CBTH Abstracts

Presented at

American Association of Petroleum Geologists
Annual Convention & Exhibition
10-13 April 2011
Houston, Texas, USA

Caribbean Basins, Tectonics, and Hydrocarbons

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Subduction-to-Strike-Slip-Transition in the Southeastern Caribbean Imaged Using Deeply-Penetrating Seismic Reflection Lines and Tomography

Tricia Alvarez¹, Carlos Vargas², Paul Mann³, and Joan Latchman⁴

The subduction-to-strike-slip transition (SSST) zone of the southeastern Caribbean is one of thirty identified locations where active subduction and strike-slip tectonic styles transition along strongly curved and seismogenic plate boundaries. This SSST zone provides a field laboratory for understanding how sedimentary basins, faults, basement areas and subducted slabs change from an area of dominantly westward-directed subduction beneath the Lesser Antilles arc to an area of dominantly east-west strike-slip faulting along northern South America. We use two geophysical data types to image the lithosphere and study the relationships between lithospheric scale deformation and basin scale response to the transitional tectonic configuration. Interpretation of deeply-penetrating seismic reflection lines recorded down to 16 seconds two-way time, or depths of about 18 km, is combined with tomographic slices of the upper mantle and lower crust which were constructed using the coda method on ~ 700 earthquakes in the depth range of 70-250 km.

Results from the tomographic study are compared with nine seismogenic zones in the southeast Caribbean SSST zone which are defined based on the depth, and focal mechanism of earthquake events. These zones include: (1) the Paria slab tear region; (2) Caribbean/South American strike-slip zone; (3) Hinge area separating continental margin in Trinidad from Tobago forearc basin; (4) Central Range –strike-slip fault zone, onshore Trinidad; (5) Underthrust zone of South American beneath southern onshore and offshore eastern Trinidad, including the prolific hydrocarbon-bearing Columbus Basin; (6) Venezuela foreland and fold-thrust belt; (7) flexural bulge area of oceanic crust located east of Barbados accretionary prism (BAP); (8) Subducted slab beneath the stabilized and supracomplex zones of the BAP; (9) Inner accretionary prism of the BAP. Primary controls on the seismogenic character of each curving tectonic belt include the strike of the plate boundary faults relative to the plate vector for crustal earthquakes and the location and morphology of the subducted slab for sub-crustal earthquakes.

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Lower Magdalena Basin, Colombia: A Forearc Basin Formed above a Zone of Active, Shallow Subduction

Roccio Bernal¹, Paul Mann², and Carlos Vargas³

The Lower Magdalena basin (LMB) is one of the largest (42,000 km²) and thickest (~8 km) sedimentary basins in Colombia, yet has yielded only 17 oil discoveries with 77 million barrels of oil and 1112 GCF over the past 40 years of exploration. We integrate seismic tomographic data capable of imaging to depths of 200 km with a compilation of on- and offshore industry seismic profiles recorded to depths of 20 km (16 sec TWT) tied to 30 wells to better understand slab controls on basin geometry. Seismic lines recorded to depths of 20 km show that the Colombian basin crust is subducted eastward at a shallow angle beneath an active submarine accretionary prism (Sinu belt) and an onshore forearc high composed of an older prism of folded and eastwardly-tilted rocks of Eocene to Upper Miocene age (San Jacinto belt). Tomographic data reveal the subducted slab at depths from 17 km dipping at an angle of ~5° to a depth of 30 km beneath the eastern side of the asymmetrical and synclinal LMB. Structural styles affecting the 8 km of basin fill includes ~2 km-thick Eocene rifts, controlled by ENE-striking normal faults, truncated by a prominent Middle Miocene unconformity that is in turn cut by high-angle faults associated with the Santa Marta strike-slip fault. Based on these observations, we classify the LMB as a forearc basin formed in a zone of shallow, eastward and southeastward subduction. The synclinal LMB is defined on the west by the uplift of an older, accretionary wedge (San Jacinto forearc high) and to the east by sub-vertical strike-slip faults (Santa Marta fault zone). The lack of an active volcanic arc east of the LMB in the Santa Marta massif is explained by the low dip of the subducting Caribbean slab that does not allow the presence of a mantle wedge that can be melted to form volcanoes.

