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Provenance of the Northern Range, Trinidad Using Detrital Zircon U-Pb Geochronology: Implications for Northern South American River System Paleogeography

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Abstract
The Northern Range of Trinidad is located in a key area for evaluating the Mesozoic-Cenozoic evolution of the Caribbean and South American plates. Here, we present detrital zircon U-Pb geochronology for 2391 grains from ten samples collected from metasedimentary rocks of the Northern Range. These data are used to bracket the maximum depositional age of the fossil-poor metasedimentary rocks from the Northern Range and to investigate the provenance of their sedimentary protoliths. Detrital zircon ages range between 3136.5 ± 22.9 Ma and 139.0 ± 5.4 Ma, reflecting apparent contribution from a variety of crustal affinities; however, since the youngest ages are 199.5 ± 7.4 Ma to 139.0 ± 5.4 Ma, it is unlikely that sediments were sourced from the Caribbean Plate, which is ca. 88 Ma. Samples from the western Northern Range exhibit significant peaks clustering around 1.0 Ga, suggesting a prominent Grenville basement sediment source. In contrast, samples from the eastern Northern Range have bimodal peaks at ca. 1.4 Ga and 1.75 Ga, which overlap with Central Amazonian crustal ages. Central Northern Range rocks exhibit a single, well-constrained peak at ca. 2.0 Ga, which may be associated with Eburnean-West African to Northern-Central Amazonian terranes. While all samples show significant contributions from the South American craton, suggesting this was their primary sedimentological source, potential source area changes were explored because samples were collected from different structural horizons. These results are among the first to quantify the maximum depositional age of the metasedimentary rock and indicate that the youngest Northern Range clastic sediments were deposited in the Early Cretaceous (Valanginian). Based on the high frequency of detrital zircons from the western interior of South America, our data suggest that the proto-Orinoco River may have begun draining to the northeast coast of South America earlier than previous research suggests.

1. Introduction

Trinidad is located in the southeast corner of the South American-Caribbean plate margin, adjacent to Venezuela (Fig.1). This region has undergone immense change as a result of tectonic plate movement, metamorphism, exhumation, uplift, erosion, and changing sea levels (Babb and Mann 1999; Pindell et al. 2009; Arkle et al., 2017a). The Northern Range of Trinidad consists of greenschist to amphibolite facies metamorphic rocks that are presumed to be Jurassic-Cretaceous based on very few fossils scattered across the mountains (Algar and Pindell 1993). The age of and protolith lithology of the Northern Range bedrock are very loosely constrained due to late-Miocene metamorphism and deformation of the metasediments.

Researchers have identified two hypotheses on how the rocks were deposited in the Northern Range: 1) the sediments were accreted to Trinidad as the Caribbean plate moved eastward during dextral motion (Erlich and Barrett 1990; Algar and Pindell 1993, Algar et al. 1998) or 2) the sediments originated from the Guyana Shield (the inner craton of South America) and were deposited by terrestrial drainage systems (Diaz de Gamero 1995; Escalona and Mann 2011) (Fig. 2).

Thus far, previous research has been able to loosely constrain the depositional age of Northern Range bedrock and have constructed hypotheses on how the sediments transpired to Trinidad. However, the provenance, or region of origin for detrital sediments, of the sediment has not been identified with certainty. The U-Pb detrital zircon data presented in this study are used to understand the provenance and provide more certainty to the formation of the Northern Range. Provenance and geochronology are methods often used to understand how sediments have traveled and distributed throughout geologic time. Rivers, wind and tectonic plates are a few examples of mechanisms that transport and deposit sediments away from the terranes they originated from. Knowing the provenance of sediments helps to reconstruct paleogeography and consider paleo-depositional environments. This study uses U-Pb detrital zircon geochronology to answer what the provenance of the Northern Range, Trinidad bedrock is and to better understand how river and tectonic systems interacted with each other to form the island of Trinidad.

2. Background

2.1 Tectonic and Geologic History

Trinidad is located along the southeast corner of the Caribbean-South American Plate margin. The proto-Caribbean seaway formed after the rifting of Pangea during the Jurassic (Fig. 3). The Caribbean Plate formed ~88 Ma, in the Cretaceous (Babb and Mann 1999). At this time, the Caribbean plate was moving northeast, colliding with the western coast of South America and uplifting the Andes Mountains. The eastern coast of South America, which later became Trinidad, was a passive margin; the northern range sediments were deposited throughout the Cretaceous (Trenchman 1935; Spath 1939, Imlay 1945, Saunders 1972, Gennaro et al. in review; Algar and Pindell 1993).

This region remained a passive boundary until the Eocene when the Caribbean plate abruptly changed motion to eastward oblique collision along the southern boundary of the plate and subduction at the east edge of the plate (Pindell et al. 1998; Weber et al. 2001). The Caribbean Plate stepped southward ~10 Ma, causing a series of basins and ranges to form in Trinidad. The current tectonic motion is dextral (Pindell et al. 1998; Weber et al. 2001).

The Northern Range consists of weakly metamorphosed sandstone, quartzite, shale, slate, phyllite, siltstone, conglomerate and limestone. On the northeast tip of the island, the San Souci Group consists of turbiditic shale, quartzo-feldspathic sandstone, basalt, dolerite and gabbro (Algar and Pindell 1993) (Fig. 4). The San Souci Group is separated from the Northern Range Group by the Toco-Grande Riviere fault zone and is thought to be an allochthonous group. Algar and Pindell (1993) suggest the San Souci group was derived from either a younger, now subducted, part of the Proto-Caribbean seafloor, or the Caribbean Plate during dextral translation. The complex tectonic history of the Caribbean, proximity of Trinidad to multiple sources of sediment and lack of data in this area of study has left the provenance of the Northern Range, Trinidad rocks unknown.

2.2 Sediment Provenance and Transport Hypotheses

Researchers identified two primary hypotheses on the provenance and transportation methods of Northern Range sediments. The first hypothesis suggests Northern Range sediments are sourced from the South American craton (Algar et al. 1998; Diaz de Gamero 1995). This hypothesis suggests when Trinidad was a shallow marine environment in the Cretaceous, sediment from terrestrial drainage systems was deposited on the passive margin. During oblique collision throughout the Eocene-Miocene the passive margin sediments were metamorphosed, uplifted and exhumed to form the Northern Range rocks (Fig. 2).

