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PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
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2010-2011 PROJECTS

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LATE PLEISTOCENE EDIFICE FAILURE AND SECTOR COLLAPSE OF VOLCÁN BARÚ, PANAMA
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Students: *SHANNON BRADY*, Union College. *LOGAN SCHUMACHER*, Pomona College, *HANNAH ZELLNER*, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION
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EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING
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Keck Geology Consortium: Projects 2010-2011
Short Contributions— Volcán Barú, Panama

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Project Faculty: THOMAS GARDNER, Trinity University, KRISTIN MORELL, Penn State University

PETROLOGIC EVIDENCE FOR MAFIC RECHARGE AT VOLCÁN BARÚ, PANAMA
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LOGAN SCHUMACHER, Pomona College
Research Advisor: Eric Grosfils

VOLCÁN BARÚ DEBRIS AVALANCHE FACIES AND AGES
HANNAH ZELLNER, Trinity University
Research Advisor: Thomas Gardner

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VOLCÁN BARÚ DEBRIS AVALANCHE FACIES AND AGES

HANNAH ZELLNER, Trinity University
Research Advisor: Thomas Gardner

INTRODUCTION

The Central American Volcanic Arc forms the backbone of Central America and stretches unbroken from Mexico to central Costa Rica. In central Costa Rica, subduction of the Cocos Ridge (Gardner, Fig. 1, this volume) causes a cessation of volcanism for ~ 175 km along the Cordillera de Talamancas and then active volcanism resumes again to the southeast in (Gardner, Fig. 2, this volume), where Volcán Barú marks the beginning of volcanism in Panama (Morell, 2008). There have been around 40 major sector collapses from an estimated 24 different volcanoes in the Central American Volcanic Arc (Siebert et al., 2006). Volcán Barú is the site of possibly the largest of these collapsed edifices in Central America. Sector collapses are marked by massive debris avalanche deposits and hummocky topography (Crandell, 1984). I hypothesize that sometime in the recent past, Volcán Barú experienced a very large sector collapse, at least an order of magnitude larger than the 1980 sector collapse on Mt. St. Helens (Siebert et al., 2006). The evidence for this event can be found in the topography and stratigraphy of the deposits around Volcán Barú.

GEOLOGIC SETTING

The Central American volcanic arc results from the subduction of the Cocos and the Nazca plates under the Caribbean plate. The tectonic activity off of the western coast of Central America involves three plates, the Caribbean, the Cocos and the Nazca plates. These three plates meet at the Panama Triple Junction (PTJ). The rougher and thicker Cocos plate is subducting shallowly and orthogonally under the Caribbean plate at the Middle America Trench (DeMets, 2001; Shuanggen and Zhu, 2004; Hey, 1977). The Nazca plate is subducting steeply and obliquely under the Caribbean plate. The transform boundary between the Cocos and the Nazca plate is called the Panama Fracture Zone (PFZ) and forms one of the three spokes of boundaries that meet at the PTJ. As the Cocos and Nazca plates continue to subduct at different rates and angles, the PTJ migrates to the southeast at a rate of 55 mm/yr. Volcán Barú is located roughly inboard of the subducting PFZ.

Volcán Barú is a large calc-alkaline andesite stratovolcano that currently stands 3477 m high (Siebert et al., 2006; De Boer et al., 1988). It is considered to be an active volcano, with four eruptive episodes in the past 1,600 years. The most recent event was 400 to 500 years ago. The structure is composed of 280 km^2 of overlapping pyroclastic flows, lahars, and lava flows (Sherrod et al., 2007). The edifice is cut by a 6 x 10 km horseshoe-shaped caldera that opens to the west. The missing portion is the source of possibly the largest sector collapse in Central American history. The geometry of the caldera indicates that more than one collapse may have taken place (Siebert et al., 2006). The debris avalanche deposits from the collapse extend beyond the Pan-American Highway into the Gulf of Chiriqui, >60 km from the collapse scarp. Hummocky topography extends to the southwest, affecting river systems such as the Rio Chiriqui Viejo. The hummocky terrain contains many closed depressions, often forming the basins for small lakes, especially in the area within 20 km of the summit (Siebert et al., 2006).

