Geologic Mapping of Chirripò National Park, an Overview of Lithology, Stratigraphy, and Tectonics Within the Talamanca Cordillera, Costa Rica

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GEOLOGIC MAPPING OF CHIRRIPÓ NATIONAL PARK, AN OVERVIEW OF LITHOLOGY, STRATIGRAPHY, AND TECTONICS WITHIN THE TALAMANCA CORDILLERA, COSTA RICA

by

RUSSELL KIRN

Under the Direction of Paulo Hidalgo, PhD

ABSTRACT

Cerro Chirripó, located in Chirripó National Park, Costa Rica, is the highest peak in the Central American isthmus. Though there already exist published geologic maps that encompass the study area, they lack the resolution and detail of the map produced by this study. Other materials produced by this study include a stratigraphic column, rock unit descriptions, and three cross-sectional transect profiles. These materials demonstrate the position and attitude of the rock units, their mechanism of emplacement, as well as their ages relative to one another. The aims of this study were to describe and map the observed rock units, characterize the spatial and temporal relations among said units, and elucidate current and past geologic processes that shape the tropical landscape of Chirripó National Park.

INDEX WORDS: Igneous petrology, Intrusive, Talamanca, Mineralogy, Ventisqueros, Chirripó
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by

RUSSELL KIRN

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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DEDICATION

I dedicate this thesis to my wife, Julia, and my father, Russell Kirn II. Without her, I would have forgotten my name, blood type, and place in the universe. Without him, I would never have looked deeply enough.
ACKNOWLEDGEMENTS
I would like to thank Tim Herold, whose camaraderie and fervor for science was made abundantly clear as he graciously lugged rock filled zip-loc bags all up and down the craggy peaks of Chirripó National Park. I would like to thank Dr. Hidalgo, who has had more impact in my development as a scientist than any other living being.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS .................................................................................................................. V

LIST OF TABLES ................................................................................................................................. IX

LIST OF FIGURES ............................................................................................................................. X

1 INTRODUCTION ............................................................................................................................ 1

1.1 Goals ............................................................................................................................................ 1

1.2 Tectonic setting .......................................................................................................................... 2

1.2.1 Origin of Cocos and Nazca Plates ......................................................................................... 3

1.2.2 Cocos-Nazca Paleogeographic Reconstruction .................................................................... 4

1.2.3 Subduction of the overthickened Cocos Ridge ................................................................. 5

1.3 Lithology and Ages of the Cordillera de Talamanca ............................................................ 6

1.4 Relevant volcanic geologic history of Costa Rica ................................................................... 6

1.5 Geological review of Talamanca .............................................................................................. 7

1.6 Scope of project .......................................................................................................................... 8

2 METHODS ....................................................................................................................................... 9

2.1 Sampling campaign .................................................................................................................... 9

2.2 Thin section microscopy ............................................................................................................. 10

2.3 Bulk major element analysis ..................................................................................................... 10

2.4 Geologic mapping ..................................................................................................................... 11

3 RESULTS ....................................................................................................................................... 11
3.1 Geologic map ............................................................................................................. 11

3.2 Pirámide sedimentary unit ......................................................................................... 12

3.2.1 Petrographic analysis of the Piramidé sedimentary unit .............................. 14

3.3 Ventisqueros lava unit .............................................................................................. 15

3.3.1 Petrographic analysis of the Ventisqueros lava unit .................................. 18

3.3.2 Major element analysis of the Ventisqueros lava unit .............................. 19

3.4 Talamanca comagmatic group .................................................................................. 23

3.4.1 Talamanca dioritic unit ....................................................................................... 23

3.4.2 Talamanca Gabbroic Unit ................................................................................... 30

4 DISCUSSION .................................................................................................................. 36

4.1 Observations regarding formation of rock units .............................................. 36

4.1.1 Formation of the Piramidé unit ................................................................. 36

4.1.2 Formation and relative-age of the Ventisqueros lava unit .................... 37

4.1.3 Age and emplacement of the Talamanca comagmatic group ................ 39

4.2 Hydrothermal alteration ........................................................................................... 40

4.2.1 Uplift of the Talamanca comagmatic group ............................................. 41

4.2.2 Hydrothermal alteration of Crestones summit ........................................ 41

5 CONCLUSIONS ............................................................................................................ 45

REFERENCES ................................................................................................................. 47

APPENDICES .................................................................................................................. 51
Appendix A: Geologic map of Chirripó National Park. .............................................. 51

Appendix B: Cross-sectional profiles.............................................................................. 52
LIST OF TABLES

Table 1: Average major element composition and standard deviations for 8 samples from the Ventisqueros lava unit ............................................................... 21

Table 2: Average major element composition and standard deviations for 13 samples from the Talamanca dioritic unit ............................................................... 30
LIST OF FIGURES

Figure 1: 3-D topographic map of the study area ................................................................. 1

Figure 2: Tectonic setting location map of Southern Central America and the Eastern Pacific plate boundaries. Cocos and Nazca plates are divided along the east-west boundary by the Cocos-Nazca Spreading Center and along the north-south boundary by the right-lateral strike-slip transform fault Panama Fracture Zone. CR: Costa Rica, MAT: Middle American Trench, CFZ: Coiba Fracture Zone, BFZ: Balboa Fracture Zone, PFZ: Panama Fracture Zone. Plate motion vectors are taken from deMets et al. 1994. (Modified from Gräfe et al., 2002.) .............................. 3

Figure 3: Hand Sample (CC-007) of Piramidé sedimentary unit ........................................... 13

Figure 4: Thin section of Piramidé sedimentary unit (CC-007). Plane polarized light on the left and cross polarized light on the right. (Qz) Quartz, (Ksp) potassium feldspar, (PF) Planktonic Foraminifera, (Ox) oxide. Petrographic analysis of sample CC-007 will serve as a mean representation for samples BA-7, BA-11, BA-15, BA-11, BA-22, DK-009, and BA-44 and approximates the general texture and mineralogy of the entire Piramidé unit................................................................. 14

Figure 5: Hand sample (BA-4) of the Ventisqueros lava unit. Sample claimed due approximately 1.0 km northeast of the lodge, approximately 50 m east of the trail. ................................................................................................................................. 16

Figure 6: Block and matrix texture along a parallel fracture set indicates metasomatic alteration. 5b: A red transparent overlay depicts the ‘block’ and the gray transparent overlay depicts the ‘matrix’. Intersection of FS1 (fracture set 1) and FS2 produce blocks which are preferentially altered along the block walls. This
type of metasomatism is common throughout the study area, however is most
apparent at the summit of Crestones. Photo taken near the Crestones summit. ... 17

Figure 7: Close-up of corestone from block and matrix texture with alteration rim flanked
by subparallel fracture veins. Picture taken along trail to Crestones summit. ....... 17

Figure 8: Thin section of Ventisqueros lava unit (BA-4). Plane polarized light on the left
and cross polarized light on the right. (HV) Hydrothermal vein filled with (Qz)
Quartz, (Ox) oxide, (Pl) Plagioclase, (Ep) Epidote. Petrographic analysis of
sample BA-4 will serve as a mean representation for samples VQ-001, VQ-002,
VQ-020, VQS-01, VQS-06, VQS-07, VQS-08, VQS-09A, VQS-12, CC-003, CC-
008, CCS-01, CCS-02, CCS-03, CCS-04, CRS-01, CRS-02, CRS-03, CRS-04,
CRS-05, BA-17, BA-22, BA-24, BA-25, BA-36, BA-37, CT-015, CT-016, CT-
017, CT-018, QBA-7, DK-009 and approximates the general texture and
mineralogy of the entire Ventisqueros unit...................................................... 18

