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Caribbean Basins, Tectonics, and Hydrocarbons

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Table of Contents

Schedule Of CBTH Presentations

AAPG Annual Convention & Exhibition
Morial Convention Center - New Orleans, LA

Monday, April 12	
Alvarez and Mann. Tectonic habitat of hydrocarbons in the deep- and ultra-deepwater frontier areas of Trinidad and Tobago	8:30 am to 12:00 pm Exhibition hall
Punette et al. Tectonic and eustatic controls on the origin of shelf sands and associated facies,offshore NCMA area of Trinidad and Tobago	
Rodriguez et al. Effects of Laramide foreland basin tectonics on structure, subsidence, and hydrocarbons of the Mexican sector of the Gulf of Mexico	
Whitehill et al. Tectono-stratigraphic framework of the western Maracaibo block, Colombia-Venezuela: Implications for hydrocarbon exploration	
Lunch with Sponsors	12:00 pm to 1:15 pm TBA
Emmet and Mann. Early Cenozoic rift inversion: key to understanding the structural framework and petroleum potential of the Nicaraguan Rise	4:25 pm Room 252/253/254
Tuesday, April 13	
Bingham et al. Creaming curves and discovery trends of 5 basins from the Gulf of Mexico to Northern South America	1:15 pm to 5:00 pm Exhibition Hall
Vargas et al. Morphologic expression of the accretion process in the SW margin of the Pacific of Colombia interpreted by means bathymetric high-resolution data	
Wenxiu et al. Tecton-stratigraphic evolution of the continental shelf of Guyana and Suriname	
Wednesday, April 14	
Bernal and Mann. Characterizing the structural style and age of the Romeral fault zone in the subsurface of the Lower Magdalena basin, Colombia	8:30 am to 12:00 pm Exhibition hall
Campos and Mann. Tectonic influence of the Cordillera Oriental thrust salient on the shortening and subsidence history of the Llanos foreland basin of Colombia	
Mann et al. Tectonic setting and hydrocarbon trendology of a reported 7-8 TCF giant gas Discovery, eastern Gulf of Venezuela	11:10 am Room 243/244/245

Tectonic Habitat of Hydrocarbons in the Deep- and Ultra-deepwater Frontier Areas of Trinidad and Tobago

Tricia Alvarez [1] *and Paul Mann* [2]

The Trinidad deepwater and ultra-deepwater provinces together form a structurally complex, frontier basin adjacent to the prolific and well studied Columbus Basin shelf province that has produced over 3 billion barrels of oil and 22 trillion feet of gas. The Trinidad deep and ultra-deepwater area includes the southern termination of the Barbados accretionary prism (BAP). The only commercial hydrocarbon discovery to date in the BAP is located in southern Barbados where 9 million barrels of oil have been produced from the Woodbourne field. The deepwater area remains largely underexplored withonly eight dry exploration wells and the ultra-deepwater area remains undrilled to date.

We use a grid of 2D seismic lines and wells to construct regional transects traversing the Columbus Basin shelf, slope, deepwater and utra-deepwater basins. Transects restore deformation related to three tectonic belts that converge in the deepwater and ultra-deepwater area of Trinidad: 1) Northeast-striking and strongly curving folds, thrusts and deformed shale diapirs of the BAP, 2) East-northeast-striking folds, thrusts and strike-slip faults including imbricated thrust sheets of the Central Range-Darien Ridge uplift and Southern Basin provinces, 3) Northwest-southeast-striking regional and counter-regional listric faults which sole out along the top of the Cretaceous carbonate unit.

Seismic interpretation of the seafloor and shallow horizons illustrate a 50-km-wide, northeast-trending transition zone between normal faults of late Neogene age in the west and thrusts and normal faults of late Neogene age in the east. The transition from extension to compression coincides with an increase in the eastward dip of the undulating top Cretaceous surface at depths of 12.5 to 18.8 km from 5° to 23°. This change in top Cretaceous dip also aligns with a 40-80 km wide, northwest-trending, lineated gravity low that parallels other fracture zones in the down-going oceanic crust of the Atlantic Ocean. We show how the configurations of the down-going Atlantic plate affect the three tectonic provinces that merge in the deep and ultra-deepwater area and explain how these structures are affecting the habitat of deepwater hydrocarbons.

