Conjugate Basins, Tectonics and Hydrocarbons (CBTH) – Phase VII (2023-2026)

Submitted
by:

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Project background

The CBTH Project, or "Conjugate Basins, Tectonics and Hydrocarbons Project" began with the financial support of a consortium of oil companies on September 1, 2005 and has operated continuously for the past 18 years within six three-year phases identified as I (2005-8), II (2008-11), III (2011-14), IV (2014-17), V (2017-2020), and VI (2020-2023). This proposal requests funds to continue the consortium for Phase VII that would begin on September 1, 2023, and extend for a three-year period to August 31, 2026. For Phases I-IV, the previous title of the consortium was "Caribbean Basins, Tectonics and Hydrocarbons (CBTH) Project," which was changed to the new title of "Conjugate Basins, Tectonics and Hydrocarbons (CBTH) Project" for Phase V in 2017.

Personnel, project management, and reporting to sponsors for CBTH Phase VII at the University of Houston

As in previous phases of this study (2005-2023), the proposed CBTH Phase VII will be led by Dr. Paul Mann at The University of Houston (UH) and staffed by BS, MS and PhD-level students and post-doctoral researchers at the UH Department of Earth and Atmospheric Sciences who are employed by the CBTH Project. As of May 2023, the staff of the CBTH Project includes Mann, project consultant Jeff Storms, post-doctoral researchers Sharon Cornelius and Jose Gorosabel, PhD students Juan Pablo Ramos Vargas, Kenneth Shipper, Daniella Easley, Ruth Beltran, Mohamed Abdelfatah, and Chesney Petkovsek, and undergraduate student Faith Walton.

Information on all current researchers involved with both the UH group is summarized on the CBTH website: http://cbth.uh.edu/proj_res.php

All personnel will work on various CBTH-funded projects in our expanded study area. Mann and the two post-doctoral researchers also manage the editing of information from the BS, MS and PhD-level students who add to our GIS database.

For annual summaries of project results to sponsors, the CBTH Project hosts a one-day CBTH year-end meeting (YEM) the first week of October of each year of the project (next year-end meeting scheduled for Friday, October 6, 2023). During this day-long meeting, all CBTH researchers will summarize progress for the year in a series of talks. Ample discussion periods with sponsors allows for them to provide input and feedback into the work in their areas of interest - as the work is progressing.

The meeting is held in a hybrid in-person and online mode in order to reach the international sponsors and their affiliates located outside of the Houston area. We also organize a luncheon at each annual IMAGE meeting. This luncheon provides a good opportunity for sponsors to meet with the CBTH group and learn more about our presentations at the meeting, which is the primary conference to present at for most CBTH researchers at UH.

Finally, we can schedule office in-person office visits to those companies and arrange online meetings with companies outside of the Houston area. For these visits we report only on the areas of immediate interest using those CBTH personnel who are actively working in that area. Our company visits can be completed in as little time as 1.5 to 2 hours.

Cost of CBTH Phase VII

The total cost of the three-year CBTH Project Phase VII is $216,000 per sponsor.

We will require a three-year financial commitment from all CBTH Phase VII sponsors with a minimum annual fee of $72,000 US due by August 15 of each year starting with year one of the project in September 2023. These costs include both support for the original work done during the three years of Phase VII as well as curating and maintaining the collective knowledge acquired over the previous 18 years that is organized into our GIS database.

Data sources for CBTH Phase VII

As with the previous CBTH Project phases, CBTH Phase VII data sources include 2D and 3D seismic data, well data, outcrop data, previous publications on the region, and original seismic and well data provided with permission by the sponsoring companies or government agencies.

As we have done over the previous phases of the study, CBTH Phase VII will continue to respect the conditions placed on the use of donated data by our data partners which for CBTH Phase VII will include TGS, Geoex-MCG and PGS. We have successfully worked with these companies since the earliest phases of CBTH and through several periods of industry mergers and acquisitions.

Project deliverables of CBTH Phase VII

The CBTH Phase VII study will integrate the results of our own seismic interpretation and well correlations over the entire region to produce structural, isopach, and paleogeographic maps, which we make available to our sponsors in digital format. Over the past two phases, we have both provided sponsors with the map products but will also include Genesis-Trinity hydrocarbon basin models for the regions discussed in more detail below for each of our focus areas. These quantitative basin models provide our sponsors with an assessment of the maturity of the primary source rocks in our various study areas that are validated using drilling results from those areas. This approach is a time and cost-effective manner for our sponsors to focus their exploration only on areas with high-quality and mature source rocks.

Supporting materials used to constrain these types of basin models are delivered to sponsors for integration into their own databases. These include: (1) an integrated, regularly-updated, and user-friendly GIS database accessible via Geopost and secure FTP; (2) iterative updates of plate tectonic and paleogeographic models built in PaleoGIS and GPlates and posted with documented data sources such as wells and radiometric dates; (3) structural and stratigraphic maps of key seismic surfaces in the region; (4) our original interpretations of seismic data and well data; (5) student and researcher poster and oral presentations from international meetings including GeoGulf, IMAGE, , the HGS Africa meeting, and other meetings held in areas of interest like AAPG ICE; (6) access to the full archive of CBTH publications from 2005 to present, including in-progress publications; (7) access to the CBTH sponsor website, which provides real-time updates on project deliverables throughout the year; and (8) expanded-abstract format annual reports to sponsors for years 1 and 2, and a large-format, map-based atlas for year 3 of Phase VII.

Web-based delivery of map products of CBTH Phase VII

Beginning in 2018, CBTH partnered with Geopost Brazil to develop a web-based

application custom built on the ArcGIS Online platform that enables the sponsors to visualize CBTH annual release data in a web browser that eliminates the need to load the data on their own ArcGIS system. The interface is user-friendly and regularly updated throughout the year.

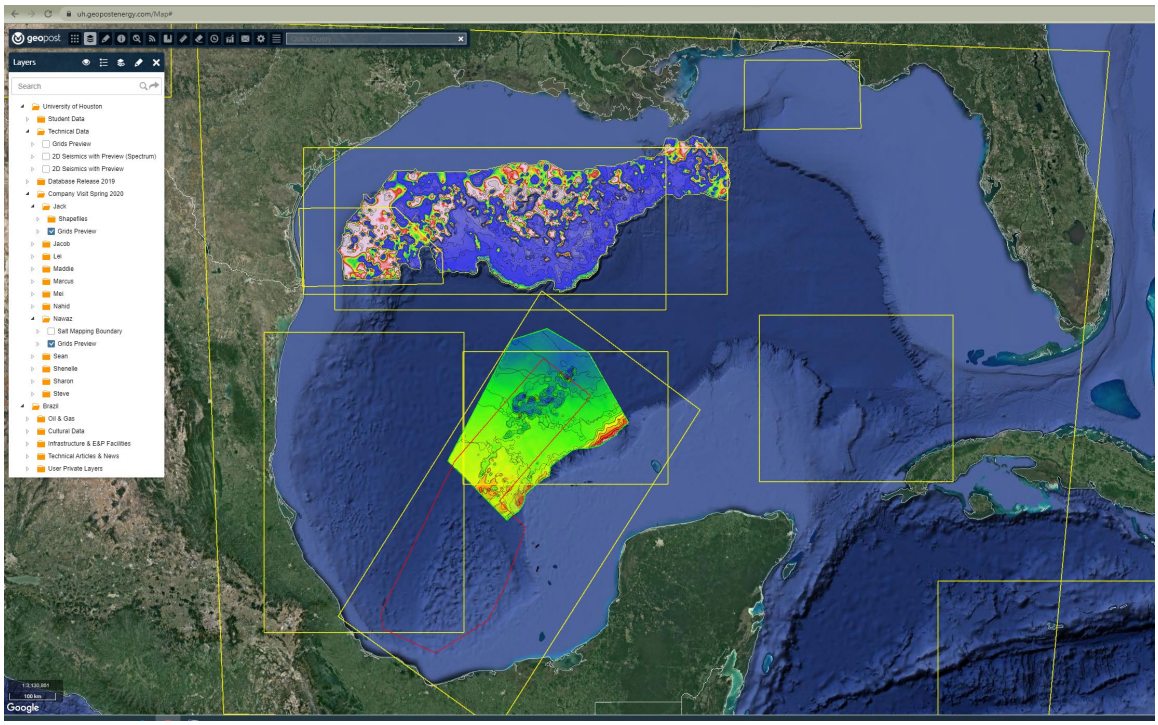

Figure 1. Gulf of Mexico projects with selected surfaces as viewed on the secure Geopost data portal that is accessible only to paid CBTH sponsors.

Over the past six years, CBTH personnel have been working with Geopost to populate our online data portal with all CBTH deliverables going back to Phase I in 2005. During this process, we worked to ensure that all relevant materials are posted in the highest quality possible, often going back to the original thesis and publication files to ensure that figures and maps are posted in the highest resolution available.

We have also worked to eliminate redundancy by consolidating outdated materials, merging datasets, and meticulously comparing materials to our ongoing CBTH Contributions List that is posted on our website. By performing a high level of quality control, workers with CBTH and Geopost are making certain that the new data portal will be the most streamlined version of the CBTH database yet.

The additional costs for the CBTH use of the Geopost online platform are now included in the annual membership cost for the CBTH Project. For continuing sponsors, credentials are generated and distributed by Geopost following each annual sponsor meeting. All current and previous data releases will still be available through our secure FTP.

