3-7-2014


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Probabilistic Modeling of Lava Flows:

A Hazard Assessment for the San Francisco
Volcanic Field, Arizona

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Date of Approval:
March 7, 2014

Keywords: spatial density, Monte Carlo simulation, Flagstaff,
natural disaster, monogenetic fields

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Acknowledgments

I would like to first and foremost thank my thesis advisor, Dr. Charles B. Connor, for his expert advice, guidance, and encouragement during my research and preparation for this thesis. I would also like to thank my committee members, Dr. Stephen McNutt and Dr. Rocco Malservisi, for their suggestions and support. I would like to express my gratitude to Laura Connor and Jacob Richardson for their seemingly endless patience in helping me brainstorm and debug. Thank you to Aurelie Germa for assisting me with fieldwork and editing, Marci Wills for graciously hosting us in Flagstaff, and Samantha Kinman for digitizing so many mapped vent locations. I would like to extend my appreciation to those at the Arizona Department of Emergency Management for the opportunity to contribute to the volcanic event annex of the state’s response plan. I owe many thanks to Dr. Michael Ramsey and Dr. Charles Jones for their advice and support during my time as an undergraduate student at the University of Pittsburgh.

I am so grateful to Margaret Wilkins for being my “nudge” and to Emily Lupton for always being there for me. I would like to extend my most sincere thank you to Michael Wilkins for the immense emotional, intellectual, tangible and intangible support of your companionship. And finally, to my parents, whose love has guided me to so many of my achievements: thank you for instilling me with curiosity, dedication, integrity, and compassion.
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Abstract

This study serves as a first step towards a comprehensive hazard assessment for the San Francisco volcanic field in northern Arizona, which can be applied to local response plans and educational initiatives. The primary goal of this thesis is to resolve the conditional probability that, given a lava flow effusing from a new vent in the San Francisco volcanic field, it will inundate the city limits of Flagstaff. The spatial distribution of vents within the San Francisco volcanic field was analyzed in order to execute a lava flow simulation to determine the inundation hazard to Flagstaff. The Gaussian kernel function for estimating spatial density showed that there is a 99% chance that a future vent will be located within a $3.6 \times 10^9$ m$^2$ area about 20 kilometers north of Flagstaff. This area contains the location of the most recent eruption at Sunset Crater, suggesting that the model is a good predictor of future vent locations. A Monte Carlo analysis of potential vent locations (N = 7,769) showed that 3.5% of simulated vents generated lava flows that inundated Flagstaff, and 1.1% of simulated vents were located within the city limits. Based on the average recurrence rate of vents formed during the Brunhes chronozone, the aggregate probability of lava flow inundation in Flagstaff is $1.1 \times 10^{-5}$ per year. This suggests that there is a need for the city to plan for lava flows and associated hazards, especially forest fires. Even though it is unlikely that the city will ever have to utilize such a plan, it is imperative that thorough mitigation and response plans are established now—before the onset of renewed volcanic activity.
Chapter 1: Introduction

Approximately 500 million people around the world live near active and potentially active volcanoes. Every year, two to eight volcanoes produce paroxysmal eruptive episodes with a Volcanic Explosivity Index (VEI) rating of 3 or higher. These eruptions are those considered moderate to colossal eruptions of Plinian to Ultra-Plinian style, injecting over 100 million cubic meters of tephra into the troposphere in eruption columns 10-25 km in height. All eruptions, even those smaller than VEI 3, can have long durations and even longer lasting impacts. Although the initial eruption may last for weeks or months, the total time of an eruption may last for years. For example, Stromboli in Italy has maintained a low level of activity for 2400 years, while the most recent paroxysm began on February 27, 2013 after a 10 day interval of normal activity, and the eruption continued for seven days (GVP, 2013). The long term impacts of similar volcanic events not only affect physical infrastructure, local economy and society, but also the political climate in nearby communities for years thereafter.

Such effects result from activity at all types of volcanoes: iconic and well studied stratovolcanoes like Mount St. Helens in Washington, broad, low lying shield volcanoes like Kilauea in Hawaii, and small cinder cone volcanoes that are located on the flanks of larger edifices or clustered in monogenetic fields of their own. Of all of these types, the monogenetic field is arguably least understood by the scientific community. The San
Francisco volcanic field (SFVF) in northern Arizona, U.S.A., is one such active field with potential for future volcanism, yet no comprehensive hazard assessment for the area has been carried out.

Although the patterns of monogenetic volcanism within the field have been studied with respect to regional tectonics (e.g., Tanaka, et al., 1986) and magma-fault interactions (Takada, 1994; Connor, et al., 2000; Le Corvec, et al., 2013), spatio-temporal probabilities have only been modeled for one select region of the field (Conway, et al., 1998). This spatio-temporal model estimated the probability of a vent forming within the SP cluster based on recurrence rates, but did not assess impacts of specific hazards originating from such an eruption within the SP cluster. Additionally, no such probability has been modeled for other clusters of vents, or for the field as a whole. As such, a comprehensive hazard assessment for the entire SFVF has yet to be completed. Once such an assessment, which considers all potential hazards, is conducted, an effective mitigation and education program can be established.

This study approaches one segment of the greater problem by determining the level of threat of basaltic lava flows to people and infrastructure in and around Flagstaff, Arizona. A spatial density model assesses which locations within the field are the most probable sites of future vents. Then, a Monte Carlo simulation of lava flows issuing from these potential vents assesses the lava flow hazard to Flagstaff. The primary goal of this study is to resolve the conditional probability that if a lava flow effuses from a new vent in the SFVF, it will inundate the city limits of Flagstaff. At the time of writing, this is the first lava flow code to be executed for an area of monogenetic volcanism in the southwestern United States.
Chapter 2: Review of the Literature

Geologic setting of the SFVF

The SFVF formed in northern Arizona during the Late Tertiary and Quaternary periods and lies on the southwest margin of the Colorado Plateau (Figure 1). It is one of several mostly basaltic volcanic fields of Cenozoic age on the southern Colorado Plateau (i.e., Springerville and Zuni/Bandera) and is located approximately 50 km north of the Transition Zone between the Colorado Plateau and the Basin and Range Province to the south and it is bounded to the east by the Rio Grande Rift Zone. The Basin and Range Province is characterized by a thin lithosphere (<25 km) and extensional tectonics, whereas the Colorado Plateau is characterized by a thicker lithosphere (~60 km) and a stable tectonic history (Hunt, 1956; Summer et al., 1976; Keller et al., 1979; Thompson and Zoback, 1979; Reiter and Shearer, 1979; Morgan and Swanberg, 1985; Kaufman et al., 1986; Mauser et al., 1987) An interpretation of why this region is volcanically active, based on gravity signatures, is provided in Appendix A.

The SFVF overlies an approximately one kilometer thick moderately dipping to flat-lying sequence of Paleozoic and Mesozoic sedimentary rocks capping Precambrian basement (Ulrich et al., 1984). The field extends approximately 100 km east-west and 70 km north-south, and is situated just north of Flagstaff. It contains 606 basaltic vents and eight large dome complexes, and the associated volume of lava flows and pyroclastic
deposits (500 km$^3$) covers an area of about 5,000 km$^2$ (Tanaka et al., 1986; Conway et al., 1998).

The southwest boundary of the field is not well defined due to the “rim basalts” that are a part of the Mogollon Rim on the southern margin of the Colorado Plateau. Though the rim basalts erupted from 8 Ma to 5 Ma, it is unclear whether or not there was a gap between the formation of the rim basalts and the onset of SFVF volcanism (Luedke and Smith, 1978; Tanaka et al., 1986).

It has been established, however, that the oldest rocks in the SFVF (6 Ma to 5 Ma) were erupted in the western third of the field and that volcanism has gradually migrated to the east-northeast at an average rate of 2 cm/yr (Tanaka et al., 1986). Eruptive units in the SFVF are binned into three age brackets according to radiometric age dating and polarity-chronostratigraphic correlation as follows: 147 pre-Matuyama vents (5.0-2.59 Ma), 220 Matuyama vents (2.59-0.78 Ma), and 243 Brunhes vents (<0.78 Ma) (Tanaka et al., 1986). In general, vents with normal polarity are located in the far west extremity of the field (pre-Matuyama age), as well as in the eastern half of the field (Brunhes age), while reverse polarity vents exist in the western half of the field (Matuyama age).

Matuyama rocks of intermediate composition lie along the trace of the Mesa Butte Fault and intermediate Brunhes rocks roughly following the buried trace of the Oak Creek Canyon Fault system. Tanaka and others (1986) determined that basaltic volcanism migrated northeastward in pre-Matuyama time (>2.59 Ma) at a rate of 1.2 cm/yr. For the past 2.5 m.y. migration has been occurring in the eastward direction at an increased rate of 2.9 cm/yr. This eastward migration of volcanism mimics the rate and direction of westward motion of the North American plate in reference to a stable African plate. The
most recent eruption conforms to the trend of overall eastward younging of volcanism, as it occurred at Sunset Crater cinder cone within the eastern third of the field.

