A Capstone Course in Ecuador: The Andes/Galápagos Volcanology Field Camp Program

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ABSTRACT

We developed and implemented the Galapagos Volcanology Field Camp, a 3 week, 3 credit hour course for upper-level university students with a major course of study in geology. The course is offered by the South Dakota School of Mines and Technology, is open to any student, and is usually populated by students from many universities across the U.S. The course offers the essential skills of field geology, such as lithologic description, unit identification and correlation, stratigraphic logging, and geologic mapping, taught exclusively in an environment of volcanic rocks. Beginning in the subduction setting of the Andes, students are introduced to the regional volcanic and tectonic history. The course visits volcanoes that have produced andesitic, dacitic, and rhyolitic products. Students study lava flows, pyroclastic flows, ignimbrites, lahar flows, and debris avalanche deposits. Students are also introduced to the volcanic hazards and monitoring efforts in Ecuador. During the second phase of the course, the group flies to the Galápagos Islands to examine the basaltic features of hotspot volcanism. Students study recent lavas erupted from well-developed shield volcanoes, lava tunnels and collapse features, and the history of uplift, subsidence, and sea-level variation. Through design and implementation of this program, a sequence of exercises has been found that build a robust curriculum while fitting into an itinerary that is logistically feasible. Study of volcanic deposits in this classic setting leads to strong student learning, with 84% of students who have participated scoring higher than 80% on activities designed to assess the stated learning objectives. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/15-131R2]

Key words: field camp, volcanology, experiential learning

INTRODUCTION

Geology has always been rooted in the field. For this reason, teaching in the field has been shown to be a particularly effective means of training geologists (Douglas et al., 2009). This is true in an academic sense, but it is also recognized by industry professionals as an important training experience (Anderson and Miskimins, 2006; Puckette and Suneson, 2009). While the practice of taking students into the field might have been camping and exploring in the early days, pedagogical practices have become creative and robust (De Paor and Whitmeyer, 2009) with an emphasis on learning and assessment (e.g., Pyle, 2009). As technology has developed for both data collection in the field and building maps in the office, educators have brought these innovations along into field courses (Vance et al., 2009; Whitmeyer et al., 2009a). Field-based exploration and activities have proven to be strong tools for training both geoscience researchers (de Wet et al., 2009; May et al., 2009) and future geoscience educators (Thomson et al., 2006; Bishop et al., 2009).

In the spirit of sharing one's expertise with students, educators have developed remarkable learning experiences in international settings, often in places they have studied (Aitchison and Ali, 2007). Others have shared their expertise through discipline-specific exercises (McKay and Kammer, 1999; Bauer et al., 2009; May et al., 2009) and entire programs (Anderson and Miskimins, 2006). Through the 1980s and 1990s, a trend developed in the decline of the number of geology programs in the U.S. offering a field camp (Whitmeyer et al., 2009b). However, many of these programs, as well as smaller programs that never had their own field camp, still require their students to complete a field geology course in order to earn a degree. Therefore, many of the larger field camp programs regularly have numerous students from universities other than their own. Additionally, some field camps host visiting students as the majority, or up to the entire roster (Uzunlar, 2012).

COURSE DEVELOPMENT

In order to provide an option for the many students across the country that are looking for a field camp, to provide a volcanology-based field geology course, and to provide students with experience working in a classic locality, we developed the Andes/Galápagos Volcanology Field Camp (GVFC). This course teaches the fundamentals of working in volcanic terrains in the classic settings of continental arc deposits in the Andes and hotspot basalts in the Galápagos Islands. Herein, we discuss the development and implementation of the GVFC. This course was developed to provide a unique combination of an international educational experience, a course that offers the traditional skills of field geology, and an opportunity for students to get experience studying volcanic rocks in the

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field. While there are many field camp choices for students, there are few that provide the experience in the context of volcanic rocks. We decided to take advantage of the classic volcanic settings in the Ecuadorian Andes and the Galápagos Islands to provide this experience for students. In addition to the wealth of outcrops that illustrate volcanic processes, another advantage to holding the program in active volcanic settings is the ability to include a component of volcano monitoring, which we have done through collaboration with the Instituto Geofísico de la Escuela Politécnica Nacional (IGEPN).

This field camp program is offered by the Black Hills Natural Science Field Station (BHNSFS), a unit of the Department of Geology and Geological Engineering at South Dakota School of Mines and Technology (SDSMT). This camp offers a three-credit course that teaches the fundamental skills of field geology by utilizing in situ volcanic rocks and associated deposits, and discussing volcanic processes. The prerequisite courses for this program are mineralogy and petrology, with structural geology recommended.

The program was first presented in 2013 after a scouting trip to locate adequate field areas and to make contact with local geoscience instructors and logistical handlers. While in some cases, a field camp is set up after some experience conducting research in the area (e.g., Aitchison and Ali, 2007), this one was chosen deliberately due to the tectonic setting and diverse volcanic geology. In the first 3 y of the program, there have been different locations, exercises, and logistical arrangements that have been used in order to refine the overall quality of the experience. The curriculum discussed here is the most recent iteration used in 2016, but we note that there will likely continue to be changes in the future.

The course consists of four major exercises. The first two are set among the products of continental arc volcanoes, and the latter two are set in the basaltic hotspot products of the Galápagos Islands. The first is a volcanic stratigraphy exercise conducted either at Pululahua Volcano or at Tungurahua Volcano. The second is a mapping exercise at Cotopaxi Volcano. The third involves study and mapping of lava tunnels on the island of Santa Cruz, and the fourth is a mapping exercise in a small basaltic eruptive center on the flanks of the classic shield volcano, Sierra Negra. Other mapping exercises and shorter general study exercises have been used in the past or are being considered for the future. These four exercises have been used most often and are thus considered to be the "normal" list of activities for this field camp (see schedule in Table I). This set of exercises allows for a scaffolding of field geology skills along with understanding of volcanic and tectonic processes, as well as a demonstration to the students of the best variety of volcanic geology while visiting classic localities in Ecuador. In addition to the field-based stratigraphy and mapping exercises, we have also included some short exercises for the students to work on in the evenings based on the physical volcanology of the deposits that we have discussed, and these require a bit of calculation. The full syllabus and all of the exercise descriptions are offered as an electronic supplement to this article (available in the online journal and at http://dx.doi.org/10.5408/15-131s1 and http://dx.doi.org/10.5408/15-131s2).

