Neuro-Fuzzy Classification of Felsic Lava Geomorphology at Alarcon Rise, Mexico

Christina Hefron Maschmeyer
University of South Carolina

Follow this and additional works at: https://scholarcommons.sc.edu/etd
Part of the Geology Commons

Recommended Citation

This Open Access Thesis is brought to you by Scholar Commons. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Scholar Commons. For more information, please contact dillarda@mailbox.sc.edu.
NEURO-FUZZY CLASSIFICATION OF FELSIC LAVA GEOMORPHOLOGY AT ALARCON RISE, MEXICO

by

Christina Heffron Maschmeyer

Bachelor of Science
College of Charleston, 2014

Bachelor of Arts
College of Charleston, 2014

Submitted in Partial Fulfillment of the Requirements
For the Degree of Master of Science in
Geological Sciences
College of Arts and Sciences
University of South Carolina
2016

Accepted by:
Scott White, Director of Thesis
Michael Bizimis, Reader
Brian Dreyer, Reader
Lacy Ford, Senior Vice Provost and Dean of Graduate Studies
DEDICATION

This thesis is dedicated to Dr. Jim Carew for making me go to graduate school.
ACKNOWLEDGEMENTS

Data for this study were collected during cruises in 2012 aboard the R/V Zephyr and R/V Western Flyer and during 2015 on the R/V Rachel Carson and R/V Western Flyer from the Monterey Bay Aquarium Research Institute. I want to thank the captains, crews, ROV pilots and science parties for their work during these expeditions. Special thanks to Brian Dreyer, Dave Clague, and Jenny Paduan at the Monterey Bay Aquarium Research Institute for sharing their data, insights, and knowledge with me during this project. Support for this project was provided by the College of Arts and Sciences at the University of South Carolina.

Special thanks to my primary advisor, Scott White, for his support and guidance during this project. I also want to acknowledge my committee members, Michael Bizimis and Brian Dreyer for their insight to my work. Thank you to my family, friends and mentors for their love and encouragement throughout my education and life. Finally, I want to thank my husband, Josh Maschmeyer, for his continual love, insight, and laughter as I pursued this degree. Thank you for being my best friend.
ABSTRACT

The Alarcon Rise is the only submarine oceanic spreading ridge setting where rhyolitic lavas have been found. This intermediate-rate spreading ridge provides a unique natural laboratory for studying the geomorphology of felsic submarine lava flows at oceanic spreading ridges. Seafloor observations of felsic lava indicate the flow morphology differs from typical submarine basaltic lava at the few other oceanic spreading ridges where differentiated compositions have been recorded. Morphologic variation between mafic and felsic lava flows, especially rhyolites, was also observed at Alarcon Rise.

The Monterey Bay Aquarium Research Institute conducted mapping surveys with autonomous underwater vehicle D Allan B. in 2012 and 2015. The 1 m lateral resolution bathymetry produced from these surveys allowed sampling expeditions with the remotely operated vehicle Doc Ricketts in 2012 and 2015. We recovered all felsic lava samples along a ridge at the heavily-faulted north end of Alarcon, just south of the Pescadero Transform Fault. The ridge included a steep sloping, sub-rectangular rhyolitic complex. Angular, blocky spires at this complex are spaced ~10 m apart, appearing jagged in the 1 m resolution bathymetry.

To determine if morphology can be used to identify compositional variation in lava, we produced a semi-automated pixel-based classification that identifies geomorphic characteristics we believe to be indicative of felsic lava flows. We constructed an
adaptive-neuro fuzzy inference system to distinguish between the jagged, rough lava flows produced by felsic lavas and smooth basaltic lava flows. To capture the steep sloping high-silica dome features, we derived local max slope over a 3 m distance from the 1 m resolution bathymetry. We also calculated bathymetric position index at a 0.5 km radius to distinguish the surface roughness in the felsic region from smoother basaltic flows at Alarcon Rise. Our classification is the first attempt at automating recognition of compositional variation of lava erupted at oceanic ridges.
# TABLE OF CONTENTS

DEDICATION .................................................................................................................. iii

ACKNOWLEDGEMENTS ................................................................................................... iv

ABSTRACT ....................................................................................................................... v

LIST OF TABLES ................................................................................................................. ix

LIST OF FIGURES ............................................................................................................. x

CHAPTER 1 INTRODUCTION ............................................................................................. 1
  1.1 BACKGROUND .......................................................................................................... 1
  1.2 GEOLOGIC SETTING ................................................................................................. 2
  1.3 RIDGE DESCRIPTION ............................................................................................... 4
  1.4 SUBMARINE LAVA MORPHOLOGY .......................................................................... 4

CHAPTER 2 DATA COLLECTION ....................................................................................... 9
  2.1 SEAFLOOR MAPPING EXPEDITIONS .................................................................... 9
  2.2 IGNEOUS ROCK SAMPLE COLLECTION ................................................................ 9

CHAPTER 3 DATA PROCESSING ..................................................................................... 11
  3.1 VISUAL INSPECTION .............................................................................................. 11
  3.2 BATHYMETRIC PROCESSING ................................................................................ 12
  3.3 TRAINING AND TESTING DATASETS .................................................................... 14

CHAPTER 4 CLASSIFICATION METHODOLOGY ............................................................... 17

CHAPTER 5 RESULTS ....................................................................................................... 21
5.1 Accuracy Assessment .................................................................24

Chapter 6 Discussion .....................................................................26

6.1 Geomorphic Implications ........................................................26

6.2 Pixel-Based versus Object-Based Classification ......................28

6.3 Future Work ...........................................................................28

Chapter 7 Conclusions ..................................................................35

