Vertical Datums in a Fault Zone: Influences of Plate Tectonics in Trinidad, West Indies

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Key words: vertical datum

SUMMARY

Trinidad lies in the South East of the Caribbean Sea, seven kilometres at its closest point to Venezuela and the South American continent to which it was once joined. The fault zone of the East West lateral strike slip between the Caribbean and the South American tectonic plates has created the Gulf of Paria, which now separates the land masses. The fault zone extends across Trinidad in its entirety, with three major faults extending East West. It has been determined that in recent times it is the fault across the centre of the island that has been active, moving at a rate of 11mm a year. This fault runs North South in the Gulf of Paria before turning West again along the North coast of Venezuela. It is therefore hypothesised that the East West movement on the North South line has caused Trinidad to separate from Venezuela and created the Gulf of Paria as a pull-apart basin.

The void that has been created as Trinidad has moved away from the main continent has rapidly filled with sediments and organic material deposited by waters from the Orinoco river. Physical evidence of the rapid nature of deposition exists in the form of mud volcanoes and occasional eruptions of sub-surface natural gases that cause islands of mud to temporarily appear from the sea. Further verification is given by the local geoidal model, which shows a hollow to the South West of the island and a 3m variation in the geoid spheroid separation from a large mass comprising the Northern Range of the island to this Southern area, just 50km away.

Not only is the void filling with sediments, but it is also likely to collapse the South Western part of Trinidad and lead to a differential in the vertical displacement of the island through time. Analysis of tidal observations taken over 8 years in the North of the Gulf of Paria and 6 years in South Trinidad show that while sea level is rising at 1mm a year in the North, it is four times this amount in the South. The vertical datum that was established with reference to MSL in the North in 1938, but levelled to the South in earlier times when the railway was established, is now severely distorted. Chart datum is 0.730m below MSL in the North and 0.824m below this level in the South, but the survey marks that are in place no longer accurately represent MSL.

This contribution contrasts the advantages and disadvantages of different vertical referencing systems. This is important in the context of a small island state where the deflection of the vertical is an average of 11 seconds, the land mass is subject to vertical movement at different rates and discontinuities arise when existing standards for chart datum are adopted.

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1. INTRODUCTION

In modern times, geospatial data is readily transportable and applicable to a wide variety of applications. The information must therefore be seamless in nature and standards are of utmost importance. Differences in datums used for horizontal control are being addressed at national levels to enable the use of international positioning systems. While different techniques are available, mapping and charting agencies are enabling solutions that best suit their particular circumstances. Consequently, there is a move towards the use of WGS84 and ITRF reference frames that enable the integration and exchange of geographical data between independent bodies. Miller (2003) documents the status within the developing countries of the Caribbean.

Similar needs exist for vertical references, but the problem is quite different. On land a level surface is adopted and this would normally be connected to the geoid by establishment of Mean Sea Level (MSL). Even this is insufficient as level surfaces are not parallel and the surveyor levels an instrument on the local surface above the geoid to transfer levels across the terrain. Mather, Barlow and Fryer (1971) report that in Australia a 5m discrepancy was found to exist between the true geoidal height and the levelled height at the Johnson datum point, which is located centrally within the country. For the purposes of Charting, the datum is defined as "*a level so low that the tide will not frequently fall below it*", George (1995), and this vague specification has been interpreted differently by different agencies. It relates to sea level and is realised by data acquired using a tide gauge. This provides MSL and further analysis reveals a local correction to chart datum. Values are available for standard Ports, and can vary considerable over short distances depending on the nature of the local tidal constituents. Particular problems that are experienced in inland waterways and estuarine locations are discussed by the Canadian Hydrographic Service (2003).

