Geophysical Evidence for Mid-crustal Magma Reservoirs in the Lassen Volcanic Region, California

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Geophysical Evidence for Mid-crustal Magma Reservoirs in the Lassen Volcanic Region, California

by

Samantha C. Kinman Tavarez

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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Date of Approval: October 29, 2015

Keywords: gravity, magnetotelllourics, volcanism, Lassen, hazards, modeling

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Acknowledgments

I would like to thank my thesis advisor, Dr. Charles B. Connor, for his expert advice, guidance, and leadership throughout the course of this entire research project. Thank you to my committee members, Dr. Sarah Kruse and Dr. Rocco Malservisi, for their patience and support as I worked to prepare this thesis. I would also like to extend my sincerest gratitude to Laura Connor for the use of some of her wonderful Perl scripts, as well as all the help that came along with them.

None of this would have been possible without the unending presence and encouragement of my family and friends. I would like to thank, first and foremost, Jeremiah Smith. Your unwavering love and emotional support is an enormous part of why I was able to see this through to the end. For that, I love you and am forever grateful for your patience and compassion. To our daughters, Jiana and Serenity, I love you both very dearly and always will. I am also incredibly grateful to my parents, Dave and Margie Kinman, who have always believed in me and supported my dreams and academic pursuits. Finally, thank you to Anita Marshall, Lis Gallant, Ophelia George, Cassandra Smith and Jacob Richardson for creating the greatest, most helpful office environment a fellow graduate student could ask for. I certainly could not have made it through several of these notorious, hair-pulling days without you and all the laughter.
Table of Contents

List of Tables .................................................................................................................................. ii  
List of Figures ................................................................................................................................ iii  
Abstract. ...........................................................................................................................................v  
Chapter One: Introduction ...............................................................................................................1  

Chapter Two: Review of the Literature ..........................................................................................7  
  The Cascadia Sduction Zone .....................................................................................................7  
  Lassen Region: Tectonic Setting and Scales of Volcanism .......................................................9  
  Potential Volcanic and Seismic Hazards ..............................................................................11  
  Previous Gravity Studies in the Cascade Range ..................................................................13  
  Distribution of Magmatism: The Hot Fingers Model ..........................................................22  
  Model for Magma Genesis: Deep Crustal Hot Zones ......................................................23  
  Magnetotelluric Studies in the Lassen Volcanic Center ....................................................25

Chapter Three: Modeling Gravity Data in Oasis Montaj / GM-SYS ..............................................43  
  Methods and Results: Gravity Modeling ...........................................................................43  
  Model and Anomaly Sensitivites .......................................................................................46

Chapter Four: Excess Mass Calculation ...........................................................................................51  
  Methods and Results: Gauss's Law and Excess Mass ......................................................51

Chapter Five: Discussion & Interpretation ......................................................................................61  
  Discussion & Interpretation of Results ..............................................................................61  
  The Hot Fingers Model ......................................................................................................63  
  The Deep Crustal Hot Zone Model ...................................................................................64

Chapter Six: Conclusions ...............................................................................................................71

Chapter Seven: Recommendations ..................................................................................................72  
  3D Modeling ......................................................................................................................72

References ......................................................................................................................................73
List of Tables

Table 3.1: Gravity model density values .................................................................49
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Bouguer gravity anomaly map of the central-southern Cascade volcanic arc</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Plate Tectonics map of the Cascade volcanic arc</td>
<td>30</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Lassen Volcanic Center hazards map</td>
<td>31</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Aerial View of Lassen Peak</td>
<td>32</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Aerial View of Chaos Crags domes</td>
<td>33</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Southern Cascades gravity and magnetic anomalies</td>
<td>34</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Medicine Lake volcano Bouguer gravity profiles</td>
<td>35</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Volcano locations of southern Oregon and northern California</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Southern Cascades fault orientations and patterns</td>
<td>37</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>Bouguer gravity profile along the Japan Sea Coast</td>
<td>38</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Conceptual illustration of the Hot Fingers model</td>
<td>39</td>
</tr>
<tr>
<td>Figure 2.11</td>
<td>Conceptual illustration of the Hot Zone model</td>
<td>40</td>
</tr>
<tr>
<td>Figure 2.12</td>
<td>Magnetotelluric model summary interpretation</td>
<td>41</td>
</tr>
<tr>
<td>Figure 2.13</td>
<td>Lassen magnetotelluric study profile (map view)</td>
<td>42</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Magnetotelluric and gravity profiles</td>
<td>47</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Lassen gravity model</td>
<td>48</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Lassen prominent gravity low</td>
<td>50</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Lassen region gravity anomaly map (isolated low)</td>
<td>55</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Isolated gravity low around Lassen Peak</td>
<td>56</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Lassen gravity model aligned with gravity profile</td>
<td>57</td>
</tr>
</tbody>
</table>
Figure 4.4: Approximate shape and dimensions of Lassen body (a) .............................................. 58
Figure 4.5: Elliptical cylinder (volume and excess mass calculation) ............................................. 59
Figure 4.6: Simple ellipsoid (volume and excess mass calculation) .............................................. 60
Figure 5.1: Gravity anomaly map of the southern Cascade volcanic arc ........................................ 68
Figure 5.2: Conceptual illustration of the Hot Zone model ............................................................ 69
Figure 5.3: Estimated model body geometries ............................................................................. 70
Abstract

Regional-scale complete Bouguer gravity anomalies underlying the Lassen and Shasta-Medicine Lake regions in northern California and southern Oregon are associated with subduction of the Gorda plate beneath North America. These generally negative anomalies reflect where underplating has deepened to form the mantle wedge, and where subduction has given rise to a series of Quaternary volcanoes comprising the southernmost end of the Cascade range. Multiple conductive bodies were identified by Park and Ostos (2013) in their magnetotelluric (MT) study of the broader Lassen volcanic region. Their broadband and long period measurements were conducted along a 250 km profile spanning from the California-Nevada border, to just west of the Great Valley in California. Utilizing their MT conductor geometries as a starting point, a forward gravity model was generated along the same profile, and agrees well with what they interpret to be the locations and depths of mid-crustal magma bodies in the Lassen and surrounding regions. The excess mass and volume of modeled anomaly (a) - most closely attributed to underlying Lassen Peak - were estimated at \(-2 \times 10^{14}\) kg and \(7 \times 10^{11}\) m\(^3\), respectively.
Chapter One:
Introduction

Developing an understanding of relationships that exist between earth's crustal structure and the magmatic evolution of volcanic systems is crucial to the refinement of probabilistic volcanic hazards models and the progression of successful hazards mitigation on a global scale. According to 2009 World Bank population data, it is estimated that a minimum of 600 million people reside within range of negative exposure to active or potentially active volcanoes (Auker, et al., 2013). In order to mitigate volcanic risk for such a large population, we must first improve our understanding of the distribution of magma source regions within the mantle and crust, including where partial melts originate, and the means by which magma is transported from source region to the surface.

The evolving nature of volcanic systems creates one of the greatest challenges in hazards assessment. Spatial correlations amongst various features, such as crustal manifestations of stress, faults, volcanic vents, geothermal systems, and high and low seismic velocity zones provide the main clues about where magma is and how it is transported through the lithosphere. Probabilistic hazards assessments should account for - or, at very least, be consistent with - the manner in which these observed correlations reflect of the dynamic properties of the Earth's crust and upper mantle.
(Blakely, et al., 1997). In addition to these spatial correlations, there is a complex interplay between volcanism and tectonism over time. For example, active tectonics may create crustal structures that persist into the future and act as controls on magma migration and ascent. Likewise, subduction triggers changes in the mantle over a long period of time, suggesting that partial melting may well persist even after subduction has ceased.

In this thesis, my interest is to explore the complex spatial relationships that exist between magma source regions, volcanism and crustal structure in the Lassen volcanic region, northern California (Figure 1.1). Specifically, my objective is to utilize gravity data, sensitive to the abovementioned structural features, as a means of furthering our understanding of magma generation and transport in the Lassen region. I accomplish this by first isolating the regional versus residual gravity field. I show that a $2^{\frac{1}{2}}$D gravity model of the lower crust in the broader Lassen volcanic region can be developed from these data, and furthermore, that it demonstrates consistency with magnetotelluric (MT) data and models. I calculate the excess mass of a lower crustal body appearing to most directly underlie Lassen Peak near the MT survey line, and compare it with the modeled mass distribution. Using these methods as a means to generate discussion of the implications for the Lassen magma source region, and to improve our understanding of spatial relationships among crustal features, I hope to help improve probabilistic volcanic hazards models on a global scale.

As demonstrated in the following chapters, using the Park and Ostos (2013) MT model summary interpretation as the starting model for the large-scale structure of the
lithosphere, I was able to construct a residual gravity model that suggests the presence of multiple lower crustal intrusive bodies of varying density, along the same 250 km profile. Beginning approximately 100 km west of Lassen volcanic center, this extensive MT line traverses Quaternary to Holocene volcanism including - and extending to the east of - Lassen Peak, Hat Creek, and Poison Lake (Park and Ostos, 2013). The reason for the extent of the profile is to ensure the most complete picture of the mid-to-lower crustal region above the subducting slab. This includes having the ability to make observations about transitions in subsurface geometry from above the subduction zone, well into the Basin and Range.

