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At the March 5, 2010 UW-Madison Chemistry Department Colloquium, Prof. Bassam Z. Shakhashiri, the director of the Wisconsin Initiative for Science Literacy (WISL), encouraged all UW-Madison chemistry Ph.D. candidates to include a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

Over 50 Ph.D. degree recipients have successfully completed their theses and included such a chapter.

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Faulting in southern Guatemala and implications for the North America – forearc – Caribbean triple junction

By

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PART 1, CHAPTER 1: Guatemala City: Living between two tectonic plates.

Bridget Garnier, chapter from PhD dissertation entitled “Faulting in southern Guatemala and implications for the North America – forearc – Caribbean triple junction”.

This is a non-scientist summary of my research in fulfillment for the Wisconsin Initiative for Science Literacy (WISL) award for communicating PhD research to the public. Guidance and editorial support were provided by the science communication program of WISL.

My PhD research is centered on understanding the tectonics of Guatemala by analyzing small faults that were measured throughout the country. For me, this research was an introduction to Central American geology, as well as life in Central America. When I started my PhD 6 years ago, I knew that I would be living and working in Costa Rica by the time that I finished. My husband, also a geologist, is Costa Rican and we moved to Costa Rica over three years ago after he finished his doctorate and I finished my PhD coursework. While my undergraduate and Masters research also focused on analyzing faults, I have never worked in a volcanic environment that would be relevant to doing future fieldwork in Costa Rica. Luckily, my PhD advisor had a project I could join that was based in Guatemala, which is part of the same volcanic and tectonic system that encompasses all of Central America. This project has allowed me to further my expertise on fault analysis methods and learn the techniques needed to evaluate faulting in volcanic environments, all while giving me a broader view of Central American geology.

One country: Three tectonic plates

Guatemala has a history of destructive earthquakes and active volcanoes, caused by three tectonic plates moving past one another: The North America, Caribbean, and Cocos plates (see Figure 1). The North America and Caribbean plates are continental tectonic plates and meet along an east-west boundary in central Guatemala consisting of multiple faults[1]. The main faults of this boundary are the Motagua and Polochic faults, which accommodate most of the motion between the North America and Caribbean plates. Across the boundary, in a relative sense, the North America plate (north of the boundary) moves to the west as the Caribbean plate (south of the boundary) moves to the east[2]. The third plate, the oceanic Cocos plate, travels beneath the two plates, or subducts, at the Middle America Trench off the Pacific coast of Central America (Figure 2).

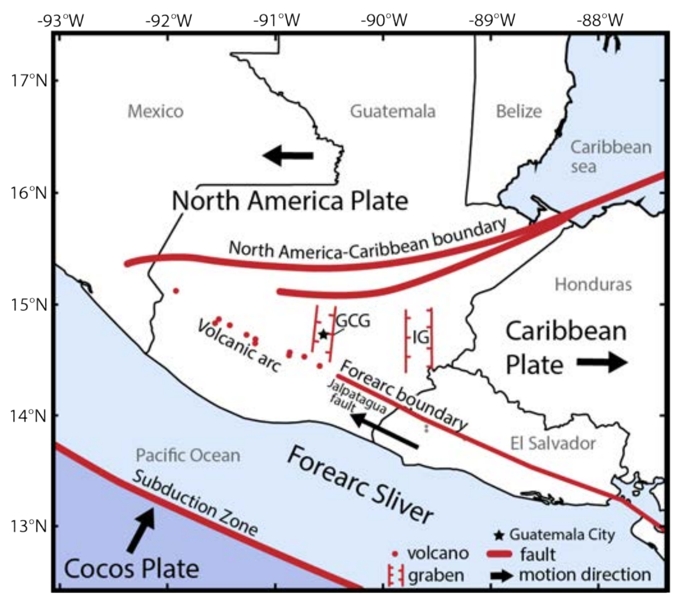

Figure 1. The important geologic features in Guatemala. The two overlapping faults across Guatemala and the subduction zone mark the two tectonic plate boundaries in this area. Arrows indicate the movement direction for each tectonic plate. Two additional features are the forearc sliver, between the subduction zone and the Caribbean plate, and the two large north-south grabens, explained below, in central and eastern Guatemala. GCG – The Guatemala City graben; IP – Ipala graben.

