2013

Using a GIS Site Suitability Analysis to Locate Springs in Mantle Units of Ophiolites

Alexandrea Bowman
University of Rhode Island, abowman@my.uri.edu

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

Recommended Citation

Bowman, Alexandrea, "Using a GIS Site Suitability Analysis to Locate Springs in Mantle Units of Ophiolites" (2013). *Open Access Master's Theses*. Paper 75.
<https://digitalcommons.uri.edu/theses/75>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons-group@uri.edu.

USING A GIS SITE SUITABILITY ANALYSIS
TO LOCATE SPRINGS IN MANTLE UNITS OF
OPHIOLITES

BY
ALEXANDREA BOWMAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
ENVIRONMENTAL AND EARTH SCIENCES

UNIVERSITY OF RHODE ISLAND

2013

MASTER OF SCIENCE THESIS
OF
ALEXANDREA BOWMAN

APPROVED:

Thesis Committee:

Major Professor Dawn Cardace

Pete August

Brian Savage

Steve Carey

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2013

ABSTRACT

Springs sourced in the mantle units of ophiolites serve as windows to the deep biosphere, and thus hold promise in elucidating survival strategies of extremophiles, and may also inform discourse on the origin of life on Earth. Spring locations associated with serpentinites have traditionally been located using a variety of field techniques. The chemical properties of these springs are unique; they reflect a reducing subsurface environment reacting at low temperatures producing high pH, Ca^{2+} -rich formation fluids with high dissolved hydrogen and methane. This study applies GIS site suitability analysis to locate high pH springs in Coast Range Ophiolite serpentinites in Northern California. Available geospatial data (*e.g.*, geologic maps, elevation data, fault locations, known spring locations, etc.) were overlain in a site suitability analysis using ArcGIS software to predict new spring localities. Important variables in the suitability model were: (a) bedrock geology (*in particular*, serpentinite/peridotite occurrence), (b) fault locations, (c) regional data for the location of groundwater, and (d) slope. The GIS model derived from these data sets predicts the most likely regions for novel and known high pH springs sourced in serpentinite outcrops in California, thus focusing fieldwork. Although preliminary model confirmation in the field was not successful, two subsequent refinements to the model are presented here: the integration of gabbro-serpentinite unit boundaries via neighborhood analysis, and internally consistent aerial image analysis. Strong recommendations can now be made to focus future fieldwork. This thesis highlights a powerful GIS-based technique for accelerating field exploration in this area of ongoing research.

ACKNOWLEDGMENTS

Special thanks to my advisor Dr. Cardace who believed in me when I did not believe in myself. The encouragement and advice has been invaluable and without her knowledge and support I would not have been able to finish. I would like to especially thank my committee members Dr. Pete August (whose patience and knowledge of GIS has been invaluable in the completion of this work), Dr. Brian Savage, and Dr. Steve Carey.

I would also like to thank the Geology Department at URI, especially Joe Klinger and Dr. Fastovsky, both of whom provided advice and mentoring when my committee was unavailable. I am extremely grateful to my friend and colleague Justice Mensa for his advice on this project. I would never have been able to finish this manuscript without the help of Michael Kieron who acted as a proof-reader and gave sound advice when needed. When Dr. August was not available and a GIS question arose, Justice was always able to walk me through the issue.

I gratefully acknowledge funding for this project from the Sloan Foundation Deep Carbon Observatory: Deep Life I: Microbial Carbon Transformations in Rock-Hosted Deep Subsurface Habitats, Project number 0003148, the University of Rhode Island College of the Environment and Life Sciences and Geosciences department. I would also like to thank Dr. Cheryl Wilga, LEPC of AISES, and Catalina Martinez for their mentorship and advice.

PREFACE

This thesis is in manuscript format for the journal Geoinformatica.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iii
PREFACE.....	iv
TABLE OF CONTENTS.....	v
LIST OF FIGURES	vii
LIST OF TABLES	x
INTRODUCTION.....	1
GEOLOGIC BACKGROUND	8
MODELING AND LAB METHODS.....	11
<i>3.1 Modeling Methods.....</i>	<i>11</i>
<i>3.2 Stream Essentials</i>	<i>15</i>
<i>3.3 Uncertainty of models</i>	<i>16</i>
RESULTS	17
<i>4.1 Maps of Spring Locations Predicted by Model.....</i>	<i>17</i>
<i>4.2 Summary Findings of Initial Ground-truthing</i>	<i>18</i>
<i>4.3 Techniques</i>	<i>19</i>
DISCUSSION	21
<i>5.1 Value of the modeling approach</i>	<i>21</i>
<i>5.2 Limitations of the modeling approach</i>	<i>21</i>
<i>5.3 Description of the highest probability sites determined from revised model</i>	<i>23</i>
CONCLUSIONS	26

APPENDICES	28
<i>A. Protocol for ArcGIS data.....</i>	28
<i>B. Figures.....</i>	30
<i>C. Tables</i>	117
REFERENCES CITED	130

LIST OF FIGURES

FIGURE	PAGE
Figure 1. Raw data in vector format used to create the GIS site suitability analysis	30
Figure 2. Preliminary GIS model shows eighteen potential field locations.	31
Figure 3. The optimized model contains 33 new field locations.	32
Figure 4. This map represents only high slope angle and serpentinite	33
Figure 5. White Seep and gray scale values used in Stream Essential	34
Figure 6. Example for Indian Valley Reservoir Site 1 (at 20 meters) also showing grey scale values from Stream Essentials.....	37
Figure 7. The area around Indian Valley Reservoir zoomed in to the high probability areas.....	40
Figure 8. This figure shows the new predicted sites that extend along a fault line from Lake into Napa County.....	42
Figure 9. The Napa county group	43
Figure 10. This is a potential new high probability site near the Napa and Sonoma county boundary.....	44
Figure 11. Sonoma Group.....	45
Figure 12. Willow Creek Road in the optimized model shows a larger area than the preliminary model predicted	46
Figure 13. Optimized model with old and new predicted sites.	47
Figure 14. New predictions in relation to existing NHD+ spring data.	48
Figure 15. Indian Valley Reservoir site 1 as predicted by the optimized model.....	49
Figure 16. Indian Valley Reservoir site 4 as predicted by the optimized model.....	53
Figure 17. Indian Valley Reservoir site 5 as predicted by the optimized model.....	55
Figure 18. Lake Berryessa 3 is on a steep slope and was predicted by the optimized	

model as a “5”.	57
Figure 19. Lake Berryessa 4 aerial images processed using Stream Essentials.....	59
Figure 20. Lake Berryessa 5 aerial images processed using Stream Essentials.....	61
Figure 21. Napa is a potential field location predicted by the optimized model.....	63
Figure 22. Lake County Group 1 is around a body of water as seen in the aerial image	65
Figure 23. Lake County Group 2 is a new predicted site around a body of water.....	67
Figure 24. Lake County Group 5 was only predicted by the optimized model.	69
Figure 25. Lake County Group is a continuation of the fault line shown on the optimized GIS map	71
Figure 26. Lake County Group 3 is a continuation of the fault line shown on the optimized GIS map	73
Figure 27. Napa County Group 1 is a continuation of the fault line shown on the optimized GIS map.	75
Figure 28. Napa County Group 2 is a continuation of the fault line shown on the optimized GIS map	77
Figure 29. Napa County Group 3 is a continuation of the fault line shown on the optimized GIS map.....	79
Figure 30. Napa County Group 4 is a continuation of the fault line shown on the optimized GIS map..	81
Figure 31. Napa County Group 5 is a continuation of the fault line shown on the optimized GIS map..	83
Figure 32. Napa County Group 6 is a continuation of the fault line shown on the optimized GIS map.	85
Figure 33. Napa County Group 7 is point appears to be on the edge of private property, and appears to be a vineyard.....	87
Figure 34. Napa County Group 8 appears to be private property	89
Figure 35. Just north of Napa County Group 9 there appear to be several patches of	

what appear to be travertine	91
Figure 36. Napa County Group appears to be a vineyard.....	93
Figure 37. Napa County Group 11 is an area that is relatively easy to reach.	95
Figure 38. Napa County Group 12 is near a body of water, which is to the east of the point..	97
Figure 39. Napa County Group 13 is an area that is relatively easy to reach and contains patchy vegetation.	99
Figure 40. Napa County Group 14 is located on unnamed road and is an area that is relatively easy to reach and contains patchy vegetation	101
Figure 41. Napa County Group 15 is an area that is relatively easy to reach and contains patchy vegetation.	103
Figure 42. Willow Creek Road is an area that is relatively easy to reach and contains patchy vegetation along a fault line	105
Figure 43. Sonoma 1 is located along Lake Sonoma, a recreational area.....	107
Figure 44. Sonoma 2 is a recreational area.	109
Figure 45. Sonoma is located off of Fall Creek Road, on private property	111
Figure 46. Sonoma 4 is, on private property off of Merlo Lake	113
Figure 47. Sonoma 5 appears to be a vineyard	115

LIST OF TABLES

TABLE	PAGE
Table 1. Table showing data sources and links between data and maps/groups.....	117
Table 2. Modified table from Goff et al. (2001) shows springs with pH values 8.5 and higher.	118
Table 3. Modified table from Goff et al. (2001) shows springs that have been discounted from our research due to reported pH values lower than 8.5.....	119
Table 4. Field locations and coordinates from the preliminary model.....	125
Table 5. Field locations sampled in December of 2012 and data collected in the field show areas predicted as “2” in both the preliminary and optimized model.....	126
Table 6. Field locations and coordinates from the optimized model	127

INTRODUCTION

Springs sourced in the mantle units of ophiolites provide a window to the deep biosphere and hold promise in elucidating survival strategies of extremophiles and may also hold important clues about the origin of life on Earth. Identifying the environments and processes that allowed the first cells on Earth to originate, and evaluating the habitability of other planetary settings, constitute a great scientific challenge. In the presence of water, peridotite (mantle rock composed primarily of the mineral olivine) alters to serpentinite (Muntener, 2010), accompanied by the production of diagnostic trace minerals, methane, and very high pH formation fluids.

Chemical reactions between water and mafic or ultramafic rocks produce chemical energy, and may have created clement conditions pertinent to the origin of life. The detection of alkaline springs in ophiolites allows assessment of continental serpentinites for information they bring to problems of the deep biosphere and the origin of life (Hazen et al., 2008). Some prominent chemical reactions that take place during serpentinization are as follows:

There are several chemical reactions that can free hydrogen, including $3\text{Fe}(\text{OH})_2 \rightarrow \text{Fe}_3\text{O}_4 + 2\text{H}_2\text{O} + \text{H}_2$ (Kelley et al., 2005; Schulte, et al. 2006; McCollom and Bach, 2008; Fryer, 2011), and all are important potential sources of energy, particularly diatomic hydrogen. Through serpentinization, hydroxide phases (*e.g.*, brucite) are produced and may dissolve in formation fluids: abundant aqueous hydroxyl ions drive pH up. Recall that pH is defined as $-\log_{10}aH^+$, where aH^+ is equal to the proton activity. Free hydrogen becomes an energy source for chemolithoautotrophs in environments where active serpentinization is occurring. The serpentinization process is associated with high Ca^+ (likely derived from pyroxene weathering) and elevated Ca/Mg ratios, with highly alkaline waters resulting from extremely high OH^- loads (Barnes et al. 1972).

Through the serpentinization of peridotite, hydrogen is released abiotically as H_2 ($3\text{Fe}_2\text{SiO}_4 + 2\text{H}_2\text{O} = 2\text{Fe}_3\text{O}_4 + 3\text{SiO}_2(\text{aq}) + 3\text{H}_2$) and is used by hydrogenotrophic methanogens as an energy source (Sleep et al., 2011). Hydrothermal vents associated with serpentinization would have provided a secure, low temperature location with an abundant source of energy for the first living organisms to arise (Hazen et al., 2008; Kelley et al., 2005; Kelley et al., 2007; Martin et al., 2008; Muntener, 2010; Russell et al., 2010). The process of serpentinization can take place anywhere that peridotite occurs with the presence of water—certainly at slow spreading ridges, passive margins, and fore-arcs (Kodolanyi et al. 2011) and at subduction zones in the mantle wedge due to mantle hydration (Plummer et al., 2012; Poli and Schimidt 2002; Schmidt and Poli 1998), though certainly in the last case, temperatures are too high to sustain life.

