The Couva Children's Hospital and Training Centre: Geotechnical Site Assessment; Soil Mechanics and Engineering Seismology

1.0 Background

The Urban Development Corporation of Trinidad and Tobago (UDeCOTT) engaged the services of Dr Derek Gay of Earth Investigation Systems Limited (EISL), to prepare a position paper/commentary on geotechnical site investigations as relates to soil mechanics and engineering seismology. These areas were indeed covered in the Preliminarily Site Investigations by Trintoplan Consultants Limited (Trintoplan, January 2012), and by EISL in the Final Geotechnical Site Investigation Report for this facility (EISL, September 2012), as commissioned by SCG International (Caribbean) Limited (SCG), the Design Build Contractor for this project. These reports are contained in Appendix A1 and A2 respectively.

This position paper/commentary was commissioned in response to queries raised by Dr Joan Latchman – Ag. Head of the UWI Seismic Research Centre (SRC), Mr Shyankarran Lalla - Chairman of the Building Codes Committee of Trinidad and Tobago, the ODPM, Mr Mark Francois - Director/Engineer BBFL Consultants Limited and a group of engineers who wished to remain anonymous. These concerns were first raised in the print media beginning with a cover page article dated Friday August 9th 2013 of the Trinidad Guardian. Subsequent to additional print media articles on Sunday August 11th 2013, Dr Latchman forwarded a letter to The Honourable Dr Roodlal Moonilal, Minister of Housing, also dated August 11th 2013, voicing formally her concerns regarding the siting and building of the proposed Facility at the location intended. This letter is attached as Appendix B.

In response to this letter, Dr Moonilal convened a meeting co-chaired by The Honourable Dr Fuad Khan, Minister of Heath, to meet the concerned parties so that their views/concerns could be formally heard. This meeting was held on Friday August 16th 2013. The SRC was represented by Dr Joan Latchman, Mr Lloyd Lynch and Dr Richard Robertson. Also in attendance were Mr Shayankarran Lalla, Dr Krishna Persad (an eminent Petroleum Geologist), engineers and other representatives from the executing agency, UDeCOTT, and the design-build Contractor, SCG International. Mr Lloyd Lynch spoke on behalf of the SRC, Dr Krishna Persad spoke briefly on the integrity of the Central Range fault system and I addressed the meeting on behalf of UDeCOTT and SCG. Mr Mark Francois was notably absent, although he indicated via personal communication that he was not formally invited to attend. All issues indicated in the letter by the SRC to the Minister were raised and discussed and a press conference hosted by the presiding Ministers was held immediately afterwards. A summary of the findings and conclusions of this meeting, as articulated by Ministers Moonilal and Khan, was reported in subsequent press releases.

After the meeting further concerns continued to be raised, but these appeared to be centered principally on the issue of "site-specific analysis" which Mr Francois was quoted to have raised, as reported in the first press article on this matter. Should subsequent press releases prove to be accurate, "anonymous engineers" also raised similar concerns, suggesting that site investigations might be flawed and demanded that the Site Investigation Report be released. In the wake of these publicly articulated questions, and to assure concerned stakeholders that this project was indeed not standing on "shaky ground", the UDeCOTT thought it prudent to address these concerns by agreeing to release the Geotechnical Site Investigation Report along with an articulation/commentary/position paper outlining the procedures followed to date as they relate to site development and building design. In addition, this commentary was also mandated to speak directly to the issues aired in the public domain and in a letter from the Ag. Head of the SRC to the Honourable Minister Moonilal dated August 11th 2013. This articulation is the subject of this report.

Although the concerns raised could be presented as a numbered list and addressed in like manner, I believe that addressing the concerns raised might be better served through a description of the engineering design process executed to date, and treating with said concerns as they might be related to any particular element/stage of the design process. Those that are not would be dealt with separately.

2.0 Site Selection

Although site selection did not form part of EISL's brief by the SCG, we are aware that this site was one of two locations evaluated for the proposed hospital and after internal evaluations by UDeCOTT, the current location was thought to be more appropriate. However, we were mandated to report back to the client any findings that might negatively impact the development of the project upon completion of the site Reconnaissance, Desktop studies and review of the Preliminary Site Investigations. This first phase of our investigation indicated no significant areas of concern except that the mapped site soils appeared to include clays of high plasticity, which indicated a potential for volume change (expansive clays) and instability on slopes. Both these phenomena are well known to geotechnical/civil engineering practitioners who have encountered and treated with such challenges in the past.

The site of the proposed hospital is located at approximately 1150510 N, 673419 E, as illustrated in Figure 1.1 (EISL, Sept. 2012), which is approximately 25 km south of the CRH/UBH intersection and 1.5 km from the Couva Overpass along the Sir Solomon Hochoy Highway.

3.0 Site Investigations

Details of the site investigation brief by SCG are described in our report dated September 12th, 2012 as contained in Appendix A2. The site was assessed under its typical headings consistent with a final design geotechnical assessment report in accordance with ASTM and British Standards. In summary, the Field Investigations included 15 boreholes, 9 test pits and several DCPs (Dynamic Cone Penetrometer) tests along proposed roadway routes. Site characterisation and assessment studies were also carried out under the following headings: Topography and Drainage, Geology and Seismicity, Hydrogeology, Climate, Vegetation, Soils and Landslide Susceptibility. The results of Field Investigations, Laboratory Investigations, Geotechnical Foundation Analyses, Conclusions and Recommendations also form a substantive part of the report, details of which are included in EISL's report as Appendix A2.

The principal findings of the site investigations as they pertain to this commentary can be summarised as follows:

3.1 The site is located at approximately 1150510 N, 673419 E, about 25 km south of the CRH/UBH along the Sir Solomon Hochoy Highway. This places it within 6 km of Central Range Fault System (CRFS as referred to in the EISL Report Figure 3.1, but shall be referred to as the CR/WS fault hereinafter). Although EISL identifies and acknowledges that this system could be active (slip displacements along a fault lineament), it believes this feature to be predominantly aseismic. It does not support the view that a Magnitude 7.5 event should be recommended for consideration as the arguments put forward in the literature appear to be preliminary and inconclusive at this time. EISL is of the view that the seismic hazard is adequately served by the probabilistic processing of historical seismicity as carried out by the Seismic Research Centre in currently available seismic hazard maps. This Probabilistic Seismic Hazard Assessment (PSHA) methodology using historical data and source modelling is a globally accepted standard and is consistent with the methodologies and source zone processing executed by the UWI

Seismic Research Centre since 1997 to date (September, 2013). This topic will be expanded upon further in this report as it appears to relate to a substantive concern raised by the SRC and others.

3.2 The results of borehole site investigations indicate the site soil stiffness profiles as inferred from SPT correlated [1]shear wave velocities (V_s m/s), to be classified as [2]Site Class D as per the analyses carried out in the report. EISL collaborated with the design architects and engineers HKS to develop the site by creating terraces at major structures so as to remove the influence of the relatively weak and fissured near-surface soils (within 2.5-3.0 m). However, EISL recommended the site be placed in a lower Class E (more critical), given the importance of the facility and the uncertainty associated with fissured plastic soils on slopes. See Figure C1 of this commentary.

3.3 The majority of soils founded at the site can be classified as clays of medium-high volume change potential (expansive clays). A sand formation was also encountered at the site. Recommendations to implement foundation designs to mitigate the effects of expansive clays are also presented.

3.4 The site topography and soils encountered on slopes also suggest a potential for the development of shallow landslides. Recommendations were made that all cut slopes be maintained at less than 1:3, in conjunction with surface and sub-surface drainage close to principal infrastructure.

It is clear that items (3.1) and (3.2) above, relate to the principal concerns of the Seismic Research Centre and others, hence, these shall be addressed as follows:

[1] The speed that a seismic wave would travel within the medium; high speeds=hard soil/rock, low speeds=soft soils/clays

[2] Site Class scale A-F: A=very stiff soils/rock, F=soft relatively unconsolidated sediments (swamp/saturated alluvium)

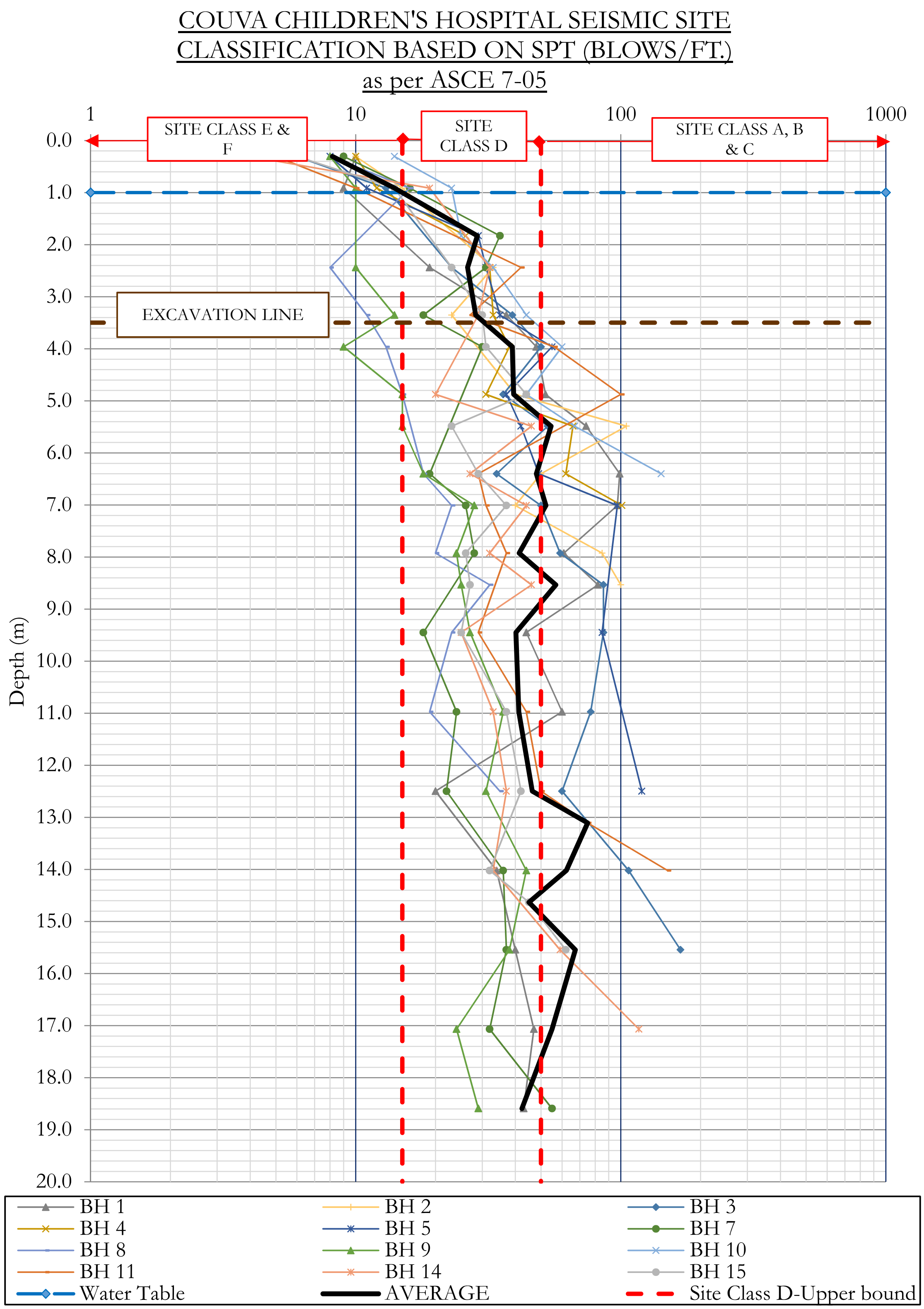


Figure C1 SPT N value distribution over depth, all site Boreholes and Site Class ranges indicated (dotted red lines).