A change in the vertical reference between discrete points is acceptable when information is presented over particular areas, such as on a paper chart. In digital format however, when the technology exists to provide continuity of the chart, the use of traditional datums becomes a problem. Due to the nature of the tides and spacing of datum points interpolation is not a practical solution. This problem is further complicated by modern data acquisition techniques that refer to a mathematical surface rather than a level surface, and differences between the two are not easily resolved at the required accuracy. Further difficulties arise when time is considered as a factor. Changes in both absolute and relative sea level impact on the traditional reference marks placed on land.

The West Coast of the island of Trinidad provides an ideal case study area to review the issue of vertical datums. On a daily basis the mixed, mainly semi-diurnal, tidal regime is at the micro-tidal level, and there is a change in chart datum along the coast. The local geology impacts by giving a significant variation in Bouguer anomalies that result in a depression in the local geoidal model. The geological cause of this feature may also be responsible for a relative change in mean sea level between datum points through time. This is quantified, but initially a review of the local geology is provided as a means of explaining the cause. On the basis of these results, the options for adopting a uniform datum that accommodate modern requirements are examined.

2. GEOLOGICAL SETTING AND THE LOCAL GEOID

Figure 1 shows the location of the Caribbean within the plate tectonic setting of the surrounding region. Global tectonic models such as GRSM 1.2 (2005) suggest that the lateral strike slip eastward motion of the Caribbean Plate is about 20mm a year relative to the South American Plate. This is accommodated within a broad and complex boundary zone within which Trinidad is located (Figure 2). Thus, unlike many of the islands in the Lesser Antilles, it is not volcanic in origin, and geologically is linked to Venezuela on mainland South America. However, Trinidad is now geographically separated from Venezuela by the formation of the Gulf of Paria. This was initiated about 10Ma ago by transfer of major strike slip displacement from the El Pilar and Caranay faults in the Paria Peninsula to the Warm Springs Fault across Central Trinidad. Thus a zone of transtension developed to form the pull-apart basin of the Gulf of Paria. Figure 3 provides an interpretation of the main characteristics and has been compiled using information provided by Teyssier and Weber (2004), Babb and Mann (1999) and Flinch *et al* (1999).

The map in Figure 4 is the CARIB97 (2004) model of the separation between the geoid and the WGS84 spheroid. The model provides support to tectonic models for the region. The geoidal depression in the Atlantic that parallels the Lesser Antilles island arc is an expression of the trench that is created by the subduction of Atlantic Ocean lithosphere under the Caribbean plate.

Another depression in the geoidal model occurs in the South West region of Trinidad. Topographic maps and bathymetric charts of the region show that there is no hollow in the terrain, and that in the geoid reflects a region of low density material that has been deposited rapidly in recent times. The undercompaction that accompanies very rapid sediment deposition leads to much onshore ground instability as evidenced by the state of many buildings. Further indications of young and rapid sediment deposition in the Gulf is demonstrated by numerous mud volcanoes and natural gas venting to the sea bed.

Considering that tectonic models suggest 20mm of Eastward movement across the land mass of Trinidad, indications from the local geology are that this may be taken up across a number of lines. A study undertaken by Balkaransingh (2001) used data acquired throughout the last century to show that movement across Central Trinidad was 11mm a year (see also subsequent reports by Weber *et al*, 2001 and Saleh *et al*, 2004). These authors refer to movement on the Central Range fault, however at the scale of the measurements taken this displacement could exist across either the Central Range Fault or the Warm Springs Fault. Other faults showed much less movement during this period, below the level of quantification using the techniques adopted. Further observations by Miller and Jules-Moore (2002) and Miller and Gopee (2003), confirm the value of 11mm per year across Central Trinidad over the period from 1998 to 2002. As the Caribbean plate has moved East, the Northwest-Southeast extensional fractures between the Warm Springs fault and the Casanay fault in Venezuala have caused Trinidad to move away from Venezuela creating the Gulf of Paria. As this space has opened, the void has filled with sediments from the Orinoco River creating the loose deposits of low density that are indicated in the geoidal model. Furthermore, the land mass of South West Trinidad is free to subside into the hollow.