References ....................................................................................37
LIST OF TABLES

Table 3.1 Training and testing datasets from 2012 and 2015 samples .......................16
Table 4.1 Classification training results.......................................................................20
Table 5.1 Error matrix.................................................................................................25
Table 5.2 Accuracy matrix............................................................................................25
LIST OF FIGURES

Figure 1.1 Tectonic setting of the Alarcon Rise .........................................................3
Figure 1.2 Bathymetry of the Alarcon Rise and study area locations .......................5
Figure 1.3 Submarine lava morphology for basaltic lava at Alarcon Rise ..............7
Figure 1.4 Submarine lava morphologies of felsic lava at Alarcon .........................8
Figure 3.1 BPI scale analysis .....................................................................................13
Figure 3.2 Side-scan sonar backscatter shadows and holidays ..............................15
Figure 4.1 ANFIS workflow .....................................................................................19
Figure 5.1 Determining mafic and felsic classes .....................................................22
Figure 5.2 Classified lava flow at the Alarcon Rise .................................................23
Figure 6.1 Relative abundance of classified ground referenced samples .............27
Figure 6.2 Pixel-based classification of high-silica dome and basaltic mound .......30
Figure 6.3 Slope profile locations for felsic lava......................................................31
Figure 6.4 Locations of mafic lava slope profiles ....................................................32
Figure 6.5 Slope profiles of 5 felsic lava flows .........................................................33
Figure 6.6 Slope profiles of mafic lava flows .........................................................34
CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Oceanic crust erupted at oceanic spreading ridges covers 60-70% of the Earth’s surface. Oceanic crust is generally basaltic composition from the upwelling of mantle at divergent plate boundaries [White and Klein, 2014]. However, some instances of felsic submarine lava flows have been recorded at oceanic spreading ridges. These instances are generally associated with specific tectonic settings including areas of ridge-hotspot interaction, zones of ridge-tip propagation, and at ridge-transform fault intersections [Wanless et al., 2010]. The evolution of chemically evolved lava at these locations is attributed to cooler crust and/or low magma supply [Wanless et al., 2010; White and Klein, 2014].

Observations of submarine lava at oceanic spreading ridges describe different geomorphic characteristics for mafic and felsic compositions. We developed methods in this study that distinguish between the geomorphology of mafic and felsic lava flows at oceanic spreading ridges. We determined geomorphic characteristics from 1 m resolution multibeam bathymetry collected at the Alarcon Rise, Mexico. We created a semi-automated pixel-based classification to map areas along the spreading ridge where basaltic and more evolved lava compositions were identified. Identification of a geomorphic fingerprint of felsic lava may contribute to a better understanding of felsic lava formation at the oceanic ridge system.
1.2 GEOLOGIC SETTING

The Alarcon Rise is the southernmost en-echelon spreading ridge in the Gulf of California, located between Baja California Sur and mainland Mexico (Figure 1.1). The Gulf of California opened in the late Miocene as continental crust rifted. During the Pliocene and Pleistocene, rifting evolved to seafloor spreading as the tip of the East Pacific Rise propagated into continental lithosphere [Castillo et al., 2002]. Oriented northeast to southwest, Alarcon Rise is a typical intermediate spreading rate ridge with a full spreading rate of 50 mm/a [Fisher et al., 2001]. Two transform faults form the boundaries of the small spreading ridge (~5 km long). To the south, the Tamayo Transform separates the Alarcon Rise from the East Pacific Rise. The Pescadero Transform forms the northern boundary of the ridge and is located less than 8 km from North American continental crust [Castillo et al., 2002]. In 2002 Castillo et al. chose the Alarcon Rise as their study site to study the Transform Fault Effect (TFE).

TFE states cooler magmatic temperatures, elevated pressure fractionation and decreased melt extent produce a wider range of erupted lava composition at oceanic ridges intersected by transform faults [Langmuir et al., 1986]. Although Castillo et al [2002] expected to collect differentiated volcanic samples from both the south and north ends of the Alarcon Rise, they only retrieved differentiated basalt and basaltic andesite samples near the Pescadero Transform Fault. Castillo et al. [2002] tested the samples for contamination by continental lithosphere located ~ 8 km north of the Pescadero Transform. The Sr, Nd, and Pb isotopic signature from Alarcon was compared to that of Indian mid-ocean ridge basalt, which contains fragments of continental lithosphere embedded in the upper mantle beneath the Indian Ocean. No isotopic effects of
Figure 1.1. Tectonic setting of the Alarcon Rise. The Alarcon Rise (red box) is located in the Gulf of California, approximately 100 km east of San Jose del Cabo, Mexico. A series of en echelon spreading ridges comprises the Gulf of California, as the North American Plate diverges from the Pacific Plate. The Alarcon Rise is an intermediate-rate spreading ridge, with a full-spreading rate of ~50 mm/yr (Fisher et al., 2001). The Tamayo Transform Fault separates the Alarcon Rise from the East Pacific Rise as it propagates into the Gulf of California. The Pescadero Transform Fault intersects the Alarcon to the north.
continental crust assimilation were observed in the Alarcon samples [Castillo et al., 2002].

The Monterey Bay Aquarium Research Institute (MBARI) collected igneous rock samples from the Alarcon Rise in 2012 and 2015. The composition of the samples included basalt, basaltic andesite, andesite, dacite and rhyolite. The 2012 and 2015 expeditions by MBARI produced similar results to those conducted by Castillo et al. [2002]: samples collected from the northern region of the Alarcon Rise included both mafic and felsic lava uncontaminated by continental lithosphere.