Early life on Earth required a sustainable energy system that was sheltered from the extreme temperatures and ocean acidity (due to high dissolved CO₂) that would have been found on the early Earth's surface (Russell et al., 2010). Russell et al. (2010) use the models of Wood et al. (1990, 2006) and Frost et al. (2004) that speculate early Earth had a similar atmosphere to that of Venus or Mars, containing large amounts of CO₂ and nitrogen with minor amounts of NO, CO, P₄O₁₀, SO₂ and native sulfur. With volcanic eruptions speculated to be between 10 and 100 times greater than what they are today, these gases could have easily built up in Earth's atmosphere creating a hostile atmosphere, acidic with high pressures like those found on Venus, (Russell et al., 2010).

It can also be argued that the evolution of life on Earth was only possible after Earth's core, mantle, and crust differentiated and a liquid ocean was stable, perhaps after 4.4 Ga (Russell et al., 2010). Earth's primary atmosphere, hydrosphere, and lithosphere may have had additions from other planetary objects during the early heavy bombardment period as well (Zahnle et al., 2010; Schaefer and Fegley, 2007; Schaefer and Fegley, 2010). Whatever the geochemical conditions were, early Earth depended on a sheltered start with sufficient raw materials for growth. In this Early Earth, gradients in energy and geochemistry that were important for the establishment of the first cells may well have been furnished by serpentinization (Russell et al., 2010). Earth's early atmosphere may have been derived from the impacting planetary objects' mineralogy rather than Earth's mantle in the pre-tectonics era (Zahnle et al., 2010; Schaefer and Fegley, 2007; Schaefer and Fegley, 2010).

Early Earth's solid crust would likely have had a komatiite-type component (komatiites are rocks formed from the eruption of lava consisting of high Fe and high Mg ultramafic minerals) because the temperature of early Earth would have been hot enough to support the eruption of this kind of magma (McCollom and Seewald, 2013). This may have made serpentinization more widespread than it is today, and created energy sources for chemolithoautotrophs (McCollom and Seewald, 2013), effectively creating an environment where life could sustain itself and evolve.

Earth's early atmosphere would have contained large amounts of carbon monoxide and methane. With methane, trace amounts of hydrogen cyanide and ammonia would also have been present (Zahnle et al., 2010). Schaefer and Fegley (2007; 2010) showed that ordinary chondrites, when heated to approximately 1225 K, produce CH_4 , H_2 , H_2O and NH_3 gases, which constituted the atmospheric condition for the first life on Earth (Schaefer and Fegley 2007; 2010). During an early bombardment of chondrites, iron from planetary bodies would have melted and settled into the earth's core due to an abundance of heat, while lighter material would have moved towards the lower and upper mantle and the earth's crust. The lighter volatile gases would have entered Earth's primitive atmosphere (Zahnle et al., 2010).

Earth's primitive atmosphere would likely have had ample carbon dioxide. Earth's early ocean would have been acidic as carbon dioxide dissolved from Earth's early atmosphere into the early oceans. The process of serpentinization releases basic fluids in the pH range of 9 to 12 (Barnes et al., 1972) both on land and on the seafloor; these basic fluids would have acted as a buffer between more acidic waters, perhaps constituting a clement aqueous setting in which the first cells might have

evolved. Modern serpentinite-sourced submarine hydrothermal vents are good analogs for the kinds of environments that may have supported early life (Sleep et al., 2011; Russell et al., 2010). Hydrogen and methane are produced abiotically at hydrothermal systems by the process of serpentinization (Charlou et al., 2010), providing energy and carbon sources for life, making the environment even more habitable.

In general, serpentinites on land are well-mapped and more easily accessible than deep ocean serpentinites, and related spring systems that move water and microorganisms from depth beg further study (Sleep et al., 2011). Serpentinization has probably been ongoing since the Earth had solid peridotite and was cool enough to form oceans of liquid water, which might have been as early as 4.2 billion years ago (Martin et al., 2008). One of the earliest serpentinites, the Isua Supracrustal Belt in Greenland, dates to the Early Archean (3.81– 3.70 Ga) and is interpreted to be the oldest known section of ocean crust (Pons et al., 2011). Pons et al. (2011) infer from isotopic evidence from the Isua serpentinites that processes resembling those active at the Lost City Hydrothermal Field were occurring as early as 3.70 Ga on the early Earth and could have provided a stable place for life to take hold.

Located in the mid-Atlantic Ocean, 15 km east of the Mid-Atlantic Ridge, the Lost City Hydrothermal Field (LCHF) is one of the most studied hydrothermal submarine serpentinization systems. Unlike the magmatically driven “black smoker” hydrothermal vent systems which vent acidic, CO₂- and sulfur-rich waters, the alkaline vents of the LCHF are driven by low temperature fluid flow through serpentinizing mantle rocks. While the temperatures of black smoker hydrothermal vent systems can reach 400°C, the temperatures emitted by the LCHF are

typically between 40°C and 90°C and the pH is very high, from 9 to 11 (Kelley et al., 2005). The site is marked by large, white carbonate chimneys up to 60 m tall on faulted blocks of ocean floor peridotite. Seawater passes through the faults and fractures of the peridotitic blocks and reacts with the exposed mantle rock (Kelley et al., 2005). Through serpentinization reactions, the vent fluids are rich in H₂ and CH₄, and bear a distinct signature of high dissolved cations and hydroxyls. In fact, the alteration of olivine to serpentine involves a net increase in volume, often causing pervasive fracturing in the host rock, allowing for more serpentinization in those very fractures (Kelley et al., 2005). As vent fluids mix with ocean water, the available cations react with available anions—first hydroxide ions from the vent fluids, then (spectacularly) bicarbonate ions from seawater; abundant carbonate mineral precipitation results. The networks of fractures, faults, and joints are lined with brucite (Mg(OH)₂) and filled with calcite, resembling deposits in many older ophiolites such as those in the Alps (Kelley et al., 2005). In continental settings, Barnes et al. (1967, 1972) pioneered the documentation of related spring expressions, and reported high pH and high Ca to Mg ratios in actively serpentinizing springs in California, such as Cazadero A in Sonoma County, Complexion Spring in Lake County, TC-2 in Trinity County and Aqua de Ney in Siskiyou County (Barnes et al., 1972). Given the promise of serpentinite-sourced springs as accessible environments with relevance to the origin of life on Earth, domestic ophiolite fragments in Northern California (exceedingly well mapped and georeferenced) were screened for likely spring distribution using ArcGIS.

In particular, here I apply a multi criteria suitability analysis to data for four counties (Lake, Yolo, Napa, and Sonoma) in California that span blocks of the

Coast Range Ophiolite, in an effort to predict new deeply sourced spring localities. Data for bedrock type, fault locations, documented springs/seeps/water sources, proximity to unit boundaries, and slope measurements greater than 45° were integrated in a model engineered to predict new springs, sourced in serpentinites/peridotites. The goal is to test the applicability of these GIS modeling methods and review pertinent regional aerial imagery to ascertain, at least preliminarily, whether predicted site localities hold promise.

GEOLOGIC BACKGROUND

The Coast Range Ophiolite (CRO) is a tectonically reworked ophiolite with blocks of altered peridotite, gabbro, and basalt. It is believed to have formed approximately 169 million years ago as part of a rifting zone (Shervais et al., 2004). Approximately 156 million years ago, arc magmatism began and continued until approximately 145 million years ago. Shervais et al. (2004) believe that the CRO was accreted onto the North American plate when rapid subduction continued as part of Stage 4 in their model. It is believed that the CRO formed in a back arc basin-setting (McLaughlin et al., 1988) due to extension during the middle to late Jurassic. The CRO is segmented along 700 km and is composed of igneous, mafic, and ultramafic rocks, making it one of the longest terrains in North America (Choi et al., 2008; Shervais et al., 2004).

Within the tectonic framework provided above, the CRO has a complex geology. It overlays the Franciscan Complex and consists of younger rocks bearing high-pressure metamorphic facies; this is characteristic of deeply subducted material tectonically placed below older rocks that are characterized by low pressure, shallow metamorphic rocks (Constenius et al., 2000). This supports the interpretation that extensional faulting gave rise to the Coast Range Ophiolite (Constenius et al., 2000; Shervais et al., 2004; Choi et al., 2008). Additionally, Shervais et al. (2004) clarified that the CRO formed in four stages, resulting in the emplacement of the CRO onto the North American plate. The first stage is characterized by assembly of layered gabbros, sheeted dikes, and volcanic rocks that have been classified as arc tholeiites, basalts high in silica and

poor in sodium, which are typical of the beginning phases of an arc system. The second stage is indicated by gabbros and wehrlite-clinopyroxenes, diorites and volcanic rocks (possibly high calcium boninites). The third stage is indicated by diorite and quartz plutons, calc-alkaline igneous rocks, and felsic sill and dike complexes. These three stages represent the beginning of a complex subduction zone during the middle Jurassic (Shervais et al., 2004).

The next stage of CRO formation occurred when formation of the supra-subduction zone was suddenly stopped by the formation of a new spreading ridge (Shervais et al., 2004), indicated by chemical petrology of basalts adjacent to the CRO. When subduction began again, the CRO was accreted onto the North American continent because of an accretionary wedge that made the CRO buoyant (Shervais et al., 2004). The incorporation into the down-going slab of more buoyant, warmer, newly formed crust forced a shallower angle of subduction forcing volcanism to cease near the trench and continue further inland (Shervais et al., 2004). Subduction likely restarted along a transform fault and Choi et al. (2008) believe that peridotite blocks in the Stonyford volcanic complex represent unaltered mantle wedge before subduction re-initiation.

Peridotite and altered peridotite slices in the CRO are disseminated in the landscape, cut by regional faults, and may be deeply buried. Field investigations have provided some coverage of the relevant mantle geochemistry (*e.g.*, Choi et al., 2008) but few surface springs plumbing these units have been so far detected, though the mantle blocks are surely dewatering in the subsurface. Morrill et al. (2013) describe comprehensively the current understanding of the Sonoma County spring at The

Cedars, an extremely high pH spring with a microbial consortium cycling hydrogen and possibly hydrocarbons. In order to constrain the relevance of these continental serpentinite springs to biological oceanography and theories on a serpentinite-hosted origin of life on Earth, it is crucial that multiple comparable field sites be characterized in short order. This thesis provides direction to field investigations in this critical area of research.

MODELING AND IMAGE ANALYSIS METHODS

3.1 Modeling Methods

In general, a site suitability analysis uses a set of pre-chosen criteria that is organized and layered in ArcGIS. Multi criteria evaluations (MCE) in ArcMap use multiple layers of georeferenced data, with each layer being assigned a weight (a number). The methods that are used are at the discretion of the end user, but can include Analytic Hierarchy Process (AHP) or any other MCE. AHP uses a weighting system first described by Saaty (1980) and is the most commonly used MCE (Haines, 1998). Issues can arise in MCE decision making and weighting schemes (Rahman et al., 2012; Haines, 1998). These issues arise when more than one decision maker is in charge of choosing a specific set of criteria for a given region. Weighting can also be questioned. Choosing a weighting scheme is not easy, as one criterion may or may not be more important than another. Here I have chosen to weight all criteria as a “1” in order to first determine importance of each layer; this decision has also kept the models simple. The data here have been converted into raster format. Georeferenced datasets are chosen based on logic and suitability for the area being studied. GIS can enable end-users to locate strategically specific areas of interest before field investigations begin. These types of modeling approaches take multiple georeferenced layers, select a certain type of criteria and then add the number of selected criteria for a given pixel.