The gravity data utilized in my research was obtained from the online Gravity Database of the U.S. at the University of Texas at El Paso (UTEP, 2015). All data points in the survey were collected from ground-based stations throughout the northern California and southern Oregon regions. The resulting map (Figure 1.1) is based on the complete Bouguer gravity anomaly and contains several general features related to overall subduction zone geometry and crustal structure. Generally positive gravity anomalies are observed to the west where dense crust underplates the North American plate at the subduction zone. General negative anomalies in the east are reflective of where this underplating deepens and forms the mantle wedge. Prominent regional gravity lows associated with Lassen, Shasta-Medicine Lake, and (to a lesser extent) Crater Lake can be seen in this southern portion of the Cascade arc. It is postulated that crustal thickness varies from north to south along the entire Cascade arc, with an approximate thickness range of 43-46 km in the southern end of the Cascades range.
(Das and Nolet, 1998; Mooney and Weaver, 1989). There is also a prominent visible north-to-south transition along the arc where initial underplating is occurring to the west. The generally positive westward anomalies previously mentioned become markedly more positive north of approximately 42° latitude. This is indicative of the where the border lies between the actively subducting Gorda and Juan de Fuca plates, to the south and north, respectively.

Using a fast Fourier Transform (FFT) filter on my data set, I was able to isolate the residual gravity anomaly near Lassen Peak (LP). Using Gauss's Law and numerical integration of the gridded gravity data across the area, I calculated an excess mass attributed to the body that appears to most directly underlie Lassen Peak along the MT line. I was then able to compare this excess mass to the modeled mass distribution.

My methods were largely based on the work of Carol Finn and colleagues (1982), who published gravity research on Medicine Lake volcano, located just north of Lassen Peak. They identified a 27-mgal positive residual gravity anomaly and considered this to be evidence for a shallow intrusion of dense igneous rocks beneath the volcano. Prior to quantitatively estimating the source of the anomaly, they employed constraints from MT soundings to corroborate the presence of a resistive body approximately 1.5 km beneath the caldera. Based on its position, the resistive body was ascribed as a plausible source body for the gravity anomaly, and its excess mass was determined to be 2.0 x $10^{14}$ kg (Finn and Williams, 1982). Due to some broad similarities between Lassen and Medicine Lake on a regional gravity scale, such as the ability to correlate MT and
gravity models, I adopted the same approach taken by Finn and Williams (1982) to consider magmatism beneath Lassen volcano.

Calculating excess mass from gravity anomalies is an important means of quantifying large-scale features in the crust, such as the volume of intrusions. In essence, excess mass tells us about the mass discrepancy between a body of interest, and the total mass of surrounding country rock that would otherwise fill the space it occupies. By improving our knowledge regarding potential sizes, shapes and dimensions of bodies within magmatic systems, we hope to better understand the evolution of those systems and the potential hazards they impose.
Figure 1.1. Gravity anomaly map showing locations of Cascades Range volcanoes from central Oregon to northern California. The primary area of interest in this thesis surrounds Lassen Peak, which is located in the southeast corner. Volcano locations are indicated by small white triangles. Small black dots are gravity stations.
Chapter Two:

Review of the Literature

The Cascadia Subduction Zone

The west coast of North America is characterized by its tectonic complexity, particularly along the Cascade Arc spanning from southern British Columbia into northern California. In the Oligocene, what remained of the Farallon plate completed its fragmentation into the three smaller remnants now known as the Explorer Plate (to the north), the Juan de Fuca plate (off the Washington and Oregon coasts), and the Gorda plate (to the south) (Figure 2.1). Today, these three remnants are collectively seated between the Pacific plate (to the west) and North American plate (to the east) (Govers & Meijer, 2001; Stock & Lee, 1994).

At present, this complex system of plates, transform faults, and subduction is referred to as the Cascadia Subduction Zone (CSZ). The Juan de Fuca and Gorda plates are both currently subducting beneath North America in a generally oblique, northeasterly direction; the former converging at a rate of approximately 40 mm/yr toward N50E. Over the last 7 million years, this rate of convergence has actually experienced a steady decrease of 20-30 mm per year (to its current, abovementioned rate) (Swanson et al., 1989).
Approximately 35 Ma, the rate of volcanism throughout the Cascade Range was markedly higher than in more recent history, likely due to higher rates of plate convergence in the Paleogene (Priest, 1990). A deformational event taking place around 25 Ma caused regional tilting and faulting, as evidenced in the rocks of the surrounding region (Priest, 1990). Approximately 16.9 Ma, the decreasing rate of convergence contributed to a subsequent, distinctive decrease in volcanism, but only until about 7.4 Ma. According to Priest (1990), the level of stress on the upper plate may have been the catalyst for a slight upswing in the rate of volcanism around this time.

To the west, spreading along the Juan de Fuca ridge continues to contribute young oceanic lithospheric material to the Juan de Fuca plate being fed into the Cascadia Subduction Zone (Hyndman and Hyndman, 2010). With an approximate 25 to 35 mm/yr half spreading rate, it is estimated that material reaching the subduction plate boundary is a maximum of 11 million years old (Govers and Meijer, 2001).

The ongoing subduction and partial melting of the Juan de Fuca and Gorda slabs beneath the North American plate have produced a series of Quaternary volcanoes that comprise the Cascade Range (Rogers, 1988; Priest, 1990). Extending approximately 1,300 km in total length, this arc consists of a multitude of stratovolcanoes that average over 3,000 meters in elevation, as well as nearly three thousand other volcanic features ranging from broad shield volcanoes to smaller scoria cones (USGS, 2015). A notable increase in basaltic composition is observed from north to south over the length of the range, and as a result, significantly fewer andesitic to dacitic rocks are found in the southern part of the range (Swanson et al., 1989). Although there have been multiple
periods of known eruptive activity throughout the entire history of the Cascade Range, it is the southern end - Lassen Volcanic Center, in particular - that is the primary focus of this study (Figure 2.2).

Lassen Region: Tectonic Setting and Scales of Volcanism

Straddling the southern cusp of the Cascade arc, above the subducting Gorda plate, the Lassen volcanic region is characterized by two distinctive scales of volcanism since 7 Ma (Guffanti and Weaver, 1988; Clynne, 1990; Guffanti et al., 1996; Clynne et al., 2012). From a regional perspective, eruptive activity is generally non- to weakly-explosive and attributed to hundreds of small, clustered, scoria cones. These are interspersed with larger shield volcanoes and steep-sided lava cones. (Clynne et al., 2012).

The most abundant regional-scale volcanoes are monogenetic scoria cones, which are typically accompanied by base-erupted, low-volume lava flows. The larger shield volcanoes and lava cones amassed by eruptions from central or high edifice flank vents have a resulting slope that's heavily dependent on effusion rate and the viscosity of the erupted material (Clynne et al., 2012; Kilburn, 2000; Walker, 1973). These larger volcanoes experience intermittent episodes of activity that range in duration from decades to a number of millenia, and can accumulate total edifice volumes of as much as a few cubic kilometers (Clynne et al., 2012).

There are fewer, substantially larger and longer-lived intermediate to silicic volcanic centers superimposed on the aforementioned broader regional volcanic
platform. (Guffanti et al., 1996; Clynne et al., 2012). These focal centers denote locations of prolonged magmatism along the southernmost segment of the Cascade arc (Clynne et al., 2012). Volcanism on this scale is divergent from the other, particularly in terms of composition, lifespan, and substantially larger volume. There are five identifiable volcanic centers along this sector of the arc, all of them less than ~ 3.5 MY in age. Lassen Volcanic Center (LVC) is the youngest of these, and is currently active with continuing silicic volcanism and a complex hydrothermal system. (Clynne et al., 2012).

Active vents within the LVC, unlike the archetypal composite vents found elsewhere in the Cascades, are comparatively widely distributed. They span a total area of upwards of 25 km east-west by 20 km north-south (Clynne et al., 2012). Over the last 825,000 years of activity within the Lassen Volcanic Center, there have been hundreds of eruptive events that have taken place. At least 14 of these have occurred over the last 100,000 years (Clynne et al., 2012).

A number of volcanic hazards have historically accompanied eruptive events in the LVC, including the emplacement of lava domes and flows, tephra fallout and destructive lahars. Despite the LVC apparently maintaining a state of relative quiescence for approximately 25,000 years, three eruptions within the last 1,050 years have demonstrated that it is still active. The most recent eruptions between 1914 and 1917 (Figure 2.3) consisted of relatively small explosive episodes. The last large-scale event (around 1,050 years ago) resulted in the emplacement of the Chaos Crags (Figure 2.4) - a cluster of silicic lava domes and associated intermediate tephra deposits north of Lassen Peak (Clynne et al., 2012; Heiken & Eichelberger, 1980).
The likelihood of an eruptive event within the Lassen Volcanic Center is relatively minor within a given year (odds of approximately 1 in 7,000). However, the potential hazards associated with future activity could have substantial regional significance (Clynne et al., 2012). The annual odds of an eruption occurring within the surrounding region are higher than they are directly within Lassen Volcanic Center (about 1 in 2,000). Considering that regional volcanism predominantly involves less explosive basaltic magmas, however, the associated hazards would likely be less severe in comparison (Clynne et al., 2012).

