Senior Thesis

Geophysical Attributes of Earth's Hotspots and Their Potential Associations with Mantle Plumes

By
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Approved by:

Dr. R.R.B. von Frese

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Acknowledgments

I would like to dedicate this thesis to all those that patiently gave their time to help me to learn of this process that greatly influences our planet, namely; Dr. R.B. von Frese, Dr. Barton, Dr. Noltimier, Orlando Hernandez, Tim Leftwich, Mohammad Asgharzadeh, The Department of Geological Sciences of The Ohio State University, and my friends and family.
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Images of an experiment using chilled lighter density Kroger hand soap and heavier Avon bath soap. A) This image shows the quick turning over of fluids as they are settling. A rippling affect is beginning to take place at the surface of the soap. B) More displacement is taking place in the soap. The clear Kroger soap has moved above most of the purple Avon bath soap. More distinct rippling is taking place. C) At the top the rippling effect is taking place and now 3 plume bodies are apparent in the purple Avon soap. D) More of the clear Kroger soap has moved to the top of the container and plume bodies are moving up and also developing.
Geophysical Attributes of Earth’s Hotspots and Their Potential Associations with Mantle Plumes

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Abstract

On the global scale, hotspots vary gravimetrically and in their elevation and magnetic properties. Some hotspots may have shallow origins and some may be from deeper mantle plumes. I investigate these properties for insight on what makes up hotspots and their subsurface attributes. I model the mantle plume geometry to help define their gravity signals. By comparing the observed and simulated gravity signals, we can constrain the geometry of the subsurface. Scale modeling with soaps can help us visualize the analogous dynamics of mantle plumes due to the related subsurface.

Introduction

Earth Scientists experience observed changes in our moving and morphing planet that we live on. Since the acquisition of satellite technology, we have observed plate motions and tidal changes. We can see geoidal anomalies or swells in the assumed spherical-like shape of our planet. On these swells in the oceans we see anomalous relief of the water’s surface with hundreds of feet in height variation. These zones of high
gravity in the oceans can vary the heights of sea level by hundreds of feet. What is causing this swelling in the crust?

Some of these zones are speckled with volcanoes that sometimes follow various patterns. These volcanoes may align in straight lines while others may be scattered. In some cases near the swells we find massive flood basalts. The basalts are very thick layers of mantle magma that cover huge areas of the sea floor. It is the same type of magma that we see covering large portions of the moon.

Dating these magmas by paleomagnetism and radiometric methods shows that the oldest sections are much more extensive than the younger ones. One could assume that something is coming up from the depths, causes a swell and cracks the crust to produce conduits for volcanoes. The magma is first quickly released and then slows down. What is going on down there?

Since the seventeenth hundreds very profound scientists have studied gravity extensively. They found slight gravity variations on the earth’s surface at different locations. Now we know that these variations tell us about the different shaped structures of the subsurface that may include sources at relatively shallow and/or great depths. Gravity observations allow us to observe plate subduction, spreading centers, mantle anomalies at depths, and of course, we can see what is thought to be mantle plumes.

These bubbles of basaltic magma have different densities than the surrounding mantle and crustal rocks. They move slowly but ascend faster than the viscous flows of the mantle. Additionally, they may take millions of years to ascend to their final destination point. As they ascend, they bring all sorts of mantle xenoliths with them. This allows us to see what is happening at great depths. It is thought that these plumes begin
their journey from the core mantle boundary and (depending on the mantle flow direction) move as other forces act on them. These phenomena can be observed gravimetrically in many instances (Condie, 2001).

Once this plume body reaches the crust its response varies depending on the crustal thickness and composition. A plume ascending underneath North America, for example, responds like The Yellowstone Hotspot, creating significant flood basalts, zones of hydrothermal activity and calderas. On the other hand, if the plume ascends under an oceanic ridge, mixed volcanism is observed. As a result, variations in the gravity at each of these zones are observed. The response is analogous to an iceberg floating in the North Sea and an American Navy Submarine needing to ascend. In this case, the submarine would pop through a few feet of ice with minimal trouble whereas if there were a very large and deeply rooted iceberg in the submarine’s path, there would be many more complications. When the submarine was ascending one may assume it would rise along the path of least resistance. Most hotspots are observed on oceanic crust where extensive crustal roots pushing down into the mantle are generally absent. Is that surprising?