My objectives for this study are to:

1. Describe the stratigraphy of the debris avalanche deposits from Volcán Barú;
2. Use radiometric dating to better constrain the age of the most recent debris avalanche deposits and therefore the age of the most recent sector collapses;
3. Create a facies map of the debris avalanche deposits based on revised facies descriptions from Palmer (1991);
4. Hypothesize a potential cause for the collapse

using evidence from the stratigraphic record.

METHODS

To achieve the first objective, I kept detailed field notes of exposed stratigraphy in outcrops where samples were collected. Recent construction of several hydroelectric dams in the study area provided an unprecedented amount of outcrops that would otherwise be covered by tropical vegetation. At all of these locations, I created a photomosaic of the outcrop and recorded descriptions of the sediments and allostratigraphy (Hughes, 2010) of the outcrops. Later, I created stratigraphic line drawings and allostratigraphic columns from the photomosaics and field notes showing the location and age of the carbon samples in relation to a debris avalanche unit. To achieve the second goal of better constraining the age of the sector collapse, I collected organic samples to submit for radiocarbon dating. We collected 2 carbon samples in outcrops in closed depressions on the debris avalanche (samples 1 and 2). These are sites where rivers had been diverted after the sector collapse carrying organic material with them. We also located a carbon sample entombed in exposed lahar flows (sample 3).

I achieved the third objective of creating a facies map of the debris avalanche deposits by combining Julie Herrick's map of hummock distribution (Herrick, 2011), field observations and photographs, as well as stereoscopic air photographs. Following and augmenting Palmer's (1991) facies of debris avalanche deposits, I divided a map of the debris avalanche into 2 km sized grids and systematically categorized each square into one of three facies by the percentage of hummocks in the square grid. The four facies I identified are axial-A, axial-B, a marginal facies and an extra-marginal facies. The axial-A facies contains over 5% hummocks and axial-B contains below 5% hummocks per area. The marginal facies is defined as a lahar plain with no hummocks. The extra-marginal facies are closed depressions deposits and could not be shown at the scale of the map.

To hypothesize a possible cause for the sector collapse, I utilized the same outcrops and allostratigraphic columns from the outcrops where samples were collected to try to identify juvenile eruptive material, such as pumice, that would indicate whether an eruption occurred around the same time as the debris avalanche.

