Field Guide

20th Caribbean Geological Conference (2015)

Port-of-Spain, Trinidad and Tobago

Central Range:

Evidence of Early Tertiary Petroleum Systems

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Trip Objectives:

This trip will evaluate the evidence in the Central Range for the missing Early Tertiary Petroleum system that once existed in the Northern Basin. That system included a thick package of Eocene Pointe-à-Pierre Formation reservoir and the Cretaceous Naparima Hill Formation source rocks that entered the oil-generating window between the late Eocene and the early Oligocene. Uplift and subsequent erosion in the late Oligocene to the Middle-Micoene halted generation. The concurrent erosion produced pebbles and cobbles that were redeposited within the Cunapo, Brasso, Tamana and Nariva Formations. The trip will first take participants to visit the outcrops to see the source rock and the reservoir components of that system and then to sites where cobbles of the source rock and the reservoir are found in Miocene and Oligocene sediments.

Trip Locations

2A. Day 2: Central Range – Early Tertiary Petroleum Systems

Trip Leader - Philip Farfan

Stop 1: San Fernando Hill: Naparima Hill Formation

Keywords: Source rocks, thrust faults, oil migration, charge, folds, secondary porosity, unconventional reservoirs and "beef."

Access and Safety

The drive time from the Hyatt Hotel in Port of Spain to San Fernando Hill will be about 60 minutes. There will be three stops on the hill. The first will be at the top and please take advantage of the toilet facilities there; a second, on the side of the road on the way down, and the third at the base. The walks are all less than a few hundred meters and we should be only about 30-45 min at each stop. The principal safety concerns are rock-falls and traffic as you get on and off the bus, especially at the second stop. Please wear hats if you prefer and please be very vigilant of the traffic. The furthest part of the outcrop will be a 10-minute walk from the bus. It will be hot so please drink and you should wear and carry protective gear.

Overview

At San Fernando Hill, the Naparima Hill Formation is hard and the argillite was quarried and used for aggregate. An overview from the top illustrates how Trinidad's broad-scale tectonic geomorphic features support the hypothesis that the active Venezuelan El Pilar Fault steps southward across into the Central Range Fault (CRF) in Central Trinidad and because of that shift the Northern Gulf of Paria -Northern pull-apart basin was created (Babb et al 2000). Weber, J, (2005) proposed that western Trinidad, east of Mahaica, is actively subsiding into the basin. There are no commercial oil discoveries in the Northern Gulf-Northern Basin and the gas found there is biogenic. The Central Range does not extend far past the Paria coastline but on the other side of the island the northeast-trending uplift is structurally evident far into the Atlantic. The Central Range on shore has a few oil fields and there are a few on trend offshore either side of the island, but it is the Southern Basin south of the Nariva Fold Belt that is the really prolific hydrocarbon province. That trend extends east from the eastern Venezuelan basin to the Atlantic shelf . This visit will focus on the evidence for the timing of the migration of the hydrocarbons that fill the pervasive fractures and the structural, geochemical and stratigraphic facies of the Naparima Hill Formation so that they will be recognised when reworked into pebbles in the late Tertiary stratigraphy.

Description

Stratigraphic

The Naparima Hill Formation is widespread in the subsurface and is found in wells throughout south Trinidad, in a few outcrops across the Central Range and in wells offshore the east coast along the Central Range trend. It is the equivalent to the Querecual and San Antonio Formations in Eastern Venezuela where they charge the most prolific hydrocarbon basin in the world, that includes the Orinoco Tar Belt, which alone, has more than a trillion barrels of oil and bitumen in-place. It has an estimated thickness of 2,000 feet (Kugler, H., 2001) and has fauna indicative of the Turonian, Coniacian, Santonian and early Campanian age, (approximately 100 to 70 MYBP). Limited well control points to its absence in the Northern Basin, either through erosion or non-deposition. This distinctive facies is also absent in the Northern Range where there are low grade metamorphic, age-equivalent rocks.

At San Fernando, the Naparima Hill Formation is predominantly "argillite" that is capped by a yellow 'chalky' facies that appears less dense and less fractured. The chalky facies is widespread and is found in many wells in the Southern Basin (Suter, N., 1951). The more siliceous argilline facies weathers white, typical of oil-impregnated rock at surface, but fresh surfaces of this "argillite" smell of hydrocarbons and are dark. Studies have shown that the highest petroleum potential is associated with the siliceous and carbonate lithofacies, which consist of hemi-pelagic sediments deposited under low oxygen conditions (A.G. Requejo et al., 1994). The kerogen is Type ll and the rock is in the oil window (Persad et al, pers. com.). We may see evidence for bitumenisation. In places petroleum has been concentrated in veins that were opened and are now filled by sparry calcite. Seeps are common in and around the hill. The unit appears well bedded but this apparent bed-form can look like thrust faults. Chert is not common here, but there are a few chert 'balls' near the top of the section that are known to become more abundant up section. Here at San Fernando it has been almost been completely mined out. Chert is well developed at Chert Hill, in wells in the Southern Basin and in Venezuela. Photographs of core and a log (Erlich, R. et Al. 2003) recovered from nearly 14,000 feet under the Rock Dome anticline (assumed straight hole) confirm the presence of thick, clean, well-consolidated grey sandstones that are contemporaneous to the organic-rich Naparima Hill sediments but that are not seen in outcrop.