Pushing, pulling, and twisting forces occur within the Earth's crust when tectonic plates move past one another along a plate boundary. These forces create geologic structures, or deformation,

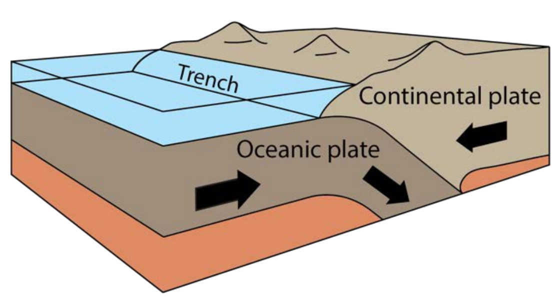

Figure 2. Cartoon of an oceanic plate subducting beneath a continental plate.

such as faults, folds, mountains, and basins. Destructive earthquakes can also be triggered by movement along plate boundaries. When a plate boundary is on-land, like the North America-Caribbean plate boundary, the deformation can be greater and destructive earthquakes can affect populations living nearby. As an example, a highly destructive 7.5 magnitude earthquake occurred on the Motagua fault of the North America-Caribbean plate boundary in 1976. This earthquake and its aftershocks killed 23,000 people, injured approximately 76,000 people, and left 1.2 million people homeless[3]. This devastating event caused geologists to study Guatemala, in order to understand how the tectonic plates are moving and interacting, and how earthquakes on the major faults could pose a further risk to those who live there.

In general, whenever three tectonic plates interact – called a triple junction – the deformation is not simple. This is particularly true for Guatemala because unlike a typical triple junction where all three plates meet at one point, the North America-Caribbean plate boundary ends near the Mexico/Guatemala border and does not extend to the Cocos plate at the Middle America Trench[1] (the third plate). Due to this complicated feature and many others, it has been difficult to determine how the three tectonic plates interact in Guatemala.

To address this problem, two approaches were taken. First, over 200 GPS stations across northern Central America were installed by several groups from different countries. The most recent study[2] determined that the North America-Caribbean plate boundary forms a wedge shape that ends near Guatemala City in central Guatemala. Second, and the approach that I took, is that one can study the faults directly. There are relatively few rock outcrops in Guatemala, because of widespread volcanic ashes and abundant plant life. Moreover, major fault zones are usually not exposed, because the rocks within them are pulverized. As a result, my approach was to measured small faults across southern Guatemala. Small faults can be observed in recently made roadcuts, and provide information about how an area is deforming. I also determined the age of volcanic rocks within faulted areas, to learn when faulting was active or when faulting stopped due to changes in deformation or plate boundaries. With this information, we separated areas of active/current faulting from past faulting and developed a new story on how the deformation near plate boundaries changed over time.

A guide to the faults of Guatemala

Measuring and analyzing faults can tell geologists how an area has changed, and sometimes when that change occurred. Faults are breaks in rock that occur in response to different forces in the Earth's crust (Figure 3). Geologists cannot measure the past forces in the Earth, but we can measure the deformation that was left behind and use that information to determine how it may have happened. Geologists are forensic scientists for the Earth.