One would think the geometries and general properties of plumes would be observable in the surficial hotspots they form. In this study, the hotspots are categorized by their gravitational signals to determine general features attributed to hotspots on a global scale. I also investigate the geometry of the Iceland’s Plume and hotspot. This is of great significance because there is much to learn about hot spots and mantle plumes and how they may potentially impact our planet.
Gravity Across Hotspots

A hotspot is the location of mid-plate magmatism that may or may not be plume related. It is a zone of higher heat flow and noticeable magmatisim. Figure 1 shows an example of the Hawaiian hotspot. It is plume derived with petrology consisting of basalts with greater amounts of heavier metals and usually a gravity high and geoidal high or swell in the crust. The thickened crust and excess of mantle rock produces a gravity high.

A plume body presumably is a bubble like structure composed of rocks of a lower density than the surrounding mantle. The magma is injected into the lithosphere, the solid crust, and erupted onto the Earth’s surface to form basalt flows. It is possible to observe a plume body without an associated hot spot or by some anomaly a hotspot, however. It is thought that a hotspot may be a stage of an erupting plume body. A large eruptive event may occur due the forces of a plume to create flood basalts, which are large magmatic bodies of great thickness covering a lot of terrain. When a plume first erupts, it could cause a large event with the tail causing the later hot spot. Also, the plume body may reside within the crust and allow for a certain amount of magma to ascend to produce a hotspot at the surface. Nature generally has a multitude of variations so there may be many possibilities as to what lies beneath a hot spot and how mantle plumes operate.
The gravity across a plume varies from plume to plume. It is generally understood that there are three gravity components associated with of the entire plume body as shown in Figure 2. These components include the terrain gravity effect, the gravity anomaly from the lower density ascending mantle, and the summation of these effects.

When the plume makes the accent from the Core-Mantle boundary (i.e., the D" zone), it has a cylindrical geometry that may interact with other mantle bodies upon accent to alter the direction of the plume's accent. The plume is brought up by a combination of mantle convection and buoyancy forces due to the related density variation within the mantle that leads to observed gravity variation.

For simplicity let us assume there are no interactions with other mantle bodies. In this case, a circular gravity low characterizes the region above the plume. Once the plume
body reaches the Moho, or the crust – mantle boundary, it changes shape therefore modifying the observed gravity. According to laboratory experiments this density variation can cause either large bubbles with a tail or a lateral spreading mushroom geometry. The fluid dynamic model of a plume body (van Keeken, 2000) may produce a geometry with curled wings that would open up upon ascent as shown in Figures 2 and 3. If the plume expressed lateral spreading or mushroom geometry, a negative smaller gradient signal will appear over a large region as well.

Once the magma has come closer to the surface or been expelled, a hotspot is produced. By definition the location is still extremely hot with temperatures maybe 1,000°C at depth. Figure 2 gives the regionalized gravity defined by a significant gravity high close to 20 mgals relative to the country rock or adjacent rock body.

When the negative plume gravity is added to the positive terrain gravity, a total residual gravity anomaly is determined as shown in Figure 2. According to the cross section, the plume gravity is about -40 mgals and the terrain gravity is over 80 mgals resulting in a reduced residual gravity at the anomaly's center that is a little over +40 mgals. Figure 2 shows that the gravity anomalies change depending on the geometry of the plume body. If the region was in a significant regional low, like The Bermuda Hotspot for instance, the hotspot itself may only produce a small field of relative increase in gravity with respect to the surrounding country rock. In the global gravity field of Figure 4, only a regional low would be perceived due to the lesser detail in the map. For the Iceland Plume that is in a regional high, an even higher gravity anomaly characterizes the hotspot. The regional effect plays significantly into the interpretation of the overall gravity observations.
Figure 2 Generalized distribution of gravity anomalies across a plume body. (http://bullard.esc.cam.ac.uk/~keith/Physics_Earth_Planet/Dan1/figures.html)