Figure 1 shows the CBTH Geopost data portal with selected mapped surfaces from our previous study areas in the Gulf of Mexico. With Geopost, a user can open a geographic window, easily display the many categories of CBTH data from this area, and

then download various files including thesis and publication PDFs, raster grids, and vector data including wells, seismic locations, seeps, basement terranes, and much more.

Role of publications in the CBTH Project

As CBTH is a research consortium at the University of Houston, publication plays a key role both the professional development of the post-doctoral researchers and BS, MS and PhD-level students but also by comparing and integrating our work with being done by research groups both at other universities and in large exploration companies.

Our CBTH-supported theses at UH are organized into chapters with each chapter being written as a stand-alone publications, allowing each part of the study to be more comprehensible for the sponsors. Chapters that are submitted for publication go through an intensive peer-review process by experts in their field of study that improves the overall quality of the work.

Topics of continuing regional interest for CBTH Phase VII

Improving our understanding of rifted, conjugate margins.

A major theme continuing into Phase VII is the question of how widely-separated conjugate margins of the Gulf of Mexico and circum-Atlantic exhibit structural and stratigraphic similarities given their original and shared, pre-rift ancestry. Another topic of continuing, regional interest is how volcanic vs. non-volcanic margins can affect the distribution of source rocks and the hydrocarbon potential of margins. Both of these themes are especially relevant for assessing syn- and late-rift source rocks that are potentially shared on both margins.

In the 2022 Elsevier volume titled *Deepwater Sedimentary Systems*, Paul Mann published a synthesis of rifted-passive margins and their conjugates with hydrocarbon comparisons of volcanic vs. non-volcanic margins (Mann, 2022). In this same volume, Md Nahidul Hasan (PhD, 2022) and Mann collaborated on a compilation on most of the well-studied passive-margin foldbelts in the CBTH study area (Hasan and Mann, 2022). At the recent Geogulf meeting Shahriar and Mann (2023) presented a new study using gravity data to reveal the non-volcanic and recessed, non-volcanic rifted margin of Mauritania and its along-strike transition with the protruding volcanic margin of the Guinea Plateau.

We now have completed studies on the conjugate margins of the Gulf of Mexico, including an MS study by Andrew Steier (2018) and PhD studies by Pin Lin (2018), Mei Liu (2021), and Nawaz Bugti (2022).

For the conjugate margins of northeastern South America and central Africa, we have completed PhD studies by Zinecker (2020) and recently began new PhD projects by Kenneth Shipper and Upal Shahriar that are focused on the conjugate margins of northeastern South America (Guyana and Suriname) and west Africa (Guinea Plateau and Mauritania). Recent presentations by our group at the 2023 GeoGulf meeting have compared the source rock distribution, rift style and stratigraphy of these “look-alike” conjugate rift margins (Beltran and Mann, 2023; Shahriar and Mann, 2023; Shipper and Mann, 2023).

We also have studied conjugate margins in Brazil and West Africa in the completed PhD study by Kyle Reuber (2017), Reuber and Mann (2019), and Reuber et al.

(2019) for the Austral South Atlantic, Romito (2021), and Romito and Mann (2022). These South Atlantic conjugate margins are a major focus area for Phase VII given the recent giant discoveries in Namibia as discussed below. Another focus area of conjugate studies is the Equatorial margin of Brazil and West Africa that is also discussed below in greater detail. We also have completed projects by Romito and Mann (2022) and Zhang (PhD, 2021) in northeastern Brazil and in-progress studies by Cornelius (postdoctoral study) and Beltran (PhD student) in the Campos-Santos basins.

Improving regional-scale plate models

Building on the widely-accepted Pacific-derived origin of the Caribbean Plate, Alejandro Escalona (UiS), Ian Norton (University of Texas Institute for Geophysics), and colleagues have finalized the reconstructions and paleogeographic maps the Gulf of Mexico, Caribbean and northern South America. They expanded this iteration of the plate model to include the rest of the Caribbean, Central America, the Gulf of Mexico, and the Andean foreland basins of Colombia and Ecuador. This plate model has been used extensively for paleogeographic compilations including the paper by Escalona et al. (2021a).

A particularly time-consuming effort is to fully integrate the data points in our GIS database with the reconstructed maps to strengthen the plate model and paleogeography. For the Caribbean area, we have addressed this with a published plate reconstruction using PaleoGIS software in AAPG Memoir 123 (Escalona et al., 2021b). This plate model serves as the main template for the paleogeographic maps and for the sponsors to visualize a regional framework.

Recent work by PhD graduate Nawz Bugti (PhD, 2022; Bugti and Mann, 2023) and in-progress studies by PhD students Kenneth Shipper and Juan Pablo Ramos aim to improve the Escalona et al. (2021) Gplates model for the critical sub-areas of the Gulf of Mexico (Bugti, 2022), Guyana-West African conjugates (Kenneth Shipper, PhD in-progress), and the Panama-Colombia collisional area (Juan Pablo Ramos, PhD in-progress), respectively.

Defining continent-ocean boundaries

Defining continent-ocean boundaries (COBs) is critical for deepwater exploration as the abrupt contrast in crustal types can play a major role both the distribution and maturation of source rocks. In his recent review paper on hydrocarbon aspects of rifted-passive margins, Mann (2023) reviews the significance and methods of defining the COB. For this critical task, we rely on a variety of filters of gravity and magnetics data integrated with interpretations of seismic reflection and refraction data.

Regional flexural studies

Another topic of broad regional interest is to apply cross-section restorations and flexural modeling in 2D and 3D to key, hydrocarbon-rich and frontier areas like the Venezuela-Trinidad-Guyana-Suriname margin and northern Moroccan margin.

We previously completed flexural studies in the northern Llanos basin (Campos and Mann, 2015) and the Putumayo basin (Pachon et al., 2020) of Colombia and in the interior of the Caribbean plate (Romito and Mann, 2020). We have one in-progress

flexural study by new PhD student Kenneth Shipper focusing flexural effects on the Guyana-Suriname margin.

New frontiers for Phase VII targeting exploration opportunities

During Phase VII, we are expanding our research CBTH research into four frontier areas: Uruguay/Argentina – Namibia, and Equatorial Guinea – Brazil. The presence of potential source rock intervals has been previously proposed for these areas (Lawrence et al., 2016; Conti et al., 2019; Da Cruz et al., 2021; De Souza et al., 2021). However, none of these previous studies has produced an integrated and quantified basin model for these areas. For these reasons, our goal for Phase VII will be to produce a detailed and integrated basinal model for these areas.

Our modeling approach will include be to use thermal stress modeling, which includes the geothermal gradient of the basin, the thickness and properties of the underlying crust, the organofacies of the source rock intervals, and the paleo-water depths. Thermal stress modeling incorporates a borader array of information on crustal types, sedimentary thicknesses, and heat flow of the basin and contrasts with the alternative approach to basin modeling that relies on a more narrowly-focused, vitrinite-based approach to modeling. Secondary objectives of Phase VII to support the basin modeling effort will include the seismic interpretation of potential source rock intervals, mapping of target horizons, and determination of geothermal gradients.

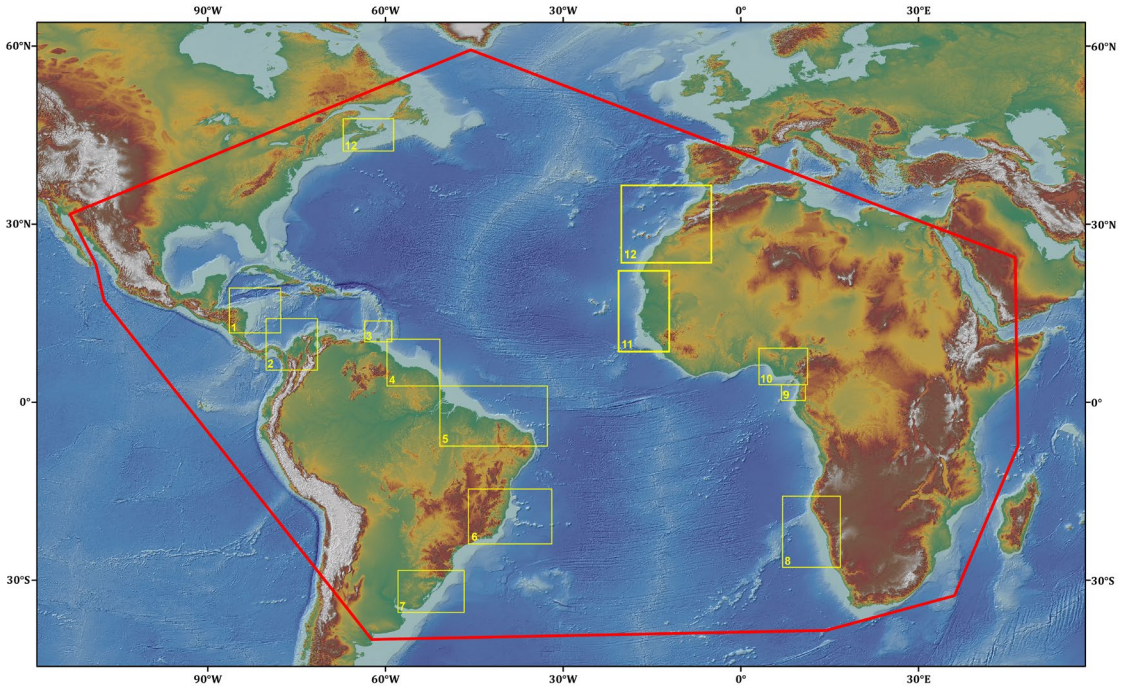

Figure 2. Proposed study areas for Phase VII. The red outline represents the full CBTH study area from Phase I to present. Numbered boxes correspond to the following areas:

1) Nicaraguan Rise, Caribbean Sea
2) Colombian Basin, Colombian and Panamanian Caribbean margins
3) Barbados accretionary prism, Caribbean
4) Guyana-Suriname margin, northeastern South America
5) Equatorial Brazil
6) Campos-Santos basins, Brazil

7) Uruguayan/Argentinian margin
8) Namibian margin, west Africa
9) Equatorial Guinea margin, west Africa
10) Niger Delta, west Africa
11) Mauritania-Guinea Plateau margin, northwest Africa
12) Morocco-Nova Scotia conjugate, northwest Africa and east coast of North America

Focus areas and deliverables, part 1: Nicaraguan Rise

Current level of understanding

Regional mapping and correlation are required to understand the plate evolution of the vast, underexplored area of the western Caribbean Sea (Escalona et al., 2021a,b). We have made considerable progress in our regional study considering that most of the data used dates to the 1970s and has limited depth penetration, especially in submarine carbonate environments. We have supplemented these vintage data with a complete compilation of all vintage exploration well logs available in the Honduran and Colombian sectors, and where available, with data available from modern, deeper penetration seismic surveys. These results are contained in completed PhD dissertations and related publications by Bryan Ott (PhD, 2015), Luis Carlos Carvajal (PhD, 2017), Javier Sanchez (PhD, 2015), Lucia Torrado (PhD, 2018), and Steve Leslie (2020). Three chapters were published from these student theses in *AAPG Bulletin*: Carvajal and Mann (2018), Sanchez et al. (2019) and Torrado et al. (2019) – along with one chapter in *Marine and Petroleum Geology* (Carvajal et al., 2020) and one in *Interpretation* (Leslie and Mann, 2020). We also published one paper on gas hydrates in the deepwater Colombian basin which remains a topic in its early stage of study (Leslie and Mann, 2022).

Luis Carlos Carvajal (PhD, 2017) and Lucia Torrado (PhD, 2018) and have also integrated both data and drilling results from the publicly-available, high resolution, stratigraphic wells completed by the Deep Sea Drilling Project (DSDP), the Ocean Drilling Project (ODP), and from data agreements with Spectrum and PGS. The PhD study by Torrado (2018) and the resulting published study (Torrado et al., 2019) produced regional subsurface maps that encompass the various sectors of the Nicaraguan Rise and then use these maps to continue improving our PaleoGIS plate reconstructions (Escalona et al., 2021). PhD graduate Sean Romito integrated all of these previous studies into regional maps of basement structure that was published by the Geological Society of London in 2020 (Romito and Mann, 2020). We also published one paper on hydrocarbon occurrence in Hispaniola based on a compilation of vintage data (Tillman and Mann, 2020).

Allied researchers at the University of Stavanager (Dr. Sverre Ohm, Andres Cedeño, and Guro Skarstein) have sampled oil seeps and oil wells in Jamaica, Cuba, Barbados, Venezuela, and Suriname to type the geochemical signatures of the various Caribbean oil families in order to relate these families back to a plate model. Cedeño has three published papers on these oil families in AAPG Memoir 123 in the Barbados area (Cedeño et al., 2021a,b) and for the Guyana margin (Cedeño et al., 2021c).

Project deliverables for Phase VII

As we have completed the mapping and evaluated all potential source rocks based on our analysis of vintage well data, our goal is to complete a Genesis-Trinity basin model for the Nicaraguan Rise to better understand the petroleum generation in this basin. This modeling approach involves constructing a full-lithosphere thermal transient model which integrates mapped source rock intervals, downhole temperatures, subsidence, stratigraphy, overburden thickness, source rock characteristics, crustal type, and crustal thickness, then mapping thermal stress trends. Thermal stress is the standard temperature which a source rock must attain at a standardized heating rate of 2 °C/Myr in order to achieve approximately the same extent of kerogen degradation as when heated to the actual temperature in the sedimentary basin.

This basin modeling task will be completed by the accomplishment of the following preliminary objectives:

1) Integration of previous crustal models with mapping of the main stratigraphic sequences and source rock evaluation.
2) Study of the geothermal gradient based on well data (BHTs, Tmax and Vitrinite Reflectance) and previous work.
3) Determination of paleo-water depths.
4) Thermal stress modeling of the basin using the Trinity-Genesis software
5) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Our deliverables for the Nicaraguan Rise would include:

1) Grids of the main sedimentary sequences, including the Top of Basement and Moho.
2) Geochemical characterization of potential source rocks based on well data in the basin and regional data from previous works.
3) 2D basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 2: Colombian Basin, Panama and the Colombian Caribbean margin

Current level of understanding

Over the past few years, we have developed a major regional study in this area to assess the role of the Caribbean "Great Arc" collision in the Late Cretaceous-Paleogene that was followed by the Panama arc collision that we infer began during the Late Miocene (Vence and Mann, 2020). CBTH previously studied the Caribbean "Great Arc" collision in the areas of Venezuela, Trinidad, and Tobago, along with the subsequent Late Miocene Panama arc collision (Bernal-Olaya, 2014; Mata, 2014; Sanchez, 2015).

Current PhD student Juan Pablo Ramos is studying the structure and evolution of the South Caribbean deformed belt, an accretionary complex extending from the Panama-Colombia border to eastern Venezuela, along with the Panama deformed belt in the western Caribbean. His study combines gravity, magnetics, seismic reflection, and seismic tomography in collaboration with Dr. Jonny Wu at the University of Houston.

Work in progress by PhD student Juan Pablo Ramos and reported on at the 2023 GeoGulf meeting focuses on this question using a regional compilation of seismic reflection data, gravity and magnetic data, wells, thermochronologic, and outcrop data (Ramos and Mann, 2023). This study includes Colombia, western Venezuela, and Panama and their offshore areas.

Project deliverables for Phase VII

As mapping is now well underway, the next goal is to complete a Genesis-Trinity basin model for this area. For this purpose, CBTH has exclusive access to 3D and 2D PSDM seismic acquired by the oil industry in the last 10 years. This study will be completed by the accomplishment of these preliminary objectives:

1) Integration of previous crustal models with mapping of main stratigraphic sequences and source rock evaluation. This mapping will allow us to understand the crustal differences found with the amalgamated Caribbean (Romito and Mann, 2020), which would in turn allow us to have a more detailed analysis of the tectonostratigraphy of the basin and the variations in the thermal regime of the basin since the Cretaceous.
2) Study of the geothermal gradient based on well data (BHTs, Tmax and Vitrinite Reflectance) and previous work.
3) Determination of the paleo-bathymetry.
4) Thermal stress modeling of the basin using the Trinity-Genesis software.
5) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Basin modeling for the Colombian Basin, Panama and the Colombian Caribbean margin will be supported and integrated with the presence of oil seeps currently present in the Colombian Basin and into what has been recovered in piston cores that have recovered evidence of a petroleum system with oil from the presence of diamondoids and biomarkers with affinity of a system with liquid hydrocarbons. Furthermore, these results will be integrated with the results obtained in the Nicaraguan Rise in previous work by CBTH to develop a broader picture of the variations in the evolution and crust in the Caribbean Plate and the implications of this tectonic history in the presence of petroleum systems in the region.

Our goal for Phase VII is to produce the following deliverables for the Colombian Basin region:

1) Grids of the main sedimentary sequences, including the Moho, top of basement, Cretaceous, Eocene, Oligocene, Lower Miocene, Middle Miocene, Miocene, Pliocene, and recent.
2) Geochemical characterization of potential source rocks based on well data in the basin and regional data from previous works.
3) 2D mapped basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 3: Barbados accretionary prism

Current level of understanding

It is important to understand the distribution and limits of tectonic terranes and how these contrasting basement blocks control overlying source rock families and structural styles in overlying hydrocarbon-bearing basins as revised for the Caribbean area by Romito and Mann (2020). A key problem in this region is the complex, three-way intersection of disparate tectonostratigraphic terranes in Trinidad that includes the Barbados accretionary prism, the South American passive margin, and the Caribbean arc (Tobago terrane).

In 2018, Shenelle Gomez completed her PhD study on petroleum systems in the Barbados prism area. Shenelle integrated her Spectrum (now TGS) data and mapping results with the mapping results of PhD graduate Tricia Alvarez (Alvarez, 2014; Alvarez et al., 2021a,b; Gomez et al., 2021) and used ION data (now TGS) to provide detailed mapping that encompasses the area of Trinidad and Tobago, Barbados, and the surrounding offshore deepwater areas now being actively explored. Recent MS graduate Bryan Moore (MS, 2022) integrated all of these previous Barbados mapping studies along with a grid of data provide by Geoex-MCG into a basin model to predict areas of more favorable hydrocarbon occurrence.