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Characterizing the structural style and age of the Romeral fault zone in the subsurface of the Lower Magdalena basin, Colombia

Roccio Bernal and Paul Mann

The Romeral fault zone (RFZ) crops out over a distance of 1200 km from Ecuador to northwestern Colombia where the fault trace is buried beneath 2.8 km of Lower Miocene and younger rocks of the Lower Magdalena basin (LMB). The Romeral fault is widely accepted as the main fault boundary separating South American continental crust and accreted Caribbean oceanic plateau crust now exposed in the Cordillera Occidental of western Colombia. We use 750 km of seismic data, 15 wells and compilation of previously published gravity and aeromagnetic data to better define the trace and history of this important crustal boundary. This data from the LMB show that the 157-km-long continuous subsurface RFZ, forms a 700-m-wide alignment of structural highs as defined by the top of the Pre- Tertiary basement. Seismic and well data show that the fault zone creates an elongate high with 200 m vertical relief that became emergent during Late Eocene- Early Oligocene? shedding clastic wedges to the east and west, that were subsequently buried by Miocene and younger clastic rocks linked to the uplift and erosion of the northern Andes. Traces of the RFZ do not penetrate sedimentary rocks younger than Lower Miocene in age and indicate that this segment of the RFZ became inactive at this time. Seismic data show that east-dipping reverse faults adjacent to the Romeral fault are presently active and localize NE- SW trending, fold axes that deform the youngest rocks of the LMB. We propose that this NE-SW shortening is part of a broad region of folding linked to shallow subduction along the South Caribbean deformed belt and collision of the Panama arc beginning about 12 Ma.

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Creaming Curves and Discovery Trends of 5 basins from the Gulf of Mexico to Northern South America

Lisa Bingham[1]*, Alejandro Escalona*[1]*, Paul Mann*[2]

The ideal discovery path of a basin begins with the most profitable well continuing to the least profitable without drilling dry. While this may be the ideal discovery path, it is not very realistic. The path, which when plotted as a graph of cumulative reserves versus total number of wildcats, is seen to follow “steps”, or more commonly, a “creaming curve." In general, these "steps" can be explained as giant field discoveries. We have taken three giant-producing areas, the Villahermosa Uplift in Mexico, the Maracaibo basin and the Eastern Venezuela basin in Venezuela and looked at the creaming curves for those petroleum systems. We compared these data to creaming curves for limited giant producing areas of the Guajira Peninsula in Colombia and northern offshore of Trinidad and the non-giant producing area of the Guyana-Suriname continental. We have compiled data from public databases, such as the USGS, and the Caribbean Basins, Tectonics and Hydrocarbons project. Using ESRI ArcMap, we have attempted to show discovery trends by way of geologic location and technological advances. This information may be used to predict more potential areas of discovery.

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Tectonic influence of the Cordillera Oriental thrust salient on the shortening and subsidence history of the Llanos foreland basin of Colombia.

Henry Campos [1] *and Paul Mann* [2]

In contrast to foreland basins of Venezuela that show a west-to-east progression in subsidence related to the time-transgressive and oblique collision of the Caribbean arc, the Llanos foreland basin of eastern Colombia shows a major pulse of Middle Miocene subsidence taken as the onset of the foreland basin in response to shallow subduction and collision events along the Pacific margin of western Colombia. Middle Miocene to recent, east-west shortening, driven in part by collision of the Panama arc along the Pacific margin of Colombia, has created a major thrust salient, the Cordillera Oriental, which overthrusts the Llanos foreland basin along an arcuate thrust front that extends basinward by 130 km. In this study we used 2000 km of 2D-seismic data and 32 wells, for which structure maps of key horizons and subsidence curves were constructed and analyzed both parallel and perpendicular to the chord of the thrust salient. Subsidence curves show an increase in the rate of tectonic subsidence in the salient area during the middle to late Miocene, coeval with the collision of the Panama arc with northwestern South America plate. Regional balanced cross-sections north and south of the salient apex, show shortening across the Cordillera Oriental of ~30 km and ~40 km, respectively. Most known hydrocarbons in the thrust belt and foreland basin are located either south of the salient (Cusiana-Cupiagua, Rubiales) or north of the salient (Cano Limon-La Victoria) but not within the salient where subsidence, source rock thicknesses and fracturing may be greatest according to the model of Macedo and Marshak (1999). We discuss whether this lack of major fields in the salient is a result of geologic conditions or reflects underexploration.

