, and the Yakutat block. Volcanoes are represented by red triangles, depth to the top of the subducting slab by dashed blue lines, and major faults by solid green lines. (Figure after Eberhart-Phillips, 2006)
Chapter 2

Background

The aim of this chapter is to provide a detailed explanation of current knowledge and unanswered questions about earthquake swarms, and about the Strandline Lake earthquake swarm in particular. A detailed description of the geographic and tectonic setting, and the seismicity of Strandline Lake, as well as the tools and methods used to monitor the area are fundamental to this understanding. Additionally, general characteristics of earthquake swarm activity, and particularly that which occurs in non-volcanic areas, need to be examined before any interpretations of the Strandline Lake swarm can be made.
2.1 Earthquake Swarms

Earthquake swarms are characterized as spatio-temporal clusters of seismic events which lack a dominant earthquake at the onset of the sequence (Fischer and Horalek, 2005). The number of earthquakes that constitute a swarm can range from tens to hundreds of thousands, yet swarm earthquakes generally have a maximum magnitude of less than 4 (Ma and Eaton, 2009). Earthquake swarms are common occurrences in volcanic regions, in which case they are referred to as volcanotectonic (VT) earthquake swarms (Lahr et al., 1994), however, many have also been recorded in non-volcanic areas (Cappa et al., 2009; Ma and Eaton, 2009; Jakobsdottir et al., 2008; Von Seggern et al., 2008; Ibs-von Seht et al., 2006; Vidale and Shearer, 2006; Fischer and Horalek, 2005; McNutt and Marzocchi, 2004; Smith et al., 2004; Chiu et al., 1984). While swarms are clearly observed in the seismic record, their source mechanisms are complex and poorly understood. Earthquake swarms are thought to be caused by one or more of the following processes: Tectonic activity leading to a critical change in stress of the region, intrusion of highly pressurized crustal fluids (including magma), or aseismic slip along a fault plane (Fischer and Horalek, 2005; Vidale and Shearer, 2006).
2.1.1 Volcano-Tectonic Earthquake Swarms

Earthquake swarms are observed predominantly in volcanic environments and these VT swarms are one of the earliest detectable precursors to volcanic unrest (Roman and Cashman, 2006). High frequency (≥ 5Hz) seismicity within these VT swarms (Figure 2.1) is attributed to the brittle failure of rock.

Several conceptual models for the occurrence of VT swarms have been proposed. Hill (1977) first proposed that VT swarms are the result of a series of inflated dikes with their long axis orientated in the direction of maximum principal stress. Hill (1977) made field observations that dikes commonly exhibited an en echelon pattern and proposed that offset dikes were connected by shear fractures and that VT seismicity occurred along these fractures (Figure 2.2A). Ukawa and Tsukahara (1996) suggested a different model based upon the seismicity distribution of several earthquake swarms within a monogenetic volcanic field off the east coast of the Izu Peninsula in central Japan. They proposed a spatio-temporal relationship between hypocentral depths of the VT earthquakes and dike propagation. The VT seismicity is focused in a zone at the top of the dike as tensile stress is elevated when the adjacent tip of the dike opens (Figure 2.2B). A third model proposed by Roman (2005) suggests that VT seismicity is focused laterally outward from the dike as its walls are pushed outward during inflation. Notable characteristics of this model are the random spatial distribution of VT seismicity surrounding the dike as well as an approximate 90° rotation of VT fault-plane solution p-axes relative to regional maximum compression (Figure 2.2C).
Figure 2.1 Examples of VT seismicity at Kuchinoerabujima Volcano, Japan (Figure from Triastuty et al., 2009).

Figure 2.2 Existing models showing the relationship between the propagation of a magma-filled dike and the observed VT seismicity. (A) Map view of the model by Hill (1977) shows VT earthquakes along a shear plane extending from the tips of dikes. (B) Cross section of the model by Ukawa and Tsukahara (1996) shows a progressive upward migration of VT seismicity ahead of the tip of the inflating dike. (C) Cross section of the model proposed by Roman (2005) shows a random temporal and spatial distribution of the VT seismicity along with a 90° rotation of the fault plane solution as the dike inflates (Figure from Roman and Cashman, 2006).
None of the three models mentioned can explain VT seismicity at all volcanic areas (Roman and Cashman, 2006). Instead, each model appears to address magma-induced stresses in different areas surrounding a propagating or inflating dike. However, taken together, they provide a combined model for VT swarms. Roman and Cashman (2006) observed that the models supporting VT seismicity associated with dike propagation (e.g., Hill, 1977 and Ukawa and Tsukhara, 1996) are consistent with VT swarms at volcanoes with a basaltic composition while VT seismicity associated with dike inflation (e.g., Roman, 2005) occurred more commonly at stratovolcanoes with a more silicic magma composition. They concluded that mechanisms of VT seismicity are most likely related to pre-existing structural features, the orientation and magnitude of regional stress, and the rheological properties of the ascending magma.
2.1.2 Non-Volcanic Earthquake Swarms

While most common in volcanic areas and continental rift zones, earthquake swarms can also occur in areas without an active volcano (e.g., Brauer et al., 2009). Seismic activity in these areas generally results from failure along pre-existing fault planes and typically exhibits mainshock-aftershock sequences characterized by a rate of decay defined by the Omori Law (Hainzl and Ogata, 2005, Utsu, 1961). However, non-volcanic swarms, which deviate from Omori-type behavior, may occur when either magmatic or hydrothermal activity induce hundreds to thousands of small events with no precursory mainshock.

A survey of previous studies of earthquake swarms shows that swarms in volcanic regions tend to be shallower than swarms in regions where volcanic activity is absent (Jakobsdottir et al., 2008; von Seggern et al., 2008; Ibs-von Seht, 2006; Vidale and Shearer, 2006; Jones and Malone, 2005; McNutt and Marzocchi, 2004; Roman et al., 2004; Smith et al., 2004). In examining these studies, it appears that volcanic swarm activity is generally concentrated between ~10km and the vent of the volcanic edifice, while non-volcanic swarms occur near the base of the seismogenic crust. It should be noted, however, that two of the examined studies of non-volcanic swarms (Ma and Eaton, 2009; Cappa et al., 2009) document shallow (< 10km) hypocentral depths. Both of these swarms may have also been induced by the circulation of hydrothermal fluids within the shallow crust. Ma and Eaton (2009) stated that fluids play a critical role in swarm seismogenesis and that some swarms may be triggered by anthropogenic activities, such as the injection or removal of fluids (e.g., Ake et al., 2005).
2.2 Strandline Lake, Alaska

Strandline Lake is a small glacially-dammed lake in south-central Alaska, and was the site of an intense earthquake swarm beginning in mid-1996 and continuing until mid-1998. The following sections will give a comprehensive background of this swarm from a geographic, geophysical, and tectonic perspective.

The seismicity of the area is continuously monitored by the AVO and the AEIC. The Mount Spurr seismic network, which is operated by the AVO, 30 km to the southwest of Strandline Lake, is the main source of seismic monitoring in the region. However, the AEIC operates numerous seismic stations throughout the state of Alaska, and one of their stations (SKN) is located ~50 km northeast of Strandline Lake. A second AEIC station (SSN) is located ~60 km east of Strandline Lake.

Strandline Lake is located in a complex tectonic setting at the northern end of the Aleutian volcanic arc. As previously stated, it is located near the junction of the North American and Pacific plates and the subducting Yakutat block (Figure 1.2) and sits between two major active fault systems, the Castle Mountain and Denali. Dextral transpression of the entire Cook Inlet area appears to be driven by coupling between the North American and Pacific plates, and by lateral escape of the Yakutat block (Haeussler, 2000).