This hypothesis is supported by the presence of limestone in the Northern Range containing Cretaceous aged fossils, indicating the sediment was generated in place with very little transport (Trenchman 1935; Spath 1939; Imlay 1945; Saunders 1972; Gennaro et al. in review). Based on the principle of uniformitarianism, it is assumed the stratigraphic layers the ammonite fossils in the Northern Range are found in, are the same layers the organisms would have lived in (Simpson 1970). Additionally, studies on Cenozoic sedimentary rocks that compose southern Trinidad have a South American cratonic provenance. Thus, it may be possible that the sediments were deposited over the area of the Northern Range, which aligns with Tobler's first law of geography and lateral continuity (Tobler 1970; Erlich et al. 1993; Xie et al. 2010; Xie and Mann 2014).

In contrast, the second hypothesis suggests the Northern Range sediments are sourced from the Caribbean plate and were metamorphosed and accreted to Trinidad during Eocene-Miocene oblique collision (Algar and Pindell 1993; Arkle et al. 2017). The Sans Souci Formation in the Northern Range supports this hypothesis. The San Souci Formation is allochthonous and believed to have been accreted to the Northern Range during tectonic movement. This hypothesis would imply the entire Northern Range is also allochthonous. Young U-Pb ages would support this hypothesis because the Caribbean Plate is only ~88 Ma (Fig. 2).

2.3 Previous Regional Provenance Studies

Tectonic activity has greatly influenced the evolution of landscapes and geologic formations in the Caribbean-South American region. Provenance studies conducted in areas proximal to the Northern Range provide insight into the development of depositional areas in the Caribbean. Sediment deposits are laterally continuous, so sediment sources and depositional environments throughout the Caribbean can be compared to each other to create a more comprehensive picture of deposition throughout time and space.

Weber et al. (2016) used U-Pb zircon geochronology to determine provenance of sediments from the northeast Venezuelan offshore basin, west of Trinidad. U-Pb ages from 6 cores collected from the region placed the sediment ages at Late Miocene-Early Pliocene. Using a map of compiled bedrock ages of South America, Weber et al. (2016) concluded that the sediments were sourced from the Andean province and South American craton. During this time period, the proto-Orinoco drainage was diverted to the east due to uplift along the north coast of South America. Weber et al. (2016) concluded that the proto-Orinoco transported sediments offshore, then the Guyana current carried them northward to offshore northeast Venezuela (Weber et al

2016).

Xie and Mann (2014) studied the U-Pb age and provenance of Central Range Trinidad rocks which were deposited during the Early Oligocene and Late Oligocene. The U-Pb ages suggest the Early Oligocene rocks are sourced from the Guyana Sheild while the Late Oligoene rocks had sediment contributions from both the Guyana Sheild and Andean Mountains; sediments were transported to via proto-fluvial systems and Guyana current. These findings suggest an abrupt change in contributing sediment sources likely due to the Caribbean Plate uplifting the north coast of South America during this time period. The sudden increase in topographic highs would have diverged proto-fluvial systems draining the Andes Mountains to the east towards modern-day Trinidad (Xie and Mann 2014). Goldstein et al. (1997), Restrepo-Pace and Cediel (2010), Weber et al. (2010) and Noguera et al. (2011) have also used U-Pb dating to discern provenance in the Caribbean-South American Plate region. The data presented in this paper uses the same methods as the authors mentioned above to discern the provenance of Northern Range, Trinidad.

3. Methods

3.1. Samples

Bedrock samples were collected from 16 locations in the Northern Range, and approximately 1.4 kg of bedrock was collected for each sample (Fig. 4). The samples are a variety of metasandstones, slates, phyllites, schists and quartzites. Samples were collected across the Northern Range from different structural blocks (geographically spread) and structural levels (depth) including, 5 samples from the east, 2 samples from the west, and 9 samples from the central region collected within the Chupara Fault zone. Samples were processed and separated at the Augustana College Geochemistry lab to isolate zircon grains, and 10 samples were sent to the University of Calgary, Canada for Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) (Fig. 4). The 10 samples analyzed were chosen based on their zircon yield after separation and their geographic location.

3.2. Sample Separation

Sample separation was done in the Augustana College Geochemistry Lab to isolate zircon grains. The separation process used known physical properties of minerals (e.g., grain size and density) to isolate zircons.

Each sample was broken with a rock hammer into gravel-sized pieces that were processed through a rock crusher 3-4 times. The rock crusher had one stationary and one vibrating ceramic plate which breaks down the sample to fine-grained sand. The samples were sieved using a 500μm mesh and the portion of the sample <500μm was then panned to remove large, and lower density grains. Short, fast movements with the pan suspend low-density sediments (such as organic matter, or quartz and feldspar that have typical densities of 2.65 g/cm^3 and 2.55-2.76 g/cm^3, respectively) allowing the sediments to be emptied into another bucket, while dense, heavy minerals, such as zircon (4.6 g/cm^3) stayed at the bottom of the pan. The dense fraction of the sample was transferred to another container to dry.

A Franz magnetic separator was used to divide magnetic material (e.g., magnetite and hematite) from non-magnetic (or weakly magnetic) minerals (e.g., zircons and mica). Each sample was processed 4 times at varying degrees of amplitude, side tile angles (ST) and back tilt angles (BT): 1) 0.5 amps, 25° ST, 5° BT; 2) 1.0 amps, 25° ST, 5° BT; 3) 2.0 amps, 25° ST, 5° BT; 4) 2.0 amps, 20° ST, 5° BT. This procedure ensured non-magnetic minerals were not removed with the magnetic minerals. Non-magnetic minerals were placed and folded inside of a paper packet to ensure safe transportation.

The final portion of the separation process utilized lithium heteropolytungstates (LST) and Methylene Iodide (MEI) heavy liquids. Zircon has a density of 4.6 g/cm^3, so when a sample was placed in LST (density of 2.85 g/cm^3) and MEI (density of 3.3 g/cm^3) zircons sunk, along with any other minerals with densities greater than the density of the heavy liquid. Separate pieces of weight paper were folded into cones and labeled for the "floats" and "sinks". The heavy liquid was poured into a separation beaker. The sample was poured from the paper packet into the separation beaker and occasionally agitated to allow all heavy minerals to sink to the bottom of the beaker. The sunken minerals were emptied into the "sinks" cone. The separates were washed thoroughly with acetone, left to dry overnight and transferred to a new paper packet for analysis. The remaining "floats" separates were washed out and the beaker was cleaned using acetone.