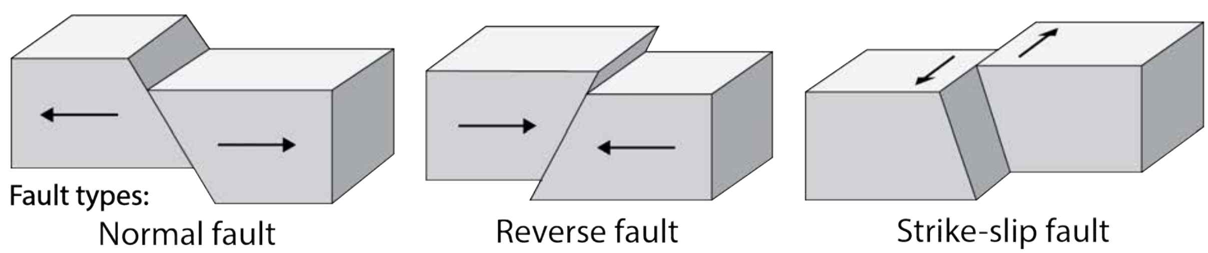

Figure 3. Types of faults that form from forces in the Earth's crust.

There are three major fault systems in Guatemala, all of which are relevant to my study. First, the Motagua and Polochic faults (Figure 1), discussed above, separate the North American and Caribbean

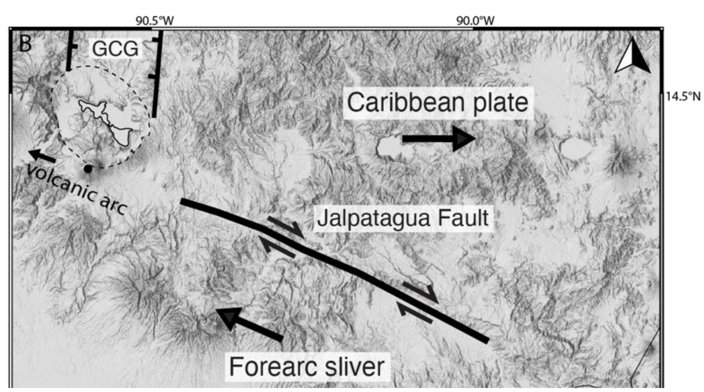

Figure 4. Digital elevation map (DEM) showing the movement of the Caribbean plate and forearc sliver on either side of the Jalpatagua fault.

plates. These are strike-slip faults, which accommodate side-by-side motion. Second, south of the North America-Caribbean plate boundary, the Jalpatagua fault of southeastern Guatemala is also a strike-slip fault (Figure 4). The Jalpatagua fault allows the Caribbean plate (north of the boundary) to move to the east, in relation to the coastal part of Guatemala as it moves to the northwest (Figure 4). Coastal Guatemala is not part of the Cocos plate, but part of a "forearc", which is a thin strip of earth's crust between the subduction zone and the Caribbean plate (Figure 1). The forearc is bounded by the Cocos subduction zone on its southern side. In southeastern Guatemala, the forearc is bounded to the north by the Jalpatagua fault, which ends near Guatemala City, and does not continue into western Guatemala. In western Guatemala, the forearc is bounded to the north by a line of volcanoes (the volcanic arc).

The Motagua and Jalpatagua faults seem to end near Guatemala City, along a North-South-oriented feature called the Guatemala City graben, the third major fault system of this study. A graben is a geologic structure that has a down-dropped block of the Earth's crust bordered by parallel faults (Figure 5). The faults tilt towards each other and the structure is typically created by pulling forces in the Earth's crust. As pulling or extension occurs, the block between the two faults drops lower and lower. The most prominent graben in Guatemala is the Guatemala City graben, which is located in central Guatemala and home to the capital, Guatemala City, and a metropolitan area containing 2.7 million people (shown in Figure 5). There are other North-South trending grabens in eastern Guatemala and Honduras, such as the Ipala graben.