RESULTS

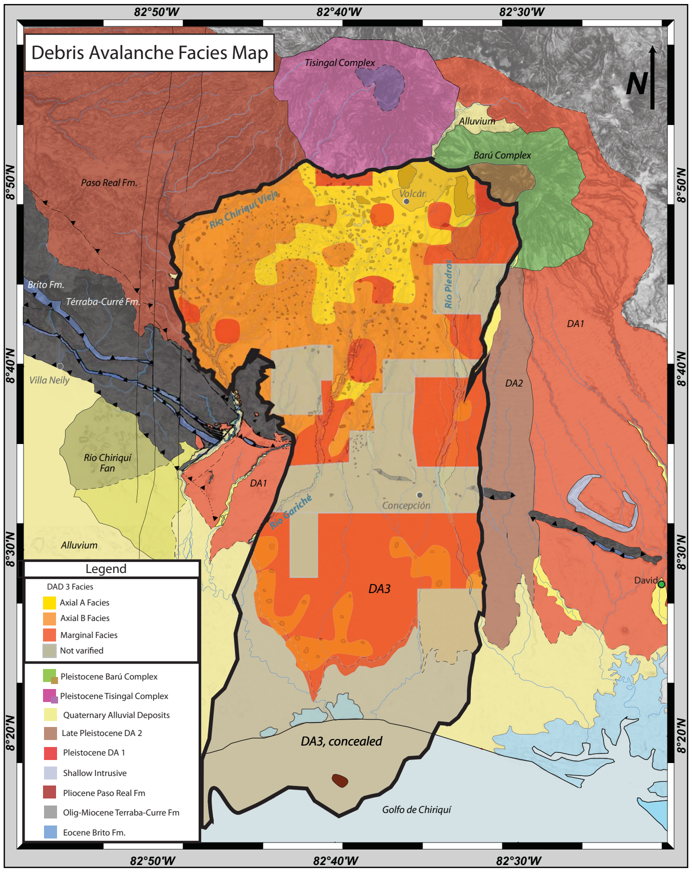
Facies

The debris avalanche deposits can be categorized into four distinct facies (Fig. 1). The axial A facies (>5% hummocks) extends from the edifice to the southwest. This facies incorporates large intact toreva blocks closest to the edifice and areas farther from the edifice with more concentrated hummocks. Axial B extends further to the southwest containing fewer and mostly smaller hummocks and shattered blocks that were able to travel farther from the edifice. The marginal facies lahar plain extends to the south towards the Chiriqui Gulf. All of these mapable facies are discontinuous and their boundaries are not sharp. The fourth facies is the extra-marginal facies of the closed depressions. These areas are generally too small to be mapped at this scale but were critical for constraining the age of the debris avalanche. The axial-A, -B and marginal facies were added to a geologic map of the area showing facies distribution as well as older debris avalanche deposits (Fig. 1).

Ages

Radiocarbon and 40Ar/39Ar of debris avalanche deposits indicate at least three major sector collapse events on Volcán Barú (Table 1). These are designated DA1, DA2, and DA3 (Fig. 1). There are twelve 14C samples and two Ar^39/ Ar^40 samples from debris avalanche deposits originating from Volcán Barú. Samples 1, 2, 3, 8 and 9 were collected during this study and samples 4, 5, 6, 7, 10, 11 and 12 are from previous studies (Frels, 2009; Morell, 2011).

Samples from DA3 were all dated around 10 ka. DA3 samples include samples 1, 2, and 3 collected in this study and samples 4, 5 and 6 from a study done in 2009 (Frels). Sample 1 was taken from a closed depression on the west bank of the Rio Chiriqui Viejo and is the sample nearest to the edifice. The sample came from an organic layer 2.5 m above one lahar deposit (possibly DA3) and 0.25 m below another. The 14C age of the sample was 7170 to 6790 yBP.



Radiocarbon Age Control

Sample ID	Sample Number (Beta)	Northing	Easting	Conventional Radio Carbon Age (YBP)	Calendar Calibrated (yBP)
DA3					
1	PA-10-2-HZ-2 (282784)	973758	316753	6100 ± 70 yBP	Cal BP 7170 to 6790
2	**PA-10-2-HZ-3 (282785)**	**973558**	**314478**	**10840 ± 70 yBP**	**Cal BP 12900 to 12790**
3	**PA-10-2-HZ-11 (282788)**	**968930**	**298456**	**9110 ± 120 yBP**	**Cal BP 10570 to 10120 AND Cal BP 10070 to 9920**
4	PA-08-06-07 (247421)	906254	293279	9200 ± 70 yBP	Cal BP 10570 to 10230
5	PA-08-06-15 (247426)	948406	301889	7840 ± 70 yBP	Cal BP 8970 to 8880, 8870 to 8830, 8800 to 8460
6		943148	298600	8740 ± 90 yBP	
DA2					
7	PA-09-15A (255931)			40960 +/- 480 yBP	
DA1					
8	PA-10-2-HZ-7 (282786)	957975	299723	>41230 yBP	
9	PA-10-2-HZ-9 (282787)	958247	299846	>43500 yBP	
10	PA-09-14 (255174)	948699	301795	>44,000 yBP	
11	PA-09-19 (255176)	948883	301644	>45,000 yBP	
12	PA-09-30	962945	297881	>43,510 yBP	

Ar/Ar Age Control

Sample ID	Sample Number	Northing	Easting	Total Fusion Age	Isochron Age
13	Pa-09-11 #4	910333	293105	480 ± 36 ka	352 ± 77 ka
14	PA-09-18 #1	948882	301639	264 ± 23 ka	231 ± 32 ka

Figure 1: Late Pleistocene debris avalanche facies (DA3) distribution and geologic map of Volcan Baru (after Kristin Morell and Julie Herrick). Beige areas were not covered by air photographs and therefore hummock concentration could not be confirmed.

Sample 2 was taken further west downstream on the Rio Chiriqui Viejo (Fig. 2). It was found in a closed depression containing fluvial and lacustrine deposits. The 14C age of the sample was 12900 50 12790 yBP. Sample 3 came from a carbon ball found in a 30 m thick lahar exposure in a dam excavation (Fig. 3). The 14C age of sample 3 was 10570 to 10120 yBP.