Not only has the migration rate increased from Pre-Matuyama to Brunhes time, but recurrence rate appears to have increased as well. Based on the number of mapped Pre-Matuyama aged vents and the established time period of the chronozone, recurrence rate was $6 \times 10^{-5}$ vents per year. In Matuyama time recurrence rate increased to $1 \times 10^{-4}$, and in Brunhes time the recurrence rate is even faster, at $3 \times 10^{-4}$. Recurrence rates may be underestimated if there are any Brunhes aged vents that are buried today. A similar increase in recurrence rate is observed in other volcanic fields in the American southwest. One example includes Cima volcanic field in California, which experienced a pulse of activity during the last 0.7 Ma (Connor and Conway, 2000). This pulse of activity at Cima volcanic field also was part of a significant migration in the locus of activity.

The migration of volcanism in the SFVF has been attributed to either movement of the North American plate over a fixed thermal anomaly, erosion of the keel of the Colorado Plateau due to shear heating from the Basin and Range province, or propagation along the Colorado Lineament (Tanaka et al., 1986). Conway and others (1998) concluded that large-scale geologic processes controlling clustering and migration in the SFVF are “not well understood”; clustering may result from localized mantle melting in restricted asthenospheric zones (Tanaka et al., 1986, Kempton et al., 1991) as opposed to being sourced by lithospheric extension.

The regional fault systems discussed by Shoemaker and others (1978) are related to large, ancient fault systems which cut through the crystalline basement rock. The silicic volcanic centers within the SFVF tend to align with the Mesa Butte, Oak Creek
Canyon, Doney, and Bright Angel Fault systems, suggesting that ascending magmas may exploit pre-existing regional fault systems (Kear, 1964; Breed 1964; Shoemaker et al., 1978; Settle, 1979; Connor 1990; Connor et al., 1992).

**Monogenetic Fields**

The SFVF is composed of monogenetic volcanoes, which, by definition, formed during a single episode of activity ranging from a few days to several years. Monogenetic vents are frequently found clustered in the area of a volcanic field or aligned with crustal structures, such as faults and fractures. Such clusters are also formed on the flanks of large shield and composite volcanoes and within the walls of calderas. These volcanic fields may be comprised of hundreds to thousands of individual vents, spread across hundreds of square kilometers. However, there has been no correlation found between the number of vents in a given volcanic field and the duration of field activity (Connor and Conway, 2000).

Timing and recurrence rate of eruptions are fundamental characteristics of basaltic volcanic fields. Recurrence rate is calculated as the number of mappable events occurring over time, where events are defined by discrete eruptive units or individual edifices. It is important to note that the number of volcanic events is not always equal to the number of volcanic eruptions, as units and edifices tend to be destroyed by subsequent activity and multiple vents and units may be created during a single eruptive episode. Long-term averages of recurrence rates smooth variations of clustered temporal activity due to episodic behavior (Connor and Conway, 2000). Such average recurrence rates are useful for measuring relative activity within a field including eruptive volumes over time.
Linear relationships of eruptive volume over time are especially valuable in forecasting future volcanic activity.

Additionally, Condit and Connor (1996) conclude that spatio-temporal recurrence rate models account for clustering better than average recurrence rates because recurrence rate may change depending on the timing and distribution of past events. When recurrence rate is not uniform in a volcanic field at a given time—even if magma output volumes are steady—spatial clusters exist. In other words, spatial patterns display underlying magma generation and ascent processes. By mapping areas of waxing and waning activity within volcanic fields at different times, it is possible to see the changing loci and petrogeneses. This offers a more complete view of the field development and results in better hazard forecasts.

In addition to episodic temporal recurrence patterns, basaltic volcanic fields display characteristic spatial patterns. Such patterns include a migration of the locus of activity within the field over time, discretely clustered cinder cones, and linear vent alignments—both locally and regionally. These patterns may be explained by spatial variation in recurrence rate, despite steady-state magma output volumes (Connor and Condit, 2000). All of these spatial patterns have been observed in the SFVF as mentioned in the previous section (Tanaka, et al., 1986; Conway et al., 1998).

For example, the SFVF exhibits alignments along the Mesa Butte Fault. These cinder cone alignments formed as a result of existing faults in the shallow subsurface capturing ascending magma (Conway et al., 1997). This is consistent with the idea that small volume, discrete magma batches lead to low recurrence rate, varied duration of activity at the alignment, and geochemically heterogeneous basalts (Wolfe et al., 1987;
Ulrich and Bailey 1987). Silicic vents in the SFVF align with and are largely controlled by the southern portion of the Mesa Butte Fault. The correlation between faults and fractures and vent alignments is most visible in active fields; in older fields, such correlation is difficult to identify if structures have been covered by basalt flows or tephra deposits.

_Eruptive style of cinder cones within the SFVF_

The most recent eruption occurred at Sunset Crater circa 1075 ± 25 A.D. (Ort et al., 2002). This eruption was characterized by two early lava flows extruding from a fissure, followed by at least two episodes of ashfall, as well as fumaroles, spatter cone formation along the fissure, and continuous release of volcanic gasses (Smiley, 1958). The ash plume is estimated to have been between three and five kilometers high with fire fountains reaching anywhere between 260 meters and 660 meters (Elson et al., 2007). This eruptive style has been compared to the 1943 formation of Paricutin and 1759 formation of El Jorullo in Mexico, the 1538 formation of Monte Nuovo in the Phlegrean Fields, Italy, and the 1975 Great Fissure Eruption at Tolbachik, Russia, which suggests that these eruptions may also be used to predict eruptive style at the SFVF. Analyzing accounts and data from these five eruptions allows for better preparation for the impacts of a future eruption within the SFVF.

The Sunset Crater eruption was likely foreshadowed by earthquakes, as Paricutin exhibited earthquake foreshadowing prior to the onset of eruptions. There, earthquakes began 45 days prior to the eruption with 300 earthquakes on the day of the eruption (Luhr and Simkin 1993). Both volcanoes were active for a short period of time, on the order of
50 years or less for Sunset Crater (Ort et al., 2002) and nine years for Paricutin (Luhr and Simkin, 1993). Paricutin also grew in size very quickly: the cone height grew to 30 meters in the first 24 hours, 148 meters in the first month, and had reached 336 meters (80% of its final size) by the first year (Luhr ad Simkin, 1993). It can be inferred that Sunset Crater grew—and future SFVF cones will grow—at a similar rate. Regarding the effects of an eruption, the formation of Paricutin resulted in widespread forest fires and smoke in the surrounding areas; considering the arid pine forests in the San Francisco volcanic field, forest fires beyond the limits of lava flows likely accompanied the Sunset Crater eruption and should be expected for future eruptions (Elson et al., 2007).

El Jorullo is located within the same volcanic field as Paricutin, but it formed earlier, in 1759. The eruption chronology began with two months of earthquakes and tremors, followed by phreatic and phreatomagmatic activity, where ash falls and outflows of groundwater accompanied the eruption (Luhr and Carmichael, 1985). After about a month, activity shifted to be magmatic in nature, and the cone had formed after a total of two months. Explosive eruptions and lava flow emplacement then continued for 15 years (Rowland, et al., 2009). The presence of multiple tuff rings and maars, such as Rattlesnake Crater, in the SFVF suggests phreatomagmatic behavior may also be present in future SFVF eruptions.

Monte Nuovo shares a similar birth story with Paricutin and Jorullo. According to witness accounts and stratigraphic interpretation outlined by D’Oriano and others (2005), for two years prior to the formation of the cone the area experienced increased earthquake intensity and hydrothermal activity. Then, in 1538 a bulge formed with fractures, much like Smiley (1958) relates at Sunset Crater. For two days, ash, ballistics, and pyroclastic
density currents plagued the area as the cone formed most of its final size. After two days of quiescence another explosion occurred, followed by two more days of rest and one final explosion of scoria and pyroclastic flows (D’Oriano et al., 2005). This eruption contrasts with the others as there is no record of associated lava flows.

The 1975 Tolbachik eruption has implications for hazard assessments of monogenetic fields in the American southwest. Doubik and Hill (1999) describe the eruption as follows. Precursors included a swarm of over 300 earthquakes, and gas and ash emissions from nearby Plotsky Tolbachik. After approximately 10 days of this precursor activity, a 300 meter long fissure opened up forming three spatter cones. After one day of activity these cones coalesced to form a single cinder cone which produced ash columns up to 18 km high. Three weeks later, two lava flows effused from the vent accompanied by decreased explosivity. Activity at this cone ended after a total of 30 days, at which point a second fissure opened nearby. This fissure formed two more cones that produced lava flows and relatively smaller tephra columns for five weeks.