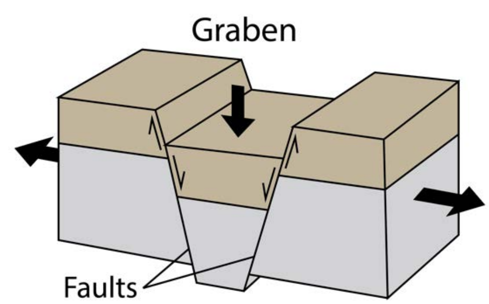

Figure 5. Cartoon of a graben

The Caribbean Wedge

To understand the three-plate system as a whole, geologists look at both large structures and small structures to understand how the crust is deforming. With all the major faults identified, our research is concerned with the Caribbean plate, which has a wedge shape (pink shaded area in Figure 6). This Caribbean "wedge" is bounded by the Motagua and Polochic faults to the north and the Jalpatagua fault to the south. The N-S grabens within the wedge show that the area is being stretched as the Caribbean plate moves eastward, but we do not know where this stretching ends to the west. Previous studies did not collect much data west of the Guatemala City graben and they placed the western end, or the tip, of the Caribbean wedge near the Mexican border, based on where the forearc boundary meets the North America-Caribbean plate boundary[1]. For this study, we used a recent GPS study and fault data collected across southern Guatemala to show where the Caribbean wedge ends and where potential earthquake risk may lie.

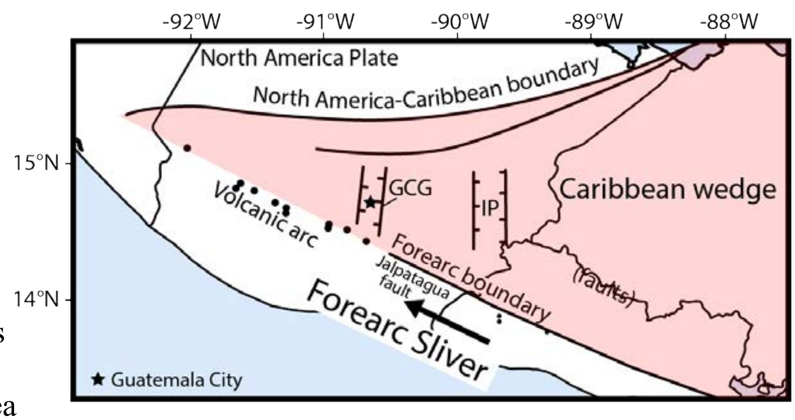

Figure 6. Map showing the boundaries of the Caribbean wedge in pink shading.

Geological studies of faults

When studying faults, geologists measure a fault's orientation in space and how much movement occurred across the fault. They use this information to compare fault orientations (e.g., Are all the faults pointing in the same direction at one place? What is the average orientation and the range of orientations? How do the fault orientations compare between

Location A and Location B?). Geologists can also calculate how much an area has stretched or shortened (e.g., Movement across the 20 faults in this outcrop show that the area is 20% wider that it was originally.). In some locations, faults are topped with unfaulted rock, which often means that the faults formed in the past, but are not active now. These inactive faults are a clue that deformation has changed over time. By dating the unfaulted rock, geologists can determine by *when* the faults stopped moving. If faults are not covered by unfaulted rock, this could mean that they are still active, or are at least younger than the age of the rock they cut through. All of this information gathered from faults helps geologists build a history of an area, to determine what happened, when it happened, and hopefully, why it all happened.