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Flexurally-driven subsidence history of the Llanos foreland basin of Colombia: Implications for hydrocarbon exploration

Henry Campos¹, Paul Mann², and Nestor Cardoza³

The Llanos basin of Colombia is located in the eastern side of the northern Andes and it is bounded to the north by the Merida Andes, to the east by the Guyana Shield, to the south by the Serrania de la Macarena and the Vaupes Arch, and to the west by the frontal thrust system of the Eastern Cordillera. This basin became a foreland since the Maastrichtian and shows a sudden and accelerated pulse of Middle Miocene subsidence recording the basin's response to distant shallow subduction and collision events along the active Pacific margin of northwestern South America. Regional east-west shortening, driven in part by collision of the Panama arc along the Pacific margin of Colombia, has built the widest part of the northern Andes including a prominent arcuate thrust salient, the Cordillera Oriental, which overthrusts the Llanos foreland along a broad V-shaped tip projecting 40 km eastward into the Llanos basin. In this study we integrate 1200 km of 2D-seismic data, tied to 18 wells, and divided in four 300 to 400-km-long, regional transects spanning the basin. 2D flexural modeling using OSXFlex2D was carried out along all four transects to illustrate and understand the effect of tectonic and sedimentary subsidence. Sedimentary backstripping was applied to the observed structure maps of interpreted horizons in the foreland basin to remove sedimentary and water loading effects. Regional subsidence maps show an increase in the rate of tectonic subsidence in the salient area during the middle to late Miocene. Flexure models predict changes in the Middle Miocene to recent position of the eastern edge of the foreland basin as well as the changing locations and vertical relief of the flexurally-controlled forebulge. Most light oil fields in the thrust belt and foreland basin are located either south of the thrust salient (Cusiana-Cupiagua, Rubiales oilfields) or north of the salient (Guafita-Cano Limon, Arauca oilfields) but not directly adjacent to the salient where subsidence, source rock thicknesses and fracturing may be most favorable for hydrocarbons according to previous studies. There are no reported light oil accumulations on the present or past positions of the forebulge but comparisons of seismic data to model predictions show onlaps and wedges that could provide possible traps for hydrocarbons.

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Nicaraguan Rise Offshore Honduras: Upper Cretaceous Source Rock May Contribute to a Proven Eocene Hydrocarbon System at Main Cape-1 in the Mosquitia Basin

Peter Emmet\textsuperscript{1}, Paul Mann\textsuperscript{2}, and Rick Roberson\textsuperscript{3}

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 structures 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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Role of Panama Arc-Indentor for Late Cenozoic Deformation in Colombia and Implications for Regional Distribution of Hydrocarbons

Paul Mann¹ and Carlos A. Vargas-Jimenez²

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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Crustal Structure, Sequence Stratigraphy and Petroleum Potential of the Western Colombian Basin Adjacent to Costa Rica and Nicaragua

Maria I. Prieto¹, Harm Van Avendonk², Paul Mann², Steve Holbrook³, Daniel Lizarralde⁴, and Percy Denyer⁵

Maps showing the location and thickness of the late Cretaceous Caribbean Large Igneous Province vary widely from a small plateau centered on the Beata Ridge in the central Caribbean Sea to an extensive plateau covering the entire Caribbean Sea and southern Nicaraguan Rise along with fringing land areas in southern Central America and the Greater Antilles. Seismic reflection and OBS refraction data collected in 2008 on the RV Marcus Langseth have revealed that the westernmost Colombian basin near Costa Rica and Nicaragua is underlain by thick crust with velocities consistent with a more extensive Caribbean oceanic plateau. Lower crustal velocities are consistent with high-temperature, mantle-derived picritic basalts of late Cretaceous age that are widespread in southern Central America and have been previously linked to a late Cretaceous mantle plume head formed at the Galapagos hotspot. Seismic reflection data and ODP wells show that the late Cretaceous plateau crust is overlain by up to 500 m of late Cretaceous carbonate and shale with TOC up to 33%. These organic-rich deposits have been linked to an anoxic event previously linked to the formation of the Caribbean oceanic plateau and described from ODP wells and from outcrops in surrounding onland regions. We illustrate the distribution of this organic-rich horizon using two, newly-processed MCS reflection lines in the Colombia Basin that are correlated with existing MCS and well data. A possible petroleum play includes this late Cretaceous source with traps in overlying deepsea, turbiditic sandstone derived from the erosion of mountains in Costa Rica and the northern Andes.