3.3. Detrital Zircon U-Pb Geochronology Background

Uranium gets trapped inside of a zircon mineral when it is crystallized and begins to decay; lead is excluded from the zircon grain when it crystallizes. It is assumed that any lead detected in the grain came from the decay of uranium. Therefore, the ratio of uranium to lead is related to the crystallization age of each zircon.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) was used to determine the composition of the samples and to calculate the crystallization age of individual zircon grains from the samples (Sláma and Košler 2012; ThermoFisher Scientific). During the LA-ICPMS process, a laser heated the surface of a zircon, which suspended and transported atoms that moved into a chamber containing plasma. The plasma transitioned the atoms to ions before they were funneled through a cone, called a vacuum interface, and sent through a pressurized, curved channel. Based on the specific mass, the ions moved through the curved channel at different, specific locations. Precisely placed microscopic tubes collected ions based on their mass, and calculate the concentration of each isotope for the sample (Goldstien et al. 1997; Gehrels 2014; Xie et al. 2014; ThermoFisher Scientific). For each sample, 250-300 individual zircon minerals underwent LA-ICPMS. The following ions were used to calculate the crystallization age of each zircon mineral: ^{207}Pb, ^{206}Pb and ^{238}U.

4. Results

The U-Pb ages for each sample were reviewed, and ages that were not concordant and yielded >30% standard deviation from the mean age were removed from the analyses. Kernel density estimations (KDE) were created using Microsoft Excel and DZStats for each sample displaying the range of calculated ages and the normalized probability of each age peak based on the 2-sigma error. Significant age peaks were identified relative to intra-sample dispersion of the ages. Age peaks were used to identify the relative contributions of known terrane ages that could have contributed a significant amount of sediment to the Northern Range rocks. There were 10 samples analyzed for U-Pb dating, and they yielded peak age distributions that all generally fall into 3 main age peak patterns. For this thesis, one representative sample from each group was analyzed in-depth and is described in the remainder of this thesis.

4.1. North-Central Amazonian Group: MAR-2020

In total, 246 crystallization ages for single detrital zircon grains were calculated from sample MAR-2020. Sample MAR-2020 yielded ages between 2836.0 ± 55.1 Ma to 533.0 ± 16.8 Ma. There is 1 significant age peak at ~1.9-2.1 Ga. Approximately ~80% of the total grain ages fall within this age peak. Within the entire sample population, ~54.5% of the grain ages correspond to the Central Amazonian tectonic period, ~45% of grain ages correspond to the Eburnean/ North -Central Amazonian tectonic period, and only one grain (533.0 ± 16.8 Ma) is correlated to tectonic events younger than 1.3 Ga (Fig. 5.).

4.2. Pangea and Maya Group: MARBay-2020

In total, 273 crystallization ages for single detrital zircon grains were calculated from sample MARBay-2020. Sample MARBay-2020 yielded ages between 2557.6 ± 30.8 Ma to 172.1 ± 5.5 Ma. There are significant age peaks at 1.0 Ga, 550 Ma and 250 Ma. These ages correspond to the Grenville orogeny, Pan-African Brasiliano orogeny and Maya Black Events/Pangaea Rifting, respectively. Approximately 27% of the grain ages are concentrated between 0.9 and 1.1 Ga, corresponding with the Grenville tectonic events; ~30% of the grain ages are concentrated between 400-650 Ma, corresponding with the Pan African Brasiliano tectonic events; and ~20% of the grain ages are concentrated between 195-300 Ma, corresponding with Maya Black Events and Pangaea Rifting tectonic events. In total, 34% of the grain ages correspond to Grenville tectonic periods and ~14% of the grain ages correspond to the Central Amazonian and Eburnean/North-Central Amazonian tectonic periods (Fig. 5.).

4.3. Grenville Group: SS-2020

In total, 280 crystallization ages for single detrital zircon grains were calculated from sample SS-2020. Sample SS-2020 yielded ages between 2482.9 ± 65.2 Ma to 139 ± 5.5 Ma. There are age peaks present at 1.8 Ga, 1.45 Ga, 1.0 Ga, 450 Ma. These ages correspond to the Central Amazonian orogeny, Grenville orogeny, and Maya Block events, respectively. In total, ~7% of grain ages correspond to Maya Block tectonic events, ~ 4% of grain ages correspond to Pan-African Braziliano tectonic events, ~81% of grain ages correspond to Grenville tectonic events, ~5% of grains correspond to Central Amazonian tectonic events and 2 grains correspond with the Eburnean/North-Central Amazonian tectonic events (Fig. 5).

5. Interpretations

5.1. Maximum Depositional Age and Implications for Northern Range Deposition

One objective of this study was to investigate the age of the Northern Range rocks. The age of the Northern Range rocks is loosely constrained to Late Jurassic-Cretaceous, by only a few deformed ammonite fossils found in the Northern Range. Additional age constraints are also limited due to the complex deformation history of the Northern Range that occurred in the Miocene (Arkle et al., 2021). This study constrains the maximum depositional age of the Northern Range bedrock by using the youngest U-Pb ages of zircons from the samples. Maximum depositional age refers to the oldest period of time sediments could have been deposited to form a sedimentary layer. It is assumed the youngest U-Pb age within a sample correlates to the oldest time period the sediments were deposited before lithification because a zircon mineral must have existed before the formation of the sedimentary layer that it was collected from. Thus, no sedimentary layer can be older than the youngest U-Pb zircon age contained within. The four youngest U-Pb ages from the analyzed samples are 139.0 ± 5.5 Ma (SS-2020), 179.1 ±5.5 Ma (MARBay-2020), 199.5 ± 7.4 (BAR-2020) and 244.1 ± 11.2 Ma (DB-2020). These data suggest the Northern Range rocks were primarily deposited during the Jurassic and could be as young as Early Cretaceous (Valanginian). The dominantly Jurassic ages of these rocks provide an important new lithologic age constraint and also have implications for the provenance of Northern Range Rock.

Throughout the Jurassic-Cretaceous, the proximity of landmasses and the shape of the landscape were rapidly changing due to Pangaea rifting and Caribbean Plate formation. The timing of rifting and uplift directly correlates with sediment provenance because it creates a more holistic view of potential sediment sources at different periods in time. The maximum depositional age provided by this data excludes certain terranes as sediment sources due to the terrane not having been formed yet or lack of transportation methods.

Previous researchers have identified two hypotheses on how the rocks were deposited in the Northern Range. Based on the U-Pb data, the crystallization ages of the Northern Range sediments are all too old to have been sourced from the Caribbean plate. The Caribbean plate formed ~88 Ma and the grain ages determined here (139.0 ± 5.5 Ma to 3136.5 ± 22.9 Ma) are consistently older than grains that would have originated from the Caribbean plate. This means the majority of Northern Range sediments were not accreted during the eastward migration of the Caribbean plate, but rather were deposited from other sources.