4.0 Engineers Design to Seismic Codes:

4.1 Introduction

Concerns Are:

"It is a very serious situation. It is in the interest of any society that is in a zone where you have significant seismic activity to put every measure in place to ensure that your hospital is functional after a major earthquake," [Attributed to Dr Joan Lacthman]

"It is almost impossible to mitigate the effects of damage that is expected in the near fault zone of a large shallow earthquake.

For this reason, the international best practice is to establish setback from mapped active faults and apply strict zoning rules." [Latchman, August 11th 2013, letter to MP]

I could not agree more with the sentiments expressed by Dr Latchman, as it is indeed something to be taken seriously, and I, like many other Civil Engineers that practice in the region have indeed taken this very seriously

4.2 The Early Years

I can attest to the period, post mid nineteen seventies when academic and consulting professionals adopted the then SEAOC (Structural Engineers Association of California, first published in 1959) as a part of their own due diligence and best practice, mandated only by a moral obligation to *best practice* at that time. After its last version in 1999, the SEAOC's *Recommended Lateral Force Requirements and Tentative Commentary*, gave way to the UBC (Uniform Building Code), then to the International Building Code (IBC) which references the ASCE7 (American Association of Civil Engineers, Building Standard), beginning around 2000 to its most recent incarnation ASCE7-10 and IBC 2012.

4.3 Current Code Status

The current standards as mandated by the MOWI refer to ASCE7-2005 and IBC 2006, but their current printed communication on this suggests an expiry date of December 2010. However, the 2009 update of the IBC provides little change over the 2006 edition. These Codes include strategies to address near-source seismic effects, soils of widely varying stiffness, liquefaction susceptibility and can be used to implement user defined extreme value probabilities or the minimum recommended code-based recommendations as desired. Seismic Design Codes also contain building occupancy factors (for important/critical facilities) and design requirements for non-structural building elements.

Most engineers in Trinidad and Tobago find the current guidelines onerous as the newly adopted risk level changed from a 10 % probability in 50 years, to a 2% probability and if we adopt the 2012 to a 1% probability, these correspond to 475, 2475 and 5000 year return periods for the design event (Maximum Considered Earthquake MCE and Risk Targeted MCE). However, in some areas the US seismicity risk levels have been **decreased** with the ASCE7-2010, IBC 2012 revisions for areas of low background seismicity not unlike the levels experienced in Trinidad.

4.4 Location and Setbacks from Faults

According to Section 1613 of IBC 2009, a building or structure assigned to seismic design category D, E or F as defined in Section 1613 of the IBC or ASCE 7-05 shall not be sited over an identified active fault.

Currently, there are no definitive setbacks from active fault zones. Different building codes specify different minimum setback requirements. For example, in Snohomish County, Washington, the ***Snohomish County Code*** has specified a 50 ft. (15.2 m) setback from the closest edge of the active fault.
(http://www.codepublishing.com/wa/snohomishcounty/html/SnohomishCounty30/SnohomishCounty3051A.html).

McCalpin (1987) has recommended minimum setbacks of 40 ft. on upthrown side and 50 ft. on the downthrown side for Wasatch Normal Fault in Utah.

In California, the ***California Building Code*** defines the distance from an active earthquake fault as "*the distance measured from the nearest point of the building to the closest edge of an* ***Alquist-Priolo Earthquake Fault Zone*** *for an active fault, if such a map exists, or to the closest mapped splay of the fault.*"
(http://publicecodes.cyberregs.com/st/ca/st/b200v10/st_ca_st_b200v10_16a_sec013.htm)

In response to the San Fernando Earthquake in 1971, the Alquist-Priolo Earthquake Fault Zoning Act (formerly known as Alquist-Priolo Special Studies Zones Act of 1972) was enacted. The main purpose of the act is to prevent the construction of buildings used for human occupancy on the surface trace of active faults.

The California State Geologist defines an active fault as a fault that has previous surface displacement within the Holocene period (the last 11,000 years). A potentially active fault is defined as any fault that has surface displacement during Quaternary time (last 1,600,000 years) but not within the Holocene period. Earthquake Fault-Rupture Zones have been delineated along the traces of active faults to prevent the construction of urban development across the trace of active faults.

The boundary of the fault zone is approximately 500 feet from major active faults and 200 to 300 feet from well-defined minor faults. Geologists can mitigate the hazards associated with active faulting by identifying the location of the fault and allowing for a setback for structures for human occupancy from the zone of previous ground rupture.

(http://www.ci.arcadia.ca.us/docs/deir_4.6_geology_7-19-10.pdf)

In Trinidad and Tobago we have no detailed fault maps to the scales of the topography and soils 1:25,000 and better. The fault maps that engineers currently use are of the order of 1:150,000, where the width of the ink that draws the fault line is approximately 1.5 km wide. Hence, setbacks of the order of that indicated in the previous paragraphs can hardly be set out at such scales. As stated previously the site of the Couva Hospital is approximately 6 km from the CR/WS fault at its closest projection.

4.5 Implementation of Codes can make the difference: Empirical Evidence

In earthquake prone areas like California USA, there are strict building codes requiring the design and construction of buildings and other structures that will withstand a large earthquake. In 1986 an earthquake near San Francisco, California with a Richter Magnitude of 7.1 killed about 40 people. Most were killed when a double decked freeway collapsed. About 10 months later, an earthquake with magnitude 6.9 occurred in Armenia, where no earthquake proof building codes existed. The death toll in the latter earthquake was about 25,000! (Nelson, 2012)

Another contrast occurred in 2010. On January 12, an earthquake of Moment Magnitude 7.0 occurred in Haiti, epicentre close to the town of Leogane. The destruction was of biblical proportions with an estimated 200,000 deaths. On February 27, a Moment Magnitude 8.8 earthquake occurred in Chile, a country where earthquake resistant building codes are enforced. The death toll from this larger earthquake was about 520, again, proving the effectiveness of building codes. (Nelson, 2012)

On my visit to Haiti 5 days after the 12^{th} January 2010 Magnitude 7.0 earthquake as part of the Caricom Technical Team/Mission, I had the opportunity to witness first-hand what appeared to be almost complete devastation of Port Au Prince and Leogane (Town close to Epicentre of Earthquake). However, amongst the ruins and to my complete surprise there were buildings in Port Au Prince and Leogane that survived the earthquake with minor structural damage. The most striking of these was a church in Leogane approximately 7 km from the earthquake epicentre and within the fault fracture zone (Near Field), which stood with only minor cracks. Being of Roman Catholic provenance some of the surviving residents confided that it was really God that saved the church. I am hence reluctant to assign credit to the design being carried out to the French (Antilles) Seismic Building Code (as my Civil Engineer guide had subsequently indicated). He also indicated that many of the structures that survived the earthquake in Port Au Prince were also built to this or similar Code, including that of the Caricom Ambassador's home and his own. However, the number of non-engineered buildings in Haiti is in the vast majority.

Port Au Prince Haiti 2010; lower two buildings on Dense Soils/Rock (Site Class B), all others on alluvium (Site Class C-E), (Gay, 2010).

Leogane, Haiti 2010. All buildings on Alluvium (Site Class D-E), (Gay 2010)

5.0 Seismic Hazard: Maximum Expected Ground Acceleration

5.1 PSHA DSHA

Seismic Hazard in engineering design can be expressed as the maximum expected value of a ground motion parameter (displacement, velocity, acceleration) that can be experienced at a site of a proposed building. In most current codes of practice the ground motion parameter used is typically horizontal acceleration (vertical some codes) at bedrock and these are derived through either through Probabilistic Seismic Hazard Assessment (PSHA) methods or Deterministic Seismic Hazard Assessment (DSHA) or a combination of both.

I shall attempt to describe briefly here the PSHA methodology here as this is the type that currently applies to the Seismic Hazard Maps and Design Codes that we use in the region. Interested persons can review any of the standard texts on Earthquake Engineering/Engineering Seismology for detailed treatments of these methods.

The PSHA methodology produces values of ground acceleration at a site/location at its bedrock horizon (which could outcrop the surface or be buried below weaker sediments) as generated by earthquake vibration energy emanating from a particular area, line or point (source), within a specified timeframe. The problem is posed in a geometric, temporal and probabilistic space;

(i) Where am I located?
(ii) Where/how far away is the earthquake energy coming from and in what direction?
(iii) What is the size of earthquakes that I can expect?
(iv) How many times in my lifetime are these going to visit me?

If you gave a good answer to all of these questions, then you can carry out a Deterministic Seismic Harzard Analysis (DSHA) on the back of a large envelope or mobile smartphone. If you are not sure of the answers to any or all of these, you must turn to a PSHA.

In a PSHA analysis, the maximum expected ground acceleration value at bedrock at a site is normally computed at a 10%, 2% and 1% (ASCE7-2010, IBC 2012) [3]probability of exceedance in 50 years. Given a Poisson type distribution of the earthquake occurrence, the return period of the expected earthquake event would be 475, 2475 and 5000 years respectively. The PSHA methodology therefore requires knowledge of the location(s) of the causative source, defined as a Point, Line or Area. The earthquake sizes/magnitudes associated with these sources are then

[3] The likelihood (1/10) that the specified value of ground acceleration (g) would be equalled or exceeded at a specific site in the design life of a structure placed there. In this case the structure's design life is assumed to be 50 years.

characterised as a rate/frequency (event per year > M; recurrence rate) and the probability derived that you would experience a specified value if you sit at that site for 50 years.

Prior to 1978 the issue of engineering seismic risk in the English-speaking Caribbean, had never been addressed using probabilistic methods that could be applied to then current seismic design codes. It was in 1978 that the First Caribbean Conference on Earthquake Engineering was held in Trinidad (Chin, 1978 editor). It was at this Conference that this author presented one of the first papers in this area of Probabilistic Seismic Hazard Assessment (Pereira and Gay, 1978) for Jamaica and Trinidad respectively. This probabilistic methodology was based on algorithms presented on a ground-breaking paper by Allin Cornell and implemented/modified by Mc Guire and is now known as the Cornell-Mc Guire methodology (Cornell, 1968, Mc Guire 1976). This fundamental algorithm/methodology has remained the same over the years and remains the cornerstone of PSHAs, notwithstanding tweaks to the probabilistic models and the manner of handling epistemic and aleatory uncertainties (Mc Guire 1976, 1977, Bozzoni et al. 2011).

5.2 PSHA SRC Studies/Maps

During his tenure as Director of the Seismic Research Centre, Professor John Shepherd, produced Probabilistic Seismic Hazard Assessment (PSHA) maps from about 1997 through 2008 for the Eastern Caribbean tailored to the requirements of the Uniform Building Code (UBC) and then International Building Code (IBC) Standards requiring the Seismic Hazard to be represented by maximum expected values of bedrock acceleration at a 2% probability of exceedance in 50 years (Shepherd 1997, 2003). These post-2000 maps provide acceleration values at two spectral periods; S_s = 0.2 seconds and S_1 = 1.0 seconds. Engineers then use these values as primary inputs into their seismic design considerations as per the ASCE7-05 IBC 2006 procedures. These maps remained in place until around 2010.