In addition to curricular considerations, this type of course requires a great deal of logistical arrangements to be made and monitored throughout the program. It is not a trivial undertaking to assemble in South America a group of students, faculty, and staff who are all coming from different places. Then, lodging, food, and transportation must be provided while travelling to a list of sites over a relatively short amount of time. Furthermore, this all needs to be coordinated in as efficient a manner as possible in order to provide an affordable option for students. In this case, collaboration with Ecuadorian guides and academic professionals has been very important.

The budget of this course is based on a model that was already in place at SDSMT for other international field camp programs. The student fee has settled at $4995 and includes the tuition for three credit hours. The faculty salaries are paid from this money, and the university takes a percentage to cover overhead costs. Students are required to arrange their own transportation to Quito. Upon arriving, all lodging, transportation, and most meals are provided. This includes roundtrip airfare to the Galápagos Islands from Quito.

PURPOSE AND LEARNING GOALS

This program offers first and foremost a three-credit course in field geology. Therefore, the primary learning objectives are to provide the skills and philosophies necessary to investigate deposits in the field in order to understand the geologic history of a region, which is often done through the creation of maps and cross sections. However, the curriculum of this course has been designed to accomplish those learning objectives by using Holocene volcanic rocks rather than the Paleozoic and Mesozoic sedimentary bedrock units that are commonly studied at field camps in the western U.S. This allows for the ability to address added learning objectives related to the principles of volcanology. While many traditional field camps offer a taste of volcanic rocks (e.g., Judge et al., 2011), this camp allows for a greater depth of understanding of the processes controlling melting, transport, eruption, and deposition along with the classic understanding of mapping techniques.

Table II provides an overview of the learning objectives of the GVFC, the activities that have been included in the itinerary in order to address those learning objectives, and the assessment tools that are used to track student achievement of said learning objectives. The assessment in this course is primarily done through analysis of the field notebook that the students use to collect data, several small 1 d assignments, and two to three longer reports, which include stratigraphic columns and/or maps and/or cross sections to illustrate the geology that has been observed and interpreted during several days in the assigned field area. Notebooks and field reports have been shown to be a strong assessment of learning in the field (Park, 2003; Buddington, 2006). Prior to working at each site described below, the students are required to read key research publications in order to develop an understanding of the scientific questions that have been asked and answered as well as the methods of investigation. This strategy helps students to see the big picture relevance of the skills that they are working to acquire. Some portion of the grade for the course also comes through points that are assigned based on contribution to group work, both academically and logistically. The latter

TABLE I: Example itinerary for the program with sites visited, content covered, and transportation required. This is the itinerary that was used in 2016.

Day	Activity	Content	Transportation
0	Arrive in Quito		
1	Breakfast, opening meeting at Escuela Politécnica Nacional, intro lecture on Andes volcanology, visit Instituto Geofísico, lecture about monitoring in Ecuador	Discussion of geologic history Discussion of hazards and monitoring strategies for the entire country	Walking in Quito
2	Drive to Baños, visit Observatorio del Volcán Tungurahua (OVT), lecture on eruptive history of Tungurahua, field stops, set up camp	Discussion of volcano history Discussion of operations of a volcano observatory	Bus
3	Field sites around Tungurahua	Locating oneself on a map, lithologic descriptions, notebook formatting, discussion of lava flow, pyroclastic flow, air fall	Bus
4	Stratigraphic logging at Tungurahua in AM, half office day	Note taking, measuring stratigraphy, lithologic description	Bus
5	Half office day, half free day in Baños	Professional report writing	
6	Drive to Cotopaxi National Park up the mountain, overview of eruptive history, set up camp, walk into field area for overview of mapping exercise	Discussion of eruptive history and hazards	Bus
7	Mapping at Cotopaxi	Mapping	
8	Mapping at Cotopaxi	Mapping	
9	Half day mapping at Cotopaxi, drive back to Quito	Mapping	Bus
10	Office day	Professional report writing Creation of geologic map Interpretation of cross section	
11	Free day in Quito		
12	Fly to San Cristobal Island, visit Galápagos Academic Institute for the Arts and Sciences (GAIAS) for intro lecture to Galapagos geology, Interpretation Center hike to Frigatebird Hill	Discussion of hotspot volcanism and basaltic eruptive features	Bus, airplane, taxis
13	Boat tour: Frigatebird Hill, Witch Hill, Kicker Rock, Punta Pucuna	Mapping flow features, describing basaltic features, formation of cinder cones and tuff cones	Boat
14	Transfer to Santa Cruz Island, visit lava tunnels	Discussion of formation of lava tunnels, mapping lava tunnels	Boat, bus
15	Transfer to Isabela Island Mango Mirador Cerro Pelado Airport	Shield volcano formation, mapping cinder cones and flows, island uplift and relative sea level	Boat, bus
16	Sierra Negra and Volcan Chico	Shield volcano formation, mapping basaltic eruptive features	Bus
17	Transfer to Santa Cruz Island, half office day	Map making, report writing	Boat
18	Fly to Quito, end of program		Bus, airplane

component seeks to ensure that all participants are equally "chipping in" when it comes to the life of a field camp program.

POPULATION

This field camp, like the others offered by BHNSFS (Uzunlar, 2012), is mostly populated by students who are not regularly enrolled at SDSMT. The students are generally entering into their senior undergraduate year or have recently graduated. In the latter case, students usually have graduated with the condition of completing field camp in order to get their diploma, or they have applied and been accepted to a graduate program that requires that they earn credits in field geology in order to fulfill a deficiency. In the first year, the course was run as a "pilot" project and had only five students along with one American and one Ecuadorian instructor. As it was successful, it was run in future years with a population ranging between 11 and 16 students, with 16 being the predetermined maximum size due to logistical considerations, primarily in the Galápagos Islands. In each of these years, there was one or two American instructors and one Ecuadorian instructor as well as one teaching assistant. Overall, in 4 y, the population has been 54% male and 46% female.

In 2016, an innovation was made regarding the student population. An agreement was reached with the Department of Geology at Escuela Politecnica Nacional in Quito, in which they offered credit to some of their students who were to join the American students for the mainland Ecuador portion of the program. In that year, there were seven Ecuadorian students along with 11 American students.

TABLE II: Learning objectives for the course, the activities used to achieve those learning objectives, and the tools used to assess the achievement of those learning objectives. Locations for activities include Pululahua (Pu), Cotopaxi (Cpx), Tungurahua (Tu), Sierra Negra (SN), lava tunnels (t), Cerro Brujo (CB).