Potential Volcanic and Seismic Hazards

Past patterns of activity in the broader region surrounding Lassen Volcanic Center suggest the most probable type of future eruption is a short-lived (weeks to months) strombolian to violent strombolian eruption leading to the formation of a small-volume mafic volcano. This could involve the formation of a cinder or spatter cone, as well as lava flow(s) that reach a few tens of kilometers away from the vent. Periodic explosions could potentially cause the ejection of hot lava blocks that impact the ground near the vent. The protrusion of ash clouds likely to reach ~10 km into the atmosphere would impact areas on the ground <100 km downrange. The majority of ash accumulation would be within a 10 km radius, and consist of more than ~5 cm thickness. The dispersion of markedly smaller amounts of ash could extend as far as ~100 km downwind, though the volume dispersed would not likely impose a direct threat to buildings and infrastructure at this distance from the vent. Both military and
commercial air traffic would potentially be affected. Implicitly more hazardous than tephra dispersion, however, is the potential for fluidized lava flows reaching tens of kilometers out from the vent and covering up to 100 km² in area. (Clynne et al., 2012).

More explosive future eruptive activity possible within the LVC is associated with silicic volcanism. Sporadic steam explosions preceding the main phase of eruption would likely expel large, cold-rock ballistics near the vent. The magmatic [main] phase would produce a vertical eruption column extending possibly >10 km in height, which would have even more extensive impacts on both military and commercial aviation. A partial collapse of said column would generate violent pyroclastic flows and/or surges capable of traveling tens of kilometers down valleys around the volcano. The extent of resulting ash fallout and dispersion would be substantially greater than in the case of less explosive, mafic volcanism. The proliferation of lava flows and/or lava domes is another possibility, via effusive (non-explosive) eruption persisting anywhere from months to years. Pyroclastic flows and surges, again, become a potential hazard in the case of the partial collapse of lava domes that don't maintain stability (Clynne et al., 2012).

The high elevations of peaks within the Cascade Range means they are often covered in ice and deeply packed snow. This creates the potential for massive lahars triggered by a combination of rapid melting, loose sediments and steep gradients. Freshly deposited ash is also susceptible to rapid erosion with heavy rainfall, which can trigger fast-moving lahars by remobilizing thick ash and pyroclastic flow deposits. A small rain-fall induced lahar of this type actually occurred along the lower slopes of
Lassen Peak in 1963. Unfortunately, these gravity driven events don't require volcanic eruption to be activated, and can have incredibly devastative effects that are far-reaching over many kilometers down-slope (Clynne et al., 2012).

Although Lassen Peak is the largest edifice within the LVC, it is small compared to many of the other Cascade composite volcanoes in the range. It has no glaciers, and only one small permanent snow field. For this reason, the expected size of lahars at LVC is less than what might occur elsewhere. Evidence for lahars does appear to be sparse in the geologic record at LVC, but this is likely due to the effects of glaciation that may have effectively obscured events prior to 15,000 years ago (Clynne et al., 2012).

There are a number of other potential hazards associated with volcanism in the Lassen volcanic region. Amongst these are landslides and rock-falls attributed to extensive hydrothermal alteration of materials in the vicinity of Lassen Peak. Abundant fumaroles and mudpots pose a risk in their ability to release toxic gases and/or cause severe burns. Seismic activity is another source of concern due to the underlying tectonic setting, including a number of major faults in the surrounding area that are deemed capable of moderate to large (up to magnitude 7.0) earthquakes (Clynne et al., 2012).

Previous Gravity Studies in the Cascade Range

In 1936, a north-trending, east-facing fault scarp forming the structural boundary between the High and Western Cascades in Oregon was proposed and named the “Cascade fault” by T.P. Thayer (1936). The surface expression of the inferred Cascade
fault, however, was largely buried by eastern Cascade volcanism when subsequent
movement along it triggered 600 meters of uplift of the Western Cascades relative to the
eastern block. A second fault, approximately 30 km east, also north-trending, down-
dropped to the west, and parallel to the original Cascade fault was later proposed by
volcanoes are all housed within the resulting graben, whose trend fluctuates to the
southeast to exclude Mount McLaughlin (Allen, 1965; Blakely et al., 1985).

Couch and colleagues (1981, 1982) analyzed residual Cascades gravity data, from
which they interpreted the presence of a narrow, north-trending minimum extending
from the Columbia River to almost the Oregon-California border (Blakely et al., 1985;
Couch et al., 1981, 1982). This minimum is approximately coincident with Allen’s (1965)
graben, however, it is only just west of Three Sisters and Mount Jefferson. Couch and
colleagues proposed the aforementioned as indicative of either a major fracture or
brecciated fault zone (Blakely et al., 1985; Couch et al., 1981, 1982).

Blakely and colleagues (1985) upwardly continued gravity data in the same
region of the Cascades and were able to describe the regional characteristics of the
anomaly initially identified by Couch and others. In their subsequent gravity studies,
they were able to ascertain that Three Sisters, Crater Lake, Mount McLaughlin, Mount
Shasta, and Medicine Lake volcanoes are all located along the edge of a 370 km long,
north-trending gravity depression (Blakely et al., 1985). Furthermore, its position in
Oregon coincides with the buried graben proposed by Allen in 1965, with the exception
that it does, in fact, also encompass Mount McLaughlin (Blakely et al., 1985).
In addition to the positioning of these volcanoes, Blakely and colleagues were able to discern that Lassen Peak also sits in a gravity depression separated from the abovementioned primary depression by an east-trending gravity high at a latitude of approximately 41°10’N (Figure 2.5). The important commonality here is that all of the volcanoes in the study were determined to be positioned along the edge of gravity minima (Blakely et al., 1985; Blakely et al., 1997).

The original reduction density assumed by Blakely and colleagues for topographic features in their data processing was 2670 kg/m³. They realized this left some room for argument that their inferred graben and local gravitational depressions might only be artifacts of the data reduction. Working on the notion that their initial reduction density might be too high for typical Cascades volcanic rocks, they reprocessed and upwardly continued the same gravity data set using reduction densities of 2430 and 2280 kg/m³. In all cases, the features originally described were preserved. This corroborated their supposition that the gravity minima described were not merely a result of improper Bouguer density selection (Blakely et al., 1985). Ultimately, Blakely and colleagues proposed that each of the gravity minima actually reflect the subsidence of substantial volumes of low-density volcanic material, and that the positioning and formation of the volcanoes along perimeter faults is related to where magma most easily propagates toward the surface (Blakely et al., 1985).

With the exception of Medicine Lake, all of the active volcanoes included in the study by Blakely et al. (1985) were determined to be positioned near the southern end of their respective gravity depressions (Figure 2.5) (Blakely et al., 1985). In an earlier study
of Medicine Lake with David Williams, however, Carol Finn (Finn and Williams, 1982) conversely described a positive residual gravity anomaly associated with shallow intrusion of dense material emplaced within a several kilometers thick older volcanic layer underlying Medicine Lake volcano. After visually separating the gravity high from the regional low, Finn and Williams were able to fit a 27 mGal positive residual anomaly with what they inferred to be a large (2.5 km in thickness), shallow body of high density contrast (+410 kg/m$^3$) (Finn and Williams, 1982).

Through their analysis of the Medicine Lake topographic profile accompanied by a series of corresponding Bouguer gravity profiles reduced at different densities, Finn and Williams determined a reduction density of 2200 kg/m$^3$ to be most appropriate. This was based on their observations of how the amplitude and shape of the gravity signal would change with varying reduction densities (Figure 2.6). They observed very little change within small range of 2200 kg/m$^3$ (say, ±100 kg/m$^3$). Any further deviation from this value led to blending of the gravity high with topographic effects, which notably altered the principal shape and amplitude of the anomaly (Finn and Williams, 1982).

When modeling gravity data, the separation of regional and [localized] residual anomalies is also crucial. Finn and Williams utilized different methods to accomplish this anomaly separation, but ultimately “visually” removed the Medicine Lake high from the regional field and extended regional contours through the surrounding region. In light of the subjective nature of the visual method, Finn and Williams additionally calculated a regional field using a second-order polynomial surface fitted to the gravity
data. Their determination was that the basic shape of the Medicine Lake residual wasn’t significantly changed (Finn and Williams, 1982).

Prior to quantitative assessment of the source of the positive anomaly at Medicine Lake, Finn and Williams chose to look to other methods to minimize uncertainty. Gravity alone provides useful source information, but can also leave room for multiple viable interpretations about the underlying configuration. For this reason, they examined the work of Stanley (1982) and his magnetotelluric (MT) soundings that show a resistive body (>100 ohm/m) located approximately 1.5 km beneath the caldera. Finn and Williams considered the location and depth of the MT anomaly to be a plausible source body for the Medicine Lake gravity anomaly. By incorporating the geologic and MT data, they were able to estimate a thickness (2.5 km) and vertical extent of the proposed source body. This enabled them to subsequently constrain the gravity model and calculate an excess mass of $2.0 \times 10^{14}$ kg (Finn and Williams, 1982).

Finn and Williams’ ultimate interpretation of the model is that the source contributing to the gravity high is largely intrusive material within a layer of less dense extrusive volcanic rocks. This conjecture is supported by the presence of a resistive body in the MT data, given that young intrusions often have high resistivity. They believe the intrusive material was most likely built up throughout the volcano’s history, with the intermittent injection of new magmas into the older ones (Finn and Williams, 1982). Based on the presence of a near-boiling-temperature fumarole and multiple young (~1,000 yr old) basaltic lava flows and silicic domes, it is reasonable to assume
part of the intrusive body could still be hot and/or molten (Donnelly-Nolan, 1981.; Finn and Williams, 1982).

Unfortunately, the gravity data alone are not sufficient to resolve whether the intrusive material is ultramafic, mafic, intermediate, felsic, or multi-compositional. If the volcanic layer is assumed to have a density of 2400 to 2500 kg/m³ (LeFehr, 1965), the resulting calculated density range of 2810 to 2910 kg/m³ for the intrusive body is - according to Finn and Williams (1982) - too high for rocks of felsic composition. From this, they infer that mafic to intermediate composition is far more probable (Finn and Williams, 1982). Given their supposition of incremental intrusion of a variety of magmas over time, however, multiple compositions seems possible.