As a cost- and time-saving measure, GIS suitability analysis has been used previously by geologists to locate potential geologic hazards (Nandi and Shakoor, 2009; Pourebrahim et al., 2011), and even fossils (Oheim, 2006).

Here GIS site suitability analysis is applied for the first time to the problem of locating largely fault- or interface- controlled springs in some CRO mantle blocks.

In this thesis, GIS site suitability analysis was used to predict high pH springs sourced in serpentinites in California, using a multi-criteria site selection model within ArcMap 10 and 10.1. Data were downloaded from the USGS (<http://earthquake.usgs.gov/hazards/qfaults/>; <http://www.brenorbrophy.com/California-DEM.htm>; <http://pubs.usgs.gov/ds/424/>) and NHD+ (<http://nhd.usgs.gov/data.html>) websites. The map projection used was Universal Transverse Mercator (UTM) Zone 10, World Geodetic System (WGS) 1984. This projection was chosen because it provided an accurate spatial representation of the study area which was encompassed within a single zone (Maher, 2010). National data sets as outline in Table 1 (criteria selected included serpentinite/peridotite, fault lines, swamps and marshes, lakes and rivers, slope ≥ 45 degrees, serpentinite-gabbro unit boundary, and observed springs and seeps, see Figure 1) were clipped to the four areas of interest to facilitate modeling (Figure 2). I used the weighted sum analysis tool in Arc Toolbox in order to create the MCE that I used for my models.

A MCE as I have described requires all data to be in raster format. Therefore, source data that were in vector format were converted to raster format prior to analysis.

The model was re-evaluated after an attempt to ground-truth the first model (Figure 3). This consisted of driving to and hiking in areas predicted by the first model. Where samples were available, they were collected (water, rock, and biological samples). Exact coordinates were not reached due to heavy rains and washed out roads near Indian Valley Reservoir (the most promising area for future field work based on map predictions, literature review, and aerial photography). Based on physical observations (after an attempt at ground-truthing) the model was expanded to include serpentinite contact boundaries and *mélange*. It appears that the two most important factors for this particular model are a slope greater than forty-five degrees overlaying serpentinite (Figure 4). These two features were evaluated when the model predicted The Cedars and Complexion Spring as a “2”, despite the fact that they are both known high pH springs.

Another observation is that the highest possible number of co-occurring parameters would be a “7”, but the highest value the model generated is a “5”. Lakes and Streams were combined into a single raster dataset for simplicity. Swamps and Marshes remained a separate dataset. As these springs are deeply sourced with some surface interaction, it could be that surface water has no significant impact on the model. It is also important to note that the revised model added new high probability areas (from the 6 novel sites in the preliminary model to 33 novel sites in the optimized model) and changed one of the predicted locations around Indian Valley Reservoir. Several points that were a “5” in the first model show up as a “4” in the final model due to the addition of

a dataset. In order to determine the accuracy of the model, a table (Table 2) was modified from Goff et al. (2001) and the GPS coordinates were turned into a shape file and added to the GIS analysis; this table contained springs studied by Goff et al. (2001) that had a pH of 8.5 or higher. Next a second table (Table 3) was modified from Goff et al. (2001) with springs not considered high probability sites based on the low pH of the waters sampled. Based on all models, the sites studied by Goff et al. (2001) fell in the range of “0” to “2”, with most falling in the “0” to “1” range (Figures 2 and 3; Tables 2 and 3).

3.2 Stream Essentials

Stream Essentials is an image analysis program created by Olympus that allows a user to analyze in a consistent fashion images saved to a file. The image software can be run on any PC. For a set of images of consistent quality (obtained through collected satellite and aerial imagery presented via GoogleEarth), I allowed a set of grayscale intensity values to be applied across images, and colorized the region of interest (http://www.lri.se/pdf/olympus/Olympus_Stream_Software.pdf). The user sets all parameters. Figures 4 and 5 are examples of what images look like before and after analysis in Stream Essentials.

Images were first downloaded from GoogleEarth and imported into Stream Essentials. Next all images were gray-scaled in order to get uniform gray pixel values. Next, using a known travertine gray scale values were chosen and set (Min 112, Max 240). The software automatically colors the values chosen red. A person can visually edit the photos to remove red blotches from roads and other surfaces

that appear not to be travertine. This software is useful in visually aiding in future field work.

3.3 Uncertainty of Models

As with all modeling projects, GIS analyses are entirely dependent on high quality georeferenced data inputs. If a data set is out of date, at an inappropriate scale, or not of high quality then the model may be inaccurate. The data used in this modeling were of good quality, but data integrity can be an issue when working in other parts of the world. Additionally, a site suitability analysis only predicts where an area may contain a given feature (surface springs) or might be suitable for a specific purpose (waste water treatment plants). The model cannot determine that these features actually exist. They must be ground-truthed and compared with other available data (such as aerial imagery, and by field campaigns, ideally). GIS models may also underestimate an area's indexed suitability, as they are constrained by input data quality and may be hindered by embedded human error.

RESULTS

The purpose of this project was to use a GIS site suitability analysis to predict field locations of deeply sourced springs in serpentinites, and use aerial photographs processed in Stream Essentials in order to determine whether suitability analysis appeared successful, thus building confidence in the relevance of these data sets to future field work. The main focus of this project was to determine whether or not a GIS site suitability analysis can be used successfully and accurately to predict spring locations in serpentinites. After preliminary model assembly, the test models were reevaluated and new parameters were added to build the optimized model. This better constrained the original results and added probable field localities to the final analysis. With the addition of aerial imagery, the results of the site suitability analysis were visually assessed.

4.1 Maps of Spring Locations Predicted by Model

Figure 1 shows the preliminary model predictions at potential spring locations. This model predicted a total area of 150,100 m² for potential field sites. Area is determined from a raster dataset by squaring the pixel size and multiplying by the number of pixels (in this case $82.6 \times 82.6 \times 21 = 150,100 \text{ m}^2$). Each site was given a coordinate that was exported from GIS into a KMZ file and then input into an excel table (Table 4). The total area of predicted sites increased to 375,251 m² ($82.6^2 \times 55$). As the total area of predicted sites increased, there were location changes to some high probability sites and identification of new ones (Figure 2). Location of one site was moved considerably to the east (Indian

Valley Reservoir Site 3). Several new sites near the Lake and Napa county boundary, in Sonoma County, and a new area along Lake Berryessa were indicated in the model (Figures 7-12 show most of these areas in GIS zoomed in). Figure 2 show new potential field locations predicted by the revised model. The coordinates for each new site are listed in Table 5.

The maximum possible number of co-occurring parameters would be “7”, however no site scored higher than a “5”. Figure 1 shows the final map after processing. From this analysis, it was determined that in this study area marshes had no effect on the model. The map depicted in Figure 2 generated five high probability sites (scored as a “5”) as seen in Table 4.

4.2 Summary Findings of Initial Ground-truthing

After the first map was generated (Figure 1), a brief field survey provided some experience in the terrain. Chalk Mountain, a travertine deposit with flowing water, did furnish water, rock, and biological samples to be analyzed; however as shown in Tables 2 and 5 pH values fall below 8.5 and as shown in Figures 2 and 3 the area was predicted as a 2. This confirms low probability areas within the model. Table 5 contains all field locations where samples were taken. As a result of field work the model was revised to include the boundary between serpentinite and gabbro.

The revised model has been evaluated against existing spring data from the NHD+ data set (Figure 14) and shows a correlation between known springs and the model predictions. Aerial imagery (Figures 15 – 39) allows

visual confirmation of water bodies in most, though not all, images. It appears that the model has predicted up to 33 promising new field locations, several in Sonoma County near the Cedars locality, and one of which falls within ten kilometers of Complexion Spring, a known high pH spring studied by Barnes et al. (1972).

4.3 Selected model spring profiles

A. Chalk Mountain: a low-valuation site, ranked “2”

Chalk Mountain is rated as a 2 in the optimized model and therefore it is no surprise that the surface spring was not a high pH spring. Despite prominent biofilms on the travertine, this surface spring lacked the high pH values of interest. Figure 14 shows that there are no known springs at Chalk Mountain. The first model (Figure 1), and the optimized model (Figure 2) and the models with the discounted field sites all show that the area around Chalk Mountain are a “2”, which means that only two of the requirements (out of the seven put into the model) have been met in this area. Current known field locations, such as Complexion Spring and the Cedars, are valued at a “2” in the optimized model. The only way of knowing which two requirements have been met is to create various models of only two requirements. An educated guess can be made just by overlaying the original vector data sets. In this last case only the slope would be missing visually.

B. Intermediate valuations, ranked “3” to “4”

Some predicted spring localities that are ranked as “3” and “4” and are within 1-5 km of known high pH spring locations, when cross-referenced to the literature. This is likely due to the structure of the optimized model.

C. On the lack of sites ranked “7”

Recall that the highest probability attainable in the optimized model is a “7”; however, the highest ranking in the model result is only “5.” This means that no single site has all seven features, co-occurring. Perhaps in adjacent counties, if considered, sites ranked “7” would be detected. On the other hand, if future work determines that areas not selected as high probability sites by the optimized model do indeed have active springs, a critical missing feature or gaps in data quality may provide an explanation. Certainly, the lack of sites rated as “7” in the model suggest the possibility that not all of the criteria considered here are important for the model; future iterations of the model may consider hydrologic flow directions, if available, and perhaps additional topographic information.

D. Apparent controlling factors on spring expression

Thus far, the most important controlling factors for spring localization appear to be serpentinite and slope values greater than forty-five degrees, with other factors as secondary considerations. This has been determined by evaluating the model and where Complexion Spring and The Cedars both place on the map. It seems that faults, bedrock contact, the presence of water are important factors, but are secondary features. The co-occurrence of these features provides an excellent basemap for future field work.

E. Assessment of data inputs

Figure 14 shows the actual proximity to the first predicted sites in relation to known springs and seeps in the NHD+ data set. The figure also shows that

many of areas predicted by both models fall on or near (within ten kilometers) of existing springs. Aerial photography of the high probability sites were processed through Stream Essentials and the results are listed in Table 6 and Figures (15-47).

Aerial images were taken from GoogleEarth and were obtained by Google from NASA, Digital Globe, United States Forest Service, the United States Department of Agriculture and other federal organizations, as reflected in image credits visible in GoogleEarth. Many of the aerial images confirm that there is surface water and/or signs of seasonal water at the surface.

DISCUSSION

5.1 Value of the modeling approach

A GIS site suitability analysis can be used to further field studies based in biogeochemistry by reducing the time spent to locate these sites using traditional field and literature searches. With high quality georeferenced data, we can narrow the search field by looking for those specific features and qualities that we have observed are associated with the serpentinization process (*e.g.*, ultramafic contact boundaries, faults). The application of GIS as a powerful tool and resource for field geology can increase research productivity and enhance success in remote field settings.

5.2 Limitations of the modeling approach

GIS-based modeling of this kind can only predict where springs are likely to occur. Models are not able to predict how the springs express themselves or even if they will exist. A suitability analysis can only show that an area is most appropriate for a particular feature based on the available georeferenced data. If a spring or seep for reported spring/seep data was not included in the dataset, it is excluded outright from the optimized model results; this facilitates field work by providing clear coordinates for known spring sites, but nonetheless might obscure otherwise promising field areas. Future model iterations might reduce the value of the springs/seeps feature, and increase the value of serpentinite contacts and fault lines to determine which field areas appear more promising under those model conditions. Additionally, it is evident that high pH springs are subjected to changing environmental conditions, and in fact

meteoric water is very aggressive with respect to what may be very porous carbonate or carbonate-serpentine-brucite precipitates. In fact, there is seasonal degradation of soft carbonate terraces driven simply by the erosive power of rainfall and the subtle dissolving action of meteoric waters. The interaction of meteoric waters and surface runoff makes these surface springs difficult to find using a modeling approach that is checked by aerial image analysis, as in the present work, given that minor spring deposits may be quite ephemeral.