Learning Objective	Activity to Achieve Learning Objective	Assessment Tool
Conduct a regional-scale study of the geology of an area	All observations, instruction, and reporting throughout the continental portion of the course. Pu, Cpx, Tu	Written reports
Learn about volcanic processes, eruption, and deposition and reinforce concepts of geology and volcanology learned previously in classroom setting	Observation of multiple styles of volcanic deposits. Pu, Cpx, Tu, SN	Notebook
Identify and describe geologic units in the field	Observation of multiple styles of volcanic deposits. Pu, Cpx, Tu, SN	Notebook, written reports
Measure, describe, and record: thicknesses, orientations, distances, elevation differences	Practice and instruction as group. Practice during mapping exercises individually and in small groups.	Notebook, written reports
Locate oneself accurately on a map using topography, global positioning system (GPS), aerial imagery, or other information	Practice and instruction as group. Practice during mapping exercises individually and in small groups. Practice during map making in office setting.	Field maps, final maps, written reports
Identify and define contacts between units in the field and place them on a map	Practice and instruction as group. Practice during mapping exercises individually and in small groups. Practice during map making in office setting.	Field maps, final maps, written reports
Produce geologic cross sections with reasonable interpretation of subsurface geology	Instruction in group and individually.	Final maps and written reports
Produce professional geologic maps and reports	Instruction in group and individually. Includes both paper and digital map making.	Final maps and written reports
Learn about monitoring, detection, hazard assessment, and disaster mitigation	Lesson at Instituto Geofísico. Visit to Tungurahua Volcano Observatory.	Written reports
Practice collaborative learning, field work, reporting	All field exercises. Cpx, Pu, Tu, SN, t, CB	Final maps and written reports

SETTING

Ecuador is a country roughly the size of Nevada that is set in northwestern South America at the equator. The Andes mountain range extends more or less north to south through the full extent of the country. The Andes range is a continental volcanic arc resulting from the subduction of the Nazca Plate beneath the western margin of the South American Plate. Continental Ecuador has over 50 volcanoes that have erupted in the Holocene and over 25 that are still active. Figure 1 provides a map of the country, with notable geographic features and several active volcanoes that were visited during this program indicated. The Andes range is divided into the Eastern Cordillera and the Western Cordillera, separated by the Interandean Valley, as it runs through Ecuador. The volcanoes of the Western Cordillera have erupted predominantly dacitic lavas, while those of the Eastern Cordillera have produced mostly andesitic lavas, leading to the construction of classic stratovolcanoes (Hall et al., 2008).

The archipelago of the Galápagos Islands is a province of Ecuador that lies approximately 1000 km offshore in the Pacific Ocean. The islands were built as a result of volcanism over a mantle plume beneath the Nazca Plate. Figure 2 provides a map of the islands. Generally, the youngest islands are at the west end, and the oldest islands are in the

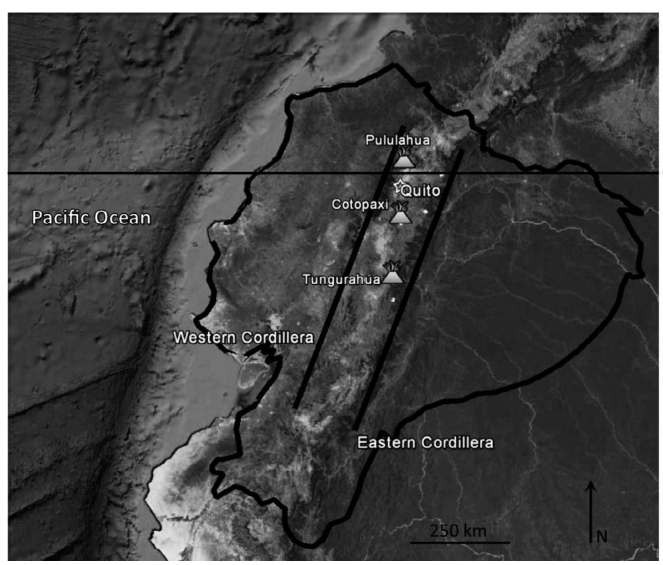

FIGURE 1: Geographic map of Ecuador showing selected volcanoes in the Andes Range where field exercises were located. Note oceanic trench parallel to the coast of the country.

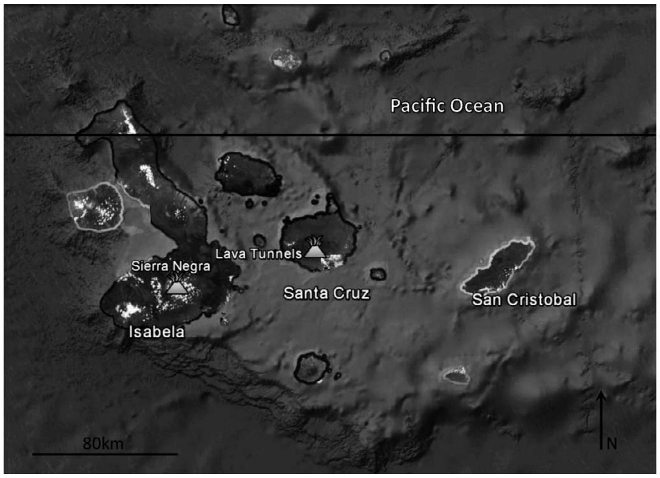

FIGURE 2: Geographic map of Galápagos Islands showing locations of selected exercises.

east. This is expected due to the eastward movement of the Nazca Plate. However, this model is not straightforward because there are young rocks that have erupted in most islands, including the far eastern island of San Cristobal (Geist et al., 1986). The volcanoes of the Galápagos Islands erupt basaltic lava and thus primarily form shield volcanoes and cinder cones. The country of Ecuador, therefore, is ideal for the purposes of the field geology course discussed here in that it provides examples of two varieties of volcanism resulting from two different plate-tectonic settings.

IMPLEMENTATION

Volcano Monitoring

On the first day of the program, the students visit the national headquarters office of the IGEPN of Ecuador in downtown Quito. This visit allows the staff of the IGEPN to describe to the students the history of volcanic activity in Ecuador, the hazard assessment studies that have been done, and the monitoring systems that are in place. The next day, the group visits the Tungurahua Volcano Observatory, where staff explain the types of data that are collected at the volcano and relayed back to Quito. This practical introduction to professional volcanology is the basis for the first assignment of the course, in which the students are prompted to write a summary of the hazards and monitoring processes in place in Ecuador.