To the South of the Central Range fault the terrain is undulating with two ranges of low lying hills that rarely exceed 150m in height. To the North the land is very low as far as the El Pillar fault, a large range of hills then extends across the North coast of Trinidad reaching a height of 940m. This land form continues beyond the Gulf of Paria into Venezuela. The differential between the low density material that fills the pull apart basin in the South West and the large land mass to the North creates a variation of 3m in the geoidal model in the North South direction shown in Figure 4.

3. SEA LEVEL

A vertical reference system was first established in Trinidad in the mid 19th century when the railway was introduced. An arbitrary datum point was located within Port of Spain and levelling was undertaken from this location, reaching Point Fortin in 1913 (Anthony, 1985). It was not until 1938 that a tide gauge was installed in Port of Spain and MSL established through one year of observations (Admiralty, 1987). Lowest Astronomical Tide (LAT) was calculated to be 0.730m below MSL. Point Fortin was established as a secondary tidal port sometime later using a lesser amount of data. LAT is documented in the Admiralty Tide Tables (Admiralty, 1987) as being 0.824m below MSL at this location.

More recently, the Hydrographic Unit within the Lands and Surveys Division of the Government of Trinidad and Tobago established tide gauges at both Port of Spain and Point Fortin. Hourly observations were made between 1984 and 1992 at Port of Spain and between 1986 and 1992 at Point Fortin, with both data sets being about 80% complete for their respective periods. Analysis undertaken by Miller (in press) used the Least Squares method presented by Wells, Vanicek and Pagiatakis (1985) to derive the coefficients for 14 harmonic constituents. In addition, coefficients were determined for atmospheric pressure and linear trend. Results show that sea level at Port of Spain increased at a rate of 1.0±0.1mm per year while the rate of rise at Point Fortin was 4.2±0.2mm per year. The result for Port of Spain is confirmed by considering MSL, which in 1984 was found to be 0.04m above the level that was established 46 years earlier. This corresponds to an increase of 0.9mm per year, which confirms the result and suggests that the average rate of sea level rise is consistent between establishment of the first tide gauge in 1938 and the end of the Hydrographic Unit data set in 1992.

At Point Fortin, an arbitrary level was established relative to Port of Spain in 1913, and this was tied to MSL in Port of Spain 18 years later. There is no connection documented between the early tidal observations made in this location and the level network. Experiences of Neale (author) who has spent the last 20 years undertaking hydrographic survey work in the region suggests that in the early 1990's MSL was about 0.4m above the local bench marks in Point Lisas, which lies about 30km South of Port of Spain. A similar variation was reported at Point Fortin by Jules-Moore (personal communication, 2002), a former employee of the Hydrographic Unit. This indicates that in 80 years, from the time of establishment of the arbitrary level, sea level rose by 0.4m, a rate of 5mm per year. This is a crude estimate as the total rise is approximate and it assumes that the early levelling was precise. It does however give credibility to the result obtained from the analysis of observations that were made between 1986 and 1992.

It is apparent that the rate of sea level rise in South West Trinidad is about four times that in the North West. The difference is likely to be due to the subsidence of South West Trinidad into the pull-apart basin of the Gulf of Paria.

4. RELATIVE VERTICAL LAND MOVEMENT

The Caribbean region is lacking in Continuous Operating GPS Reference Station (CORS) sites and other regularly observed control points. Repeat GPS observations have been made at just one point on Trinidad for extended periods with the aim of obtaining an accurate vertical solution. This point is adjacent to the tide gauge in Port of Spain, and being on the port is far from ideal in location. Observations were made for 60 hours in 1998, 36 hours in 2000, and 60 hours in 2002. It is reported by Miller and Jules-Moore (2002) that there is no relative vertical displacement when these data are processed in conjunction with data sets from CORS sites in South America (French Guyana, Brazil and Colombia). Due to the length of baselines involved and the poor site location, the accuracy achieved in the vertical component is ±7mm. This is similar to the displacement that might be expected and so this result is inconclusive.