Any modeling approach has limitations which can cause inaccuracies in the final output of the data. Those inaccuracies can be limited by the quality of data that have been chosen for the model. In this case, a variety of techniques were used to improve the accuracy of the model. Existing data from three different sources (USGS, NHD+ data base, and DEM) were imported into the model in an attempt to strengthen the data inputs. Given more time to evaluate in the field the highest probability sites, the model's accuracy could be assessed better. The intersections of the model predictions and existing data (at sites ranked "3" and "4", as described above) do show that this model has potential to locate these springs.

5.3 Description of the highest probability sites determined from optimized model

The optimized model (Figure 3) identifies 33 areas of high probability for spring occurrence. These high probability areas may contain surface springs or could host groundwater of relevance to this research problem.

All of the following prospective field sites have at least five out of six characteristics in common. These are the parameters that were used to create the

model (confirmed presence of serpentinite/peridotite, fault lines, swamps and marshes, lakes and rivers, slope ≥ 45 degrees, serpentinite-gabbro unit boundary, and observed springs and seeps). Recall that in this optimized model, the maximum number that can be assigned to an area of high probability is “7”; the highest number predicted for any site considered is nonetheless “5”. No one site has all seven of the parameters satisfied. Below, the 33 sites are grouped by geographic regions, listed as A through G, and land ownership and brief landscape descriptions are provided. For reference, all of the original data sets are shown in Figure 1. Data source for all groups can be found in Table 1.

Group A: Indian Valley Reservoir Group

Indian Valley Reservoir (IVR) is an artificial lake, used for recreation, and is administered by the Bureau of Land Management (BLM), Ukiah field office. All three areas are in Lake County and are part of the Indian Valley/Walker Ridge recreation area. The following three sites have been predicted in the model (Figure 3) and are shown to be near known springs (Figures 14). Figure 7 shows the area in ArcMap, zoomed in. Figures 15, 16, and 17 are aerial images of the three sites. These sites are ideal study sites because they are located on BLM land. To test pH and collect hand samples, there are no permits required. These locations are priority sites.

Group B: Lake Berryessa Group

This area shows patchy vegetation and what appear to be small areas of white rock, proposed here to be travertine. Lake Berryessa is a recreational area, owned by the Bureau of Reclamation, and it is a reservoir that was designed to irrigate land in California and was founded by the Solano Project

(http://www.usbr.gov/projects/Project.jsp?proj_Name=Solano+Project). The area has many recreational uses including hiking, camping, fishing, and boating. Figures 18, 19, and 20 show the areas described. This land is public use land. These field sites should be investigated during future field work. As seen in Figures 2, 3 and 4, and information given in Table 1, these sites contain all of the features that are considered likely to host springs based on the literature of Barnes et al. (1967,1972) and Morrill et al. (2013). These sites should be investigated in future field work.

Group C: Napa County

This site is located off of an unknown road and contains patchy vegetation. This does not seem to be private property and is easily accessible. I propose this as a secondary site based on the lack of visible water.

Group D: Lake County Group

These sites fall on a fault line that starts in Lake County and continues into Napa County. They are characterized by steep slopes, patchy vegetation, and a water body (Figures 22-26). All of these locations fall on or near a body of water and are priority sites. They are all easily accessible and are not on private property. There is no mention of these sites in the literature and Goff et al. (2001) did not study the springs associated with these sites. Many of the springs in this area remain

unknown and would be an intriguing area to study. These sites, like the Napa County Group, have springs associated with them that are un-named and not reported in the literature.

Group E: Napa County Group

This area is a continuation of the Lake County Group and is characterized by steep slopes, patchy vegetation and a body of water (Figure 27-41). These locations are easy to get to and Napa County sites 1-3, 6, 11-15 are not on private property and are off of a public road. Napa County Group Sites 4, 5, 7-10 appears to be located on private property. Springs associated with these sites have not been studied.

Group F: Willow Creek Road Group

This secondary site is located to the northeast of Willow Creek Road. This is an area that is relatively easy to reach and contains patchy vegetation along a fault line, but has no detectable water expression (Figure 42). This site does not appear to be a promising site.

Group G: Sonoma County Group

This area is characterized by steep sloping terrain with patchy vegetation directly off of Lake Sonoma (Figure 43-47), which is a recreational area on public land (Sonoma sites 1-2). Sonoma sites 3-5 are located on private property and permission would be required to collect samples or survey in the area. Many of these sites are located beneath Lake Sonoma. These sites could be an interesting comparison for Lost City and would require a survey done by boat.

CONCLUSIONS

In conclusion, a GIS site suitability analysis is useful in predicting where high pH springs are most likely to occur. Thirty-three high probability sites have been identified and preliminarily described, guiding future field research. Assuming sufficient high quality data for bedrock, structure, and water/stream locations are available, a site suitability analysis can be created to locate deeply sourced springs in serpentinites.

Future work should include systematic ground-truthing of the optimized model. For efficiency of field work, the sites located by the GIS site suitability analysis have been confirmed by both the location of known springs in the NHD+ dataset and screened visually by aerial photographs. The pH of the spring localities predicted by the model are as yet unknown, and many of the springs have no formal names. The importance of this GIS-based modeling project rests in its power to highlight the highest probability sites in the ongoing survey of ultrabasic springs sourced in serpentinites. The process of serpentinization releases heat, hydrogen, and methane, and provides energy sources for chemolithoautotrophic microbes. The alkaline fluids associated with serpentinization may well have acted as a buffer between acidic oceans on early Earth and fostered the beginning of life. Given otherwise uninhabitable planetary environments beyond Earth, serpentinization- driven self-sustaining systems [proposed for Mars, considered for some moons of the Jovian planets, and theoretically possible for scores of exoplanets] may well be where life is able to thrive.

APPENDICES

A. How to Guide:

In order to create this site suitability analysis all data were downloaded for free from the United States Geological Survey (NHD+, DEM, bedrock data, and fault line data). The size of national data sets are quite large, so the next step in data processing was to clip the data to the study area, in this case four counties in Northern California (Lake, Napa, Sonoma, and Yolo counties). The projection was then chosen as UTM Zone 10 North, NAD 1983.

Once data processing and projection transformations were complete, attributes from data sets were selected and turned into separate shape files. Point and line data sets were then given a 250 km buffer and then turned into raster data sets (seeps, rivers, and faults). All other shape files deemed necessary for this analysis were converted directly into raster format.

Once all files were in raster format the files were further processed by using a tool called Reclassify in ArcTool box. This tool allows the user to set No Data fields equal to “0” and specific attributes equal to any other number for the purpose of a weighted sum analysis as described in the methods section of this thesis. The digital elevation files had to be downloaded as separate tiles and were already in raster format. These tiles were processed using the Mosaic tool located in ArcTool box under the heading Data Management and the subheading Raster Dataset.

Next two files were chosen (bedrock geology and fault lines) to start the analysis to make sure that the method would work. Multiple iterations of the model

were then run, zeroing in on more and more specific locality predictions, with greater geologic support (*i.e.*, the integration of unit contact boundaries) embedded in the model. GPS coordinates for known high pH spring localities from previous studies (Barnes et al., 1969 and 1972; Goff et al., 2001; field work completed by Dr. Cardace in the summer of 2011 and by Dr. Cardace and myself in December of 2012) were uploaded into ArcMap and added to the map in order to test the accuracy of the map; it was satisfying to note both where (i) highly ranked predicted localities coincided with known high pH spring localities, and (ii) low ranked predicted localities coincided with known acidic or near-neutral pH spring localities.

In order to obtain GPS coordinates from the map; a new shape file was created and edited. Points were added visually, which required visual examination of high probability areas while the map was zoomed in enough to locate red pixels. All thirty-three points were created, edits were saved, and points were associated with xy coordinates (using the ArcTool “add xy coordinates,” located under the data management section). Coordinates were thus visible in the map projection, allowing conversion of all thirty-three points from UTM’s to latitude and longitude. This facilitated the location of relevant aerial photographs for use in Stream Essentials.

B. Supplemental Figures

FIGURE 1. The following shows raw data in vector format used to create the GIS site suitability analysis. See companion Table 1 for sources.

FIGURE 2. The map shows the results of the preliminary GIS site suitability model, which gave a total area of 150,100 m² for predicted field sites. The ranking system used here indicates that “0” has no likelihood of containing a spring. As the number increases (“1”, “2”, “3”, “4” and “5”), so does the likelihood that a spring will be located in that area. Please see Figure 1 for a companion map emphasizing site topography and regional water bodies. Red pixels are symbolized by green hexagons in the following GIS Map. Large navy blue circles represent two known and studied high pH springs (Complexion Spring and the Cedars). Goff field sites (symbolized by brown rounded squares) as in Goff et al. (2001) show low probability sites based on pH data collected by the author; please see Table 3 for more details.

FIGURE 4. This model was created after the optimized model to determine why Both Complexion Spring and the Cedars are a “2” in the models. Notice the proximity of the original predictions, the new predictions and known sites. This model shows that the two most important factors for surface spring expression are the presence of serpentine and a high slope (>45°). Based on this map, some of the predicted sites from the first model may be worth ground-truthing. Symbology is the same as the maps above.

(a)

(b)

(c)

FIGURE 5. McLaughlin Natural Reserve exemplar: White Seep. (a) White Seep is a known travertine located on McLaughlin Natural Reserve. (b) The color image was gray scaled in Stream Essentials and then pixel values were chosen based on known travertine deposits and edited. (c) The gray scale values chosen were between 112 and 240.

(a)

(b)

(c)

FIGURE 6. Example for Indian Valley Reservoir Site 1 (at 20 meters), (a) was used to test Stream Essentials software for this project. (b) The color image was converted to gray scale to normalize the photo and (c) gray scale values were set to the same values for White Seep.

(a)

(b)

FIGURE 7. (a) The area around Indian Valley Reservoir (Group A) zoomed in to the high probability areas around the reservoir in the optimized model. (b) Figure shows that the new model is close to the old model for Indian Valley Reservoir site 1, but off for site 3.

FIGURE 8. New area of high probability (Lake County Group) is shown, based on optimized data input. This is a fault line that extends from Lake County into Napa County for approximately 16-20 km.

FIGURE 10. This figure shows a potential new high probability site near the Napa and Sonoma county boundary.

FIGURE 11. Show the Sonoma Group zoomed in. Many of these sites lay in Lake Sonoma (a manmade recreational area).

FIGURE 12. Willow Creek Road showed up as a high probability area in the first model, in the revised model the area has become larger.

FIGURE 13. This map shows the new areas predicted by the final optimized model in relation to the former predicted areas. Notice that field locations where off by only five to ten kilometers.

FIGURE 14. New predictions are presented in relation to known spring data from the National Hydrologic Dataset Plus (NHD+) website. Indian Valley Reservoir 1 which was predicted by all of the models is in the same location, and is less than ten kilometers from Complexion Spring. Indian Valley Reservoir site 4 from the optimized GIS map and Willow Creek Road (predicted by both the preliminary and optimized models) were both predicted in both models. Most of the predictions along the fault line in Napa and Lake County and the sites around Lake Berryessa are surrounded or directly on existing sites that are known as springs and seeps from the national NHD+ data set.