Using these four historic eruptions to fill in the gaps of what is known about a cinder cone eruption in the SFVF, it can be assumed that a future eruption will be foreshadowed by weeks to months of seismic activity and will form from a fissure in the earth or from a phreatic explosion. It will also likely include an eruption of hot gas and ash, spatter, lava, and ballistics, as well as the potential for pyroclastic flows and wildfires.
Current state of hazard assessment

Although numerous hazard assessments have been carried out for other volcanic fields around the world, very few studies have centered on the SFVF in particular. In addition, at the time of this writing, any such hazard assessment has yet to be translated into a statewide emergency response plan.

Conway and others (1998) considered the recurrence rates of volcanism within the SP cluster in the northern portion of the SFVF. Conway and others (1998) used $^{40}$Ar-$^{39}$Ar age determinations (between 5.6 Ma and 16 ka), coupled with information from vent stratigraphy, paleomagnetic data, and cone morphology diffusion models to determine mean recurrence rates. Such data yielded that on average, steady-state activity formed one vent every 15 k.y. and that recurrence rate increased faster than output rate after 780 ka with no sign of waning activity. Therefore, the field is considered to be volcanically active. Mean recurrence rates were used to estimate probabilities of future eruptions within the cluster, so results were not affected by changes in recurrence interval based on age uncertainties. Conway and others (1998) find that recurrence rate for SP cluster peaks after a recurrence interval of 10-20 k.y., and may be as high as $1.4 \times 10^{-4}$/yr. This leads to a <13% chance of eruption within SP cluster during the next 1000 years, based on 95% confidence on the upper limits of age uncertainty.

Though not strictly a hazard assessment, the aforementioned study of basaltic volcanism along the Mesa Butte Fault (Conway et al., 1997) concludes that mapped structures which have previously hosted volcanic activity should be taken into account when modeling probabilities of eruption recurrence. Buried or unmapped faults or intrusions have yet to be considered in SFVF assessments. Recent geochemical studies
(e.g. Rittenour et al., 2012) provide the constant need to revise eruption ages used as parameters for eruption probability models. One advantage to the methods used in this thesis is that the results are easily updated with the addition of new vent locations or age data.

One way to think about all the components of a hazard assessment is with an event tree. Newhall and Hoblitt (2001) describe this method as “a graphical, tree-like representation of events in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes,” which is used to show the range of outcomes resulting from volcanic activity. An event tree has been constructed for an SFVF eruption (Figure 2) that is intended to guide emergency managers in their decision making process regarding planning, mitigation, and ultimately response strategies. This tree shows the progression of events that are possible given volcanic unrest in the region, and also specifies which particular chain of events is considered for the purpose of this study: given that an effusive eruption occurs within the SFVF, what is the conditional probability that lava will inundate Flagstaff? Although monogenetic fields may exhibit explosive styles of eruptions with VEI ≤ 4, the impacts of explosive activity are not considered in this study. That being said, future work expanding the hazard assessment to explosive styles should consider the fact that volcanic hazards associated with explosive eruptions are different than those associated with effusive eruptions. As such, those studies must account for the magnitude of the explosive eruption, as well as hazards posed by debris flows, tephra fallout, pyroclastic flows, and volcanic earthquakes. These hazards are not included in this thesis,
however, as this study is limited to determining the conditional probability of lava flow inundation only given an effusive eruption.

This study is meant to be used as one component to a broader long-term hazard model. Such a hazard model would be applied for the coming years to centuries until volcanic unrest is observed within the field. In its current state, the SFVF is not exhibiting increased seismicity or geodetic change, though the field also lacks the proper instrumentation required for active monitoring. This is the stage, however, that is ideal for establishing thorough hazard models so that when the field does show signs of renewed activity, scientists and public safety officials alike will be able to revise previous models according to the data produced by monitoring initiatives. This study is intended to both help with future mitigation plans within northern Arizona, as well as be used in conjunction with increased volcanic risk and hazard education for the local public.
Figure 1. Location of the SFVF. Late Cenozoic volcanic fields outlined (from Luedke and Smith, 1978), with Colorado Plateau-margin volcanic younger than 5 m.y. filled in with black. Inset details the local vent locations within the SFVF relative to Flagstaff and transportation routes.
Figure 2. Event tree for an SFVF eruption. Given volcanic unrest, the conditional probabilities that a magmatic intrusion and eruption will occur, leading to the conditional probability that Flagstaff will be inundated by a lava flow. This serves as a road map for emergency managers to see the potential outcomes of volcanic unrest (green and blue), and which of those outcomes are considered in this study (blue).
Chapter 3: Procedures and Methodology

The purpose of this study is to determine the conditional probability that a lava flow will inundate some part of the city of Flagstaff, Arizona, given that basaltic lava erupts from a new vent within the San Francisco volcanic field. A spatial density model was made based on the distribution and age of vents. This model was then synthesized with topographic digital elevation model (DEM) data as inputs for a Monte Carlo simulation of lava flow inundation.

This study employed the two-step technique used by Connor, et al. (2012), modified for the city limits of Flagstaff. The major components of this study involve using kernel density estimates to locate the most probable areas for the formation of a new vent based on the timing and locations of past volcanic events, followed by numerical simulations of basaltic lava flows used in conjunction with local topographic DEM data. The following section describes the procedures and methodology for the study.

Spatial density model

As discussed in Chapter 2, the vents in the SFVF are spatially clustered in several areas, including those around SP crater, Sunset Crater, the Mesa Butte Fault, and the town of Williams. Draper et al. (1994) find that 30% of cinder cones and maars are
located in alignment with regional faults. Such alignments are sensitive to stress orientation and preexisting faults align oblique to maximum horizontal compressional stresses (Connor et al., 1995). The spatial density estimate is used to model such clustering patterns in the distribution of vents.

A Gaussian kernel function is used based on the assumption that the distribution of volcanoes may be explained by diffusion processes. A spatial density estimate using a kernel function is purely data driven, based on the locations of point data. Though this can be an advantage in many ways, including being able to quickly repeat the analysis given new location data, there are also significant drawbacks. One drawback is that the spatial density analysis is not inherently sensitive to geologic boundaries or constraints like the locations of faults or buried magma bodies. Such geological boundaries were not explicitly accounted for in the spatial density estimate in this thesis.

In order to model spatial intensity—the expected number of volcanoes per area—the distribution of vents was analyzed by using ArcGIS. It is difficult to isolate which events are truly independent from each other and which were caused by the same batch of magma rising toward the surface. For the purposes of this study, all vent sites were treated as independent volcanic events. Five hundred eighty-five basaltic vent locations were manually digitized according to satellite imagery in conjunction with the 1987 USGS map of the volcanic field and their coordinates were logged (Wolfe et al, 1987). Each vent was then assigned to one of three magnetic chronozones as follows—determined by field relations and paleomagnetic investigations carried out by Tanaka and others (1986): the 135 Pre-Matuyama vents display normal polarity and are older than 2.59 Ma, the 211 Matuyama vents display reversed polarity and erupted at 2.59-0.78 Ma,
and the 239 vents with eruptions during the most recent chronozone, Brunhes (0.78 Ma to present), display normal polarity. Each age section served as an input into the first part of the non-parametric spatial intensity estimate, the kernel function, which estimates the distance to nearby volcanoes (Silverman, 1978; Diggle, 1985; Silverman 1986; Wand and Jones, 1995; Connor and Connor., 2009).

After determining which vent locations would be used, the second part of the spatial density estimate to be determined was the smoothing constant, or bandwidth. The bandwidth, in this case of a Gaussian kernel function, is the variance of the kernel. The selected value of this bandwidth affects the rate of change in density with distance from the vents so that small bandwidth values focus future eruptions as having a higher probability closer to existing volcanoes (clustering), while a high bandwidth value results in a smoother, more uniform field.

The Gaussian kernel for estimating spatial density is given by:

$$ \hat{\lambda}(s) = \frac{1}{2\pi h^2 N} \sum_{i=1}^{N} \exp \left[ -\frac{1}{2} \left( \frac{d_i}{h} \right)^2 \right] $$  \hspace{1cm} (1)

The local spatial intensity estimate, $\hat{\lambda}(s)$, is based on $N$ total events and depends on the distance, $d_i$, among each vent location and point, $s$, of the spatial density estimate, and the smoothing constant, $h$. Here, $h$ is constant as the kernel is radially symmetric.

For this study, the sum of the asymptotic mean squared error (SAMSE) pilot bandwidth selector was used to select the optimal bandwidth matrix and corresponding square-root matrix for the spatial density model (Wand and Jones, 1995; Duong and Hazelton, 2003; Connor et al., 2012; Bebbington and Cronin, 2011).
Lava flow simulation

The conditional probability that basaltic lava will inundate the city of Flagstaff was calculated using the lava flow simulation code in PERL developed by Connor and others (2012). The area of inundation depends on eruption rate, eruption volume, rheological properties, and the slope of the underlying topography (Dragoni and Tallarico 1994; Griffiths 2000; Costa and Macedonio 2005; Connor et al. 2012). This code is driven by the common data available for lava flows—thickness, area, and volume—and determines the conditional probability that inundation within the Flagstaff city limits will occur, given randomly selected vents located by the spatial density estimate.