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Early Cenozoic Rift Inversion: Key to Understanding the Structural Framework and Petroleum Potential of the Nicaraguan Rise

Peter Emmet [1] *and Paul Mann* [2]

The Nicaraguan Rise is known as a Late Eocene to Recent carbonate province because vintage industry seismic and well data documenting its pre-carbonate history have remained largely unpublished. We have used 13 offshore wells, 2 wells in the coastal area of eastern Honduras, and 5000 line km of seismic data collected between 1970 and 1980 to reveal for the first time the importance of early Cenozoic rift inversion for the tectonic history and petroleum potential of the Nicaraguan Rise where numerous oil and gas shows have been reported since the 1970s but no production has resulted. Using these data we map numerous inverted normal faults striking roughly W-E. These normal faults bound non-marine rifts of Upper Paleocene-Lower Eocene age similar in fill but not orientation to the NW striking Wagwater and Montpelier-Newmarket rifts of Jamaica. NNW-striking deep bathymetric channels that segment carbonate banks of the eastern Nicaraguan Rise may be late Neogene grabens or may simply reflect the distribution of the Paleogene uplifts upon which they aggraded. The newly-recognized inversion structures are characterized by steep fault dips and modest fault heaves, although some Paleogene growth faults have up to 1000 m of extensional throw. An angular unconformity separates a Middle Eocene onlap surface from older tilted strata and positive turtle stuctures related to inversion of wedge-shaped Paleogene rifts and fanning normal faults framing the turtle structures are common. The initial inversion event occurred in the Middle to Late Eocene but intermittent extension and compression have continued into the late Quaternary. Areas of maximum inversion provided a substrate for carbonate banks and are now areas of the thickest carbonate sections. Areas of "false basement" may document local rift-related volcanism as is well known from Jamaican rifts. Geochemical work shows that the highest quality source rock is confined to successor basins adjacent to the inverted Paleogene rifts. The Cretaceous is overmature in 6 of 10 well penetrations but may provide an additional HC source in some locations. Variations in inversion from area to area could mean that burial depths have varied greatly. Younger rifting of Miocene to Recent age is observed in the borderlands province adjacent to the Cayman Trough. One possibility is that the Paleogene rifts we observe are analogous to these younger rifts and accompanied the Eocene opening of the Cayman Trough.

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Tectonic Setting and Hydrocarbon Trendology of a Reported 7-8 TCF Giant Gas Discovery, Eastern Gulf of Venezuela

Paul Mann [1], *Alejandro Escalona* [2], *and Yang Wenxiu* [2]