5.2. Provenance of Northern Range Rocks

These new U-Pb results were used to identify the terranes that the sediment could be sourced from as well as which terranes contributed the most sediment to the Northern Range, Trinidad. To do this, a paleo-reconstruction of the Caribbean during the Cretaceous (137 Ma) was created after Pindell et al. (2021) (Fig. 6). This time period was chosen based on the maximum depositional age of the samples. During this late Cretaceous period the Northern Range rocks are thought to have been deposited on a passive margin due to the presence of limestone and ammonite fossils (Trenchman 1935; Spath 1939, Imlay 1945, Saunders 1972, Gennero et al. in review; Algar and Pindell 1993). This paleo-reconstruction map was also used to consider the proximity and transportation of sediments.

I propose that the metasedimentary bedrock of the Northern Range likely came from the South American craton. Sample MAR-2020 has one major age peak at ~1.9-2.1 Ga accounting for ~80% of the U-Pb ages from the sample. Whereas samples MarBay-2020 and SS-2020 have significant age peaks that correlate with the Rio Negro-Juruana (1.78-1.55 Ga), Venturi-Tapajos (1.98-1.81 Ga) and Maroni-Itacaiunas (2.25-2.05 Ga) terranes in South America.

Alternatively, there are a few terranes present in Africa and within the Yucatan Block and Suwanee Terrain in present-day North and Central America that have similar ages to the Northern Range ages. However, based on the paleogeography at the time of deposition it is unlikely that sediments would have been transported from these distal regions (Fig. 6). Firstly, sediments would have to travel over the spreading centers in the Atlantic and proto-Caribbean seaway, which are presently ~6,000 km bathymetric barriers (underwater mountains). Additionally, based on hand sample observations, the grains in Northern Range rocks are too coarse to have been wind-blown (~50 μm-2 mm) from Africa or Central America. In contrast, the South American terranes (e.g Venturi-Tapajos and Maroni-Itacaiunas) are in closer proximity to Trinidad's depositional passive margin and have far fewer topographic barriers to overcome. Furthermore, Pindell et al. (2020) identify igneous plutons in the Andean Belt that formed throughout the rifting of Pangea, which could have formed some of the younger rock formations found in the Andean Belt and contributed sediment to the Northern Range (Fig. 6.). Within all grain ages for samples MAR-2020, MarBay-2020 and SS-2020, ~52% of the U-Pb ages correlate with the Andean Belt (Fig. 5 and Fig. 6).

5.3. Transportation Methods of Northern Range Rocks

Based on the new provenance constraints, the arrangement of landmasses found through the paleogeographic reconstruction, and the time of maximum deposition, I propose that the Northern Range Rocks were deposited on a passive margin during the Cretaceous by continental river systems draining South America (Fig. 5. and Fig. 6.). The rivers could have either drained to the north coast of South America wherein the sediments were then carried by ocean currents to Trinidad's passive margin or rivers may have drained directly to the east coast of South America adjacent to modern-day Trinidad. Given that the rocks in the Northern Range are coarse-grained, it is unlikely that the grains would have been able to be transported long distances by ocean currents. It is more likely that sediments were transported by an east-west flowing river system and deposited on the east coast of South America because a river would have been able to transport the coarser grains across the continent.

In addition to the grain size, the U-Pb data distribution patterns suggest a westward migration of a large terrestrial drainage system during the Jurassic and Cretaceous when the Northern Range rocks were deposited. The U-Pb data presented in this research display three general distribution patterns which imply at least three points in time when drainage patterns and sediment contribution differed. These data suggest at one point in time the drainage systems depositing sediment to Trinidad only reached terranes closest to eastern South American coast. At other points in time, the drainage system reaches terranes farther west, wherein the three samples analyzed show an increase in U-Pb ages that match the terranes on the western side of South America. Based on river behavior, these observations are best explained by a headward migration of a river system westward. This conclusion is based on the assumption that SS-2020 is relatively older than MarBay-2020, and MarBay-2020 is relatively younger than MAR-2020. A clearer understanding of the stratigraphy of Trinidad would help to place the relative changes in source regions and depositional patterns.

The high frequency of Grenville aged zircons is significant to understanding the evolution of drainage systems in northern South America. Currently, the Orinoco River is the primary drainage system in northern South America and it drains a significant portion of the northern Andes. Researchers such as Diaz de Gamero (1995) and Xia and Mann (2014) used the occurrence of Grenville U-Pb ages in samples to constrain the timing of changes in the Orinoco River drainage patterns. These studies postulated that the Orinoco River flowed to the north draining into the Maracaibo Basin until the late Miocene when the Caribbean plate uplifted the Eastern Cordillera in Columbia and diverged drainage systems eastward to the present day Orinoco River delta located south of Trinidad in Venezuela (Diaz de Gamero 1995; Xia and Mann 2014). The data presented in this study shows a significant occurrence of U-Pb ages correlating with the Andean Range in the Northern Range rocks, which are constrained in this study to be deposited during the Cretaceous. This may suggest that the Orinoco River began draining to the east earlier than previous research supported. The exact timing of when the Orinoco River began draining to the eastern coast of South America presents a new and important geologic discovery. Although, this will be challenging because of unknown formation ages and the complex deformation history of the Northern Range, which makes it difficult to understand the stratigraphy of the region before deformation.

6. Conclusions

This thesis focused on using detrital zircon U-Pb analysis to determine the provenance of the metasedimentary bedrock of the Northern Range, Trinidad. The major conclusions of this thesis include: 1) a total of 10 samples yielded U-Pb ages ranging from 139.0 ± 5.5 Ma - 3136.5 ± 22.9 Ma; 2) the youngest zircon ages range from 139.0 ± 5.5 Ma - 199.5 ± 7.4, indicating a depositional age of Jurassic-Early Cretaceous (Valanginian); 3) paleogeographic reconstruction indicates sediment was transported from the South American craton by terrestrial drainage systems; 4) high frequencies of Grenville aged zircons suggests the paleo-Orinoco River started draining to the eastern coast of South America ~170 Ma earlier than previous research has suggested. This adds to the understanding of the complex formation of the Northern Range and provides important new insights to how depositional environments changed in the Caribbean and northern South America.