The code assumes that each cell on the DEM that is inundated by lava will retain or accumulate an amount of residual lava, which corresponds to the modal thickness for that flow. The residual lava is then passed on to adjacent cells, acting to retain a steady flow thickness. Adjacent daughter cells only receive lava if their effective elevation (lava thickness + original elevation) is less than the effective elevation of the parent cell. Excess lava is distributed evenly throughout viable adjacent cells, thereby simulating the downhill flow of effusive lava.

Since the modeling code is guided by measurable parameters such as flow volumes and thicknesses (residuals), thicknesses for 18 clearly exposed lava flows within the SFVF were measured in November 2013 using an LTI TruPulse 360 laser range finder (Figure 3). The locations of these flows with respect to the basaltic vents within the SFVF are shown in Figure 4 and a full list of flow thicknesses may be found in Appendix B.
Areas for these lava flows were determined in ArcMap by manually outlining flows based on with the 1987 USGS map of the volcanic field (Wolfe et al, 1987) and then using the “Calculate Geometry” tool. A list of average flow thicknesses, measured areas, and volumes is shown in Table 1. Volumes may be overestimated as a single average thickness was assumed for the entire area of the measured flows, and though measurements were taken at the edges of flows, the average thicknesses often reflect the maximum thickness observed at the field site.

The resolution of the DEM used to set underlying topography can affects the resolution of the lava flow simulation, where high resolution provides more detailed flow, but the resulting increase in number of grid cells also increases the necessary computation time. The topography and flow rate are critical considerations for the ideal grid size. Because the SFVF is characterized by low viscosity lavas which would be unresolved in a coarse DEM, a high resolution 30-meter DEM was downloaded from the USGS National Map Viewer and compared to a 90-meter DEM produced by the Shuttle Radar Topography Mission (SRTM). Using GDAL (Geospatial Data Abstraction Library), both elevation datasets (SRTM in WGS84 and USGS in NAD83) were converted from latitude-longitude to UTM meters, the USGS dataset was warped to the WGS84 projection, and then both datasets were translated into ArcInfo ASCII format. During a test simulation, it was observed that the coarser resolution elevation data did not affect the path of simulated lava flows and both data sets produced the same inundation result given a specified vent location, flow volume, and flow thickness. Therefore, to minimize computing time, the 90-meter DEM was chosen for use in the Monte Carlo simulation.
Using a range of values for the input parameters, a Monte Carlo simulation estimated the probability of inundation based on 7,769 iterations. The range of flow volumes for the simulated flows was determined to be log-normally distributed, with a \log(\text{mean}) of 8.4 \left(10^{8.4} \text{ m}^3\right) and a \log(\text{standard deviation}) of 0.6. Based on these observations, the lava flow code stochastically chooses a total erupted lava volume from a log-normal distribution with a mean of 8.4, a standard deviation of 0.6 (Table 2). This range samples more frequently from smaller volumes, but still allows rare sampling of comparatively larger-volume flows.

The boundaries for the lava flow inundation target were defined as a 217 km$^2$ rectangle best fitting the Flagstaff city limits shown in Figure 5. For this study, any lava that is simulated to cross into the boundaries of this polygon is treated as an inundation. The range of flow thickness values from 15 observed lava flows was determined to also be log-normally distributed, with a \log(\text{mean}) of 1.2 \left(10^{1.2} \text{ m}\right) and a \log(\text{standard deviation}) of 0.4. Based on these parameters, the code stochastically chooses a value for modal lava flow thickness from a log-normal distribution having a mean of 1.2, and a standard deviation of 0.4 (Figure 6).

Connor and others (2012) concluded that only one flow from each vent is necessary to estimate the length of a flow, and that multiple flows from the same vent tend to broaden the affected field, but not lengthen it. For the purpose of this study, the forward extent of the lava flow—rather than the lateral extent—is a greater predictor of hazard to the city.
Figure 3. Photos of select SFVF lava flows. Taken a) on top of Strawberry Crater lava flow, b) from the edge of the Bonito flow at Sunset Crater, and c) from a Route 505 exposure of the Cochrane Hill lava flow.
Figure 4. Locations of 18 measured SFVF lava flows. Identification numbers correspond to names found in Table 1.
Table 1. Measured values of SFVF lava flows.

<table>
<thead>
<tr>
<th></th>
<th>Volumes (m$^3$)</th>
<th>Areas (m$^2$)</th>
<th>Average Thicknesses (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>SP Crater</td>
<td>3.3E+08</td>
<td>1.84E+07</td>
</tr>
<tr>
<td>2)</td>
<td>Strawberry Crater</td>
<td>3.62E+08</td>
<td>9.71E+06</td>
</tr>
<tr>
<td>3)</td>
<td>Kana-a Flow, Sunset Crater</td>
<td>4.77E+07</td>
<td>6.30E+06</td>
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<tr>
<td>4)</td>
<td>Ebert Mountain</td>
<td>1.98E+08</td>
<td>2.39E+07</td>
</tr>
<tr>
<td>5)</td>
<td>Red Mountain</td>
<td>1.20E+09</td>
<td>4.04E+07</td>
</tr>
<tr>
<td>6)</td>
<td>Observatory Mesa</td>
<td>1.44E+09</td>
<td>6.02E+07</td>
</tr>
<tr>
<td>7)</td>
<td>Bonito Flow, Sunset Crater</td>
<td>8.34E+07</td>
<td>7.05E+06</td>
</tr>
<tr>
<td>8)</td>
<td>Cochrane Mountain</td>
<td>6.92E+08</td>
<td>4.64E+07</td>
</tr>
<tr>
<td>9)</td>
<td>Merriam Crater Secondary</td>
<td>8.01E+07</td>
<td>1.78E+07</td>
</tr>
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<td>10)</td>
<td>Merriam Crater Main</td>
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<td>8.60E+06</td>
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<td>11)</td>
<td>Cinder Mountain</td>
<td>1.26E+09</td>
<td>3.74E+07</td>
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<td>12)</td>
<td>Rattlesnake Crater</td>
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<td>9.14E+06</td>
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<td>Merrill Crater, South Flow</td>
<td>2.56E+08</td>
<td>2.05E+07</td>
</tr>
<tr>
<td>14)</td>
<td>Merrill Crater, North Flow</td>
<td>2.87E+08</td>
<td>1.45E+07</td>
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<td>15)</td>
<td>Antelope Mountain</td>
<td>1.02E+08</td>
<td>8.90E+06</td>
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<td>16)</td>
<td>KB</td>
<td>1.53E+08</td>
<td>5.47E+07</td>
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<tr>
<td>17)</td>
<td>“Qtwb”</td>
<td>2.19E+07</td>
<td>1.39E+06</td>
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<tr>
<td>18)</td>
<td>V176</td>
<td>2.86E+07</td>
<td>4.08E+06</td>
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Table 2. Input parameters for the lava flow simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Notes</th>
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</thead>
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<tr>
<td><strong>Flagstaff boundary</strong></td>
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<td>Boundaries used in analysis</td>
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<tr>
<td>East (km)</td>
<td>452.7</td>
<td></td>
</tr>
<tr>
<td>West (km)</td>
<td>435.5</td>
<td></td>
</tr>
<tr>
<td>North (km)</td>
<td>3899.8</td>
<td></td>
</tr>
<tr>
<td>South (km)</td>
<td>3886.9</td>
<td></td>
</tr>
<tr>
<td>Lava thickness (m)</td>
<td>1.4 – 197.5</td>
<td>Log-normal distribution; (log)Mean = 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(log)Standard Dev. = 0.4</td>
</tr>
<tr>
<td>Lava flow volume (m$^3$)</td>
<td>$10^7$-$10^9$</td>
<td>Log-normal distribution; (log)Mean = 8.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(log)Standard Dev. = 0.6</td>
</tr>
<tr>
<td>Iteration volume</td>
<td>$10^6$</td>
<td>Lava volume added at source vent in each iteration</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>7,769</td>
<td></td>
</tr>
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</table>
Figure 5. Map of Flagstaff. City limits are marked by the white dashed line and the area selected for the area of interest for lava flow inundation is contained by the green box.
Figure 6. Histogram of lava flow volumes, thicknesses, and log(thicknesses) for the 18 measured flows. Thickness and volume are both log-normally distributed with common low values and rare high values.
Chapter 4: Results

The results of this thesis are highly sensitive to the recurrence rate chosen to be used to estimate future recurrence of vents within the SFVF. Rather than using the average recurrence rate of the entire field, the average recurrence rate for Brunhes-aged vents is used as a predictor. This method, however, does not take into account any increase in recurrence rate observed over the last 10,000 years or the temporal clustering behavior often observed in volcanic fields such as the SFVF. The lack of age data for vents within the field leaves the maximum likelihood method as the best choice for estimating recurrence interval. The following results of the spatial density analysis and Monte Carlo simulation are used with the average recurrence rate to find the annual lava flow inundation hazard posed to Flagstaff.