Project deliverables for Phase VII

As mapping is now well underway for this focus area, our goal is complete a Genesis-Trinity basin model for this area to better understand the hydrocarbon generation in this basin. This will be completed by the accomplishment of the following secondary objectives:

1) Integration of previous crustal models with mapping of main stratigraphic sequences and source rock evaluation.
2) Study of the geothermal gradient based on well data (BHTs, Tmax and Vitrinite Reflectance) and previous work.
3) Determination of paleo-water depths.
4) Thermal stress modeling of the basin using the Trinity-Genesis software.
5) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Our goal for this area for Phase VII is to produce the following deliverables for the Barbados accretionary prism:

1) Grids of the main sedimentary sequences, including the Top of Basement and Moho.
2) Geochemical characterization of potential source rocks based on well data in the basin and regional data from previous works.
3) 2D mapped basin modeling including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 4: Guyana-Suriname margin

Current level of understanding

The Guyana-Suriname margin represents the southern end of Jurassic Central Atlantic opening, yet many questions remain on the induced crustal deformation, paleogeography, thermal history, volcanic flows, or uplift and erosion events due to lacking kinematic indicators. These include magnetic isochrons, gravitational flow lines, and, most importantly, Jurassic-aged well data. To address some of these uncertainties, a 3D crustal model was created by integrating industry-quality 2D seismic reflection data with open-file gravity, sediment thickness, topography, and seismic refraction data. The sedimentary thickness grid was produced by interpreting seven (7) key stratigraphic horizons throughout the Stabroek block and merging with public data. The mapped stratigraphic events have implications for several key features:

1) Thick-skinned, extensional faults underlie and intrude high-amplitude, chaotic and discontinuous interpreted volcaniclastics,
2) The interpreted volcaniclastics lose amplitude to the northwest, which could be indicating a transition to clastic rocks,
3) Overlying accommodation space is filled with dim discontinuous reflectors possibly indicating Jurassic carbonaceous shale
4) The slope of the Cretaceous carbonate platform decreases to the SE, indicating an increase in accommodation space made during the Equatorial Atlantic opening.

Our 3D model indicates a highly-tapered rifted profile that thins from a pre-rift thickness of 40-50 km in the Guiana cratonic shield to a rifted thickness of 6-8 km across a the 170-km-wide, continent-to-ocean transition throughout NW Guyana and beneath the volcanics of the Demerara plateau. The 3D gravity inversion converges to 1 mGal with a 1 km error to its nearest refraction and reflection controls (Shipper and Mann, 2023).

This crustal model can be applied to construct a full lithosphere thermal transient model that can be extended along the entire margin to predict variations in thermal stress and source rock maturity with the Genesis and Trinity modeling packages from Zetaware, Inc. Four calibration wells (Jaguar-1, NCO-1, SPR-1, and AKT-1) with known lithologies (Nifuku et al., 2020; Yang and Escalona, 2011; Casson, 2020; Polo, 2013) were used to estimate the radiogenic heat production of the crust at each well location. The modeling methods used apply a lower boundary condition with a fixed temperature of 1330 °C at the base of the lithosphere and are run in transient mode to allow for the effects of rapid sedimentation.

We performed what we believed to be the first paleowater depth inversion honoring a post-Jurassic, rift tectonic subsidence curve of the passive margin of the Equatorial Atlantic to constrain these rapid sedimentation events by integrating conjugate subsidence trends of public well data on the Guinea plateau. The resulting radiogenic heat production (RHP) values and geothermal gradients at 5.25 km below mudline throughout different crustal provinces are: 1) rifted, non-volcanic necked zone in northwest Guyana (RHP = 46-12 mW/m² and geothermal gradient = 48 °C/km); 2) rifted, volcanic necked zone on the Demerara Plateau of Suriname (16 mW/m²and 14-19 °C/km); and 3) oceanic crust of the deep Guyana basin (0 mW/m²and 5 °C/km).The presence of thin continental crust beneath the volcanic margin and shallower source rocks combine to delay the

timing for oil expulsion from Late Cretaceous to Pleistocene as a result of the decreasing thermal stress from the diminishing RHP. Transient thermal effects above cold oceanic crust related to 1.9 km of Miocene to recent clastic sedimentation results in oil expulsion during the Pleistocene (Shipper and Mann, 2023).

Project deliverables for Phase VII

For the Guyana-Suriname area, the mapping, a 3D crustal model, and 1D basin modeling have been completed (Shipper and Mann, 2023). The outstanding questions to be tested involve uplift and erosional events induced by flexural deformation throughout the dual-phase tectonic history of the Guyana-Suriname basin and its effect on the transient thermal lithosphere. The recent flexural modeling software LIFFE (Lithospheric Flexure with Finite Elements) allows for multiple phases of deformation to be modeled along the same cross-section.

Through our data partner, TGS, we are using an extensive dataset of 2D seismic reflection lines covering the margin from French Guiana to Venezuela which we have used to constrain the crustal structure. Once the transient amount of uplift along each cross-section is modeled, the location can be tied to a reconstruction in GPlates to identify uplifted areas over time. These uplift and erosional events can then be added to any basin model to reduce the uncertainty in source rock maturity as exploration continues further offshore. Having uplift events tied to a tectonic reconstruction may also provide a new perspective into regional migration pathways throughout the basin over time.

Finally, we will provide the following deliverables for the Guyana-Suriname margin:

1) Seven key grids of the main sedimentary sequences, including Basement, Oxfordian, Aptian, Albian, Maastrichtian, Paleogene, and Neogene.
2) Crustal thickness grid from French Guiana to Venezuela.
3) Full lithosphere thermal transient 1D model made by mapping thermal stress with Trinity throughout the Guyana-Suriname basin, then modeling transient flexural uplift from French Guiana to Venezuela.

Focus areas and deliverables, part 5: Equatorial Brazil

Current level of understanding

Despite the presence of oil fields on its west African conjugate margin and within the Ceara and Potiguar basins, the Barrerinhas Basin along the equatorial margin of northern Brazil remains largely unexplored. Drilling activities have been limited to the continental shelf, with only two wells located in deep-water. However, after our preliminary basin analysis, we have identified some key points that identify equatorial Brazil as a promising exploratory area:

1) Good potential source intervals have been identified at the onshore segment of the basin and at adjacent areas (Ceara and Potigual). Specifically, previous works have proposed the presence of Albian-Aptian and Turonian-Cenomanian source rock intervals (Pellegrini and Ribeiro, 2018; Da Cruz et al., 2021; De Souza et al., 2021). Note that these intervals are considered the

main source rock along its west African conjugate margins in Ghana and the Niger Delta.

2) Previous works have also identified and mapped a well-developed Upper Cretaceous turbidite fan system at the Barreirinhas Basin (De Souza et al., 2021), which is considered the main reservoir intervals in this area of Brazil along with its conjugate margin in Ghana, where the Jubilee field has been highly productive.
3) Previous basin modeling for Equatorial Brazil is mainly based on the determination of the geothermal gradient calculated through the Simulated Bottom Reflectors (SBR; Berryman et al., 2015; Da Cruz et al., 2021), that have provided estimates of a geothermal gradient between 15ºC/km (cold case) and 20ºC/km (warm case). This gradient combined with the overburden may support the generation and expulsion of hydrocarbons at the deep-water area.
4) There is a good control of the crustal structure and the continent-ocean boundary (COB; e.g., Castro et al., 2022).

Project deliverables for Phase VII

The main objective of our Phase VII research in Equatorial Brazil will be comprehensive basin modeling to better understand the hydrocarbon generation at the basin. This will be completed through these preliminary objectives:

1) Seismic interpretation and mapping of the main stratigraphic sequences.
2) Identification of potential source rock intervals (Lower? and Upper Cretaceous).
3) Geochemical characterization of potential source rocks, including regional samples to complete the dataset.
4) Integration of previous crustal models.
5) Study of the current geothermal gradient based on well data (BHTs, Tmax and Vitrinite Reflectance).
6) Determination of paleo-water depths.
7) Thermal stress modeling of the basin using the Trinity-Genesis software.
8) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

To complete these objectives, CBTH is collaborating with Brazilian academic researchers at the Universidade Federal do Rio Grande do Norte, who are working on the interpretation and mapping of the basin. This group, led by Professor David Castro, has compiled excellent control of the crustal structure of the basin and has granted CBTH access to the geochemical and well data needed for basin modeling.

We propose the following deliverables for the Barreirinhas Basin at the Brazilian Equatorial Margin:

1) Grids of the main sedimentary sequences, including: Seabed, Miocene, Oligocene, Eocene, Paleocene, Maastrichtian, Turonian, Cenomanian, Albian Aptian?, Break up unconformity, Top of Basement, and Moho.
2) Geochemical characterization of potential source rocks based on well data of the basin and regional data from previous works.

3) 2D mapped basin modeling including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 6: Campos-Santos basins, Brazil

Current level of understanding

The Campos and Santos basins are collectively one of the most prolific hydrocarbon basins in the world. Structurally, this rifted-passive margin is divided into a failed internal rift system (Merluza graben), an external high, and an external rift adjacent to the COB. Since most of the production is limited to the Merluza graben and the external high, CBTH is carrying out the complete mapping of both basins with an emphasis on the basement structure and the main sedimentary sequences.

In addition, our research will include a detailed analysis of the external rift in the northern Campos Basin to better understand the hydrocarbon potential of this frontier area by combining state-of-the-art seismic data with all available wells (Beltran and Mann, 2023).

Project deliverables for Phase VII

The main objective in this focus area will be to complete a comprehensive basin model using the Trinity/Genesis software to better understand the hydrocarbon generation of the external rift (Beltran and Mann, 2022). This will be completed by the accomplishment of the following preliminary objectives:

1) 3D inversion of gravity data for crustal type and thickness.
2) Seismic interpretation and mapping of the main stratigraphic sequences, including the pre-rift, early and late syn-rift, sag, salt, and overburden.
3) Restored cross section for timing and kinematics of the external rift.
4) Identification of potential source rock intervals (Lower? and Upper Cretaceous).
5) Geochemical characterization of potential source rocks with regional data from previous works, including the organofacies classification of the main intervals.
6) Integration of previous crustal models and the refining of the continent-ocean boundary.
7) Study of the current geothermal gradient based on regional available data and previous works on the scientific literature.
8) Determination of paleo-water depths.
9) Thermal stress modeling of the basin using the Trinity-Genesis software.
10) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

To achieve these objectives, we will have access to the following datasets:

1) Depth-converted ION 2D regional SPAN lines
2) Regional magnetic and gravity grids
3) PGS Campos Deepwater GeoStreamer X MultiClient 3D data
4) Additional lines and wells to be requested from ANP as needed.