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Figures:

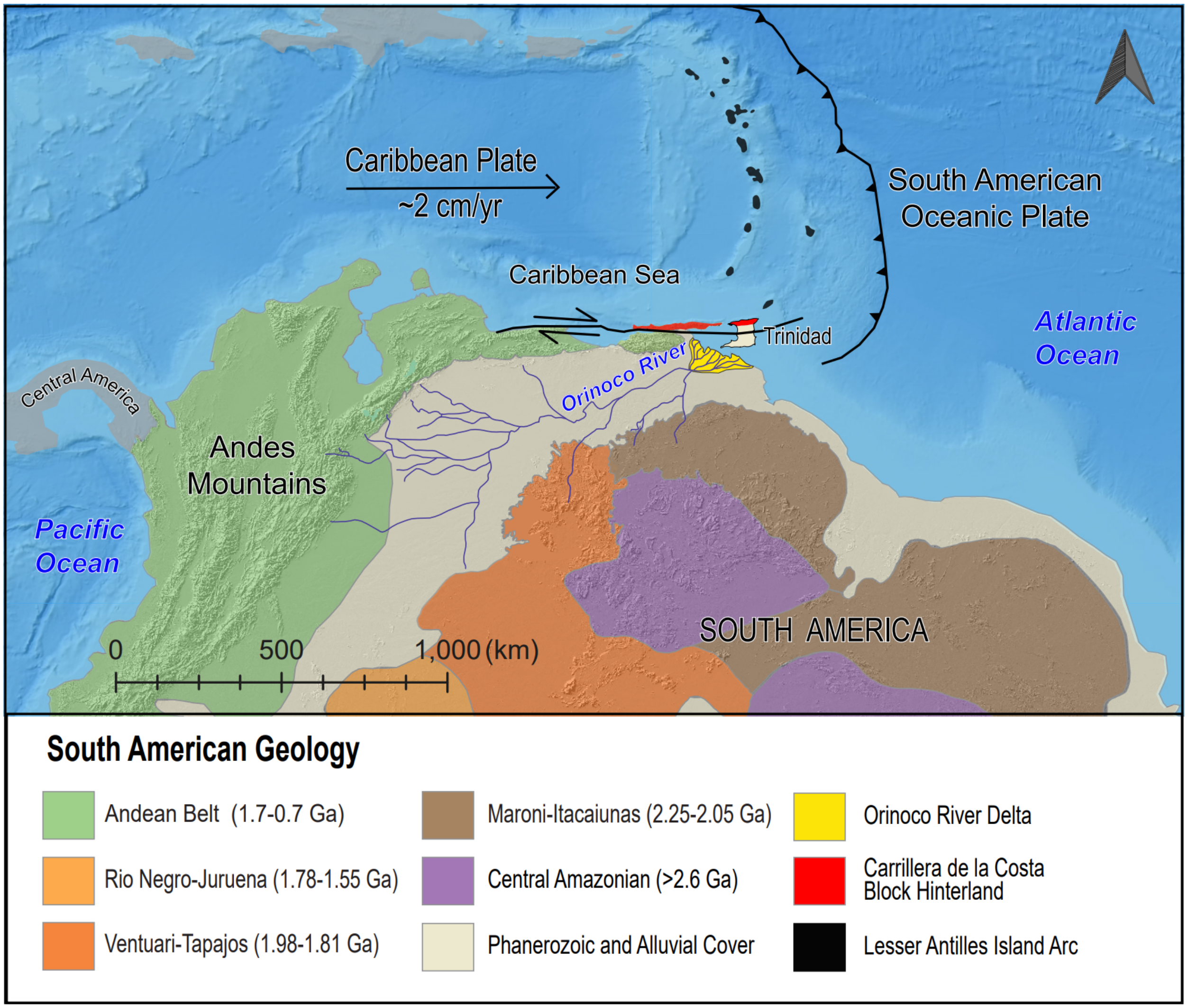


Figure 1. Regional site map of South America and Trinidad. Blue lines show the Orinoco River's modern drainage path. Black lines represent tectonic plate boundaries and fault locations. The geology is based on work from Chew et al. (2010).

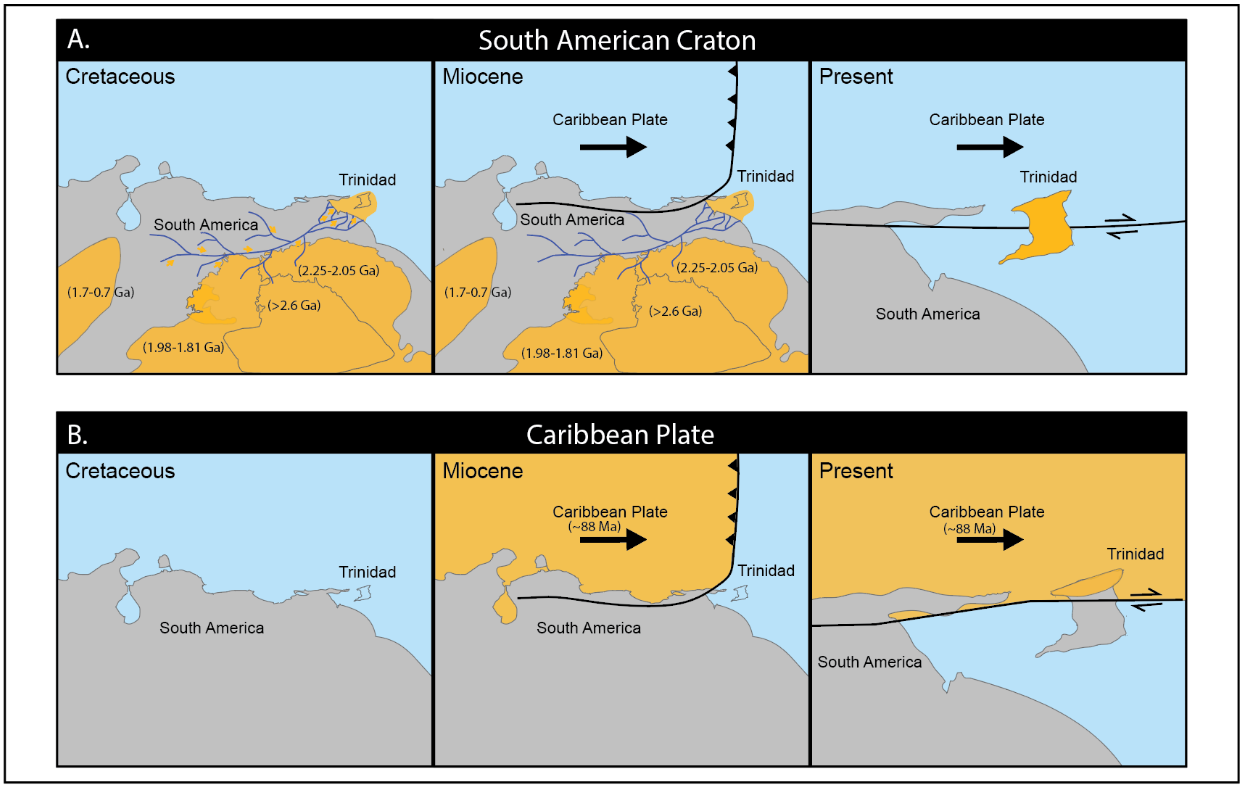


Figure 2. Schematic of two provenance hypotheses. The grey represents the modern-day coastlines of South America and Trinidad. Trinidad is shown as a thin black outline during the Cretaceous and Miocene and represents its approximate location before the island forme d. Thick, solid black lines show the Caribbean Plate boundary; arrows and teeth signify directional movement and the boundary type. Blue lines represent the paleo-drainage systems transporting sediment to the passive margin. The color orange signifies sediments in situ, being transported, and where the sediments were deposited. Figure A. shows the depositional environment if the sediments only came from the South American Craton. Sediments would have been carried by paleo-drainage systems and deposited on a shallow marine continental shelf. During the Miocene when the Caribbean plate was moving dextrally relative to northern South America, the sediment on the shallow marine shelf would have been metamorphosed and uplifted. Figure B. shows the depositional environment if the sediments originated from Caribbean plate accretion.