Pululahua

Pululahua Volcano is an ideal place to begin the course for a number of reasons. The volcano has an interesting history that can be discussed in relative and absolute ages. The evolution of the volcano consists of an early period of nonexplosive dome building and collapse, followed by an eruptive hiatus, and then an explosive caldera-forming eruption, which finally was followed by emplacement of a cluster of domes within the crater. This history yields opportunity for good discussion of various volcanic processes. The variety of eruptive styles at Pululahua has produced a diversity of eruptive products. The early dome-collapse stage produced block-and-ash flows of dacite. During Pululahua's hiatus, an accumulation of distal fine-ash–sized eruptive material, known locally as cangahua, was deposited across the region, sourced from a different volcanic center. This is mostly reworked devitrified ash. Then, during the explosive eruption of Pululahua, various products were erupted, ranging from ash-dominant to pumice-rich layers of fall deposits and surge deposits emplaced by pyroclastic flows. All of these latter deposits also include xenoliths from the oceanic basement crust through which the explosion occurred. There are good exposures to show the effects of volcanic deposits being placed in paleovalleys. This is an important observation to make prior to the mapping exercise at Cotopaxi, where the lahars and ignimbrites to be mapped have been channeled in valleys. Most students have experience looking at laterally continuous sedimentary units that are relatively uniform in thickness. This is not necessarily the case with volcanic deposits. Young, valley-filling units can often be mistaken for stratigraphically older units. The domes that were emplaced also allow for the observation and description of highly porphyritic glass-poor fresh dacitic dome rock.

As this is the first exercise, the students are instructed in the field on strategies of field notebook setup and use. They are shown how to observe, describe, and characterize the rock units that have been created by this volcano. The students create a stratigraphic column in the field notebook that will later be reproduced in the office. They pay close attention to scale and lithology. While visiting five sites in 2 d, they also are instructed on the concept and use of global positioning system (GPS) units to record the location of each place where they are collecting data. Pululahua crater also provides a good location to discuss the skills of locating oneself on a map by topographic analysis, triangulation, and GPS.

The assignment for this exercise includes a detailed written report of the volcano, including its eruptive history, current physiology, and eruptive products, with citations to three linked stratigraphic columns that they create. The students also create a map of the area around the volcano where all data were collected. This allows relative distance to the eruptive center to be discussed. Students also are given a first chance to display in three dimensions the relative order of events and deposits by constructing a schematic cross section of the crater, the old domes, and the new domes.

This locality is also good as the first exercise for logistical reasons. There is a good lodging option in the nearby town of San Antonio de Pichincha. This is located close to the north side of the capital city of Quito, and so it provides an easy place for all students to meet after flying into the country. While the elevation is high at over 2850 m above sea level (masl), it is not as high as the mapping area at Cotopaxi (3900 masl) for exercise 2, so it is a good first place for students to acclimate to working and living at altitude. Finally, there are a number of quarries and road cuts in the area that provide exposure of the eruptive products of the volcano, so the story is easy to comprehend from a field-based perspective.

Tungurahua

In some years, the group has visited Tungurahua Volcano, which is further south from Cotopaxi (Fig. 1). This composite volcano has been active in recent years, with periodic eruptions since 1999. There are, therefore, a number of fresh lahar flow deposits that can be observed. While

FIGURE 3: Photo of students observing an ignimbrite deposit (outcrop on left) while standing on lahar deposits from Cotopaxi Volcano. The mountain looms in the background.

FIGURE 4: GVFC group in 2016 at the rim of Sierra Negra Volcano on Isabela Island.

some lahars are observed and mapped at Cotopaxi, they are more weathered and vegetated than the very fresh deposits at Tungurahua. In one case, students were able to study the deposits of a lahar that was less than 2 weeks old. There is also a volcano observatory at Tungurahua, which is managed by the IGEPN. This small station, which houses various types of geophysical monitoring equipment, also serves as a hub for first-hand reports by local people who serve as eyes and ears on the mountain. Visiting this station is meaningful to the students. They get the opportunity to see where and how the data are collected to monitor an active volcano. Generally, 1 to 1.5 d is all that has been spent at Tungurahua. However, there are many deposits in the region, and a longer mapping or stratigraphy exercise could certainly be developed. The town of Baños is near the volcano and is popular for tourism and so could provide many lodging and food options.

Cotopaxi

The second exercise of the GVFC is a mapping assignment of the eruptive products of Cotopaxi Volcano. Cotopaxi is a large, classic stratovolcano. It has been built through successive layering of a mix of ash falls, pyroclastic flows, lahars, lava flows, and volcanic debris avalanche deposits. To the north of the volcano, the students are given a 6 km^2 area to map. On a base map showing the topographic contours in the area, the students plot the locations of the different erupted units and the contacts between them. This mapping is done using the aid of GPS units for location control. The map area contains 1 Ma deposits of the neighboring Rumiñahui Volcano, and the 211 ka Chalupas ignimbrite deposit (produced by another neighboring eruptive center). These older deposits provided the paleotopography onto which the relatively young deposits of Cotopaxi eruptions have flowed. The pyroclastic flow deposits, lahar deposits, and debris flow deposits that can be mapped in the area have all been produced within the past several thousand years. Most of the erupted products are andesitic to basaltic andesites in composition. Therefore, the students study a different suite of minerals and textures than those at the dacitic Pululahua.

This exercise challenges students who are used to looking at sedimentary rocks. The three-dimensional nature of these types of units is that they are quite thin, and they follow valleys. Their thickness and lateral extent are not uniform. This is also a very striking place to do work. There is a true added value to the appreciation of the emplacement of these types of deposits by the presence of the large volcanic cone looming nearby while mapping (Cotopaxi's summit has an elevation of 5889 masl, 2000 m higher than the map area; Fig. 3; Semken et al., 2009).

Lava Tunnels

The first exercise in the Galápagos Islands takes place on Santa Cruz Island. The island contains many lava tunnels that are accessible to tourists and to scientists. The tunnels help the students to learn how a basaltic shield volcano is built and how these lavas travel long distances from their source.

The exercise incorporates the traditional field camp skills of a pace and compass exercise with the added challenge of working underground. Students use their pace distance and compass bearings to create a map of the tunnel system. First, the group visits a number of simple lava tunnels that are straight ahead in their construction. The tunnel system that is then used for mapping is somewhat branching. In addition to a tunnel map, the students submit a short report that describes the features of the tunnel, an assessment of the history of flows, and how they relate to the larger story of shield development. This is generally done as a 1.5 d assignment, with a whole day spent touring and describing several tunnels and large collapse craters around the island, and then another half day spent conducting the mapping of the final tunnel on which they will report.