Structural

The beds at San Fernando Hill are mapped as a hanging wall, half-anticline truncated to the southeast by a northeast trending reverse (thrust) fault. Near the top of the hill there are examples of duplexes that have propagated through one particular layer and are one of the few examples of bona fide low-angle structures in the Central Range. The fault surfaces are highlighted by what appears to be a bituminous gouge or "beef" on the glide planes. Altered hydrocarbons are also concentrated in veins in which there are multiple generations of calcite growth. Fractures are orthogonal to the thrust or bedding surfaces. The temporal relationship between the thrusts, fractures, veins and the anticlinal fold is not understood. These beds were uplifted along with sediments as young as the Talparo Formation, confirming that the uplift of the Naparima Hill Formation at San Fernando Hill is a young event probably in response to the ongoing stresses developed adjacent to the Central Range Fault (CRF) The local Naparima Hill and Cipero Formation beds were previously overlain mostly by Nariva, Brasso, Springvale and Talparo formations; a shallowing succession that in Nariva time, thickened southward (Kugler, H., 1959). For reasons unknown to the author, this isolated body of Naparima Hill Formation was thought to sit at the leading edge of a high angle reverse fault, whereas almost all other local early-Tertiary and Cretaceous bodies strewn across the Nariva Belt are interpreted to be olistoliths (Kugler, H., 2001), derived from the north and shed into the Southern Basin. The "olistoliths" have also been interpreted as tectonically detached 'flakes' in a melange within a Nariva Formation matrix (Algar, S., 1995).

Discussion

Clasts and argillites with facies very similar to the scree that is seen in these quarries occur abundantly in the thick conglomerates that are penetrated by wells in the Northern Basin, (Payne, N. 1985), in outcrops, especially on the north flank of the Central Range and they find their way into turbidites in the Southern Basin. In the Northern Basin and the Central Ranges the late Oligocene to recent, late tertiary sedimentary succession unconformably overlies early Cretaceous to Eocene sediment (Kugler 1959). The Naparima Hill facies pebbles and pebbles from the Eocene Caratas Formation are also found in the conglomerates of the Carapita Formation (Oilgocene-Miocene) of Eastern Venezuela (Lamb J.L. and Sulek J. A. 1965). Based on the thicknesses of these conglomeratic successions it is evident that a substantial thickness of sandstone and argillite was originally present then subsequently eroded.

The Naparima Hill beds at San Fernando have reached high levels of thermal maturity based on the presence of hydrocarbons in the matrix of the argillite, in lattices of calcite filled open fractures and in the "beef"; the latter two which are thought to be linked to permeability networks that propagate when pressures, emanating from volume changes caused by the chemical alteration of the kerogen during the thermal maturation process, initiate hydraulic fracturing. It has also been observed that the propagation of thrusts that emanate from source intervals are considered complicit in the maturation and migration of hydrocarbon (e.g. Niger Delta). The maturation of the oil and the presence of related thrusts and fractures imply that these developed contemporaneously and when the rock was deeply buried. Based on the local stratigraphy this burial could have occurred at two alternative times; either in the Eocene under a thick early tertiary clastic system for which there is no direct evidence or in the late Tertiary under the combined overburden of the Nariva, Brasso, Manzanilla, Springvale and Talparo Formations. Samples of apatite taken from the Eocene, Pointe-à-Pierre Formation in the Central Range show that they were buried and heated to over 100° centigrade (the oil window), and were subsequently uplifted between 18 and 12 MYBP (Giorgis, S. in press), but were never reburied to temperatures past 100º C about the same temperature as type II Kerogen matures. This data strongly implies that the early Tertiary beds were responsible for the burial of the Naparima source, so there must have been a thick Eocene succession. The late Pliocene never got thick enough to have buried the Eocene and (by inference) the underlying Late Cretaceous source rocks deep enough to heal the apatite tracks. It might also be possible that the oil migrated up from the under limb of the thrust but that would not explain how the source rock here got mature and how the oil got into the matrix of the sediment. The maturation and hydrocarbon emplacement at San Fernando Hill in the late Eocene or early Oligocene was probably concurrent with a compressional event that created the duplexes and the fractures. The subsequent folding which is similar to most of the Central Range folds and probably related to CRF activity may have resulted in some extension that encouraged some remigration in a post-Miocene event.

The evidence of early tertiary migration of oil at San Fernando Hill would support a hypothesis that there could have been two phases of hydrocarbon charge in the Southern Basin both from Naparima Hill Formation source rocks. The first in the late Eocene-early Oligocene from matured source the Northern Basin from which oil and gas would have migrated southwards through Cretaceous and Eocene carrier beds (Gautier, Naparima Hill and Pointe-à-Pierre Formations) in the into traps on the shelf margin and potentially further up on to the shelf that was to become the

Southern Basin. The second charge, the more familiar pulse, also emanated from source rocks that became mature in the Plio-Pleistocene and which charged Miocene and Plio-Pleistocene reservoirs in recent traps.

An Upper Cretaceous sandstone play has become very topical in Trinidad due to recent discoveries along the Atlantic margin of South America. Past and current onshore exploration wells have mostly targeted the sandstone facies of the Gautier and Naparima Hill Formations. Fractured Naparima Hill Formation has also been considered a potential reservoir but there has not been any significant discovery with sustained production. Successful exploration for any of these reservoirs will rely on understanding timing of the charge history in relation to trap formation.