A previous study of seismic activity in the Mount Spurr area (Roman et al., 2004) and a study looking at elevated seismic activity along the entire Aleutian Arc in 1996 (McNutt and Marzocchi, 2004) both document the swarm seismicity in the Strandline Lake area. While McNutt and Marzocchi, (2004) suggest that the seismic swarm at
Strandline Lake is representative of a strain transient, it is also possible that this swarm may be a precursor to the birth of a new volcano, due to its location along the volcanic front (Figure 1.1). Aside from this, little literature currently exists on the swarm and is limited mostly to informal communications from the AVO. A review of the studies which reference the swarm at Strandline Lake will be included at the end of this section.
2.2.1 Physiographic and Geologic Setting

Located at 61.47N and 152.03W, Strandline Lake sits within a remote region of the Alaskan wilderness, northwest of the Cook Inlet. It lies approximately 30 km northeast of Mount Spurr volcano and 110 km west of the city of Anchorage (Figure 1.1). Strandline Lake sits at the foot of the Tordrillo Mountains to the west, which give way to the Susitna lowlands to the east. Strandline Lake itself is the result of the damming of the Beluga River by the Triumvirate Glacier. The south end of the lake is dammed by the glacier and is subject to frequent outburst floods called jökulhlaups during melting or collapse of the glacier. However, there are no records of a jökulhlaup in 1996 at Strandline Lake (Matthew Sturm, personal communication).

To make interpretations of rock units surrounding the Strandline Lake area, two geologic maps of the Cook Inlet region (Magoon et al., 1976 and Wilson et al., 2009) were reviewed. The lake is bounded to the east and north by Late-Cretaceous/Early Jurassic low-grade metamorphosed rock, consisting primarily of slate and rocks of volcanic origin (Figure 2.3). To the west, the lake is bounded by Paleocene plutonic rocks composed mostly of granite, quartz monzonite, and syenite. The area around Strandline Lake also contains rocks of volcanic origins which appear to “dot” the landscape. To the north and east of Strandline Lake, several Paleocene to Early Cretaceous volcanic intrusions are present. To the north- and southwest of the lake, several Cretaceous volcanic intrusions are present. No Quaternary volcanic deposits, such as those found near Mount Spurr, are found adjacent to Strandline Lake, and no historical eruptive events have been recorded there.
Figure 2.3 Geologic map of the Strandline Lake, Alaska area. Strandline Lake is denoted by the black box. Strandline Lake is bounded to the east by a metamorphic rock unit (Kivs), to the west by a granitic intrusive unit (Tpgr), and to the south by the Triumvirate glacier. Volcanic intrusions (TKv and Kv) also dot the landscape around Strandline Lake. Quaternary volcanic deposits (Qv), which are prominent around Mount Spurr, are absent in the area immediately surrounding Strandline Lake. For simplicity, only those units which are relevant to the region immediately surrounding Strandline Lake are listed above. For a full list of map units please refer to Wilson et al. (2009). (Figure modified from Wilson et al., 2009)
2.2.2 Tectonic Setting

Strandline Lake is located in a compressive tectonic regime where the oceanic crust of the Pacific plate is being subducted beneath the continental margin of the North American plate. This subduction has given rise to the Aleutian volcanic arc, one of the most active volcanic arcs in the world. It has also been the cause of some of the most intense earthquakes ever recorded in human history (Plafker, 1965; Kanamori, 1971). Additionally, the Yakutat block, an exotic terrane, is actively accreting and subducting along the southern margin of Alaska (Brocher et al., 1994). It is widely thought that the three tectonic plates/blocks converge somewhere near Strandline Lake (Figure 1.2).

Strandline Lake is directly aligned with the volcanic front formed by the active volcanoes in the Cook Inlet region (Mount Spurr, Redoubt, Iliamna, Augustine, and Fourpeaked) (Figure 1.2). Thus, Strandline Lake sits in the correct location to be an incipient (crypto)volcano. Additionally, as seen in Figure 2.3, small un-named faults striking in a general NW-SE direction have been mapped in the area around Strandline Lake. The area sits at the boundary between the Aleutian megathrust and the Alaska Range, between the Denali and Lake Clark-Castle Mountain fault systems (Figure 1.2). The area is therefore subjected to a wide range of tectonic activity and the observed seismic activity may be a result of stress transfer from the larger fault systems to the smaller un-named faults. However, this hypothesis becomes problematic due to the fact that a main-shock aftershock sequence, commonly associated with brittle failure of rock under pure tectonic stresses, has not been observed. An alternative hypothesis is that fluid upwellings from the edge of the subducting slabs play a key part in the seismogenesis of the swarm.
2.2.3 Geophysical Monitoring

The seismicity of the Strandline Lake area has been monitored continuously since the early 1990’s by the AVO and AEIC. Seismic monitoring is the only method of continuous geophysical monitoring currently being conducted at Strandline Lake. Data from gas monitoring overflights and a global positioning system (GPS) network do not exist for this area. The bulk of the seismic network consists of seismometers installed and operated by the AVO on Mount Spurr and Crater Peak (Figure 2.4). However, for larger Strandline Lake earthquakes, arrivals recorded by the seismic network of Redoubt volcano, 125 km to the south, are useable for event analysis as well. Three seismometers (AVO station STLK and AEIC stations SKN and SSN) to the east and north of Strandline Lake are vital to this study due to the fact that they provide azimuthal coverage for determining precise locations and fault plane solutions for the events. Station SKN, north of Strandline Lake, has been in operation since 1991 and recorded a large number of the events from the 1996-1998 swarm. Station STLK, just east of Strandline Lake, was installed by AVO in 1997 midway during the swarm, and thus only the second half of the swarm was recorded on this station. Station SSN, to the east of Strandline Lake is an AEIC station located on Mount Susitna which recorded many of the 1996-1998 swarm events.
Figure 2.4 Seismic network surrounding Strandline Lake. The majority of monitoring stations (red triangles) come from the Mount Spurr network to the south. Station STLK was added in 1997, during the middle of the swarm. Stations SKN, to the northeast, and SSN, to the east, close the azimuthal gap when constraining earthquake locations.
2.2.4 The 1996-1998 Earthquake Swarm

In late August 1996 an intense seismic swarm began beneath Strandline Lake, Alaska. The swarm formed a dense cluster initially thought to be centered between 5 and 7 km BSL (Figure 2.5). The AVO noted this seismicity in their day-to-day monitoring of Mount Spurr; however, Strandline Lake events were seen as anomalous and classified separately. The AVO catalog indicates a total of 2,999 events recorded in the immediate vicinity of Strandline Lake during the two-year period. Figure 2.6 displays a histogram of the seismic activity at Strandline Lake before, during, and after the swarm. Activity reached its peak intensity during September 1996, when 42 events were recorded during one 24-hour period.

Swarm earthquakes typically have an average magnitude of less than $M_w$ 1.0. The largest earthquake recorded during the Strandline Lake swarm was a $M_w$ 3.1 on July 1, 1997, almost exactly at the mid-point of what is defined as the swarm period (Figure 2.7). Intense seismic activity continued until late August, 1998. The cumulative seismic moment released during the swarm is $2.03 \times 10^{15}$ N-m, or the equivalent of a $M_w$ 4.2 earthquake (Figure 2.8). In the period following the swarm, seismic activity was not as energetic, however, as Figure 2.6 shows, it remained noticeably higher than pre-swarm conditions. This may be due to the presence of a local seismic station (STLK) that did not exist prior to the swarm.

It is not entirely clear whether the swarm was caused by tectonic or magmatic processes. However, tectonic earthquakes typically show a pattern of a large earthquake (mainshock) followed by numerous smaller earthquakes (aftershocks) whereas volcanic
Figure 2.5  Plot showing the catalog depths of the swarm earthquakes over time. These depths were determined prior to development of the 1-D velocity model for Strandline Lake.