Although data derived from GPS observations refer to a different surface, the implications are that there is less relative vertical displacement of land masses between North Trinidad and mainland South America, than between North Trinidad and the region of Point Fortin in the Gulf of Paria. Displacement experienced in South West Trinidad is therefore localised.

5. VERTICAL DATUMS

Over a distance of 50km across the Eastern side of the Gulf of Paria there is:

- A difference between chart datum and MSL of 0.094m, which represents 6% of the average tidal range.
- A difference of 3m in the geoid spheroid separation, using the WGS84 spheroid, which gives an average deflection of the vertical of 11 seconds.
- A difference in the rate of sea level rise of 3.2mm per year caused by localised vertical displacement of the land mass of South West Trinidad.

The impact of relative vertical movement has had a significant impact on the vertical reference points that were established early in the last century. Bench marks established in the South West of the island are now about 0.3m lower than those in the North, and neither correspond to MSL. Hydrographic surveys that were undertaken in the early 1990's with reference to a tide gauge located in the Point Fortin region that is referred to local bench marks by levelling will then relate to a level that is about 0.3m above LAT.

The satellite positioning technology that has allowed tectonic deformation to be quantified also requires reference frames to be adopted internationally. Now, similar concepts need to be adopted for vertical references to integrate data from different geographical regions and from both land and hydrographic surveys. It is now time to reconsider the vertical datum issue and identify a standard that considers these factors to be applied internationally. This has been achieved in some geodetic applications that incorporate satellite positioning by the use of International Terrestrial Reference Frames (ITRF). These accommodate tectonic displacement to provide control at the sub mm level. However, while they may be appropriate for geodetic work generally, they may not be suited to providing control in the vertical component.

In considering requirements for vertical control the following factors should be addressed:

1. The reference surface must be defined continuously. In the case of Trinidad the use of LAT for charting is defined at discrete points, and while LAT will be continuous between these points there is no knowing how it varies.
2. The same surface should be adopted for both land and hydrographic survey work. Users often require integration of land with hydrographic information in applications such as GIS. Data collected for the production of navigational charts should also be available for applications such as drainage, structural engineering, oceanographic studies and geophysical investigations.
3. The reference surface should be a physical surface such as a level surface rather than a mathematical surface such as a spheroid. Water flows across a level surface and applications such as drainage where water flow is the main requirement then height or depth relative to a level surface must be provided. Over large areas the use of dynamic heights would be a requirement whereby points on the same potential surface have the same height value irrespective of distance above the geoid.
4. Given the requirements for use of a level surface and that a geoidal model has not yet been developed to a sufficient accuracy to provide corrections to spheroidal heights, the use of a spheroid is not appropriate. In the case of the CARIB97 (2004) model, it is stated that "*systematic errors may appear as extreme (30+ ppm) tilts, over very short ranges, island by island*", and this is likely to be true in the case of the Gulf of Paria. Furthermore, the horizontal resolution of the grid on which CARIB97 is based is 2'x2', which provides insufficient detail at the island level. A more detailed model for Trinidad with better resolution has been developed by Edwards (1999) using local gravity data acquired by marine research vessels and exploration companies. A lack of data in the inaccessible Northern range and in Venezuela means that this does not provide the required accuracy either. A full assessment has yet to be made.
5. In a practical sense, the term orthometric height usually refers to a theoretical geoid that has been approximated by MSL for realisation. This is only an approximation, and in estuarine situations MSL is likely to be above the geoid. In the Gulf of Paria the North Westerly current from the Atlantic that brings water from the Amazon, together with the flow from the Orinoco, that includes watershed from the Andes in Colombia, will take MSL above the geoid. Modern techniques in satellite altimetry are capable of measuring this sea slope.
6. Any physical realisation of the vertical reference surface must accommodate vertical land movement. When considering CORS sites for GPS for example, velocity components are provided in addition to displacement at a particular epoch. Equivalent circumstances in the vertical component are documented for the region of the Great lakes, where the Canadian Hydrographic Service (2003) suggest a revision of the vertical reference system every 25-30 years to accommodate differential movement of the earth's crust.