It can be argued that Lassen Peak bears some resemblance to Medicine Lake volcano in terms of its location with respect to gravity anomalies. That is, it also sits within a north-south trending isostatic residual gravitational depression. These kinds of isostatic residual anomalies are observable subsequent to the removal of long-wavelength variations in the gravity field inversely related to topography. The broad gravity low that Lassen sits in, however, is spatially separated from the regional trough that contains both Mount Shasta and Medicine Lake volcano (Blakely et al., 1997). This particular low that includes the LVC is at the southwestern end of an expansive, linear gravity trough that extends 300 km into northwestern Nevada and southeastern Oregon. Blakely et al (1997) termed this large depression the Lassen gravity lineament, which is similar in size and orientation to the Shasta gravity lineament that houses both Mount Shasta and Medicine Lake volcano (Figure 2.7) (Blakely et al., 1997).
The Shasta and Lassen gravity lineaments are separated by a chain of northeast trending high gravity anomalies that have been suggested as being caused by basement structures underlying the Modoc Plateau (Blakely et al., 1997; Chapman and Bishop, 1968; Griscom, 1980b). The anomaly farthest to the west of the chain overlies an exposure of pre-Tertiary rocks of the Eastern Klamath Belt, between just south of Mount Shasta and northwest of Lassen Peak (Blakely et al., 1997; Irwin, 1966). Griscom, (1980b) contends that the early Paleozoic mafic to ultramafic rocks causing the gravity high are part of the Eastern Klamath belt assemblage called the Trinity ophiolite complex.

The Lassen and Shasta gravity lineaments are both part of a “fabric” of anomalies that trend northeast throughout central to eastern Oregon, northeastern California and northwestern Nevada. Blakely et al (1997) refer to this “fabric” as the Oregon Plateaus (OP) gravity province. Pre-Tertiary Basin and Range province exposures border the southern end of this region, as do portions of the northern Sierra Nevada. The north end of the OP gravity province is additionally bounded by pre-Tertiary exposures of the Blue Mountains uplift (Blakely et al., 1997).

Considering where the thickest segments of low-density eruptive materials and symmetric subsurface geothermal conditions exist, the expectation is that you might find major volcanic centers at or near the focus of these gravity lows. Instead, it is along the east or west margins of the gravity depressions that many of the major recent volcanic centers of the Cascade arc are positioned (e.g., Lassen Peak, Medicine Lake volcano, and Mount Shasta) (Blakely et al., 1997; Blakely et al., 1985; Christiansen, 1985). There is some conjecture that perimeter faults surrounding much larger tectono-
magmatic structural troughs may have presented a means for magma migration and ascent to the surface (Blakely et al., 1997; Heiken, 1976; Dzurisin et al., 1991). It could be the lower density of the materials both filling and underlying these large troughs that cause the similarly-sized gravity anomalies. It is important to note, however, that no definitive evidence is currently known to corroborate the presence of faults producing these perimeter gradients. (Blakely et al., 1997).

In the LVC, north-northwest vent alignments suggest east-northeast extension that is highly characteristic of the adjacent Basin and Range province (Blakely et al., 1997; Guffanti et al., 1990a). Guffanti and Weaver (1988) spatially, temporally and compositionally divided the Cascade arc into five distinct segments, based on observations of non-uniformity of volcanism throughout the range. They found Lassen to be isolated within a 50 km long segment to the south, which is distinguished from the more northern (also isolated) Shasta-Medicine Lake segment. These distinctions, throughout entire range, have been determined on the basis of geochemical, geophysical, geothermal and tectonic markers (Blakely et al., 1997; Guffanti and Weaver, 1988).

There are a number of older major volcanic centers in the Lassen and Shasta-Medicine Lake segments that were active between 3.1 and 1.1 Ma (Blakely et al., 1995). With the exception of Yana (active 3.4-2.7 Ma) (Blakely et al., 1997; Muffler et al., 1989), all of these major volcanic centers fall within the bounds of the Shasta-Medicine Lake or Lassen gravity lows. Yana lies approximately 7 km outside of the Lassen gravity lineament (Blakely et al., 1997). Even more interestingly, the vast majority of these older
major volcanic centers are positioned along the perimeter of their respective, approximately equidimensional gravity depressions (Blakely et al., 1997).

It's important to note that the volcanoes (and volcanic deposits) distributed throughout these broader depressions and lineaments do have lower densities, and as such are capable of producing localized gravity lows themselves. However, they [collectively] could not generate such broad troughs and zones, as these are actually reflective of longer wavelength features at greater depth.

Quaternary faults located within and adjacent the Lassen Peak gravity low have a north-south orientation well-displayed by the central and northern portions of the [Holocene] Hat Creek fault zone (HCFZ). (Blakely et al., 1997; Muffler et al., 1994; Wills, 1991). This orientation continues to the south of the HCFZ, where it bends back to a predominantly northwest strike. In this region, Quaternary faults appear to bend a “z-like” pattern as they weave in and out of zones of relatively low gravity and higher vent density (Figure 2.8) (Blakely et al., 1997). In simplified terms - within the zones of low gravity and high magmatism, the Quaternary faults are oriented in a north-south direction. Conversely, within the interposing amagmatic regions, they tend to strike to the northwest-southeast (Blakely et al., 1997). This relationship is observed as part of a regionally extensive fault zone informally referred to as the Fall River fault zone (Blakely et al., 1997; Guffanti et al., 1994). On an even larger regional scale, this zone is additionally part of a 400 km-long structural alignment of right-stepping, en echelon tectonic depressions collectively termed the Tahoe-Medicine Lake trough (Blakely et al., 1997; Page et al., 1993).
According to Blakely and colleagues (1997), spatial correlations between isostatic residual gravity anomalies, the orientation of Quaternary faults, and the positioning and distribution of Quaternary vents in the southern Cascade Range is likely reflective of a complex history of lateral crustal variations and magmatic conditions. Three dimensional variations in density are manifestations of this history, and are demonstrated by the semi-evenly-dimensional (50-80 km diameter) gravity anomalies over Lassen Volcanic Center and the Shasta-Medicine Lake region. These anomalies may point to pre-Tertiary basement structures beneath the southern portion of the Cascade arc, which are directly related to the distribution of magmatism (Blakely et al., 1997). This conjecture is corroborated by the spatial correlation between aforesaid gravity anomalies, the northerly orientation of the Shasta and Lassen gravity lineaments, as well as the entire fabric of the Oregon Plateaus gravity province (Blakely et al., 1997).

*Distribution of Magmatism: The Hot Fingers Model*

Some elements of the southern Cascades range gravity and volcanological data can be compared with similar data from the Tohoku volcanic arc, north Honshu Island, Japan. Observations by Tamura et al. (2001) along the rear of the Tohoku volcanic arc revealed correlations among the clustering of volcanic centers, low-velocity zones in the mantle wedge, and the shape and positioning of local negative Bouguer gravity anomalies. Their model suggests the presence of multiple inclined, hot, finger-like zones within the mantle wedge of the subduction zone, all perpendicular to the arc-
trench system (Tamura et al., 2001). Averaging 50 km in width and ~80 km separation, these ten "fingers" are purported to extend from the deep mantle (>150 km) beneath the back-arc toward the shallower mantle (~50 km) (Tamura et al., 2001). Tamura and colleagues cite tomographic results as evidence for the presence of these fingers within the mantle wedge, and believe the Bouguer gravity anomalies are attributed to the low-density magmas they supply and the accumulation of these magmas at the Moho discontinuity (Figure 2.9). Ultimately, their model suggests uneven clustering of Quaternary volcanoes immediately above these hot mantle fingers and the low-velocity mantle wedge (Figure 2.10) (Tamura et al., 2001).

The Tamura et al. (2001) hot fingers interpretation for the Tohoku volcanic arc seems to, in many respects, parallel what has been modeled by Blakely et al. (1997) in the southern Cascade arc. The negative gravity anomalies described in southern Oregon and northern California are of relatively similar size, shape and spatial correlation, and they too exhibit the uneven distribution and clustering of volcanoes as observed in northeast Japan (Figure 2.7) (Blakely et al., 1997).

*Model for Magma Genesis: Deep Crustal Hot Zones*

Annen et al. (2006) published their work on subduction-related magmatism, using numerical modeling to describe what they believe is a deep crustal hot zone generated by a succession of mantle-derived hydrous basalt sills emplaced in the lower crust (Annen et al., 2006). Their results support the conjecture that there are two discrete sources of melt generation in deep crustal hot zones. The first is partial crystallization of
emplaced mantle basalts to produce $\text{H}_2\text{O}$-rich melts, and the second is the partial melting of existing lower crustal material (Annen et al., 2006).

The length of the incubation period between initial injection of mantle basalts and their crystallization is controlled by a number of factors: (1) the initial geotherm, (2) the input rate of the magma, and (3) initial emplacement depth. Subsequent to this incubation, it is the temperature of the surrounding crust into which the basalt is being intruded that actually becomes the control on melt fraction and composition of the residual melts. The transfer of heat and water from the crystallizing basalt induces partial melting of the surrounding crust, which may be comprised of meta-igneous and meta-sedimentary basement rocks, as well as older intrusions of basalt (Annen et al., 2006).