Figure 2.6  Histogram of the seismic activity at Strandline Lake, Alaska over a 10-year period. The onset of the swarm in question is clearly visible in the middle of 1996. After the end of the swarm in mid-1998, seismic activity remained elevated beyond the levels of pre-swarm activity, but relatively quiet compared to the swarm itself. (Figure from Roman et al., 2004)
Figure 2.7  Plot of earthquake magnitudes over time for earthquakes at Strandline Lake. The onset of the swarm is denoted by the red arrow. The largest events ($\geq M 2.0$) are clearly seen to occur during the middle of the swarm.

Figure 2.8  Plot showing the cumulative release of seismic energy from the earthquake swarm at Strandline Lake. The onset of the swarm is denoted by the red arrow.
ones do not. Yet, the lack of gas, thermal, and continuous deformation monitoring means
that few other signs of possible volcanic unrest can be diagnosed. The European Remote
Sensing (ERS)-2 satellite made several orbits (before, during, and after the swarm) during
which SAR images of Strandline Lake were acquired, allowing for analysis of surface
deforation during the swarm in addition to seismological analysis of swarm
earthquakes.
2.2.4.1 Previous Work

Several published studies have referenced seismicity at Strandline Lake (Jolly and Page, 1994; Flores and Doser, 2005) and one study (McNutt and Marzocchi, 2004) has attempted to explain the cause of the swarm. Jolly and Page (1994) described seismicity at Strandline Lake two years prior to the onset of the swarm in an analysis of seismicity around Mount Spurr. Earthquake depths from the surface to 20 km BSL were reported at Strandline Lake during this time. Jolly and Page (1994) state that earthquake depths observed at Strandline Lake are consistent with maximum crustal depths observed elsewhere in south-central Alaska.

Flores and Doser (2005) reference seismicity at Strandline Lake in their analysis of shallow seismicity in the Anchorage, Alaska area between 1964 and 1999. They describe seismicity at Strandline Lake as a shallow (<10 km) cluster which appears to show a tabular feature at 9-10 km depth. They further show that in cross section, seismic activity at Strandline Lake appears to be spatially independent of the Castle Mountain fault system. Volcanic activity is presented as a possible cause of the seismicity, but this hypothesis is supported only by Strandline Lake’s proximity to Mount Spurr volcano.

A statistical approach was used by McNutt and Marzocchi (2004) in an attempt to explain the likelihood of multiple volcanic eruptions and seismic swarms happening simultaneously in Alaska during the fall of 1996. They describe the Strandline Lake swarm as deep (3-12 km) and even though no volcano exists at the site, they include it in their analysis of volcanic swarms under the assumption that, because it lies within a volcanic arc, the seismicity at Strandline Lake is related to the same stresses that result in
the formation of volcanic centers. Using relationships between swarms and eruptions at Iliamna, Martin-Mageik, Strandline Lake, and Peulik they speculated that the most likely mechanism for arc-wide unrest in 1996 was a deformation pulse or strain transient which affected the eastern half of the Aleutian arc.
Chapter 3

Methods

The purpose of this research is to investigate the earthquake swarm at Strandline Lake, Alaska and to determine its driving mechanism. To do so, five main methods are used: (1) Calculation and analysis swarm and background statistics (2) development of a new 1-D velocity model appropriate for the subsurface at Strandline Lake, (3) relocation of Strandline Lake earthquakes from the AVO catalog using the new velocity model, (4) calculation and analysis high-quality fault-plane solutions, and (5) deformation analysis of InSAR images. Within this chapter, a detailed description of the procedures and programs used in this research is provided.
3.1 B-values

In reviewing the literature on non-volcanic earthquake swarms, one common theme is apparent; b-values are often used to augment other structural data, deformation measurements made by global positioning satellites (GPS), and monitoring of gas emissions (e.g., Brauer et al., 2009; von Seggern et al., 2008; Fischer and Horalek, 2005; Smith et al., 2004). B-values indicate the magnitude distribution of the earthquakes within a swarm and are determined from the slope of the frequency-magnitude regression curve in a log-linear plot. Swarms and aftershock sequences driven by regional tectonic activity typically have a b-value of $\leq 1.0$ while swarms driven by intruding fluids and/or magma can have b-values greater than 2.0 (Smith et al., 2004; Jakobsdottir et al., 2008). Analysis of b-values combined with analysis of the earthquakes, available deformation and gas data, and observations of the overall temporal and spatial evolution of the swarm may provide information about the source mechanism of the swarm.

To calculate the b-values for the background and swarm periods for the Strandline Lake area, events from the AVO earthquake catalog are first sorted by magnitude. The total number of earthquakes for each magnitude from $M_w -0.9$ to 3.7 by increment of 0.10 is then cumulatively tallied. The log of each of these tallies is then calculated and plotted on the y-axis along with the corresponding magnitude values on the x-axis. A regression line is added to the plot, but only takes into account magnitude values above the threshold of completeness (the point at which $< 100\%$ of the earthquakes for a given increment are reported due to equipment detection limits). The slope of this regression line corresponds to the b-value for the given events. Therefore, data sets with a large fraction of smaller earthquakes should have a steeper slope and yield a higher b-value and vice-versa.
3.2 Velocity Model

An important part of this research is the development of a new 1-D velocity model. Development of this model is completed using the program VELEST and is critical to the subsequent relocation of Strandline Lake earthquakes, because locations of earthquakes are inherently dependent on the velocity model used. The AVO locates events in the Strandline Lake area using the 1-D velocity model developed by Jolly and Page (1994) for Mount Spurr (Table 3.1). However, horizontal and vertical location errors, along with root mean square (RMS) residuals for events located using the Mount Spurr velocity model are high and do not provide a high degree of confidence. Earthquakes are located on a second run with an additional velocity model, the generic Alaska velocity model (Table 3.2) to provide an added degree of confidence and another data set for comparison during analysis of the results. Diagrams of both the Mount Spurr and Generic Alaska velocity models are shown in Figure 3.1.

The program VELEST (Kissling, 1995) inverts phase arrival times for a set of input earthquakes for the best 1-D velocity model ($V_p$ and $V_s$) along with individual station corrections. The first step in this process is to acquire a set of repicked Strandline Lake earthquakes which have clear and impulsive first arrivals. This is done by going through the waveforms from each station for each earthquake within the AVO catalog and placing a pick only on impulsive P- and S-wave arrivals (Figure 3.2). In this way, error associated with variation in user picks is minimized. Those earthquakes with enough clear first arrivals are then located with the program Seisan (Havskov and Ottemoller, 2000) using the Mount Spurr velocity model (Table 3.1). It is important to note that to maintain an azimuthal gap of less than 180 degrees, all earthquakes within
Table 3.1. The four layer Mount Spurr 1-D velocity model developed by Jolly and Page (1994). The AVO currently uses this model to locate events in the Strandline Lake area.

<table>
<thead>
<tr>
<th>Depth to Top of Layer BSL (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
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</thead>
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<td>-3.0</td>
<td>5.10</td>
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<tr>
<td>-2.0</td>
<td>5.50</td>
<td>3.04</td>
</tr>
<tr>
<td>5.3</td>
<td>6.30</td>
<td>3.62</td>
</tr>
<tr>
<td>27.3</td>
<td>7.20</td>
<td>4.04</td>
</tr>
</tbody>
</table>

Table 3.2. The nine layer generic Alaska 1-D velocity model. This model was used in addition to the Mount Spurr velocity model to provide an extra data set for analysis.