1.3 RIDGE DESCRIPTION

The Alarcon Rise exhibits a variety of volcanic landforms associated with intermediate rate spreading ridges (Figure 1.2). The south portion of the rise is covered by a lava shield associated with increased spreading rate or magma supply [Perfit and Chadwick, 1998]. Sheet flows cover the majority of the shield except for a large (~700 m diameter) pillow mound west of the spreading axis. The central portion of the spreading ridge has a wider range of volcanic features including a flat-topped volcanic cone ~700 m in diameter. Sheet flows and pillow mounds also cover the surface. The heavily faulted north end of the Alarcon Rise resembles low temperature slow-spreading rate ridges [Perfit and Chadwick, 1998]. The abundance of faults and fissures 400-600 m long increases at north Alarcon Rise. Felsic volcanic edifices and basaltic pillow mounds create high-relief bathymetry.

1.4 SUBMARINE LAVA MORPHOLOGY

Basaltic submarine lava flows exhibit three basic morphologies (Figure 1.3). Submarine lava morphology reflects ridge spreading rate, lava effusion rate, underlying
Figure 1.2. Bathymetry of the Alarcon Rise and study area locations. The Alarcon Rise is approximately 50 km long and ranges in depth from ~2200-2800 meters below sea level (mbsl). 1 m resolution bathymetry was collected by AUV D Allan B. in 2015. We chose three study sites to compare the morphologies of felsic lava and mafic lava. ROV Doc Ricketts recovered all felsic lava from the north end of Alarcon Rise. Only basaltic lava samples were recovered in the central and south portions of the spreading ridge. The 1 m resolution bathymetry is underlain by a shaded slope layer calculated from the nearest-neighbor pixels of bathymetry.
topography, lava viscosity [Gregg and Fink, 1995; Perfit and Chadwick, 1998]. Cylindrical tubes or spherical pillow lava are commonly found at slow-spreading rate oceanic ridges. Pillow lava flows can create mound and dome shapes by piling on top of one another during eruption as lava cools slowly [Perfit and Chadwick, 1998]. Lobate flows represent a transitional phase to higher effusion rate and lower lava viscosity. Sheet flows are commonly found at fast-spreading ridges. Increased effusion rate and decreased viscosity creates low-relief sheet flows that take a variety of forms – from jumbled to smooth [Perfit and Chadwick, 1998].

The majority of submarine lava flow morphology studies have been conducted on basaltic lava. Our understanding of felsic lava flow morphology at oceanic spreading ridges comes from few seafloor observations. Wanless et al. [2010] describes andesites and dacites as large pillows with heavily corrugated surfaces. They also note that block talus and faulting is often associated with felsic lava. During the expeditions in 2012 and 2015, we also observed the occurrence of mega-pillows (~1 m diameter) with heavily corrugated surfaces. However, the most distinctive felsic morphologies were blocky, angular flows that occurred near the north felsic complex (Figure 1.4).
Figure 1.3. Submarine lava morphology for basaltic lava at Alarcon Rise. Three main submarine lava flow morphologies describe oceanic ridge basalt. Basaltic lava flow morphology is the product of ridge spreading rate, lava effusion rate, underlying topography, and lava viscosity [Gregg and Fink, 1995, Perfit and Chadwick, 1998] Basaltic pillows (left) form at oceanic ridges with slow spreading rates, or where lava viscosity is high (low temperature) and effusion rate is low. The bulbous shape of pillow basalts results from warm interior lava pushing outward through the quenched rind. Lobate and sheet lava flows (middle and right) form where lava effusion rate is high and viscosity is low. Sheet flows represent the fastest-moving lava. They can form smooth lava shields from laminar flow or ropy whorls and jumbled lava morphologies from turbulent flow. Lobate lava represents a transition from the conditions under which pillow and sheet flows form.
Figure 1.4. Submarine lava morphologies of felsic lava at Alarcon Rise. Morphologies of submarine felsic lava flows are not as well understood as those of basalt. Few instances of andesitic and dacitic lava have been documented at specific tectonic settings [Perfit and Fonari, 1983; Regelous et al., 1999; Wanless et al., 2010]. Many andesites and dacites have been described as large pillows with diameters of several meters (left). These pillows exhibit a “bread crust” texture with deep corrugations and extreme radial jointing. Some dacitic lava and rhyolitic lava (only found at the Alarcon Rise) form blocky, angular lava flows (right). These have been recorded at jagged domes ~500 m in diameter.
CHAPTER 2
DATA COLLECTION

Submarine volcanic features at oceanic ridges can be characterized with multibeam bathymetry and side-scan sonar backscatter [Chadwick et al., 2001; McClinton et al., 2013]. MBARI used autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) to collect seafloor mapping data and igneous rock samples from the seafloor to study the unique volcanic processes at the Alarcon Rise.

2.1 SEAFLOOR MAPPING EXPEDITIONS

During April 2012, MBARI deployed AUV D Allan B. from the R/V Zephyr to conduct high-resolution seafloor mapping of the Alarcon Rise. Equipped with a 200 kHz multibeam sonar system, D Allan B. completed 10 surveys along the spreading axis, operating 60-90 m above the seafloor. ~125 km² of seafloor were mapped at 1 m lateral resolution and 0.1 m vertical resolution. In 2015, MBARI conducted another survey at the Alarcon Rise, filling in critical sonar holidays at the rhyolitic lava complex at the north end of the spreading ridge. Using the methods outlined in Caress et al. [2008], multibeam data were processed in MBSystem to produce a digital elevation model that we used in this study.