Finally, we will provide the following deliverables for the Santos-Campos basin in Phase VII:

1) Grids of the main sedimentary sequences for the external rift.
2) Crustal thickness maps of the basin.
3) Geochemical characterization of potential source rocks based on regional data from previous works.
4) 2D mapped basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
5) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 7: Uruguay/Argentina conjugate margin

Current level of understanding

Traditionally, magma-rich margins have been considered as high-risk hydrocarbon exploration targets because most of the syn-rift deposits are volcanic in nature and therefore have no source rock potential (Mann, 2022). However, after the latest discoveries in Namibia (Orange Basin), the exploratory interest has increased for the Pelotas (Brazil), Punta del Este (Uruguay), Salado, and Colorado (Argentina) basins.

Successful plays in Namibia consist of Aptian-Barremian source rock and Cretaceous reservoirs within turbidite fan systems that are sealed by deep-water shales. It should be noted that in this region, the Lower Cretaceous source rock intervals were deposited above the volcanic SDRs. Previous works have addressed the similarities between the conjugate margins of Namibia and South America, proposing the presence of potential source intervals in a similar setting to the Orange Basin. This interpretation is not only based on the structural evolution of both conjugate margins, but is also based on the identification of potential source rocks on seismic data (e.g., Eastwell et al., 2018; Rodriguez et al., 2022).

After our preliminary basin analysis, we have identified some key points that reveal the hydrocarbon potential of this focus area:

1) The structural evolution framework agrees with the deposition of source rock intervals during the Aptian-Barremian, as observed for other South Atlantic basins.
2) Previous works have identified and mapped a well-developed Cretaceous turbidite fan system that might act as potential reservoirs (Zalan et al., 2022).
3) Based on geothermal gradients calculated from the bottom-simulating reflector (BSR) (Morales et al., 2017), previous authors have estimated the generation of hydrocarbons at the South American margin (Uruguay - Argentina).
4) There is a good control of the deeper crustal structure and the continent-ocean boundary from refraction lines and deeply-penetrating seismic reflection transects (Reuber and Mann, 2019).

For this focus area, two out of three wells were drilled in shallow water and only one well was drilled in the deep region of the margin (Raya-1). Unfortunately, the objective of this well was an Oligocene turbidite fan lobe, and the deeper targets, including the Aptian-Albian and Upper Cretaceous ones, remain untested.

Project deliverables for Phase VII

The main objective of this study will be to carry out comprehensive basin modeling to better understand hydrocarbon generation in the basin. This will be completed by the accomplishment of the following secondary objectives:

1) Seismic interpretation and mapping of the main stratigraphic sequences.
2) Identification of potential source rock intervals based on their seismic character and thickness estimation.
3) The geochemical characterization of source rocks based on regional data from available sources, including the organofacies classification of the main intervals.
4) The integration of previous crustal models with new data.
5) The study of the current geothermal gradient based on available data.
6) Determination of paleo-water depths.
7) Thermal stress modeling of the basin with Trinity-Genesis.
8) Identification of the main kitchens and timing for the hydrocarbon generation and expulsion.

To complete these objectives, CBTH is working on a new agreement with TGS to access to seismic data in the region. Finally, we expect to produce the following deliverables for the Uruguaya/Argentina margin:

1) Grids of the main sedimentary sequences and the characterization of the basement and Moho.
2) Geochemical characterization of potential source rocks based on regional data from previous works and available sources.
3) 2D mapped basin modeling for the main potential source rocks, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps for the Aptian-Barremian and Turonian-Cenomanian.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

As exploration activity in this area is currently increasing, deliverables will be subject to the availability of data and the final agreement between CBTH and TGS to access the seismic data.

Focus areas and deliverables, part 8: Namibian margin

Current level of understanding

The Namibian margin has caught the attention of exploration companies since the recent discoveries of the Graff, Jonker, and Venus prospects (Shell and Total Energies, respectively), now considered an emerging sweet spot. As previously mentioned in the last section, the main plays consist of Lower and Upper Cretaceous sediments, with

Aptian-Barremian and Turonian-Cenomanian source rocks and Upper Cretaceous turbidite fan systems as reservoirs.

Project deliverables for Part VII

To better understand the conjugate margins, our objective is to complete the basin modeling for the Namibian margin. This will be achieved by the accomplishment of the following secondary objectives:

1) Seismic interpretation and mapping of the main stratigraphic sequences.
2) Identification of potential source rock intervals based on their seismic character and thickness estimation.
3) The geochemical characterization of source rocks based on regional data from available sources, including the organofacies classification of the main intervals.
4) The integration of previous crustal models with new data.
5) The study of the current geothermal gradient based on available data.
6) Determination of paleo-water depths.
7) Thermal stress modeling of the basin using the Trinity-Genesis software.
8) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

To complete these objectives, CBTH is working on a new agreement with TGS to access seismic data. Finally, we intend to produce the following deliverables for the Namibian margin:

1) Grids of the main sedimentary sequences and the characterization of the basement and Moho.
2) Geochemical characterization of potential source rocks based on regional data from previous works and available sources.
3) 2D mapped basin modeling for the main potential source rocks, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps for the Aptian-Barremian and Turonian-Cenomanian.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

As exploration activity in this area is currently increasing, final deliverables will be subject to the availability of data and the final agreement between CBTH and TGS to access the seismic data.

Focus areas and deliverables, part 9: Equatorial Guinea margin

Current level of understanding

The recent production sharing contracts awarded to Panoro, Kosmos, and GEPetrol, open the door for future exploration in the offshore margin of Equatorial. The Douala and Rio Muni basins were formed after the rifting of the region during the Aptian – Albian period. Their evolution also includes a transitional period during the late Albian until the Turonian and a phase of mature passive margins from the Santonian to

Quaternary, which has led to the accumulation of a thick sedimentary sequence (Lawrence et al., 2016).

As with any frontier basin, the identification and characterization of the main hydrocarbon kitchens is essential for locating hydrocarbon resources. In the case of the Douala and Rio Muni Basins, previous work is limited to the interpretation of widely spaced 2D seismic lines (e.g., Lawrence et al, 2016). However, after our preliminary basin analysis, we have identified a number of key points to consider this region as a promising frontier basin:

1) Both basins have followed a similar evolution to other productive basins in the region.
2) Hydrocarbons have been discovered or identified at different locations surrounding the Douala and Rio Muni basins.
3) Previous works have proposed the presence of potential source rock intervals deposited in a similar setting (Albian-Aptian and Turonian-Cenomanian).
4) Different works have interpreted the rest of the elements of the petroleum system, such as good reservoirs and seals in a well-developed Upper Cretaceous turbidite system.
5) The presence of structural and stratigraphic traps has been already addressed (Lawrence et al., 2016 and references therein).
6) Despite the crustal structure and type, most of the basin was developed over oceanic crust. The generation of hydrocarbons might be possible due to the great accumulation of sediments.

Project deliverables for Phase VII

The main objective of our research in Equatorial Guinea will be to carry out comprehensive basin modeling to better understand hydrocarbon generation in the basin, especially in an oceanic setting. This will be completed by the accomplishment of the following secondary objectives:

1) Seismic interpretation and mapping of the main stratigraphic sequences.
2) Identification of potential source rock intervals (Lower? and Upper Cretaceous).
3) The geochemical characterization of potential source rocks with regional data from previous works, including the organofacies classification of the main intervals.
4) The integration of previous crustal models and the refining of the continent-ocean boundary.
5) The study of the current geothermal gradient based on available data in the region and previous works.
6) Determination of paleo-water depths.
7) Thermal stress modeling of the basin using the Trinity-Genesis software.
8) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Recent 3D surveys acquired by GeoEx MCG in the offshore Douala and Rio Muni basins will be used to interpret the main target horizons and carry out the basin

modeling. This will contribute to a better understanding of hydrocarbon generation in this frontier basins with a limited level of their geological knowledge.

Finally, we expect to produce the following deliverables for the Equatorial Guinea margin:

1) Grids of the main sedimentary sequences, including the Seabed, Base Miocene (uplift unconformity), Top Paleocene, Top of Basement, and Moho.
2) Geochemical characterization of potential source rocks based on regional data from previous works.
3) 2D mapped basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP), and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 10: Niger Delta

Current level of understanding

The Niger Delta is a well-known hydrocarbon province located at the African Equatorial Margin. There are three potential petroleum systems: Tertiary (deltaic), Upper Cretaceous–Paleocene (marine), and Lower Cretaceous (lacustrine). However, only the Tertiary system has contributed to the production in the area. Despite the prolific potential of the Cretaceous in other adjacent basins, the other two petroleum systems have not been proven (Diab et al., 2023).

Project deliverables for Phase VII

The main objective of this study will be to carry out comprehensive basin modeling to better understand the hydrocarbon generation of the Niger Delta including other plays beyond the Tertiary. This will be completed by the accomplishment of the following secondary objectives:

1) Seismic interpretation and mapping of the main stratigraphic sequences.
2) Identification of potential source rock intervals.
3) The geochemical characterization of potential source rocks with regional data from previous works, including the organofacies classification of the main intervals.
4) The determination of the crustal structure and the delineation of the continent-ocean boundary.
5) The study of the current geothermal gradient based on available data in the region and previous works.
6) Determination of the paleo-bathymetry.
7) Thermal stress modeling of the basin using the Trinity-Genesis software.
8) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Finally, we expect to produce the following deliverables for the Niger Delta:

1) Grids of the main sedimentary sequences, including basement and Moho.
2) Geochemical characterization of potential source rocks based on regional data from previous works.