Figure 3 A) The mushroom shaped geometry. According to this model it would open up laterally. The image represents a plume body ascending from the core mantle boundary and spreading near the base of the crust. (http://www.le.ac.uk/geology/art/g1209/lecture7/qsts/7_qsta.html) B) The global distribution of mantle plumes. (http://www.geolsoc.org.uk/photos/plumes1.gif)
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**Table 1.** Hotspot correlations with gravity anomalies and tectonics.
Figure 4, gives the earth’s gravity anomalies overlain with the hotspots for comparison. Some hotspots are characterized by regional gravity highs while others are on gravity lows. For example, compare the MacDonald hotspot versus the Cape Verde hotspot in Table 1. The Macdonald hotspot is 5 mgals while the Cape Verde hotspot is 30 mgals. However, from Figure 4 we see that they are both on oceanic plates. To determine why these hotspots yield different gravity signals, we must compare the regional bathymetric signals versus the gravimetric signals.

According to Morgan (1971), there are 20 plume bodies while Condie (2001) suggests forty hotspots. A single plume body may contribute to a number of hotspots. In the Ring of Fire of the Pacific Ocean, there is a concentration of hotspots that may result from a single plume body that would produce a significant geoidal anomaly. When a plume ascends, it pushes up on the crust creating a swell about a kilometer or more in height variation (Condie, 2001). For most hotspots, there is a geoidal anomaly.

Table 1 compares the different gravity signatures for assessing potentially similar subsurface properties. The hotspots with lower gravity may have little terrain effect and very large sizes while some of the older hotspots developed large masses of basalt that will give a higher gravity signal. Compared to oceanic hotspots, there clearly are very few continental hotspots. It appears that plume bodies prefer to move along the flanks of the continental crust.
Figure 5. World geoid anomaly with hotspots (Condie, 2001).
(http://www.csr.utexas.edu/grace/gallery/gravity/03_07_GRACE_earthgeoid.html)

Figure 5 suggests an apparent correlation between geoid anomaly and the global hotspot distribution. The Hawaiian or Yellowstone hotspots, for example, are characterized by strong positive geoidal anomalies. The hotspots in geoid lows may be young hotspots or are products of small plume bodies not large enough to produce significant swells. Figure 6 shows the strong correlation between the geoid anomaly and the topography on Oahu, Hawaii. Hawaii has significant flexure in the crust with the islands popping up out of the curved crustal mass. The islands work like a piece of paper moving across a burning candle with flames that pierce through and push the paper up.
At global, regional, or local scales the residual gravity, geoidal anomalies, and topography form a relatively strong correlation. The combination can be analyzed to determine what is happening in the crust or in the mantle. For example, Figure 6 shows that the Hawaiian topography and gravity are fairly well correlated.

Hotspots in oceanic basins sit on swells with relief of 500-1000 feet relief and have widths between 1000-2000 feet (Condie, 2001). On continental plates the vertical relief can be as much as 4 kilometers. Yellowstone is an example of a continental hotspot with significant continental swelling and extended flood basalts.

Figure 7 shows another association between hotspot gravity anomalies and the petrology of the magmas that were extruded. There is a direct correlation between the isotopic analysis of strontium and gravity highs in hotspots. Where there is a greater ratio of heavier strontium to lighter strontium there is also a higher gravity signature. On a
global scale, higher density plume magmas involve heavier isotopes of strontium that along with the plume geometry produce a higher gravity anomaly. By determining the density variations of the magmas due to the strontium isotopic ratio, we can infer greater accuracy in our geometric models of hotspots and mantle plumes.