2.2 IGNEOUS ROCK SAMPLE COLLECTION

Following the AUV mapping expeditions, MBARI completed two cruises in 2012 and 2015 to collect igneous samples along the Alarcon Rise. Using the remotely operated
vehicle (ROV) *Doc Ricketts*, we recovered 349 in situ lava flow samples in 2012 and 2015. 29 samples were collected from a rock crusher deployed off the R/V *Western Flyer*. Subsequent MBARI cruises retrieved an additional 21 samples. A total of 399 igneous samples were collected during the 2012 and 2015 field seasons.

The ROV navigation system (Sonardyne Ranger 2720 USBL with Lodestar AHARS) relayed the geographic coordinates for each sample to a geographic information system (GIS) aboard the R/V *Western Flyer*. The geographical uncertainty of samples collected by ROV *Doc Ricketts* in 2012 was approximately ~20 m. This uncertainty was reduced in 2015 to ~5m. Samples collected by rock crusher were assigned the ship’s geographic location at deployment. The location of the R/V *Western Flyer* is recorded by the Simrad MX512 global positioning system, and the locations of these samples were accurate within 10 m.

The majority of samples collected had basaltic compositions with melt MgO values (recovered from glass) ranging from 6.0-8.6 wt% [Dreyer et al., 2015]. However, some samples were collected from a ridge at 23° 33’ N, 180° 25’ W. These samples had low values of MgO and SiO2 values ranging from 57-78 wt%. [Dreyer et al., 2015] The range of lava compositions recovered from Alarcon Rise made it the perfect setting to study how submarine lava flow geomorphology varies with composition at oceanic spreading ridges.
CHAPTER 3
DATA PROCESSING

Data processing comprises a three-step workflow. First, we visually inspected the 1 m resolution bathymetry to analyze characteristics of the seafloor where we collected felsic samples. Second, we used the observations from visual inspection to create bathymetry-derived layers that represented our visual analysis. Third, we separated the ground-referenced samples into training and testing datasets for classification using an adaptive neuro-fuzzy inference system (ANFIS).

3.1 VISUAL INSPECTION

To determine physical characteristics that distinguished felsic lava flows from basaltic flows, we examined the 1 m resolution bathymetry collected by MBARI during 2015. We visualized the igneous samples in their spatial context using ArcGIS 10.3. Felsic lavas at the north end of the Alarcon Rise create jagged flows that span approximately 50 m diameter. Each feature contains multiple peaks spaced approximately 10 m apart from one another. These flows build elongate ridges and sub-rectangular, steeply-sloping jagged domes. Elongate fissures and faults ~400-600 m also dominate the north Alarcon area. Basaltic lava flows, even quasi-circular pillow mounds, appear smooth in 1 m resolution bathymetry. Basaltic dome slopes are generally lower than those found in the felsic area. Seafloor texture appears “bumpy” at a regional scale.
3.2 BATHYMETRIC PROCESSING

Bathymetric data at 1 m resolution are particularly useful to identify volcanic features related to diking, faulting, and lava flow emplacement [Chadwick et al., 2001]. We used processed 1 m resolution bathymetry rasters collected and post-processed by MBARI to classify the geomorphology of felsic lava at Alarcon Rise. We created two secondary layers from the original bathymetry. Maximum slope was calculated in degrees from nearest neighbor measurements. Slope was assigned to the central pixel in a 3x3 moving window as the greatest difference between the central and adjacent pixels. Slope has proven useful in description and classification of submarine lava morphologies [Batiza et al., 1989; White et al., 2002; Meyer and White, 2007; McClinton et al., 2012].

Bathymetric position index (BPI) was also derived from the high-resolution bathymetric imagery. BPI is the vertical difference between the depth of a point on the seafloor and the mean depth for a region [Lundbald et al., 2006]. BPI is a measure of seafloor roughness at different scales and has been successfully used to classify benthic terrain [Lundbald et al., 2006; Diesing and Stephens, 2015]. We calculated BPI at multiple scales – 10, 25, 50, 100, 200, 500, 700, and 1,000 m – to capture the variation in roughness between the felsic lavas and mafic lavas. The 0.5 km scale was large enough to distinguish local shallow spots (bumps) from the mean depth and small enough to account for variation in volcanic structures including basaltic pillow mounds and the felsic complex (Figure 3.1).

Although backscatter intensity collected from side-scan sonars have proven useful in classifying submarine lava morphologies [e.g. Stewart et al., 1994; Gao et al., 1998; McClinton et al., 2012], we decided not to incorporate sonar backscatter to our .
Figure 3.1. BPI scale analysis. Bathymetric position index (BPI) is calculated as the difference between the depth of an individual pixel and the mean depth over a user-defined radius of seafloor. In our study we experimented with various BPI radii to create a classifier input that captured the bumpy texture of felsic lava. Smaller radii (top) showed little to no difference between the mean texel depth and the depth of an individual pixel, even if that pixel represented a bathymetric high. Therefore, we increased the radius to 0.5 km to get a regional mean depth to find localized bumps in the seafloor (bottom).
classification. Acoustic backscatter energy is influenced by seafloor roughness and surface acoustic properties [Gao et al., 1998]. The spatial density of faults at the north end of the Alarcon Rise created extensive sonar shadows and data gaps in our area of interest (Figure 3.2). We calculated gray-level co-occurrence matrices (GLCMs) from sonar backscatter to determine if we could extract any useful seafloor texture information that would distinguish between mafic and felsic flows [Haralick et al., 1973]. When we compared the mean values of different GLCMs for mafic and felsic flows, the values were similar for felsic lava flows and mafic pillow mounds. Thus, we based our classification on bathymetry-derived products.