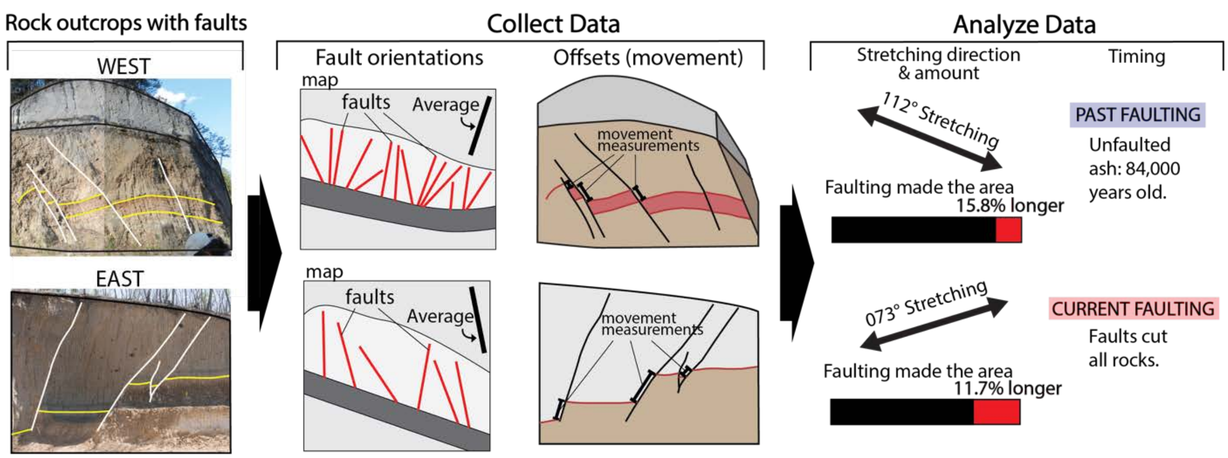

Figure 7. The process of analyzing faults. 1) Geologists find rock outcrops containing faults. There are two photos of outcrops, one from west of the Guatemala City graben and one from the east. 2) Fault orientations and the amount of movement are measured. Rock samples are also taken to determine their age. 3) We analyze the collected data to determine the direction of stretching that the faults record, how much stretching took place, and the age of our rock samples, which can tell us when faulting stopped at certain locations.

By finding faulted outcrops in southern Guatemala, I applied the principles and methods described above to create a picture of how and when the earth's crust changed near the plate boundaries and large faults (Figure 7). Small faults were measured at eight outcrops across the Caribbean wedge, east and west of the Guatemala City graben (red dots in Figure 8). These small faults are abundant and give a more complete picture of how the crust is deforming in the area. Similar to how when a rock hits a windshield, there are many small fractures, but an overall circular pattern to show where the rock hit. Small faults fill in the picture outlined by large faults and offer more detail. Faults were typically found at rock faces, or outcrops, along recently constructed roads (Figure 7). At each outcrop, we measured the orientation of each fault, how much movement occurred on each fault, and collected rock samples for dating. Most of the outcrops contained normal faults, which is a type of fault that records stretching or pulling in the area, and showed centimeters to meters of movement. With this data, I calculated how much stretching occurred at an outcrop and in what direction.

We learned three new things from analyzing the fault data:

1) *The Caribbean wedge has been stretched east to west.* The presence of the Guatemala City and Ipala grabens already indicate that the Caribbean wedge is being stretched east to west. However, we see the same stretching direction in my small fault data within the wedge as well, on past and recent faults and on both sides of the Guatemala City graben (Figure 8). Therefore, the small fault data agrees with the larger structures and indicates that this type of stretching has been going on for a while.

2) *The area of stretching has changed over time.* Most faults located west of the Guatemala City graben are capped by unfaulted units. This pattern means that nearly all the faults are **past** faults and are **not** active now (blue shaded area in Figure 8). An exception is one large fault just west of the graben which may still be active today. Within the Guatemala City graben and to the east, all the small faults reach the surface, which means that these faults are **current** and movement could still be happening (red shaded area in Figure 8). Therefore, we can say that, *in the present*, stretching is active immediately near the Guatemala City graben and to the east. However, *in the past*, stretching occurred west of the Guatemala City graben as well.

3) *The western end of the Caribbean wedge is farther to the east than previously thought.* The fact that there is nearly only past faulting west of the Guatemala City graben shows this area is not part of the Caribbean wedge right now. Therefore, the Caribbean wedge does not continue to the Mexican border to the west[1]. Rather, since the last structure of active faulting occurs just west of the Guatemala City graben, the western end of the Caribbean wedge is located at or near the Guatemala City graben (Figure 9).