Partial melting of the mantle wedge in subduction zones produces these hydrous primary mafic magmas. $\text{H}_2\text{O}$-rich fluids released from the subducting slab effectively lower the viscosity and density of these hot zone melts. Consequently, they may readily detach from their source and begin to rapidly, adiabatically ascend toward the surface. Country rock fragments and crystals entrained during initial crustal emplacement are resorbed, due to the melt's lack of heat loss or transfer. As the magma ascends to shallower depths (intersecting its $\text{H}_2\text{O}$-saturated liquidus), crystallization is reinitiated by decompression and degassing (Annen et al., 2006). Substantial increases in viscosity due to crystallization and degassing can cause magmas to stall at shallow depths, giving rise to either volcano-feeding magma chambers or plutons (see Figure 2.11 for illustration of the hot zone model proposed by Annen et al., 2006).
The Annen et al. (2006) hot zone model ties in well with the work of Tamura et al. (2001), as well as with the magnetotelluric (MT) study of Park and Ostos (2013) discussed later in this chapter. Though the hot fingers model focuses on depths beneath the Mojo discontinuity (deep within the mantle wedge), there is reasonable congruency between it and the lower crustal melt generation conditions described by Annen and colleagues (2006). One plausible explanation is that the finger-like bodies are a deeper source for mantle-derived hydrous basalts, which Annen et al. (2006) conclude are being emplaced in the lower crust.

*Magnetotelluric Studies in the Lassen Volcanic Center Region*

Park and Ostos (2013) conducted broadband and long period magnetotelluric (MT) studies along a 250 km profile spanning from the California-Nevada border (latitude 40.5°N, longitude 120°W) to just west of the Great Valley (longitude 123°W). This profile consists of 14 collocated stations, and traverses the buried extension of the Sierra Nevada, the southern portion of the Cascades arc, as well as the edge of the currently subducting Gorda plate (Park and Ostos, 2013).

Their subsequent resistivity cross-section (Figure 2.12) reveals multiple conductive bodies at 100 km depth, where dewatering of the subducted metasomatized Gorda lithosphere is taking place. These bodies also appear at 40-60 km depth in zones of partial melting of the mantle wedge, as well as in melt zones shallower than 40 km. Estimated depth to the Moho in the MT model interpretation is ~40 km (Park and Ostos, 2013).
The Lassen MT (Figure 2.13) line is the northernmost in Park and Ostos’ study of the Sierra Nevada lithosphere. It traverses a zone of great geologic complexity, including the edge of active subduction of the Gorda plate, which represents the magmatism that comprises the southern end of the Cascade arc. Just ~150 km to the west of the profile, the North American, Gorda, and Pacific plates meet to form the Mendocino triple junction. The Lassen MT line passes just north of Lassen Peak, the most active volcano in the southern Cascade Range. Further to the east, the profile intersects multiple Pliocene and Pleistocene volcanic fields where it extends into the Basin and Range province (Park and Ostos, 2013).

The selected MT profile for Lassen crosses an expansive swath of Quaternary volcanic rocks that includes Lassen Volcanic Center, Hat Creek and Poison Lake (Park and Ostos, 2013). The resulting electrical image from Park and Ostos' (2013) study reveals multiple bodies of interest in the zone underlying Lassen Peak and the surrounding region. These include: three small crustal conductors (bodies a, b and c in Figure 2.12), a crustal resistor (body H) presumed to a Mesozoic intrusive body, and a more ambiguous upper mantle conductor lying just beneath the general region. The bodies (d) and (e) are two additional crustal conductors determined to be unassociated with the zone directly beneath Lassen, but do lie above the mantle and fall within an eastern region of Quaternary volcanism (Park and Ostos, 2013).

Park and Ostos (2013) contend that the conductive foci (bodies a and b) in the resistivity image beneath Lassen Volcanic Center are melt reservoirs at depths of approximately 15-30 km. This is interpreted to be where mantle basalts reside, heating
and partially melting the lower crust. This conjecture is supported by the petrology and geochemistry, which shows that rising mantle basalts heat and melt the lower crust, assimilating it to form andesites (Park and Ostos, 2013; Clynne and Muffler, 2010). Moreover, small amounts of rhyolite and felsic ash observed at Lassen Volcanic Center help to substantiate the idea of melting of the lower crust (Park and Ostos, 2013).

Discussion of subduction-related magmatism and the generation of intermediate and silicic melts is at the forefront of the deep crustal hot zone model proposed by Annen et al. (2006). This model, as previously discussed in this chapter, only serves to further corroborate the abovementioned inferences by Park and Ostos (2013).

Numerous (100-110 Ka) calc-alkaline basaltic eruptions at Poison Lake (PL, Figure 2.13) in the Caribou volcanic field characterize some of the most mafic arc magmas found in the entire Lassen region (Park and Ostos, 2013; Clynne and Muffler, 2010). Muffler et al. (2011) believe these do not derive from a common parent through crystal fractionation, but are instead the result of discrete pulses of mantle-source magma. There is little, if any, crustal contamination observed, which indicates brief storage in the lower crust prior to eruption (Park and Ostos, 2013; Muffler et al., 2011). The crustal conductors (a and b) beneath Lassen Volcanic Center and Poison Lake are inferred to be discrete, with differing extents of lower crustal melting. The supposition by Park and Ostos (2013) is that melting of the lower crust in body (a) is more extensive than in body (b). They believe this may be attributed to the ongoing development of Caribou volcanic field into a volcanic center, which has yet to experience sufficient
basaltic magma input to trigger crustal melting or assimilation (Park and Ostos, 2013; Clynne and Muffler, 2010).

The 24 ka eruptions at Hat Creek (HC, Figure 2.13) consist of tholeiitic basalts that show very little evidence of crustal melting or assimilation. It is inferred that they reached the surface via normal faults associated with Basin and Range extension and thus, are not related to arc magmatism (Park and Ostos, 2013; Clynne and Muffler, 2010). Despite there being three active loci of volcanic activity within this region (Lassen Volcanic Center, Hat Creek, and Poison Lake), there are only the two crustal conductors (a and b) shown in the MT resistivity cross-section. Park and Ostos (2013) assert that this may be attributable to the lack of residence time of the basaltic melt beneath Hat Creek.

The magmatic system associated with the subduction of the Gorda plate beneath North America is complex and involves fluids from dehydration metamorphic reactions fluxing the mantle wedge. This results in the generation of basaltic, wedge-derived magmas (Park and Ostos, 2013). The conductivity of the mantle wedge directly beneath Lassen, according to Park and Ostos (2013), is explained by melt fractions of less than 10%. Previous studies of Cascades subduction (Soyer and Unsworth, 2006) did not observe conductive anomalies beneath the volcanic arc. The results of Park and Ostos (2013), however, show a direct correlation with the foci of active volcanism. Ultimately, the inference is that there is an arc-related source of basaltic magmatism directly within the arc itself, whereas the impinging Basin and Range asthenosphere is most likely the second source of basalts at the eastern end of the MT profile (Park and Ostos, 2013).
Ultimately, the MT model of Park and Ostos (2013) coincides well with the Annen et al. (2006) hot zone model. It provides some corroborative evidence of deep crustal [electrically conductive] bodies emplaced above the Mojo discontinuity, within a low velocity zone much like what is described by Tamura et al. (2001) in the Tohoku volcanic arc. In general, all of the models discussed throughout this chapter, including the work of Blakely et al. (1997), appear to overlap in multiple ways that also serve to support my own research.
Figure 2.1. Map showing plate tectonics in the Cascade volcanic arc. Arrows show the net vectors in kilometers per million years of Juan de Fuca plate motion relative to the North American plate. Figure modified from Priest [1990].
Figure 2.2. Map showing the extent of Lassen Volcanic Center, including associated hazards and their respective zones, as determined by the USGS. Figure taken from USGS, Cascades Volcano Observatory [2014].
Figure 2.3. Aerial view of Lassen Peak (looking southwest) following the 1915 eruption. Visual markers of the lahars and pyroclastic flows that occurred between May 15 and May 22, 1915 can be seen. In addition, the image shows a remnant lava flow from the same eruptive period. The composite dacite dome of Lassen Peak is 27,000 years old. Figure taken from Clynne et al. [2012].
Figure 2.4. View (from the southwest) of the Chaos Crags domes formed approximately 1,050 years ago. The majority of the area immediately surrounding all of the domes is inundated with as much as 1 m of air-fall pumice from the very first pyroclastic eruptions. Figure taken from Clynne et al. [2012].
Figure 2.5. Map showing gravity and magnetic anomaly interpretations. Solid lines (dashed where uncertainties lie) are indicative of approximate boundaries of magnetic and gravity sources as interpreted by Blakely et al. [1985]. Light and Darker blue ovoids with stippled and dotted patterns indicate north-south graben and local subsidence structures, respectively, according to gravity data analysis. Solid dots indicate major volcanoes: LA = Lassen Peak, SH = Mount Shasta, ME = Medicine Lake, MC = Mount McLaughlin, CL = Crater Lake, NE = Newberry Crater, TS = Three Sisters, JE = Mount Jefferson, and HO = Mount Hood. Figure modified from Blakely et al. [1985].
Figure 2.6. Bouguer gravity profiles (solid lines) at Medicine Lake volcano in California. The dashed line is representative of smoothed topography. Each solid line shows the Bouguer gravity anomaly calculated with a different reduction density (in g/cm³). V.E. is vertical exaggeration. The Bouguer anomaly highlighted in green indicates the reduction density value Finn and Williams [1982] determined to be the best for the purposes of their processing and excess mass calculation. Figure modified from Finn and Williams [1982].
Figure 2.7. Map showing the volcano locations of southern Oregon and northern California. Stars indicate locations of major volcanoes as named. Pink and white dots indicate ages (0-2 Ma and 2-7 Ma, respectively). Colors on map indicate isostatic residual gravity. The regions bounded by dashed lines indicate the gravity lineaments described by Blakely et al. [1997]. SGL is the Shasta gravity lineament and LGL, the Lassen gravity lineament. Figure taken from Blakely et al. [1997].
Figure 2.8. Stylized interpretation of fault orientations and patterns (indicated by bold black lines) in the southern Cascade Range, from southern Oregon to northern California. Figure taken from Blakely et al. [1997].
Figure 2.9. Illustration showing the Bouguer gravity profile along the Japan Sea coast. There is lateral relation between the crests and troughs of the Bouguer anomalies to the topographic highs and lows (gaps of volcanoes), respectively. Figure taken from Tamura et al. [2001].
Figure 2.10. Conceptual illustration of hot fingers inferred by Tamura et al. (2001) to exist in the mantle wedge of northeast Japan. Clusters of Quaternary volcanoes are positioned immediately above these hot fingers. Dashed lines show depth contours to the surface of the dipping seismic zones for the region. Figure taken from Tamura et al. [2001].
Figure 2.11. Conceptual illustration (not to scale) of a deep crustal hot zone, as modeled by Annen et al. (2006). Diagram shows sills of mantle-derived basaltic magma injected at various depths, including: (1) the Moho, (2) the lower crust, and (3) the Conrad Discontinuity (between the upper and lower crust). Figure taken from Annen et al. [2006].
Figure 2.12. Summary interpretation of the Park and Ostos [2013] MT model. Conductive bodies are indicated by the lower-case letters a, b, c, d, and e. The resistive body H lies between bodies (b) and (c). Locations of Lassen Peak (LP), Hat Creek (HC) and Poison Lake (PL) are indicated along the top line above the model. Figure taken from Park and Ostos [2013].
Figure 2.13. Geologic map showing measurement locations along Park and Ostos' Lassen profile (original geologic map adapted from Luddington et al. [2005]). Distributions of Tertiary and Quaternary volcanic rocks are also shown. LP = Lassen Peak; HC = Hat Creek; PL = Poison Lake; R = Redding; S = Susanville. Thick black lines indicate roads. Figure taken from Park and Ostos [2013].
Chapter Three:
Modeling Gravity Data in Oasis Montaj / GM-SYS