Figure 9: Total alkalis versus SiO₂ diagram with a boundary line between the alkaline
(above) and sub-alkaline (below) magma series (Irvine and Baragar, 1971).
Samples from previous studies were obtained by Drummond et al., (1995) and

Figure 10: AFM diagram of Ventisqueros lava unit. Yellow triangles indicate samples of
the Ventisqueros lava unit collected from this study. Grey triangles are previously
obtained by Drummond et al., (1995) and Abratis, (1998)................................. 21

Figure 11: Harker diagrams of the Ventisqueros lava unit. Yellow triangles indicate
samples of the Ventisqueros lava unit collected from this study. Grey triangles are
previously obtained by Drummond et al., (1995) and Abratis, (1998).............. 22
Figure 12: Intrusion of diorite into gabbro within the Talamanca comagmatic group. 11b shows gabbro with a red transparent overlay and diorite with a gray transparent overlay. Photo taken near trail the false summit along the trail to Cerro Ventisqueros. .............................. 24

Figure 13: Hand sample I-8. Coarse-grained diorite of the Talamanca comagmatic group. Sample claimed approximately 1.0 km from the beginning of the trail in San Gerardo and approximately 2,000 m lower in elevation than the peak of Chirripó. ................................................................. 25

Figure 14: Hand sample VM-013. Fine-grained diorite of the Talamanca comagmatic group. Sample claimed in the Valley of the Moraines, just northeast of Cerro Chirripó ................................................................. 25

Figure 15: Thin section of Talamanca dioritic unit (VM-013). Plane polarized light on the left and cross polarized light on the right. (Pl) plagioclase, (Ksp) potassium feldspar, (Opx) orthopyroxene, (Ox) oxide. Petrographic analysis of sample VM-013 will serve as a mean representation for samples I-2, I-3, I-4, I-5, I-6, I-7, I-8, VQS-02, VQS-04, VQS-05, VQS-11, CC-004, CC-005, CC-006, CCS-05, 2CCS-04, 2CCS-05, 2CCS-06, 2CCS-08, IC-1, IC-5, XIC-2, VM-010, VM-011, VQ-021, VQ-022, VM-010, VM-011, and VM-013 and approximates the general texture and mineralogy of the entire Talamanca dioritic unit. .............................. 26

Figure 16: TAS (total alkalis versus silica) classification scheme for intrusive igneous rocks (Middlemost, 1994). (Pg) peridotgabbro, (Gb) gabbro, (Gbd) gabbrodiorite, (D) diorite, (Grd) diorite, (Gr) granite, (F) foidolite, (FG) foid-gabbro, (FMd) foid-monzodiorite, (FM) foid-monzosyenite, (Fs) foid syenite, (Sy) syenite,
(Qm) quartz monzonite, (M) monzonite, (Md) monzodiorite, (Mg) monzogabbro.

Dividing line between alkaline (above) and subalkaline (below) magma series taken from Irving and Baragar (1971).

Figure 17: AFM diagram of the intrusive Talamanca dioritic unit.

Figure 18: Harker diagram of major elements versus SiO$_2$ in the Talamanca dioritic unit. Blue diamonds indicate samples of the unit collected during this study. Grey diamonds are samples previously obtained by Drummond et al., (1995) and Abratis, (1998).

Figure 19: Hand sample (VM-014). Fine-grained gabbro of the Talamanca comagmatic group. Sample claimed in the Valley of the Moraines.

Figure 20: Thin section of Talamanca gabbroic unit (VM-014). Plane polarized light on the left and cross polarized light on the right. (Opx) orthopyroxene, (Ur) uralite, (Pl) plagioclase, (Bi) biotite. Petrographic analysis of sample VM-014 will serve as a mean representation for samples BA-5, BA-6, BA-48, QBA-14, VQ-022, VQ-023, VQ-024, VQ-025, VQS-03, VQS-09b, VQS-10, VQ-019, VM-012, 2CCS-03, 2VSS-01, and IC-5 and approximates the general texture and mineralogy of the entire Talamanca gabbroic unit.

Figure 21: TAS (total alkalis versus silica) classification scheme for intrusive igneous rocks (Middlemost, 1994). (Pg) peridotgabbro, (Gb) gabbro, (Gbd) gabbrodiorite, (D) diorite, (Grd) diorite, (Gr) granite, (F) foidolite, (FG) foid-gabbro, (FMd) foid-monzodiorite, (FMg) foid-monzosyenite, (Fs) foid syenite, (Sy) syenite, (Qm) quartz monzonite, (M) monzonite, (Md) monzodiorite, (Mg) monzogabbro.
Dividing line between alkaline (above) and subalkaline (below) magma series
taken from Irving and Baragar (1971). ................................................................. 33

Figure 22: AFM diagram for samples from the Talamanca gabbroic unit (Irvine &
Baragar, 1971) ........................................................................................................ 34

Figure 23: Harker variation diagram showing major oxides plotted versus SiO₂ within the
Talamanca gabbroic unit. Dashed lines indicate divergent ‘fanning’ of the data at
the end of the SiO₂ range for gabbro formation.................................................... 35

Figure 24: Re-mineralized hydrothermal vein. Photo taken near Crestones summit. ...... 41

Figure 25: Crestones summit. Photo taken north of summit facing south.................... 42

Figure 26: Chlorite-rich zone of hydrothermal alteration. Photo taken near Crestones
Summit....................................................................................................................... 43

Figure 27: Block hydrothermally altered to jasper. Photo taken near Crestones summit. 43

Figure 28: Fe oxide-rich zone of hydrothermal alteration. Photo taken near trail west of
Ventisqueros summit. ............................................................ 44
1 INTRODUCTION

1.1 Goals

The Central American arc is one of the most volcanically active in the world, as well as one of the most thoroughly studied arcs. Despite the extensive study of arc volcanism in the region, the Quaternary volcanic gap that the Cordillera de Talamanca in Costa Rica represents remains largely uninvestigated. This study focuses on some of the most remote and inaccessible locations in the Talamancas, namely Cerro Chirripó National Park.

Figure 1: 3-D topographic map of the study area
I present a geologic map and geological history of the area. My findings may be used to address one of the most important questions in the geological sciences. How is continental crust produced? The Talamancas are one of the few regions of the world where recent volcanism has composition matching that of Archean continental crust. A model for evolution of continental crust is one of the most important frontiers of the geosciences. Answering this question would have major reverberations throughout the
Earth Science community. In my project, the goal is to set the stage to answer this question by mapping with great resolution the rapidly uplifted plutons and lava flows which offer an excellent opportunity to study mid and low crustal processes and how differentiation during arc volcanism in a thickened oceanic crust might have produced magmas that resemble silicic continental crust.