<table>
<thead>
<tr>
<th>Depth to Top of Layer BSL (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
</tr>
</thead>
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<td>4.0</td>
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<td>6.90</td>
<td>3.88</td>
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<td>20.0</td>
<td>7.40</td>
<td>4.16</td>
</tr>
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<td>25.0</td>
<td>7.70</td>
<td>4.33</td>
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<td>33.0</td>
<td>7.90</td>
<td>4.44</td>
</tr>
<tr>
<td>47.0</td>
<td>8.10</td>
<td>4.55</td>
</tr>
<tr>
<td>65.0</td>
<td>8.30</td>
<td>4.66</td>
</tr>
</tbody>
</table>
Figure 3.1 Diagram of the Mount Spurr and Generic Alaska velocity models. (a) The Mount Spurr velocity does not provide much structure to the upper 20 km of the crust. (b) The Generic Alaska velocity model appears more robust, earthquakes located with it in the Strandline Lake area have high horizontal and vertical errors.
Figure 3.2 Example earthquake seismograms from Strandline Lake. Top: Impulsive P-wave from a Strandline Lake earthquake showing a downward first motion. User error in making a pick is minimized when using high-quality waveforms such as this. Bottom: Emergent waveform from a Strandline Lake earthquake. A high-quality pick on the first arrival of this earthquake is not possible. Such earthquakes are not used in developing the 1-D velocity model.

this set must have a high quality first arrival pick on station SKN. The phase arrival picks, time, and location of each of the high-quality earthquakes are then input into VELEST along with the names and locations of the surrounding AVO and AEIC stations and the number of velocity model layers to be solved for. An initial velocity model is input as a starting reference for the program. For this study a modified version of the generic Alaska velocity model is used as the reference model, because five of the nine layers in the generic Alaska velocity model are within the first 20 km BSL as opposed to only three layers in the Mount Spurr model. The remaining four layers of the generic Alaska model were omitted due to the fact that the majority of the Strandline Lake earthquakes appeared to occur within the upper 20 km of the crust based on P- and S-wave separation times. Using an iterative process, VELEST then inverts for the 1-D velocity model which results in the lowest average RMS value for the input earthquakes. If there is a large (>1.00 km/s) difference in $V_p$ between adjacent layers in the resulting
model, an additional layer is inserted and the process is repeated. If the difference in $V_p$ is small (<0.15 km/s), a layer is deleted and the process is repeated until a stable solution resulting in the lowest average RMS is found.
3.3 Hypocenter Relocations

Relocation of the events is done with the program HYPOELLIPSE and the input of the new 1-D velocity model. The earthquakes at Strandline Lake are currently located (in the AVO catalog) using the Mount Spurr velocity model developed by Jolly et al (1994). The depths of the swarm earthquakes in the AVO catalog are between 3-12 km BSL (McNutt and Marzocchi, 2004). Using the program HYPOELLIPSE (Lahr, 1999), all swarm events are relocated and examined here to determine precise 3-dimensional locations of the earthquakes. HYPOELLIPSE is a suitable program to use because of its ability to account for large topographic variations. This is accomplished by embedding the seismic stations within the newly developed Strandline Lake velocity model, which extends 3 km above sea level (ASL).

Three trials are conducted in this study; one for each of the Mount Spurr, Generic Alaska, and new Strandline Lake velocity models. Arrival times from the AVO catalog are input into HYPOELLIPSE along with a velocity model and its associated station corrections. Travel times are then determined and hypocenters are found using Geiger’s Method to minimize the RMS of the travel-time residuals (Lahr, 1999). The equation used to determine the RMS residual is

\[ RMS = \sqrt{\frac{\sum_i W_i R_i^2}{\sum_i W_i}} \]

(1)

where \( R_i \) is the observed minus the computed time for the \( i^{th} \) phase, and \( W_i \) is the user-specified weight of the \( i^{th} \) phase. Each of the output data sets are then plotted using Generic Mapping Tools (GMT) in map view to highlight lateral differences in hypocenter
locations as well as in cross section to show shifts in hypocenter depths. Horizontal and vertical location errors, along with RMS residuals for relocated earthquakes, are then examined and compared to determine the effect of relocation with different velocity models.
3.4 Fault-Plane Solution Analysis

By analyzing the fault-plane solutions of Strandline Lake earthquakes, the crustal stress field during the swarm can be understood. Strandline Lake may lie within a transitional tectonic regime due to interaction between the three converging tectonic blocks, and understanding the crustal stresses beneath it may be key to understanding the cause of the 1996-1998 earthquake swarm.

The approach taken in this study is to attempt to calculate fault-plane solutions only for the largest magnitude Strandline Lake earthquakes, which in this case is the same set used in developing the 1-D velocity model. Focal mechanisms are calculated using the program Seisan (Havskov and Ottemoller, 2001) and FPFIT (Reasenberg and Oppenheimer, 1985). Seisan is a set of programs used to analyze and locate earthquakes. FPFIT calculates a fault plane solution based on the first-motion polarities and locations of the earthquake; hence the need for high quality events when initially searching through the data set. The FPFIT calculation is accomplished through a two-stage grid-search procedure that finds the source model minimizing a normalized, weighted sum of first-motion polarity discrepancies. Two weighting factors are incorporated in the minimization: one reflecting the estimated variance of the data, and one based on the absolute value of the theoretical P-wave radiation amplitude. In addition to finding the minimum-misfit solution, FPFIT finds alternative solutions corresponding to significant relative minima in misfit. Such solutions, when they exist, generally correspond to faulting mechanisms distinctly different from the minimum-misfit solution, and may be deemed the preferred solution after consideration of possible data errors, unmodeled
refractions and a priori knowledge of the tectonic environment (Reasenberg and Oppenheimer, 1985).

After FPFIT outputs the set of candidate fault-plane solutions, they are manually examined to determine whether they meet additional quality criteria. The conditions each solution must meet to be considered for stress analysis are as follows: (1) the RMS for the earthquake location must be below 0.20 seconds, (2) the azimuthal gap must be less than 180 degrees, (3) the horizontal and vertical error must be less than 5 km each, (4) the percentage of misfit polarities, or first motions plotted in a quadrant of the fault-plane solution, which represents the opposite polarity, must be less than 10\%, and (5) the strike, dip, and rake uncertainty must be less than 20°. If multiple solutions exist for an earthquake that meets the above criteria the earthquake is removed from further analysis on the basis of ambiguity in the data. Only the high-quality fault-plane solutions are given and analyzed in the following chapters.

Additional analysis of the crustal stress field is done using plots of Rose diagrams and stereonets. For this study, the orientations of p-axis (σ₁) and t-axis (σ₃) for all high-quality earthquakes are plotted in a Rose diagram along with their corresponding stereonets to highlight the main trends. Data used in the plots are taken from the orientations of the nodal planes of each fault-plane solutions calculated by FPFIT. All plotting is done using custom GMT scripts.
3.5 Surface Deformation

For this study, InSAR images were used to determine whether ground deformation occurred during the 1996-1998 earthquake swarm at Strandline Lake, Alaska. Most importantly, InSAR imagery may provide insight into the roles played by magma or geothermal fluids during this swarm which seismic data analysis is unable to do, and may aid in pinpointing a likely source mechanism.

A GPS monitoring network does not exist in the remote regions surrounding the Cook Inlet in Alaska. In an attempt to supplement the seismic data, deformation analysis is accomplished by analyzing the InSAR images. Image pairs from before, during, and after the swarm period are analyzed to detect any temporal changes in ground elevation. A schematic diagram showing the process in which SAR images are collected and the principle of SAR imagery is shown in Figure 3.3. Images used in this study were taken by the SAR instrument aboard the ERS-2 satellite.

The ERS-2 satellite was launched in April 1995 and frequently made passes over the southern Alaska region. A search of ERS-2's archives yielded 49 images along descending track 229 which captured the Strandline Lake area. Of the 49 images, 18 were selected based upon time of capture (1995-1999) relative to the swarm. Four of the selected images were taken prior to the swarm (1995-1996), six during the swarm (1996-1998), and the remaining eight were taken post-swarm (1998-1999).