Methods and Results: Gravity Modeling

Gravity data from the Lassen region coincide with the MT stations of Park and Ostos (2013). The approach in my research is to model these gravity data starting with a geometry suggested by the MT model interpretation. The hypothesis is: MT conductors identified by Park and Ostos (2013) should also produce density contrasts in the crust and create gravity anomalies. Modeling of gravity data, starting with interpreted MT conductor geometries, provides a means of testing the idea that gravity anomalies in the region might be associated, in part, with mid-crustal magma reservoirs.

Broadband and long period MT measurements of time variations in Earth's natural electric and magnetic fields were taken at 14 stations along a 250 km profile (Park and Ostos, 2013). These measurements span from the California-Nevada border (latitude 40.5°N, longitude 120°W), to just west of the Great Valley (longitude 123°W). Using the coordinates for each of the 14 stations, the distances between each were interpolated in Matlab. The `grdtrack` function in GMT was then used to extract the entire profile from the FFT filtered gravity data set, which was imported into OASIS Montaj and GM-SYS for forward modeling (Figure 3.1).
The OASIS Montaj and GM-SYS software packages facilitate user-driven forward modeling of sub-surface geometries and densities. This allows for comparison between resulting, calculated gravity anomalies and observed data using a $2\frac{1}{2}$D approach. This type of model allows user-specification of the extent of bodies/objects into and out of the plane along the profile. Beyond the defined shapes and boundaries of these bodies/objects, however, the surrounding area can only be assigned a single set of attributes (e.g., density or magnetic susceptibility values). For the purposes of the Lassen region gravity model, this area was given the designation "country rock", and assigned the same the same density (2670 kg/m$^3$) as used for reduction of the gravity data. To simplify things, every modeled body was assigned a uniform extent of 3 km (into and out of the plane, perpendicular to the profile). This determination was made largely on the basis that the model is only minimally sensitive to this parameter. In reality, this means that most of the bodies are wider in the cross section of the traverse than they are perpendicular to it.

The model interpretation (resistivity cross section) by Park and Ostos (2013) was imported into GM-SYS to be utilized as a background and general starting point for generating the gravity model. Despite the minor issue of vertical exaggeration, the MT cross section was successfully geographically aligned along profile and at depth. Using the positioning, shape, and size of each body presented in the MT model, as well as information on conductivity versus resistivity, a series of sub-surface bodies with varying densities were correspondingly incorporated in the gravity model. The estimated densities appear well within reason for what are assumed to be partially
molten bodies or dense solid intrusions at the locations of the electrical conductivity anomalies. The overall result is a fairly impressive alignment (2.4% margin of error) between the modeled and observed gravity data, as well as with the sub-surface structure proposed by Park and Ostos (2013) based on MT models (Figures 3.2 and 3.3).

Looking at the correlation between the survey profile on the FFT-filtered gravity map and the gravity profile itself (Figure 3.3), there appears to be suitable alignment between the two. While the profile doesn't directly transect the most prominent gravity lows (in particular, the anomaly directly underlying Lassen Peak) on the map, it does transect a region of low gravity just slightly to the north. It is assumed that the prominent low in the gravity profile, which is closest in proximity to Lassen Peak, is at least partially attributable to the negative anomaly beneath the volcano on the gravity map. Relating back to the concepts outlined by Blakely et al. (1997), it makes sense that the profile behaves in this way. Lassen sits along the edge of a broad gravity depression approximately 50-80 km in diameter (Blakely et al., 1997). So the fact that a substantial dip in gravity is also reflected along the profile just slightly to the north (± 25 km) seems well within reason.

Among the primary drivers in constructing this model, was to test the viability of the MT anomalies being associated with mid-crustal intrusions. Despite the complexity of the MT model interpretation, including the number of bodies it identifies, it does help to clarify conductor geometries used to guide the development of the gravity model. Although simpler gravity models are entirely possible to construct using the same data, this one was constructed with the intention of testing the robustness of the
MT mid-crustal model in the broader Lassen Volcanic region. Overall, no short wavelength anomalies along the profile were modeled, which makes sense in consideration of the fact that the zone of interest is the mid to lower crust. Shorter wavelength anomalies are associated with features in the shallow crust, which is not the primary focus of this research.

Model and Anomaly Sensitivities

As briefly addressed earlier, there were certain parameters that the model appeared to be only marginally sensitive to (i.e., the extent of the body into and out of the plane, perpendicular to the profile). Other factors, however, were substantially more constrained because they have a much greater impact on the fit of the model with the data.

Gravity is relatively non-unique in a stand-alone sense, in that a wide variety of simple shapes can often be used to produce similar model results. In this instance however, the greatest sensitivities were, in fact, body shape, size, depth, and density. This actually speaks to the viability of both the gravity and MT models, particularly given the mid-to-lower crustal region [depth] of interest and the conductor geometries that were implemented. Longer wavelength anomalies were the focus, due to the fact that they are reflective of deeper source features. In modeling these potential structures, it was evident that even very minor alterations to the abovementioned parameters proved to have a profound impact on the fit (or misfit) between the model and data.
Figure 3.1. (A) Geologic map showing the measurement locations along Park and Ostos' Lassen profile (original geologic map adapted from Luddington et al. [2005]). (B) FFT filtered gravity map showing the same profile with interpolation between the MT measurement locations.
Figure 3.2. Lassen gravity model developed in Oasis Montaj and GM-SYS; includes the MT model interpretation used as a backdrop. The solid black outlines indicate body shapes, sizes and positions as incorporated in the gravity model (for visual comparison with geometries in the MT model). It is important to note that vertical exaggeration is prevalent in GM-SYS.
Table 3.1. Density values, as assigned to each of the bodies in the gravity model developed in Oasis Montaj and GM-SYS.

<table>
<thead>
<tr>
<th>BODY</th>
<th>DENSITY (IN MODEL)</th>
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<tr>
<td><strong>a</strong> (conductive)</td>
<td>2400 kg/m³</td>
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<tr>
<td><strong>b</strong> (conductive)</td>
<td>2450 kg/m³</td>
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<td><strong>c</strong> (conductive)</td>
<td>2450 kg/m³</td>
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<td><strong>d</strong> (conductive)</td>
<td>2550 kg/m³</td>
</tr>
<tr>
<td><strong>e</strong> (conductive)</td>
<td>2300 kg/m³</td>
</tr>
<tr>
<td><strong>f</strong> (basin sediments)</td>
<td>1700 kg/m³</td>
</tr>
<tr>
<td><strong>g</strong> (resistive)</td>
<td>2600 kg/m³</td>
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<tr>
<td><strong>H</strong> (resistive)</td>
<td>2550 kg/m³</td>
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<tr>
<td><strong>i</strong> (conductive)</td>
<td>2450 kg/cm³</td>
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Figure 3.3. Image showing the correlation between the survey profile on the FFT gravity map and the gravity profile itself. Though the profile doesn't directly transect the most prominent gravity lows (in particular, the anomaly directly underlying Lassen Peak) on the map, it does transect a region of low gravity just slightly north. Black dotted line (top) represents the actual gravity data. Black solid line (top) represents the gravity model. The blue dots and line in the anomaly map show the actual profile along which the gravity data was extracted and modeled.
Chapter Four:
Excess Mass Calculation

Methods and Results: Gauss’s law and Excess Mass

Gauss's law states that the total mass in a region is proportional to the normal component of the gravitational attraction integrated over the closed boundary of the region (Blakely, 1995). Amongst the most common geophysical applications of this concept is the approximation of excess mass beneath a surface over which the normal component of gravity is known (Blakely, 1995; Hammer, 1945). Given a volumetrically constrained mass, no other assumptions regarding its depth, shape or density distribution are necessary. This is with the exception, however, that the mass be small with respect to the overall dimensions of the study area. (Blakely, 1995).