1.2 Tectonic setting

Chirripó National Park is in Costa Rica on the Panama Block inside the Caribbean plate approximately 120 km due northeast of the Middle American trench (MAT) where three tectonic plates interact (Figure 2). The tectonic region that encompasses the Panama Block, Nazca plate, and the Cocos plate is one of the most complex active tectonic areas of the western hemisphere. The MAT forms the boundary between the Cocos and Caribbean plates (Denyer, 2006). A series of Cocos-Nazca spreading centers (CNS) constitute the E-W trending boundary between the Cocos and Nazca plates. The Panama Fracture Zone (PFZ) is a right-lateral strike-slip transform fault that forms the N-S trending boundary between the Cocos and Nazca plates (Lowrie et al., 1979). The Cocos and Carnegie Ridges are massive bathymetric plateaus, resultant of Galapagos hotspot volcanism, that trend from the Galapagos hotspot along their respective plate motions to the MAT in which they are subducted (de Boer, 1995; Duncan and Hargrave, 1984; Meschede & Barckhausen, 2001; MacMillan et al., 2004; Hey, 1977; Lonsdale & Klitgord, 1977).
1.2.1 Origin of Cocos and Nazca Plates

The consanguineous Cocos and Nazca plates formed due to the fission of the larger Farallon plate during the early Miocene at a minimum age of ~22.8 Ma (Hey, 1977; Lonsdale, 2005; Meschede & Barckhausen, 2000). The age of the Farallon split was determined by dating of the oldest magnetic anomalies that belonged to a precursor.
of the current Cocos-Nazca spreading system (CNS-1), the anomalies were identified as Anomaly 6B, giving an age of 22.8 Ma according to the geomagnetic polarity time scale of Cande and Kent, 1995 (Meschede & Barckhausen, 2000). The fissioning of the Farallon Plate is thought to have occurred due to (1) the divergent slab pulls between the North American and South American slab pulls in their respective trenches, (2) the detachment of part of the Farallon into the California subduction zone, and (3) the weakening of certain older parts of the Farallon by the Galapagos hotspot (Lonsdale, 2005).

1.2.2 Cocos-Nazca Paleogeographic Reconstruction

Paleogeographic reconstructions of the CNS by Meschede & Barckhausen (2001) unveil a complex tectonic history in the eastern Pacific Ocean. The position of the Galapagos hotspot has been taken as fixed since its initiation ~20-22 Ma (Hey, 1977; Lonsdale & Klitgord, 1978). Given the fixed position of the Galapagos hotspot south of the CNS beneath the Nazca plate, it follows that the existence of Galapagos hotspot volcanics on the Cocos plate would be impossible. However, the paleogeographic reconstructions of Meschede & Barckhausen describe spatio-temporal shifts in the CNS which alleviate this concern. Meschede and Barckhausen (2000) describe the shifts in the CNS orientation as follows:

"The first spreading system (CNS-1) was active until 19.5 Ma, when the orientation of the spreading axis changed from northwest-southeast to east-northeast-west-southwest. The second spreading system (CNS-2) was abandoned at 14.7 Ma, when the presently east-west oriented CNS-3 started its activity."
The shifting system of the CNS allows for the paleogeographic positioning of the Cocos plate above the Galapagos hotspot and thus provides evidence for the presence of Galapagos hotspot volcanics on the Cocos plate.

Subduction of the Cocos and Nazca plates (Figure 2) continues along the entire length of Central America until today. Presently, convergence rates of the Cocos Plate vary from about 60 mm/yr off southern Mexico to about 90 mm/yr off Costa Rica. For the obliquely subducting Nazca Plate, the orthogonal component of subduction outboard the Panama basin is estimated to be between 15 and 40 mm/yr (de Boer et al., 1988, 1991).

1.2.3 Subduction of the overthickened Cocos Ridge

The Cocos Ridge runs approximately 1,000km long by 200km wide, and stands 2.5 km in positive relief from the surrounding basin. (Meschede & Barckhausen, 2000). Projection of the Cocos Ridge inboard of the MAT correlates well spatially with the lateral extent of the Cordillera de Talamanca. Many agree that subduction of the buoyant, ridge-imprinted Cocos plate is linked to the exhumation and uplift of the Cordillera de Talamanca (de Boer et al., 1995; Gräfe et al., 2002; MacMillan, 2004; Morell, 2016).

Many have also speculated that the volcanic gap in the Central American Volcanic Arc is due to the subduction of the Cocos Ridge; however, this viewpoint has been challenged as of late. Previous models hypothesized that subduction of the buoyant Cocos Ridge would reduce the subduction angle by means of underplating between the overriding and subducting plate, effectively eliminating the mantle wedge and melt source (McGeary et al., 1985; Kolarsky et al., 1995a; Protti et al., 1995). An alternative hypothesis put forth the notion of a slab window due to subduction of a spreading center.
or by slab rupture due to ridge-trench collision (Abratis, 1998). The most recent investigations have rejected the shallow-angle subduction hypothesis. Dzierma, 2011 used receiver function image modeling to identify a steep subduction angle (up to 80°) beneath the Cordillera de Talamanca. Lücke and Arroyo, 2015 used 3-D gravity modeling to corroborate the hypothesis of steep angle subduction (Morell, 2016; Dzierma et al., 2011; Arroyo et al., 2003; Lücke et al., 2015). However, this discussion is far from settled and a high-resolution 3D seismic tomography is much needed.

1.3 Lithology and Ages of the Cordillera de Talamanca

(Alvarado & Gans, 2012) summarize the magmatic history of the Talamancan as follows:

a. Eocene volcanism due to seafloor spreading.

b. Profuse tholeiitic volcanism from the Oligocene to the Miocene.

c. Plutonic intrusives of uncertain age (Eocene to Miocene, 35.6-18.8 Ma?) due to alteration or low-K content.

d. Isolated lava outcrops during the Miocene 21-17 Ma and 14.1-8.3 Ma, the latter of which are coeval with the Miocene Talamancan intrusions.

e. Intrusive gabbro and granite of the mid to late Miocene (12.4-7.8 Ma).

f. Minor bodies of Plio-Pleistocene Adakite volcanism (4.3-1.0 Ma)

1.4 Relevant volcanic geologic history of Costa Rica

Intense volcanism has occurred in northern and central Costa Rica from the upper Miocene to the present (Alvarado et al., 1994). Ignimbrites of Pliocene and Quaternary age (Cordillera de Guanacaste, Cordillera Central) are followed chronologically by a
chain of stratovolcanoes of lower Pleistocene age. These stratovolcanoes erupt andesitic lavas and dacitic to rhyolitic pyroclastic flows.

Geographic density of the chain of calc-alkaline strato-volcanoes is reduced from the Upper Miocene to present, however, production of the remaining volcanoes is still the greatest within the Central American arc (Stoiber & Carr, 1973; Leemann & Carr, 1995).

Closure of the Central American isthmus occurred in the Pliocene (Keigwin, 1982; Tiedemann et al., 1998) which is observed in the divergent evolution of marine species in the Caribbean and Pacific as well as the convergent evolution of flora and fauna between the Americas. This closure is the final evolutionary step of Central America from island arc to peninsula, to isthmus, and to the present land bridge.

1.5 Geological review of Talamanca

The earliest scientific reporting on the geology of the Cordillera de Talamanca was from Gabb (1874a, b, 1875) who first explored the terrain from 1873-1874. Sapper (1937) produced a book which summarized existing geological knowledge of the area and contained a schematic geologic map of the Cordillera de Talamanca. He already inferred the region had experienced rapid uplift and rejected the hypothesis that the Cordillera de Talamanca contains no recent volcanic structures.

Weyl (1957, 1980) and Dengo (1962) provided important methodical studies related to the Talamancas. Their petrographic and stratigraphic findings formed the basis for completion of the first geologic maps and cross-sections of the Talamanca.

Interest in the Talamanca swelled in the 1970s when mining companies began exploration for porphyry copper ore. Published findings of the mining efforts are only described sporadically by Escalante (1990). Remote exploration and mapping by
Ballmann provided findings for relatively young volcanic activity with the Talamancas (Ballmann, 1976).