Interferograms were then processed using the Repeat Orbit Imagery Package (roi_pac) software (Cal-Tech/JPL) at the RSMAS, University of Miami. For successful interferogram processing, the two images to be compared needed to have a small
perpendicular baseline and to cover a short time span. Limits of 250 meters and three years were chosen as the boundaries of these parameters and a total of 56 interferograms (event pairs) met these conditions. Of these 56 event pairs, only those with highly coherent signals were used in further analysis. This reduced the final number of event pairs to 18. Topographic effects in the interferograms were removed during the interface with a National Elevation Dataset (NED) 2 arc second Digital Elevation Map (DEM) obtained from the U.S. Geological Survey National Map Seamless Server. Each color cycle (fringe) on the interferogram represents 2.8 cm of deformation, and error associated with atmospheric properties is typically ≤ 1 cm.

**Figure 3.3** Illustration showing the principles of SAR imagery. An image is collected from a satellite scan during its orbit. After an amount of time has passed, a second image is taken from the same satellite on the same pass. The two images are combined to highlight any displacement of the Earth’s surface that the satellite has scanned. (Image from www.geodesy.miami.edu/sar.html)
Chapter 4

Results

In this chapter, the results of the analysis of the 1996-1998 swarm at Strandline Lake are presented. The data presented herein highlight the main lines of support behind the conclusions drawn in subsequent chapters. This is achieved by graphical representations of the b-values, the Strandline Lake velocity model, the 3-D relocation of the AVO catalog using the Strandline Lake velocity model, background and swarm stress characteristics using fault-plane solutions and stereonets, and the images acquired from the InSAR processing. With these results I hope to quantify similar and contrasting characteristics of the swarm using the three aforementioned velocity models. With the exception of the locations of the earthquakes within the AVO catalog using the Mount Spurr velocity model, all results are my own work.
4.1 B-values

B-values for the background and swarm periods were calculated and the frequency-magnitude distributions of the data with corresponding best-fit lines are presented in Figure 4.1. The graphs illustrate a linear function made by the data points in log-linear space, the slope of which is the sought after b-value. A slope of 2.0 or greater implies that a relatively large amount of the seismic energy was released by smaller magnitude events, and such a slope is characteristic of seismic sequences in volcanic areas (McNutt, 2002), although there are multiple examples of VT swarms with b-values \( \sim 1.0 \). Conversely, seismic sequences driven by tectonic activity tend to yield a b-value near 1.0 (Frohlich, 1993).

Near Strandline Lake, a total of 11,138 earthquakes were recorded between January 1, 1995 and August 31, 1996, and between September 1, 1998 and September 12, 2008. These earthquakes constitute the data used for the calculations of the background b-value at Strandline Lake. From Figure 4.1a, the slope of the best-fit line is \(-1.25\) (corresponding to a b-value of 1.25). Note that the best-fit line only accounts for earthquake magnitudes above the threshold of completeness, which for the background period is \( M_L 0.3 \). Earthquakes with magnitudes below this threshold are not incorporated into the final b-value calculation. For the 2,999 swarm events, which occurred between September 1, 1996 and August 31, 1998, the best-fit line in Figure 4.1b yields a b-value of 1.33 (Figure 4.1b). The threshold of completeness for the swarm period is \( M_w 0.6 \), slightly higher than that of the background period.
Figure 4.1 Strandline Lake b-values. (a) B-value of background earthquakes in the Strandline Lake area. The red line denotes the best-fit line for the data up to the threshold of completeness. (b) B-value of Strandline Lake earthquakes in the AVO catalog which occur between September 1, 1996 and August 31, 1998 (the swarm period).
4.2 1-D Velocity Model

The development of a 1-D velocity model specific to the Strandline Lake area is an integral component of this study because it plays a key role in the new earthquake locations. After several trials using the program VELEST, a new seven-layer 1-D velocity model was developed for Strandline Lake and is presented in Table 4.1 and a diagram of it is shown in Figure 4.2. The seven layers span a depth of 3 km ASL to 25 km BSL. Of the seven layers, six of them occur in the upper 20 km of the crust, giving a more detailed velocity structure for the upper crust of the region than the other two models used by the AVO and AEIC. VELEST does not output values for S-wave velocities, therefore the average $V_p/V_s$ ratio of the Generic Alaska velocity model of 1.78 is assumed in the Strandline Lake velocity model and the $V_s$ values obtained using this ratio are presented in Table 4.1. Seismic velocities in the upper crust at Strandline Lake are slower than those given by the Mount Spurr and Generic Alaska velocity models.

When the Strandline Lake velocity model is used to relocate Strandline Lake earthquakes, the resulting RMS and location errors are dramatically reduced (Figures 4.3, 4.4, and 4.5). Locations and latitudinal and longitudinal location errors (represented by 95% confidence error ellipses for the Mount Spurr, Generic Alaska, and Strandline Lake velocity models) for the 28 large earthquakes used in developing the new velocity model are shown in Figures 4.3, 4.4 and 4.5. The Generic Alaska velocity model produces the largest location errors (Figure 4.3). The Mount Spurr velocity model noticeably reduces the size of the error ellipses, however, error values are still relatively high (Figure 4.4). Errors associated with the location of the 28 earthquakes using the new Strandline Lake velocity model are greatly reduced. The Strandline Lake velocity model also reduces the
### Strandline Lake Velocity Model

<table>
<thead>
<tr>
<th>Depth to top of layer (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
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</tr>
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</table>

**Table 4.1** New seven-layer 1-D velocity model for the Strandline Lake area. P and S-wave velocities are shown from 3 km ASL to a depth of 33 km BSL.

**Figure 4.2** Diagram of the Strandline Lake velocity model. The new model provides more structure to the upper 20 km of the crust beneath Strandline Lake than the Mount Spurr velocity model and reduces the high horizontal and vertical errors associated with the Generic Alaska velocity model.
average RMS from 0.16 to 0.11s, and the average horizontal and vertical location error from 3.3 to 2.5 km and 4.7 to 3.0 km, respectively, in comparison to the Generic Alaska velocity model.

Depths of the 28 earthquakes determined using each velocity model show vertical shifts in the swarm location as well as a reduction in vertical error calculations. A north-south cross section showing the 28 Strandline Lake events is presented in Figure 4.6. Locations of the earthquakes using the Generic Alaska velocity model are poorly constrained with a large error estimate and often give an unrealistic result of -3 km or less for the depth. Locations using the Mount Spurr velocity model have a depth range between 5 and 13 km but have a scattered distribution. The Strandline Lake velocity model shows a tight clustering of the earthquakes between 12 and 15 km. The Strandline Lake model also results in the lowest vertical location errors of any of the three models tested.
<table>
<thead>
<tr>
<th>Station Name</th>
<th>Correction (s)</th>
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<td>PLR</td>
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<td>CKN</td>
<td>-0.21</td>
<td>PMS</td>
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<tr>
<td>IVE</td>
<td>-0.01</td>
<td>SSN</td>
<td>0.25</td>
</tr>
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</table>

**Table 4.2** Station corrections (in seconds) for the Strandline Lake velocity model. Corrections are for both AVO and AEIC seismic monitoring stations.
Figure 4.3 Map showing the locations and 95% confidence error ellipses of the 28 large Strandline Lake earthquakes obtained using the Generic Alaska velocity model.
Figure 4.4 Map showing the locations and 95% confidence error ellipses of the 28 large Strandline Lake earthquakes obtained using the Mount Spurr velocity model.
Figure 4.5 Map showing the locations and 95% confidence error ellipses of the 28 large Strandline Lake earthquakes obtained using the Strandline Lake velocity model.
Figure 4.6 North-South cross sections of the 28 large Strandline Lake earthquakes using (a) the Generic Alaska velocity model (green circles), (b) the Mount Spurr velocity model (red triangles) and (c) (next page) the Strandline Lake velocity model (blue squares). Error bars associated with the depth and latitudinal location of each earthquake are added.
North-South Cross Section
Strandline Lake Velocity Model

Depth (km)

Latitude

S
N

61.2300 61.2800 61.3300 61.3800 61.4300 61.4800 61.5300 61.5800 61.6300 61.6800

(c)
4.3 Earthquake Locations

The previous section presented results related to the locations of the 28 large Strandline Lake earthquakes used in the development of the Strandline Lake velocity model. This section is devoted to the locations of the entire AVO catalog (14,138 earthquakes) of Strandline Lake events, obtained using the new velocity model. Using the Mount Spurr velocity model in the program HYPOELLIPSE, all Strandline Lake events within the AVO catalog are located and are presented in map view in Figure 4.7a. The earthquakes appear to be centered beneath Triumvirate glacier, just west of Strandline Lake itself. The average depth of an earthquake within this data set is 6.76 km BSL. Using the Mount Spurr velocity model, approximately 80% of the earthquakes within the AVO catalog are located at depths of less than 10 km BSL.