Certain complications do arise with the application of Gauss’s law in this manner. Gravity data over an infinite plane is non-existent and, therefore, the best proxy is to utilize a dataset that extends markedly beyond the confines of any major sources of interest. Complete source isolation is unfortunately not possible in the natural world. For this reason, the separation of gravitational anomalies of interest from other local and regional sources is often complicated (Blakely, 1995).

To approximate and separate the regional and residual gravity anomalies in the Lassen volcanic region, the `grdfit` function in GMT was used. A large swath of data was obtained from the gravity database of the U.S. at the University of Texas at El Paso.
(UTEP), and it spans well beyond the anomaly of interest beneath Lassen Volcano. Several variations on the Butterworth band-pass filter were attempted before determining a high band-pass filter as the most effective method of removing the average regional anomaly of -114.6 mGal. This method effectively eliminates wavelengths longer than 200 km, both preserving and better isolating wavelengths related to the mid-to-lower crustal features of interest. Improving isolation of the negative anomaly beneath Lassen in this way allows for better determination of the most suitable gravity threshold used in the excess mass calculation (Figure 4.1).

As previously implied, the term "excess mass" refers to the discrepancy between a given body of interest, and the total mass of surrounding country rock that would otherwise fill the space it occupies. To successfully compute an excess mass, the density contrast between the anomalous body and the surrounding country rock must be known. Density values were determined in the Oasis Montaj/GM-SYS modeling process as outlined in Chapter 3. In this case, the country rock density is modeled at 2670 kg/m³, and the body of interest (a) at 2400 kg/m³. The density contrast used in calculating the excess mass, therefore, is 270 kg/m³.

Following the FFT-filtering of the data set, using the \texttt{grdfft} function in GMT, an area immediately surrounding the Lassen Peak gravity anomaly was selected for the purpose of performing an excess mass calculation (Figures 4.1 and 4.2). To effectively perform this calculation, the gravity data must first be interpolated on to a regular grid. A threshold ("background") gravity value is then visually determined from the FFT gravity map. The background value, in the case of the Lassen anomaly, was determined
to be approximately -15 mGal. Utilizing a Perl script to perform numerical integration of the gridded gravity data across the selected area of interest, the anomalous mass is determined by subtracting the assigned background value from each grid point, then summing all of the values together. The sum is subsequently multiplied by $\frac{1}{2\pi G} \Delta x \Delta y$ (where \(\Delta x\) and \(\Delta y\) are representative of the grid spacing in the X and Y directions and G is Earth's gravitational constant, $6.67384 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$).

Based on the selected background value of -15 mGal (and the resulting 538 gravity values included the interpolated grid), the excess mass calculated for the Lassen anomaly is $-1.79 \times 10^{14} \text{ kg}$. To further examine the validity of this calculation, multiple bodies included in the Oasis Montaj/GM-SYS model were revisited with the intent of using volume estimates and modeled densities to calculate a range of possible excess mass values for comparison.

The primary body of interest in Figure 4.3 is body (a), which has an estimated density of 2400 kg/m$^3$, based on the forward model. Although the body appears to have an almost tear-drop shape, it is actually substantially more oblate in terms of its modeled dimensions. This is attributed to vertical exaggeration, which is a definite artifact when producing visual representations of models in GM-SYS. By manually determining the dimensions of the body (in kilometers), it becomes clear that the shape is nearly elliptical (Figure 4.4). Although there is a slight discrepancy where the body narrows at the top, simplification of its shape does allow for reasonable estimates of its volume using both an elliptical cylinder and a basic ellipsoid.
Because the model is 2\(\frac{1}{2}\)D, there are specific values (that is, distances in km) assigned in both directions, into and out of the plane, perpendicular to the profile. This gives the body a uniform thickness from top to bottom. To visualize this, imagine the shape of the body (Figure 4.4) as the face of an elliptical cylinder, turned on its side. This body is assigned a uniform thickness (H) of 3 km (see illustration, Figure 4.5).

Using \(V = \pi \cdot A \cdot B \cdot \frac{H}{4}\), the first estimated volume for body (a) is 8.82 \(\times\) 10\(^{11}\) m\(^3\). Given a density contrast of 270 kg/m\(^3\) (0.27 g/cm\(^3\)), the calculated excess mass is -2.38 \(\times\) 10\(^{14}\) kg. This is very nearly the same excess mass estimated using the gravity data, and therefore appears to be a reasonable calculation.

Using an elliptical cylinder as the simple shape, in this case, was based solely on the parameters of the 2\(\frac{1}{2}\)D model. The assigned body extent (into and out of the plane) gives it a uniform thickness (H), which lends itself to the elliptical cylinder shape. However, this not likely the most plausible shape for a magma body at depth. It seems slightly more reasonable to assume an ellipsoid shape to the body, and to thus perform an additional excess mass calculation for comparison. To account for the tear-drop shape of the modeled body, an average radius of 12.0 km was determined for the long axis (a). The second radius (b) was assigned a value of 1.5 km, and the third (c), 8.0 km. (Figure 4.6). The resulting calculated volume is 6.03 \(\times\) 10\(^{11}\) m\(^3\). Multiplying this volume by the density contrast of 270 kg/m\(^3\) (0.27 g/cm3), the excess mass then becomes - 1.63 \(\times\) 10\(^{14}\) kg. This is even closer to the excess mass of 1.79 \(\times\) 10\(^{14}\) kg calculated using the gravity data, and therefore appears to be a better proxy.
Figure 4.1. Gravity anomaly map of the Lassen region showing the 250 km long survey profile (MT reading locations indicated by small blue dots) used in the Park and Ostos (2013) magnetotelluric (MT) study. This is the same profile that was interpolated and extracted from the gravity dataset for modeling using the *grdtrack* function in GMT. The locations of Lassen Peak (LP), Poison Lake (PL) and Hat Creek (HC) are indicated with small black triangles on the map. The black box indicates the area surrounding Lassen Peak that was isolated and zoomed in on for the purposes of performing the excess mass calculation.
Figure 4.2. Zoomed in map view of the negative anomaly underlying Lassen Peak. This was used to obtain the background (threshold) value, and to perform the excess mass calculation. Coordinates converted to UTM here for the purposes running the excess mass script.
Figure 4.3. Stacked figure showing the gravity profile and model (top). The dotted line indicates the actual gravity data along the profile, the solid, thin, black line indicates the gravity model. Beneath this is the visual representation of the gravity model, showing the subsurface bodies of interest along the profile. The third section shows the original MT cross section used as a backdrop and guide, with outlines to show comparison with the gravity model.
Figure 4.4. Visual approximation of the shape and dimensions of body (a) from the Lassen gravity model created in Oasis Montaj and GM-SYS. The dimensions of the body were directly measured in the model, and subsequently used to estimate its general size and shape for the purposes of completing volume and excess mass calculations.
Figure 4.5. Illustration showing the simple elliptical cylinder shape initially used to calculate a volume and excess mass for body (a) in the Lassen gravity model.
Figure 4.6. Illustration showing the simple ellipsoid shape used to complete secondary volume and excess mass calculations for body (a) in the Lassen gravity model.
Discussion & Interpretation of Results

Gravity analysis performed by Carol Finn and David Williams at Medicine Lake Volcano, California, resulted in an estimated excess mass of $2.0 \times 10^{17}$ g ($2.0 \times 10^{14}$ kg). The primary focus of their study was the positive gravity anomaly and density contrast they attributed to a shallow, dense intrusion emplaced within a several-kilometers-thick older volcanic layer underlying the volcano (Finn and Williams, 1982).

In the case of this study in the Lassen volcanic region, the residual gravity anomaly of interest is actually negative, and therefore so is the estimated excess mass (or "mass deficit"). In either case, "excess mass" simply refers to the total mass of surrounding country rock that would otherwise fill the space being occupied by a given body of interest. In any case, the primary motivation in referencing the work of Finn and Williams (1982) is not to directly compare their results to those in the Lassen model, but instead to emulate some of their specific methods.

There are a number of reasons to avoid direct comparison of the body proposed by Finn and Williams (1982) to body (a) in the Lassen model. The Medicine Lake body is markedly different in that it is substantially shallower (beginning at approximately 4 km depth), but also notably more dense at 2610 kg/m$^3$ (versus 2400 kg/m$^3$). In the
Lassen gravity model, the depth of body (a) is substantially greater, beginning at about 19-20 km depth. The estimated volume of the Medicine Lake body, based on excess mass, is approximately $4.878 \times 10^{11}$ m$^3$.

As already indicated, Finn and Williams (1982) primarily focused on the shallow crust in their study at Medicine Lake. In particular, they were interested in the resistive, intrusive body of dense material they believe to have been emplaced into pre-existing volcanic materials. In my research, however, the focus is on the much deeper mid-to-lower crustal region beneath Lassen Peak. Despite the fact that relatively similar steps were taken in both studies to remove regional effects from the gravity data, the ultimate difference is each study concentrates on different wavelength features at different depths within the crust.