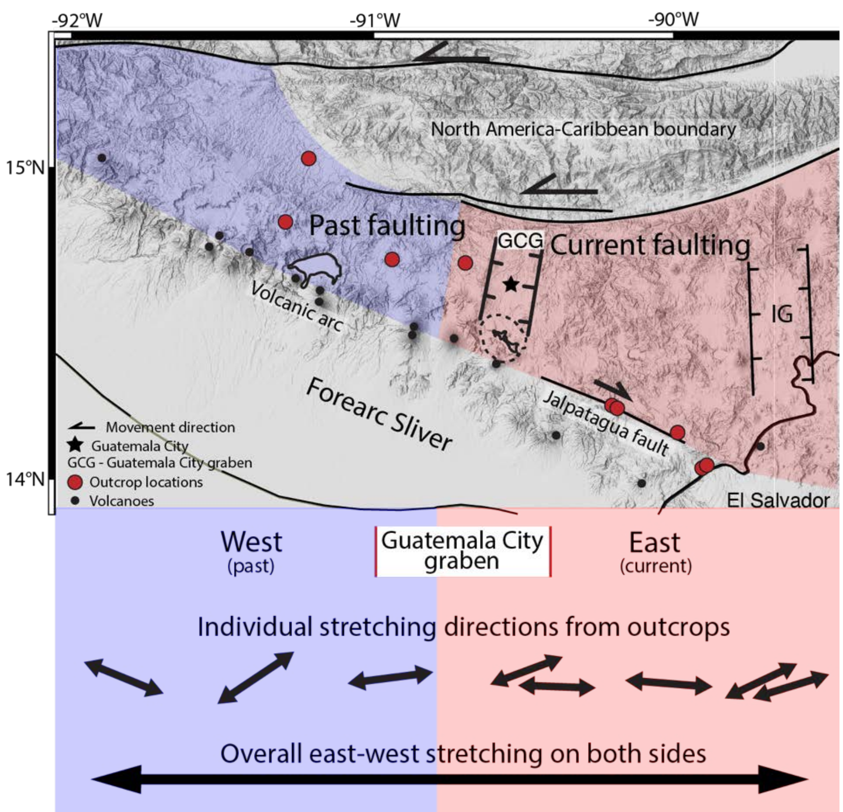

Figure 8. The map shows the terrain of the area, the large faults (white and black lines), volcanoes (black dots), and the location of the outcrops where fault data was collected (red dots). Red and blue shading indicates the areas of current (red) faulting and past (blue) faulting, with the Guatemala City graben (GCG) acting as a boundary between the two. Below the map, we show the stretching directions for individual outcrops and that they all show a general east-west stretching direction across the entire area, past and present.

The Guatemala City graben

The fault data show that the Guatemala City graben is a more important structure than previously thought, as it marks the boundary between past faulting and active faulting. (Figure 8). In a recent GPS study, Dr. Ellis and her colleagues (2019) analyzed movements from over 200 GPS stations over the past five years and found a similar relationship[2]. The GPS stations in Guatemala show that east-to-west stretching is occurring within the Caribbean wedge, from just west of the Guatemala City graben to across eastern Guatemala[2]. However, approximately 2/3rds of the total stretching occurs across the Guatemala City graben. In other words, the Guatemala City graben is the major active structure and is surrounded by areas of lesser stretching. The GPS data also indicate that western Guatemala, west of the Guatemala City graben, essentially moves along with the forearc sliver, not the Caribbean plate. These conclusions indicate that the western end of the Caribbean wedge occurs just west of the Guatemala City graben. And, the North America plate is located just north of the Motagua and Polochic fault system. That means that the Guatemala City graben is effectively the triple junction between the North America, forearc, and Caribbean plates (Figure 9).