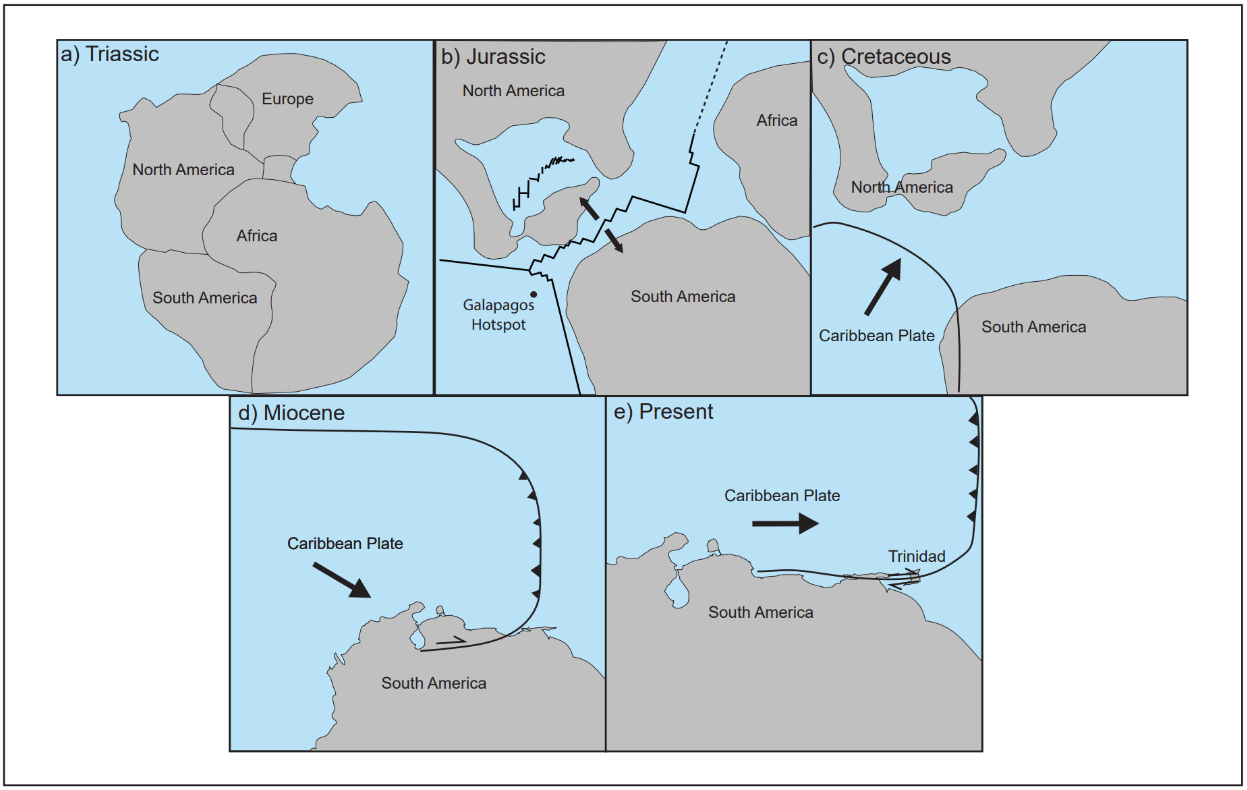


Figure 3. Schematic of tectonic plate movement in the Caribbean. Grey areas show landmasses and their relative locations to each other. Black lines represent spreading centers and outline the Caribbean Plate. Black arrows show the motion of the Caribbean Plate. The Galapagos hotspot identified in image (b) is where the Caribbean plate is hypothesized to originate from. The paleogeography is based on figures from Pindell et al. (2020) and Xie and Mann (2014).

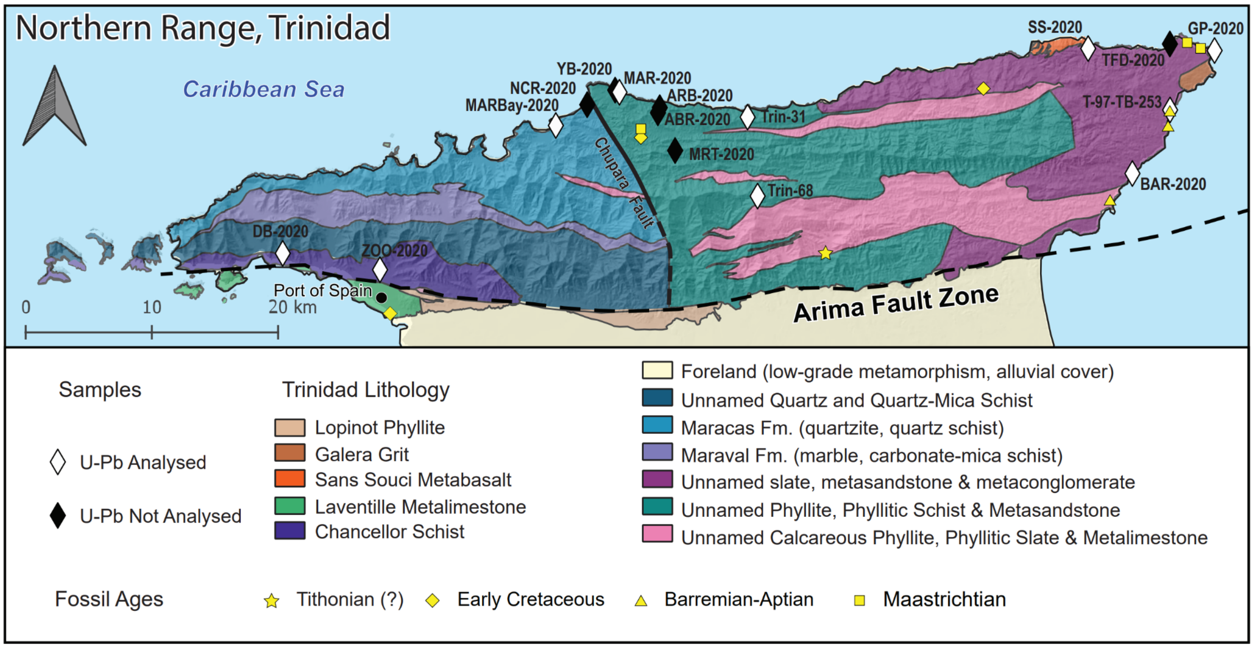


Figure 4. Lithology map of the Northern Range, Trinidad (modified from Gennaro et al. in review). Diamonds show locations of 16 samples from the Northern Range that were collected; 10 of the 16 samples were analyzed for U-Pb age determination. Yellow symbols show 11 fossil locations and their approximate ages from previous research. Black lines represent faults that have been identified throughout the Northern Range.