(a)

(c)

(d)

FIGURE 15. Indian Valley Reservoir (IVR) site 1 (ID 0 in ArcMap) as predicted by the refined model (yellow thumb tack). This area is on Bureau of Land Management (BLM) land and is multi-use. The coordinates (latitude $39^{\circ} 9' 25''$ and longitude $122^{\circ} 32' 54''$) for all sites were hand-picked by finding each high probability area and placing a point in the center (or close to the center) of each area. IVR is located to the east of Bartlett Springs Road, off of County Road 303 in Lake County, California, and this area is run by the Ukiah field office of the BLM. IVR is a man-made lake located in Lake County and is part of the Indian Valley/Walker Ridge recreation area. Figure (a) is the area at 33 meters and Figure (b) is at 114 meters to give a larger view of the area. In all pairs of images, the red fields show the areas deemed most likely to host travertine, based on grayscale image refinement in Olympus Stream Essentials software (see Methods for more details). Figures (c) and (d) show the same area zoomed out to 114 meters.

(a)

(b)

FIGURE 16. Indian Valley Reservoir site 4 (off of Bartlett springs Road) as predicted by the refined model (yellow thumb tack). This is BLM land, and the coordinates (Latitude $39^{\circ} 6' 3''$ and Longitude $122^{\circ} 29' 34''$) are not too far from the first IVR site. The image was processed in the same way as the image of White Seep was processed.

(a)

(b)

FIGURE 17. Indian Valley Reservoir site 5 (off of Bartlett springs Road) is BLM land, with latitude $39^{\circ} 6' 3''$ and longitude $122^{\circ} 29' 43''$. This area is also east of Bartlett Springs road, but is more difficult to reach. Image was processed as above.

(a)

(b)

FIGURE 18. Lake Berryessa 3 with latitude $38^{\circ} 36' 7''$ and longitude $122^{\circ} 18' 33''$, this area shows patchy vegetation and what appear to be small areas of white rock which could be travertine. This area is on a steep slope and might be hard to reach. Lake Berryessa is a recreational area that serves as a reservoir and is owned by the Bureau of Reclamation and is the reservoir for the Solano Project. Image was processed as above.

(a)

(b)

FIGURE 19. Lake Berryessa 4 is located at latitude $38^{\circ} 36' 17''$ and longitude $122^{\circ} 18' 39''$. This area is steep and shows patchy vegetation with exposed bedrock. This area is not close to a main road, though there are several smaller local roads that are unknown in the area. Even then the actual site is not close to a road and appears to be difficult to reach. Image was processed as above.

(a)

(b)

FIGURE 20. Lake Berryessa 5 with latitude $38^{\circ} 37' 50''$ and longitude $122^{\circ} 19' 30''$, this area is not steep and shows patchy vegetation with exposed ground. The actual site is across the road from private property. Image was processed as above.

(a)

(b)

FIGURE 21. Napa Latitude $38^{\circ} 26' 22''$ and Longitude $122^{\circ} 28' 52''$ is off of an unknown local road and does not appear to be private property. Image was processed as above.

(a)

(b)

FIGURE 22. Lake County 1 latitude 38° 48' 55" and longitude 122° 25' 37" located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 23. Lake County 2 latitude $38^{\circ} 48' 52''$ and longitude $122^{\circ} 25' 33''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 24. Lake County Group 5 latitude $38^{\circ} 48' 45''$ and longitude $122^{\circ} 25' 23''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 25. Lake County Group 4 latitude $38^{\circ} 48' 48''$ and longitude $122^{\circ} 25' 27''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 26. Lake County Group 3 latitude $38^{\circ} 48' 50''$ and longitude $122^{\circ} 25' 30''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 27. Napa County Group 1 latitude $38^{\circ} 45' 23''$ and longitude $122^{\circ} 22' 3''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 28. Napa County Group 2 latitude $38^{\circ} 45' 37''$ and longitude $122^{\circ} 22' 27''$ located to the east of the road named Jerusalem Grade and around a body of water. Image was processed as above.

(a)

(b)

FIGURE 29. Napa County Group 3 latitude $38^{\circ} 45' 34''$ and longitude $122^{\circ} 22' 24''$ located to the east of the road named Jerusalem Grade plotted near the center of the unnamed body of water. Image was processed as above.

(a)

(b)

FIGURE 30. Napa County Group 4 latitude $38^{\circ} 45' 28''$ and longitude $122^{\circ} 22' 19''$ located to the south of the road named Jerusalem Grade and the body of water. This point appears to be on private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 31. Napa County Group 5 latitude 38° 45' 26" and longitude 122° 22' 17" located to the south of the road named Jerusalem Grade and between two bodies of water. This point appears to be on private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 32. Napa County Group 6 latitude $38^{\circ} 45' 23''$ and longitude $122^{\circ} 22' 13''$ located to the west of the road named Jerusalem Grade plotted near the unnamed body of water. Image was processed as above.

(a)

(b)

FIGURE 33. Napa County Group 7 latitude $38^{\circ} 45' 18''$ and longitude $122^{\circ} 22' 9''$ located to the south of the road named Jerusalem Grade and between two bodies of water. This point appears to be on the edge of private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 34. Napa County Group 8 latitude $38^{\circ} 45' 15''$ and longitude $122^{\circ} 22' 6''$ located to the west of an unnamed road and of water. North of this point there appears to be several patches of what appears to be travertine. This point appears to be private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 35. Napa County Group 9 latitude $38^{\circ} 45' 12''$ and longitude $122^{\circ} 22' 3''$ located to the west of an unnamed road and of water. North of this point there appears to be several patches of what appears to be travertine. This point appears to be private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 36. Napa County Group 10 latitude $38^{\circ} 45' 10''$ and longitude $122^{\circ} 22' 0''$ located to the west of an unnamed road and of water. North of this point there appears to be several patches of what appears to be travertine. This point appears to be private property, and appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 37. Napa County Group 11 latitude $38^{\circ} 45' 2''$ and longitude $122^{\circ} 21' 53''$ located to the west of an unnamed road. This is an area that is relatively easy to reach and contains patchy vegetation. Image was processed as above.

(a)

(b)

FIGURE 38. Napa County Group 12 latitude 38° 44' 37" and longitude 122° 21' 26" located on unnamed road. This is an area that is relatively easy to reach and contains patchy vegetation. Notice the body of water to the east of the point. Image was processed as above.

(a)

(b)

FIGURE 39. Napa County Group 13 latitude 38° 44' 35" and longitude 122° 21' 22" located on unnamed road. This is an area that is relatively easy to reach and contains patchy vegetation. Notice the body of water to the east of the point. Image was processed as above.

(a)

(b)

FIGURE 40. Napa County Group 14 latitude $38^{\circ} 44' 32''$ and longitude $122^{\circ} 21' 19''$ located on unnamed road. This is an area that is relatively easy to reach and contains patchy vegetation. Notice the body of water to the south east of the point. Image was processed as above.

(a)

(b)

FIGURE 41. Napa County Group 15 latitude 38° 44' 29" and longitude 122° 21' 16" located to the east of an unnamed road. This is an area that is relatively easy to reach and contains patchy vegetation. Notice the body of water to the east of the point. Image was processed as above.

(a)

(b)

FIGURE 42. Willow Creek Road latitude $38^{\circ} 26' 29''$ and longitude $123^{\circ} 5' 36''$ located to the north east of Willow Creek Road. This is an area that is relatively easy to reach and contains patchy vegetation along a fault line. Image was processed as above.

(a)

(b)

FIGURE 43. Sonoma 1 latitude $38^{\circ} 45' 24.33''$ and longitude $123^{\circ} 5' 38.18''$ located along Lake Sonoma, a recreational area. This is an area that is relatively easy to reach and contains patchy vegetation with exposed bedrock. Image was processed as above.

(a)

(b)

FIGURE 44. Sonoma 2 latitude $38^{\circ} 45' 21.64''$ and longitude $123^{\circ} 5' 31.32''$ located in Lake Sonoma, a recreational area. Notice the patchy vegetation and greenish white bedrock to the east of the coordinates. Image was processed as above.

(a)

(b)

FIGURE 45. Sonoma 3 latitude $38^{\circ} 41' 37.98''$ and longitude $122^{\circ} 59' 49.20''$ located off of Fall Creek Road, on private property off of Merlo Lake. This appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 46. Sonoma 4 latitude $38^{\circ} 41' 25.98''$ and longitude $122^{\circ} 59' 45.79''$ located off of Fall Creek Road and is on private property off of Merlo Lake. This appears to be a vineyard. Image was processed as above.

(a)

(b)

FIGURE 47. Sonoma 5 latitude $38^{\circ} 41' 19.23''$ and longitude $122^{\circ} 59' 42.24''$ located off of Fall Creek Road, on private property off of Merlo Lake. This appears to be a vineyard. Image was processed as above.

C. Tables

TABLE 1. Table lists where data sets came from, which datasets were used and which datasets were present at each (a) group predicted by the optimized model. (b) Shows which datasets were present in each model, including initial test models (which were created as steps in the final process).

Dataset	Website	Group A	Group B	Group C	Group D	Group E	Group F	Group G
Serpentinite	http://pubs.usgs.gov/ds/424/	Yes	Yes	Yes	Yes	Yes	No	Yes
Serpentinite Contact Boundary	http://pubs.usgs.gov/ds/424/	Yes	Yes	Yes	Yes	Yes	No	Yes
MélangeMélange	http://pubs.usgs.gov/ds/424/	No	No	No	No	No	Yes	No
Fault Line Dataset	http://earthquake.usgs.gov/hazards/qfaults/	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Springs and seeps	http://nhd.usgs.gov/data.html	No	No	No	No	No	Yes	No
Lakes, ponds, rivers and streams	http://nhd.usgs.gov/data.html	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Swamps and marshes	http://nhd.usgs.gov/data.html	No	No	No	No	No	Yes	No
Elevation Data (Slope >45°)	http://www.brenorbrophy.com/California-DEM.htm	Yes	Yes	Yes	Yes	Yes	No	Yes

(a)

Dataset	Website	Test Model 1	Test Model 2	Test Model 3	Test Model 4	Preliminary Model	Optimized Model
Serpentinite	http://pubs.usgs.gov/ds/424/	Yes	Yes	Yes	Yes	Yes	Yes
Serpentinite Contact Boundary	http://pubs.usgs.gov/ds/424/	No	No	No	No	No	Yes
MélangeMélange	http://pubs.usgs.gov/ds/424/	No	No	No	No	No	Yes
Fault Line Dataset	http://earthquake.usgs.gov/hazards/qfaults/	No	Yes	Yes	Yes	Yes	Yes
Springs and seeps	http://nhd.usgs.gov/data.html	No	No	No	Yes	Yes	Yes
Lakes, ponds, rivers and streams	http://nhd.usgs.gov/data.html	Yes	Yes	Yes	Yes	Yes	Yes
Swamps and marshes	http://nhd.usgs.gov/data.html	No	No	Yes	Yes	Yes	Yes
Elevation Data (Slope >45°)	http://www.brenorbrophy.com/California-DEM.htm	No	No	No	No	Yes	Yes

(b)

TABLE 2. This table shows geochemical data that has been modified from Goff et al., (2001) and is a list of known spring locations with high pH values that were used to test the accuracy of the model.