Tournon (1984) provided a summary on magmatism in Costa Rica with a focus on geochemistry, geochronology, and detailed descriptions of sample locations. Kussmaul (1987) provided a study of petrographic classification which was enhanced with major element comparison for intrusive rocks within the Talamancas and other locations in Costa Rica. Alvarado et al. (2012) produced a synthesis of geochronological data for Costa Rican igneous rocks. Alvarado’s compilation was expanded specifically in the Talamancas by Defant et al. (1992) and de Boer et al. (1995).

De Boer et al. (1995) and Drummond et al. (1995) are to date the most comprehensive geochemical and geochronological studies of the igneous rocks within the Talamancas. Their study of the Talamancas was concentrated in the central portion of the range; however, they did explore the Panamanian portion of the Talamancas as well. De Boer and Drummond describe four distinct lithologies (mid-Oligocene tholeiitic gabbro, mid-Oligocene El Barú plutonic rocks, Late Miocene calc-alkaline plutonic rocks, and a Pliocene-Pleistocene undifferentiated volcanic group) that overlap with groups proposed in this study.

1.6 Scope of project

The study area presents acute challenges: remote and arduous terrain, tropical flora, and unpredictable weather at the summit. Despite the demanding nature of tropical mapping and field work, we provide the densest network of samples yet obtained, as well as the highest resolution mapping yet completed in the study area. Descriptions of lithology, mineralogy, stratigraphy, and structure of the study area will be presented to
illustrate temporal and spatial relations among the distinct rock units. The production of a geologic map of Chirripó National Park will benefit park officials and visitors, as well as the broader geoscientific community at large. Cerro Chirripó is the highest peak in Central America, and as such, is a critical point in our understanding of the wider landscape of Central American geology.

2 METHODS

2.1 Sampling campaign

A suite of 75 hand specimens were collected during three separate trips (totaling 15 days) to the study area. Sampled outcrops were selected based on the following conditions:

1) Availability of ‘fresh rock’ – for thin section microscopy and XRF, selected hand samples need to be as unaltered as possible.

2) Obtaining a spatially distributed sample suite with respect to topography and contacts to provide the data points for a geologic map.

3) Outcrops containing distinct rock units and/or unusual specimens were sampled whenever possible.

4) Since the study area is within the boundaries of a national park it was important to claim samples off-trail from discrete areas, as not to scar the landscape for future visitors. Permission was obtained from park officials so long as samples were to be claimed in a considerate manner.

Hand samples were bagged, provided a sample ID, and labeled with coordinates logged using a handheld GPS which is accurate to the meter.
Handheld notes were collected identifying any relevant geologic features such as faults, dikes, fractures, contacts, and metasomatism. Attitudes of relevant features were obtained using Brunton compass.

2.2 Thin section microscopy

50 Thin sections were examined with an Olympus BX40 petrographic microscope. Reports were drafted for each of the samples based on the following qualifications:

1) Primary mineralogy – mode, grain size, crystal habit.
2) Secondary mineralogy which often identified extent of alteration due to metasomatism.
3) Textures – pliotaxitic/trachytic indicating flow or lack of flow in magma/lava.
4) Determination of groundmass in extrusive samples based on apparent mineralogy and proportion to phenocrysts.

In addition to ascribing rock units to each sample, petrographic analyses were also used to ascertain stratigraphic relations. These interpretations were based on secondary features and alteration products that demonstrated subsequent intrusion of a felsic magma into preexisting rock units.

2.3 Bulk major element analysis

30 hand samples were chosen for major element analysis by X-ray fluorescence (XRF). The hand samples that were chosen were deemed to be the least altered by weathering and metasomatism. Selected samples were powdered to a clay-size fraction using a ceramic disk pulverizer. Harder samples, more resistant to powdering, were
ground further with an automated ceramic mortar and pestle ball grinder. Powders were sieved through a 2-micrometer sieve to ensure the desired fineness had been achieved.

Powders were shipped to Michigan State University for major element analysis by XRF. Following the methods described by Rooney et al. (2012b), powders were combined with a lithium tetraborate flux to produce a glass disk. The glass disks were analyzed for major elements using a Bruker S4 Pioneer XRF.

2.4 Geologic mapping

Field mapping was performed by canvassing the topography as thoroughly as possible. However, there were limitations as large areas of the field are inaccessible due to steep terrain or are completely obscured by dense tropical flora. Based on these difficulties, it was necessary to obtain samples, attitudes, and notes from as many accessible topographic inflection points as possible. Consideration of transects for geologic profiles was taken into account during route planning so the best possible stratigraphic associations could be inferred. Coordinates were logged not only for sampling locations, but also for geologic features, such as dipping beds, faults, fractures, and dikes. Coordinates were also taken for outcrops that were thought to represent a continuation of the previously recorded rock unit.

3 RESULTS

3.1 Geologic map

The southern portion of the map is dominated by the Ventisqueros lava unit which forms the Terbi peak and Crestones summit (Appendix A). A fault (020,49W) due
northeast of Cerro Terbi is also observed in this area of the map. The middle-west portion of the map contains the Ventisqueros peak and is comprised of the Talamancan comagmatic series and the Ventisqueros lava unit. Dengo (1962) referred to this group of intrusives as the Talamancan comagmatic series because he interpreted these rocks to be derived from a genetically common magma. A pair of Talamancan comagmatic diorite dikes approximately one-meter thick cut through the gabbroic Talamancan comagmatic unit due southeast of the Ventisqueros peak atop a false summit. The middle portion of the map contains the Chirripó peak which is a hypabyssal gabbro of the Talamancan comagmatic unit flanked to the east and west by the Piramidé sedimentary unit. A diorite of the Talamancan comagmatic unit forms a ridge that trends northwest from the Chirripó peak. The Lagos del Chirripó due west of the peak are tarns situated in a Quaternary glacial alluvial valley. North of the Chirripó peak is a triple point between the Piramidé sedimentary, Talamancan dioritic, and Ventisqueros lava units. Due north of the triple point is the Ventisqueros lava unit, followed by the Talamancan gabbroic, and the Talamancan dioritic units, which precede another Quaternary glacial alluvial terrain, the Valley of the Moraines.

3.2 Piramidé sedimentary unit

The Piramidé sedimentary unit is correlated to the Tobitas Marinas unit described by Calvo (1987). The unit is at least 180 meters thick and is found outcropping along the northbound trail to Cerro Chirripó as well as both east and west of the Chirripó summit, conforming topographically to the glacial cirque valleys (Appendix A). The unit is composed of fine sandstones which are dark gray to light-green in hand specimen (Figure 3). The unit is overlain by the Ventisqueros lava unit in the Valle de los Conejos and
Valle de las Morenas as well as by Quaternary glacial alluvium in the Lagos del Chirripó glacial valley. The unit is intruded by both members of the Talamanca comagmatic group with a narrow saddle of the Piramidé unit exposure along the trail to the summit.

Metamorphism of the Piramidé sedimentary unit have increased the hardness and grain-size of the unit. Given the similarity in color to the Ventisqueros lava unit as well as the overall rigidity of the rocks due to their metamorphic recrystallization, it is not uncommon to mistake outcrops of the Piramidé sedimentary unit for the Ventisqueros lava unit.

Figure 3: Hand Sample (CC-007) of Piramidé sedimentary unit.