Although Venezuela is the sixth largest oil producer in the world, there is no significant oil or gas production from its offshore basins. The reported discovery of a 7-8 TCF giant gas field in the Gulf of Venezuela would boost Venezuela into the top tier of world gas producers (in 2008, Venezuela had 2.6 percent of the world's proven natural gas reserves). The purpose of this presentation is to review the tectonic setting and hydrocarbon trendology of surrounding oil and gas occurrences of the proposed giant discovery in the eastern Gulf of Venezuela using a compilation of: surface geologic data, radiometric dates of exposed and subsurface basement rocks, gravity, magnetic, seismic, well, and plate tectonic reconstructions. The Gulf of Venezuela is underlain by an east-west-trending belt of Cretaceous metamorphic basement rocks that extends eastward beneath the onland Falcon basin of western Venezuela and the Bonaire basin of offshore Venezuela. This belt of Cretaceous metamorphic basement is distinct from Paleozoic to Precambrian basement to the south beneath the Maracaibo basin and from Cretaceous arc basement to the north that underlies the Leeward Antilles islands. The Cretaceous metamorphic belt is not overlain by proven organic-rich, Cretaceous carbonate rocks and high-quality, Paleogene clastic reservoir units - as present in the supergiant Maracaibo basin to the south - but is instead overlain by a late Eocene to Pleistocene section of sand, shale and limestone. Gas and oil fields to the south and southeast of the Gulf of Venezuela in the Urumaco trough and Falcon basin are sourced by marine organic matter from Oligocene and Miocene shale-rich units within this succession. Oil and gas traps include structures related to the inversion of the Falcon basin and stratigraphic traps produced by sandy pinchouts into thick shale units. Bright spots in late Miocene fans of the offshore Bonaire basin indicate the possibility of an east-west hydrocarbon trend extending eastward from the Falcon basin towards the NCMA gas fields of northern Trinidad.

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Tectonic and eustatic controls on the origin of shelf sands and associated facies, offshore NCMA area of Trinidad and Tobago

Stefan Punnnette [1], *Lesli Wood* [2], *and Paul Mann* [3]

Basins along the North Coast Marine Area (NCMA) of Trinidad and Tobago have received large volumes of coarse-grained Tertiary sediments shed from the South American continent. These sediments are deposited within actively deforming basins in shallow marine settings along the northern margin of Trinidad and are subject to significant reworking by the northwestward-moving Atlantic Equatorial Current. Similar current-influenced sand deposits worldwide are host to significant hydrocarbon accumulations and such is the case for basins along the offshore North Coast regions of Trinidad and Tobago which host giant biogenic gas fields in sandstone of Miocene and younger age. Seismic geomorphic analysis and architecture of shelfal sands found in the offshore northern shelf of Trinidad and Tobago have been examined using 1350 km^2 of high quality 3D seismic and numerous well penetrations, as well as high-resolution 2D lines. We characterize two, ~400 ms (~275 meters) thick Pleistocene-age sequences and assess the varying influences of sea-level, continental climate and syn-depositional tectonics on their formation and morphology. Sequence thicknesses vary across the shelf in response to syn-depositional tectonic accommodation development, and post-depositional uplift and erosion by both subaerial and submarine processes. "Channeled" bodies form a near braided network of complex meandering to straight incisions over the older clinoform packages. Channels range in width from 100 to 550 m. Clinoform geometries dip from south-southwest to north-northeast at angles of 0.14° and are over 25 m in height. Key observations from this data set include the 3D hierarchical nature of key surfaces bounding facies packages in these units, the relationship between the paleo-shelf edge and the lowstand shelf wedges, and the influence of shallow fault deformation on delta top thicknesses.

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Effects of Laramide Foreland Basin Tectonics on Structure, Subsidence, and Hydrocarbons of the Mexican Sector of the Gulf of Mexico

Anthony Rodriguez [1], *Paul Mann* [2], *William E. Galloway* [2]