Spatial density model

For the 135 basaltic Pre-Matuyama vents and 211 basaltic Matuyama vents, the SAMSE bandwidth selector yielded respective bandwidth matrices of:

$$H = \begin{bmatrix} 13330575 & -3095056 \\ -3095056 & 12492263 \end{bmatrix} \quad (2)$$

$$H = \begin{bmatrix} 15021059 & 1379942 \\ 1379942 & 25355226 \end{bmatrix} \quad (3)$$
The upper left entry represents the smoothing in the E-W direction, while the lower right entry represents N-S smoothing. The corresponding square root matrix indicates that the actual E-W smoothing distances are 3651.1 m and 3875.7 m, respectively, and the N-S smoothing distances are 3534.4 m and 5035.4 m, respectively. The spatial density estimate for the Pre-Matuyama and Matuyama vents using these bandwidths are shown in Figure 7.

Using the vent locations of 239 vents from the Brunhes chronozone, the SAMSE bandwidth selector yielded the following optimal bandwidth matrix and square-root matrix:

\[
H = \begin{bmatrix}
21645633 & -5662539 \\
-5662539 & 11696280
\end{bmatrix}
\] (4)

The upper left entry represents the smoothing in the E-W direction, while the lower right entry represents N-S smoothing. The corresponding square root matrix indicates that the actual E-W smoothing distance is 1000 m and the N-S smoothing distance is 4000 m. The shape of the bandwidth ellipse (Figure 8) displays the northwest-southeast lineation of clusters exhibited by the Brunhes vents. The spatial density estimate for the Brunhes vents using this bandwidth are shown in Figure 9.

There is a 25% chance that given a volcanic event, it will occur within the area of \(2.67 \times 10^8 \text{ m}^2\) contoured in Figure 9. This area is split into two clusters, demonstrating the spatial pattern of basaltic vents is divided by San Francisco Mountain. The smaller area to the north contains SP Cluster, including SP Crater (3931495N, 433964E). The larger area to the southeast contains Sunset Crater (3912925N, 446825E) as well as Merriam Crater (3910387N, 473798E). This demonstrates the model’s suitability in predicting the most recent eruptions within the entire field. The vent density within this area is 1.86 x
10^{-11} \text{ m}^2. \text{ Given an eruption in the SFVF, there is a 99\% chance it will occur within the } 3.6 \times 10^9 \text{ m}^2 \text{ area of } 7.57 \times 10^{-10} \text{ m}^2 \text{ density, enclosed by one broad contour and the area around the outlier to the southwest. Figure 10 illustrates the broader context of the spatial density of the SFVF as a whole.}

*Lava flow simulation*

Of the 7,769 lava flows simulated to extrude from vents located by the spatial density model of Brunhes vents, 274 inundated the area defined as Flagstaff. This is equal to 3.6 \% of the total number of simulations and may be used to evaluate the probability of lava flow inundation hazard from a new SFVF vent to Flagstaff. A total of 88 simulated vents were located within the area defining the Flagstaff city limits, yielding a 1.2\% chance that a vent will form within Flagstaff.

The locations of the 7,769 simulated vents are shown in Figure 11, which distinguishes between vents that produced Flagstaff-inundating flows (red dots) and those that did not (blue dots). Vents located southeast of San Francisco Mountain pose a greater threat to Flagstaff than those vents located north of San Francisco Mountain. The eastern half of the field is the most likely location for future vents based on the spatial density analysis and therefore contains a greater number of simulated vents. Higher elevation features such as San Francisco Mountain and Elden Mountain tend to protect the city from lava flows, while low topography between existing cinder cones and lava flows tends to funnel flows towards the city. An example of 10 simulated lava flows is shown in Figure 12.
In order to assess the lava flow hazard at any given point within the SFVF, the cumulative number of lava flows affecting each 90 meter pixel is mapped in Figure 13a. This shows that lava flows have good coverage over the entire region to the north, northwest, and northeast of Flagstaff, with thinner coverage at the fringes and no coverage over peaks such as San Francisco Mountain and Elden Mountain. This image also shows which parts of Flagstaff are affected by inundation; lava flows entering the defined boundary enter from the north, northwest, and northeast, and do not extend far into the city limits. For reference, as smaller sample of simulated flows is shown in Figure 13b, which also more clearly shows the directional tendencies of flows in various locations. Flows originating in the north-central part of the field tend to flow north and northeast, away from the city. The flows originating just north and northeast of the city, however, tend to flow south—towards the city limits. This indicates that the lava flow hazard is greatly dependant on small variations in source location.

Comparing the properties of the simulated lava flows to those of the measured SFVF flows validates the model. The properties that were compared include thickness, area, and log (volume), and this comparison shows that distribution of values for simulated flows mimics those of flows measured in the field (Figure 14).
Figure 7. Spatial density models of a) Pre-Matuyama and b) Matuyama vents. Vent locations are denoted by black dots. Contours are drawn and colored at the $25^{th}$, $50^{th}$, $75^{th}$, $95^{th}$, and $99^{th}$ percentile boundaries.
Figure 8. Shape of the kernel density function. Coordinates are in meters and contours are at the 68\textsuperscript{th} and 95\textsuperscript{th} percentiles. Northwest-southwest shape is consistent with the alignment of clusters of Brunhes age.
Figure 9. Model for the spatial density of Brunhes vents. Vent locations are denoted by black dots. Contours are drawn and colored at the 25\textsuperscript{th}, 50\textsuperscript{th}, 75\textsuperscript{th}, 95\textsuperscript{th}, and 99\textsuperscript{th} percentile boundaries. Given that an eruption occurs within the mapped areas, there is a 99\% chance it will happen where the density is $1.864174 \times 10^{-11}$ m\textsuperscript{2}, a 95\% chance at $6.895643 \times 10^{-11}$ m\textsuperscript{2} density, a 75\% chance at $2.766953 \times 10^{-10}$ m\textsuperscript{2} density, a 50\% chance at $5.344185 \times 10^{-10}$ m\textsuperscript{2} density, and a 25\% chance at $7.570898 \times 10^{-10}$ m\textsuperscript{2} density.
Figure 10. Spatial density of vents in the SFVF. Vents are not weighted by age. Red contour to the southwest indicates cluster of vents of Pre-Matuyama age, Matuyama cluster is in the west-central region, and Brunhes vents are the two clusters in the eastern half of the field.
Figure 11. Locations of simulated vents. Blue circles indicate vents producing lava that did not result in an inundation of Flagstaff. Red circles indicate vents either located within the designated Flagstaff area, or vents producing lava that inundated Flagstaff.
Figure 12. Example of lava code output for 10 randomly selected flows. Bright green rectangle represents the Flagstaff boundary, blue squares show locations of vent openings according to the spatial density analyses.
b) Figure 13. Map of cumulative lava flows. A) Each of the 7,769 simulated lava flows plotted at 99% transparency, where the green box represents Flagstaff. Inundation by these flows affects the northern margin of the city. B) Random sample of 20 simulated lava flows overlapping at 99% transparency for a frame of reference regarding the coverage in 12a.
Figure 14. Comparison of simulated flows (red) to measured flows (black). Histograms show range of values for flow thicknesses, volumes, and log(volumes). Plots show that distributions of values in the Monte Carlo simulation match the distribution of observed values reasonably well.
Chapter 5: Discussion

One way to assess the total hazard posed by lava flow inundation is to create a logic tree. This may be used to decide which approach to take when performing a hazard assessment like the one described in this study. The logic tree created for this study is shown in Figure 15.

First, it must be decided whether or not the magmatic system under consideration is extinct. In the case of the SFVF, the most recent eruption was less than 1 ka, which is akin to a blink of an eye with respect to active magmatic systems. With an average recurrence rate of one vent per 10,000 years, the field has experienced much longer periods of inactivity than the current one without becoming extinct. Of course, it is possible that the Sunset Crater eruption was the last for the volcanic field as activity at each volcanic system eventually comes to an end. For the purpose of this study it is assumed, based on the average recurrence interval, that the field is not yet extinct. A probability of ‘1’ is assigned to the “not extinct” option, while a probability of ‘0’ is assigned to the “extinct” option.