3.3 TRAINING AND TESTING DATASETS

399 of the 480 samples collected during 2012 and 2015 were igneous rocks. The remaining samples were a combination of mudstones and sulfides created at hydrothermal chimneys. Igneous sample compositions encompassed basalt, basaltic andesite, andesite, dacite and rhyolite. We divided the ArcGIS point shapefiles with corresponding composition tables for these rocks into two datasets: training data and testing data. Of the 399 igneous samples only 334 samples could be used for these datasets (Table 3.1).

Training data are geo-referenced points with a ground-referenced composition that best represent a specific class. The two classes we wanted to identify were mafic and felsic (including basaltic andesite, andesite, dacite, and rhyolite). We did not require a sediment class because we focused on the neo-volcanic zone with little sediment cover. Even where sediment cover was thick (~1 m), distinct lava geomorphic features could be distinguished from the surrounding area. 134 rock samples were chosen to train ANFIS.
Figure 3.2. Side-scan sonar backscatter shadows and holidays. Faulting at north Alarcon Rise created sonar holidays and shadows that created a striped pattern along the felsic ridge. Although the rhyolitic complex appears to exhibit a distinctive backscatter texture, too many samples along the ridge were located within the striping zone to determine a distinctive felsic seafloor texture using GLCMs.
We identified 72 basaltic samples and 62 felsic samples along the mapped neovolcanic zone of AlarCON Rise. Training points were picked where multiple ground-referenced samples had the same composition. Samples within the training dataset were used during the ANFIS learning cycle to identify geomorphic differences between mafic and felsic lava; thus it was important that training points represented the seafloor composition to decrease confusion during classifier learning.

The remaining ground-referenced igneous samples were combined into a testing dataset. Testing data were reserved to determine the accuracy of the trained classifier. Testing data were also representative samples of the mafic and felsic lava. 200 samples comprised the testing data.

Expert-identified basaltic data were also incorporated to the training and testing data. These points were picked along ROV tracklines on basaltic domes which were rarely sampled. Sampling basaltic domes was difficult due to uneven surfaces for landing the ROV. 48 expert-defined points were incorporated to the training dataset and 47 were incorporated to the testing dataset.

**Table 3.1. Training and testing datasets from 2012 and 2015 samples.**

<table>
<thead>
<tr>
<th></th>
<th>Training Data</th>
<th>Testing Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic</td>
<td>72</td>
<td>137</td>
</tr>
<tr>
<td>Felsic</td>
<td>62</td>
<td>63</td>
</tr>
<tr>
<td>Expert-Defined basalt dome</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td>182</td>
<td>247</td>
</tr>
</tbody>
</table>
CHAPTER 4
CLASSIFICATION METHODOLOGY

Artificial intelligence classification has become a powerful tool for mapping submarine volcanic features [Stewart et al., 1994; Meyer and White, 2007; McClinton et al., 2012, McClinton et al., 2013]. We chose to classify the occurrence of mafic and felsic lava at the Alarcon Rise with an adaptive neuro-fuzzy inference system (ANFIS). ANFIS is a neural network that applies fuzzy logic to classification [Jang, 1993]. Modeled after the human nervous system, nodes connected by weighted paths build neural networks. The mutual interconnection of multiple nodes enhances the computational power of the classifier [Stewart et al., 1994]. Unlike hard classifications that assume discrete boundaries between homogenous classes, ANFIS uses fuzzy logic to assign a continual grade of classification to heterogeneous classes of objects [Zadeh, 1965, 1973; Jang, 1993]. Fuzzy classification mimics the natural continuum of lava composition as it is expressed through submarine lava flow morphology.

Like other neural-network classifications [Stewart et al., 1994], ANFIS beings classification with a learning phase during which patterns to be recognized are stored as a knowledge base in the nodes and connections of the system [Jang, 1993]. ANFIS develops the knowledge base from our initial inputs of training data. The three step learning process includes 1.) construction of fuzzy if-then rules, 2.) assignment of membership distribution functions that fit the training values, and 3.) creation of the neural-network structure. With each training cycle, ANFIS adjusts the weights of paths
between nodes to minimize error between the training input values and the output classification.

The ANFIS learning phase uses slope and BPI values extracted to our training samples to create a knowledge base for the two classes (Figure 4.1). 4 membership functions were required for the classifier to distinguish between class 1 (mafic – encompassing basaltic ground-referenced samples and expert-picked pillow mound samples) and class 2 (felsic – comprising basaltic andesite, andesite, dacite and rhyolite samples). ANFIS completed 30,000 learning iterations with root-mean-square uncertainty of 0.36. When we incorporated more inputs to the learning phase, the training uncertainty decreased (Table 4.1); however, ANFIS could only classify areas where we already had ground-referenced data. When we included multiple inputs, ANFIS created weighted paths and nodes that only described the training data. Therefore we minimized inputs to ANFIS and accepted a 36% uncertainty to maximize classification flexibility.

We created point grids in ArcGIS 10.3 that covered the length of the Alarcon Rise between the Pescadero and Tamayo Transform Faults. Each point represented 4 m² of seafloor. We extracted seafloor slope and BPI at the 500 m scale to each point. We then classified each section of seafloor in MatLab. After classification, we imported the classified grids to ArcGIS 10.3 and created classification rasters gridded at 4 m². The raw classification was then majority filtered at a 10 cell radius.