Whatever the disparities may be, the Shasta-Medicine Lake and Lassen gravity lineaments do look markedly similar on a regional scale. They are both discrete, broad gravity lows separated by a chain of northeast trending higher gravity anomalies, potentially related to basement structures underlying the Modoc Plateau (Blakely et al., 1997; Chapman and Bishop, 1968; Griscom, 1980b). As previously touched on, both Medicine Lake and Lassen volcanoes lie within their respective, approximately equidimensional gravity depressions in the southern end of the Cascade Range (Figure 5.1). Both are positioned along the edge of the gravity depression they sit in, which has led to some conjecture regarding perimeter faults bordering larger tectonomagmatic structural troughs as a means for magma migration and ascent toward the surface. (Blakely et al., 1997; Heiken, 1976; Dzurisin et al., 1991).
There is definitive spatial correlation between these regional anomalies, including the northerly orientation of the Shasta-Medicine Lake and Lassen lineaments, as well as the fabric of the entire Oregon Plateaus gravity province. These may be indicators of pre-Tertiary basement structures beneath the southern portion of the Cascade arc that directly relate to the distribution of magmatism (Blakely et al., 1997). In essence, it isn't out of the realm of possibility that the magmatic systems and evolutionary processes underlying Medicine Lake volcano and Lassen Peak could be relatively similar.

*The Hot Fingers Model*

In northeast Japan, Tamura et al. (2001) made observations about the relationships between regions of volcanic clustering, low-velocity zones in the mantle wedge, and the overall shape and positioning of local negative Bouguer gravity anomalies. What they propose is the existence of multiple hot, finger-like zones that extend all the way from deep within the mantle wedge (>150 km depth), to approximately 50 km depth (Tamura et al., 2001). Tomographic results and Bouguer gravity anomalies (not unlike those described in this research and that of Blakely et al. 1997) are cited as evidence for the presence of these fingers. They believe the Bouguer gravity anomalies are directly attributed to the supply of magma from the hot fingers, which subsequently accumulates at the Moho discontinuity (Tamura et al., 2001).

Although the hot finger model focuses on depths within the mantle wedge (substantially deeper than the mid-to-lower crustal region of interest in my research), it
still ties in well with other concepts that my model serves to validate. The hot fingers model ties in well with the volcanic clustering observed within the bounds of discrete negative gravity lineaments in the southern Cascade arc, as discussed by Blakely et al. (1997). It also provides a plausible deeper mantle source structure beneath the lower crustal hot zone proposed by Annen et al. (2006).

The Deep Crustal Hot Zone Model

The work of Annen et al. (2006) discusses subduction-related magmatism and what they propose is a deep crustal hot zone generated by successively emplaced, hydrous mantle-derived basalt sills. Their results support two isolated melt generation sources, including (1) the partial crystallization of emplaced, H₂O-rich mantle basalts, and (2) partial melting of surrounding deep crustal material (Annen et al., 2006).

Hydrous primary mafic magmas are generated by partial melting of the mantle wedge, and it is the abundance of H₂O-rich fluids from the subducting slab that contributes to lowering their viscosity and density. This means they easily detach from their source, and subsequently experience rapid, adiabatic ascent toward the surface (Annen et al., 2006). As the magma approaches shallower depths and begins to crystallize (due to decompression and degassing), its viscosity also increases. This can cause it to stall in the shallow crust, and to form either a volcano-feeding magma chamber or an intrusive body like a pluton (see Figure 5.2 for conceptual rendering of the hot zone model) (Annen et al., 2006).
With Park and Ostos' (2013) MT model and cross-section as a general guide for lower-to-mid-crustal conductor geometries - the Lassen gravity model results appear to fit decently within the parameters of the hot zone model. While Annen et al. (2006) primarily focus on deep crustal structure and processes, their conceptual representation of their model (Figure 5.2) also provides some illustration of what they describe in the upper crust (~3-10 km depth). It seems reasonable to consider that the shallow, resistive, intrusive body proposed by Finn and Williams (1982), beneath Medicine Lake volcano, is actually the end-member body in a system similar to what is described by Annen et al. (2006). It may be the result of multiple injections of magmas formed by partial melting that adiabatically ascended through the crust, crystallized (increasing in both viscosity and density), and then stalled and cooled. This coincides with Finn and Williams' (1982) conjecture that the Medicine Lake intrusion was most likely the result of multiple injections of magma built up over time, and may actually still be partially hot or even molten. It wouldn't make sense to entirely discount the possibility that similar systems could exist at depth beneath both Lassen and Medicine Lake Volcanoes.

The primary focus of my research has been the lower crustal body (a) from the gravity model, which may or may not directly underlie Lassen Volcano. Due to the nature of my model, and one of its principal objectives being to test the validity of the mid-to-lower crustal conductor geometries proposed by Park and Ostos (2013), it was necessary to model gravity data extracted precisely along the same profile as where their MT measurements were taken. It is important to note that this profile does not directly transect Lassen Peak, but rather traverses an area just slightly to the north
Figure 5.3 provides a projected view of the modeled bodies (and their respective geometries) in conjunction with their approximate locations along the actual profile. It's clear that body (a) cannot explicitly be attributed to the negative anomaly that underlies Lassen Peak (for which the excess mass calculation was also performed). It is also well within reason to suggest, however, that the negative anomaly directly beneath Lassen is either (a) actually attributed to body (a), as supported by both the gravity and MT models, or (b) is incredibly similar.

Looking at sections (2) and (3) (the 'Hot Zone' portion) of the Annen et al. conceptual representation of their model (Figure 5.2), it makes sense how a body of similar shape, size, and density readily fits in with their hypothesis. The lower crustal body (a) modeled beneath Lassen appears to consist of slightly older residual mantle-source melt that is rapidly rising through the hot zone. This agrees with the inference by Park and Ostos (2013) that there is an arc-related source of basaltic magmatism directly within the arc itself, and that the impinging Basin and Range asthenosphere is most likely just a second source of basalts. Furthermore, Park and Ostos (2013) speculate that Lassen is explained by melt fractions of less than 10%. The framework of the hot zone model by Annen et al., (2006) suggests that mantle basalts (sills) crystallize from their injection temperature to that of the geotherm. This results in a wide variety of residual melt fractions at any given time. These range from near 100%, in the case of newly injected material near the Moho, to 0% in the case of older material being injected into the lower crust. It is plausible that, eventually, this residual melt (at depth) may detach
and rapidly, adiabatically ascend through the upper crust to form a shallow storage reservoir directly beneath Lassen Volcano.
Figure 5.1 Gravity anomaly map generated using airborne gravity data and GMT. The white circles indicate the discrete gravity depressions that house Medicine Lake and Lassen volcanoes in northern California. As you can see, Medicine Lake and Shasta are both near the out edges of their trough, as is Lassen Peak.
Figure 5.2 [Taken from Annen et al., 2006] Conceptual representation of hot zone model (not to scale). Illustration shows sills of mantle-derived basaltic magma injected at various depths, including (1) the Moho, (2) the lower crust, and (3) the Conrad Discontinuity (between the lower and upper crust).
Figure 5.3 An estimation of model body geometries from above, including their approximate locations along the profile.
Chapter Six: Conclusions

(1) The overall interpretation of gravity anomalies in the Lassen region provides additional evidence of mid-crustal magma bodies (hot zones) beneath Lassen volcano and in the surrounding Lassen Volcanic Center.

(2) Gravity anomalies analyzed within the scope of this study agree well with previous observations made by Richard Blakely et al. (1997) in the Lassen region, particularly with respect to regional characteristics and clustering of volcanoes. The overall shape and orientation of the equidimensional regional gravity depressions described in their work, as well as the distribution of volcanism, appear to tie in well with the *Hot Fingers* model proposed by Tamura et al. (2001).

(3) The forward gravity model in this study agrees well with the magnetotellurics (MT) study conducted by Park and Ostos (2013), which they interpret as indicative of locations and depths of mid-crustal magma bodies in the Lassen region.

(4) The excess mass and volume of anomaly (a), approximately underlying Lassen volcano, are estimated to be $-2 \times 10^{14}$ kg and $7 \times 10^{11}$ m$^3$, respectively.

(5) The occurrence of the hot zone(s) may well provide a means of relating silicic volcanism at Lassen Peak with regional, distributed mafic volcanism.
Chapter Seven: 
Recommendations

3D Modeling

Among the primary recommendations in terms of continued study at Lassen Peak and in the surrounding region, is to explore more advanced 3D modeling capabilities. Geosoft has developed a GM-SYS 3D extension for Oasis montaj that enables the construction of layered earth models using various combinations of gravity, magnetic and seismic data. This enables visualization and modeling of complicated three dimensional subsurface structures at a variety of scales, and could potentially improve our interpretation and understanding of the complex magmatic system that exists beneath Lassen (Geosoft, 2015).

This method of modeling presents a unique advantage in that it allows for the construction of an unlimited number of irregular layers, as well as to view them in three dimensions from any angle and/or position inside or outside of the model (Geosoft, 2015). This allows closer, more thorough examination of various aspects and portions of the model than is possible in a $2^\frac{1}{2}$ or $2^\frac{3}{4}$ case. In addition to gravity and magnetic data, integration of seismic data enables the user to derive time horizons and velocities that can be directly converted into a "depth" model (Geosoft, 2015).
References