Sierra Negra and Cerro Pelado

Sierra Negra Volcano on the island of Isabela is the most accessible example of a shield volcano in the islands. The crater is accessible by a road that goes most of the way up to the rim, which is 1000 masl. A short hike to the rim provides spectacular views of the caldera. This caldera was mostly paved with new lava flows during an eruption in 2009. This fresh basalt makes a striking contrast with the green vegetated walls of the crater (Fig. 4). The caldera is notably wide at 12 km in diameter. It is possible to hike around the rim toward Volcan Chico, a cluster of parasitic cones on the east side of the larger shield volcano. The Volcan Chico area provides the opportunity to see many fresh basaltic eruptive features and landforms. The hike there and back is ~8 mi (13 km) and will take most of the day with a group of students.

There are a number of opportunities to study the structure and history of Sierra Negra Volcano in more detail elsewhere on the island. An overlook called El Mango Mirador provides views of the lower flanks of the volcano, eruptive centers on the flanks, and the larger profile of the mountain on clear days. There are some sites of younger parasitic eruptions outside of the town of Puerto Villamil, well out on the flanks of the volcano. One such site produced a cinder ridge and an adjacent area of nested cinder cones. This ridge is known as Cerro Pelado. The cones and their associated lava flows are a good example of cinder cone and lava flow development during eruption. However, this cone is being quarried by the municipality for construction material. It has diminished in size notably over the past several years and will likely not be observable as a cinder cone soon.

The GVFC incorporated a 3 d mapping exercise at Cerro Pelado in each of the first 3 y of the field camp. This exercise is done with students working as partners or in small groups. The students start with a topographic base map and aerial imagery. The students use GPS units to aid in map location. They are to place on the map contacts between several lava flows of various ages. The youngest is the lava from the Cerro Pelado eruptive center. It is in contact with two older lavas that were sourced from the Sierra Negra crater. The students also map craters and other potential vents and indicate direction of flow. This exercise illustrates to students that looking closely at flow textures is important for interpreting an area that consists of only one rock type (basalt in this case). This locality was selected for mapping because it is controlled by the municipality of Puerto Villamil rather than the national park. Therefore, it is permissible for students to move around freely to investigate the geology. Other sites for mapping exercises exist, but they would require a special activity permit from Galápagos National Park.

Evaluation Plan

While the itinerary and list of locations for exercises have been modified a bit from year to year, the core focus on volcanic stratigraphy and mapping remains robust. The learning objectives listed in Table II are achieved through stratigraphic logging at outcrops provided in road cuts and quarries as well as through geologic mapping. These stratigraphic columns, geologic maps, and accompanying cross sections are used in the writing of professional-style geologic reports. Students are generally given one full "office day" to prepare and submit their reports.

RESULTS

Evaluation of Student Work

Here, we show an example of a stratigraphic column constructed by a student that represents block-and-ash flow, surge flow, and air-fall deposits created by Pululahua Volcano (Fig. 5). Through careful observation, logging, and office work, the students are able to provide a geologically reasonable explanation of the history of the eruptive activity at this volcano in the past 20,000 y. In Fig. 6, we provide an example of a map and cross section created for an area on the northern perimeter of Cotopaxi Volcano. The mapping and interpretation are on a fine scale compared to any available geologic maps and are consistent with interpretations based in long-term professional study (Hall and Mothes, 2008). The map and cross section were two figures within an ~10 page written report on the geology of the field area.

Performance on course assignments provides ample evidence that learning objectives are being met. In 3 y of running the course, 27 out of 32 students have scored over 80% for the overall grade for the course, with none scoring below 60%. Further, a final written exam is given at the conclusion of the course. This exam assesses the students' understanding of volcanic processes, how to describe certain lithologies and features in the field notebook, and mapping skills. In total, 26 out of 32 students have scored above 80%, with only one instance below 60%. The complete grading scheme for the course can be seen in the syllabus (supplemental file 1).

Finally, students report in exit surveys that they feel strongly that they have learned the principles of field geology and volcanology. Some selected comments are listed in Table III. Anecdotally, most students have also said that they would recommend the program, and we have begun to find in the first several years that students are coming from some of the same universities in multiple years, having been encouraged by their peers.

DISCUSSION

Program Logistics

Field-based geology education opportunities for students can only be made possible when logistical plans are in place. We share here some insights regarding the logistical arrangements. With any field-based program, the arrangement of transportation, lodging, food, and the resulting budget can be as time-consuming as the design of the geology education components of the course. The issues here are similar to those that will be encountered in the design of other international or volcanology-based programs. There are many options with regard to teaching in Ecuador. The following issues should be considered during planning stages.

Lodging, food, transportation, and other logistics are relatively inexpensive in continental Ecuador. During this program, the group is regularly on the move. A combination of buses, trucks, airplanes, and boats is needed to get from site to site. Transportation accounts for the majority of the budget of this program.

While in continental Ecuador, the primary means of transportation is a rented bus with a driver. This is more cost-effective than renting multiple vans. Also, having a driver included makes the running of the course easier for the instructional staff. Navigating traffic in Quito is best left to a professional. The bus is not needed every day, and so it is hired for the days when needed (see Table I). At the end of the continental portion of the program, the group travels together from the Quito airport to the Galápagos Islands. These tickets are purchased as part of the program budget and so are booked as a group. At least 3 h are needed to move a group through the customs and security process when departing.

The arrangement that has been settled on after 3 y of running this program involves lodging in locally run hacienda and lodge-style accommodations. Tent camping has been investigated as an option, but the cost savings are

