DOI : https://doi.org/10.7186/wg483202201

Does the Caribbean hold lessons for SE Asia? Part 1: The geology of Trinidad

Harry Doust

Department of Earth Sciences, Vrije Universiteit, De Boelelaan 1105, Amsterdam 1081 HV, the Netherlands
Author email address: harrydoust@hotmail.com

Abstract: Together with a second note (Warta Geologi, April 2023) I summarise the geological development of the island of Trinidad and the adjacent margins of the Caribbean Sea in order to compare them with parts of Southeast Asia. I believe the two provinces provide valuable analogues for each other and I illustrate this by considering examples of tectonic style taken from transpressional fold belts in Trinidad and eastern Java, from the evolution of foreland- and wrench basin stratigraphy and from striking similarities between the stratigraphy and structure of Borneo and Trinidad Tertiary continent margin deltas.

Keywords: Geological evolution, Trinidad, Java, transpression, Borneo, deltas

INTRODUCTION

The geological histories of Southeast Asia and the Caribbean have much in common (Figure 1). Almost uniquely, they share a Late Mesozoic to Tertiary evolution driven by active plate tectonics and are surrounded by subduction zones or wrenched plate boundaries. Both include continental margin sedimentary basins that record ongoing extensional and transpressional movements and include small ocean basins, several resulting from back-arc extension.

In this note I summarise the geology of Trinidad. In part 2 (to be included in Warta Geologi of April 2023) I consider some lessons we can perhaps take from comparing these two areas.

WHERE DOES TRINIDAD FIT IN THE CARIBBEAN?

Trinidad is situated at the south-eastern extremity of the Caribbean Sea, adjacent to the boundary between the Caribbean and South American plates (Figure 2). Its sedimentary basin evolution records the opening of the Central Atlantic, 'intrusion' of Pacific derived ocean crust into the gap between North and South America and the Tertiary collision along the margin of South America. In spite of its small size, nearly all of the elements that reflect Caribbean evolution come together here and it has contributed much to studies of the interplay between structural development and stratigraphic evolution.

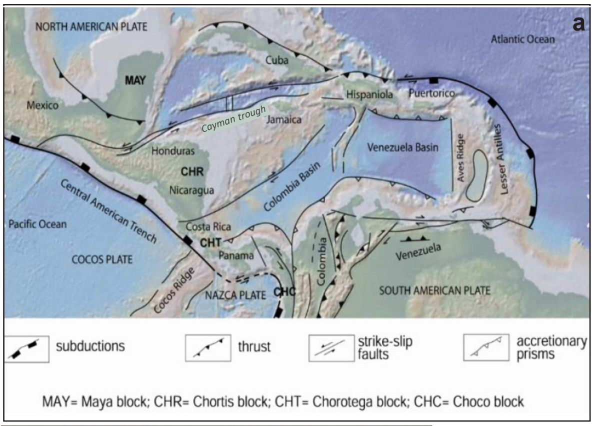
From the moment in 1595 when the notorious corsair Sir Walter Raleigh sent home reports of a huge lake of pitch in the southern part of the island, a tradition of geologic tourism grew and was succeeded in the 20th century by exploration for the petroleum resources. Among the most creative geologists to have worked there were Hans Kugler and Hans Bolli, who made ground-breaking advances in micro-palaeontological correlation in the post-war years and applied these to the interpretation of the complex subsurface structure.

What is most impressive is that so much geological variety is packed into this small area. The region appears to be so geologically rich and complex that, in spite of the extensive subsurface well data, it remains a huge challenge to unravel how structural and stratigraphic developments are linked.

SEDIMENTARY BASIN EVOLUTION AND TRINIDAD

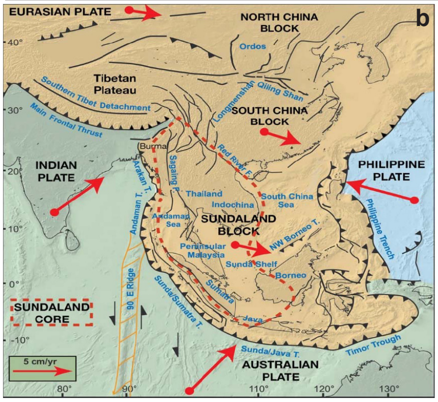
Sedimentary basin development can commonly be divided into distinct phases or cycles that reflect the evolution of the overall geodynamic environment. Many basins evolve from creation through crustal extension and subsidence (often associated with seafloor spreading), eventually to compression induced by plate collisions. Basins on the northern margin of South America follow such an evolution, complicated by extensive time-transgressive dextral wrench movements. Trinidad lies in a crucial location in this respect, since most of the collisional events are recent and the resulting geology is relatively "fresh", although complicated by extensive transpressive and transtensional shear deformation.