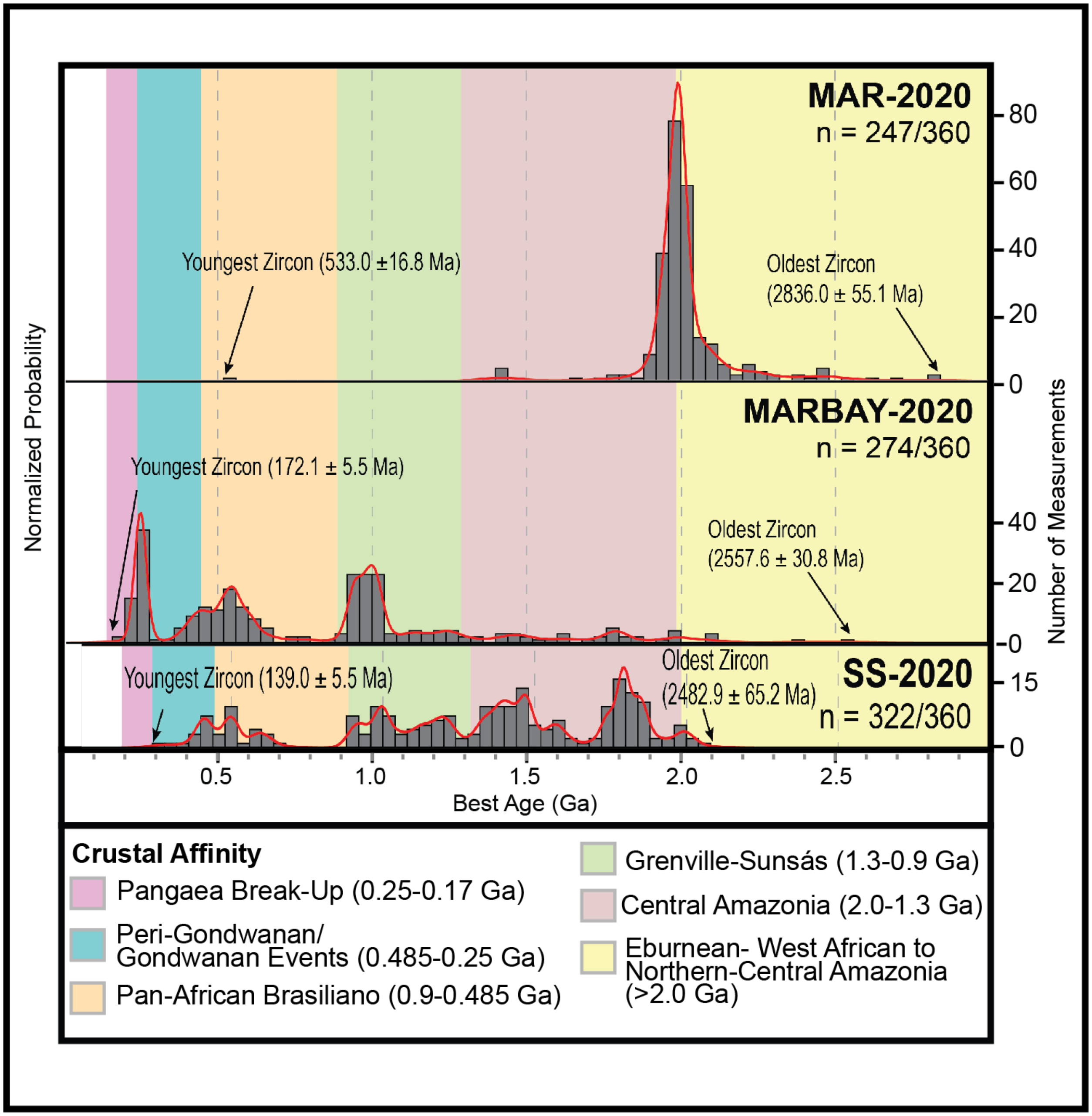


Figure. 5. Kernel Density Estimations (KDEs) for samples MAR-2020, MARBay-2020 and SS-2020. Grey histogram bars show the number of zircons within 40 Ma year bins. The red lines represent the normalized probability. The colors behind the data relate to crustal affinity or significant tectonic events that occurred during the time range.