Next, the recurrence rate of vent formation must be estimated. The results of this study are very sensitive to the recurrence rate chosen, so this is the greatest source of uncertainty. The options described here are 1) maximum likelihood, 2) temporal clustering, 3) increasing rate of recurrence, and 4) decreasing rate of recurrence. The
maximum likelihood model suggests that new vents form according to \([N-1] / [\text{Age}_{\text{oldest}} - \text{Age}_{\text{youngest}}]\). This assumes that vents will continue to form at the current average recurrence rate. The temporal clustering model assumes that vents form irregularly through time forming clusters not seen in the maximum likelihood model. The last two models predict that the rate of vent formation will either wax or wane. Using the maximum likelihood method to compare recurrence rates for vents erupted during each chronozone, the annual recurrence rates for Pre-Matauyama, Matuyama, and Brunhes vents are \(6.0 \times 10^{-5}\), \(1.2 \times 10^{-4}\), and \(3.1 \times 10^{-4}\), respectively. Because this shows a strong chance that recurrence rate will increase, and temporal clustering is a known pattern to occur in the field, models 1, 2, and 3 are each assigned a probability of 0.33, with the decreasing rate model assigned a probability of ‘0’. However, high resolution ages of Brunhes-age rocks are needed in order to confirm details of an increase in recurrence rate. Therefore, even though other models may be more accurate predictors of future recurrence rate the future recurrence rate is estimated in this study using the maximum likelihood method. As noted earlier, this is a great source of uncertainty and the choice was made based on the available data.

Next, questions regarding vent selection must be considered. Which vents should be considered for the spatial density analysis, and should some be weighted higher than others? Three models were considered here: 1) using all SFVF vents and weighting them equally, 2) using all SFVF vents but weighting younger vents more than older vents, and 3) only using the most recent vents. The most recent vents are defined as those having formed during the Brunhes chronozone (780,000 y.a. to present). This arbitrary chronozone cut-off date is used, again, because of a lack of radiometric ages for SFVF
vents. If all vents’ ages were known, the age cut-off used would likely be much more recent than 780,000 y.a. in order to reflect the length of time magma source locations are stable. Ultimately, the third model—using the most recent vent locations—was chosen because the distribution and centroid position of Brunhes vents is located very near to the location of the last eruption. Therefore, this model is assigned a probability of ‘1’, while the other models are assigned a probability of ‘0’.

From here, future lava flows will either extrude the same volume as past flows, higher volume, or lower volume. In this study, it is assumed that future flows will behave the same as past flows, so this model is assigned a probability of ‘1’, and the other models are assigned a probability of ‘0’. The resulting probability of inundation based on the Monte Carlo simulation is therefore equivalent to the aggregate probability considering probability values at each step of the logic tree. This study only pursues this branch of the logic tree, however future studies can calculate the inundation probability given other branches of the tree and compare the results to those provided here.

*Spatial density model*

Because of the negligible likelihood that a hot magma source still sits below the western half of the volcanic field, in conjunction with the fact that the centroid position of the Brunhes vents calculated by Tanaka and others (1986) is located in close proximity to Sunset Crater—the site of the most recent eruption, Brunhes vents clusters alone are considered to be the best predictors of a future SFVF eruption in this study. In Figure 9, the smaller area to the north contains SP Cluster, including SP Crater (3931495N, 433964E). The larger area to the southeast contains Sunset Crater (3912925N, 446825E)
as well as Merriam Crater (3910387N, 473798E). This demonstrates the model’s suitability in predicting the most recent eruptions within the entire field.

Additionally, though there is a clear northwest-southeast alignment of vents that matches the alignment of Brunhes vents, the Pre-Matuyama model of spatial density is still a poor predictor of new events, as not even the 99th percentile contour for Brunhes vents overlaps with the 50th percentile contour of Pre-Matuyama vents. This would also apply to the 75th percentile contour of Pre-Matuyama vents if not for several outliers to the east of the main cluster.

As for the Matuyama model of spatial density, the pattern of clustering may be a good predictor of future eruptions if it were migrated approximately 30 km to the east. The overall vent alignments, however, are dominantly north-south when considered alone. This alignment is less obvious in the spatial density model of the field as a whole where it does appear to cluster in northwest-southeast directions.

The areas of the 99th percentile contours of the Pre-Matuyama, Matuyama, and Brunhes chronozones of vents are 3,005 km², 5,628 km², and 3,605 km², respectively. This yields an average area of 4079.3 km² and an average radius of 18 km. According to Tanaka and others (1986), before Matuyama time volcanism migrated to the northeast at a rate of ~1.2 cm/year, and for the last 2.5 m.y. volcanism migrated due east at a rate of 2.9 ± 0.3 cm/year. Therefore, as a long-term predictive model, over the next 1 m.y. volcanism in the field will migrate further east a total of ~30 km. Using a radius of 18 km, a circle of future eruption potential is drawn 30 km east of the Brunhes centroid position (Figure 16).
**Lava flow simulation**

Based on the results of the Monte Carlo simulation, there is a 3.5% chance that Flagstaff will be inundated by lava sourced by a new vent within the SFVF. To find the annual probability of one or more lava flows inundating Flagstaff, we must consider the recurrence rate of vent formation for the volcanic field in combination with the aforementioned conditional probability of inundations. This may be expressed as:

\[
P[I \geq 1] = P[E \geq 1] \times P[I|E] \tag{2}
\]

where the probability of an event, \(P[E]\), is equal to \(1 - \exp(-\lambda t)\), where \(\lambda\) is the recurrence rate and \(t\) is time. The average recurrence rate for Brunhes vents in the SFVF is \(3.1 \times 10^{-4}\) vents/year. Therefore, the annual probability of one or more flows inundating Flagstaff is \(1.1 \times 10^{-5}\), which, according to the National Safety Council (2013), is the same as dying from post-surgical complications. This probability may be underestimated if Brunhes aged vents have been buried or remain unmapped. This aggregate annual probability may be assessed for each branch of the logic tree (Figure 15), though this calculation only represents the branch of the tree followed for this study.

This probability is low enough that it is not relevant to current or future homeowners in the area. However, critical infrastructure like hospitals, government buildings, and major transportation arteries should be built in areas of lower risk. Avoiding building such critical infrastructure in topographic lows in the north and east sides of the city is recommended.

The estimated probability of inundation also indicates a need for the city to plan for such a hazard. It is likely that the city will never utilize such a response plan, but if an event does occur without a plan in place, the city will be forced to face many problems. If
a vent forms within five kilometers of Flagstaff, lava flows will not be the only hazard posed to the city. Ballistics can easily affect populations and infrastructure at this range as would any ash or volcanic gasses escaping the vent. A partial response plan drawn up for the Arizona Department of Emergency Management may be found in Appendix C. Because lava flows may cause large scale forest fires, it is important for the state response plan regarding lava flows to include a plan for mitigating the effects of forest fires.

More devastating than a lava flow is the possibility of a new vent forming within the city limits. The results show that 1.1% of the simulated vents were located within the designated area of interest. This yields an aggregate annual probability of $3.4 \times 10^{-6}$, which is the same as the annual probability being involved in a fatal airplane accident (NTSB, 2012). If the next vent forms not just near to Flagstaff but inside of it, then all infrastructure at the site of the vent and adjacent to it would be destroyed permanently. If, for example, such an eruption devastates an area within 5 kilometers of the vent, and that whole area was within the defined 217 km$^2$ area used for this study, 35% of Flagstaff would be affected. This figure is underestimated since the actual area of Flagstaff is smaller than the approximated rectangle. Such an eruption may disrupt communication lines, power, water supply, highways, or sewage lines and would disrupt daily life for years to come if the vent exhibits continued activity. These results reinforce the need for monitoring for precursors in Flagstaff and the central and eastern portions of the SFVF.
Figure 15. Logic tree for an SFVF hazard assessment. The tree displays successive decisions required regarding the models used in an assessment. The models used in this study are outlined in blue.
Figure 16. Long term hazard model for SFVF vent locations. The average area of each individual chronozone spatial density model was taken and shifted east according to the average migration rate. The red circle shows the estimated location that will host the centroid position of new vents in one million years from now.
Chapter 6: Conclusions

A lava flow hazard assessment of the SFVF is of interest to residents of Flagstaff as well as to emergency planners at the state and local level. The conditional probability that lava may inundate the city concerns the local populations, those using Interstate-40 and the parallel railroad, as well as anyone needing medical assistance at the Flagstaff Medical Center. Though studies have been conducted regarding magmatic processes within the field and cluster-specific recurrence intervals, a comprehensive hazard assessment has yet to be completed for the volcanic field. This study serves as a first step towards such a comprehensive assessment, which can be applied to response plans and education initiatives.

This thesis includes a spatial density analysis of vents within the SFVF as a precursor to a lava flow simulation to determine the inundation hazard to Flagstaff. Methods were adapted from a similar study by Connor and others (2012) which involved the development and application of the lava flow simulation to a nuclear power plant in Armenia.