0126-5539; 2682-7549 / Published by the Geological Society of Malaysia.



Tectonic map of the Caribbean Plate (Colombian and Venezuelan basins). The surrounding deformed margins are dominated by large-scale wrench-induced inversion structures and island arcs bounded by opposing fold belts. The driving mechanism of basin evolution is the westward movement of the Atlantic Plate (including South and North America) relative to an essentially static Caribbean. Trinidad is situated at the SE corner of the Caribbean.

From Giunta and Orioli 2010, DOI:5772/18723



Tectonic map of Southeast Asia. As in the Caribbean, the area includes continental and arc-related terranes and ocean basins. Tertiary geological history was dominated by convergence of the Indian Ocean and Philippine Sea plates, accompanied by repeated transtensional back-arc extension. The province outer boundary is defined by a continuous active arc zone of subduction and transpression. (For a recent compilation of Caribbean Tertiary history see Geol. Soc. Sp. Publ., 328(2009).

From Metcalfe 2011, https://doi.org/10.1144/SP355.2

Figure 1: Tectonic maps of the Caribbean (a) and Southeast Asia (b), highlighting the similarities between their geodynamic frameworks.

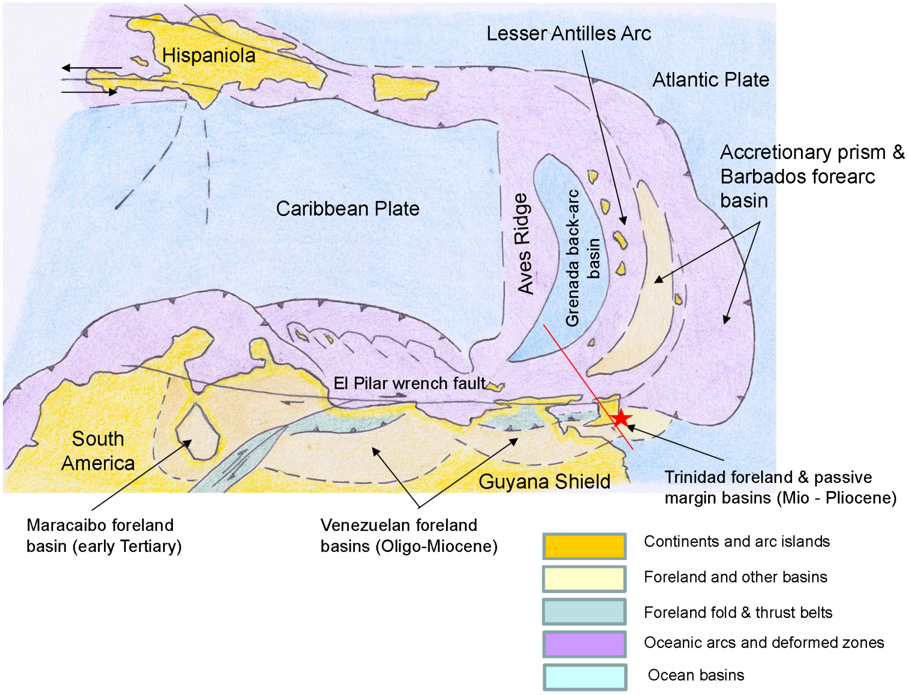


Figure 2: Geological province sketch map of the eastern Caribbean. The red line shows line of section Figure 3. Map not to scale.

CARIBBEAN EVOLUTION

Jurassic:

Opening of the North Atlantic was accompanied by the early break-up of Pangea, with rifting and drifting of North America away from South America. In the gap between North and South America, a Proto-Caribbean Ocean linked to the Atlantic developed which, by the Late Jurassic, was bounded to the south by a passive margin.

Cretaceous:

The South American plate started to be displaced westwards, triggering eastward subduction of the Pacific Ocean plate below its western margin. The Proto-Caribbean, however, started to subduct westwards below the Pacific Plate, producing an eastward-facing island arc (the Lesser Antilles). By the latest Cretaceous, the Pacific Plate started to over-ride the Proto-Caribbean and protrude between North and South America. As it did so, it became isolated between opposing subduction zones to form a separate plate, the (Neo) Caribbean Plate.