In March 2010 the EUCENTRE in conjunction with the SRC completed studies to update the existing maps using Probabilistic Seismic Hazard Assessment (PSHA) methods. These revised maps and the methodologies implemented were first presented in a report dated March 2010 (Giovanni Lai et al., 2010 [EUCENTRE-SRC]). The comprehensive technical paper describing the details of this methodology in a paper entitled "*Probabilistic Seismic Hazard Assessment at the Eastern Caribbean Islands*" was published in an esteemed journal, the Bulletin of the Seismological Society of America (BSSA) a year later in October 2011 (Bozzoni et al 2011). The SRC were co-authors on both these publications, as represented by Dr Joan Latchman, Mr Lloyd Lynch, and Dr

Richard Robertson. These publications are included in Appendix D and illustrations of the seismic hazard maps and models are included in Figures C2 through C6.

Note that in all seismic hazard maps between 1997 to present September, 2013, the influence of the CR/WS fault is notably absent. The Eastern Caribbean model uses a total of 15 Source Zones as illustrated in Figure C5. Trinidad is influenced by Source Zones 10a, 10b, 11 and 12, in particular Zone 12 which covers the full areal extent of Trinidad, representing an areal source of **uniform seismic hazard, despite the knowledge of the alledged activity of CR/WS fault coming to light in 1992 (Latchman 2013, Appendix B), as endorsed in their 2010 and 2011 analyses.** See Figures C13a, C13b and C14 in following sections.

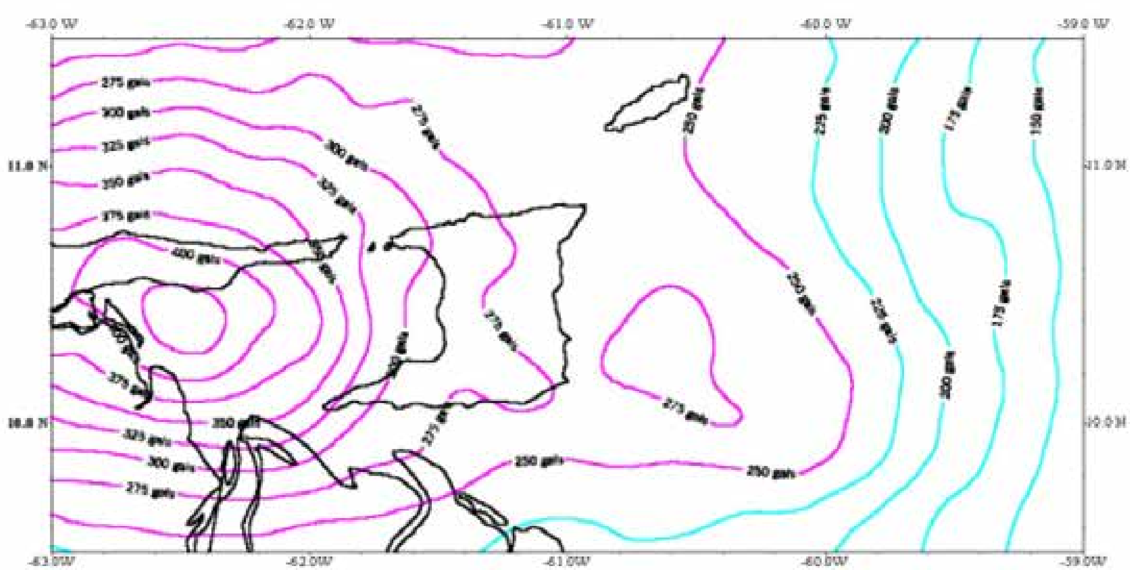


Figure 5: 1997 Seismic hazard map for Trinidad and Tobago

Figure C2 Shepherd 1997; Note absence of CR/WS fault

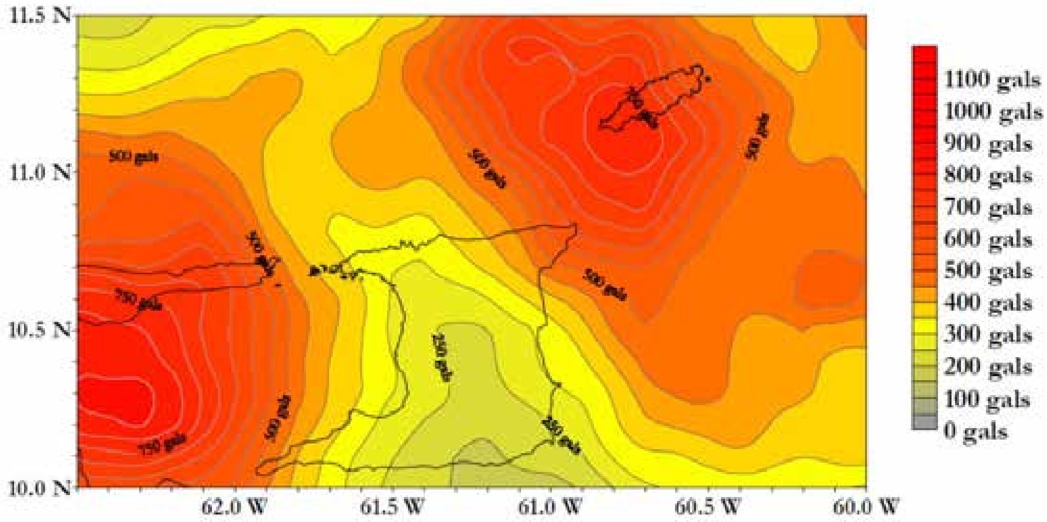


Figure 10: Spectral acceleration at 1.0 seconds period. Ground acceleration with 2% probability of exceedance in any 50-year period. Units are gals.

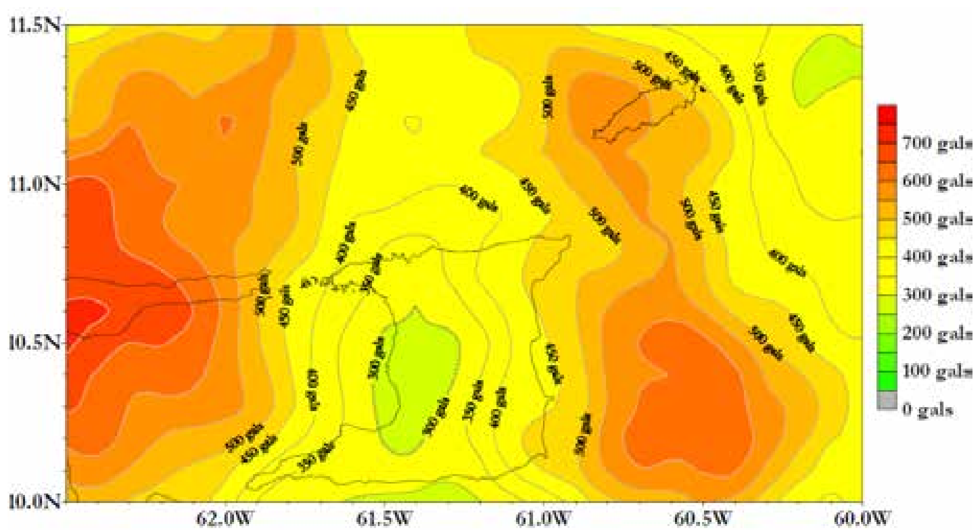


Figure 9: Spectral acceleration at 0.2 seconds period. Ground acceleration with 2% probability of exceedance in any 50-year period. Units are gals.