The spatial density analysis showed that there is a 99% chance that a future vent will be located within the 3.6 x 10^9 m^2 area of 7.57 x 10^{-10} m^{-2} density based on Brunhes aged vents. This spatial density model accurately predicts the location of the most recent eruption at Sunset Crater, 20 kilometers due north of Flagstaff.
The Monte Carlo simulation showed that 3.5% of generated lava flows inundated Flagstaff, and 1.1% of generated vents were located within the city limits. Vents located southeast of San Francisco Mountain were more likely to result in inundation. The high elevation often blocked lava flows from the north, and those flows that did inundate the boundary did not reach the heart of the city. The aggregate probability of lava flow inundation in Flagstaff is $1.1 \times 10^{-5}$ per year. In order to produce a comprehensive hazard assessment widely useful to local officials there is a need for further research. Hazards posed by an explosive eruption must be accounted for, and the impacts to populations living outside of the city limits and to vital infrastructure in Flagstaff must be assessed. In spite of the low recurrence rates in the SFVF, this information should be produced sooner rather than later in order to best prepare for future volcanic activity.
References


Appendices
Appendix A:

Transition Zone magma source? A gravity and magnetic survey of the San Francisco volcanic field region.

Introduction

The great number of basaltic volcanic fields, including the San Francisco volcanic field (SFVF) that occur on the southern margin of the Colorado Plateau and overlie the lithospheric transition zone between the Plateau and the Basin and Range province has led many to conclude that this transition zone has been the cause of regional magmatism (Tanaka et al., 1986; Condit et al., 1989; Mickus et al., 1996). This study seeks to determine if gravity and magnetic anomalies support this long-held conclusion.

Methods

Gravity and magnetic data for north-central Arizona were gathered from the UTEP Gravity and Magnetic Database of the United States. Using Perl to contour both datasets (Figure A1), anomalies were compared to locations of vents, composition of vents, as well as structural zones defined by previous regional volcanic studies (Tanaka et al., 1986; Condit et al., 1989; Mickus et al., 1996).

Excess mass due to the positive and negative anomalies within the volcanic field were calculated using perl. First, the map projection (NAD83), hemisphere (north), and UTM zone (12) were set, and proj4 was used to convert values from latitude-longitude to UTM values. GMT was used to place the data on a grid after setting the map boundaries (N = 3927500, S = 3885000, E = 4750000, W = 3900000), scale (1:1,000,000), minimum and maximum gravity values (-225/-140 mGal), and contour interval (2 mGal).
The gravity data was interpolated onto a regular grid as seen in Figure A2. The background gravity value was first set at -190 mGal to calculate the deficit mass due to the butterfly shaped negative gravity anomaly. Next, the background value was set at -174 mGal to calculate the excess mass due to the positive gravity anomaly in the northeast section of the volcanic field.

For each point, these two threshold values were subtracted and then multiplied by \((1/2\pi G)\times dx\times dy\) to find excess mass, where dx and dy are the grid spacing values. This method does not account for the SW-NE regional background trends of decreasing gravity values.

**Results**

The gravity anomaly in Figure A1 follows the structural trends, with a high (-80 mGal) anomaly associated with the BRP, a low (-200 mGal) anomaly at the CP, and a 40 mGal transition at the Transition Zone. The magnetic anomalies do not follow structural trends. On a local scale, SFVF gravity signature shows southwest-northeast trending anomalies, matching the vent migration outlined by Tanaka and others (1986). Negative anomalies are to the northwest and southeast, with a linear positive anomaly in the northeast quadrant.

The excess mass for the ~10 mGal positive anomaly in the northeast quadrant of the SFVF is shown in Figure A2. Using a background value of -174 mGal (marking the outline of the anomaly), the resulting excess mass is \(6.52 \times 10^{12}\) kg. Deficit mass for the butterfly shaped ~25 mGal negative anomaly in based on a threshold value of -190 mGal. This yields a mass deficit of \(2.51 \times 10^{14}\) kg.
Figure A1. Gravity (left) and Magnetic (right) anomalies of north-central Arizona at the transition between the Colorado Plateau and Basin and Range province. Basaltic vents of the San Francisco volcanic field are shown in the insets (silicic centers outlined).

Figure A2. Contoured gravity data accounted for in the excess mass calculation.
Discussion

The regional gravity anomaly shows high gravity in the BRP, low gravity in the CP, and intermediate gravity values matching with the transition zone described by Tanaka, et al. (1986), among others. This is likely due to the thinning of the lithosphere in the BRP (<25 km) overlying dense asthenosphere, as compared to the ~60 km thick lithosphere of the CP (Condit et al., 1989). The gravity signature clearly mimics these boundaries, and this indicates that the transition zone at the southern margin of the CP can be a source of magmatism. This is consistent with the conclusion that the interaction of Basin and Range extension with the resistive keel of the Colorado Plateau controls the location of deformation and melt production (Wannamaker et al., 2008). Shear heating at the base of the lithosphere can explain the magma source region and erosion of the keel can account for migration patterns of volcanism within the SFVF.

At a local scale, the SFVF has a butterfly shaped negative gravity anomaly, with the positive anomaly beginning at the northern end of the silicic San Francisco Mountain. The speckled pattern in the map in Figure A1 is an artifact of the wide station spacing, as each small scale anomaly corresponds to a single data point in the west and northeast of the field. Figure A2 shows the local gravity anomalies without these station spacing based artifacts. The southwest to northeast linear patterns of these local gravity anomalies correspond with the southwest to northeast migration of volcanism within the SFVF (Tanaka et al., 1986). The positive anomaly indicates buried dense material, in this case interpreted as a crystalline intrusion and the source of recent volcanic activity. The most recent eruption was located at Sunset Crater, just south of the western margin of the positive anomaly (Figure A2). It is possible that since the formation of Sunset crater in
1085 AD (Ort et al., 2002), the magma source has migrated 20 km to the north. The highest magnitude gravity value is situated below Vent 5831, which extruded a lava flow dated at 0.22 +/- 0.05 Ma (Ulrich and Bailey, 1987). Though the field has been active for approximately 6 million years (Duffield et al., 2001), this lava flow is still older than many in the field and this area may be the site of renewed volcanism in the future.

The excess mass of the aforementioned positive anomaly was calculated based on a background value of -174 mGal. Therefore the excess mass calculations include all positive anomalies in the region, including the linear extension to the southwest. The resulting excess mass is $6.52 \times 10^{12}$ kg. The mass deficit modeled from the negative anomaly matching clusters of basaltic vents is $2.51 \times 10^{14}$ kg based on a background value of -190 mGal.

The regional magnetic data does not display strong correlation with the transition zone boundaries. In fact, positive magnetic anomalies appear to be randomly scattered around the mapped area. There is a very strong anomaly within the transition zone, but the magnetic value is so high compared to the surrounding areas that it is regarded as being influenced by some highly magnetic man-made material on the ground. Some of the local magnetic highs correspond to silicic centers (outlined in Figure A1) such as Howard Mesa, San Francisco Mountain, and Hochderffer Hills, but the other silicic centers show no positive anomaly. The remaining positive anomalies do not appear to correspond to silicic vents or clusters of basaltic vents. Therefore the magnetic data does not aid in understanding the transition zone between the BRP and CP as a source of volcanism.
Conclusions

1) The gravity profile of north-central Arizona correlates with the BRP-CP transition zone.

2) The magnetic profile does not obviously correlate with the transition zone, but anomalous areas do correlate with some silicic vents in the SFVF.

3) The excess mass due to the positive gravity anomaly at the volcanic field is $6.52 \times 10^{12}$ kg, interpreted as the current location of magmatic source of SFVF volcanism.

References


Appendix B: Full list of measured basaltic lava flow thicknesses

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Appendix C:
Volcanic Event Annex Prepared for the Arizona Department of Emergency Management

Introduction

Purpose

The purpose of the Volcanic Event Annex is to establish a coordinated framework of response in the case of a volcanic event affecting the State of Arizona. This Annex identifies State organizations responsible for volcanic hazard assessment, response, and recovery, and facilitates preparedness for the response to and recovery from volcanism in the American Southwest. This Annex is written to complement existing State emergency management plans.

Scope

This incident annex is applicable to state agencies with volcanic event response and recovery roles. Certain state agencies that are not identified here may also be called upon to provide support. This Annex does not address mitigation measures or policies, programs or procedures that may be implemented prior to a State of Emergency Declaration or an ADEM coordinated response.

In order to achieve the goal of coordinated response and recovery, the following objectives are outlined:

- Establish efficient protocols for a warning system and for coordinating emergency
management roles;

- Initiate the process of communication to responsible agencies and relaying pertinent information to the public;

- Ensuring the process of declarations is transparent and that declarations are made as necessary;

- Prioritizing the allocation of resources in the event of a volcanic eruption.