Many of these requirements are understood and accommodated by existing standards. The difficulty lies in extending the function to include the capacity of modern technology and the dynamics of the environment, such as has been identified in this research.

6. CONCLUSIONS

The situation in Trinidad and the Gulf of Paria is typical of that which might be encountered anywhere else in the World, but the scale at which sea level variations are being considered is perhaps unique. Only relative variations have been considered and explained in terms of geology and geophysics, and there has been no mention of sea level variation at a global scale. Surveyors undertaking topographic or bathymetric survey work in Trinidad, using the network of bench marks that are supported by the Lands and Surveys Division of the Government, will now introduce errors in excess of 0.3m in some locations when stating the reference surface to which the vertical measures relate.

Given the island nature of the Eastern Caribbean, and environment in which people live, a significant change in sea level will have a direct impact on habitation and livelihoods. The complexity of the geology in the region is likely to lead to variation in trends over short distances. Such a scenario is possible in Trinidad, and a case was put forward in the preceding sections of this paper. A first initiative in monitoring must be the consideration of reference frames that enable different technologies to be employed, yet provides a comprehensive understanding of rate of change at regional, national and localised levels.

When considering the advances in technology that demand integration of survey data, together with those that provide heights from satellites, it is time for change rather than update. The survey community as a whole needs to reconsider the vertical datum issue to reconsider the applications, surfaces and physical realisation of reference frames.

REFERENCES

Admiralty (1987). *Admiralty Tide tables and Tidal Stream Tables, Volume 2, 1987.* NP 202-87. The Hydrographer of the Navy.

Anthony M (1985). *First in Trinidad.* Paria Publishing Co Ltd.

Babb S and Mann P (1999) *Structural and Sedimentary Development of a Neogene Transpressional Plate Boundary between the Caribbean and South American Plates in Trinidad and the Gulf of Paria.* In Mann P, *Caribbean Basins. Sedimentary Basins of the World*, Elsevier Science BV, Amsterdam, pp 495-557.

Balkaransingh S (2001). *The Computation of the Tectonic Displacement Field in Trinidad During the Twentieth Century.* MPhil Thesis, Department of Surveying and Land Information, University of the West Indies, St Augustine, Trinidad.

Canadian Hydrographic Service (2003). *Tides, Currents and Water Levels.* http://www.lau.chs-shc.dfo-mpo.gc.ca/english/VerticalDatums.shtml

CARIB97 (2004). http://www.ngs.noaa.gov/GEOID/CARIB97

Edwards K (1999). *The Computation of a Precise Geoid for Trinidad.* MPhil Thesis, Department of Surveying and Land Information, University of the West Indies, St Augustine, Trinidad.

Flinch JF, Rambaran V, Ali W, DeLisa V, Hernandez G, Rodriguez K and Sams R (1999). *Structure of the Gulf of Paria Pull-Apart Basin (Eastern Venezuela-Trinidad).* In Mann

P, *Caribbean Basins. Sedimentary Basins of the World*, Elsevier Science BV, Amsterdam, pp 477-494.

George K (1995). *Tides for Marine Studies.* Institute of Marine Studies, University of Plymouth, UK.

GRSM 1.2 (2005). *Plate Motion Calculator*. http://sps.unavco.org/crustal_motion/dxdt/model

Jules-Moore (2002). Personal communication.

Mather RS, Barlow BC and Fryer JG (1971). *A Study of the Earth's Gravitational Field in the Australian Region.* In UNISURV Report No 22. *Communications from Australia to Section V, International Association of Geodes.* XV General Assembly, International Union of Geodesy and Geophysics, Moscow.

Miller KM (2003). *Caribbean Datums and the Integration of Geographical Data*, Caribbean Journal of Earth Science, Geological Society of Jamaica, Vol 37, pp1-10.