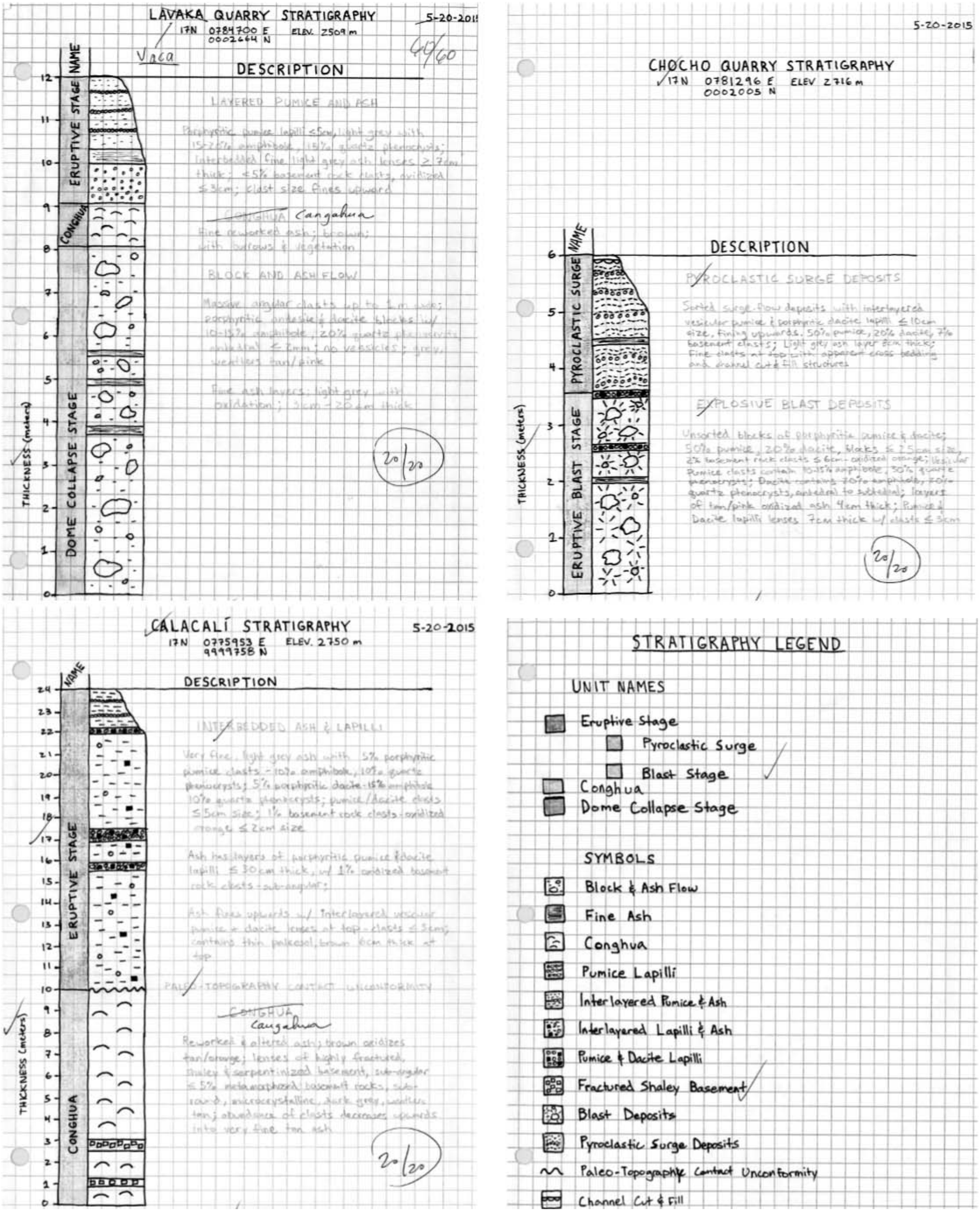

FIGURE 5: Example of student work in reporting the stratigraphy in three outcrops in the vicinity of Pululahua Volcano.

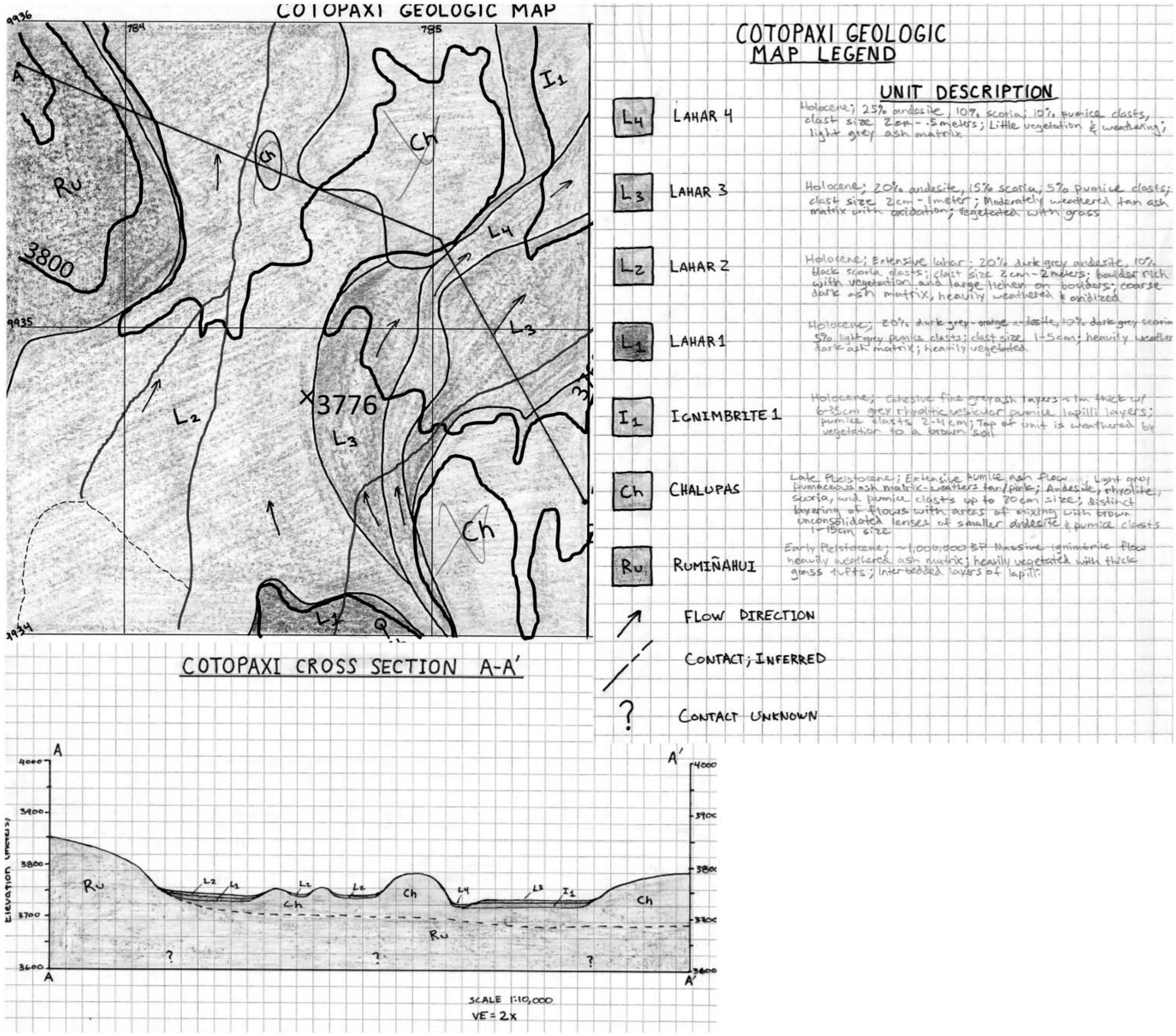

FIGURE 6: Student-created geologic map and cross section of volcanic deposits to the north of Cotopaxi Volcano. Map depicts ∼4 km^2.

negligible compared to the benefit of avoiding purchasing and preparing food. It is the norm while working in continental Ecuador that the people do not speak much English. A working knowledge of Spanish by at least one staff member is necessary unless a local guide or other translation arrangement is made.