When the Strandline Lake velocity model, along with the new station corrections, is substituted into HYPOELLIPSE and the AVO catalog is re-located, the swarm appears to shift to the north and center itself beneath the “peninsula” of land between Strandline Lake and the Triumvirate glacier (Figure 4.7b). However, the most noticeable change is in the new depth locations. A cross section in Figure 4.8 shows the depths of the Strandline Lake events obtained using the new velocity model. The average depth of the re-located events is 12.14 km BSL and, using the Strandline Lake velocity model, approximately 20% of the earthquakes within the AVO catalog are located shallower than 10 km BSL. The deepest of these events are located near the base of the brittle crust. There is a shoaling of events located between 8 and 9 km BSL which appears to form a horizontal linear feature in the cross section in Figure 4.8 (note that this corresponds to a layer boundary in the velocity model and is thus an artifact).
Figure 4.7 (a) Epicenters of Strandline Lake earthquakes using HYPOELLIPSE and the Mount Spurr velocity model. (b) Epicenters of Strandline Lake earthquakes using HYPOELLIPSE and the Strandline Lake velocity model.
Figure 4.8 North-South cross section of the relocated earthquakes using the Strandline Lake model, corresponding to Figure 4.7b.
4.4 Stress Analysis

Using the methods outlined in Chapter 3, fault-plane solutions (FPS) are calculated for eight large background earthquakes near Strandline Lake (Figure 4.9). Seven of the eight earthquakes show predominantly strike-slip motion. Only one of the background earthquakes deviates from the rest and shows an almost pure dip-slip motion. Four of the eight background events are located in the immediate vicinity of Strandline Lake, west-northwest of station STLK. The other four events are more distant from Strandline Lake and are located north-northeast of station STLK.

Rose diagrams and steronet plots of the P-axis ($\sigma_1$/maximum compression) and the T-axis ($\sigma_3$/minimum compression) of the eight background earthquake FPS are shown in Figure 4.10. The Rose diagram shows the P-axis/$\sigma_1$ orientation having a somewhat scattered distribution; however, a predominant northeast-southwest orientation is apparent. The stereonet plot for the P-axis of the background earthquakes also shows a scattered distribution with most of the P-axes exhibiting a steep dip. The T-axis/$\sigma_3$ orientation exhibits a dominant northwest-southeast orientation, perpendicular to that of $\sigma_1$ and is thus consistent with the observed predominance of strike-slip faulting. The stereonet plot for the T-axis of the background earthquakes shows a clustering in the northeast and southeast quadrants.

FPS of the swarm earthquakes (Figure 4.11) shows a much more localized and systematic distribution. The locations of these earthquakes are confined to the peninsula of rock between the north-eastern boundary of the Triumvirate glacier and the western
Figure 4.9 Map of the Strandline Lake region showing focal mechanisms of eight large earthquakes recorded during the background period.
Figure 4.10  Rose diagrams and stereonet plots of the P- and T-axes of the eight large background earthquakes at Strandline Lake.

An earthquake FPS exhibit strike-slip, reverse, and dip-slip faulting. Rose diagrams and stereonet plots of the P- and T-axes are shown in Figure 4.12. The dominant orientation of the P-axes is northeast-southwest while the T-axes are perpendicular with a northwest-southeast orientation. The stereonet plot of the P-axes shows the swarm earthquakes having steep dips and clustered within the northeast and northwest quadrants. The stereonet of the T-axes shows a more diverse distribution of dips, indicative of a mix of strike-slip and thrust faulting. This is in agreement with the diversity of FPS which are calculated for the twenty swarm events. The results of the stress analysis are compared to those of previous studies and are discussed in the next chapter.
Figure 4.11 Map showing the FPS of the 20 large Strandline Lake earthquakes which occurred during the swarm period (between September 1996 and August 1998).
Figure 4.12 Rose diagrams and stereonet plots of the P- and T-axes of the twenty large swarm earthquakes at Strandline Lake.
4.5 InSAR Analysis

A total of 13 InSAR image pairs (Table 4.2) were found to have coherence in the Strandline Lake area (all 13 InSAR images can be viewed in Appendix A). The 13 image pairs are examined individually for any indication of surface deformation associated with the Strandline Lake swarm. Particular attention is given to image pairs which have dates pre- and during swarm and during and post swarm. One such InSAR image is shown in Figure 4.13. Only five of the 13 images yielded high-quality results while the rest exhibited abundant background static which appears pixilated and provides little insight into surface deformation. Factors such as the considerable topographic relief of the adjacent Tordrillo Mountains, the abundant snow cover in the area, and the presence of a moving glacier possibly attributed to the low quality of the other eight InSAR images. Color bands in the high-quality InSAR images of Strandline Lake area have long distances between them and appear broad. Slight (< 2cm) changes in surface elevation may have occurred d, however, any deformation exhibited in the InSAR images of Strandline Lake likely falls outside the margin of error associated with the instruments onboard the ERS-2 satellite. The Triumvirate glacier is adjacent to Strandline Lake and any changes in elevation found within its area cannot be determined to be from deformation of the ground surface or due to the mechanics of the glacier. While each InSAR image of Strandline Lake has its own unique characteristics, none show the stereotypical “bulls-eye” pattern indicative of ground uplift or subsidence (e.g. Mount Peulik volcano, 1998 (Lu et al., 2007) and South Sister volcano, 2000 (Wicks et al., 2002)).
Table 4.3  Image pairs of the 13 InSAR images of Strandline Lake.  Date 1 shows the date on which the ERS-2 satellite first captured an image of Strandline Lake and Date 2 shows the date of the image to which Date 1 was compared.  Image pairs in bold denote the high quality InSAR images.  Note that the dates span times before, during, and after the swarm.

<table>
<thead>
<tr>
<th>Date 1</th>
<th>Date 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/19/1996</td>
<td>07/09/1997</td>
</tr>
<tr>
<td>07/24/1996</td>
<td>07/14/1999</td>
</tr>
<tr>
<td>10/02/1996</td>
<td>06/04/1997</td>
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<td>06/04/1997</td>
<td>07/29/1998</td>
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<td>08/13/1997</td>
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<td>06/09/1999</td>
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<td>09/22/1999</td>
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<tr>
<td>10/07/1998</td>
<td>07/14/1999</td>
</tr>
<tr>
<td>06/09/1999</td>
<td>07/14/1999</td>
</tr>
</tbody>
</table>

Figure 4.13  Example InSAR image of Strandline Lake, Alaska.  The image pair used in this figure were captured on 06/19/1996 (pre-swarm) and 07/09/1997 (during swarm).  The red circle denotes the Strandline Lake area.
Chapter 5

Discussion

Strandline Lake lies within a non-volcanic area and is analogous to other non-volcanic areas which have experienced seismic swarms (e.g. Chiu et al., 1982, Fischer and Horalek, 2005, Ma and Eaton, 2009, Smith et al., 2004, Vidale and Shearer, 2006). This chapter will examine the results presented in the previous chapter and compare and contrast them to published results from studies of other non-volcanic seismic swarms. The results to be compared include the depth of the swarms, the largest event within the swarms, the total number of earthquakes constituting the swarms, the b-value, amount of any measurable deformation, and the suggested source mechanism.