Miller KM and Jules-Moore SA (2002) *Preliminary Results from CPACC Climate Monitoring*, 1st Caribbean Environmental Forum, CWWA, St Lucia, October 2002.

Miller KM and Gopee A (2003). *Validation of the Geodetic Transformation Parameters for Trinidad and Tobago*. Report to the Ministry of Agriculture, land and Marine Resources, Government of Trinidad and Tobago, August 2003

Miller KM (in press). *Variations in Sea Level on the West Trinidad Coast*. Marine Geodesy, Taylor and Francis.

Saleh J, Edwards K, Barbaste J, Balkaransingh S, Grant D, Weber JC and Leong T (2004). *On Some Improvements to the Geodetic Infrastructure of Trinidad and Tobago.* Survey Review, CASLE.

Simkin T, Unger JD, Tilling RI, Vogt PR and Spall H (1994). *The Dynamic Planet: World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics.*

Teyssier C and Weber J (2004). *Lithospheric coupling at the Caribbean-South America plate boundary: deformation and exhumation of ductile crust in oblique convergence.* http://www.geo.umn.edu/struct/caribbeanproject

Weber JC, Dixon TH, DeMets C, Ambeh WB, Jansma P, Mattioli G, Saleh J, Sella G, Bilham R and Perez O (2001). *GPS Estimate of Relative Motion Between the Caribbean and South American Plates, and geologic Implications for Trinidad and Venezuela*. Geology, Geological Society of America, Vol 29, No 1, January 2001, pp75-78.

Wells DE, Vanicek P and Pagiatakis S (1985) *Least Squares Spectral Analysis Revisited*, Technical Report No 84, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada.

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Figure 1. The Caribbean and Surrounding Tectonic Plates