Figure C3 Shepherd 2003; Note absence of CR/WS fault

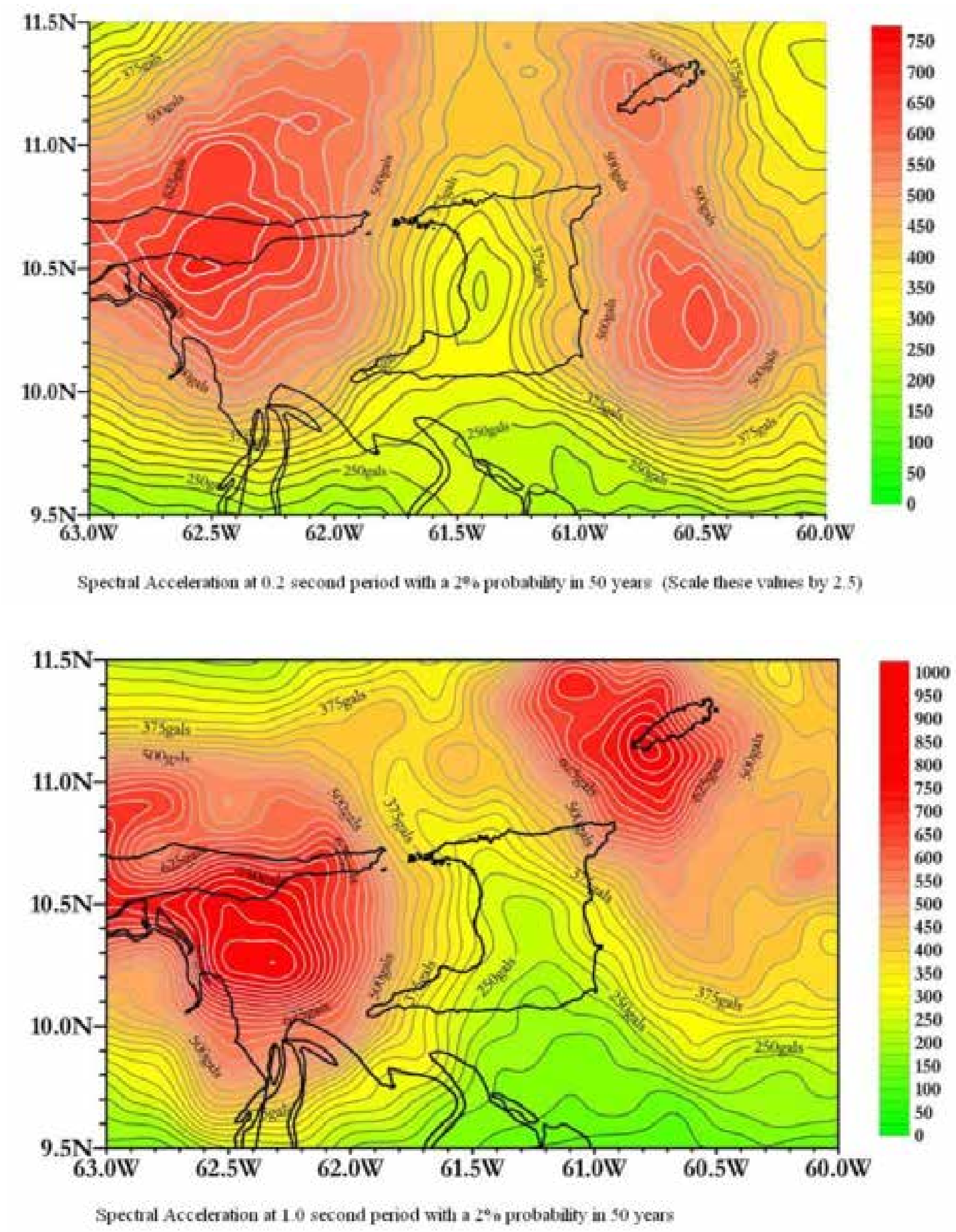


Figure C4 Shepherd 2003-2008; Note absence of CR/WS fault

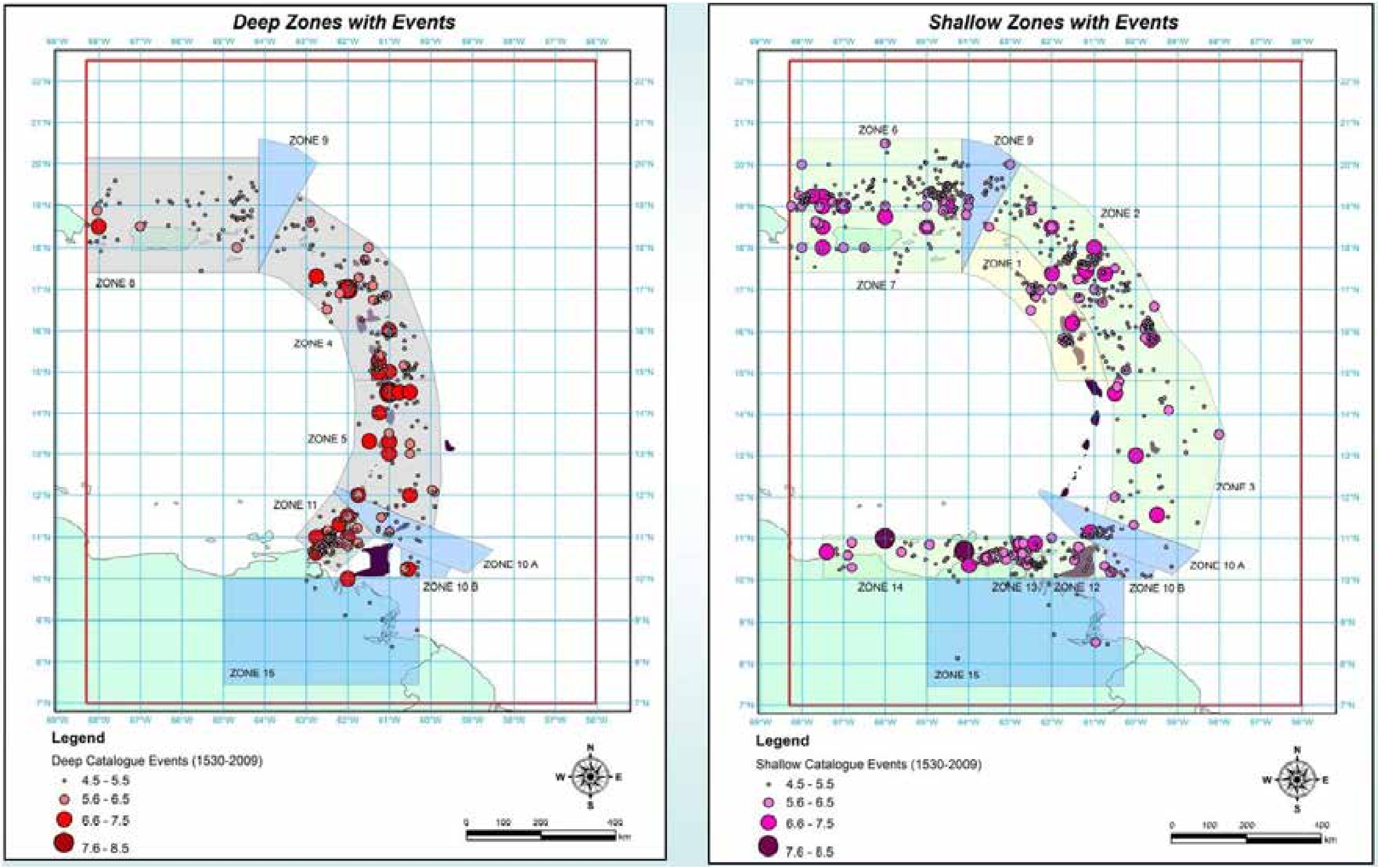


Figure C5 EUCENTRE, SRC 2010-2013; Source Zones with overlapped Seismicity used in PSHA of Eastern Caribbean. Note absence of CR/WS fault as source Zone (Giovanni-Lai et al. 2010, Bozzoni, et al. 2011), SRC 2010, 2011.

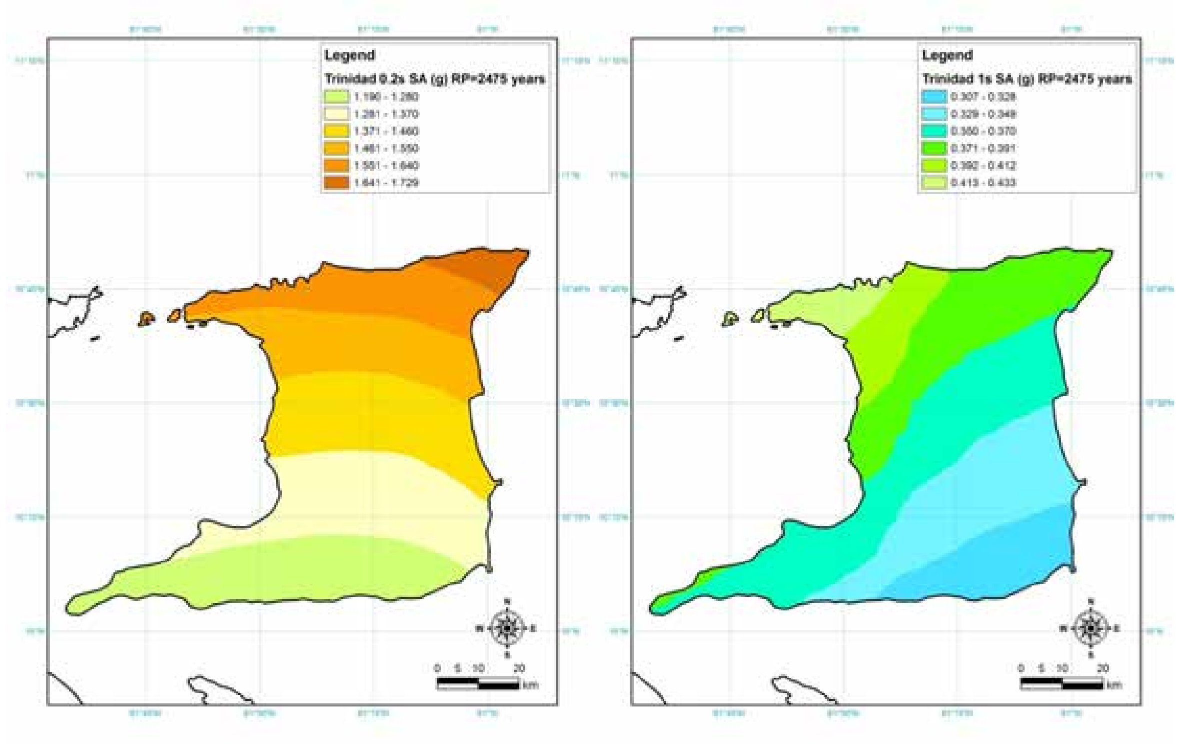


Figure C6 EUCENTRE; Seismic Hazard for Trinidad, 2% probability of exceedance, maximum expected bedrock acceleration in 50 years SRC website 2010-2013; Note absence of CR/WS fault seismic influence (Giovanni-Lai et al. 2010, Bozzoni, et al. 2011).

6.0 New Activity Old Fault: CR/WS Potential for Magnitude > 7-7.5 Earthquakes.

"Using declassified seismic exploration data, Soto and Mann have mapped offshore extensions of the fault on either side of Trinidad and have estimated that a full rupture will result in an earthquake of magnitude 7.5," the report contended. [Attributed to the ODPM].

"A full rupture of the fault may result in an earthquake of magnitude 7.0 or larger. Prentice *et al (2010/* trenched the fault in the Samlalsingh region and uncovered traces of a prehistoric earthquake in the sediments, which they consider supports this potential." [Latchman, August 11th 2013, letter to MP]

Over the period, 2007 – 2010, two publications came out in the research arena, alleging that the CR/WS fault crossing Trinidad obliquely from east to west could generate earthquakes of magnitude M > 7 and/or 7.5. Soto and Mann (2007) concluded:

> *"The Central Range fault zone has likely accumulated sufficient elastic strain over at least the past two centuries to generate a great earthquake that could threaten the onshore population of Trinidad and offshore industrial infrastructure, including submarine oil and gas pipelines constructed across the active trace of the Central Range fault zone. Since the advent of accurate descriptions of Trinidad's historical earthquake in A.D. 1800 (Robson, 1964), there has been no historical record of an earthquake rupture along the Central Range fault zone. <u>At a rate of 17–19 mm/yr, ~3.7 m of elastic strain is available to be released during the next earthquake. This amount of slip suggests the possibility of a destructive future earthquake of ~M7.5 (Wells and Coppersmith, 1994)</u>".*

In a later publication, Prentice, Weber, et al. (2010), based on earlier geodetic measurements by Weber et at (2001, 2009) concluded similarly:

> *Our paleoseismic investigations demonstrate that the CRF is a Holocene fault that has produced at least one earthquake large enough to rupture the ground surface within the past 2710 yr. We conclude that this fault is capable of producing similar earthquakes again, and therefore constitutes a significant seismic hazard for Trinidad. Our data suggest that the most recent earthquake is prehistoric and occurred between 550 and 2710 yr B.P. This is consistent with the historical record, which does not show a significant earthquake felt in central Trinidad that is likely to have originated on the CRF since European settlement in the sixteenth century (Robson, 1964). No Holocene geologic slip rate data are available for the onshore CRF. However, <u>if the geodetic rate of 9–15 mm/yr (Weber et al., 2010) is typical of the last several thousand years, then a lapsed time of >550 yr suggests that strain energy equivalent to over 4.9 m of slip is currently available for seismic release, corresponding to an earthquake of M > 7 (Wells and Coppersmith, 1994)</u>.*

I was disturbed by these statements (and still am) as my engineering mechanics could not come to terms with these conclusions. I felt somewhat comforted though by the silence of the EUCENTRE-SRC on this matter, given that they are the arbiters of the Probabilistic Seismic Hazard Maps for the region which local and international engineers have been using to design buildings for the last 30 years or so. I thought then that they too had had difficulty verifying the mathematics used by the authors in arriving at their conclusions. Indeed, Mr Lloyd Lynch, at his presentation at the National Consultation of Earthquake Safety in July 2010 (Lynch 2010) after presenting the vector maps and CR/WS fault referenced in the paper by Prentice et al. (2010), had this to say (slides #16 and #17):

"Conclusion drawn from these investigations

- CR Fault is active and accounts for most of the Ca-SA motions
- The dimensions and activity rate are such that it could generate a maximum M7.5 earthquake if locked
- The El Pilar right steps across to the CRF creating a Pull-Apart Basin in the Gulf of Paria
- The fault is aseismic. More work is needed to determine whether it has been accumulating strain or it has been slipping without generating earthquakes

On his final conclusions slide, # 37, he states:

- There is a substantial knowledge gap in respect of the understanding of the tectonic processes driving these events as well as their hazard potential. There is even a larger gap between what is known and that which is converted into policy and action for a safer Trinidad and Tobago.