While studying Pululahua Volcano, the group has stayed at a family-run venue called Hostería Alemana, with lodging rooms, dining room, and rooms for class meetings and for office work. In Cotopaxi National Park, the lodging is done at Tambopaxi Lodge. This is the only option within the park and is ideally situated within the mapping area that has been used as part of the curriculum. At the beginning and end of the time in continental Ecuador, different options have been used. Hotels near Pululahua, or in Quito, or in areas near Quito are options. The location for the beginning of camp should be somewhere that students will not have trouble finding in order to meet up on arriving in Ecuador. The location at the end of camp will need to provide easy transport to the airport on the morning of the flight to the islands.

Usually, breakfast is provided at hotels, and box lunches can be arranged. In some settings, dinners at hotels are the best or only option. In nights when lodging in the city, students enjoy exploring dinner options on their own. Fresh produce, lunch meats, bread, and juice are relatively easy to find if the group were to spend some days camping. At all times, all water in Ecuador needs to be purchased. It is inexpensive by American standards and can be found readily, but the group needs to plan to bring enough along for any cooking, cleaning, and hydration while working in the field.

In the Galápagos Islands, there is neither the option nor the need to rent a vehicle. There are many trucks and small

TABLE III: Selected student responses to exit survey questions.

What did you learn geologically from this experience?
My understanding of field volcanic deposits is greatly improved.
Lava tunnel morphology, dacite dome mass wasting, the influence of magma chambers on elevation. Lahar triggers.
I learned a lot about how field work is conducted with regards to volcanoes. I had little experience before.
Much more about igneous processes.
A ton about the tectonic settings, geologic settings, types of eruptions, types of rocks and lava in each place.
How to interpret screwy volcanic units from one another, which I have always had trouble with.
What did you get from this course that you did not expect?
A newfound respect for volcanology.
An appreciation for the diversity of volcanic environments.
I did not expect the amount of field experience that I collected in such a short time. I liked that we worked on short, quick projects – but learned in depth geology for each.
The amount of knowledge about volcanoes. For such a short course, I did not expect to be able to learn this much.
What was the most memorable part of this course?
Meeting and talking to the Ecuadorian students.
Ecuadorian students joining the first half of the trip. I wish that they could have stayed for the whole trip.
Interacting with Ecuadorian students.
Galapagos boat rides.
Other comments.
I loved the field camp. I got to experience seeing multiple volcanoes first hand. Not only that, but in a place where not many people will see in their lifetimes.

buses to be hired like taxis. With a big group, it is necessary to arrange buses ahead of time. The number of buses is limited, and the number of groups visiting the islands is increasing every year. Many exercises require day trips around the coast of an island in a boat. These boats need to be arranged ahead of time. Other days require transfer from one island to another with all people and luggage. There are options to book seats on public transport boats, but with a large group, it is best to hire a private boat for this transfer. This also certainly needs to be arranged ahead of time. All of these transportation arrangements (as well as lodging) are best done locally. There are many licensed naturalist guides in the islands who can be hired to make all arrangements.

In the islands, scheduling becomes complicated because of the layout of the islands, the location of the airports, and travel between them. In addition to scheduling sufficient time for teaching activities and student-led exercises, transportation has to be taken into account when planning the itinerary. As is the case with most field-based courses, there is some truck- or van-based transportation from the lodging site to the field area at the beginning and the end of each day. However, boat transportation between islands also needs to be accounted for several times during the course. There is usually a 2 h travel time from one island to the next, but this also requires customs at each port, taxi boats to and from the piers, and checking out and checking in at hotels on each end. Commuting from one island to another takes at least a half day. In addition to this, students may become sick during a particularly rough ride. In this case, getting right to work upon arrival is not always popular or possible.

Nearly all of the land of the Galápagos Islands is part of the Galápagos National Park. Therefore, any group outings or activities require that a licensed guide accompany the group. Guides can be hired for the day for different activities each day, but the simplest approach is to hire a guide to work with your group for the duration of your time in the islands. This guide can set up all transportation needs, lodging needs, meals, and be with the group during all activities as required by law.

While working in the Galápagos Islands, there are some different options for lodging and transportation. The best option for a geology course is to stay in hotels, and hire trucks and boats to move about the islands. There are tour guides who can set up ship-based itineraries as well, but they generally offer less flexibility in planning an itinerary.

Challenges

With this wealth of teaching opportunities, however, come a lot of logistical challenges. The challenges in mainland Ecuador are primarily logistical. It is not easy to rent vehicles, to find safe, secure, and adequate camping sites, or to purchase food and water when wanted. These logistics require a lot of planning ahead. It is not a place where one can work "on the fly" with a group of students.

Another possible challenge is the adaptation by students to the altitude. The field areas are at high elevation (up to 3800 m at Cotopaxi). We have been fortunate to not have any students with altitude sickness. We suggest to the students that they arrive in Ecuador several days before the start of the program if possible. This provides some time for them to become acclimatized to the lower oxygen levels. Also, by starting the program in Quito, then working around Tungurahua Volcano, and then finally at Cotopaxi Volcano, there is the added bonus of building in more time in the Andes before working at the very highest elevation that is encountered during the course.

In the Galápagos, the challenges do include outcrop availability. The roads, paths, and trails are primarily established for the purposes of guided tours, and most of the islands are protected. It is very difficult to get permission to conduct activities outside of the usual tour areas. Also, much of the islands are covered with dense vegetation. This means that outcrop is limited. The other challenges working in Galápagos are related to logistics. There are two major airports. It is necessary to plan an itinerary that begins and ends on the correct islands and minimizes the cost of boat transfers, but still provides the teaching activities that are desired.