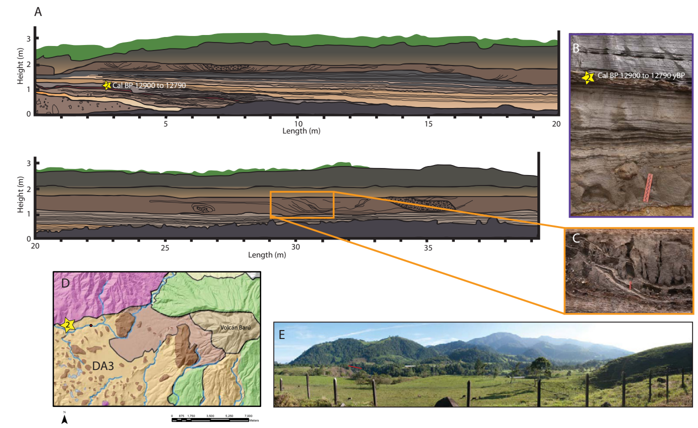


Figure 2: A) stratigraphic line-drawing of an outcrop in a closed depression derived from a photographic mosaic of the outcrop. The orange box encloses the area shown in D. The star indicates location of carbon sample 2 (Table 1). This sample provides a minimum age constraint for the debris avalanche. B) A closer look at the outcrop showing the location of dated sample 2. C) Close-up of the sedimentary structures in the exposure showing the Gilbert delta structure indicative of fluvial deposition into a lacustrine environment. D) Map of Volcán Barú and a portion of the DA3 deposit showing the location of sample 2. E) A photograph showing the hummocky topography surrounding the outcrop. The red line approximates the location of the outcrop.

Samples 4 and 5 from Frels (2009) and were calendar calibrated at 10570 to 10230 yBP and 8970 to 8880 yBP, 8870 to 8830 yBP, and 8800 to 8460 yBP. Sample 6 came from an unpublished manuscript and its 14C age was 8740 ± 90 yBP (Frels, 2009). Samples 5 and 6 are from terraces eroded into the DA3 deposit making them younger than the debris avalanche.

Samples 2 and 3 are the most relevant for constraining the age of the most recent debris avalanche. At 12900-12790 yBP and 10570-10120 yBP, they are consistant with constraints made in previous studies, but provide a more precise age constraint. Stratigraphically, they form good constraints because sample 2 was found around 1 m above a debris avalanche (Fig. 2, DA3). It was probably deposited relatively soon after the lahar. Sample 3 was found within a lahar flow related to the debris avalanche (Fig. 3, DA3). This suggests that lahar activity continued well after the sector collapse, a reasonable scenario given the unstable nature of the landscape after the