Sample Number	Location	Map number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling Point Comments
CL93-70	Borax Lake	40; Clearlake Highland	38 59' 07"	122 40' 29"	404	10	10.2	na	Southeast shore
CL91-15	Complexion Spring	15; Hough Spring	39 10' 30"	122 30' 43"	518	8.9	11.5	Seep	From source
CL93-72	Little Borax Lake	41; Lucerne	39 00' 13"	122 45' 13"	405	11	8.5	na	Shore closest to club house
CL93-51	Elbow Hot Spring	12; Wilbur Springs	39 02' 14"	122 25' 31"	413	70	8.5	2	From source
CL93-67	Elgin Hot Spring Main	38; Wilbur Springs	39 03' 30"	122 28' 27"	658	69	8.2	20	Main pool, S edge of pond
SC94-19	Elgin Hot Spring, Orange Bathtub	38; Wilbur Springs	39 03' 42"	122 28' 32"	652	63	8.2	41.6	Site 300 m E of main site
CL91-12	Jones Hot Spring	12; Wilbur Springs	39 02' 02"	122 25' 36"	416	61.9	8	0-10	Disappearing spring, by bricks
SC94-9	Sulphur Creek, 200 m above Bear Creek	13; Wilbur Springs	39 02' 19"	122 24' 27"	408	26.5	8.5	190	Narrow spot in Creek
SC94-11	Sulphur Creek, scarp dnstrm W. End Mine	13; Wilbur Springs	39 02' 02"	122 26' 12"	414	31	8.5	127	Upstream of Jones/Elbow
SC94-18	Turkey Creek	34; Wilbur Springs	39 00' 22"	122 26' 22"	512	26	8.3	39	About 50 m north of highway
CLJ95-10	Wilbur Spring, Don White's	13; Wilbur Springs	39 02' 21"	122 25' 14"	412	54.5	8	Nm	About 50 m E of main site
CL93-53	Wilbur, spring between Main and road	13; Wilbur Springs	39 02' 20"	122 25' 18"	412	55	8	10	Concrete pool with pink algae

TABLE 3. This table of geochemical data is modified from Goff et al. (2001); these springs show pH values lower than 8.5. Spring locations were added to the final GIS map in order to test the accuracy of the model. These locations all fall in areas with predicted values of “0” to “3”.

Sample Number	Location	Map Number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling Point Comments
CL93-45	Adams Spring	33; Whispering Pines	38 51' 71"	122 43' 12"	829	15	6.5	seep	Pavilion Ruins
CL91-27	Adrienne's Well	27; Lucern	39 01' 16"	122 45' 15"	420	11.2	6.8	0-40	Faucet by house
CL91-8	Ag. Park Well	8; Kelseyville	38 55' 58"	122 45' 34"	640	65.7	5.8	0-300	Manhole by well
CL92-37	Allen Spring	31; Bartlet Springs	39 09' 38"	122 39' 54"	579	17	6	10	During low creek flow
CL91-5	Baker Soda Spring	5; Lower Lake	38 53' 31"	122 31' 53"	427	21.3	6.8	1	Pool, travertine summit
CL91-14	Barrel Spring	14; Leesville	39 08' 56"	122 28' 44"	720	10.8	6.8	1	From Source
SBM95-8	Big Mother Spring in Clear Lake	42; Lucern	39 00' 56"	122 46' 49"	404	22	na	unknown	Gas sample only
CL91-2	Big Soda Spring	2; Lucern	39 00' 53"	122 47' 15"	404	31.3	5.8	50	Concrete crib, low lake level
CL91-28	Borax Gas Seep	28; Clearlake Highlands	38 59' 10"	122 40' 05"	410	10	na	na	From plastic pipe in ground
CL91-17	Chalk Mt. Spring	17; Benmore Canyon	39 04' 23"	122 34' 38"	390	16.1	6.8	1	Solitary Bubbling
CL91-25	Clear Lake, Konocti Bay	25; Clearlake Highlands	38 57' 01"	122 38' 28"	404	10.2	6.8	na	Lake Shore
CL93-69	Clear Lake, City of Clearlake	39; Clearlake Highlands	38 59' 28"	122 44' 22"	404	12	6	na	City park fishing pier
SBM97-5	Clear Lake, Clear Lake Highlands	52; Clearlake Highlands	38 56' 45"	122 38' 07"	404	13.3	8.1	na	Lake Shore
CL91-3	Cold Spring near Cross Spring	3; Benmore	39 01' 40"	122 35' 09"	451	9	6	60	Near paved road

Table 3. Continued

Sample Number	Location	Map Number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Fiel)	Flow (l/min)	Sampling Point Comments
CLH96-4	Copage Spring	47; Hopeland	38 59' 13"	122 03' 31"	200	19	6.3	0 at surface	Pit in travertine
CL92-39	Crabtree Gas Seep	29; Potato Hill	39 17' 27"	122 49' 18"	698	28	6	0	Gas only, bubbling river
CLH96-3	Duncan Soda	46; Yorkville	38 56' 50"	123 07' 40"	280	16	6.7	Nm	Also called Duncan Spring
CL91-9	Ettawa Spring	9; Whispering Pines	38 51' 02"	122 41' 23"	591	21.7	6.5	2	From pipe near gazebo pines
CL91-24	Gas Spring	24; Bartlett Springs	39 11' 18"	122 41' 46"	759	10	5.8	4 total area	From Source
CL91-20	Gordon Cold Spring	20; Whispering Pines	38 49' 59"	122 44' 15"	735	9	6.5	60	Near house
CL91-21	Gordon Warm Spring	21; Whispering Pines	38 50' 05"	122 43' 53"	732	34.6	6.8	4	From Source
CL91-16	Grizzly Spring	16; Wilbur Springs	39 00' 12"	122 29' 50"	384	19.4	7	2	Concrete crib, top of travertine
CL98-1	High. Spring Reserv.	6; Highland Springs	38 56' 21"	122 54' 23"	448	22.4	nm	nm	Gas vent, southeast shore
CL91-4	Hog Hollow	4; Benmore Canyon	39 01' 19"	122 35' 31"	439	30	6	8	From Source
CL95-14	Horseshoe Spring	43; Clearlake Highlands	38 59' 39"	122 44' 35"	404	40	6.5	unknown	Water collected from hot tub
GYS95-2	Hot Springs	43; The Geysers	39 47' 22"	122 46' 41"	576	95.2	7	na	Gas vent in creek
CL93-50	Hough	35; Hough Spring	39 09' 43"	122 36' 43"	485	14	6.2	seep	Travertine west of ruins
CL91-26	Howard	26; Whispering	38 51' 29"	122 40' 24"	659	46.3	6.5	14	Main spring in bath house
CL91-11	Joe's	11; Clearlake highlands	38 52' 35"	122 40' 34"	622	13.6	6	2	Basin along side of road
CL91-7	Kelseyville	7; Kelseyville	38 58' 37"	122 49' 53"	428	10.4	na	Na	Gas vent on hill by old well
GYS95-	Little	51; The Geysers	38 46' 00"	122 44' 54"	747	98.3	5	na	Along creek
GYS95-	Little Geysers	43; The Geysers	39 47' 09"	122 46' 49"	550	95.8	5	na	Below hot springs
CLH96-6	Lucchetti "Bad"	49; Hopland	38 59' 35"	123 03' 14"	245	19.5	6	Pumped	Faucet by wellhead
CL92-30	Mayfield	30; Lower	38 53' 33"	122 32' 04"	420	17.3	6	0-100	Faucet by wellhead
CL91-18	New	18; Clearlake Hights	39 52' 33"	122 43' 37"	800	10.7	6	0-100	Faucet by wellhead
CL91-23	Newman Spring	23; Bartlett Springs	39 11' 53"	122 42' 54"	585	29	6.8	10 Total	Springs upstream of main site

Table 3. Continued

Sample Number	Location	Map Number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling Point Comments
CL92-38	Newman Spring II	23; Bartlett Springs	39 11' 55"	122 42' 46"	581	29	6.55		Main Spring
GYS95-1	Old Geysers	50; The Geysers	38 48' 00"	122 48' 13"	442	98.7	7	na	Main site, old geysers resort
CL92-41	Pinnacle Rock Spring	32; Bartlett Mountain	39 08' 08"	122 46' 18"	1128	13	6.512		Culvert, Bartlett Springs Road
CLH96-1	Reeves Well	44; Hopland	38 59' 08"	123 03' 38"	258	18.5	7.3	pumped	Faucet by wellhead
CL91-10	Spiers Spring	10; Whispering Pines	38 49' 49"	122 36' 51"	412	24.2	6.25		Spring by serpentine cliff
CL91-22	Sulfur Creek Spring	22; The Geysers	38 51' 41"	122 45' 15"	854	21	6	5	Springs by creek
CL95-11	Sulphur Mound Mine	8; Kelsevville	38 55' 44"	122 45' 27"	560	20	na	0	Gas only, cracks in tuff
CL96-2	Tribal I Well	45; Hopland	38 59' 06"	123 03' 16"	232	18.5	6.9	pumped	Faucet by wellhead
CLH 96-5	Vintage Well	48; Hopland	38 58' 46"	123 02' 50"	255	21	6.5	pumped	Faucet by wellhead
CL91-19	Anderson Hot Spring	19; Whispering Pines	38 46' 20"	122 42' 23"	488	49.4	5.5	3 total area	Main spring; faulted argillite
CL98-2	Anderson, New Hot Spring	19; Whispering Pines	38 46' 21"	122 42' 23"	488	90.4	6	0.5	Creek 40 m NW of main site
And99-5	Creek, below hot springs	19; Whispering Pines	38 46' 26"	122 42' 22"	473	20.5	6	45.5	At collapsed mine adit
And99-3	Fe-rich Spring	19; Whispering Pines	38 46' 20"	122 42' 29"	518	21.1	6	nm	Upstream of 'hot creek'
CL98-4	Schwartz Mine Adit	19; Whispering	38 46' 19"	122 41' 26"	476	22	6	4.5	From mouth of adit
And99-6	Schwartz Mine Adit	19; Whispering	38 46' 22"	122 42' 27"	476	18.8	5.5	11.4	From mouth of adit
And99-7	Drainage from 99-6	19; Whispering	38 46' 23"	122 41' 23"	439	12.4	4.5	11.4	About 100 m up from road
SBM95-6	Basalt (North)	1; Clearlake Oaks	39 00' 18"	122 39' 56"	404	25	2.8	na	Evaporated bubbling pool
SB99-15	Clear Lake, Middle Rip Rap, SBM	1; Clearlake Oaks	39 00' 12"	122 40' 14"	404	26.2	6.5	na	Lake water 2 m from shore

Table 3. Continued

Sample Number	Location	Map Number;	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling
SBM97-4	Clear Lake, S. Rip Rap, SBM	1; Clearlake Oaks	39 00' 07"	122 40' 13"	404	15.6	7.5	na	Lake water 2 m from shore
CL93-59	Dry vent on embankment near leaking	1; Clearlake Oaks	39 00' 15"	122 39' 48"	405	20	nm	na	Crack near haul road
SB99-5	Dry vent 30 m E of leaking	1; Clearlake Oaks	39 00' 16"	122 39' 47"	405	32.2	nm	na	Small vent in ground
CL93-64	Frog Pond (Green Bubbling Pool)	1; Clearlake Oaks	39 00' 14"	122 39' 27"	409	25.6	5	na	Bubbling pond, SW shore
SB99-8	Green Pool	1; Clearlake Oaks	39 00' 13"	122 39' 33"	407	22.2	nm	na	Bubbling pond, S shore
CL93-54	Herman Pit, east end	1; Clearlake Oaks	39 00' 11"	122 39' 54"	404	23.5	3.3	na	NE shore near haul road
CL93-57	Herman Pit, east end, 25 m W. of 56	1; Clearlake Oaks	39 00' 17"	122 39' 45"	404	14	3.5	na	Gas vent, pH of pit water
CL91-1	Herman Pit, site 4, near leaking well	1; Clearlake Oaks	39 00' 16"	122 39' 47"	404	10.1	na	na	Gas vent, pH of pit water
CL93-63	Herman Pit, west end	1; Clearlake Oaks	39 00' 57"	122 39' 57"	404	14	3.8	na	Pit water
SB99-12	Rip Rap Seep	1; Clearlake Oaks	39 00' 12"	122 40' 13"	404	22.8	5.5	0.05	Pit water leaking through bank
CL95-15	"Sister of Green Bubbling Pool"	1; Clearlake Oaks	39 00' 15"	122 39' 29"	408	26	3.5	na	Pool west of paved road
CL93-61	Well CL #1, leaking geothermal fluids	1; Clearlake Oaks	39 00' 16"	122 39' 47"	405	nm	na	sputtering	Old well head, leaking plug
SBMM00-3	Well MW25D, gas bleed, 60 psig WHP	1; Clearlake Oaks	39 00' 18"	122 39' 27"	409	cold	nm	na	Open well, gas only
Sc94-15	Bear Creek, downstream of Sulphur Creek	36; Wilbur Springs	39 02' 22"	122 24' 22"	369	26	7.5	≥300	About 50 m south of bridge
SC94-14	Bear Creek, upstream of Sulphur Creek	36; Wilbur Springs	39 02' 26"	122 24' 26"	369	26	7.8	≥300	About 50 m north of bridge
CL93-66	Blanck Hot	37; Wilbur Springs	39 01' 53"	122 25' 53"	436	43	7.5	12	At pipe into tub