In reading these sentences, I felt a sense of relief and vindication, in that these were the same conclusions I had come to after reading the stream of references on this subject over the past 10+ years. In addition, it seemed prudent to infer that since the EUCENTRE and/or the SRC had not updated their models and/or maps to include this linear source hazard (CR/WS fault, capable of producing an earthquake of Magnitude 7.5) and neither had they issued any official warnings and/or advisories on these new findings, that they too had come to a similar conclusion that such pronouncements were premature.

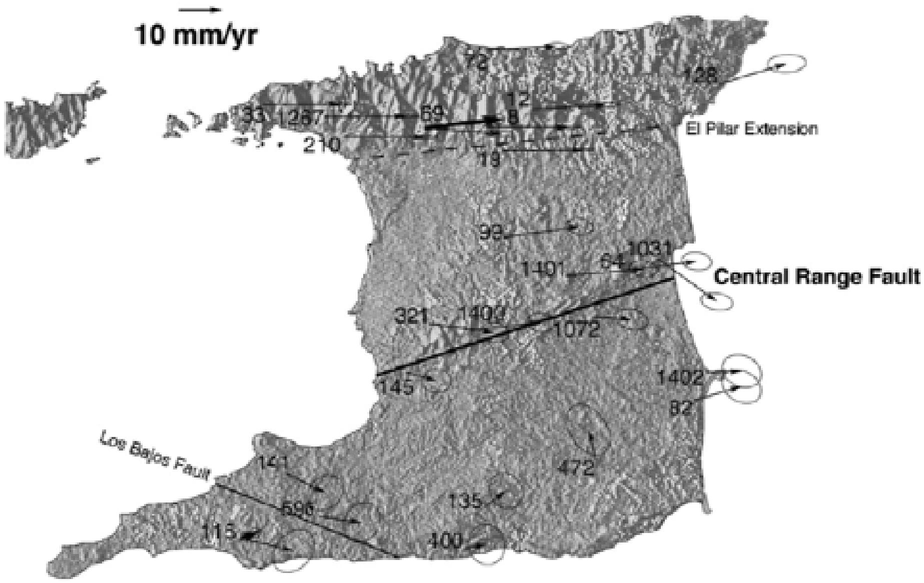
My attempt at verification: The authors quote a rate of geodetic displacement rate of 17-19 mm/year, multiply this (average value) x time elapsed since the last earthquake AD 1800-2007, 207 years and obtain 3.726 metres, which they call ***elastic strain***. Then say that this length is the length of an earthquake surface fault fracture that would generate an earthquake, the authors then use the Wells and Coppersmith (1994) relationship to convert this value to at a magnitude M=7.5.

As a student of mechanics of many years, elastic strain is dimensionless and is equal to ΔL/L or ΔL/H, where in the case of earthquake fracture of blocks, this strain is shear strain, where the displacement ΔL is the displacement across the strain field of dimension H (see Figures C10, C11 and C12). Weber uses this elastic model in his analyses. So to speak of shear strain the deformation must be applied across a width of shearing/straining material. Prentice also carries out the identical analysis using a 9-15 mm/yr displacement rate over 550 years to obtain a strain energy equivalent to 4.9 m of slip [on the fault plane] to arrive at a magnitude of M > 7. Again the conversion of slip displacement to strain energy is baffling.

Notwithstanding that I might not have understood the nature of the analyses carried out, I carried out an elastic dislocation fault model based on the data and model presented described in Weber, 2009, 2011, using the methodology as described by Trucotte (2002) as illustrated in Figures C10 through C12. This methodology computes the actual displacement on a fault due to shear strain developed across a domain of width 2b in this case 30 m.

This methodology gives a range of Magnitude; 4.6 < M < 6.1, when using the Wells and Coppersmith (1994) relationships. These magnitudes are more in keeping within the range of Historical Magnitudes experienced in this Trinidad Zone 12. As such I concluded that the seismic hazard as represented by the current SRC maps can adequately serve seismic risk design risk calculations.

However, in order to further exercise due diligence, not assuming that these calculations are the final word, I also carried a study of the risk analysis recurrence relationships of the PSHA use by the EUCENTRE-SRC within zone Zone 12, to include the range of magnitudes predicted by the stated publications. This is the subject of the next section.



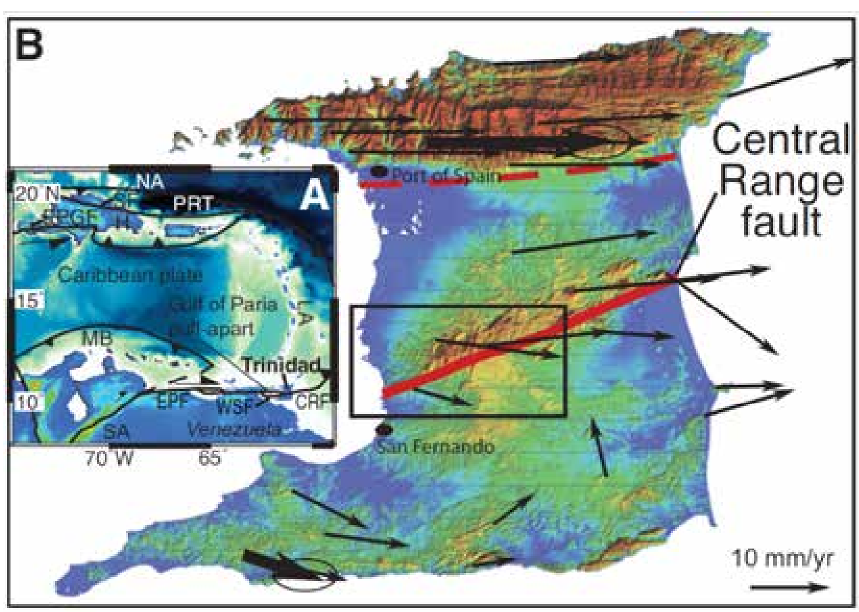


Figure C7 Weber 2009-2011, Geodetic Vector Maps

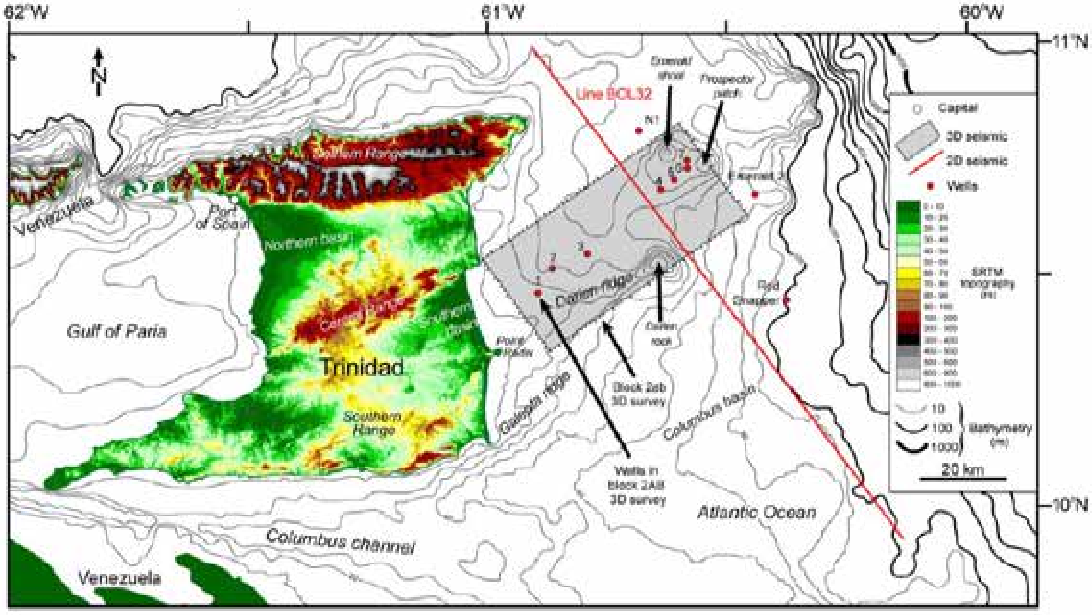


Fig. 2. Topographic–bathymetric map of Trinidad region showing location of 3D seismic data used from study area in eastern offshore exploration block 2AB, shown in gray. Wells used in the study are shown as red dots. Regional 2D seismic line 32 which passes through block 2A is shown in red and partially reproduced in Fig. 5. Topography of onland Trinidad compiled from SRTM; bathymetry is compiled from NIMA (2001) and DMA (1993). Highest elevations in Trinidad are in the Northern Range (~900 m ASL) with lower elevations in the Central Range (~300 m) and Southern Range (~200 m). The 100 m-deep bathymetric contour represents the approximate position of the modern shelf-slope break. Bathymetric intervals on the shelf are shown at 10 m intervals while slope contours are shown at 100 m intervals. Three submarine highs (Emerald shoal, Prospector Patch, and Darien rock) are indicated in the block 2AB study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

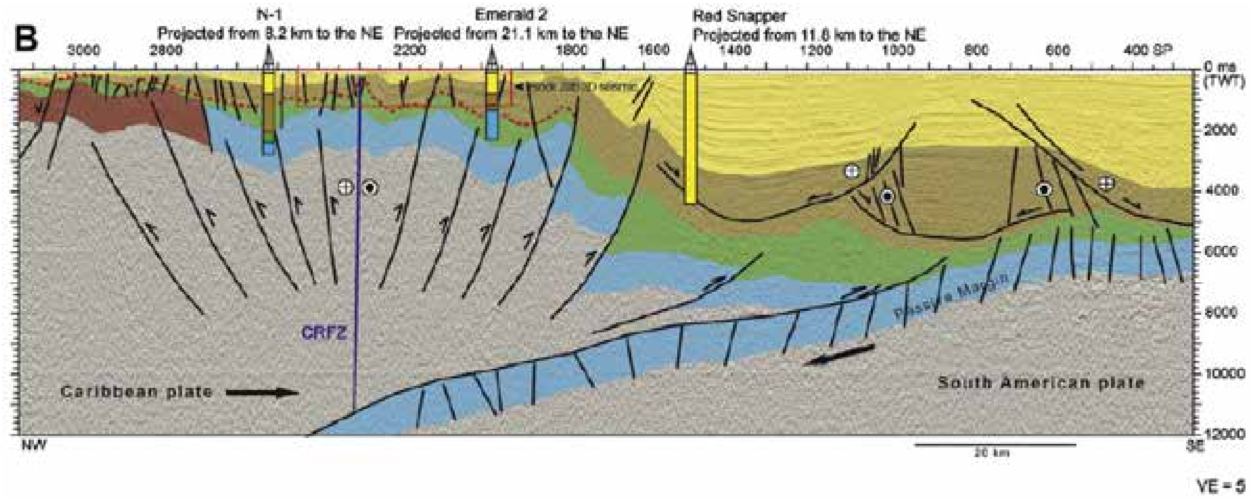


Figure C8 Soto and Mann 2007-2011, Flower Formation consistent with Transpressional fault zones. Depth estimated to 10 km, NW dippimg basement South American Plate below, highly fissured/fractured porous Shales, Sandstones and Mudstones; Oil and Gas Reservoirs to 5 km.