The Gulf of Mexico (GOM) is traditionally interpreted as a basin formed in a Mesozoic rift and passive margin setting that was subsequently modified by gravity-driven salt tectonics during Cenozoic time. Feng et al. (1994) proposed that anomalously rapid tectonic subsidence of 2.5 to 3.5 km calculated in deep wells along the western edge of the basin reflect the onset of foreland basin tectonics as a result of eastward directed Laramide-age thrusting along the Sierra Madre Oriental fold-thrust belt (SMOFTB). Since the time of their 1994 study, the stratigraphy of both the US and Mexican sectors of the GOM have undergone a major stratigraphic revision based on the recognition that the ubiquitous "mid-Cretaceous unconformity" is now recognized from biostratigraphy in deep exploration wells to be a much younger surface of Late Cretaceous age (e.g., Cantú-Chapa and Landeros-Flores, 2001). Using this important new stratigraphic constraint, we have compiled seismic and well information on this surface over a petroliferous region of approximately 560,000 km2 that includes giant fields at the Golden Lane and Cantarell. This top Cretaceous carbonate surface dips uniformly seaward into the GOM at angles of 2° to 5°, is complexly deformed by thrust faults near the modern Mexican coastline, and acts as an extensional detachment surface for 3-6 km of overlying Paleogene to Recent clastic sediments. Our backstripping of four wells in the offshore area east of the Golden Lane and synthetic wells derived from age-dated horizons on regional seismic lines show a major pulse of subsidence at ~66 to ~40 Ma that we infer as the onset of Laramide-related thrusting in the western GOM that is consistent with other areas of Laramide deformation in North America and Mexico dated in the interval from Late Cretaceous to Paleocene (80 to 55 Ma). Reservoirs of giant oil fields in the Chicontepec, Veracruz, and Macuspana basins are located in the overlying and extensionally-detached Cenozoic clastic section although most workers agree that key source rocks are within the Late Cretaceous carbonate section. Previous work shows that thrust-related traps deform the late Cretaceous carbonate section in the area between the SMOFTB and the modern coastline: areas seaward of the modern coastline show that the upper Cretaceous limestone dips uniformly seaward with no compressional deformation.

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Trans-Andean mega-regional seismic reflection line extending from the Caribbean coast to Cordillera Oriental of Colombia: Implications for hydrocarbon exploration

Carlos A. Vargas-Jimenez [1], *Paul Mann* [1], *Clemencia Gomez* [2], *Luis Alberto Briceno* [2], *and Carlos A. Rey 2*

During 2007-8, the Colombian government working through the National Hydrocarbons Agency (ANH) collected a 383 km-long, triaxial high-resolution seismic reflection line using active sources that were recorded to depths of 20 seconds two-way travel time. Several types of supporting data were also collected along the same transect that included surface geology, gravity, magnetics, and geochemistry of hydrocarbons. The purpose of the study was to constrain 1) the deep structure and stratigraphy of the Sinu-San Jacinto belt - the onland late Cretaceous accretionary prism; 2) the tectonic boundary separating these accreted oceanic rocks from the South American continental margin (Romeral fault zone); 3) the Eocene-Oligocene unconformity of the Lower (LMB) and Middle Magdalena basins (MMB), and 4) the tectonic boundary between the Cordillera Oriental and the MMB. Features best imaged on the line include the unconformity and overlying sedimentary fill of the San Jorge and Middle Magalena basins. Both gently folded, synclinal basins have been shortened in the east-west direction by much less than estimates of 110-150 km based on previous balanced cross sections. Geochemistry of hydrocarbons in the San Jorge and Middle Magdalena basins show that all source rocks are contained within these gently deformed synclines. Sub-vertical, active strike-slip faults of northern extension of the La Salina fault are seen crossing the eastern part of the line in the MMB. Seismic penetration into the sub-unconformity section was disappointing but more recent seismic processing shows the general eastward dip of thrust-imbricated strata of the Sinu-San Jacinto belt. In this area, the Eocene-Oligocene unconformity at the base of the western margin of the LMB may act as a trap for hydrocarbons for known source rocks of the Sinu-San Jacinto belt. The boundary between the Cordillera Oriental and MMB is defined by the Cambao-La Salina thrust system that dips 25 degrees to the east beneath the Cordillera Oriental.

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Tectono - Stratigraphic Evolution of the Continental Shelf of Guyana and Suriname

Yang Wenxiu [1], *Alejandro Escalona* [1], *and Paul Mann* [2]

The Guyana & Suriname continental shelf is located along the passive margin of north eastern South America, just south of the eastern Venezuelan and Trinidad large hydrocarbon provinces. With no major oil discoveries, the region is considered the second less explored basin in the world. We integrated ~ 3000 km of industry 2D seismic reflection and information from 13 offshore published wells to provide a regional framework.