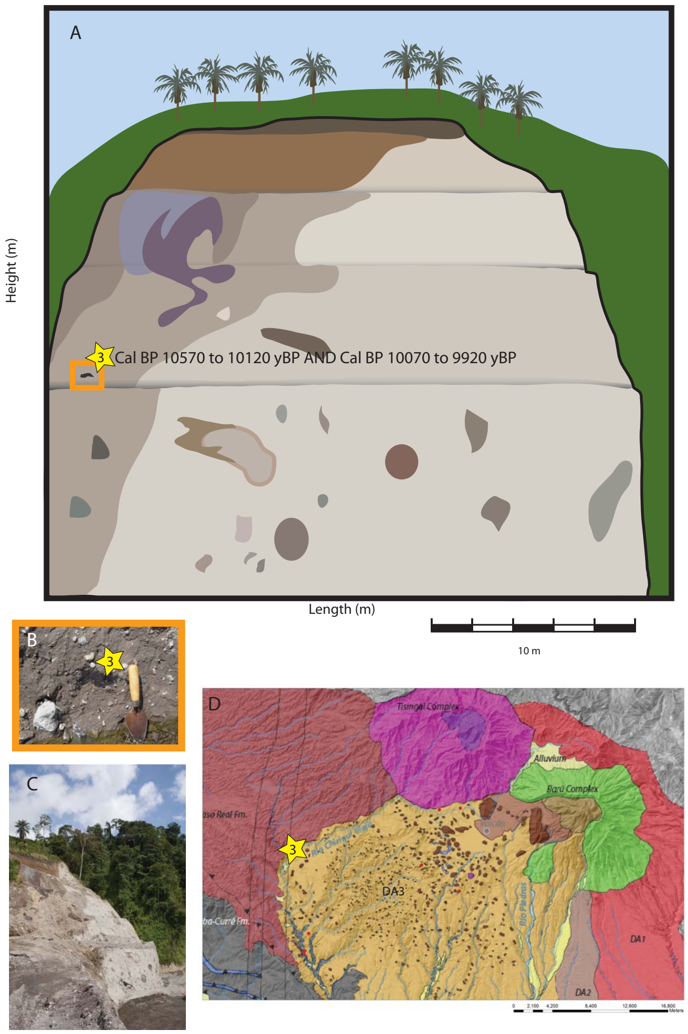


Figure 3: A) Interpreted illustration of an exposure of a lahar-flow (DA3) showing the location of sample 3 (Table 1). B) Photograph of the carbon ball sample 3 with a spade for scale.
C) Photograph showing the outcrop from the side. D) Map showing Volcán Barú, DA3 deposits and the location of sample 3.

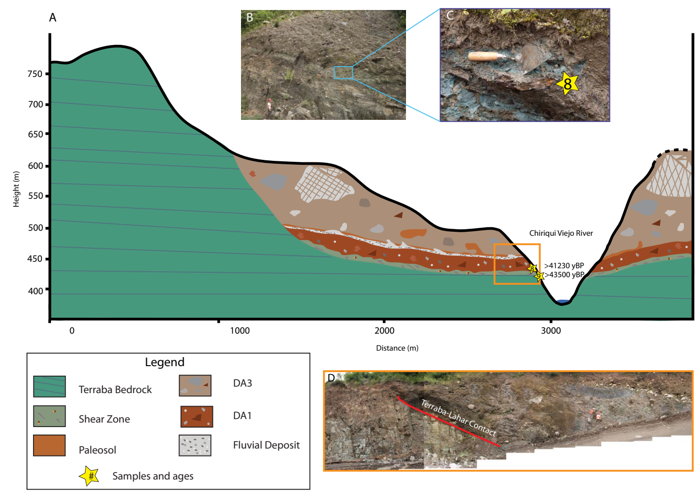


Figure 4: A) Composite cross-section across Rio Chiriqui Viejo gorge. Shows locations of samples 8 and 9 (Table 1) in the shear zone contact between the Terraba bedrock and the DA1 deposit. B) Photograph of the shear zone. C) Wood in shear zone where sample 8 was located. D) Photomosiac of outcrop showing the contact between the Terraba bedrock and the DA1.

sector collapse. Sample 1 is too young to provide a good constraint. Samples 8 and 9 are too old to be associated with the most recent event. They were found deeper in the Rio Chiriqui Viejo gorge stratigraphically below DA3. It is likely that they are from an earlier debris avalanche. No juvenile eruptive material was found in the outcrops containing samples 2 and 3 that would indicate an eruption occurring near the time of the sector collapse.
There was only one sample from DA2, sample 7, which dated that debris avalanche to 40,960 +/- 480 yBP. DA1 deposits included samples 13 and 14 from Morell (2011) as well as samples 8 through 12 which were beyond carbon dating range. Samples 13 and 14 are 40Ar/39Ar ages on hornblende phenocrysts from lahar deposits. The isochron ages from these samples are 352 ± 77 ka and 231 ± 32 ka, giving an upper age limit from DA1. Radiocarbon samples 8 through 12 are from logs in DA1 are beyond radiocarbon dating range and provide a lower age limit of >41, 230 yBP. Samples 8 and 9 came from sheared wood found in the contact between the Terraba bedrock and a lahar deposit along the Rio Chiriqui Viejo (Fig. 4). Sample 8 was dated at >41230 yBP and 9 was >43500 yBP. The other radiocarbon dead samples 10, 11, and 12 were >44,000 yBP, >45,000 yBP, and >43,510 yBP respectively.

DISCUSSION

The samples dated in the study area can be grouped into three different age groups (Fig. 1). The

40Ar/39Ar ages constrain a much older debris avalanche (DA 1) that must have occurred during the Pleistocene. The 40 ka deposits provide an age constraint for a Late Pleistocene debris avalanche (DA 2). The 10 ka samples provide an age constraint for the most recent debris avalanche associated with the youngest sector collapse (DA 3). The ages of these samples tightly constrain that collapse event to the late Pleistocene between 12900-12790 yBP and 10570-10120 yBP.