Table 3. Continued

Sample Number	Location	Map Number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling Point Comments
SC94-19	Sulphur Creek, 25 m downstream of fence	13; Wilbur Springs	39 02' 09"	122 25' 36"	412	27	8	356	Downstream of Jones/Elbow
SC94-3	Sulphur Creek, 20 m downstream of fence	13; Wilbur Springs	39 02' 10"	122 25' 35"	412	26	8	nm	Downstream of gassy area
SB99-5	Dry vent 30 m E of leaking geothermal well	1; Clearlake Oaks	39 00' 16"	122 39' 47"	405	32.2	nm	na	Small vent in ground
CL93-64	Frog Pond (Green Bubbling Pool)	1; Clearlake Oaks	39 00' 14"	122 39' 27"	409	25.6	5	na	Bubbling pond, SW shore
SB99-8	Green Pool	1; Clearlake Oaks	39 00' 13"	122 39' 33"	407	22.2	nm	na	Bubbling pond, S shore
CL93-54	Herman Pit, east end	1; Clearlake Oaks	39 00' 11"	122 39' 54"	404	23.5	3.3	na	NE shore near haul road
CL93-57	Herman Pit, east end, 25 m W. of 56	1; Clearlake Oaks	39 00' 17"	122 39' 45"	404	14	3.5	na	Gas vent, pH of pit water
CL91-1	Herman Pit, site 4, near leaking well	1; Clearlake Oaks	39 00' 16"	122 39' 47"	404	10.1	na	na	Gas vent, pH of pit water
CL93-63	Herman Pit, west end	1; Clearlake Oaks	39 00' 57"	122 39' 57"	404	14	3.8	na	Pit water
SB99-12	Rip Rap Seep	1; Clearlake Oaks	39 00' 12"	122 40' 13"	404	22.8	5.5	0.05	Pit water leaking through bank
CL95-15	"Sister of Green Bubbling Pool"	1; Clearlake Oaks	39 00' 15"	122 39' 29"	408	26	3.5	na	Pool west of paved road
CL93-61	Well CL #1, leaking geothermal fluids	1; Clearlake Oaks	39 00' 16"	122 39' 47"	405	nm	na	sputtering	Old well head, leaking plug
SBMM 00-3	Well MW25D, gas bleed, 60 psig WHP	1; Clearlake Oaks	39 00' 18"	122 39' 27"	409	cold	nm	na	Open well, gas only
Sc94-15	Bear Creek, downstream of Sulphur Creek	36; Wilbur Springs	39 02' 22"	122 24' 22"	369	26	7.5	≥300	About 50 m south of bridge
SC94-14	Bear Creek, upstream of Sulphur	36; Wilbur Springs	39 02' 26"	122 24' 26"	369	26	7.8	≥300	About 50 m north of bridge

Table 3. Continued

Sample Number	Location	Map Number; name	Latitude	Longitude	Elevation (m)	Temp °C	pH (Field)	Flow (l/min)	Sampling Point
CL93-66	Blanck Hot Spring	37; Wilbur Springs	39 01' 53"	122 25' 53"	436	43	7.5	12	At pipe into tub
SC94-19	Sulphur Creek, 25 m	13; Wilbur Springs	39 02' 09"	122 25' 36"	412	27	8	356	Downstream of Jones/Elbow
SC94-3	Sulphur Creek, 20 m downstream of fence	13; Wilbur Springs	39 02' 10"	122 25' 35"	412	26	8	nm	Downstream of gassy area
SC94-6	Sulphur Creek, upstream of Wilbur Terrace	13; Wilbur Springs	39 02' 19"	122 25' 20"	411	20	7.8	nm	Wide area in creek
SC94-7	Sulphur Creek, below bath house	13; Wilbur Springs	39 02' 18"	122 25' 10"	411	26	8.3	224	Narrow spot in creek
SC94-25A	Sulphur Creek @ Elbow Creek	12; Wilbur Springs	39 02' 07"	122 25' 38"	413	26.3	nm	nm	Junction of features
CL93-47	Turkey Run Mine Spring	34; Wilbur Springs	39 01' 02"	122 26' 22"	537	29	6.5	50	From source
SC94-25	Unnamed Hot Spring, 50 m downstream 94-1	12; Wilbur Springs	39 02' 09"	122 25' 36"	412	52	7	≤0.5	From source, S edge of creek
CL91-13	Wilbur Hot Spring, Main	13; Wilbur Springs	39 02' 20"	122 25' 18"	412	55.6	7.5	7?	Central pool in concrete crib

TABLE 4. The following sites were predicted by the first GIS site suitability analysis (Figure 2). Several sites around Indian Valley Reservoir populated as likely field sites in the optimized model (Figure 3), as did sites along Lake Berryessa and Willow Creek Road.

FID	Name	Latitude	Longitude	Notes
0	Indian Valley Reservoir	39° 9'21.88"N	122°32'54.23"W	5 points, serpentinite, large water body, vegetation
1	Indian Valley Reservoir	39° 5'17.97"N	122°34'27.45"W	Serpentinite, large water body, vegetation
2	Indian Valley Reservoir	39° 5'58.38"N	122°29'58.09"W	5 points, serpentinite, large water body, vegetation
3	Clear Lake 1	38°55'28.83"N	122°38'21.08"W	Appears to be a wetland
4	McCreary Lake	38°45'27.95"N	122°30'30.26"W	South West end of lake continues into the Bucksnot
5	Lake Berryessa 1	38°36'8.96"N	122°18'37.50"W	5 points, private property west of the lake
6	Lake Berryessa 2	38°37'48.46"N	122°19'27.73"W	5 points, farm land, private road
7	McCray Ridge	38°34'24.45"N	123° 0'9.10"W	Heavy vegetation
8	Willow Creek	38°26'29.68"N	123° 5'41.22"W	5 points, heavy vegetation, river, possibly private
9	Pine Flat Road	38°43'49.41"N	122°45'6.77"W	Gravel parking area off of road side
10	Dry Creek Road	38°43'23.34"N	123° 1'6.65"W	Recreational lake
11	County Road 127	38°42'36.07"N	122°37'4.34"W	Vegetation, possible back yard
12	Lake Berryessa 3	38°31'17.94"N	122°12'46.48"W	Near Spanish Flat Resot Road
13	Anselmo Court	38°14'53.47"N	122°16'51.22"W	Paved over
14	Little Island	38°11'10.19"N	122°22'12.89"W	No road, middle of marsh
15	Lake Pillsbury	39°24'25.84"N	122°54'50.10"W	Patches of vegetation, no easily accessible road
16	Clear Lake 2	39° 1'37.25"N	122°54'34.45"W	Next to a farm, patchy vegetation
17	Heron Drive	38°18'55.52"N	123° 1'52.00"W	Near Pinnacle Rock

TABLE 5. The table shows sites sampled in the field. These field sites were chosen based on the preliminary GIS model (Figure 1). Due to field complications, the actual sites were not reached in the field, however Figure 2 shows the proximity of the field sites sampled and the preliminary model predictions, which were within five to ten kilometers of each other in most areas.

Name	Latitude	Longitude	pH	Conductivity	DO	ORP	Elevation Meters	Temp °C	Field Notes
Anderson Marshal State Historic Park	not taken	not taken	6.5- 6.8	nm	nm	nm	nm	Nm	Red soil exposed on road cuts, public land in highly developed area.
Chalk Mountain	39 04.266'	122 35.032'	8	nm	nm	nm	341.68	nm	Running water stacked travertine terraces, all highly weathered. Black mineralized zones (possible biofilm). Possible debris flow, conglomerate matrix w/ brecciated fragments. Serpentine-chlorite altered basalt. Cemented cobbles & pebbles in white-gray matrix (possibly calcite derived).
Road Cut on 20 West	39 00.099'	122 29.882'	8	nm	nm	nm	388.92	nm	39.92 mile marker, outcrop ~40' long X 15'
Walker Ridge Road	39 04.010'	122 28.984'	nm	nm	nm	nm	827.23	nm	Collected rock samples for Amy Stander at road cut on drive to Bartlett Spring Road. Forced to turn around at low area due to washed out road.
White Seep, mid-point	38 49.516'	122 20.898'	8.2	3.101 ms/cm3	15. 50	197.7	442.87	13.47	Running water
White Seep, Top	38 49.582'	122 20.936'	nm	nm	nm	nm	470.61	nm	No running water
Temptation Creek, top	38 49.657'	122 21.045'	7.7	2.532 ms/cm3	14. 02	219.3	488.9	13.94	
Temptation Creek, downstre am upper-	38 49.608'	122 21.100'	7.7	3.371 ms/c	10. 88	208.2	484.63	13.9	Collected biological samples.
Temptation Creek, mid- low	38 49.589'	122 21.119'	8.0 3	2.963 ms/c m3	14. 31 mg /L	185	479.45	13.3	Serpentine blocks, took samples. Peridotite blocks, carbonate cemented flow path.
White seep mid-slope	38 49.522'	122 20.899'	8.22	3.124 ms/cm3	14.8 5	177	454.46	13.94	

TABLE 6. The following sites were predicted by the optimized model, which was modified after data were collected in the field (shown in Table 5). Field Identification (FID) is a number and column automatically generated in GIS.

FID	Name	Latitude	Longitude	Area predicted by Model	min (gray)	Ma (gray)	Sum area (m ²)	Notes
0	Indian Valley Reservoir 1	39° 9' 25"	122° 32' 54"	371.522	180	256	3242.52	Serpentinite, patchy vegetation overlaying white areas, possibly travertine.
1	Indian Valley Reservoir 4	39° 6' 3"	122° 29' 34"	297.2176	180	256	8761.85	Patchy Vegetation, Some exposed white ground, possibly loose sediment or travertine?
2	Indian Valley Reservoir 5	39° 6' 3"	122° 29' 43"	74.3044	180	256	1300	Patchy Vegetation, Some exposed white ground, possibly loose sediment or travertine?
3	Lake Berryessa 3	38° 36' 7"	122° 18' 33"	297.2176	180	256	458.37	Hilly Area, a lot of patchy vegetation, possible slide area
4	Lake Berryessa 4	38° 36' 17'	122° 18' 39"	148.6088	180	256	914.82	Steep hill side, patchy trees, exposed serpentinite?
5	Lake Berryessa 5	38° 37' 50"	122° 19' 30"	221.9132	180	256	0	Ranch to the right of the picture, patchy vegetation, lightly colored soil.
6	Napa	38° 26' 22"	122° 28' 52"	297.2176	180	256	811.05	Appears to be a hilly area next to or part of a vineyard
7	Lake County Group 1	38° 48' 55"	122° 25' 37"	74.3044	180	256	13113.36	Steep incline leading into lake, patchy vegetation surrounded by areas of exposed ground
8	Lake County Group 2	38° 48' 52"	122° 25' 33"	74.3044	180	256	6445.05	Patchy vegetation, some exposed white ground around the patchy vegetation
9	Lake County Group 5	38° 48' 45"	122° 25' 23"	74.3044	180	256	698.09	Patchy vegetation
10	Lake County Group 4	38° 48' 48"	122° 25' 27"	74.3044	180	256	905.77	Patchy vegetation
11	Lake County Group 3	38° 48' 50"	122° 25' 30"	74.3044	180	256	1858.34	Patchy vegetation, elevation declines towards lake/pond
12	Napa County Group 1	38° 45' 23"	122° 22' 3"	74.3044	139	215	2994.24	Patchy vegetation, clear distinction between trees and bedrock