Early Tertiary:

The westward movement of the South American Plate led to a complex shear zone that progressed eastwards along the South American passive margin, reaching Trinidad in the Mio-Pliocene. Onshore, the shear zone is marked by wrenched compressional thrusts involving continent margin sequences accompanied by an eastward progressing foreland basin. North of Trinidad the Caribbean Plate grew through cycles of back-arc extension producing, for example, the Barbados Ridge and Basin (Figure 3).

Late Tertiary to Quaternary:

The Caribbean collision created a complex southward directed transpressive fold belt with an associated foreland cycle. Today the area is relatively stable and thick late Tertiary deltaic sequences derived from the Orinoco River accumulated in and around the evolving thrust belt.

SUMMARY EVOLUTION OF TRINIDAD

Pre-Mesozoic rocks are rare in the Caribbean area and younger events dominate the geology.

The Mesozoic to Quaternary evolution charts the progress from rift through post-rift sag into transpressive collision and post-compression cycles (Figure 2).

1. The rift cycle: Low-grade metamorphic rocks, including coaly sericitic phyllites and quartzites passing up into fossiliferous rudist limestones, cropping out in the Northern Ranges (Figure 4), possibly represent a Jurassic synrift cycle. Evaporites, found in the upper part, may correlate with Jurassic salt developments in and around the Gulf of Mexico.
2. The postrift cycle: During the Late Jurassic to Early Cretaceous thick sequences of deeper marine shales with limestones were deposited along much of the South American passive margin. Volcanics and submarine slumps reflect the proximity of Atlantic transform faults. By Late Cretaceous time abyssal conditions were established along the passive margin and bituminous shales were deposited. The postrift cycle continued into the Early Tertiary, where deep marine claystone and marls with turbidites dominate the sequence.
3. The transpressive collision cycle: By Mid-Tertiary times the eastward-progressing deformation margin of the Caribbean Plate had reached Trinidad. This resulted in the emergence of northern Trinidad, SSE-directed thrusting of the passive margin sequence associated with oblique transfer zones, and the formation of a deep marine foreland basin. As in other foreland situations sediments were now derived from

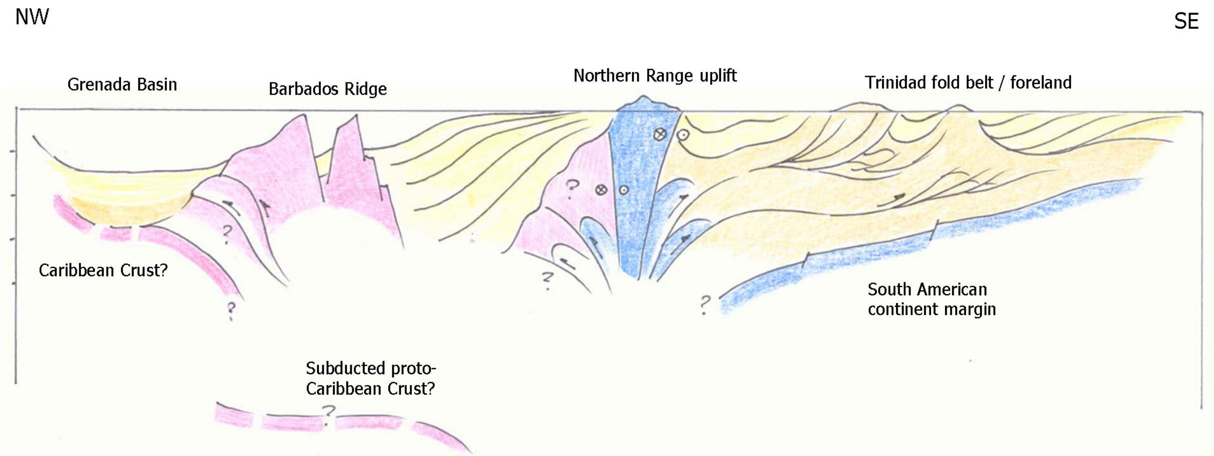


Figure 3: Sketched interpretation of structural provinces in the Trinidad area, compiled from various sources. Thicknesses approximate. The compressive wrench pop-up zone represented by the Northern Range has outward directed thrusts affecting both the Trinidad fold belt/foreland and the Barbados fore-arc ridge.

both the south (Orinoco River) and the uplifted zone to the north. The axis of deposition was displaced southwards through time and sediments filled the subsiding depressions, later to be sequentially incorporated in the southward migrating thrust belt. The foreland cycle sediments are highly argillaceous and under-compacted and often reach the surface as active mud volcanoes.