**Figure 7** Isotopic ratio correlation of plumes and gravity anomalies. (http://www.blackwell-synergy.com/links/doi/10.1046/j.1365-246X.1998.00609.x/full/)
Iceland (Figure 8) is an example of a mantle plume that produces a hotspot. It currently is adjacent to the Mid-Atlantic Ridge and significantly interacts with the ocean ridge. Regionally, there is a high gravity anomaly and a significant geoidal anomaly or swell in the crust. The petrology shows that there are zones of normal ridge basaltic magma and basalts with higher levels of rare earth metals near the hotspot. Current questions include the interaction taking place between the magmas below Iceland, as well as the nature of the mantle geometry of the plume body and the Mid-Atlantic Ridge.

It is thought that a plume body stays motionless while the plates move over it (Morgan, 1971). The Iceland hotspot started under Greenland, moved to the ridge, possibly forming Iceland and currently is adjacent to on the ridge. The gravity profiles
along with bathymetry and geoidal profiles can provide insight on what is currently taking place under Iceland.

Figure 9 shows the bathymetry of Iceland, the relative height from the base of the sea floor, and allows us to see how much the plume body pushes up below Iceland. By looking at a combination of bathymetry, geoidal anomalies and gravity anomalies, models can be developed to represent the geometry we are after.

The geoidal anomaly of Iceland in Figure 10, that is associated with the mantle plume has a kilometer or more of vertical relief. This is also the case in Hawaii where The Big Island is one of the largest mountains in the world relative to the sea floor.

Figures 9 through 11 show the observed anomalies with inferred crustal cross sections that are later used in Figure 12 to model Iceland’s Mantle Plume.

![Iceland Bathymetry](image)
The bathymetry (Figure 9a) data show an incredible view of Iceland’s relief of 1.6 km with its jagged edges that developed above and below the water level. The Ridge on this diagram is centrally located at about -22° W. The change in topography from the central valley over to the jagged ridges adjacent shows the hotspot’s ability to push up the Mid – Atlantic Ridge enough to form the Island.

Figure 10 shows the prominent geoidal anomalies for the Iceland region. It is amazing how much pressure can come from the density contrasts of the plume. In Figure 10a, it is difficult to differentiate between the plume anomaly and the Mid-Atlantic Ridge anomaly. Figure 10b makes the hotspot anomaly more apparent. Because the peak is to the right of the graph, it seems that one can assume a great part of this localized anomaly maybe due to the hotspot plume. Figure 10b also shows that the ridge is resting at -22° W so that Iceland’s geoidal anomaly maximum is located at -18.3° W.
Figure 10A) Iceland’s geoidal anomaly with profile from figure 8.B.(blue line). B) Iceland’s geoidal anomaly profile with The Mid-Atlantic Ridge at -22°W and Iceland’s Hotspot at -18.3°W. (Leftwich (in-review), and Lemoine et al).

Figures 11a and 11b represent the free air gravity anomalies at twenty kilometers altitude above the surface of the earth. It is apparent that the hotspot plume produces a much higher gravity signal than the ridge.
Figure 11

A) Iceland’s free air gravity anomalies at 20 km with profile from figure 11.B (blue line). B) Iceland’s gravity profile (67°N, -30.0°W) and (63°N, -10°W) (Leftwich (in-review), and Lemoine et al).

Figure 11b shows the free air gravity anomaly profile with the locations of the Mid-Atlantic Ridge and hotspot. These gravity highs clearly correlate with figures 9b and 10b to define the association between gravity anomalies, geoidal anomalies, and regional bathymetry.
When looking at the plume body, a gravity low, adds to the terrain effect at its location. The density of a plume body is about 3.25 g/cm³ while the mantle density is about 3.3 g/cm³. Figure 2 shows the general gravity distribution around a plume body and Figure 12 shows the free air gravity anomaly profile and the bathymetry profile of Iceland. Figure 12 also shows a 2-D view of the possible subsurface density structure of the plume that may account for its gravity and terrain effects.