We reserved testing data to perform an accuracy assessment. Testing data were ultimately classified following the same steps outlined in Chapter 3.
Figure 4.1. ANFIS workflow. Our classification workflow included a learning phase, classification phase and accuracy analysis phase. We extracted bathymetry-derived characteristics to our training ground-referenced samples for the backpropagation learning phase of ANFIS. After ANFIS created a knowledge base, we classified point grids that represented 4 m$^2$ of seafloor per point. We created a lava composition classification map and assessed the classification accuracy using a testing dataset of reserved ground-referenced samples.
Table 4.1. Classification training results.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Classes</th>
<th>Membership</th>
<th>Training Iterations</th>
<th>Training Error (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bathymetry, slope, backscatter intensity, backscatter texture pc1 and pc2</td>
<td>2</td>
<td>8</td>
<td>10,000</td>
<td>0.95</td>
</tr>
<tr>
<td>slope, backscatter intensity, backscatter texture pc1 and pc2</td>
<td>2</td>
<td>9</td>
<td>30,000</td>
<td>0.94</td>
</tr>
<tr>
<td>slope, aspect, BPI 25 m density</td>
<td>2</td>
<td>11</td>
<td>10,000</td>
<td>0.94</td>
</tr>
<tr>
<td>Slope, aspect, backscatter intensity, backscatter texture pc1 and pc2, BPI 700 m</td>
<td>2</td>
<td>14</td>
<td>90,000</td>
<td>0.66</td>
</tr>
<tr>
<td>slope, aspect, bathymetry, bpi textures at 100 and 500 m scales, backscatter intensity, backscatter texture pc1 and pc2, BPI 700 m</td>
<td>2</td>
<td>33</td>
<td>30,000</td>
<td>0.18</td>
</tr>
<tr>
<td>slope, pc1 of BPI at 500 and 100 m scale</td>
<td>2</td>
<td>4</td>
<td>10,000</td>
<td>0.39</td>
</tr>
<tr>
<td>slope, BPI 500 m scale, and curvature (slope of the slope) at 50 m majority scale</td>
<td>2</td>
<td>5</td>
<td>10,000</td>
<td>0.31</td>
</tr>
<tr>
<td>slope, BPI at 500 m scale</td>
<td>2</td>
<td>4</td>
<td>30,000</td>
<td>0.36</td>
</tr>
</tbody>
</table>
CHAPTER 5

RESULTS

To determine the value range for the mafic and felsic classes, we extracted the classified values to each of the 375 ground referenced samples along the Alarcon Rise. Mafic samples clustered at values near 1.1. Felsic samples increased in abundance from 0.9 to 2.1. The division between the mafic and felsic classes was determined by the upper 95th % confidence interval of ground-referenced basaltic samples at a value of 1.6 (Figure 5.1).

ANFIS classification produced a lava composition map for the Alarcon Rise, covering a total area of 88.8 km², or 71% of the area mapped in 2012 (Figure 5.2). Each pixel was assigned to one of two classes: mafic lava or felsic lava. Only 5.1 km², or ~6% of the classified area was classified as felsic lava. The classifier assigned the remaining 94% of the Alarcon Rise (83.7 km²) to the mafic class. This result is consistent with seafloor observations recorded in 2012 and 2015.

The north section of the Alarcon Rise contained the greatest amount of classified felsic lava. The rhyolitic complex has a mixed classification of felsic and mafic lava flows. The classification outlined an entire ridge along which felsic lava erupt. This is supported by the samples we collected with ROV Doc Ricketts. The central portion of the Alarcon Rise is classified as predominantly mafic. Edges of the steep-sided volcanic cone were classified as felsic. The classifier also misclassified a basaltic region near an inactive hydrothermal chimney system, likely due to the high slopes and jagged structure
Figure 5.1. Determining mafic and felsic classes. All ground referenced samples were used to determine the mafic and felsic classes. Basaltic samples were normally distributed around a value of 1.1. We used the upper 95% confidence interval to break the classes. Pixels with values classified >1.6 were considered part of the felsic class. Some felsic samples were classified with low values, but abundance of samples increased as classification value increased. The mode of felsic samples was 2.1.
Figure 5.2. Classified lava flow at the Alarcon Rise. The north end of the Alarcon contains the majority of classified felsic lava. The classifier recognized the majority of the central and south regions as mafic lava. The classifier misclassified the perimeter of the volcanic cone in the central region and some basaltic pillow mounds in the south region.
of chimneys. The classifier correctly assigned the mafic class to the entire south volcanic shield.

5.1 ACCURACY ASSESSMENT

To quantitatively assess the accuracy of the classification, we performed an accuracy assessment using 247 igneous reference samples not used in ANFIS training. Approximately half of the original samples collected were reserved for this purpose. Only 207 of the original 247 samples fell within the classified area. We constructed error (Table 5.1) and accuracy matrices following guidelines for remotely sensed categorical data outlined by Congalton [1991].

We report three measurements of descriptive error to assess classification accuracy. We divided the total number of points correctly classified by the total number of points used in accuracy assessment. We measured producer’s accuracy (PA) to determine error due to omission (when a point is omitted from the correct class by misclassification). User’s accuracy (UA) accounts for errors of commission when a point is assigned to the incorrect class (Table 5.2). The classification had an overall accuracy of ~85%. The mafic lava class had the highest PA at 98.6%. PA for the felsic was much lower at 51.7%, indicating that approximately half of the felsic samples were omitted from the correct class. Felsic lava had the highest UA at 93.9%. Mafic lava had a UA of 83.3%, meaning that 16.7% of the samples classified as mafic belong to the felsic class.