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Structural and Stratigraphic Synthesis of the Gas Trend on the Northern Shelf of Trinidad and Tobago

Stefan Punnnette\(^1\) and Paul Mann\(^2\)

The North Coast Marine Area (NCMA) extends across ~7000 km\(^2\) of the northern Trinidad and Tobago shelf in water depths between 50 to 200 meters. In 2009 the NCMA had two exploration blocks under active oil and gas exploration with gas production from the NCMA totaling ~ 1.1 tcf since 2002. All natural gas discovered to date in the NCMA has been interpreted as biogenic although one previous worker has speculated that a minor component of thermogenic gas is also present. The NCMA is located in a complex tectonic environment characterized by oblique strike-slip displacements between the Caribbean and South American plates at a rate of about 20 mm/yr. The main faults of the 200-km-wide plate boundary zone include: 1) the El Pilar right-lateral strike-slip fault zone to the south on the island of Trinidad and the Gulf of Paria which GPS results indicate to be largely inactive; 2) the North Coast fault zone (NCFZ) which marks the southern boundary of the Tobago basement terrane and appears to be slightly active with down-to-the-north, Miocene to recent oblique-slip movements on the NCFZ producing accommodation space for deposition of sediments along the northern shelf of Trinidad and Tobago; and 3) the Hinge Line fault zone (HLFZ) crossing through the NCMA. The ~120 km long Hinge Line fault zone has an average east-northeast strike approximately parallel to the GPS-derived plate motion direction (080°), and is a sub-vertical, thick-skinned right-lateral strike-slip fault. Localized zones of transpression and transtension form locally where the trace of the fault deviates from the 080° direction of pure, right-lateral shear and these localized areas of complex faulting and folding provide important structural traps for Pliocene and Miocene gas reservoirs in the NCMA north of the HLFZ. Growth sequences along the HLFZ indicate that the fault activated in Miocene time and continues to up to the late Pleistocene (~500 k.y.) and in some areas forms active scarps on the seafloor. Structural maps and isochron maps were made for four horizons underlying the northern shelf of Trinidad including top Mesozoic basement, top Miocene, top Pliocene and seafloor. These maps support a change in terrigenous source area for the northern shelf of Trinidad: during the Miocene and early Pliocene, terrigenous sources were coming from the southeast through the Atlantic Ocean; whereas during the mid-Pliocene to present the source area changed to the southeast through the Gulf of Paria.

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Origin of the Mexican Ridges Passive Margin Foldbelt Based on Seismic and Well Integration from the Shelf-Slope-Deep Basin and Structural Restoration

Anthony Rodriguez¹ and Paul Mann²

Passive margin foldbelts (PMFB) form by three different mechanisms: 1) toe-of-slope shortening related to sliding on tectonically-tilted surfaces; 2) gravity-spreading deformation as a result of a regional bathymetric gradient by updip sediment deposition or salt movements; and 3) mixed-mode deformation involving both 1 and 2. The Mexican Ridges province (MRP) is an example of the third, mixed mode type of PMFB that extends for ~130-150 km across strike and ~360-400 km along strike adjacent to onland Laramide (Paleogene), east-verging, convergent structures and the Tamaulipas-Oaxaca fault zone formed during early GOM opening. Vintage University of Texas seismic lines tied to published Pemex wells and SEGY-converted seismic lines illustrate the main structural features of the MRP: 1) an outer shelf and upper slope area characterized by east-dipping, listric normal faults that juxtapose syn-faulting Miocene to Recent sediments with Eocene to Oligocene sedimentary rocks in their footwall blocks; 2) an upper slope area characterized by an undeformed upper section overlying large half-grabens that sole into the thin-skinned MRP fold-thrust belt that is morphologically prominent on the middle slope; and 3) a lower slope and basinal area of large, open folds that may be underlain by the downdip extension of the low-angle detachment surface. Sedimentary growth wedges adjacent to normal faults indicate that sliding and toe of slope compression initiated in the late Miocene and has continued to the present day. Structural restorations illustrate that downslope shortening structures balance total upslope extensional structures. The ~20 Ma time delay between the end of the Laramide orogeny in late Eocene and the initiation of MRP sliding in the late Miocene indicates that Laramide shortening is not the driving mechanism for oversteepening the slope and initiation of the MRP gravity slide and toe of slope shortening structures. A more likely cause for the MRP is accelerated Oligo-Miocene uplift, regional volcanic activity and erosion of the Mexican landmass with loading and destabilization of the narrow, eastern Mexican shelf. Regional isochron maps of the Mexican GOM tying University of Texas deeper basinal lines with published Pemex slope and shelfal lines and wells distinguish an early Laramide pulse of sediment followed by a later Oligo-Miocene pulse and a Miocene and younger, clockwise shift of U.S. GOM clastic sources derived from the Mississippi fan.

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