Another challenge that presents itself in the teaching of this course comes from the range of geologic experience and preparedness of students. The students arrive from many different universities, different academic backgrounds, and levels of preparedness. It is necessary to quickly assess the understanding that each student is bringing with them with regard to tectonic settings, magma genesis and evolution processes, and physical volcanology. The instructional staff can then work to help students with specific deficiencies they might have with respect to their peers so that instruction can be best applied to all students. We have also developed a short reference handbook for students containing definitions and diagrams related to igneous petrology and volcanology. This helps to ensure uniformity in report writing and data reporting. Also, it is usually the case that some students have much more experience in the field than others. Some students have never used a Brunton compass or a GPS unit, while others have well-worn field equipment.

Successes

There is no better place on Earth to study both subduction and hotspot volcanism in one country and in close enough proximity to allow for them to be included in the same program than in Ecuador. As this program continues to run into the future, there is no worry that new exercises will cease to present themselves in mainland Ecuador. There are many volcanoes and many fresh and older deposits. It is possible to find volcanic stratigraphy to study almost anywhere within the Andean portion of Ecuador. Also, the IGEPN is very robust in their monitoring and reporting of the many active Ecuadorian volcanoes and willing to help. There are abundant opportunities that can be created for volcano monitoring–related projects that will be explored in future years.

Another success has been the integration of Ecuadorian and American students. These students quickly gained friends and colleagues that they will have for many years. Working together allowed for both groups to break down preconceived notions that they had about the other. Many students stated in exit surveys that working together with students of the other culture was the most memorable part of the course (Table III).

Ecuador and Galápagos are also very geographically and culturally interesting. Students who participate in this program learn a lot about this part of the world aside from the volcanology and mapping skills. Quito is a typical South American city, with a lot of history and culture. Many students arrive early or stay after the program to experience all that the city has to offer. There is added benefit to participation in an internationally based field camp, and it has been suggested that the learning of course content is also enhanced due to the experience of participating in an international field camp (Kelley et al., 2014).

Collaboration

Research collaboration has developed organically through the building of this educational program. We and other workers from both the U.S. and Ecuador have worked together not only on the planning for each GVFC, but now also on primary research related to volcanism in Ecuador. A model has been established for former students of the program to go on to a graduate program in which they conduct research on Ecuadorian volcanology for a master's thesis project. At least two master's thesis projects have been generated thus far for students who have been interested in pursuing Ecuadorian geology further after their field camp experience. We believe that this continued research and teaching collaborative will enhance both efforts (LaSage et al., 2006; Potter et al., 2009). Further, we hope to build primary research into the curriculum of the course in order for all of the students to actively investigate hypotheses that further the science during the program (Gonzales et al., 2001; May et al., 2009).

Also, through ongoing efforts to improve the curriculum, the authors have worked with the Galápagos National Park to seek permissions to teach mapping exercises in areas that are not usually available to visitors to the islands. In exchange for permissions to enter restricted areas, the GVFC supplies maps and reports to the park service to supplement their ongoing efforts to understand the geology of the islands.

There is now also an effort that has stemmed from this program to better educate and inform the population of licensed naturalist guides in the islands on the volcanic processes and history of the islands. In turn, better education of the guides will spread to better educate the native population of the islands, many of whom do not know much about volcanism. Ecotourism has become very big in the islands, and therefore, there is motivation on the part of the locals to better understand the geology of the islands so that they may inform tourists. In this model, geoscience education can lead to better stewardship of this important locale (Locke et al., 2012).

Future

As described above, there are many possible topics to be taught and at a number of localities both in the Galápagos Islands and mainland Ecuador. The GVFC program will likely continue evolving through future years to explore combinations of scheduling and curriculum. In the islands, the exercises will continue to change as places such as Cerro Pelado disappear to quarrying or as new areas of study are made accessible through discussions with the Galápagos National Park. There has not yet been any exercise in the GVFC to take place on the island of San Cristobal, but this will likely happen in the near future. In the mainland, new mapping areas are continually scouted to utilize the many erupted deposits all over the country. Also, when teaching a field-based program in Ecuador, it is necessary to have numerous backup plans available in the case that areas are not available during a given year due to eruption. There is the possibility of this program expanding to 4 weeks and four credits in the future to cater to student interest. It would be easily possible to spend more time in continental Ecuador by either expanding the existing projects, or adding projects.

Transferability

While other instructors may not find it necessary or realistic to duplicate this program exactly, Ecuador can provide ideal teaching conditions for a variety of goals. Aside from the senior-level field geology course described here, mainland Ecuador, Galápagos, or both could be a great setting for introductory or lower-level courses in geology. We have experience instructing an introductory-level geology course in Galápagos as well. The scale, exposure, and "textbook" examples of the volcanic geology provide a powerful educational setting.

There is also a fantastic opportunity in teaching in both mainland Ecuador and Galápagos to collaborate with courses in the fields of biology or ecology. The diversity of flora and fauna and their interaction with and response to volcanic activity are a significant natural feature of Ecuador (Geist et al., 2014). Of course, the significance of the Galápagos Islands to Darwin's theory of natural selection makes this one of the most important scientific locations in the world.

For instructors who are thinking of creating a new field camp, and particularly one in an international setting, there are rewards and challenges to be considered. It takes time to scout for sites that will provide the right level of complexity and diversity of geology that is appropriate for the level of the course. The sites then also need to be in proximity to transportation and lodging requirements. The best strategy is to choose a country or region such as Ecuador that has an abundance of geological options. This strategy will help to ensure that an affordable, safe, convenient, and academically rigorous program can be created.

CONCLUSIONS

In the first 3 y of the GVFC, experimentation in curriculum and logistics has led to a strong program. This field geology offering is unique in its focus on volcanic rocks. However, the curriculum maintains a focus on skills. The program is therefore equally of benefit to students who hope to pursue further research efforts in volcanology and to those who would simply like to diversify their education. A great strength of this program is that it provides study of rhyolitic, dacitic, andesitic, and basaltic extrusive rocks. Students who are veterans of this program will be able to take their skills and apply them to working in the field with volcanic rocks anywhere else in the world. The sequences of exercises that we have developed provide students with education during the process of collecting observations in the field, transferring field notes into quality products, and using the collected data to generate a report with robust geologic interpretation.

The setup of a program in Ecuador is quite feasible, but it requires careful consideration of budgeting, logistical, and scheduling issues. Educators who are willing to take on these challenges will produce a rewarding experience for their students.

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