The Piramídé unit age is assumed to Paleogene and is correlated with the age of the lavas of the Snowdrift Unit by Weyl (1957). The unit contains abundant and well-distributed crystalline volcanic lithics, and occasional Planktonic Foraminifera. Calvo
(1987) first described contact metamorphism of the Piramidé unit where in proximity to intrusions of the Talamanca comagmatic Group.

### 3.2.1 Petrographic analysis of the Piramidé sedimentary unit

![Figure 4: Thin section of Piramidé sedimentary unit (CC-007). Plane polarized light on the left and cross polarized light on the right. (Qz) Quartz, (Ksp) potassium feldspar, (PF) Planktonic Foraminifera, (Ox) oxide. Petrographic analysis of sample CC-007 will serve as a mean representation for samples BA-7, BA-11, BA-15, BA-11, BA-22, DK-009, and BA-44 and approximates the general texture and mineralogy of the entire Piramidé unit.](image)

Thin sections of the Piramidé sedimentary unit have an aphanitic groundmass that ranges in mode from 40-70%. Abundant volcaniclastics and occasional fossils of planktonic foraminifera account for the remainder of the mode in thin section. Clasts in the sedimentary unit have a maximum grain size of 2 mm and include plagioclase and alkali feldspar, quartz, orthopyroxene, clinopyroxene, oxides (magnetite), and fossil calcite rings of planktonic foraminifera. Most of the crystals are anhedral and well-rounded, however, occasional phenocrysts of augite appear sub/euhedral when viewed
down the c-axis. Oxides were attracted to magnetic filings, so they were determined to be magnetite.

The crystalline composition of the Piramidé sedimentary unit is uniform across the sample suite. The most conspicuous variation among samples of the Piramidé sedimentary unit is the presence of contact metamorphism near intrusions of the Talamanca comagmatic group. Piramidé sedimentary samples which have been altered by contact metamorphism exhibit highly silicified metasomatic veins. These veins are fractal in scale, visible from the meter to micrometer orders of magnitude. The groundmass of these altered samples appears to have recrystallized to fine-grained quartz, though determination in thin section was unclear.

3.3 Ventisqueros lava unit

The Ventisqueros lava unit was first described and correlated with Afaníticas unit by Calvo (1987) and is composed of laterally discontinuous bodies of phyric basalt, basaltic andesite, and andesite that overlie the Piramidé unit and are intruded sporadically by the Talamanca comagmatic group. The lava flows are extensively altered by metasomatism. Hand samples of the Ventisqueros lava unit are dark gray to light gray, though thoroughly metasomatized rocks will have a red or green oxidation tint (Figure 5). The best exposures of the Ventisqueros lava unit are along the trail from the Crestones summit to Cerro Terbi.
Figure 5: Hand sample (BA-4) of the Ventisqueros lava unit. Sample claimed due approximately 1.0 km northeast of the lodge, approximately 50 m east of the trail.

The unit is most thoroughly metasomatized at the Crestones summit where a set of fractures acts as a conduit network for hydrothermal fluids. The network leaves a ‘block and matrix’ texture where the matrix is the path of greatest hydrothermal network intrusion, and the block is the least affected (Figures 6 & 7). The block and matrix texture is easily mistaken for a volcanic autobreccia, however, the primary mineralogy present in the blocks match that of the matrix. A vertical parallel fracture set and a subhorizontal parallel fracture set cutting through bedrock of the Ventisqueros lava unit leave behind corestones that are preferentially altered along their walls leaving behind isolated rounded blocks.
Figure 6: Block and matrix texture along a parallel fracture set indicates metasomatic alteration. A red transparent overlay depicts the ‘block’ and the gray transparent overlay depicts the ‘matrix’. Intersection of FS1 (fracture set 1) and FS2 produce blocks which are preferentially altered along the block walls. This type of metasomatism is common throughout the study area, however is most apparent at the summit of Crestones. Photo taken near the Crestones summit.

Figure 7: Close-up of corestone from block and matrix texture with alteration rim flanked by subparallel fracture veins. Picture taken along trail to Crestones summit.
3.3.1 Petrographic analysis of the Ventisqueros lava unit

Figure 8: Thin section of Ventisqueros lava unit (BA-4). Plane polarized light on the left and cross polarized light on the right. (HV) Hydrothermal vein filled with (Qz) Quartz, (Ox) oxide, (Pl) Plagioclase, (Ep) Epidote. Petrographic analysis of sample BA-4 will serve as a mean representation for samples VQ-001, VQ-002, VQ-020, VQS-01, VQS-06, VQS-07, VQS-08, VQS-09A, VQS-12, CC-003, CC-008, CCS-01, CCS-02, CCS-03, CCS-04, CRS-01, CRS-02, CRS-03, CRS-04, CRS-05, BA-17, BA-22, BA-24, BA-25, BA-36, BA-37, CT-015, CT-016, CT-017, CT-018, QBA-7, DK-009 and approximates the general texture and mineralogy of the entire Ventisqueros unit.

In thin section the groundmass (50-60%) is aphanitic (0.1 mm) with apparent mineralogy of plagioclase, oxide, and uralite. Laths of groundmass plagioclase display pliotaxitic texture in some samples and trachytic flow texture in others. Plagioclase phenocrysts (20-30%) are subhedral/anhedral with maximum grain size of 3.0 mm. Plagioclase exhibits oscillatory zoning and alteration to sericite, zeolites and epidote is common. Clinopyroxene phenocrysts, up to 2.0 mm are subhedral/anhedral with simple and lamellar twinning, and are often deuterically altered to uralite. Clinopyroxene and orthopyroxene (7-12%) often form clusters with magnetite up to 4.0 mm in length.

Proportion of clinopyroxene to orthopyroxene is approximately 5:1 across the suite.
Subhedral/euhedral phenocrysts of magnetite (2-5%) are present with maximum grain size of 1.5 mm. Magnetite is always observed in contact with pyroxenes. Micro-alteration observed in thin section reveals hydrothermal alteration by the presence of quartz filled veins that lead to secondary mineralization including sericitization of feldspars and uralitization of clinopyroxenes (Figure 8). Hydrothermal silicic veins contain quartz in variable size and mode depending on extent of metasomatism in the sample. The micro-alteration observed in thin section matches the macro-alteration occurring at the centimeter scale. The grade of metasomatic alteration in the Crestones summit ranges from phyllic to propylitic, indicated by presence of quartz as hydrothermal solution, alteration of plagioclase to sericite and epidote, and alteration of clinopyroxene to chlorite and uralite. Olivine (1-5%) is sub/euhedral with phenocrysts up to 1.0 mm in length.

### 3.3.2 Major element analysis of the Ventisqueros lava unit

In the chemical classification scheme by Le Bas et al., (1986) and Le Maitre et al., (2002) the Ventisqueros lavas range from basalt to andesite with continuous transitional compositions. Normalized SiO$_2$ content of the unit ranges from 50.03-66.19 (wt.%). The unit plots within the sub-alkaline field of the TAS diagram (Figure 9). An AFM diagram (Irvine and Baragar, 1971) further subdivides the sub-alkaline magma series into the calc-alkaline and tholeiitic magma series (Figure 10). In the diagram it is seen that the Ventisqueros lava unit overlaps the boundary between the two series, however, most samples plot in the calc-alkaline field.