Stop 2: Piparo: Pierre Point Member of the Pointe-à-Pierre Formation

Keywords: Pointe-à-Pierre Formation, turbidites, reservoir facies,

Access and Safety:

The drive from San Fernando will take about 45 minutes. En-route we will stop to briefly visit some erratic boulders on the roadside. The outcrop is accessed via a driveway which has some grass cover so it will be best to walk in single file. We will be on the outcrop for about 20 minutes. There will be opportunities to access toilets shortly after this stop so please let us know. There are few apparent hazards but the equipment at the site should be avoided. It would be prudent to stick together.

Overview

The Pointe-à-Pierre Formation is found in isolated bodies throughout the Central Range but it has not been found in wells north of the Central Range and does not occur in the Southern Basin. Correlative equivalents occur far into the Atlantic, in the Tiburon Rise/ODP 110 Area (Moore, J. C, Mascle, A., et al. 1990) in Barbados and in Venezuela. At this locality we will discuss why this facies does not exist under the Northern Basin and whether these sediments should be correlated with similar facies elsewhere. Here we will review the textures to estimate the depths of burial, the potential size, width and thickness of the Eocene turbidite fairway and the potential reservoir facies of this unit in the Early Tertiary Petroleum System.

Description

Stratigraphic

At this locality the Pierre Point Member of the Pointe-à-Pierre Formation consists mainly of indurated blue-grey, sub-rounded quartzite and the grains are coated in white and reddish clay. Kugler (2001) subdivided the Pointe-à-Pierre Formation into the Pierre Point Member and the Charuma Silt Member. The Pierre Point Member contains the predominantly coarse (cobbles-sands) clastic facies, whereas the predominantly fine-grained facies belong to the overlying but sometimes interdigitating Charuma Silt Member. At Pointe-à-Pierre the type locality, the Pierre Point beds were estimated to be 144 feet thick; in the Mount Harris area the equivalent beds are between 400 and 1,000 feet thick. The quartzose sandstones contain characteristic milky blue quartz which is also found in the Cretaceous Galera Grits and in modern sediments derived from the South American craton. The heavy mineral assemblage is simple; zircon, ilmenite and tourmaline, which distinguishes it from the complex assemblages typical of the Nariva Sandstones and assemblages in the Scotland Formation of Barbados (Vincent et al. 2014) The Pierre Point Member rests on the beds of the Chaudiere Formation which are similar in appearance to the shales of the Pierre Point

Member in the Mount Harris area. The preserved micro-paleontological fauna is arenaceous and not age diagnostic. The Eocene age for the Pointe-à-Pierre is based firstly, on the age of the Eocene Navet Formation which interdigitates southeast of Mount Harris and secondly, the Charuma Silt Member in the Esmeralda-1 well, not far from this location, that had a fauna that indicated an Early Eocene to early Middle Eocene age. Algar (1995) used zircon dates to propose a date of younger than 31 MYBP for the Pointe-à-Pierre Formation and thought the beds to be Late Oligocene or Early Miocene, deposited on the shelf by waves and storms. The distribution of the Chaudiere Formation, the Pierre Point and the Charuma Silt members are (in situ) known only within 'Central' Trinidad; south of here, the Lizard Springs and Navet Formations are the contemporaneous equivalents and are virtually clastic free. The Pointe-à-Pierre has not been encountered in the Northern Basin. The equivalent beds are the Guarico and Caratas formations of the Santa Anita Group in Venezuela and the Scotland Formation in Barbados. Heavy mineral assemblages indicate, however, that these formations did not all belong to a single continuous fairway. It is likely that local provenance areas and drainages contaminated the blue quartz with a variety of minerals. Equivalent aged or slightly younger turbidites were also found on the Tiburon Rise during Leg 100 in the Offshore Drilling Program, which if continuously linked to this locality provides a substantial reservoir fairway northeast of Trinidad.

Structural

The Pointe-à-Pierre Formation is distributed in small isolated outcrops that stretch across the Nariva Belt of Central Trinidad. The beds in the Mount Harris area may be the only ones that are in situ; many of the others are probably rafts or slumped blocks (olistostromes) embedded within the Nariva Formation or they may be tectonically detached 'flakes' in a matrix of Nariva Formation (Algar, S., 1995). The beds here dip steeply, are well indurated quartzites with some feldspar and we have established from thin sections that quartz cements are common and that the contacts of the sub-rounded grains are sutured and syntaxial.