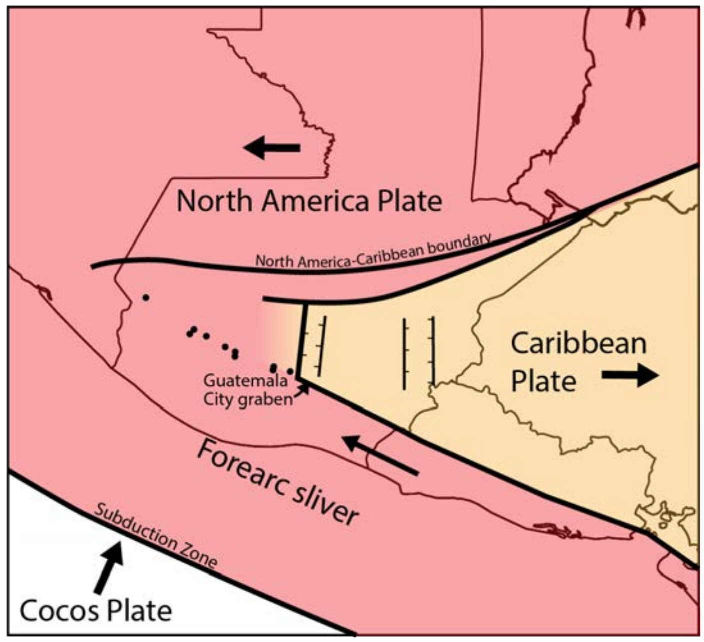

Figure 9. Model of current plate boundaries, focused on the Guatemala City graben.

Redefining the Guatemala City graben as a plate boundary between the North America, forearc, and Caribbean plates increases the importance and the earthquake risk of a structure that contains nearly 16% of the country's population. On-land plate boundaries can cause a lot of deformation and create highly destructive earthquakes. The Guatemala City graben is an extensional structure between the westerly moving North America plate and forearc sliver and the easterly moving Caribbean plate. The GPS data indicate that about 1 cm per year of stretching occurs across the graben, which is a fast rate and similar to other extensional plate boundaries worldwide. While the people living in the Guatemala City graben have always lived with a risk of destructive earthquakes by its location near the Motagua fault, the risk appears much greater now that we understand that the Guatemala City graben is an extending plate boundary. Movement along the nearby Motagua fault (the North America-Caribbean boundary) or the Jalpatagua fault (the forearc-Caribbean boundary) could trigger additional destructive earthquakes, affecting the graben and the large metropolitan area.

The last question to ask is "When did the Guatemala City graben become the plate boundary?" The past faulting found west of the Guatemala City graben can help tell this story. Past faulting shows that the Caribbean wedge extended into western Guatemala, creating a much wider wedge than there is today. The wedge was still being stretched east to west, but this happened across multiple large grabens and many smaller faults. Dating the unfaulted rocks in western Guatemala, above the faulted layers, suggests that faulting stopped in an eastward progression towards the Guatemala City graben. Specifically, faulting stopped at the westernmost outcrop before 84,000 years ago, and at the next westernmost outcrop before 54,000 years ago. The outcrop just west of the Guatemala City graben indicates that some faulting occurred after 51,000 years ago and the faulting may be still active. We suggest this eastward trend, as well as evidence of inactive faults found east of the Guatemala City graben, means that the wedge-wide stretching slowly focused onto the Guatemala City graben over the past ~100,000 years or more. For the area west of the Guatemala City graben, as faulting stopped and moved towards the Guatemala City graben, the land slowly transferred from the Caribbean plate to the forearc or North America plate, making the Guatemala City graben the plate boundary.

With our fault data and the recent GPS study by Dr. Ellis and her colleagues, we can place sharper boundaries between the North America and Caribbean plates and better understand this complicated tectonic system. While this is a fascinating discovery, we do not know what this means for the people currently living within the Guatemala City graben. Since 1976, great care has been taken to build earthquake resistant buildings and much less damage has been seen with subsequent earthquakes of lower intensity. It is impossible to know if another large earthquake could occur on this structure in our lifetimes, but continuing geologic research in this country is crucial to understanding further risk.

When I started analyzing the data collected from these faulted outcrops, I did not anticipate that they would support a redefinition of the tectonic plate boundaries and uncover a new deformational history. These are two new big ideas for the geology of this area. This work has reinforced the idea for me that small faults or other small geologic features are significant in understanding the bigger story. It has also been a privilege to see Guatemala and the people that live and work there. It is a beautiful, proud country with an amazing culture and way of life that is being strongly protected by its people. I am grateful for getting a unique glimpse of Guatemala and helping to uncover more about its complicated geology.

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