Harker diagrams (Figure 11) show loss of Al$_2$O$_3$, Fe$_2$O$_3$, MgO, and CaO with increasing SiO$_2$ while Na$_2$O, K$_2$O, and P$_2$O$_5$ are enriched in the evolving melt. TiO$_2$
shows neither enrichment nor depletion with varying SiO$_2$. Mean compositions and standard deviations for major elements are provided in Table 1.

Figure 9: Total alkalis versus SiO$_2$ diagram with a boundary line between the alkaline (above) and sub-alkaline (below) magma series (Irvine and Baragar, 1971). Samples from previous studies were obtained by Drummond et al., (1995) and Abratis (1998).
Figure 10: AFM diagram of Ventisqueros lava unit. Yellow triangles indicate samples of the Ventisqueros lava unit collected from this study. Grey triangles are previously obtained by Drummond et al., (1995) and Abratis, (1998).

Table 1: Average major element composition and standard deviations for 8 samples from the Ventisqueros lava unit.

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<tr>
<td>P₂O₅</td>
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Figure 11: Harker diagrams of the Ventisqueros lava unit. Yellow triangles indicate samples of the Ventisqueros lava unit collected from this study. Grey triangles are previously obtained by Drummond et al., (1995) and Abratis, (1998).
3.4 **Talamanca comagmatic group**

As the crow flies, the diameter of the study area covers over 12.0 km, with over 2,000 m of altitude gained. The Talamanca comagmatic group outcrops intermittently along this entire diameter, hence the classification of this group as a batholith. The Talamanca comagmatic intrusive group intrudes both the Piramidé sedimentary unit and the Ventisqueros lava unit, and is overlain by Quaternary glacial alluvium.

Compositions of the calc-alkaline Talamanca comagmatic intrusive group are bimodally distributed as distinct units of gabbro and diorite. The Talamanca comagmatic group will be described as two distinct rock units, albeit, with an implied cogenetic relation.

3.4.1 **Talamanca dioritic unit**

Outcrops of the Talamanca dioritic unit are not seen atop any of the major summits, however, some of the more minor summits and ridges are formed by outcrops of this unit (Appendix A). A ridge trending SW-NE that runs from south of Cerro Ventisqueros to an area just south of Cerro Chirripó is composed of Talamanca diorite. SW-NE trending dikes of the Talamanca dioritic unit intrude into the Talamanca gabbroic unit near a false summit en route to Cerro Ventisqueros (Figure 12). The best exposures of the Talamanca dioritic unit are found heading northwest along the ridge from Cerro Chirripó to Cerro Uran.
Figure 12: Intrusion of diorite into gabbro within the Talamanca comagmatic group. 11b shows gabbro with a red transparent overlay and diorite with a gray transparent overlay. Photo taken near trail the false summit along the trail to Cerro Ventisqueros.

In hand sample the Talamanca granodiorite unit is gray to light gray with an occasional light green tint owed to deuteric alteration. Coarse-grained outcrops are found in lower elevations closer to San Gerardo (Figure 13) while progressively finer-grained outcrops are found with increasing elevation (Figure 14). Plagioclase is lighter in color in the granodiorite unit than in the gabbroic unit.
Figure 13: Hand sample I-8. Coarse-grained diorite of the Talamanca comagmatic group. Sample claimed approximately 1.0 km from the beginning of the trail in San Gerardo and approximately 2,000 m lower in elevation than the peak of Chirripó.

Figure 14: Hand sample VM-013. Fine-grained diorite of the Talamanca comagmatic group. Sample claimed in the Valley of the Moraines, just northeast of Cerro Chirripó
Petrographic analysis of the Talamanca dioritic unit

Figure 15: Thin section of Talamanca dioritic unit (VM-013). Plane polarized light on the left and cross polarized light on the right. (Pl) plagioclase, (Ksp) potassium feldspar, (Opx) orthopyroxene, (Ox) oxide. Petrographic analysis of sample VM-013 will serve as a mean representation for samples I-2, I-3, I-4, I-5, I-6, I-7, I-8, VQS-02, VQS-04, VQS-05, VQS-11, CC-004, CC-005, CC-006, CCS-05, 2CCS-04, 2CCS-05, 2CCS-06, 2CCS-08, IC-1, IC-5, XIC-2, VM-010, VM-011, VQ-021, VQ-022, VM-010, VM-011, and VM-013 and approximates the general texture and mineralogy of the entire Talamanca dioritic unit.

In thin section plagioclase (60-70%) is subhedral with abundant sericitization and maximum grain size of 4.0mm. Clinopyroxene (augite) exhibits lamellar and simple twinning along {001} and {100} crystal faces with maximum grain size of 3.0mm. Subhedral/anhedral clinopyroxene is abundantly altered, with secondary products including fine grained amphibole (uralite), chlorite, and serpentine. Clinopyroxene and orthopyroxene (7-12%) often form clusters in association with magnetite. Sericitization of potassium feldspar (5-15%) is common, and in the more felsic samples abundant myrmekitic texture with interstitial quartz (3-7%) is observed. Magnetite (5-8%) is subhedral/anhedral with maximum grain size of 1.5mm. Opaque oxides were determined
to be magnetite by testing attraction to magnetic filings. Primary biotite is anhedral and is uncommon (less than 1%).

3.4.1.2 Major element analysis of the Talamanca dioritic unit

The Middlemost (1985) chemical classification of intrusive samples of the Talamanca dioritic unit is shown in Figure 16. The diagram shows that samples of this unit are predominately dioritic in composition and all plot within the sub-alkaline magma series. In a further subdivision of the sub-alkaline magma series the samples plot fully within the calc-alkaline field of an AFM diagram (Figure 17).

SiO$_2$ of the Talamanca dioritic unit ranges from 54.49 - 66.06 (wt.%). Harker diagrams of the Talamanca dioritic unit (Figure 18) show consistent reduction in Fe$_2$O$_3$, MgO, CaO, P$_2$O$_5$, Al$_2$O$_3$, and TiO$_2$ with increased SiO$_2$. Data points for Na$_2$O and K$_2$O show some scatter, but are generally conserved with progressive evolution. Mean compositions and standard deviations for major elements are provided in Table 2.
Figure 16: TAS (total alkalis versus silica) classification scheme for intrusive igneous rocks (Middlemost, 1994). (Pg) peridotgabbro, (Gb) gabbro, (Gbd) gabbrodiorite, (D) diorite, (Grd) diorite, (Gr) granite, (F) foidolite, (FG) foid-gabbro, (FMd) foid-monzodiorite, (FMs) foid-monzosyenite, (Fs) foid syenite, (Sy) syenite, (Qm) quartz monzonite, (M) monzonite, (Md) monzodiorite, (Mg) monzogabbro. Dividing line between alkaline (above) and subalkaline (below) magma series taken from Irving and Baragar (1971).

Figure 17: AFM diagram of the intrusive Talamanca dioritic unit.
Figure 18: Harker diagram of major elements versus SiO$_2$ in the Talamanca dioritic unit. Blue diamonds indicate samples of the unit collected during this study. Grey diamonds are samples previously obtained by Drummond et al., (1995) and Abratis, (1998).
Table 2: Average major element composition and standard deviations for 13 samples from the Talamanca dioritic unit.