3) 2D mapped basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 11: Mauritania-Guinea Plateau

Current level of understanding

The Mauritania Passive Margin is one of the least explored area of the Mauritania-Senegal-Guinea-Bissau-Conakry (MSGBC) Basins that covers the Western African Atlantic passive margin that includes:

1) The transition from the un-rifted, full-thickness, continental crust of the West African craton.
2) A relatively narrow and tapered zone of thinned continental crust in the coastal, shelf, and slope areas
3) Jurassic oceanic crust in the ultradeep area of the Central Atlantic Ocean that includes the Cape Verde volcanic islands of Miocene to recent age.

The offshore Chinguetti oil discovery in 2001, and the subsequent Banda, Tiof and Tevet Miocene discoveries, all made in the period to 2003, paved the way for the creation of a favorable environment for rapid offshore oil development and the creation of an offshore oil boom. The Mauritania basin was initiated during continental break-up and development of the Central Atlantic Ocean during Middle to Late Jurassic times (Vear, 2005).

Previous CBTH research by Marcus Zinecker (2020) on the Guinea Plateau to the south of the basin indicates that the Guinea Plateau passive margin is volcanic. A comparison between the northwest African passive margin at Mauritania with the Guinea Plateau and its conjugates in Guyana was made to understand the nature of the hydrocarbon exploration potentiality in the Mauritania basin.

We intend to analyze the nature of the Mauritania passive rifted margin using gravity maps and by comparing it with the Guinea Plateau and Guyana, which indicates the apparent absence of a volcanic margin in Mauritania. The nature of the subsurface structure below the Mauritania and the Guinea Plateau is dominated by eastward-tilting normal faults while the subsurface structure beneath conjugates at Guyana and Suriname is dominated by folding below the Albian unconformity. A good correlation of unconformities between the conjugates has been found which indicates the extent of the Central Atlantic breakup unconformity and the Albian unconformity.

Project deliverables for Phase VII

As part of this study, we will use gravity filters to reveal the boundaries of all three crustal provinces along with the localized volcanic margin of the Guinea Plateau and its transition to the non-volcanic margin that characterizes the central and northern Mauritanian margin (Shahriar and Mann, 2023). Key gravity filters to be applied include:

1) Horizontal gradient of upward-continued Bouguer anomaly reveals the extent of high-density and back-stepped frontal slope of the carbonate passive

margin and the transition area between the non-volcanic rifted margin and the volcanic rifted margin of the Guinea Plateau.
2) Vertical gradient of upward continued Bouguer anomaly that reveals a north-south marginal rift trending with the most distal area of thinned, continental crust and fractures within the oceanic crust that terminate at the continent-ocean boundary.
3) Tilt derivative map showing a possible zone of the exhumed mantle that is parallel to the continent-ocean boundary.

Finally, we intend to provide the following deliverables for the Mauritania-Guinea Plateau region:

1) Grids of the main sedimentary sequences.
2) Geochemical characterization of potential source rocks based on regional data from previous works.
3) 2D mapped basin modeling, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps.
4) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

Focus areas and deliverables, part 12: Morocco-Nova Scotia conjugate

Current level of understanding – Morocco

Our completed study of the Moroccan salt basin by Hasan et al. (in review) of the Central Atlantic Ocean interprets a grid of ~8474 line-km of pre-stack, depth-migrated, 2D seismic reflection profiles, publicly-available gravity and well data, and 2D gravity models. Gravity modeling and seismic interpretation reveal a ~750 km elongate, 50-80-km-wide marginal rift that forms a basement low overlying a zone of rifted continental crust. The marginal rift parallels the modern coastline of Morocco and crosscuts the east-northeast orogenic and Mesozoic rift grain of northwestern Africa.

Calibrations of downhole temperature measurements from the Tantan-1 and DSDP-416 offshore wells were used to constrain 1D and map-based thermal maturity models to quantify the hydrocarbon potential of source rocks ranging in age from Triassic to Late Cretaceous. Calibration of downhole temperature measurements from the Tantan-1 within the thinned, continental crust of the marginal rift and the DSDP-416 wells on oceanic crust of the Central Atlantic shows that the geothermal gradient in the marginal rift is 29 °C/km and the gradient in the oceanic crust is 23 °C/km, although variation is possible due to low number of calibration wells.

Modeling shows that the absence of radiogenic heat in the oceanic crust results in relatively lower geothermal gradients and can explain the immaturity to early oil window of source rocks in these deepwater areas. Deeply-buried Triassic and Jurassic source rocks are mature for petroleum generation along the southern ~400 km-long segment of the marginal rift as validated by a compilation of the locations of previous offshore producing wells and shows. Late Cretaceous - Base Cenozoic uplift and erosion of the margin were observed as a major angular unconformity and break in vitrinite reflectance from wells in the offshore area. The absence of Early Cretaceous deltaic deposits in the

northern 350-km-long segment of the northern marginal rift explains why Cretaceous source rocks have remained immature in this area of less sedimentary overburden.

With the publication by Hasan et al. (in review), we have largely completed this study. However, we will continue compiling information from this area for the input data needed for basin modeling. We would also like to compare the Morocco model for the proposed model for its conjugate margin in Nova Scotia.

Current level of understanding – Nova Scotia

Exploration activities at the Nova Scotia margin date back more than 50 years, with 200 wells drilled and the discovery of in place reserves of ~2.1 BBOE (billion barrels of oil equivalent). However, only 29 wells have been drilled since 1998, resulting in only one commercial gas discovery in 1998, the Deep Panuke. Preliminary post-mortem analyses pointed out the extension and maturation of source rock intervals as the main cause of the exploration failure. However, the Play Fairway Analysis (2011), carried out by the Nova Scotian government to assess the exploration potential of the margin notes a lack of geological understanding of the exploration plays as the main reason for the lack of new discoveries. Their post-mortem analysis highlighted some of these causes, possibly related to a bad subsurface image:

1) Bad reservoir properties: Poor porosity due to calcite cements close to Jurassic carbonate platforms or interpreted sandstones resulted carbonate debris.
2) Reservoir outside main delta.
3) Poor reservoir distribution in carbonates.
4) Lack on effective seal at some prospects.
5) Possible migration issues away from kitchen.
6) Poor trap integrity (fault seal).
7) Seismic attributes revealed deep-water wells were drilled away from the main sand fairway.

However, after our preliminary basin analysis, we have defined some key points to consider the Nova Scotia basin as a promising area:

1) Presence of a deepwater and largely unexplored marginal rift adjacent to oceanic crust that is similar to rifts observed in the Gulf of Mexico (Liu, 2021; Hasan et al., 2022). Its conjugate rift in Morocco is salt-filled and has sub-salt wells.
2) Presence of regional source rocks, including:
    a. Lower Cretaceous – Aptian MFS: Type III with an average TOC of 2%.
    b. Upper Jurassic – Tithonian MFS: Type II-III with an average TOC of 3%.
    c. Middle Jurassic – Misaine-Callovian MFS? Evidence limited to one well, unknown extension. Type II-III with an average TOC of 2%.
    d. Early Jurassic – Sinemurian-Pliensbachian-Toarcian? Source complex inferred by analogy to source rocks intervals identified on the conjugate margins (Portugal and Morocco). Type II with an average TOC of 5%.
3) Presence of good reservoirs:

a. Mic Mac Upper Jurassic delta sequence in the Northeast of the margin.
b. Jurassic carbonate banks.
c. Lower Cretaceous delta sequences.
d. Cretaceous deep-water turbidite system.

4) Presence of regional seals of the system.

Project deliverables for Phase VII

Based on our experience on the conjugate Moroccan margin, the main objective for this focus area will be to carry out comprehensive basin modeling to better understand the hydrocarbon generation of the basin, especially for the marginal rifts of the margin. We propose the following preliminary objectives:

1) Use of grids derived from the Play Fairway Analysis (2011), based on the seismic interpretation after the biostratigraphic analysis and the well-seismic tie.
2) Geochemical characterization of source rocks based on available data and previous works.
3) Refinement of previous crustal models and delimitation of the continent-ocean boundary and the marginal rifts.
4) The study of the geothermal gradient based on available data.
5) Determination of paleo-water depths.
6) Thermal stress modeling of the basin using the Trinity-Genesis software.
7) Identification of the main kitchens and timing for hydrocarbon generation and expulsion.

Finally, we expect to produce the following deliverables for Morocco and the Nova Scotian Margin:

1) 2D mapped basin modeling for the main potential source rocks, including standard thermal stress (STS) maps based on constant radiogenic heat production (RHP) and expelled hydrocarbons maps for the Aptian-Barremian and Turonian-Cenomanian.
2) 1D basin modeling of pseudowells, including STS and expelled hydrocarbons.

References Cited

Alvarez, T., 2014, The southeastern Caribbean subduction to strike-slip transition zone: A study of the effects of lithospheric structures and overlying clastic basin evolution and fill: PhD dissertation, University of Houston, 270 p.