Discussion

Opinions conflict between a deep or shallow water setting for the deposition of the Point-a-Pierre Formation; Renz (1942) and Butterlin considered the grits to have been deposited in upper shoreface and shallow water environments; Tiratso thought they were fresh water in origin; Kugler assumed the interdigitating of the Pointe-à-Pierre Formation with the deep water Navet Formation confirmed that deposition was by turbidity flows. Vincent et al 2007, suggested the sandstones were of slope affinity based on the overall stacking and bed – scale sedimentology. None of these hypotheses can be discounted based upon the evidence in this outcrop. The original extent of the deposit is also unknown. The hypothesis we will try to develop is that the Central Range was the southern feather edge of a northeast-directed major deepwater turbidite system that accumulated in a trough created by the oncoming Caribbean Plate and a northeast-oriented continental shelf. That system possibly covered all of the present day Northern Basin but also extended further north and east probably far into the Atlantic. The sediments here at Piparo were very compacted by a thick overburden that probably developed in the Eocene. During the Oligo-Miocene the Central Range was uplifted because in sediments of that age there is an abundance of the pebbles that look exactly like the indurated Pointe-à-Pierre Formation sandstones seen in this outcrop. Those pebbles could only have been derived from the Northern Basin where there is an Oligo-Miocene unconformity whereas south of here, there was contemoraneous and continuous deposition, mostly by of very deepwater marls of the Cipero Formation. Even the coarse-grained quartz sandstones in thin section, have syntaxial, sutured contacts and the few mica grains are bent, ample corroborative evidence that these rocks were probably buried under an overburden of more than 3,000 to 5,000 metres which is deep enough even in a low geothermal gradient setting to reach temperatures hot enough to reset all the apatite and to mature the underlying source rock. Low geothermal gradients are typical in the proposed geological settings (Pindell, J., 2007). The AFTA cooling occurred more than 12 MYBP which proves that rocks were never reburied to similar depths since the late Miocene. Punch (2004) interpreted the hydrocarbon charge in the Pointe-à-Pierre Formation at Sandstone Trace (not far from here), as arriving after the development of quartz overgrowths, hematitic cements and clay diagenesis consistent with burial, warming, and a subsequent charge. In outcrops near Mount Harris, the Pointe-à-Pierre Formation also contains traces of hydrocarbons.

The Pierre point sandstones, if not as deeply buried and indurated as they are in this outcrop, could have been a well-sorted, thickly-bedded, excellent potential reservoirs or excellent hydrocarbon migration conduits. The tops and lateral seals would have been the younger Charuma Member Silts, while Navet and Lizards Springs Formations would be excellent lateral seals if migration up-dip was towards the south.

Stop 3: Corbeau Hill: Nariva Formation

Keywords: olistrostrome, lignite, turbidites.

Access and Safety

The drive across Piparo Village will take about 10 minutes. There will be a 20-minute walk across a field to the outcrop, and since the cows departed for other pastures the grass has grown and subsequently, especially where the dung was left at the far end of the stalls. It will be wise to keep to a single file along the path that has been flattened. The grasses here are described as "razor grass" for good reason. Try to avoid contact. In the fields there are clumps of "Ti Marie" a cute sounding name that belies the presence of abundant thorns. You are advised to wear long trousers (pants). The clays have shrunk so be careful where you tread recent contraction cracks could easily turn an ankel. We will spend about 30 minutes on the outcrop.

Overview

The Nariva Formation is an enigmatic and intermediary facies that is considered a slope deposit; it occupies the space on the map between the neritic Brasso and Tamana Formations that are usually found on the north flank of the Central Range and the contemporaneous bathyal equivalent, the Cipero Formation that is extensively deposited further south. The sandstone beds are interpreted as turbidite deposits. Correlative sandstones are reservoirs at the Tabaquite and Brighton oilfields. At Brighton the base of the Nariva Formation is separated from the Cretaceous by only a few hundred feet of Tertiary sediment. These sandstones are dual sourced from both the cratonic South America and the uplifting Caribbean Mountain belt (Pindell et al 2009, Vincent et al 2014). The provenance of these sandstones is contentious and their burial history is poorly understood.

Description

The steeply-dipping, sugary quartzitic sandstones are probably reworked from the Pointe-à-Pierre Formation. Both formations are often confused in the field and without diagnostic associated fauna one has to hope that, like at this locality, they can be differentiated by the intermixed dark grains which may be chert or lignite. The sandstones are arranged either in small isolated channel-like bodies or in sheet-like graded sandstone units. At Brighton oilfield, the "blanket sand" is over 100 feet thick and rests on an eroded substrate of older Nariva Formation beds. The other sandstone units are up to 40 feet thick (Ablewhite, K. and Higgins, G; 1965). Within the sandstones here there are commonly lignites or coals and at Brighton these facies are up to 15 feet thick. The sub-rounded sandstone grains of blue quartz and black chert vary in size between coarse and fine. Porosities are variable and permeabilities in Brighton they range between 20 and 1750 mD. The thickness of the Nariva Formation is difficult to measure but at Brighton it is about 2,200 feet, thinned by erosion and overlain by the Lengua Clay Pebble Beds (Late Miocene). The age of the Nariva Formation is always problematic. It is distinguished by its lack of fossils from the contemporaneous equivalent Brasso, Tamana and Cipero formations which in contrast have abundant diverse, environmentally and stratigraphically correlatable and well preserved fauna. The Nariva Formation can only be dated where it is interbedded with the Cipero Formation so is poorly chronographically constrained. The oldest proposed Nariva age is in the Globorotalia opima opima Zone, P21/N2, or about 23MYBP late Oligocene . The youngest Nariva Formation is thought to be correlative with the Globorotalia dissimilis Zone or about N5, or 19MYBP (Carr-Brown, B., 2014), but it could be much yournger. Elsewhere, the only sign of benthonic life are preserved trace fossils of Cylindrium and Cruziana (Kugler, H., 2001). There have been no indigenous macrofossils reported but echinoid remains, coproliths, gastropods and reworked fauna from the Cuche, Lizard Springs, Navet and San Fernando Formations are found. Plant remains are common. At Morne Brulee, east of here, the Nariva Formation is seen interbedded with thick conglomeratic beds of the Cunapo Formation and in which reworked cobbles of the Pointe a Pierre Formation are common. The Cunapo is also seen interbedded with the Brasso and Tamana Formations. The Cunapo Formation near Coal Mine village is also very lignitic.