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</table>

3.4.2 Talamanca Gabbroic Unit

A continuous run of Talamanca gabbroic unit outcrops trend SW-NE from west of Cerro Ventisqueros to just south of Cerro Chirripó as well as north of the Chirripó summit in the Valley of the Moraines (Appendix A). The best exposures of the Talamanca gabbroic unit are observed at the peaks of Cerro Chirripó and Cerro Ventisqueros where hypabyssal outcrops of this unit are found. The Talamanca gabbroic unit is cut by a pair of dikes of the Talamanca dioritic unit atop a false summit along the trail to Cerro Ventisqueros (Figure 12). Hand specimens of the Talamanca gabbroic unit are gray to dark metallic gray (Figure 19). Plagioclase in the Talamanca gabbroic unit is darker in color than in the Talamanca dioritic unit.
Figure 19: Hand sample (VM-014). Fine-grained gabbro of the Talamanca comagmatic group. Sample claimed in the Valley of the Moraines.

3.4.2.1 Petrographic Analysis of the Talamanca Gabbroic Unit

Figure 20: Thin section of Talamanca gabbroic unit (VM-014). Plane polarized light on the left and cross polarized light on the right. (Opx) orthopyroxene, (Ur) uralite, (Pl) plagioclase, (Bi) biotite. Petrographic analysis of sample VM-014 will serve as a mean representation for samples BA-5, BA-6, BA-48, QBA-14, VQ-022, VQ-023, VQ-024, VQ-025, VQS-03, VQS-09b, VQS-10, VQ-019, VM-012, 2CCS-03, 2VSS-01, and IC-5 and approximates the general texture and mineralogy of the entire Talamanca gabbroic unit.
In thin section subhedral/euhedral plagioclase (60-75%) is often altered to sericite, and occasionally displays oscillatory zoning. Subhedral/anhedral clinopyroxene (10-18%) nears complete alteration to fine-grained amphibole (uralite), and to serpentine (less than 1.0%) in the most altered samples. Subhedral/anhedral orthopyroxene (2-5%) and clinopyroxene both exhibit lamellar and simple twinning. Potassium feldspar (4-7%) occurs as anhedral interstitial growths with abundant sericitization. Anhedral magnetite (5-8%) with a maximum grain size of 1.0mm occur without exception in contact with pyroxene and often aggregate as subhedral aphanitic masses (0.1mm) within phenocrysts of uralitized clinopyroxene.

3.4.2.2 Major element analysis of the Talamanca gabbroic unit

The Middlemost, (1985) classification of samples from the Talamanca gabbroic unit is shown in Figure 21. The diagram shows that samples from this unit plot fully within the gabbro field and the subalkaline series. Within the subalkaline series, the gabbroic unit may be further subdivided between the tholeiitic and calc-alkaline magma series in which the unit exhibits a slight overlap between the two series but predominately favors the tholeiitic field (Figure 22).

Normalized SiO$_2$ of the Talamanca gabbroic unit ranges from 45.71-52.14 (wt.%). Harker diagrams of the Talamanca gabbroic unit (Figure 23) show consistent reduction in Fe$_2$O$_3$, MgO, CaO, Al$_2$O$_3$, and TiO$_2$ with increased SiO$_2$. K$_2$O and P$_2$O$_5$ are enriched with evolution of the melt. Na$_2$O shows scatter but appears to correlate to an inflection feature within the data. Dashed lines have been overlain on the Harker diagram normal to an SiO$_2$ range which appears to correlate with the majority of scatter. A divergent fanning of
the data occurs at approximately 52.0 wt.% SiO$_2$ which corresponds to the maximum silica content for gabbroic compositions. Mean compositions and standard deviations for major elements are provided in Table 3.

![TAS classification scheme for intrusive igneous rocks](image)

**Figure 21**: TAS (total alkalis versus silica) classification scheme for intrusive igneous rocks (Middlemost, 1994). (Pg) peridotgabbro, (Gb) gabbro, (Gbd) gabbrodiorite, (D) diorite, (Grd) diorite, (Gr) granite, (F) foidolite, (FG) foid-gabbro, (FMd) foid-monzodiorite, (FMd) foid-monzosyenite, (Fs) foid syenite, (Sy) syenite, (Qm) quartz monzonite, (M) monzonite, (Md) monzodiorite, (Mg) monzogabbro. Dividing line between alkaline (above) and subalkaline (below) magma series taken from Irving and Baragar (1971).
Figure 22: AFM diagram for samples from the Talamanca gabbroic unit (Irvine & Baragar, 1971).
Figure 23: Harker variation diagram showing major oxides plotted versus SiO$_2$ within the Talamanca gabbroic unit. Dashed lines indicate divergent ‘fanning’ of the data at the end of the SiO$_2$ range for gabbro formation.
Table 3: Average major element composition and standard deviations for 9 samples from the Talamanca gabbroic unit.

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4 DISCUSSION

4.1 Observations regarding formation of rock units

4.1.1 Formation of the Piramidé unit

The Piramidé sedimentary unit is assumed to be a fan delta (Calvo, 1987) formed during the Paleogene (Weyl, 1957). A sandy matrix indicates continental sediment supply along a coastal environment and the combined presence of benthic planktonic foraminifera (Figure 4) suggest a shallow marine setting on a primitive continental shelf. The unit originated in an area with high pyroclastic contribution, which is evidenced by various tephra and crystals of plagioclase and pyroxene entrained into the matrix. Furthermore, the well-preserved nature of pyroxene crystals in the suite indicates short, low-energy transport. Formation of the Piramidé sedimentary unit may be described as follows:
1) Initial depositional setting resembles an active island arc surrounded by ocean basins.

2) Erosion of the islands supplies sediment to the nearby coast.

3) Deposition of sandy volcaniclastic sediment occurs at the beach where wave action spreads the material in a delta fan.

4) Continued sediment transport coupled with intermittent volcanism buries the older sediments.

5) Compaction and cementation lithify the sandy volcaniclastic material.

This study concurs with the interpretation that the Piramidé unit formed in a fan delta depositional setting, where sediment and volcanics were supplied locally from a productive island arc. Furthermore, there is reason to believe that the coalescence of such island arc fan deltas into the Caribbean and Cocos basins contributed significantly to the closure of the Central American isthmus (Kappelle, 2016). With the abundance of sediment supply in the tropics, it is logical to argue that fan delta landforms would have considerable impact in closure of the Central American isthmus.

4.1.2 Formation and relative-age of the Ventisqueros lava unit

The formation of the Ventisqueros lava unit may be described as follows:

1) Upon reaching depths of 100 km, volatiles in the subducting Cocos plate were driven off, enabling melt in the mantle wedge.

2) Buoyant melt rises and erupts at the Earth’s surface leading to the formation of an island arc.

3) Volcanic islands rise above sea level.
4) Coeval deposition of the Piramidé sedimentary unit and intermittent flows of the Ventisqueros lavas.

5) Faulting, fracture, and hydrothermal alteration of Ventisqueros lavas by uplift and exhumation of the Talamanca intrusives.

Alvarado & Gans (2012) argued that lavas of the Talamanca Cordillera must be older than their intrusive counterparts. They suggest that much of the volcanism is coeval with sedimentation prior to uplift of the Talamanca Cordillera and must predate the intrusives. This study agrees with Alvarado and Gans regarding the age relation of lavas to intrusives and sedimentary rocks. The Ventisqueros lava unit is intruded by dikes of the Talamanca comagmatic group (Appendix A). This cross-cutting relationship demonstrates the lesser age of the Talamanca comagmatic intrusive group relative to the Ventisqueros lava unit; however, there have been many flows, and it is possible that more recent lavas postdate emplacement of Talamanca intrusives. The presence of volcanic products within the Piramidé sedimentary unit affirms the coeval relation of volcanism and sedimentation.