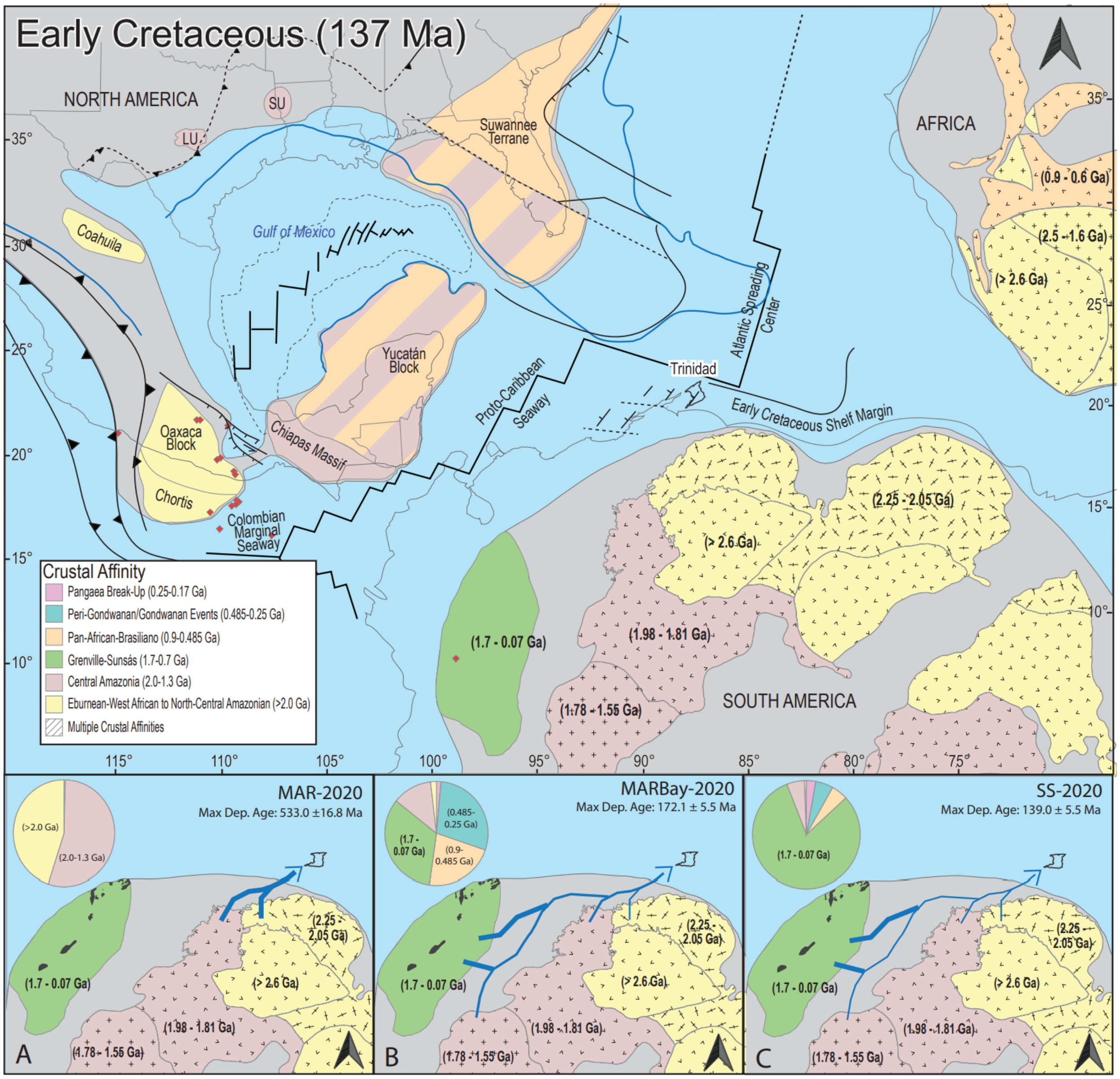
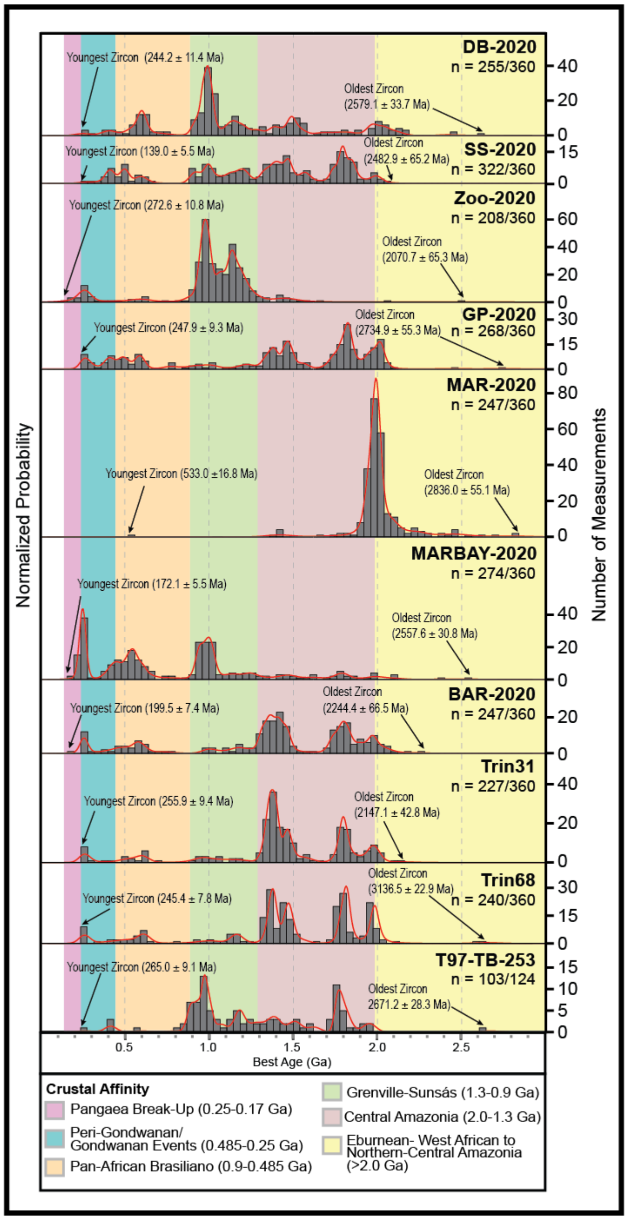


Figure. 6. Maps showing the paleogeography of the Caribbean in the Early Cretaceous (~137 Ma) are based on work by Pindell et al. (2020), Erlich and Pindell (2020), and Weber et al. (2016). This ~137 Ma time was chosen because it encompasses the approximate time period when the sediments, which later become the Northern Range metasedimentary rocks, were deposited on the northern South American passive margin. All Maps: Land (grey) is interpreted to be above ocean (light blue) and terranes are mapped based on crustal affinity (orange, green, pink, and yellow) with regional ages specified on the map. The modern-day coastlines of North America, South America, and Africa (light grey lines) and the approximate edge of the continental crust (blue lines) are shown for reference. Significant faults and spreading ridges (bold black lines) are interpreted in the Early Cretaceous. Igneous occurrences between 137-121 Ma (red diamonds) are based on Pindell et al. (2020). SU, Sabine Uplift; LU, Llano Uplift. Maps (A-C): The distribution of detrital zircon U-Pb ages (pie graphs) from this study are shown with

potential source terranes for three time periods based on samples (MAR-2020, MARBay-2020, and SS-2020) with maximum depositional ages from ~500 Ma to 139 Ma. Note that the relative frequency of Grenville age (green) grains increases in Northern Range bedrock that have younger maximum depositional ages. Inset maps also show terranes that range in age from 700-229 Ma (modified from Xie and Mann, 2014).

Appendix



Appendix 1. Kernel Density Estimations (KDEs) for samples DB-2020, ZOO-2020, GP-2020, BAR-2020, Trin-31, Train-68 and T97-TB-253. These samples were not analyzed in depth. Grey histogram bars show the number of zircons within the specified age range. The red lines represent the normalized probability. The colors behind that data relate to crustal affinity, and significant tectonic events that occurred during the time range.

For raw U-Pb data see supplemental data.