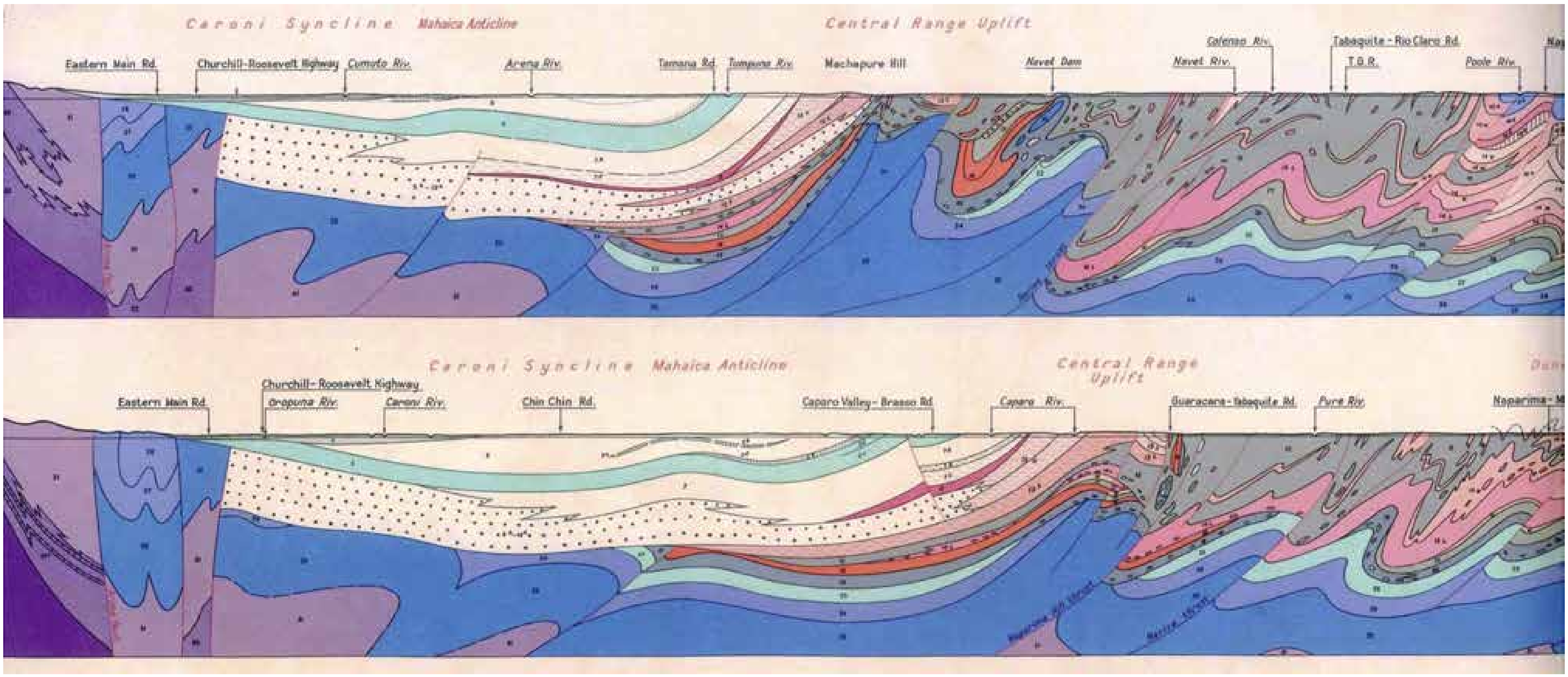


Figure C9 Kugler 1959 N-S Sections 4-5 through Central Trinidad to depth of 20,000 ft. (6.1 km). Flower Formation consistent with Transpressional fault zones. Section 4 through Navet Dam is at top. Section 5 due west of 4, below.

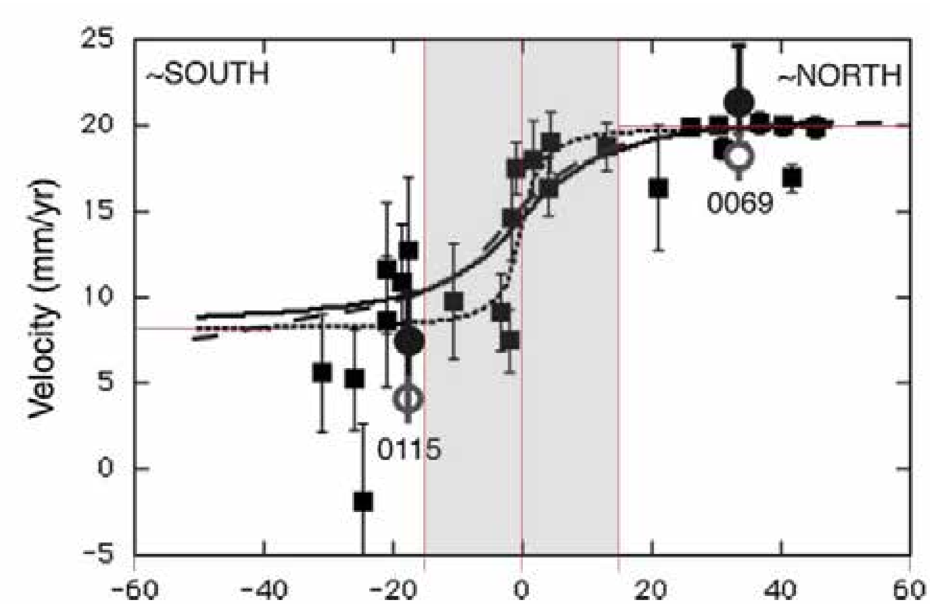


Fig. 5. Elastic dislocation fault model fits to 1901–1995 plate-motion-parallel (east) velocities. 20 _ 3 mm/yr is added to all sites so northern sites move at full Caribbean plate velocity of Weber et al. (2001a). Note the steep velocity gradient across the active Central Range Fault (CRF) located at center of profile. Best-fit CRF slip rate (short dashed black line) is 12 _ 2 mm/yr with a 2 km locking depth; solid black line represents 13 mm/yr fit with locking depth fixed at a more standard value of 10 km; best-fit two-fault model discussed in text is also shown by long dashed black line. F-tests indicate that c2 values obtained from best-fit creeping single-fault model (1–2 km locking depth) are indistinguishable at 95% significance from c2 values from models with a 10 km deep locked Central Range Fault and from a two-fault model that puts an additional 2 mm/yr of slip on the Los Bajos Fault. Repeat GPS eastern velocities and uncertainties for sites 69 and 115 from Weber et al. (2001a) (filled circles) and this study (open circles; Table 2), not used in these fits, are shown for comparison.

Figure C10 Weber (2011), ±15 km elastic rebound fault zone model shaded.

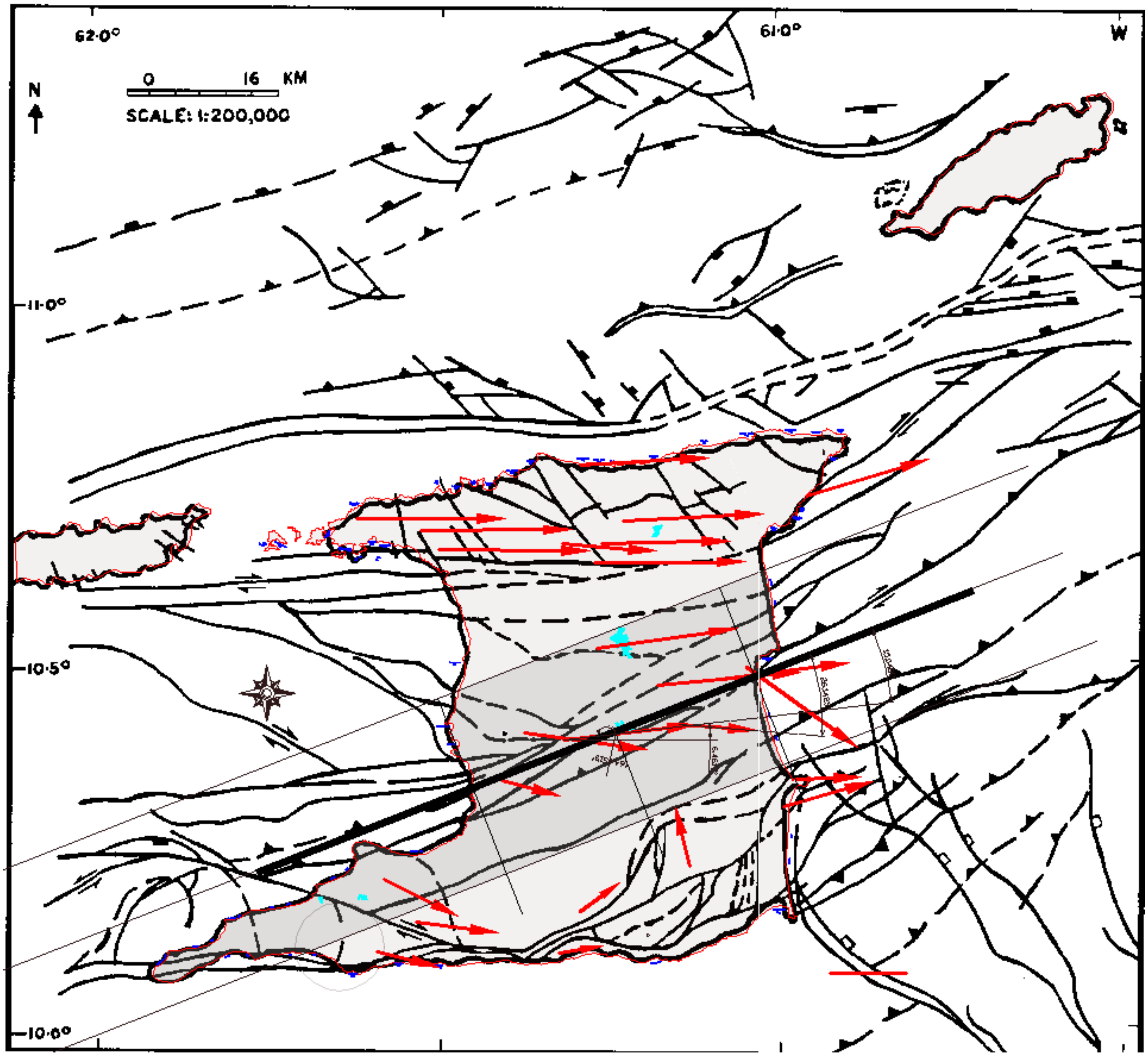


Figure C11 Weber ±15 km fault zone model over Trinidad and Tobago Fault map (Persad 1984).