4. The post-tectonic foreland to passive cycle: Tectonic activity declined through the Pliocene and by the Quaternary was limited to wrench faulting and formation of a pull-apart basin, the Caroni Basin. A second passive margin cycle developed, and sediments from the Orinoco River prograded northwards and eastwards to build shallow marine deltaic sequences on and around Trinidad.

EVOLUTION OF THE FOLD BELT AND ITS INTERPRETATION

There are few places where a complex fold and thrust belt was investigated in such detail before seismic data became widely available. The abundance of the oil-bearing accumulations meant that dense grids of wells provided abundant subsurface coverage but unravelling the complexity of the structures meant that a sophisticated means to correlate formations was needed. This came from micro-palaeontological studies and the creation of a Tertiary planktonic foraminiferal zonation (Bolli *et al*., 2007). Interpretations of the subsurface structure and stratigraphy could now be made. Cross sections published by Kugler (1996) and his colleagues (Figure 5) showed enormous insight in resolving the structural complexity of oblique transpression affecting under-compacted sequences. They have stood the test of time and are largely confirmed by subsequent seismic data. Particularly impressive are early insights into the interplay between structural development and sedimentation, seen in many of the interpretations of the oil fields.

- Northern Range. The Northern Range constitutes a major sheared and uplifted dextral wrench zone, involving syn- and early postrift cycles, probably aligned along the northern boundary of the South American crustal block. The zone appears to form a flower structure associated with the El Pilar fault, with both northward and southward thrusts. Lateral slip along this fault is probably extensive, including 10 km of dextral slip during the Pleistocene.
- Caroni Basin. This represents the eastern extension of the Gulf of Paria, a pull-apart basin created at the end of the Miocene (~5Ma) at a releasing bend between ENE-WSW wrench faults. Prior to its recent history, this formed a piggy-back basin filled with Miocene (largely fluvial?) sediments overlying pre-Cretaceous rocks. Seismic data show an essentially symmetrical thick sediment fill locally inverted by transpression.
- Central Ranges and Naparima Hill thrust zone. The Central Ranges comprise a very complex zone of stacked imbricates involving the passive margin and foreland cycle sequences. Recent interpretations using seismic data indicate that the complexity may

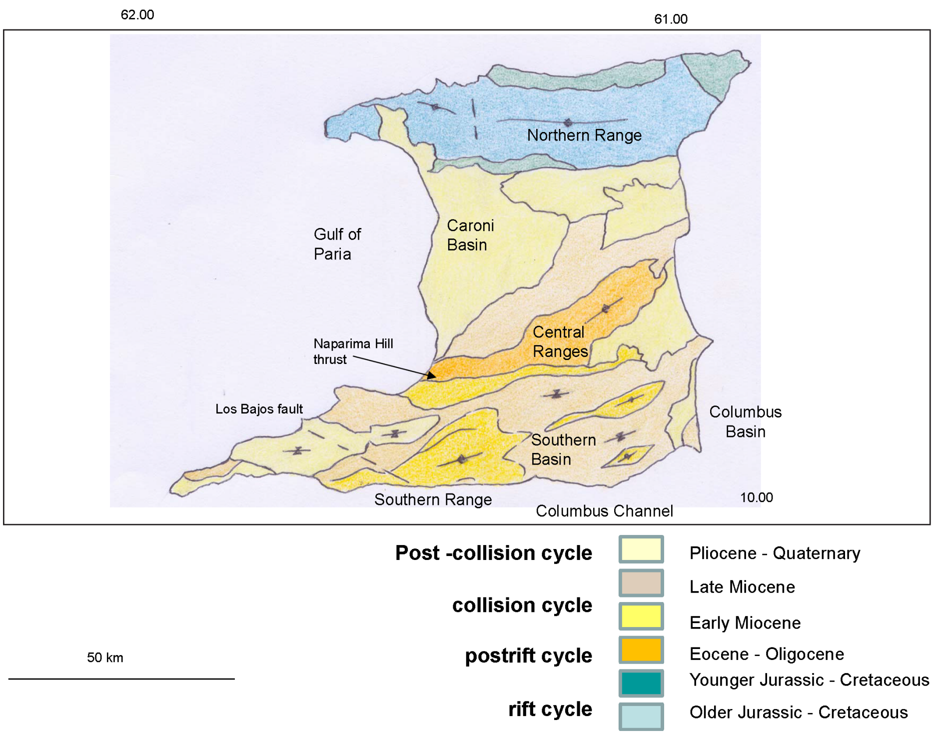


Figure 4: Sketch map of Trinidad geology, from various sources.