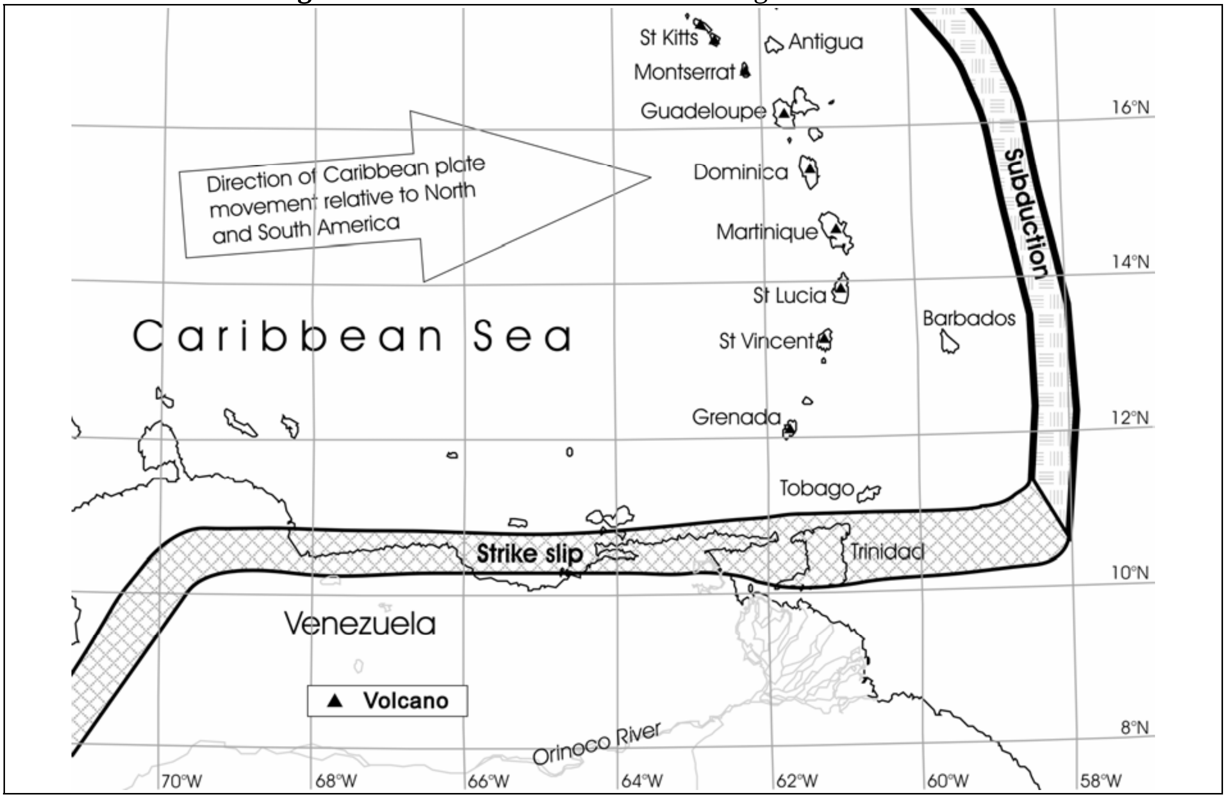

Figure 2. Plate Tectonics in the Eastern Caribbean. (Adapted from Simkin *et al*, 1994)