Friction on Faults/Elastic Rebound Theory (Trucotte, 2002)

Displacements on faults accommodate a substantial fraction of the strain occurring in the upper crust. These displacements sometimes occur in a continuous manner at tectonic velocities of tens of millimetres per year. This type of displacement is referred to as *fault creep*. However, it is much more common for the displacements on faults to occur during earthquakes. Between earthquakes the fault remains locked. This is known as stick-slip behavior. A simple model for the stick-slip behavior of a fault is illustrated in Figure 8-4. We assume that the behaviour of the fault is uniform with depth and neglect the forces at the bases of the adjacent plates. Figure 8-4a shows the situation after a major earthquake when the fault locks. The stress across the fault is τ_{fd}, the frictional stress that is operative on the fault at the end of faulting. A uniform relative velocity u_0 is applied at a distance b from the fault, and the shear strain increases with time according to $\varepsilon(t) = u_0 t/(4b)$ - see Equation (2-102)- for example, as shown in Figure 8-4b. The shear stress on the fault as a function of time t since the last displacement on the fault is therefore

$$\tau = \tau_{fd} + \frac{G u_0 t}{2b} \qquad (8\text{-}18)$$

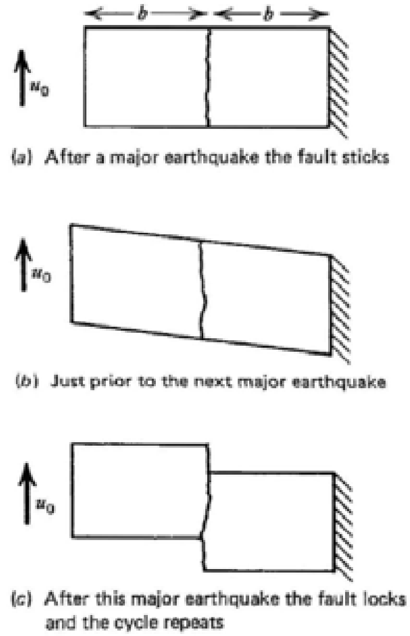
where G is the shear modulus (see Equation (3-49)). The locked fault can transmit any shear stress less than the static frictional stress τ_{fs}·, When this stress is reached, slip occurs. Therefore, the *time* $t = t^*$ when the next displacement occurs on the fault is:

$$t^* = \frac{2b}{G u_0} (\tau_{fs} - \tau_{fd}) \qquad (8\text{-}19)$$

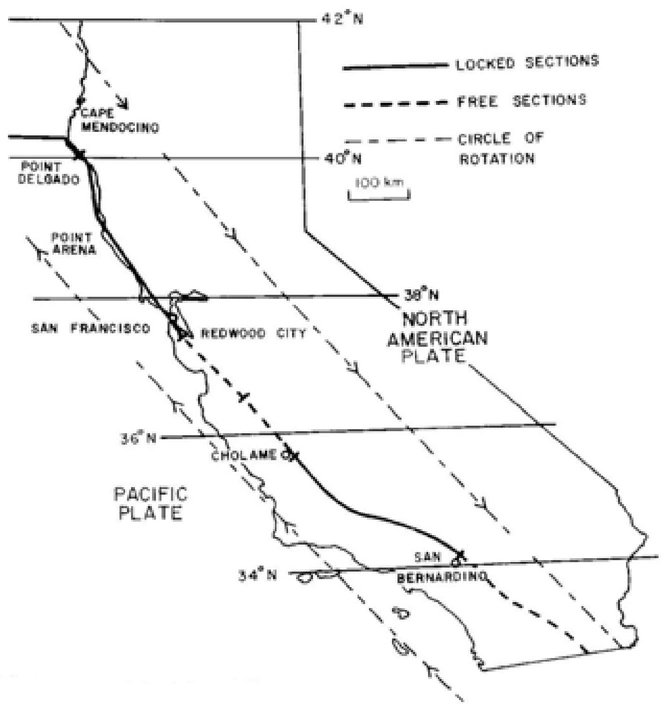
The slip on the fault generates an earthquake. The displacement on the fault during the earthquake occurs in a few seconds so that the edges of the plates can be assumed to be stationary during this time. The accumulated shear strain $\varepsilon = u_o t^* /4b$ is recovered by the plates in a process known as *elastic rebound*. The resulting displacement on the fault Δw is $2\varepsilon(2b)$ –see Equation (2-94)- or

$$\Delta w = 2\varepsilon(2b) = 4b\left(\frac{u_0 t^*}{4b}\right) = \frac{2b}{G} (\tau_{fs} - \tau_{fd}) \qquad (8\text{-}20)$$

The quantity $(\tau_{fs} - \tau_{fd})$ is the stress drop on the fault during the earthquake. After the earthquake, the fault locks and the cycle repeats, as shown in Figure 8-4c. The displacement on a fault during an earthquake can be measured from the surface rupture. A typical value for a large earthquake is 5 m. It is difficult to determine the stress drop during an earthquake. Estimates of stress drops during large earthquakes range from $(\tau_{fs} - \tau_{fd})$ = 1 to 100 MPa.



8–4 Stick–slip behavior and elastic rebound on a fault.



8-21 Surface trace of the locked and free sections of the San Andreas fault. Also shown are two small circles drawn about the pole of rotation for the motion of the Pacific plate relative to the North American plate.

Figure C12 Faulting; Stick-slip Elastic Rebound Model Trucotte (2002) top, San Andreas Fault System Below

7.0 Earthquake Activity: Probabilistic Earthquake Recurrence.

Zone 12 PSHA Modelling:

Using the recurrence relationship of Gutenberg and Richter:

$$log_{10} (\lambda) = \alpha - \beta M$$

in conjunction with the modification of Youngs and Coppersmith (1985),

$$N(m) = N(m^0) \frac{\exp(-\beta(m - m^0)) - \exp(-\beta(m^u - m^0))}{1 - \exp(-\beta(m^u - m^0))} \quad \text{for} \quad m \leqq m^u.$$

that takes in to account threshold earthquake Magnitudes on a fault, I have developed three scenarios of return period and attendant probabilities for earthquakes in the range, 6.5 < M < 7.5. I have used the same relationship for Zone 12 as indicated by the EUCENTRE-SRC analyses as illustrated in Figures C13and C14. The range of magnitudes include the magnitudes predicted by the author's analyses (lower bound) and those referred to in releases by concerned parties (Soto and Mann 2007, Prentice, Weber et al. 2010, 10, 10a).

	Threshold	Linear Open
Mmax	Return Period (Yrs)	
6.5	1209	55
7.0	2674	125
7.5	5832	263
8.0		555

Model return periods/probabilities are indeed sufficiently large/small so as to have a limited effect on PSHA at the lower bound magnitude which the author recommends, given the highly fractured fault area and the likely residual stress drop (lower bound value consistent with a fractured discontinuous porous rock mass) that are likely to visit the CR/WS fault system.

In my exercise of due diligence in my capacity as a practitioner of Geotechnical Engineering and Engineering Seismology, I have over time, examined the findings presented in the research literature to date and concluded that their assertions were insufficiently reliable and rigorous to be adopted into public policy and Codes of Practice at the current time.

However, should the SRC through their due diligence be convinced of the reliability of this new ground breaking hazard then this should, and must, be brought to the attention of all relevant stakeholders in a clear and unambiguous manner, via consultations, in order to chart a way forward toward adoption/implementation. This process in US practice (which we have embraced over the years) takes between three to six years; a timeframe that pales to obscurity when compared to the 2500 to 5000 year return period of the expected hazard, controlled by processes that have been in progress for 5-10 million years.

I believe that the methodologies outlined in the adopted Codes of Practice in Trinidad and Tobago, the ASCE7-05 and IBC 2006 as currently mandated by the MOWI Structural Division using the current PSHA derived Seismic Hazard Maps are sufficiently rigorous to be applicable to the safe Seismic Design of structures in Trinidad and Tobago at the current time..

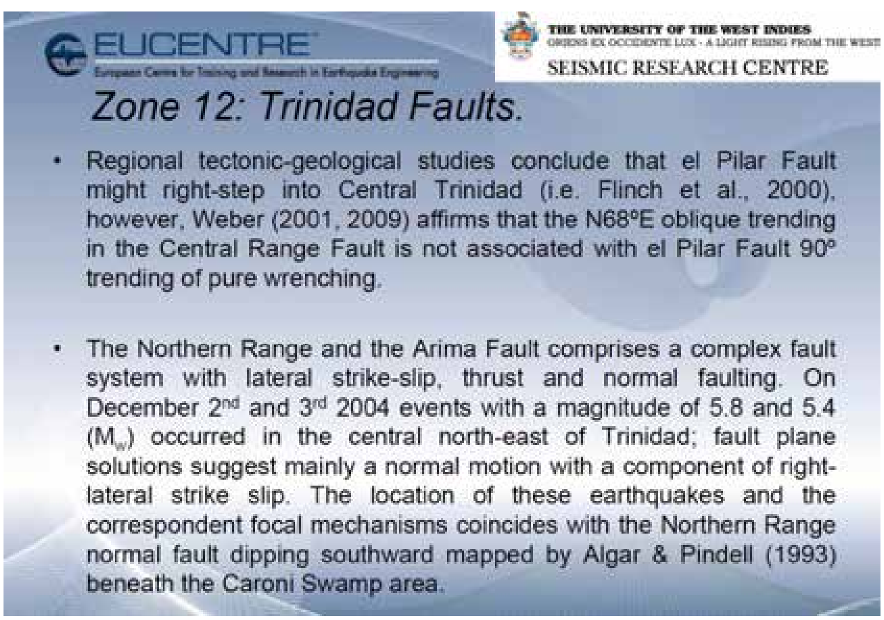
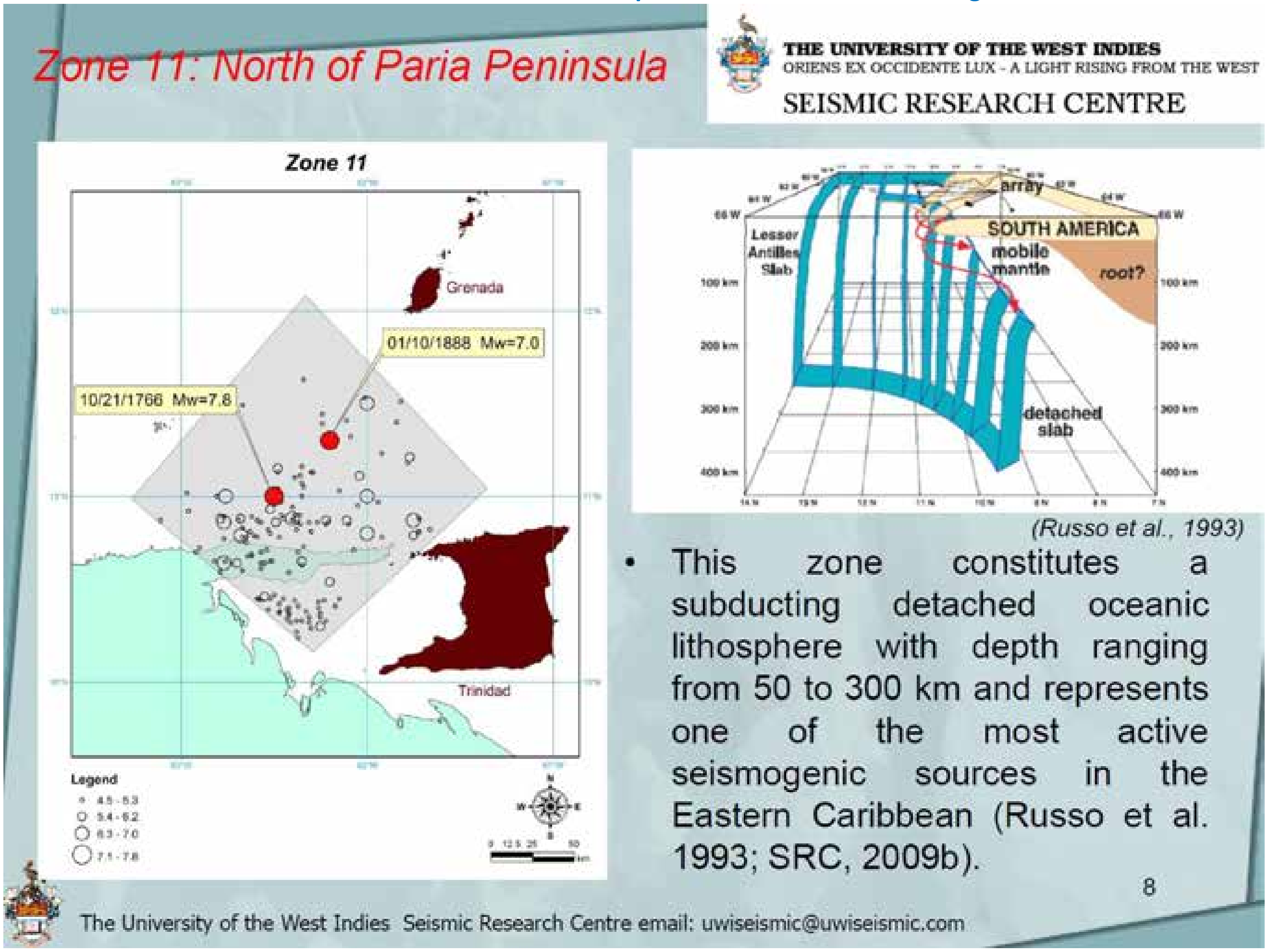