Discussion

The presence of intra-formational unconformities within the Nariva reservoirs at Brighton, the 'wildflysch' (chaotic) slumped appearance of the deposits, the abundant boulder beds, the presence of olistostromes (that could include large exotic blocks 2 km across), the ages of the AFTA cooling dates, the conglomerates in the Cunapo Formation and its unconformable relationship to the older stratigraphy in Central Trinidad are evidence for syn-tectonic, gravity driven sedimentation down an over-steepened slope that was being actively deformed and uplifted sometime between the early Oligocene and the middle Miocene. However, because the Nariva Formation cannot be exactly dated the timing for the onset of uplift is poorly constrained. At about early Miocene, N5 time, it may be inferred that north of here, correlative Brasso Formation beds were deposited in a neritic environment, while beds further south were deposited in bathyal conditions. So far the youngest AFTA cooling dates are about 18 MYBP or about N8 time which is a little younger than the oldest 'wildflych' which constrains the age of the earliest uplift in the Northern Basin. Sediment on the slope at that time must have had a northerly provenance; the fine material was derived from a mixture of Cretaceous, Paleocene and Eocene shales whereas the coarse sediments were mostly derived from reworked Pointe-à-Pierre Formation and Cretaceous sandstones contaminated with minerals derived from metamorphic terrains (Vincent, H., et al. 2014, , Suter, H., 1951). We can assume the uplift would have begun further north and west of here in advance of the eastward-progressing Caribbean plate (Pindell, J., 2007). The unroofing of the basin ahead of the deformation front would have created a forced regression laden with of sand that would have poured into the Atlantic during the Oligocene and the Miocene. Peculiar drainage conditions must have prevented much of that sand reaching the basin at this locality, but they did reach the basin at Brighton and large turbidites reached far out onto the Cipero sea floor in the Middle Miocene when the Herrera Member was deposited at about N9 or 14MYBP. Similar turbidites derived from the north deposited the massive Caripita Formation in eastern Venezuela.

These beds were probably not buried very deep, over burden was unlikely to have exceeded 3000m constrained by AFTA results that the temperature did not exceed 100-120 degrees C and that the mudstones and sandstones appear poorly consolidated, are still easily fluidized and are the source for much of the material in the local mud volcanoes. It would help if more analyses constrained the depths to which these sediments were buried.

Stop 4: Rafael Street, Tabaquite Road: Nariva Formation

Keywords: synorogenic deposits, channel lags, ptygmatic folds, polymictic conglomerates

Access and Safety

The drive from Corbeau Hill will take about 25 minutes. There will be options to make toilet stops en route, so please let us know**.** The outcrop is about 15 minutes away from the bus and the walk is low gradient. The mud, can be very slippery if wet and the grass can cut.

Overview

The Nariva Formation here has the appearance of a synorogenic deposit. At this outcrop small isolated sandstone bodies are steeply dipping were folded by slumps. The sandstones are polymictic and some pebbles are easily recognisable, probably derived from reworked Pointe-à-Pierre Formation sandstones, Naparima Hill Formation argillites and older Cretaceous beds. These appear to have a proximal provenance. The claystones are still soft and have never been deeply buried.

Description

From a lithological perspective this section looks and feels like the Nariva Formation, there are small channels that have a poorly sorted lag of mudstones and cobbles which are overlain by some very fine quartzitic sandstones and ptygmatic folds, polychromatic claystones. The channel lags are polymictic. The prevalent clasts are very polished, well rounded and reworked from the Naparima Hill Formation which was already well consolidated. The mudstones also have numerous small pockets of well sorted, fine-grained, quartzitic sandstones accompanied by conglomerates that have been contorted into little knots. There appear to be olistoliths or rounded well-lithified up to 30-centimetre long boulders which seem to float in these gypsiferous mudstones. Brent Wilson has sampled quite a few sites on this outcrop and so far found only arenaceous indigenous fauna; none age diagnostic, however he did find reworked Turonian age foraminifera.

Discussion

It would be helpful to accurately date the oldest coarse-grained sediment south of the Central Range because this would define the onset of orogenesis which would in turn help constrain the behaviour of the Caribbean Plate and the local extinction of the early Tertiary Petroleum system. In this outcrop, while the evidence for an orogenesis is prevalent, the timing of deposition cannot constrained any better than, younger than N2 (Carr-Brown, B. 2014) or between 23-18 MYBP because we have not found chronologically diagnostic foraminifera here. The soft claystones contrasts with the hard pebbles and the cobbles which, from their appearance, confirm a past that included of deep burial and consolidation before weathering, rounding and redeposition. The many dark sandstones are probably derived from Cretaceous provenances and the clasts of argillite and chert look like the scree that is currently shed from the cliffs at San Fernando so are probably derived from the equivalent interval that had also been deeply buried.