Alvarez, T., Mann, P., Vargas, C.A., and Wood, L.J., 2021, Gravity, seismic reflection and tomographic constraints on the subduction to strike-slip transition; southeastern Caribbean Plate boundary zone, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 469–512. https://doi.org/10.1306/13692255M1233848

Alvarez, T., Mann, P., and Wood, L.J., 2021, Tectonic evolution of sedimentary basins

around the arcuate southeastern margin of the Caribbean plate, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 183–238. https://doi.org/10.1306/13692246M1233848

Beltran, R., and Mann, P., 2023, Comparing Early Cretaceous, syn-rift reservoir rocks underlying the slope and ultradeepwater areas of the Campos Basin, offshore Brazil, GeoGulf 2023, Houston, Texas, April 23-25, 2023.

Bernal-Olaya, R. 2014, Tectonostratigraphic evolution of the Sinu accretionary prism and Lower Magdalena forearc basin formed above a shallow-dipping subduction zone, Caribbean margin of Colombia: PhD dissertation, University of Houston, 237 p.

Berryman J., Kearns H., and Rodriguez K., 2015, Foz do Amazonas Basin- A case for oil generation from geothermal gradient modelling. First Break, v. 33, no. 11, p. 91-95.

Bugti, M.N., 2022, Mesozoic plate reconstruction, salt tectonics, and hydrocarbon potential of the western Gulf of Mexico basin, PhD dissertation, University of Houston, 221 p.

Bugti, M.N., and Mann, P., 2023, Regional source rock thermal stress modeling and map-based charge access modeling of the Port Isabel passive margin foldbelt, northwestern Gulf of Mexico, Interpretation, in press.

Campos, H. and Mann, P., 2015, Tectonostratigraphic evolution of the northern Llanos foreland basin of Colombia and implications for its hydrocarbon potential, in C. Bartolini and P. Mann, eds., Petroleum geology and potential of the Colombian Caribbean Margin, AAPG Memoir 108, p. 517–546. https://doi.org/10.1306/13531948M1083651

Carvajal-Arenas, L.C. and Mann, P., 2018, Western Caribbean intraplate deformation, 2: Defining a continuous and active microplate boundary along the San Andres rift and Hess escarpment, Colombian Caribbean Sea, AAPG Bulletin, v. 102, n. 8, p. 1523-1563. https://doi.org/10.1306/12081717221

Carvajal-Arenas, L.C., Torrado, L., Mann, P., and English, J., 2020, Basin modeling of Late Cretaceous / Mio-Pliocene petroleum system of the deep-water eastern Colombian Basin and South Caribbean Deformed Belt: Marine and Petroleum Geology, v. 121, p. 104511. https://doi.org/10.1016/j.marpetgeo.2020.104511

Carvajal-Arenas, L.C., 2017, Hydrocarbon prospectivity of the Nicaraguan Rise and Colombia basin, Western Caribbean Sea: PhD dissertation, University of Houston, 387 p.

Casson, M., Bulot, L. G., Jeremiah, J., and Redfern, J., 2020, Deep sea rock record exhumed on oceanic volcanic islands: The Cretaceous sediments of Maio, Cape Verde, Gondwana Research, v. 81, p. 252– 264. https://doi.org/10.1016/j.gr.2019.11.007

Castro, D. L., Oliveira, D.C., Herrera, D.R.H., Bezerra, F.H.R., Romeiro, M.A.T., Araujo, M.N.C., 2022, Crustal evolution of divergent and transform segments of the Brazilian Equatorial Margin derived from integrated geophysical data: Insights from basement grain heritage, Earth-Science Reviews, v. 232, 104132. https://doi.org/10.1016/j.earscirev.2022.104132

Cedeño, A., Ahmed, M., Escalona, A., and Abrahamson, P., 2021a, Tectono-stratigraphic evolution of the western Barbados accretionary prism and the eastern Tobago

Basin: Implications for petroleum systems, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 649–676. https://doi.org/10.1306/13692261M1233854

Cedeño, A., Ohm, S., and Escalona, A., 2021b, Barbados petroleum and its role in understanding distribution of Cretaceous source rocks in the southeastern Caribbean margin: Insights from an organic geochemistry study, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 441–468. https://doi.org/10.1306/13692254M1233854

Cedeño, A., Ohm, S., Escalona, A., Narain, E., and Jager, J., 2021c, Source rocks in the Guyana Basin: Insights from geochemical investigations of 15 heavy oils from onshore Suriname, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 749–776. https://doi.org/10.1306/13692312M1233854

Conti, B., Perinotto, J.A.J., Veroslavsky, G., Castillo, M.G., Santa Ana, H., Soto, M., Morales, E., 2017, Speculative petroleum systems of the southern Pelotas Basin, offshore Uruguay, Marine and Petroleum Geology v. 83, p. 1-25. https://doi.org/10.1016/j.marpetgeo.2017.02.022

Da Cruz, C., Severiano Ribeiro, H.J.P., Da Silva E.B., 2021, Exploratory plays of the Foz do Amazonas Basin, NW portion, in deep and ultra-deep waters, Brazilian Equatorial Margin, Journal of South American Earth Sciences, v. 111, 103475. https://doi.org/10.1016/j.jsames.2021.103475

De Souza, A.C.B., Nascimento, D.R., Batezelli, A., Filho, F.N., Oliveira, K.M.L., De Almeida, N.M., Normando, M.N., Barbosa, T.H.S., 2021, Geochemical constraints on the origin and distribution of Cretaceous source rocks in the Ceara´ basin, Brazilian Equatorial margin, Journal of South America Earth Sciences, v. 107, 103092. https://doi.org/10.1016/j.jsames.2020.103092

Diab A.I., Sanuade O., and Radwan A.E., 2023, An integrated source rock potential, sequence stratigraphy, and petroleum geology of (Agbada ‐ Akata) sediment succession, Niger delta: application of well logs aided by 3D seismic and basin modeling, Journal of Petroleum Exploration and Production Technology, v. 13, p. 237–257. http://dx.doi.org/10.1007/s13202-022-01548-4

Eastwell, D., N. Hodgson, and K. Rodriguez, 2018, Source rock characterization in frontier basins — a global approach, First Break, v. 36, no. 11, p. 53–60. https://doi.org/10.3997/1365-2397.n0131

Escalona, A., Norton, I., Lawver, L., and Gahagan, L., 2021a, Quantitative plate tectonic reconstructions of the Caribbean region from Jurassic to present, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 239–264. https://doi.org/10.1306/13692247M1233849

Escalona, A., Ahmed, S.S., and Watson, L., 2021b, Late Cretaceous-Pliocene paleogeography of the circum-Caribbean region based on quantitative plate reconstruction and georeferenced databases, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin

Architecture, and Petroleum Systems, AAPG Memoir 123, p. 513–538. https://doi.org/10.1306/13692256M1233849

Gomez, S., 2018, Tectonostratigraphic evolution of the Barbados accretionary prism and surrounding sedimentary basins within the Southeastern Caribbean-South plate boundary zone, PhD dissertation, University of Houston, 247 p.

Gomez, S., Mann, P., Alvarez, T., and Krueger, A., 2021, Tectono-stratigraphic evolution of the Barbados accretionary prism and surrounding sedimentary basins within the southeastern Caribbean, arcuate, strike-slip-to-subduction transition zone, in C. Bartolini (ed.), South America-Caribbean-Central Atlantic Plate Boundary: Tectonic Evolution, Basin Architecture, and Petroleum Systems, AAPG Memoir 123, p. 265–316. https://doi.org/10.1306/13692248M1233850

Hasan, M.N., 2022, Tectonostratigraphy, structural styles, and hydrocarbon prospectivity of the rifted-passive margins of the southern Gulf of Mexico and the Atlantic margin of Morocco, PhD dissertation, University of Houston, 265 p.

Hasan, M.N., and Mann, P., 2022, Deepwater passive margin foldbelts, in J. Rotzien, C. Yeilding, R. Sears, F.J. Hernández-Molina, and O. Catuneanu (eds.), Deepwater Sedimentary Systems: Science, Discovery, and Applications, Elsevier, p. 119-147. https://doi.org/10.1016/B978-0-323-91918-0.00016-5

Hasan, M.N., Mann, P., and Powney, M., in review, Tectonic controls on source rock thermal maturity within the Triassic-Jurassic marginal rift bordering the Central Atlantic Ocean in northern Morocco, submitted to Basin Research.

Hasan, M.N., Pepper, A., and Mann, P., 2022, Basin-scale estimates of thermal stress and expelled petroleum from Mesozoic-Cenozoic potential source rocks, southern Gulf of Mexico, Marine and Petroleum Geology, 105995. https//doi.org/10.1016/j.marpetgeo.2022.105995

Lawrence, S.R., Beach, A., Jackson, O., Jackson, A., 2016, Deformation of oceanic crust in the eastern Gulf of Guinea: role in the evolution of the Cameroon Volcanic Line and influence on the petroleum endowment of the Douala-Rio Muni Basin, Petroleum Geoscience of the West Africa Margin, Geological Society, London, Special Publications, v. 438, p. 7-26. https://doi.org/10.1144/SP438.7

Leslie, S., 2020, Structure, stratigraphy, and hydrocarbon potential of the Colombian Caribbean margin and tsunamigenic hazards in the western Caribbean Sea and the South China Sea, PhD dissertation, University of Houston, 192 p.