With the given data of Iceland, GMSYS 4.6 can model the possible geometry of the plume body. In Figure 12 the black dots are the free air gravity anomaly profile and the red dots are the terrain or bathymetry. The oceanic crust was set at up to 10 km depth with a density of 2.85 g/cm³, the mantle is set to a depth 400 km for the effect with a density of 3.3 g/cm³, the mantle plume has a density of 3.25 g/cm³. There were 113 stations in the profile. The academic license for the GMSYS software would only allow 35 data points. Thus, to fit the full image on one page every fifth station reading was used. When filling in rock bodies a new gravity profile is found. This profile has to match closely to the actual gravity data in order to estimate the cross section of Iceland. This 2-D model provides a first-order approximation of the 3-D properties of the plume in the subsurface.
The Iceland Plume is very close to the geometry of this model. The modeled gravity effects on the west side of Figure 12 are fairly close to the actual data. The Plume body may not extend as far to the east but its center is very close to the high in the gravity signal. In order to bring the modeled gravity effects (black line) down on the left side of the model, more interaction or mixing between the mantle plume and the ridge may be needed. By this model there is significant plume - ridge interaction in Iceland, but the center of the mantle plume is 3.7° east of the ridge.
Scale Modeling of Mantle Plumes

In this section, I use soaps with different densities to model mantle plume dynamics. The soap representing the plume body involves lower density soap layered under higher density soap. This inverted plume model provides insight on how gravity and internal shear forces move the heavier fluid to the base of the container.

As a plume body ascends from the D” zone or the core-mantle boundary, it starts off as a small instability or bubble that stretches out vertically. Within the plume head the edges curl (Figure 3). The plume’s tail thins and a mushroom shaped structure forms. The edges of the bubble curl in toward the center. With time, the tail becomes thinner and the head spreads laterally with a thicker ring forming around its edges. By the time the plume body hits the lithosphere with a different density, there is significant lateral spreading and the tail is about the same thickness as an edge of a ring.

Figure 3 gives an idea of what the plume body would look like. The plume body would be much more complex, but for simplicity I began by making the simplest model and then progressed to models of greater complexity.

Figure 13 shows a reversal process in the room temperature soaps. The heavier soap (1.02g/cm³) is penetrating the less dense Dial soap (1.01 g/cm³) and producing the geometry we are after. The lateral spreading is due to resistive forces pushing the plume head away from its center, while the same process is most likely associated with the curling that is taking place.

In Figures 13a and 13b we can observe the plume body moving down with its bulbous head. Once there is contact with the fluid below, the red soap spreads
even more as shown in Figure 13c. There is significant curling and thickening around sides of the plume body. Figure 13d is taken from the bottom of the container to show analogous geometries of the curled ring to the tail. Figure 13e displays a view looking down on the plume body as it continues to spread laterally.

![Figure 13a](image1)

![Figure 13b](image2)

![Figure 13c](image3)

![Figure 13d](image4)

![Figure 13e](image5)

**Figure 13** Scale model of a plume body using Dial soap (1.01 g/cm³) and a more dense red bath soap from Avon (1.02 g/cm³). A) Descending higher density soap with distinct rounded head, curling wings and thick tail B) View of the higher density soap descending. C) View showing contact made between the
density boundaries. This is causing lateral spreading of the head and thinning of the tail. D) Bottom view of the soap container. The curled wings at the sides of the head are apparent and the tail is in the center. A ratio of 3:16 of the radius of the tail to the radius of the head can be observed. E) Top view of the plume body. The tail is very thin and the curled wings have a distinct ring look.

This experiment produces geometry that is closely analogous to the mantle plume geometry (van Keken, 2004). This experiment was not done to scale but merely to observe the fluid dynamics that may characterize mantle plumes. In Figures 13d and 13e, the ratio of the radii of the plume tail to plume head is about 3/16. Thus, the gravity modeling may provide useful constraints on this ratio. The modeling suggests, for example, that the tail of the Iceland plume is 45 km in diameter so that the plume’s head may be 240 km in diameter.

To observe more plume characteristics, another attempt was made using a lower density soap that was chilled with higher density, warmer soap poured on top of it. In Figure 14, the top of the soap container was cut off. This was done in order that when pouring the higher density soap on to the lower density soap, there would not be immediate displacement of just a single point on the surface. The goal of cooling the lower density soap was to prevent it from responding too quickly to the load imposed by adding the higher density soap. There needed to be enough time to completely deposit the higher density soap on the surface of the lower density soap so the plume’s ascension could be observed. The soaps chosen were relatively transparent, but colored to better depict the plume geometry.