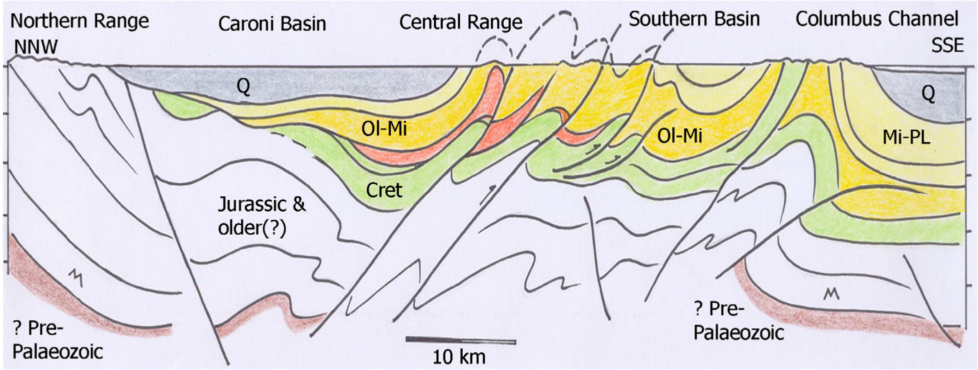


Figure 5: Simplified NNW – SSE section across Trinidad based on the insights of Kugler showing the transpressional foreland cycle basin. Re-drawn from: Kugler, 1996.

be greater than originally envisaged, with extensive wrench-induced Plio-Pleistocene out-of-sequence thrusting modifying earlier-formed structures. The concentration of such trusts may suggest that the area overlies a stepped basement, a possibility that is supported by the fact that the thrust with the greatest displacement, the Naparima Hill thrust (which brings Cretaceous rocks to the surface), extends eastwards into the offshore wrench zone of the Darien Ridge.

- Southern Basin. A shallow Pliocene piggy-back basin overlies complex out-of-sequence thrusts involving Oligo-Miocene and older rocks. As in the adjacent provinces, abundant evidence for structural detachment is seen on seismic profiles and extensive decollement horizons are probably present in the Late Cretaceous and early - middle Tertiary. Many of the oil fields lie in this zone, in complex Miocene imbrications complicated by clay diaprism. Pleistocene activity is restricted to wrench movement along the Los Bajos fault and back-thrusting.
- Southern Range. Much of this recently deformed zone probably represents inverted foreland /piggy-back cycles involving Late Miocene and Pliocene rocks. Folds are elongate with faulted axial plunges, often accompanied by Pleistocene cross-faults with clay diapirs. The southern limit is interpreted to constitute a back-thrust, probably marking the southern limit of the Trinidad fold belt and resembling the "triangle zone" at the deformation front of many fold belts. If so, this would imply that the sequence in the Columbus Channel is largely un-deformed and constitutes the present-day foreland cycle.
- Columbus Channel and Columbus Basin. In these areas thick sequences of Pliocene to Quaternary sediments derived from the eastward-prograding Orinoco Delta were deposited. The Columbus Basin delta is comparable to other Tertiary deltas such as those in West Africa (Niger Delta) and in SE Asia (Mahakam and Baram deltas), with prograding sequences affected by rows of NNW-SSE trending synsedimentary growth faults (Leonard, 1983). The delta sequence is underlain by NNE-SSW trending faults in the Cretaceous basement and where the growth faults cross these, anticlinal culminations formed in the late Pliocene.

In the second note I ask which aspects of Trinidad's geology could be relevant to the regional evaluation of Southeast Asian Tertiary basins.

ACKNOWLEDGEMENTS

I am grateful for the opportunity I have had to study these fascinating areas and am indebted to those who enabled me to indulge in my attempts to rationalise their basin evolution for myself! Constructive comments from two anonymous reviewers are kindly acknowledged.

CONFLICT OF INTEREST

I declare that there is no conflict of interest in this note.

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Manuscript received 28 May 2022;
Received in revised form 5 December 2022;
Accepted 6 December 2022
Available online 30 December 2022