The discrete multivariate technique of kappa analysis calculates a statistic as a measure of agreement or accuracy. The kappa value ranges from 1 to 0, with 1 indicating complete agreement and 0 indicating no agreement. The kappa value from this study =
0.58 which indicates moderate agreement between our ground referenced data and classification [Landis and Koch, 1977].

Table 5.1. Error matrix

<table>
<thead>
<tr>
<th>ANFIS Output</th>
<th>Ground Reference Points</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mafic</td>
<td>Felsic</td>
<td>Row Total</td>
</tr>
<tr>
<td>Mafic</td>
<td>145</td>
<td>29</td>
<td>174</td>
</tr>
<tr>
<td>Felsic</td>
<td>2</td>
<td>31</td>
<td>33</td>
</tr>
<tr>
<td>Column Total</td>
<td>147</td>
<td>60</td>
<td>207</td>
</tr>
<tr>
<td>Chance</td>
<td>0.596933417</td>
<td>0.04620878</td>
<td>0.643142197</td>
</tr>
</tbody>
</table>

Table 5.2. Accuracy matrix

<table>
<thead>
<tr>
<th>Class</th>
<th>ANFIS Total</th>
<th>Reference Total</th>
<th>Number Correct</th>
<th>PA</th>
<th>UA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic</td>
<td>174.0</td>
<td>147.0</td>
<td>145.0</td>
<td>98.6%</td>
<td>83.3%</td>
</tr>
<tr>
<td>Felsic</td>
<td>33.0</td>
<td>60.0</td>
<td>31.0</td>
<td>51.7%</td>
<td>93.9%</td>
</tr>
<tr>
<td>Column Total</td>
<td>207.0</td>
<td>207.0</td>
<td>176.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>85.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pa</td>
<td>0.85024155</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pe</td>
<td>0.6431422</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kappa</td>
<td>0.58034138</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 6

DISCUSSION

6.1 GEOMORPHIC IMPLICATIONS

Geomorphology of felsic submarine lava is poorly understood due to the dearth of samples available to study. Few examples of felsic lava flow morphology at oceanic spreading ridges have been recorded [Perfit and Fonari, 1983; Regelous et al., 1999; Wanless et al., 2010]. Wanless et al. [2010] notes that dacites recovered from eastern limb of 9°N East Pacific Rise overlapping spreading center and Galapagos Spreading Center appeared as elongate pillows several meters in diameter with heavily striated surfaces. Andesites and dacites at the Juan de Fuca Ridge were recovered from two domes (~200-500 m diameter) covered by angular lava. Because basaltic andesites, andesites and dacites may take the form of elongate pillows, it is difficult to distinguish these flows from basaltic pillow lava flows in 1 m resolution bathymetry.

Of the igneous samples collected at Alarcon Rise, rhyolite exhibits the most distinctive felsic geomorphic fingerprint (Figure 6.1). Approximately 60% of rhyolitic lava erupt as angular blocks and form jagged domes based on local slope and BPI at the 0.5 km scale. Although not all differentiated lava will exhibit a distinctive felsic geomorphology, the UA of our classification indicates that 94% of pixels classified as felsic are compositionally different from basalt. Because not all basaltic andesites, andesites, dacites and rhyolites exhibit a distinctive geomorphic fingerprint, our
classification maps the minimum amount of felsic lava at the Alarcon Rise. Felsic lava erupted at >6% of the Alarcon Rise.

Figure 6.1. Relative abundance of classified ground referenced samples. Over 95% of basaltic samples collected at the Alarcon Rise were correctly classified as mafic. ~80% of basaltic andesite samples were also classified as basalt. Slightly less than 50% of andesitic samples were classified as felsic, while the classifier only recognized 40% of dacitic samples as felsic. 60% of rhyolitic samples were classified as felsic, indicating they exhibited the strongest felsic geomorphic fingerprint. Numbers on each bar represent the number of samples within each group.

The ability to classify felsic lava, especially rhyolite, at oceanic ridges will allow us to better identify specific settings where it is produced. Because the Pescadero Transform Fault intersects the Alarcon Rise ~6 km north of the rhyolite complex, TFE may be the mechanism by which evolved lava forms in this specific setting. Castillo et al., [2002] suggested that TFE can only occur in extreme settings where the lack of melt supply causes magma to fractionate and evolve. The Tamayo Transform Fault is a typical
oceanic transform fault which will not create the conditions for TFE \cite{Castillo et al., 2002}. At specific spreading ridge settings where conditions for TFE would likely occur, we can use the geomorphic fingerprint of felsic lava to identify sites for sampling differentiated lava compositions, especially rhyolites.

6.2. PIXEL-BASED VERSUS OBJECT-BASED CLASSIFICATION

Because seafloor observations suggest mafic and felsic lava can be distinguished at the scale of individual lava flows, we chose a pixel-based classification approach to determine the geomorphic fingerprint of felsic lava flows. Object-based image analysis (OBIA) is a different classification approach that detects contiguous cells as parts of a single object. Pedersen \cite{2016} applied OBIA to identify terrestrial volcanic edifices in Iceland. The majority of pixels misclassified as felsic are located at the edges of mafic pillow mounds and domes (Figure 6.2). OBIA would consider the entire dome as a single composition. However, OBIA would not account for variation at the scale of individual lava flows which are identified with seafloor observations.