Planning Assumptions

Introduction

This section contains an explanation of two volcanic scenarios affecting the State of Arizona. One is an eruption in the San Francisco Volcanic Field (SFVF) located between Flagstaff and Grand Canyon National Park. The second scenario involves a large magnitude eruption located outside of the State whose hazards extend across state lines. The volcanic areas within and surrounding the State have little to no monitoring systems in place, therefore response plans must compensate for unpredictable and long-term volcanic eruptions. An understanding of the following two representative scenarios allow for a better planning and response framework to be established.

Scenario 1: SFVF Eruption

The SFVF lies on the southwest margin of the Colorado Plateau and consists of roughly 600 volcanoes over 1,800 square miles, most notably SP Crater in the north, Sunset Crater in the east, and the silicic San Francisco Peaks in the center
of the volcanic field. Volcanism in the SFVF is monogenetic, meaning each vent erupted for a single time period (weeks to years), after which activity at that vent ceased and renewed volcanism formed new vents. These vents progress from oldest in the southwest to youngest in the northeast, although this progression is by no means regular. The field has been active for about 6 million years, and the most recent eruption occurred at Sunset crater approximately 900 years ago. Though 900 years is a long time on a human time scale, geologically, it is negligible and the SFVF is considered active. It is common for people to underestimate this risk or misinterpret the probability, yet for low probability-high impact events, it is best to take necessary precautions in the case that volcanic activity begins tomorrow. For this reason, a response framework regarding volcanic risks id addressed in this Annex.

Hazards

The following summary of potential hazards associated with a volcanic event in the SFVF includes descriptions of the hazards and their potential effects on infrastructure. It is important to recognize that volcanic eruptions are complex processes with a variety of associated hazards, and that unlike a flood or storm, though the initial eruption causing the most devastation may last for months, the total time of the eruption may last for decades. Some or all of these hazards may occur without warning, though an eruption will likely be preceded by days to weeks of precursors, such as volcanic earthquakes or degassing at the vent. The
table below (Table A1) addresses the screening distances and impact levels on the ground. Hazards are listed in order of decreasing risk.

1) Crater, Cone, or Ring Formation: The formation of a new volcanic vent with steep sided rim and central crater. Will destroy all infrastructure at the site of the vent and adjacent to it. May disrupt communication lines, power, water supply, highways, or sewage lines.

2) Volcanic Gas: CO, CO$_2$, and HF may escape from an active vent, as well as SO$_2$, which may cause acid rain. May cause corrosion downwind, damage to vegetation, and health problems for residents.

3) Pyroclastic Density Current: Hot gas and ash (1,000 °C or 1,830 °F) that flows very rapidly (up to 450 mph) outward from the vent along the ground, particularly in topographic lows. Will destroy any infrastructure in path, and result in damage or burial of structures for up to 5 miles.

4) Lava Flows: Hot streams of molten rock (700-1,200 °C or 1,292-2,192 °F) that flow along topographic lows. Will burn or bury everything in its path, including any structures, communication lines, power lines, water supply, and wastewater. May explode with water on contact and result in fires or obstructions. May be repeated over several days to weeks after initial volcanic event.

5) Fire Fountaining: Sprays of lava from the volcanic vent, can reach hundreds to thousands of feet into the air. Will burn or damage any
infrastructure near vent, and may lead to fires on ground or in underground networks. May be repeated over several days to years after initial volcanic event.

6) Lava Bombs: Hardened volcanic material greater than 3 inches wide ejected up and out of the vent following a ballistic trajectory. All nearby infrastructure at risk of impact damage. May be repeated over several days to weeks after initial volcanic event.

7) Debris Flows: Fast moving (up to 35 mph) flows of debris, sediment, and water that move downhill carving and following topographic lows. Will bury or destroy any infrastructure in path for up to 3 miles from the vent. May be triggered if a lava flow dams a creek or stream.

8) Ash Fall: Known in volcanology as “tephra fallout”. Dust to baseball sized pieces of rock that fall to the ground from eruption clouds and are highly influenced by prevailing winds. May lead to abrasion to structures and roof collapse. Generators and air conditioning susceptible to damage. May cause widespread transportation closures.

9) Volcanic Earthquake: Ground shaking due to movements of magma upward through the Earth’s crust before and during a volcanic eruption. Will cause damage to structures near vent or built on low strength soils or man-made ground.

10) Volcanic Lightning: Lightning produced within the ash plume. May result in property damage or death.
Table A1. Hazard Matrix adapted from the Contingency Plan for the Auckland Volcanic Field

**Local Effects**

Though the initial eruption is most devastating and may last for months, the total time of an eruption may last for years to decades. The impacts of a volcanic event in the SFVF can affect physical infrastructure, local
economy and society, and political climate. The following list is not meant to be an exhaustive list, rather a general guide for the potential impacts of a volcanic event.

- Disruption to transportation infrastructure including damage or ash fall upon roads, highways, airports, electricity supply, or sewage networks
- Damage to machinery due to ash fall
- Displacement of residents and businesses, and subsequent economic loss to local businesses and psychological impacts on residents
- Health issues related to volcanic gases and ash fallout
- Permanent loss of land use
- Death of grazing animals
- Destruction of agriculture
- Forest fires
- Requirements for ash removal
- Loss of local tourism to cities and parks, though there may be an addition of volcano tourists
- Rise in insurance premiums
- Temporary or permanent loss of land use
- Long term disruptions to society and daily life
National Effects

The national effects of a volcanic event may include the following:

- Loss of use of the Phoenix airport as a major travel hub

- Effects on coast-to-coast air travel across Arizona (and neighboring states) airspace

- Damage to the Hoover Dam, leading to disruptions of water supply and electricity to Nevada, Arizona and California

- Need for National support and resources

Scenario 2: Eruption outside of Arizona

The potential sources of high impact volcanic activity outside of Arizona include Valles Caldera in New Mexico, Yellowstone Caldera in Wyoming, Long Valley Caldera in California, or Pinacate and Colima volcanoes in Mexico. Caldera eruptions occur when a large magma chamber is drained from a volcanic eruption, causing the volcano to collapse into itself. The hazards and impacts of such an event are of large scale and would affect a large portion of the continental United States. As such, thinly spread national funds and resources must be expected.

Hazards

The greatest hazard from a Scenario 2 event affecting the State of Arizona is ash fallout. Larger magnitude eruptions are associated with more fragmented ejected volcanic material and further dispersal of such material. Also, a significant caldera eruption has the potential to produce several hundred cubic miles of ash,
which is carried through the atmosphere for hundreds of miles. This will lead to a blanket of ash several inches thick to cover the State and could lead to roof collapse due to the added weight, respiratory problems for Arizona residents, as well as total disruption.

Local Effects

The main local concerns of a large eruption outside of Arizona would likely be limited to those associated with tephra fallout, specifically:

- Damage to structures
- Damage to electric and communications networks
- Temporary road, highway, railway, and airport closures
- Contamination of water supply reservoirs
- Blocking of drainage networks
- burial of crops and other agricultural land
- Respiratory health problems for residents
- Potential for accidents resulting from decreased visibility

National Effects

- Regional displacement of U.S. citizens
- Widespread destruction of agriculture
- Disruption of food supplies
- Ash cover throughout the State
- Halt to American air travel for weeks to months
- Disruption to major West Coast port activity
- Lowered temperatures contributing to a volcanic winter for several years
- Need for thinly spread National support and resources

Issues facing prediction

The following present issues for creating a contingency plan:

- The exact site at which volcanic activity will occur cannot be predicted, and the possibility of activity at multiple vents does exist;
- The warning signs before a volcanic event will be short-lived: for weeks at best, but potentially starting only several hours before the event;
- The volcanic areas of the American Southwest have minimal to no monitoring systems in place;
- The hazards associated with a volcanic event can occur over a long time period (months to a year or more) making recovery difficult;
- Volcanic activity can lead to other hazards varying in severity and geographic range.
Figure A4. Locations of volcanic centers in Arizona, colored by age of volcanic rocks. The most recent volcanic activity is located on the southern margin of the Colorado Plateau.
Concept of Operations

The primary index used for determining volcanic intensity is the Volcanic Explosivity Index (VEI). The Volcanic Explosivity Index measures eruption intensity by accounting for the volume of tephra ejected from the vent, the height of the ash column, as well as eruption type and duration. VEI does not encompass volume or extent of lava flows, which would be a predominant hazard in the case of a Volcanic Event in the State of Arizona. The index increases in explosivity from 0 to 8, with each VEI value being an order of magnitude higher than the previous value. In human history, no VEI 8 eruptions have been recorded; however, geologic data indicate that VEI 8 eruptions have occurred in the past. Table A2 shows the criteria for VEI assignments.

Table A2: Volcanic Explosivity Index Classification System

![Table A2: Volcanic Explosivity Index Classification System](http://www.volcano.si.edu/world/eruptioncriteria.cfm#VEI)