Four main stratigraphic sequences on both well and seismic data from Cretaceous to Pliocene were recognized:

Sequence 1, of Cretaceous age, consists shelfal sedimentation and submarine fan systems into the deep water evidenced by deep incised valleys in the shelf. Also, world class Turonian source rocks were deposited in the shelf. A main Cretaceous depocenter is located to the SE part of the study area. This depocenter coincides with a free-air gravity low, suggesting a basement depression inherited from Jurassic. The Turonian shales show high TOC, but maturity levels are low in shelfal area, but into the SE depocenter may be matured.

Sequence 2, of Paleogene age, is ~ 0-600 ms thick, consists of shelfal clastic and carbonate deposition. Listric faults affect the shelf edge and slope, producing turbidites into the toe of the slope. Along the Paleogene shelf, a NE-SW arch is interpreted. Onlapping Paleogene sediments into the top Cretaceous suggest the arch structure may reflect the long distance effect of the arrival of the Caribbean plate into north- and central northern South America. Possible reservoirs include deep water turbidates and shelfal sediments along the arch axis.

Sequence 3, of early to middle Miocene age, is 0-750 ms thick, and consists of isolated carbonate platforms at the margin surrounded by siliciclastics. The sequence is progradational and has a major sequence boundary of middle Miocene age with large incised valleys. This unconformity can be correlated with the middle Miocene unconformity observed in Trinidad, representing the peak of Caribbean orogeny. Possible reservoirs are sand filled incised valleys on top of the sequence. Sequence 4, of upper Miocene to Pliocene age, is between 200-2000 ms thick, showing a large terrigeonous progradational event. The shelf was built up by clear sigmoidal clinoforms from land sedimentation which may form good reservoirs (fluvio-deltaic-shallow and marine environments) with applicable seal rocks during the flooding of the shelf. The large change in the progradation pattern is related to sea level fall and change in the paleodrainage systems of northern South America.

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Tectono-stratigraphic framework of the western Maracaibo block, Colombia- Venezuela: Implications for hydrocarbon exploration

Caroline Whitehill[1], *Paul Mann*[1], *Alejandro Escalona*[2], *and Carlos Vargas*[1]

The actively deforming, Maracaibo block of Colombia and Venezuela plays a major role in hydrocarbon distribution in western Venezuela and northern Colombia. The triangular Maracaibo block is defined by the right-lateral Oca fault of northern Colombia (70-100 km slip), the left-lateral Santa Marta-Bucaramanga fault zone (SMBFZ) of northern Colombia (50-110 km slip), and the right-lateral Bocono fault of western Venezuela (30- 80 km of slip). Oil reserves in the basins overlying or adjacent to the Maracaibo block vary widely from 44 BBOE in the Maracaibo basin, 3.3 BBOE in the Middle Magdalena (MMB), 1.0 BBOE in the Lower Magdalena, 256 MMBOE in the Baja Guajira, and 13.9 BBOE (potential resources) in the Cesar-Rancheria (CRB). We present a kinematic model for the Maracaibo block and its influence on oil resources on overlying and adjacent basins based on subsurface mapping of more than 30,000 km of 2D seismic and well data from the MMB and CRB along with compiled information from previous work in the MB. A major control for oil resources is sedimentary thickness which is optimal for maturation and preservation of light oils in the northeastern MB (5-10 km) but marginal in the CRB (< 3 km) and MMB (~3-8 km). Another major control is erosion during the Eocene-Oligocene uplift event that led to a major hiatus that is greater in the western areas of the LMB, MMB and CRB (Eocene or Oligocene strata on Cretaceous) and less in the eastern area of the MB (Oligocene strata on Eocene). The greater loss of sedimentary cover (including Cretaceous source rocks) has produced less favorable conditions for hydrocarbons. Recent fission track dating shows that the uplift of the northern Andean ranges was coeval with this unconformity with topographic elevations persisting to the present-day. Structurally, we use subsurface and surface geologic data to show that the uplifted margins of ranges associated with the MB are thick-skinned inversion structures similar to Laramide uplifts of the western US rather than thinskinned structures proposed by previous authors.

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