From the age constraints for the different debris avalanches, it is clear that there has been more than one sector collapse on Volcán Barú. There are at least three distinct debris avalanche deposit ages, two in the Late Pleistocene and one earlier in the Pleistocene. The causes of the older sector collapses are unknown but suppositions can be made for their catalysts. The most likely candidate for the cause of a sector collapse would be an explosive eruption with a lateral blast much like Mt. St. Helens in 1980. Another cause could be simply gravity acting on an unstable structure, which is characteristic of a stratovolcano constructed with layers of unconsolidated material.

CONCLUSIONS

Utilizing new age constraints collected in this study, the most recent sector collapse occurred in the late Pleistocene between 12900-12790 yBP and 10570-10120 yBP. It was one of at least three sector collapses that have taken place on the Volcán Barú edifice. Two earlier collapses took place earlier in the late Pleistocene and the Pleistocene. In a congruent study by Shannon Brady (this volume), geochemical analysis of shattered blocks within the debris avalanche indicated episodes of mafic recharge which can trigger eruptions. Although Volcán Barú is active and there have been eruptions in the past, there is no evidence in the form of juvenile eruptive material in the stratigraphic record that would indicate an eruption around the time of collapse. Due to lack of evidence supporting an eruptive event near the time of the sector collapse, the sector collapse was not likely to have been caused by an eruption. Unlike the Mt. St. Helen's eruption and subsequent sector collapse, the likely cause of the collapse on Volcán Barú was simply gravity. The nature of stratovolcanos makes them inherently unstable. Previous collapses probably weakened the integrity of the structure further. Aggressive stream incision from the river system near the edifice and intense tropical weathering were likely to also have weakened the structure although more stratigraphic studies would need to be done to fully rule out an eruption as a cause for the most recent late Pleistocene collapse.

REFERENCES

Crandell, D.R. et al, (1984), Catastrophic debris avalanche from ancestral Mount Shasta Volcano, California, Geology v. 12 p 143-146.

de Boer, J.Z., et al, (1988), Quaternary calc-alkaline volcanism in western Panama; regional variation and implication for the plate tectonic framework, Journal of South American Earth Sciences, 1, 275-293.

de Boer, J. Z., M. Drummond, M. Bordelon, M. Defant, H. Bellon, R. Maury, (1995), Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca), in Geologic and tectonic development of the Caribbean Plate boundary in southern Central America, edited by P. Mann, pp. 131-157, Geological Society of America Special Paper 295, Boulder, Colorado.

DeMets, C., (2001). A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American Volcanic arc. Geophysical Research Letters. 28, 4043-4046.

Frels, J. (2009), Thrust Belt Propagation in Response to Panama Triple Junction Migration, Southwest Panama, 36 pg, Bachelor's Thesis, Trinity University.

Herrick, J. A. (2011), Recurrent voluminous sector collapses at Volcán Barú, Panama, 71 pp., Michigan Technological University, Houghton, MI.

Hey, R., (1977). Tectonic evolution of the Cocos-Nazca spreading center. Geologic Society of American Bulletin. 88, 1404-1420.

Hughes, P.D., (2010), Geormorphology and Quaternary stratigraphy: the roles of morph-, litho- and allostratigraphy, Geomorphology 123 189-199

Morell, Kristen., Fisher, D., Gardner, T. (2008), Inner Forearc Response to subduction of the Panama Fracture Zone, South Central America, Earth and Planetary Science Letters, 265, 82-95.

Morell, K.D. (2011), Late Miocene to Recent upper plate response to tectonics surrounding the Panama Triple Junction, Southern Central America, PhD Thesis, Pennsylvania State University.

Palmer, B.A., Alloway, B.V., Neall, V.E. (1991), Sedimentation in Volcanic Settings, SEPM Special Publication No. 45, 89-98.

Sherrod, D.R., Vallance, J.W., Espinosa A.T. and McGeehin, J.P., (2007), Volcán Barú - eruptive history and volcano-hazards assessment. Open file report 2007-1401, 33 p.

Jin, S. and Zhu, W., (2004). A revision of the parameters of the NNR-NUVEL-1A plate velocity model. Journal of Geodynamics. 38, 85-92.

Siebert, L., Alvardo, G., Vallance, J., and van Wyk de Vries, B., (2006). Large-volume volcanic edifice failures in Central American and associated hazards, Geological society of America Special Paper 412, 1-26