B-values much greater than 1.0 are anomalous for upper-crustal tectonic earthquakes, (Frohlich, 1993) but are sometimes observed for volcanic earthquake swarms (e.g. Smith et al., 2004). Lake Tahoe, California, and Upptyppingar, Iceland, experienced seismic swarms resulting from an intrusion of magma in the shallow crust and both swarms had b-values greater than 2.0 (Jakobsdottir et al., 2008, Smith et al., 2004). Conversely, earthquake swarms thought to be the result of hydrothermal fluid circulation in the upper crust at Bohemia, Germany and at Mount Hood, Oregon have b-values closer to 1.0 (Jones and Malone, 2005, Klinge et al., 2003). At Strandline Lake, the b-values for the background and swarm period are 1.25 and 1.33 respectively. The swarm b-value of 1.33 is significantly higher than the 1.0 “benchmark” thought to be
characteristic of tectonically driven events (e.g. aftershock sequences). However, the background value is also noticeably elevated as well, making the change in b-value only 0.08. Because of the elevated background b-value at Strandline Lake, direct comparison of the swarm b-value to other swarm b-values may be misleading, but taken together with other observations, a clearer understanding may emerge.

The results of the velocity model inversion yielded a seven-layer model which focused on the upper 25 kilometers of the crust beneath Strandline Lake. The Strandline Lake model produces a large reduction in error and RMS residuals during location of earthquakes in the area. When compared with both the Mount Spurr and Generic Alaska velocity models, the Strandline Lake model incorporates layers with generally slower P- and S-wave velocities. This may reflect the underlying lithology of the Strandline Lake region, which has properties much different than what is represented in the other two models. Future seismological research around the Strandline Lake area should incorporate the new model in any earthquake location analysis.

An important result following from use of the Strandline Lake velocity model in locating earthquakes in the region was a downward shift in hypocentral depth for the 1996-1998 earthquake swarm with respect to previously determined catalog locations. The earthquake swarm at Strandline Lake is much deeper than initially thought. McNutt and Marzocchi (2004) calculated that most earthquakes within the Strandline Lake swarm occurred from 3-12 km in depth (Figure 5.1). Using the Strandline Lake velocity model, most earthquakes are located at depths from 10-17 km BSL (Figure 4.8). By comparing Figures 4.7 and 5.1, it becomes clear that the Strandline Lake velocity model migrate earthquake locations deeper than previously thought. The new depths are comparable to
Figure 5.1  Map view and cross section from McNutt and Marzocchi (2004) showing seismic activity at Strandline Lake between October 1989 and December 2001. The 1996-1998 seismic swarm is clearly shown as the cluster of circles in both diagrams.

the depths of the swarms at Lake Tahoe in 2003 (Smith et al., 2004) and Upptytingar in 2007 (Jakobsdottir, 2008), which were both caused by magmatic intrusion. Earthquake swarms at Mount Hood (Jones and Malone, 2005), Bohemia (Klinge et al., 2002), Arkansas (Chiu et al., 1984), and Matsuhsihiro, Japan (Jakobsdottir et al., 2008), were compared to the Strandline Lake earthquake swarm as well (Table 5.1). Each of the four swarms occurred at relatively shallow depths and, with the exception of the Arkansas
swarm (for which a source mechanism is still undetermined), each is believed to have been caused by processes not directly related to magmatic activity. These observations suggest that swarms which have an origin greater than 10-15 km BSL are initiated by interactions with magma. However, Haeussler et al. (2000) shows that seismicity in the Cook Inlet area occurs as deep as 35 km BSL and argues that 35 km BSL could be a valid representation of the base of the seismogenic zone. If so, then the seismogenic zone at Strandline Lake is considerably deeper than the 15-18 km zone at Lake Tahoe (Smith et al, 2004) and the 8-11 km seismogenic zone beneath Iceland (Clifton et al., 2003). Therefore, if the seismogenic zone indeed extends to 35 km at Strandline Lake, the 1996-1998 earthquake swarm is certainly deep, but the characteristics of the seismogenic crust make it difficult to draw fair comparisons to other deep swarms based solely on this finding.

Deformation measurements from GPS networks provided an additional level of confidence in the interpretations at Lake Tahoe and Upptyppingar. While GPS measurements during the Strandline Lake earthquake swarm do not exist, the InSAR images processed at RSMAS provide some insight into the magnitude of surface deformation during the swarm. Five of the thirteen InSAR images (see Appendix A: Images A-1/2/6/8/11) of Strandline Lake show a clear view of changes in the ground elevation between capture dates. The images reveal that little to no surface displacement occurred between pre-swarm and during the swarm (Appendix A: Image 1), strictly during the swarm (Appendix A: Image 6), during the swarm and post-swarm (Appendix A: Images 2 and 8), and after the swarm (Appendix A: Image 11). The images lack the stereotypical “bulls-eye” pattern which is indicative of magma chamber inflation at
<table>
<thead>
<tr>
<th>Swarm Location</th>
<th>Swarm Dates</th>
<th>Swarm Depth (km)</th>
<th>Largest Event</th>
<th>Total Number of Earthquakes</th>
<th>b-value</th>
<th>Amount of Deformation</th>
<th>Suggested Source Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strandline Lake, Alaska</td>
<td>September 3, 1996 – August 31, 1998</td>
<td>8 – 17</td>
<td>$M_w \ 3.1$</td>
<td>2,999</td>
<td>1.33</td>
<td>No observed surface deformation</td>
<td>To Be Determined</td>
</tr>
<tr>
<td>Uppsalavágur, Iceland</td>
<td>February 2007 – December 2007</td>
<td>14 – 22</td>
<td>$M_L \ 2.2$</td>
<td>$&gt; 5,300$</td>
<td>2.10</td>
<td>2 cm horizontal</td>
<td>Magma Injection</td>
</tr>
<tr>
<td>Lake Tahoe, Nevada, California</td>
<td>August 12, 2003 – December 31, 2003</td>
<td>10 – 12, 22 – 30</td>
<td>$M_w 4.2$</td>
<td>1,611</td>
<td>2.00</td>
<td>6 mm horizontal</td>
<td>Magma Injection</td>
</tr>
<tr>
<td>Mount Hood, Oregon</td>
<td>June 29, 2002 – August 13, 2002</td>
<td>0 – 10</td>
<td>$M_D 4.5$</td>
<td>$&gt; 200$</td>
<td>0.72</td>
<td>n/a</td>
<td>Tectonic stresses on extended weakened crust</td>
</tr>
<tr>
<td>West Bohemia, Central Europe</td>
<td>August 28, 2000 – December 31, 2000</td>
<td>6.5 – 10.5</td>
<td>$M_L 3.7$</td>
<td>$&gt; 10,000$</td>
<td>1.06</td>
<td>n/a</td>
<td>Tectonic stresses on pre-existing low angle faults</td>
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<tr>
<td>Enola, Arkansas</td>
<td>January 1982 – December 1983</td>
<td>4 – 7</td>
<td>$M_C 3.8$</td>
<td>$&gt; 30,000$</td>
<td>n/a</td>
<td>n/a</td>
<td>Un-determined</td>
</tr>
<tr>
<td>Matsushiro, Japan</td>
<td>August 3, 1965 – June 1967</td>
<td>0 – 12</td>
<td>$M_w 5.4$</td>
<td>$&gt; 700,000$</td>
<td>n/a</td>
<td>0.75 m horizontal on fault trace and other local uplifts</td>
<td>Over-pressureization related to underground fluid migration</td>
</tr>
</tbody>
</table>

Table 5.1  Comparison of results and statistics of the 1996 – 1998 swarm at Strandline Lake, Alaska to six other earthquake swarms which occurred in non-volcanic areas.
depth. Instead, these images show broad, gradual changes from one color band to the next, which frequently appear to follow the topography of the area. Each color band on an InSAR image represents 2.8 cm of elevation change in the surface. At Lake Tahoe, 5.8 mm of deformation was observed at Lake Tahoe during the 2003 earthquake swarm (Smith et al., 2004) and 2 cm of deformation was observed at Upptypingar during the 2007 swarm. Therefore, while InSAR imagery did not detect uplift of the Strandline Lake area, sub-cm deformation cannot be ruled out.