Figure C13a Description of Source Zones used in PSHA (Giovanni-Lai et al. 2010, Bozzoni, et al. 2011) [EUCENTRE-SRC]



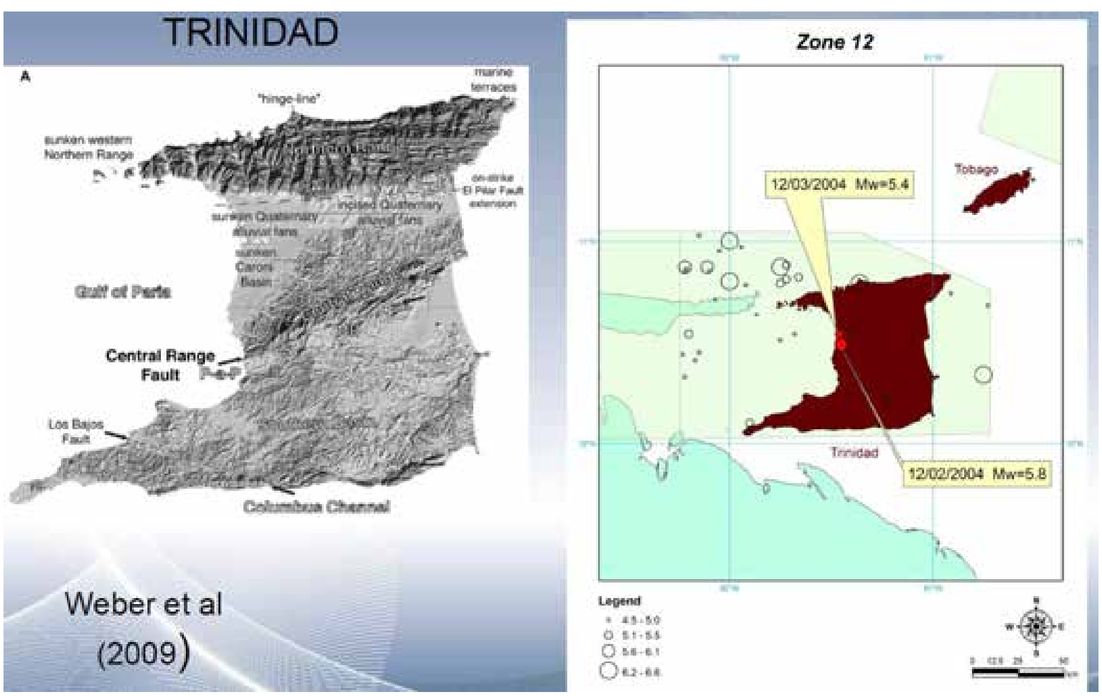
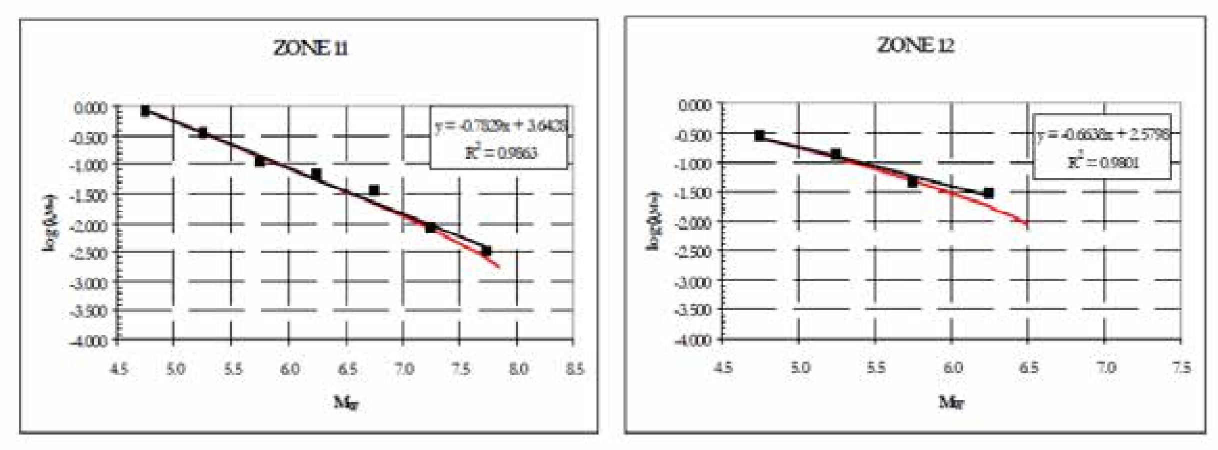


Figure C13b Source Zones 11 and 12 used in PSHA (Giovanni-Lai et al. 2010, Bozzoni, et al. 2011): EUCENTRE, SRC



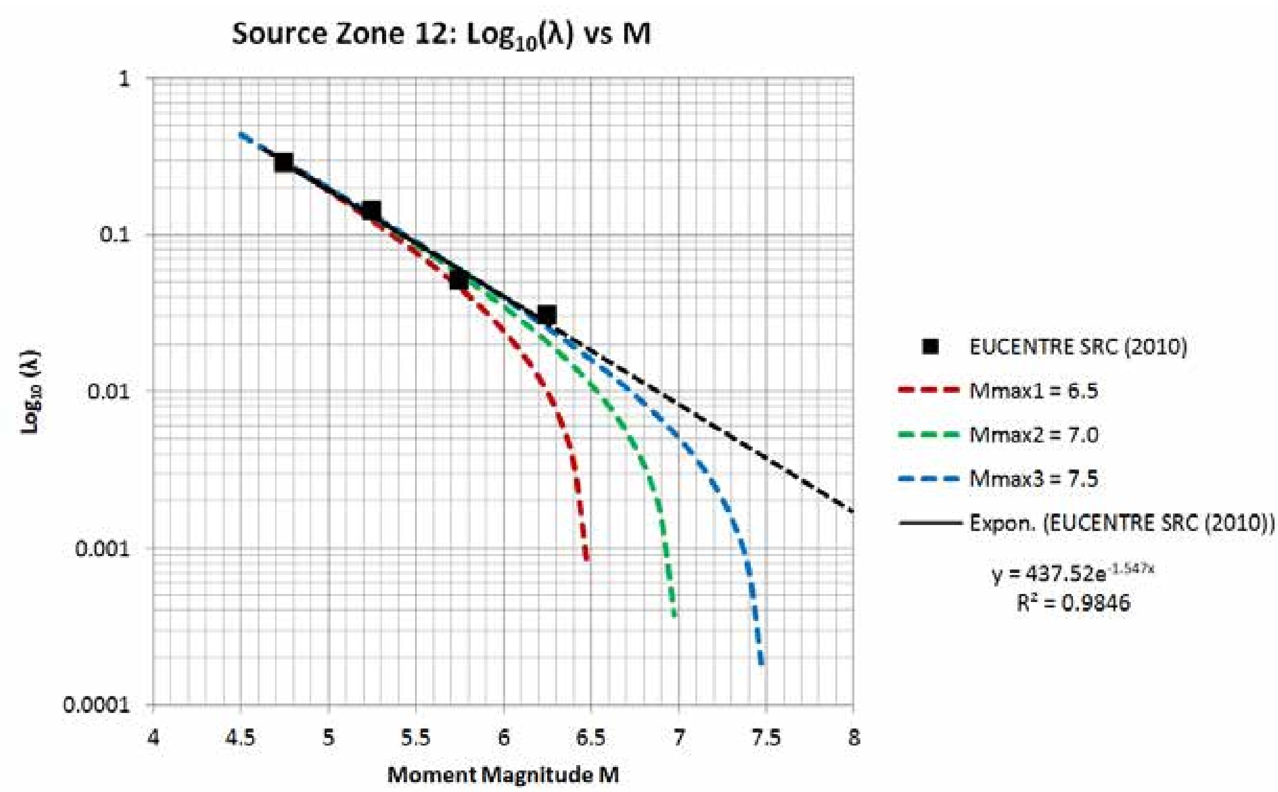


Figure C14 PSHA Source Zone 12 Modelling, Log(λ) vs M with Limiting/Threshold Earthquake Magnitudes; M = 6.5- 7.5. (Gay 2013).

8.0 Conclusions And Recommendations

1. Site Investigations, for the proposed Couva Children's Hospital, were carried out in a site-specific manner consistent with best practice and Codes of Practice as mandated by the MOWI Construction Division, Designs Engineering Branch

2. We are of the view that the current Probabilistic Seismic Hazard Analysis maps as prepared by the EUCENTRE-SRC are adequate for seismic and geotechnical design of the Couva Children's Hospital, despite research publications indicating higher than normal earthquake magnitudes magnitudes.

3. Even the author (Weber 2011) of the original studies on which other predictions are predicated had this to *say:*

The question of a locked versus creeping Central Range Fault is an extremely important issue, with significant implications for seismic risk, durability of the existing petroleum infrastructure, and the planning of future industrial and national infrastructure in Trinidad. This study was initiated, in part, as an attempt to begin <u>addressing this still open debate</u>. Our best-fit single-fault model gave a shallow (1–2 km) locking depth that essentially suggests fault creep. Statistical tests indicate that setting the locking depth to 10 km does not improve the fit to our data. <u>Thus, using just the geodetic data, we cannot discriminate between the creeping and locked fault possibilities</u>.

4. The calculations based on these geodetic measurements resulting in much higher than normal magnitudes appear to be premature at this time and we cannot be justified in incorporating these in current Seismic Hazard Assessments.

5. In my exercise of due diligence in my capacity as a practitioner of Geotechnical Engineering and Engineering Seismology, I have over time, examined the findings presented in the research

literature to date and concluded that their assertions were insufficiently reliable and rigorous to be adopted into public policy and Codes of Practice at the current time.

However, should the SRC through their due diligence be convinced of the reliability of this new ground breaking hazard then this should, and must, be brought to the attention of all relevant stakeholders in a clear and unambiguous manner, via consultations, in order to chart a way forward toward adoption/implementation. This process in US practice (which we have embraced over the years) takes between three to six years; a timeframe that pales to obscurity when compared to the 2500 to 5000 year return period of the expected hazard, controlled by processes that have been in progress for 5-10 million years.

5. I believe that the methodologies outlined in the adopted Codes of Practice in Trinidad and Tobago, the ASCE7-05 and IBC 2006 as currently mandated by the MOWI Structural Division using the current PSHA derived Seismic Hazard Maps are sufficiently rigorous to be applicable to the safe Seismic Design of structures in Trinidad and Tobago at the current time..

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