We used slope and BPI as ANFIS inputs because our felsic ground-referenced samples were located on steep, bumpy surfaces; however, ANFIS encountered difficulty in correctly classifying the steep sides of basaltic pillow mounds and volcanic cones as mafic. These areas also had high BPI values. Therefore, we need to determine other properties that distinguish the geomorphology of felsic lava flows from mafic lava flows.

6.3 FUTURE WORK

More geomorphic differences may exist between mafic and felsic lava than what we identified thus far. Physical distinctions between the jagged rhyolitic lava and smooth basaltic lava may be quantified by the derivatives of slope. We can distinguish
differences in the rate of change for slopes of basaltic and felsic lava. To illustrate these characteristics, we created slope profiles at 5 lava flows with rhyolitic and dacitic compositions (Figure 6.3) and at 5 basaltic lava flows (Figure 6.4). Both felsic and mafic lava flows have two orders of wavelength and amplitude.

First-order wavelength of felsic lava is ~20 m, and the second-order wavelength ~3 m. Felsic lava slopes oscillate between 10°-40°, resulting in an amplitude of ~15 (Figure 6.5). Overall, mafic lava flows are characterized by longer wavelengths than felsic lava. First-order wavelength is ~100-200 m, and second-order wavelength is ~10 m. The amplitude of the short wavelength is ~5° (Figure 6.6). If slope derivatives provide characteristics that distinguish felsic lava, specifically rhyolites, from mafic lava, we will be able to better identify areas where felsic lava erupt at oceanic ridges.
Figure 6.2. Pixel-based classification of high-silica dome and basaltic mound. We used a pixel-based classification approach to map mafic and felsic lava flows along the Alarcon Rise. The classification resulted in splotchy classification of dome features due to smoothing scattered classification of single pixels at a 10 cell radius. Half of basaltic lava mounds were classified as felsic while part of the rhyolitic dome along the felsic ridge was classified as mafic.
Figure 6.3. Slope profile locations for felsic lava. We chose 5 locations to assess the frequency and amplitude of slope profiles. We used these profiles to identify patterns within slope data that may prove useful in determining inherent differences between felsic and mafic lava. All slope profiles for felsic lava were confined to the north end of the Alarcon Rise where felsic samples were collected in 2012 and 2015.
Figure 6.4. Locations of mafic lava slope profiles. 5 profile locations were chosen to assess slope patterns for mafic lava. We wanted a representative sample of mafic lava flow morphologies to find underlying characteristics inherent to all mafic lava erupted at oceanic spreading ridges. Our profiles included basalt domes (A-A’ and B-B’), sheet flows (C-C’ and E-E’), and a volcanic cone (D-D’). The profile locations were geographically distributed from 23° 24’ N to 23° 33’ N.
Figure 6.5. Slope profiles of 5 felsic lava flows. Each 600 m long profile shows a dominant and secondary wavelength for felsic lava at north Alarcon Rise. First order waves appear to have a wavelength of ~20 m. Second-order waves create the jagged shapes of high-silica lava flows in the 1 m bathymetry. Second-order wavelength is ~3 m. The amplitude of second-order waves ~15°, oscillating between slopes of 10°-40°. Profile C-C’ contains the maximum slope recorded in these profiles at ~75°.
Figure 6.6. Slope profiles of mafic lava flows. Mafic lava flows exhibit longer wavelengths and smaller amplitudes for both first-order and second-order waves. Basalt domes and the volcanic cone (A-A’, B-B’, D-D’) all have first-order wavelengths on the 150-200 m scale (red arcs). The slope profiles for sheet flows (C-C’ and E-E’) have first-order wavelength of ~100 m. Second-order wavelength for all mafic lava is ~10 m. The amplitude of mafic lava slope is smaller than felsic lava. Amplitude is ~ 5° with a typical slope range of 10°-20°. The maximum slope recorded in these profiles was ~48°.
CHAPTER 7
CONCLUSIONS

We applied neuro-fuzzy classification methodology to classify areas of the seafloor with attributes derived from 1 m resolution multibeam bathymetry. We produced the first submarine lava composition map based on geomorphic characteristics for the Alarcon Rise, Gulf of California. We accurately classified 85% of the submarine volcanic samples MBARI collected in 2012 and 2015. The process of classifying felsic and mafic lava erupted at oceanic spreading ridges led us to identify some geomorphic characteristics inherent to differentiated submarine lava flows, especially rhyolites. These characteristics include: a.) formation of large, steep-sloping jagged domes, b.) eruption of blocky, angular lava that builds spires, c.) bumpy appearance in 1 m resolution bathymetry. Slope rate-of-change, wavelength, and amplitude also provide potential for further characterization of rhyolitic lava flows at oceanic spreading ridges.

Despite the complexity of identifying submarine lava composition using lava flow geomorphology, we determined rhyolites, and some other submarine felsic rocks, exhibit distinctive morphologies from basalt. We can detect geomorphic differences using local slope and BPI at 0.5 km. We correctly identified the geomorphology of 95% of basaltic samples as mafic, and we distinguished a specific felsic geomorphologic fingerprint for 60% of rhyolitic samples. We conclude that although not all basaltic andesites, andesites, dacites and rhyolites have distinctive submarine lava flow morphologies from basalt, if part of the spreading ridge is classified as felsic, there is a 94% probability that it will
have a differentiated composition. Therefore, our classification maps the minimum amount of felsic lava at the Alarcon Rise.
REFERENCES


Gregg, T.K.P., and Fink, J.H., 1995, Quantification of submarine lava-flow morphology through analog experiments: Geology, v. 23, n. 1, p. 73-76.