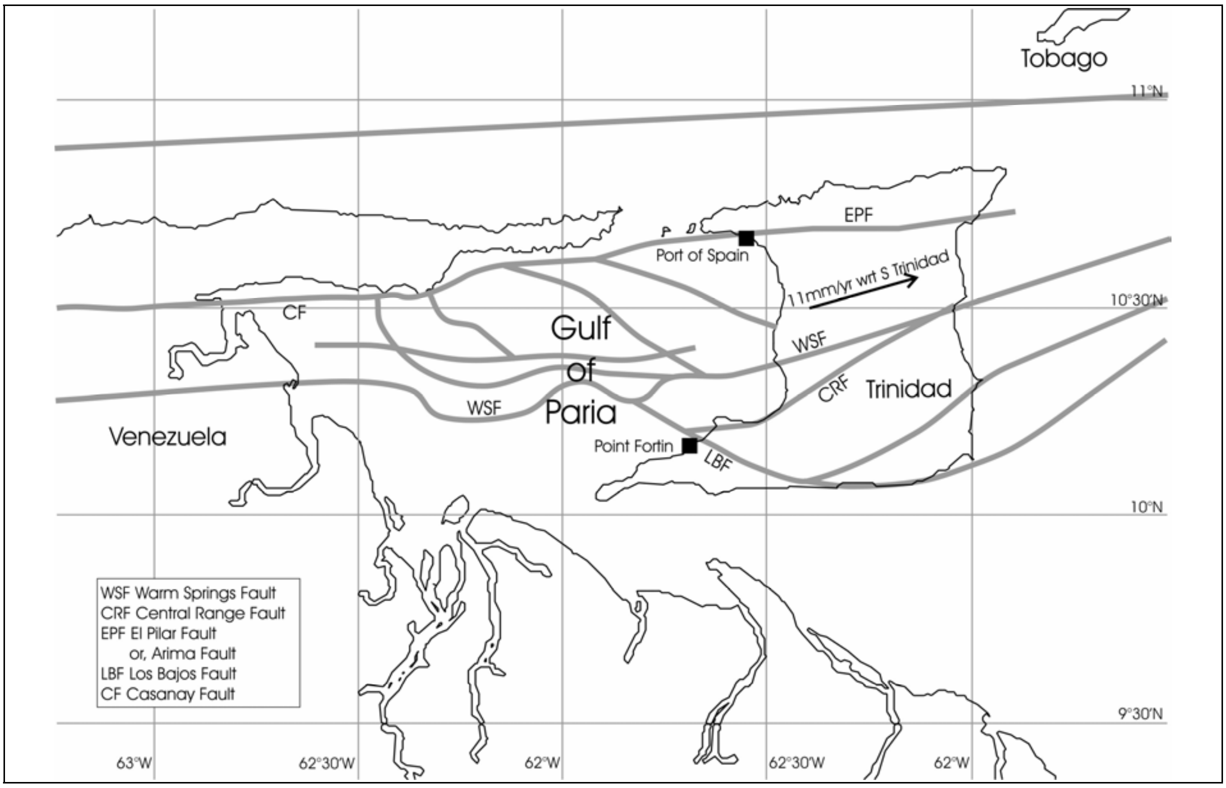

Figure 3. The Fault Zone Across Trinidad.
Adapted from Teyssier and Weber (2004), Babb and Mann (1999) and Flinch et al (1999)

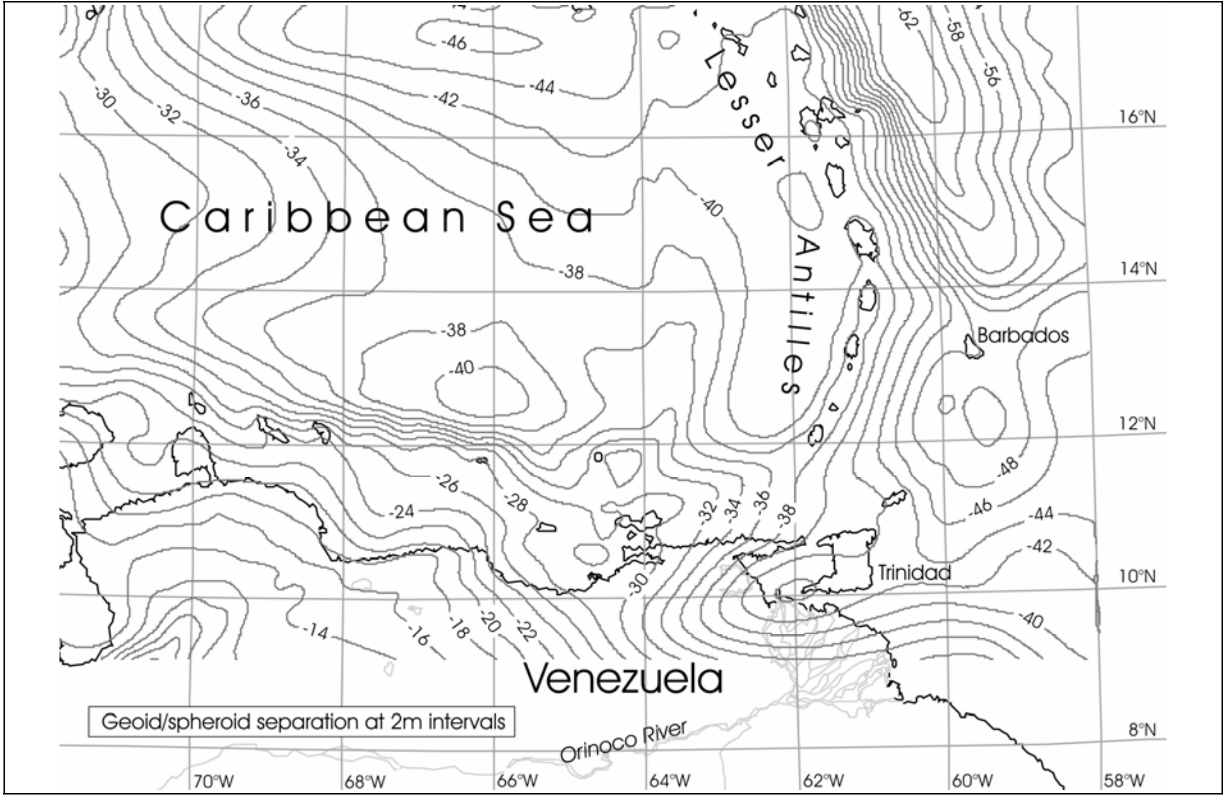

Figure 4. The Geoidal Model in the Eastern Caribbean, from CARIB97 (2004)