Leslie, S., and Mann, P., 2020, Structure, stratigraphy, and petroleum potential of the deepwater Colombian basin, offshore northern Colombia, Interpretation, v. 8, n. 4, p. 1N-T1095. https://doi.org/10.1190/INT-2020-0028.1

Leslie, S., and Mann, P., 2022, Distribution and character of bottom simulating reflections in the western Caribbean offshore Guajira Peninsula, Colombia, in J. Mienert, C. Berndt, A. Tréhu, A. Camerlenghi, and C.-S. Liu (eds.), World Atlas of Submarine Gas Hydrates in Continental Margins, p. 333-341. https://doi.org/10.1007/978-3-030-81186-0

Lin, P., 2018, Crustal structure and tectonostratigraphic evolution of the eastern Gulf of Mexico basin, PhD dissertation, University of Houston, 154 p.

Liu, M., 2021, Mesozoic rift evolution and crustal structure of the Gulf of Mexico Basin from integration of multiple geological and geophysical datasets, PhD dissertation, University of Houston, 219 p.

Mann, P., 2022, Crustal structure and tectonostratigraphy of rifted-passive margins with applications for hydrocarbon exploration, in J. Rotzien, C. Yeilding, R. Sears, F.J. Hernández-Molina, and O. Catuneanu (eds.), Deepwater Sedimentary Systems: Science, Discovery, and Applications, Elsevier, p. 83-117. https://doi.org/10.1016/B978-0-323-91918-0.00018-9

Mata, O., 2014, Cenozoic Structure, Stratigraphy, and Paleogeography of the Lower Magdalena Basin, Colombia: MS thesis, University of Houston, 177 p.

Moore, B., 2022, Subsurface structure, stratigraphy, and hydrocarbon basin modeling of the Barbados Accretionary Prism, MS thesis, University of Houston, 117 p.

Morales E., Chang H.K., Soto M., Veroslavsky G., Conti B., Santa Ana H., Santos Corrêa F.Morales et al., 2017, Speculative petroleum systems of the Punta del Este Basin (offshore Uruguay), Brazilian Journal of Geology, v. 47, no. 4, p. 645-656. https://doi.org/10.1590/2317-4889201720170078

Nifuku, K., Kobayashi, Y., Araki, Y., Ashida, T., and Taniwaki, T. 2021, Overpressure evolution controlled by spatial and temporal changes in the sedimentation rate: Insights from a basin modelling study in offshore Suriname, Basin Research, v. 33, p. 1293– 1314. https://doi.org/10.1111/bre.12514

Ott, B., 2015 Cretaceous-Cenozoic tectonostratigraphic evolution of the Nicaraguan Rise based on seismic reflection, wells, and potential fields data: PhD dissertation, University of Houston, 262 p.

Pachon-Parra, L., Mann, P., and Cardozo, N., 2020, Regional subsurface mapping and 3D flexural modeling of the obliquely converging Putumayo foreland basin, southern Colombia: Interpretation, v. 8, n. 4, p. 1N-T1095. https://doi.org/10.1190/INT-2020-0021.1

Pellegrini, B., and Ribeiro, H.J.S., 2018, Exploratory plays of Pará-Maranhão and Barreirinhas basins in deep and ultra-deep waters, Brazilian Equatorial Margin, Brazilian Journal of Geology, v. 48, p. 485-502. https://doi.org/10.1590/2317-4889201820180146

Play Fairway Analysis (2011). ATLAS Play Fairway Analysis Offshore Nova Scotia Canada. An Integrated Project for: Nova Scotia – Department of Energy June 2011. https://energy.novascotia.ca/oil-and-gas/offshore/play-fairway-analysis/analysis

Polo, T. 2013. Case study analysis of geological operations lessons learned. Repsol, https://www.iqpc.com/media/8767/29129.pdf

Ramos, J.P., and Mann, P., 2023, Direct hydrocarbon indicators and basin modeling of late Cretaceous source rocks in the the deepwater area of Panama and Colombia, Caribbean Sea, GeoGulf 2023, Houston, Texas, April 23-25, 2023.

Reuber, K., 2017, Crustal structure and Mesozoic tectonic evolution of conjugate volcanic passive margins of the south-central and South Atlantic Oceans: PhD dissertation, University of Houston, 207 p

Reuber, K. and Mann, P., 2019, Control of Precambrian-to-Paleozoic orogenic trends on along-strike variations in early Cretaceous, continental rifts of the South Atlantic, Interpretation, v. 7, n. 4, p.1-24. https://doi.org/10.1190/INT-2018-0257.1

Reuber, K., Mann, P., and Pindell, J., 2019, Hotspot origin for asymmetrical, conjugate volcanic margins of the austral South Atlantic Ocean as imaged on deeply-penetrating seismic reflection images, Interpretation, v. 7, n. 4, p.SH71-SH97.

https://doi.org/10.1190/int-2018-0256.1
Rodriguez, K., Hodgson N., Rodriguez P., and Gristo P., 2022. Conjugate Pelotas and Orange Basins Source Rock Evaluation. South Atlantic Conjugate Margins Virtual Technical Symposium December 2022.
Romito, S., 2021, Crustal structure, tectonostratigraphy, and hydrocarbon potential of the terranes underlying the Caribbean Plate and the Camamu-Almada rifted passive margin of northeastern Brazil, PhD dissertation, University of Houston, 288 p.
Romito, S., and Mann, P., 2020, Tectonic terranes underlying the present-day Caribbean plate: Their tectonic origin, sedimentary thickness, subsidence histories, and regional controls on hydrocarbon resources, in Davison, I., Hull, J., and Pindell, J., eds., The Basins, Orogens, and Evolution of the Southern Gulf of Mexico and Northern Caribbean, Geological Society, London, Special Publication 504, p. 343-377. https://doi.org/10.1144/SP504-2019-221
Romito, S., and Mann, P., 2022, Crustal structure of the Camamu-Almada margin along the northeastern rift segment of Brazil from an integration of deep-penetration seismic reflection profiles, refraction, and gravity modeling, Tectonics, v. 41, no. 9, e2021TC007157. https://doi.org/10.1029/2021TC007157
Sanchez, C.J., 2015, Comparison of Late Cretaceous-Cenozoic deformation and basin formation along the northwestern Caribbean plate boundary on the Honduran borderlands-Nicaraguan Rise and southeastern Caribbean plate boundary in Colombia: PhD dissertation, University of Houston, 229 p.
Sanchez, J., Mann, P., Carvajal-Arenas, L. C., and Bernal-Olaya, R., 2019, Regional transect across the western Caribbean Sea based on integration of geologic, seismic reflection, and magnetic data, AAPG Bulletin, v. 103, p. 303-343. https://doi.org/10.1306/05111816516
Shahriar, U., and Mann, P., 2023, Using gravity filters to reveal the non-volcanic and recessed rifted margin of Mauritania and its along-strike transition with the protruding volcanic margin of the Guinea Plateau, GeoGulf 2023, Houston, Texas, April 23-25, 2023.
Shipper, K., and Mann, P., 2023, Basin modeling of the Guyana margin: Does the continent-ocean boundary mark an outer limit for deepwater exploration?, GeoGulf 2023, Houston, Texas, April 23-25, 2023.
Steier, A., 2018, Jurassic-Cretaceous stratigraphic and structural evolution of the northern Yucatan margin, Gulf of Mexico basin, MS thesis, University of Houston, 91 p.
Tillman, T. and Mann, P., 2020, Regional hydrocarbon potential of the northeastern Caribbean based on integration of sediment thickness and source rock data, in Davison, I., Hull, J., and Pindell, J., eds., The Basins, Orogens, and Evolution of the Southern Gulf of Mexico and Northern Caribbean, Geological Society, London, Special Publication 504, p. 401-436. https://doi.org/10.1144/SP504-2019-244
Torrado, L., 2018, Tectono-stratigraphic controls on petroleum system elements in passive margin settings: Studies of the western Nicaraguan Rise and Foz do Amazonas basin, Brazil, PhD dissertation, University of Houston, 264 p.
Torrado, L., Carvajal-Arenas, L. C., Sanchez, J., Mann, P., and Silva-Tamaya, J. C., 2019, Late Cretaceous-Cenozoic sequence stratigraphic and paleogeographic controls on petroleum system elements of the Nicaraguan platform, western

Caribbean Sea, AAPG Bulletin, v. 103, no. 8, p. 1925-1962. https://doi.org/10.1306/12191817068

Vear, A., 2005, Deep-water plays of the Mauritanian continental margin, Geolgoical Society of London, Petroleum Geology Conference Series, v. 6, p. 1217-1232. https://doi.org/10.1144/0061217

Vence, E., and Mann, P., 2020, Subsurface basement, structure, stratigraphy, and timing of regional tectonic events affecting the Guajira margin of northern Colombia, Interpretation, v. 8, n. 4, p. 1N-T1095. https://doi.org/10.1190/INT-2020-0016.1

Yang, W., and Escalona, A., 2011, Basin modeling and source rock evaluation in the Guyana basin, First Break, v. 29, p. 59-69. https://doi.org/10.3997/1365-2397.2011030

Zalan P.V., Etherington R., Cvetkovic M.et al., 2022. Pelotas Basin in Brazil – A Fantastic Analogue to the Orange Basin in Namibia. GEO ExPro 5-2022.

Zhang, H., and Bird, D., 2022, Detecting hypogenic karst features in the northeastern Delaware Basin, west Texas: Applications of Full Tensor Gradient (FTG) gravity data, Journal of Applied Geophysics, 104889. https://doi.org/10.1016/j.jappgeo.2022.104889

Zinecker, M., 2020, Structural and Stratigraphic Evolution of Three Mesozoic, Rifted-Passive Margins: Guinea Plateau, Demerara Rise, and the Southeastern Gulf of Mexico, PhD dissertation, University of Houston, 302 p.