Stress analysis for this study revealed that the P-axes of representative background earthquakes are oriented in a northeast-southwest direction and matched those of the P-axes for swarm earthquakes. It is a common occurrence for the principal stress axes to change orientation from background to swarm time periods when a magmatic dike intrudes into the brittle crust (e.g. Roman and Cashman, 2006). Moreover, during the research of Wiemer et al. (1999), the background stress characteristics of southern Alaska were examined through analysis of shear-wave splitting in data from several three-component seismic stations including station SKN, located north of the Strandline Lake area. Figure 5.2 shows a Rose diagram from Wiemer et al. (1999) which indicates a northeast-southwest orientation of split s-wavelet polarizations, a proxy for the orientation of the maximum principal stress axis. However, Jolly and Page (1994) examined the background seismicity and stress characteristics around Mount Spurr, and presented fault-plane solutions for 21 large earthquakes, several of which occurred in the Strandline Lake area. Figure 5.3 shows a Rose diagram of the P-axes of these 21 earthquakes. A dominant northwest-southeast (arc-perpendicular) trend is apparent, an approximate 90° shift from the orientation found at Strandline Lake
during this study. This suggests one of two possibilities: (1) The background maximum compression orientation at Strandline Lake was northwest-southeast prior to the swarm as indicated by Jolly and Page (1994) or (2) the orientation of maximum compressive stress orientation at the Mount Spurr area is ~90° different from that at and north of Strandline Lake. As shown in Chapter 2, the tectonic characteristics of this area are complex and it is unclear whether the Strandline Lake area has a background crustal stress field similar to that at Mount Spurr (characterized by trench-parallel compression resulting from plate convergence) or to that at station SKN (characterized by trench-perpendicular compression resulting from southwestward escape of the Yakutat block). Thus, it is unclear whether the local stress field during the 1996-1998 swarm can be considered ‘rotated’ (and thus indicative of magma intrusion) or not.
Figure 5.2  Rose diagram from Wiemer et al. (1999) showing the stress orientation at seismic station SKN from split shear-wave polarizations of 69 large earthquakes. The orientation is similar to that found in Figures 4.9 and 4.11 for Strandline Lake.

Figure 5.3  Rose diagram compiled from P-axis orientations given by Jolly and Page (1994) for tectonic earthquakes around Mount Spurr. Several of the earthquakes used are located in the Strandline Lake area. Primary orientation of the P-axes is to the northwest-southeast, perpendicular to P-axis orientations for Strandline Lake swarm earthquakes.
Chapter 6

Conclusions

Through calculation of a new 1-D velocity model and analysis of b-values, stress characteristics, and InSAR images, an in-depth view of the 1996-1998 earthquake swarm at Strandline Lake, Alaska has been obtained. However, the analytical results obtained in this study do not provide conclusive evidence for or against a deep injection of magma. This still leaves unanswered the question of what initiated an earthquake swarm in a region lacking a volcano. It may seem logical to label the swarm “tectonic”, however, that conclusion does not explain why the earthquakes occurred in a concentrated volume without an initiating main-shock.

Because the earthquake swarm at Strandline Lake occurred much deeper than initially thought, the argument for magmatic intrusion as the source mechanism gains favor. Generally speaking, earthquakes related to tectonic stresses alone occur at depths shallower than 10-15 km in the western United States (Ord and Hobbs, 1989) and earthquakes deeper than this are uncommon outside of subduction zones. The earthquake swarms at Lake Tahoe and Upptyppingar were both located deeper than 10-15 km and both were attributed to an intrusion of magma. With the improved location of the Strandline Lake swarm, it is now apparent that it too is located in this approximate depth range. However, Haeussler et al. (2000) argues that the base of the seismogenic zone in the Cook Inlet could be as deep as 35 km. To assess whether the earthquake swarm at
Strandline Lake occurred at the base of the seismogenic crust, a determination of the depth to the moho beneath the area is critical. In doing so, it could verify or refute the suggestion of a deep seismogenic zone by Haeussler et al. (2000) and provide more conclusive evidence for the source mechanism of the 1996-1998 earthquake swarm at Strandline Lake.

In this study, the Strandline Lake swarm is found to be comparable to the swarms at Lake Tahoe and Upptyppingar. However, an important factor to consider concerning these other two studies is that both were monitored by continuous GPS networks. At Strandline Lake analysis of InSAR images was the only possible method of deformation analysis. No deformation was detected during the analysis of these images, however, limits on the detection threshold of InSAR measurements (2.8 cm per color band) are above the level of deformation observed during the Lake Tahoe and Upptyppingar swarms. Because surface deformation less than this threshold could have occurred undetected by InSAR analysis, the lack of deformation observed in the InSAR images should not automatically rule out the possibility of a magmatic intrusion at Strandline Lake.

From the stress analysis, it can be concluded that Strandline Lake is located in an area of transitional tectonics. The P-axes of the background earthquakes at Strandline Lake show an approximate rotation of 90° with respect to the earthquake P-axes near Mount Spurr, 30 km to the southwest, but are parallel to split shear wavelets at station SKN, approximately 55 km to the northeast. Therefore, the Strandline Lake area is of considerable importance for understanding changes in stress regimes arising from Alaskan tectonics.
This study should be viewed as the first step in understanding the earthquake swarm at Strandline Lake. Further research on this swarm, and on the Strandline Lake area in general, is warranted. Throughout this research it has been shown that deep earthquake swarms in non-volcanic areas are frequently accompanied by small amounts of surface deformation and therefore it is recommended that several continuous GPS stations be installed at Strandline Lake to obtain sub-centimeter accuracy data during future swarms. Additionally, an in-depth study of shear wave splitting, an indicator of anisotropy and crustal stress field orientations within the Earth’s crust, would provide clarification of the background stress state at Strandline Lake and an important context for interpretation of the 1996-1998 swarm FPS orientations.
List of References


Appendices
Appendix A – InSAR Images of Strandline Lake

Strandline Lake area denoted by solid black square
Appendix A – InSAR Images of Strandline Lake (Continued)

Strandline Lake area denoted by solid black square

10/02/1996 – 06/04/1997

10/02/1996 – 07/09/1997
Appendix A – InSAR Images of Strandline Lake (Continued)

Strandline Lake area denoted by solid black square


07/09/1997 – 08/13/1997
Appendix A – InSAR Images of Strandline Lake (Continued)

*Strandline Lake area denoted by solid black square*


07/09/1997 – 09/02/1998
Appendix A – InSAR Images of Strandline Lake (Continued)

Strandline Lake area denoted by solid black square


09/02/1998 – 06/09/1999
Appendix A – InSAR Images of Strandline Lake (Continued)

Strandline Lake area denoted by solid black square

09/02/1998 – 09/22/1999

10/07/1998 – 07/14/1999
Appendix A – InSAR Images of Strandline Lake (Continued)

Strandline Lake area denoted by solid black square

06/09/1999 – 07/14/1999