Drummond et al., 1995 & Abratis, 1998 describe pre-collisional (Cocos Ridge with Costa Rica) volcanics in the Talamanca Cordillera as basalts, basaltic andesites, and andesites with an evolution from the tholeiitic to calc-alkaline magma series. Based on major element analysis, the lavas obtained in this study are a compositional match to the ones described above (Figure 9). Also, the sampled lavas exhibit similar evolution from the tholeiitic to calc-alkaline magma series (Figure 10). It is noted that matching the volcanic units of this study to the work of others based primarily on major element
analysis is a precarious practice; future trace element analysis and radiometric age dating will yield more conclusive findings.

4.1.3 Age and emplacement of the Talamanca comagmatic group

The Talamanca comagmatic group is a complex system of dikes, stocks, and sills that formed as portions of the magma chamber cooled below the surface. The Talamanca comagmatic group is younger than the Piramidé sedimentary unit. This relative age determination was made by observation of contact metamorphism of the Piramidé sedimentary unit by the Talamanca comagmatic intrusives. The Talamanca comagmatic group is observed cross-cutting through older flows of Ventisqueros lava; however, there are multiple flows to be considered, and more than likely, the lavas erupted prior to, during, and post emplacement of the intrusive bodies.

Within the Talamanca comagmatic group, the gabbroic unit is older than the dioritic unit. Whole-rock K-Ar dating of the Talamanca gabbroic unit gave an age of 9.83 ± 0.23 Ma and 7.81 ± 0.31 Ma for the dioritic unit (Drummond et al., 1995). The relative age distinction between the two units was determined in the field where the younger diorite was observed cutting through the older gabbro. There is no observable mingling between the diorite and gabbro and the contact between them is sharp. It appears the diorite intruded the gabbro through a process of physical injection /inflation with little to no chemical interaction between the two magmas.

Typical island arc subduction settings have a thinner overriding crustal component than continental arcs. The relative thinness of the overriding crust enables a less impeded rise of magmas to the surface which, in turn, reduces storage time necessary
for variables of magma evolution such as fractional crystallization and assimilation of crustal components. With minimal magma evolution, products should closely resemble the primitive peridotite of the mantle wedge. Partial melting of mantle wedge peridotite produces basalt (Winter, 2010). Given a basaltic magma, gabbro would be the anticipated intrusive rock type in island arc subduction settings, thus the presence of the Talamanca gabbroic unit is not surprising. The presence of the more evolved Talamanca dioritic unit is unusual in this setting. This study proposes that the unanticipated existence of the Talamanca dioritic unit is owed to enhanced fractional crystallization and partial melting. Fractional crystallization and partial melting in this setting may be owed to all or any combination of the following:

1) Older gabbro underplated at the crust/mantle interface is partially melted by incipient rising magma and leads to a more evolved magma.

2) Subduction of Cocos sea mounts (precursors to Cocos Ridge) led to a slightly shallower subduction angle and reduced volatile addition to the mantle wedge below the arc. This would result in dryer magmas with higher crystallization temperatures, enabling fractional crystallization of basaltic magmas at depth.

3) Accretion of Cocos sea mounts enhances crustal shortening. Crustal shortening increases overburden on magma chambers and slows their ascent, enhancing fractional crystallization and assimilation.

4.2 Hydrothermal alteration

The effects of extensive hydrothermal alteration may be observed in many areas throughout Chirripó National Park. Most notably, the celebrated Crestones summit owes its unique prominence to hydrothermal alteration.
4.2.1 Uplift of the Talamanca comagmatic group

Gräfe, 2002 modeled a low-temperature cooling history for the Talamanca comagmatic group using fission track apatite ages. The short low-temperature residence times established for the Talamanca comagmatic group were attributed to rapid uplift owed to the arrival of the buoyant Cocos Ridge underneath the arc. Subduction of the Cocos Ridge resulted in crustal shortening and isostatic reequilibration. Uplift of the Talamanca comagmatic group faulted and fractured the overlying rock, providing conduits for meteoric water now subject to a steep geothermal gradient above the intrusive magma chamber.

4.2.2 Hydrothermal alteration of Crestones summit

Crestones summit, of the Ventisqueros lava unit, is situated at the intersection of two major fracture sets. Many of the fractures are open (up to tens of centimeters) and re-mineralized (Figure 24). Additional fractures of sub-vertical dip are well distributed throughout the Crestones summit (Figure 25). The fractures serve as hydrothermal fluid pathways and are observed from the meter to micrometer scale (Figure 8).

![Figure 24: Re-mineralized hydrothermal vein. Photo taken near Crestones summit.](image)
Figure 25: Crestones summit. Photo taken north of summit facing south
Epigenetic and deuteritic mineralization common to hydrothermal alteration such as: sericite, chlorite, epidote, jasper, tremolite, actinolite, talc, serpentine, Fe, Cu, and Mn oxides, are all observed in thin section and/or in the field (Figures 25-27).
Figure 26: Chlorite-rich zone of hydrothermal alteration. Photo taken near Crestones Summit.

Figure 27: Block hydrothermally altered to jasper. Photo taken near Crestones summit.
Figure 28: Fe oxide-rich zone of hydrothermal alteration. Photo taken near trail west of Ventisqueros summit.
5 CONCLUSIONS

Chirripó National Park is the highest point in Central America. Typical subduction, prior to the arrival of the Cocos Ridge to the Middle American Trench, formed the Central American island arc. The island arc formed from basaltic volcanism of partially melted peridotite in the mantle wedge. Upon reaching sea level elevation, island volcanoes became a fan delta depositional environment for volcaniclastic/shallow marine sedimentary rock. Progressive sedimentation beginning in the Paleogene, with coeval/intermittent eruptions ranging in composition from basalt to andesite, worked to close the Central American Isthmus in the early Pliocene (Molnar, 2008). Magma chambers below the arc intrude overlying volcanic and sedimentary rock as a complex system of gabbroic and dioritic dikes, stock, sills, and plutons in the mid to late Miocene (Alvarado & Gans, 2012). Arrival of the buoyant Cocos Ridge to the Middle American Trench alters subduction geometry to that of a shallower angle. Shallow angle subduction leads to rapid uplift and exhumation by crustal shortening and isostatic reequilibration (Gräfe, 2002).

A 1:12,500 scale geologic map was produced to ascertain rock units, structure, and stratigraphy. A sample suite of 75 hand specimens was claimed to petrographically describe the rock units and determine their composition. Four rock units were distinguished: the Piramidé sedimentary unit, the Ventisqueros lava unit, the Talamanca gabbroic unit, and the Talamanca dioritic unit. The four units were correlated to previous studies in the region by De Boer, 1995; Drummond, 1995; Alvarado and Gans, 2012.
Future tasks in the study area include:

- Trace element analysis of the igneous rock units to determine cogenetic relation.
- XRD analysis of secondary mineralization owed to hydrothermal alteration.
- Radiogenic dating of samples to affirm stratigraphic age relations between units.
- Determine processes that led to evolution of intrusive magmas from gabbroic to dioritic composition.
REFERENCES


Weyl, R., 1957: Contribución a la geología de la Cordillera de Talamanca de Costa Rica (Centro América).- 77 p

APPENDICES

Appendix A: Geologic map of Chirripó National Park.

- Quaternary glacial alluvium
- Talamanca dioritic unit
- Talamanca gabbroic unit/hypabyssal gabbroic unit
- Ventisqueros lava unit
- Pirámide sedimentary unit
Appendix B: Cross-sectional profiles