Kugler interpreted many of the outcrops of older rocks that lie within the Nariva Belt of the Central Range, to be olistoliths, some many cubic kilometers large, but he did not include San Fernando Hill in that group. Others, including Algar believed that the "olistoliths" are tectonic flakes. This distinction is important, because the latter infers the presence of the "olistristromic" lithologic units in the underlying strata moved upward by post-Nariva tectonics while as the former provides a mechanism denuding the provenence area of the "olistrostromic" units in syndepositional uplift. It is clear that the cobbles and boulders that float in a claystone matrix in the matrix at this locality are not tectonic flakes they are partly rounded. At the Bon Accord Boulder Bed Kugler (2001) described boulders, many cubic decameters large in a matrix of Nariva Formation mudstones, which based on this locality that is not an unreasonable observation. Could it be then that these boulders can be extrapolated to olistoliths the size of San Fernando Hill?

Most of the current plate motion (1.5 mm/yr.) is interpreted to have started after the jump that created the Northern Basin about 5MYBP along the Central Range Fault (Weber, J, et Al, 2009) and the Warm Springs Faults; (Babb. S., et Al., 2000) which are located between the northern Basin and this locality. By extension of that motion the Northern Basin has probably moved east less than about 50-70 km from this location. In contrast if the provenance area and the orogenic front did extend north of the El Pilar, then based on the same rate of movement the extended Northern Basin could have moved up to 350 km further east. That might imply a risk for the presence of a cretaceous source north east of Trinidad. Further east in areas not affected by the Oiligo-Miocene orogenesis; the Early Tertiary Petroleum System would be intact.

Many agree that there was a change in the plate motion during the Miocene. The Caribbean Plate motion had a southerly vector that would have caused south east contraction. This locality is currently mid-way between the proposed provenance area, and the bathyal environments which are less than 20 km south of here. These relatively short north-south distances invoke images of very steep paleo-gradients typical of very active tectonic margins. However, based on surface folds alone contraction has been estimated at of up to 40%. Additional contraction has also occurred along the reverse faults are currently shown on the surface maps and the synorogenic folds and reverse faults but that magnitude is unconstrained. Some interpret substantial tectonic transport distances on thrusts, so the current disposition of the facies belts could have been substantially wider on the Oilgocene and Miocene.

These compressed facies belts is not unique to the Central Range; on trend in Eastern Venezuela a similar the Caripita Formation, which is younger (N6-N9) than the Nariva Formation (N2-N5), typically contain sediment derived from unmetamorphosed equivalents of the Pointe-à-Pierre , Guayaguayare and Naparima Hill formations, shed south from an emergent and very near-by mountain range (Lamb. S and Sulek, J, 1965). Correlative equivalent of the Nariva Formation, the lower Caripita Formation, equivalent to the Nariva Formation, is often missing (Zambrano, S et al., 2010) by erosion. The age equivalent of the Caripita Formation N6-N9 will be visited at Mayo Quarry (Stop 6).

Stop 5: Whitelands; Pointe-à-Pierre Formation

Keywords: Pointe-à-Pierre Formation, turbidites, unconsolidated.

Access and Safety

The drive to Whitelands from Rafael Street will take 20 minutes mostly because the roads are bad. There are toilet stop opportunities en route if required so please let us know. We will take a 5 minute walk to the furthest part of the outcrop. This is private land; you are expected to leave no trace of your presence. We encourage you to keep hydrated, have a drink; we will be outdoors for 30 minutes and as a result please wear and carry protective apparel.

Overview

The Pointe-à-Pierre at this location consists of less indurated sandstones and claystones/shales and probably represents the less deeply-buried equivalents of the Piparo outcrop. Here the sediment has great reservoir potential.

Description

At this locality the Pierre Point and the Charuma Siltstone Members, consist mainly of steeply-dipping red and yellow sandstones and mottled grey claystones. The units show most of the typical, but rarely seen characteristic facies of the Pierre Point Member that lead to the interpretation that they were turbidite deposits. There are fining upward sequences and hints of fluted, erosional bases. Some of the beds are tabular and show few signs of grading and appear to have been deposited by a very large turbidite system. The claystones here are quite soft and the sandstones, while consolidated, are not as indurate as the ones at Piparo or those at most outcrops along the Central Range. Soft Pointe-à-Pierre Formation sandstones can be confused with Nariva Formation sandstones but the claystones here are different than the Nariva claystones we have seen so far. Scanning electron photomicrographs through some Pointe-à-Pierre sandstones show few signs of compaction, little cementation and in places coccoliths were found preserved in sandstone pore spaces (Erlich personal communication).

Discussion

While the interpretations may differ, at this locality the evidence favours very deep water settings with the sandstones transported by vigorous turbidity currents confined to bathyal conditions north of a shelf slope which also defined the northern edge of the distribution of the Navet and Lizard Springs Formations. It is thought that this location was at the southern edge of a northeast-trending trough into and along which sands and clays were transported mostly longitudinally by turbidity currents spawned from the shelf in Venezuela (Pindell, J., 2007).

In an early Tertiary petroleum system this package would make an excellent potential reservoir target; thick, massive, laterally persistent, poorly consolidated and uncemented sandstones. It contrasts with the cemented and compacted Pointe-à-Pierre at Piparo. This reaffirms the proposition that the Pointe-à-Pierre was a thick stratigraphic package, so thick that at its base it was so deeply buried that porosity was occluded while near the top of the same unit, the sandstones and claystones are unconsolidated. Uplift soon after deposition would have quickly denuded the capping seals of the Charuma Member and exposed the unconsolidated sandstones to rapidly erosion and recycling into reconfigured basins around the margins of the uplift. Later, when more consolidated sediments reached the surface these were eroded into pebbles and cobbles.