When the experiment was done, too much of the chilled lower density soap was used relative to the warmer, higher density soap that was used. Thus, a high number of plume bodies can be seen and there is significant displacement. Look at the ripple effect seen in Figure 13 from all of the plume bodies. In Figures 14c and 14d there appears to
be another set of plume bodies moving up of much larger size and magnitude. Figure 14 shows some new features such as the wrinkling at the surface and up to 3 plume bodies. Depending on the amount of lighter soap used more plume bodies will form, not just one. It is impressive that so much motion was produced in this experiment.

![Figure 14a](image1.png) ![Figure 14b](image2.png)  
![Figure 14c](image3.png) ![Figure 14d](image4.png)

Figure 14 Images of an experiment using chilled lighter density Kroger hand soap and heavier Avon bath soap. A) This image shows the quick turning over of fluids as they settling. A rippling affect is beginning to take place at the surface of the soap. B) More displacement is taking place in the soap. The Clear Kroger soap has moved above most of the purple Avon bath soap. More distinct rippling is taking place. C) At the top the rippling effect is taking place and now 3 plume bodies are apparent in the purple Avon soap. D) More of the clear Kroger soap has moved to the top of the container and plume bodies are moving up and also developing.

To better represent plume bodies, the soap densities must be better scaled to the actual plume densities. The critical plume densities include values such as 2.85 g/cm³ for the oceanic crust, 3.3 g/cm³ for the mantle, and 3.25 g/cm³ for the ascending mantle.
material of the plume. When making a representative soap model, one would need to find soaps with the same respective density ratios. However, my primitive soap experiments demonstrated possible geometries and respective ratios of parts of the plume. These size ratios have analogous geometries to that of true mantle plumes with appropriately scaled model densities.

**The Future of Plumes**

Our curiosity of mantle plumes and how to detect hotspot – plume interactions have a number of benefits. Granted the shear size of these plume bodies, depending on the amount of magma erupted one could imagine the amount of green house gases expelled. There is a direct association with the amount of basalt erupted and the amount of gas expelled (Condie, 2001). In some events there may be significant magma erupted as well as significant gas release, namely green house gases. In the event of a super plume, it may inject the atmosphere with significant CO₂ causing global warming in less than 50 Ma (Condie, 2001).

Mantle plumes have an association with kimberlite pipes. The Trinidad Hotspot at one point was on Brazil and there are numerous kimberlite pipes adjacent to its tracks (Condie, 2001). The kimberlite pipes are about 5° offset in all directions surrounding the Trinidad hotspot tracks. Globally there may be more kimberlite pipes associated with hotspots. In the case of the Trinidad hotspot, the crust may be thin and in forming the geoidal anomaly, faulting in the crust may allow for quick ascension of kimberlitic magma.
Mantle plumes historically have added to the puzzle of describing plate tectonics. In Figure 1, we can see in Hawaii the motion of the Pacific Plate due to the hot rock burning through it and thus showing us the path it has taken. This observation suggests that other plates may move relative to the plumes that are below them. Since it is thought the plume bodies are stationary, we can infer the plate history and therefore describe the dynamics of Earth’s surface through past time and possibly into the future (Morgan, 1971).

The general attributes of hotspots and their relationship to mantle plumes result in a gravity high relative to a geoidal high and a generally high crustal relief. The plumes below them yield fairly well defined gravity anomalies. Iceland functioned as one example to describe the properties and correlations of hotspots and mantle plumes. The modeling in Figure 12 reveals the possible correlation between terrain and gravity parameters of hotspots. The scale modeling of plumes displayed variations (Figure 13 to Figure 14) depending on the proportions of each soap used. If there was flow other than in the vertical direction, the plume body may move within the solution to alter its shape and size (Condie, 2001).
References Sited


(http://www.ciw.edu/plume3/abstracts/vanKeken.pdf)