Table 6. Continued

FID	Name	Latitude	Longitude	Area predicted by Model (m ²)	min (gray)	Ma (gray)	Sum area (m ²)	Notes
13	Napa County Group 2	38° 45' 37"	122° 22' 27"	74.3044	139	215	1093.04	Private Property on left, public Property property with high elevation to right
14	Napa County Group 3	38° 45' 34"	122° 22' 24"	74.3044	139	215	646.28	Private Property on left, unowned property with high elevation to right
15	Napa County Group 4	38° 45' 28"	122° 22' 19"	74.3044	139	215	1230.39	Private Property on left, un-owned property with high elevation to right
16	Napa County Group 5	38° 45' 26"	122° 22' 17"	74.3044	134	210	2288.62	Private Property on left, un-owned property with high elevation to right
17	Napa County Group 6	38° 45' 23"	122° 22' 13"	74.3044	130	206	1505.56	Private Property on left, un-owned property with high elevation to right
18	Napa County Group 7	38° 45' 18"	122° 22' 9"	74.3044	155	231	237.83	Private Property, vineyard?
19	Napa County Group 8	38° 45' 15"	122° 22' 6"	74.3044	155	231	200.06	Private Property vineyard
20	Napa County Group 9	38° 45' 12"	122° 22' 3"	74.3044	180	256	96.31	Private Property vineyard
21	Napa County Group 10	38° 45' 10"	122° 22' 0"	74.3044	180	256	621.36	Private Property vineyard
22	Napa County Group 11	38° 45' 2"	122° 21' 53"	74.3044	136	212	87.11	Patchy vegetation, water body with what looks like travertine around it
23	Napa County Group 12	38° 44' 37"	122° 21' 26"	74.3044	180	256	1110	Patchy vegetation surrounding a pond, alongside several local roads
24	Napa	38° 44' 35"	122° 21' 22"	74.3044	180	256	295.3	
25	Napa	38° 44' 32"	122° 21' 19"	74.3044	180	256	351.1	
26	Napa	38° 44' 29"	122° 21' 16"	74.3044	180	256	1906	
27	Willow Creek Road	38° 26' 29"	123° 5' 36"	371.522	180	256	1828.43	heavy vegetation, river, possibly private property
28	Sonoma 1	38° 45'	123° 5' 38.18"	74.3044	180	256	15916.36	
29	Sonoma 2	38° 45'	123° 5' 31.32"	74.3044	180	256	54195.09	

Table 6. Continued

FID	Name	Latitude	Longitude	Area predicted by	min (gray)	Ma (gray)	Sum area (m ²)	Notes
30	Sonoma 3	38° 41' 37.98"	122° 59' 49.20"	148.606088	180	256	971.1	
31	Sonoma 4	38° 41' 25.98"	122° 59' 45.79"	74.3044	180	256	702.08	
32	Sonoma 5	38° 41' 19.23"	122° 59' 42.24"	148.606088	180	256	341.24	

REFERENCES CITED

- Barnes I, Rapp JB, and O'Neil JR (1972) Metamorphic assemblages and the direction of flow of metamorphic fluids in four instances of serpentinization. *Contr. Mineral. and Petrol.* 35:263-276
- Barnes I, LaMarche VC, and Himmelberg G (1967) Geochemical evidence of present-day serpentinization. *Science* 156:830-832
- California DEM / ESRL (<http://www.brenorbrophy.com/California-DEM.htm>)
- Charlou JL, Donval JP, Konn C, Ondreas H, and Fouquet Y (2010) High production and fluxes of H₂ and CH₄ and evidence of abiotic hydrocarbon synthesis by serpentinization in ultramafic-hosted hydrothermal systems on the Mid-Atlantic Ridge. *Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges*. Geophysical Monograph Series 188, American Geophysical Union. doi:10.1029/2008GM000752
- Choi SH, Mukasa SB, and Shervais JW (2008) Initiation of Franciscan subduction along a large-offset fracture zone: Evidence from mantle peridotites, Stonyford, California. *Geological Society of America*, 36:8595-598. doi:10.1130/G24993A.1
- Frost DJ, Langenhorst F, McCammon CA, Trønnes RG, RubieDC (2004) Experimental evidence for the existence of iron-rich metal in the Earth's lowermantle. *Nature* 428, 409–412
- Fryer P (2012) Serpentine mud volcanism: observations, processes, and implications. *Annual Rev. Marine Science* 4:345-73. doi:10.1146/annurev-marine-120710-100922
- Goff F, Bergfeld D, Janik CJ, Counce D, and Stimac JA (2001) Geochemical data on waters, gases, rocks, and sediments from the Geysers – Clear Lake Region, California 1991-2000. Los Alamos National Laboratory, LA-13882-MS
- Haines LM (1997) A statistical approach to the analytic hierarchy process with interval judgments. (I). Distributions on feasible regions. *European Journal of Operational Research* 110:112-125. 0377-2217/98/\$19
- Hazen RM, Papineau D, Bleeker W, Downs RT, Ferry JM, McCoy TJ, Sverjensky DA, and Yang H (2008) Mineral evolution. *American Mineralogist* 93:1693–1720. 0003-004X/08/1112–1693\$05.00/doi:10.2138/am.2008.2955 1693
- Kelley DS, Fruh-Green GL, Karson JA, and Ludwig K (2007) The Lost City Hydrothermal Field revisited. *Oceanography* 20:90-99
- Kelley DS, Karson JA, Fruh-Green GL, Yoerger DR, Shank TM, Butterfield DA, Hayes JM, Schrenk MO, Olson EJ, Proskurowski G, Jakuba M, Bradley A, Larson

B, Ludwig K, Glickson D, Buckman K, Bradley AS, Brazelton WJ, Roe K, Elend MJ, Delacour A, Bernasconi SM, Lilley MD, Baross JA, Summons RE, and Sylva SP (2005) A serpentinite-hosted ecosystem: The Lost City Hydrothermal Field. *Science* 307:1428

Kodolanyi J, Pettke T, Spandler C, Kamer BS, and Gmeling K (2011) Geochemistry of ocean floor and fore-arc serpentinites: Constraints on the ultramafic input to subduction zones. *Journal of Petrology* 53: 235-270. doi:10.1093/petrology/egr058

Levin HL (2006) The Earth Through Time. 8th Edition, p. 169. John Wiley and Sons, ISBN:131978-0471-69743-5

Martin W, Baross J, Kelley D, and Russell MJ (2008) Hydrothermal vents and the origin of life. *Nature Reviews Microbiology* 6:805-814.

McCollom TM and Seewald JS (2013) Serpentinites, hydrogen, and life. *Elements* 9:129-134. doi:10.2113/gselements.9.2.129

McCollom TM and Back W (2008) Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochemica et Cosmochimica Acta* 73:856-875. doi:10.1016/j.gca.2008.10.032

McLaughlin RJ, Blake MC, Griscom A, Blome CD, and Murchey B (1988) Tectonics of formation, translation, and dispersal of the Coast Range ophiolite of California. *Tectonics* 7:1033-1056

Morrill PL, Kuenen JG, Johnson OJ, Suzuki S, Rietze A, Sessions AL, Fogel ML, and Neelson KH, (2013) Geochemistry and geobiology of a present-day serpentinization site in California: The Cedars. *Geochimica et Cosmochimica Acta* 109:222–240. doi.org/10.1016/j.gca.2013.01.043.

Muntener O (2010) Serpentine and serpentinization: A link between planet formation and life. *Geology* 38: 959-960. doi:10.1130/focus102010.1

Nandi A and Shakoor A (2009) A GIS-based landslide susceptibility evaluation using bivariate and multivariate statistical analysis. *Engineering Geology* 110:11-20

Oheim KB (2007) Fossil site prediction using geographic information systems (GIS) and suitability analysis: The Two Medicine Formation, MT, a test case. *Palaeogeography Palaeoclimatology, Palaeoecology* 251:354–365

Olympus / ESRL
(http://www.lri.se/pdf/olympus/Olympus_Stream_Software.pdf)

- Plummer O, Piazzolo S, and Austrheim H (2012) Olivine pseudomorphs after serpentinized orthopyroxene record transient oceanic lithospheric mantle dehydration (Leka Ophiolite Complex, Norway). *Journal of petrology* 53:1943-1968. doi:10.1093/petrology/egs039
- Poli S and Schimdt MW (2002) Petrology of subducted slabs. *Annu. Rev. Earth Planet. Sci.* 30:207–35. doi:10.1146/annurev.earth.30.091201.140550
- Pons M, Quittéa G, Fujii T, Rosing MT, Reynard B, Moynier F, Douchet C, and Albarède F (2011) Early Archean serpentine mud volcanoes at Isua, Greenland, as a niche for early life. *PNAS* 108:17639–17643
- Pourebrahim S, Hadipour M and Bin Mokhtar M (2011) Integration of spatial suitability analysis for land use planning in coastal areas; case of Kuala Langat District, Selangor, Malaysia. *Landscape and Urban Planning* 101:84–97
- Rahman MA, Rusteberg B, Gogu RC, Lobo Ferreira JP and Sauter M (2012) A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *Journal of environmental management*, 99, 61-75.
- Russell MJ, Hall AJ and Martin W (2010) Serpentinization as a source of energy at the origin of life. *Geobiology* 8:355–371. doi:10.1111/j.1472-4669.2010.00249.x
- Saaty TL (1980) *The Analytical Hierarchy Process*. McGraw Hill, New York
- Schmidt MW and Poli S (1998) Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Elsevier, Earth and Planetary Science Letters* 163:361-379. doi: 10.1130/0091-7613(2000)28<535:CSMBCB>2.0.CO;2
- Shelito BA (2012) *Introduction to Geospatial Technologies*. W.H. Freeman and Company, New York. ISBN: 13: 978-1-4292-5528-8
- Shervais JW, Murchey BL, Kimbrough DL, Renne PR, Hanan B (2005) Radioisotopic and biostratigraphic age relations in the Coast Range Ophiolite, northern California: Implications for the tectonic evolution of the Western Cordillera. *GSA Bulletin* 117: 633-653. doi:10.1130/B25443.1
- Shervais JW, Kimbrough DL, Renne P, Hanan BB, Murchey B, Snow CA, Zolglman Schuman MM and Beaman J (2004) Multi-stage origin of the Coast Range Ophiolite, California: Implications for the life cycle of supra-subduction Zone Ophiolites. *International Geology Review* 46: 289-315
- Sleep NH, Bird DK, and Pope EC (2011) Serpentinite and the dawn of life. *Philosophical Transactions of the Royal Society* 366:2857-286

Schaefer L and Fegley B (2007) Outgassing of ordinary chondritic material and some of its implications for the chemistry of asteroids, planets, and satellites. *Icarus* 186:462-483

Schaefer L and Fegley B (2010) Chemistry of atmospheres formed during accretion of the earth and other terrestrial planets, Submitted to *Icarus* 17

Schulte M, Blake D, Hoehler T, and McCollom T (2006) Serpentinization and its implications for life on the early Earth and Mars. *Astrobiology* 6: 364-376

Solano Project / ESRL
(http://www.usbr.gov/projects/Project.jsp?proj_Name=Solano+Project) USGS /

ESRL (<http://earthquake.usgs.gov/hazards/qfaults/>)

USGS / ESRL
(<http://pubs.usgs.gov/ds/424/>)

USGS / ESRL
(<http://nhd.usgs.gov/data.html>)

Wood BJ, Halliday AN (2005) Cooling of the earth and core formation after the giant impact. *Nature* 437, 1345–1348

Zahnle K, Schaefer L, and Fegley B (2010) Earth's earliest atmospheres. Cold Spring Harbor Laboratory Press *Perspect Biol.* doi:10.1101/cshperspect.a004895