Stop 6: Mayo Quarry

Keywords: The Tamana, Brasso and Cunapo formations.

Access and Safety

The drive time from Whitelands to Mayo Quarry is approximately 10 minutes. On arrival we will have to go through some formalities before we are granted access so please stay on the bus until you are invited to leave. There will be a 20 minute walk to the furthest part of the outcrop. This is a quarry site so there will be heavy equipment moving at high speeds. Please be very vigilant on the main access road in the quarry, the truck drivers always seem to be in a hurry. You may be forced to walk through water and there may be some bush; please stay with the leader and the rest of the team. Trinidad Cement Limited (TCL) requires that you to have hard hats and that you wear long trousers. This session is expected to last 60 minutes; we will be in the sun and it will be hot. You should drink before you leave the bus and you should wear or carry protective gear.

Overview

Limestones and claystones from this quarry are ground into slurry and piped to the cement factory at Claxton Bay. The combination of lithologies, the faults and the structures here proved to be a "Rosetta Stone" for understanding the Miocene evolution of the Central Range. The three key formations - the Cunapo, Brasso and Tamana - occur extensively throughout the central parts of Trinidad; but they are not often seen together. The intercalated claystones are rich in planktonic fauna, can be well dated and chronologically correlated with events in the Southern Basin, and lithologically correlated with other units deposited on trend across the island. The conglomerates, limestones and claystones provide a fascinating insight into the depositional environments together with the burial and exhumation histories of the provenance area.

Description

Stratigraphic

The Tamana Formation at Mayo is an indurated and cemented, yellowish, planar-bedded, packstone-grainstone limestone that is interbedded with grey-blue, sometimes nodular or flaggy calcareous mudstones that are correlatable with the calcareous clays of the Brasso Formation. The mudstones and limestones are deposited in repeated cycles several metres thick and there is a sense of upward gradation from bioclastic mudstone to limestone. Elsewhere, even when the mudstone beds are absent, the limestones are arranged in coarsening upward cycles. Grains in the limestones include foraminifera, shell fragments, bryozoan, calcareous algae, pellets and ooliths. These beds were called "Amphistegina Limestones" (Kugler, H.J., 2001). Corals are conspicuously uncommon in growth colonies at Mayo but corals do occur elsewhere (Erlich et al. 1993 and Warton et al. 1985) and 41 different mid-

Miocene types have been identified in the Tamana Formation (Johnson, K. 2001). Bivalves are usually disarticulated, thin walled and mostly broken. Other mollusks, echinoids and very large sharks' teeth have also been found. The micro fauna are varied and abundant. Bed-forms are often obscured by extensive networks of branched ophiomorpha burrows. Claystones are dominated by grazing trails. The mudstones are nodular, frequently contain lenses of broken or whole gastropod shells and can be densely colonized by calcareous algae. At times the beds are rich in glauconite and appear greenish when fresh. Limonite leached from glauconite, in pellets or from fossil cavities, stains the beds yellow.

At this locality, vestiges (quarried out) of once more widespread lenticular clastic conglomerate units, sometimes several meters thick, and many decametres wide, are interbedded within the limestones. The beds are predominantly stacked packages of brownish-green mudstone in which there are layers rich in cobbles and pebbles. The clasts are sub-angular to well-rounded and appear to have been derived from a wide range of substratum that include fragments of already cemented Tamana Formation, large shells, quartz from the Pointe-à-Pierre Formation, chert and argillite from the Naparima Hill Formation, and dark sandstones and limestones, probably from the Cuche Formation. Many of the clasts are pitted by boring bivalves. Most of the clasts but particularly the cherts and the siliceous argillites have a distinctive polish or patina reminiscent of desert varnish. These beds are considered the distal equivalents of the Cunapo Formation (Erlich et al. 1993).

Structural

The Central Range Fault which is moving at approximately 1.5 cm. per year passes just north of the quarry at Mayo (Weber, J., 2012). The beds at the outcrop dip southeast at about 15 degrees and like many of the other limestone bodies of Central Trinidad are remnants of northeast-trending synclinal keels. The shortening direction is southeast. The maps indicate that the synclinal axis is transected by major northwest-trending faults - a pervasive trend throughout Central Trinidad. Faults in the outcrop are near vertical, oriented northwest and have well developed slicken-sides that indicate translation. Faults have left a rubble gouge in the limestones but the claystones show more plastic behaviour. Near faults and fractures there are reddish oxidation haloes that indicate fluid alteration.

Discussion

The Tamana Formation at Mayo was deposited in shallow to outer neritic water depths, on flat banks, occasionally emergent, but not typically coralline reefs as they are sometimes described. These are laterally and vertically intercalated with the Brasso and Cunapo Formations. The adjacent Brasso Formation micro fauna indicate that bottom conditions may have been sometimes stressed by oxygen minima caused by productivity. The presence of the conglomerates within the Brasso and the Cunapo Formations is consistent with Kugler's (2001) interpretation that the Cunapo was deposited by juvenile rivers that poured their load of pebbles and micaceous sands onto a shelf from a proximal provenance located to the north. The narrow shelf was generally clastic starved and conditions favoured the deposition of limestone, however episodic input by debris flows with coarse clastics and clays flooded the lime banks, currents and waves sorted the clays from the coarser clastics. The landward costal belt where the pebbles were bored, was probably occupied by mangroves and swamps which account for the common lignite fragments and the 'coalfields' found within the Cunapo Formation near Sangre Grande. The varnish on the pebbles suggests an arid hinterland, conditions ideal for debris flows. Recent work on the fauna in the Brasso Formation (Wilson, 2007) suggests that cold ocean currents reached the Central Range in the Miocene and these may have contributed to aridity. At the shelf edge, coarse material, together with the clays of the Brasso Formation were shed by southward-directed slumps or may have evolved into turbidites that delivered sandstones of the Herrera Member (N9) to depressions in a clear deep 'Cipero' ocean floor. It is important to date the oldest neritic sediments on the shelf because these facies indicate uplift, the development of a shelf, and the emergence of a provenance area which signals the extinction of the early Tertiary Petroleum System. Originally the uplift date was thought to be between N13 and N17 about (12.5-5.3 MYBP) and that the Tamana Formation rested unconformably on older Brasso, on early Tertiary and Cretaceous sediments (Kugler, 2001). This is clearly not the case; new recent biostratigraphic work has shown that at Gasparillo (Concord), at Biche and at Brigand Hill (Warton et Al 1985, Erlich, 1993 , Wilson, 2009) the Tamana is older, between N8 and N12 (or 15.0-12.5 MYBP) and consequently is age equivalent to parts the Lower Brasso which is turn overlain by the Upper Brasso Formation. This means that the underlying unconformity is older than previously thought. The oldest Brasso Fm. with neritic affinities that has been found to date is N5 which is about 23-20 MYBP. The base of the Tamana, because it does not outcrop at many localities, has not been sampled or dated but it can be assumed that it is older than N8 because it occurs in wells have been drilled below the Tamana facies at Mayo. The oldest Miocene "Tamana facies" are found in olistoliths that outcrop south of here, entombed in the Cipero Formation at St Croix where the surrounding beds were precisely correlated with N5. It was previously thought that these could not have been derived from the Central Range because at that time, the oldest known Tamana was thought to be N13, much younger than N5 and separated by an unconformity. Now that the shelf carbonates are known to be older than N8 it becomes easier to correlate these and to interpret the St Croix outcrop as an olistolith of Tamana limestone that was originally deposited on a shelf at N5 at about the same time as the earliest known Brasso Formation. The oldest Cunapo Formation conglomerates which are interbedded with the Brasso Formation further east along the Central Range, at Morne Brulee, are placed in the Catapsydrax Stainforthi Zone of Early Miocene age, N5 (Kugler, 1951, 1959) which is only slightly older than the oldest AFTA cooling age of 18 MYBP. It is therefore clear from these data that the uplift that created the shelf on which the Tamana was deposited and the hinterland from which the Cunapo was derived began no later than about 18-20 million years ago but could have started earlier.

In the 'Cipero basin' where there are fewer and shorter diastems than on the shelf and there is a record of numerous pulses of coarse clastic material that interdigitate with the pelagic marls and chalks. The stratigraphy can be exquisitely correlated with events on the shelf because the Cipero Formation like the Brasso Formation contains and preserves rich and diverse planktonic fauna and flora. So far, four major pulses of coarse material, called the Nariva, Retrench, Herrera and Karamat sandstones, are known. For reasons we have already discussed the Nariva Formation cannot be reliably dated, and its age should, therefore, be assigned large error bars. The oldest Nariva sandstones are thought to have been deposited as early as 30 MYBP, but could be younger. The next youngest clastic pulse is marked by the sandstones of the Retrench Member and these are associated with numerous indications of reworking, including olistostromes, cobbles and sandstones. These are confidently dated as N5, the same age as the earliest Brasso Formation. The acme of clastic input into the basin is called the Herrera member and that can be precisely dated at between N8 and N10 or 17-15MYBP, coincident with the ages of the top of the middle Brasso, the Tamana and the Cunapo facies at Mayo. Waning input after the Herrera deposition is correlated with evidence of subsidence and the back-stepping of the Tamana shelf into the Northern basin in the late Middle Miocene which resulted in the extinction of Tamana deposition in the Upper Brasso Formation on the shelf and into the Northern Basin.

The tectono-stratigraphic sequences in the middle Miocene in Trinidad are matched by those of the Maturin Basin of Eastern Venezuela where uplifted and folded Vidoño, Gayuta, El Cantil and Barranquin formation sediments are the provenance for turbidites of the Caripita Formation (Lamb and Sulek, 1965). No Miocene limestones are reported, but a small band of preserved middle Miocene Morichito Formation boulders and gravels up to 2,000 metres thick, derived from Cretaceous and Tertiary sediments, the equivalent of the Cunapo Formation, are preserved in the footwalls of major high angle reverse faults.

AFTA data confirms that the sediments in the Central Range have not been very deeply buried since the middle to late Miocene. This is supported by detailed studies of the diagenesis in the Tamana limestones. It is estimated that the Tamana Formation has not been buried to much more than a depth 2,500 feet prior to exhumation (Erlich et al. 1993). The final uplift of the Central Range included beds of the Manzanilla, Springvale and Talparo formations, and so must have been quite recent. The sandstones, claystones and the organic material in these sediments, exposed along the north flank of the Central Range appear to be very immature, with little evidence of thermogenic alteration.