Identification of a Regional Earthquake Fault Zone

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Chapter 10

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As has been established, volcanic earthquakes alone cannot account for the earthquake intensity described in 3rd Nephi. When looking at the potential fault zones where a large magnitude earthquake might have taken place, the actual text of the Book of Mormon gives us some clues that will help in determining the probable regional location of the earthquake. It does not appear possible at this point to even conjecture what the specific individual fault movements were, but it should be possible to identify the most likely fault zone. In order to determine the location of the fault zone it is necessary to compare the earthquake effects with known Book of Mormon locations.

Surface Indication: Rupture/Cracking and Subsidence

The first geologic criterion to be evaluated is surface rupture or cracking. Deep earthquakes do not typically cause much surface rupture. In addition, observations of modern earthquake effects in the Isthmus have not shown areas of significant ground motion amplification at long distance. Therefore, references to surface ruptures would be expected in the fault zone for primary fault ruptures or immediately adjacent for secondary rupture features (i.e., liquefaction and lateral spreading). Where surface ruptures are identified, it should be indicative of a fault zone with shallow earthquake potential. Finally, it should be noted that strike-slip faults generally generate more types of surface rupture effects at the fault trace than other types of faults.

The following references in the Book of Mormon identify and describe the surface rupture and fractures that occurred because of the quaking of the earth:

1 Nephi 12:4

> … and I saw the earth ~~and the rocks, that they rent~~ [that it rent the rocks]; … and I saw the plains of the earth, that they were broken up;

1 Nephi 19:11

> … by the opening of the earth,

Helaman 14:21–22

> … and the rocks which ~~are~~ [is] upon the face of ~~this~~ [the] earth, which ~~are~~ [is] both above the earth and beneath, which ye know at this time are [is] solid, or the more part of it is one solid mass, shall be broken up; Yea, they shall be rent in twain, and shall ever after be found in seams and in cracks, and in broken fragments upon the face of the whole earth, yea, both above the earth and beneath.

3 Nephi 8:12–13 (in the land northward)

> … the whole face of the land was changed … And the highways were broken up, and the level roads were spoiled, and many smooth places became rough.

3 Nephi 8:18 (in the land northward)

> And behold, the rocks were rent in twain; [yea] they were broken up upon the face of the whole earth, insomuch that they were found in broken fragments, and in seams and in cracks, upon all the face of the land.

What can be gleaned from these scriptures is that there was (1) widespread surface rupture and fracturing in the land northward, and (2) "the plains of the earth" were broken up.

A second earthquake surface feature is subsidence. Without quoting each scripture, the following scriptures refer to sinking of some sort:

1 Nephi 12:4 (cities sunk, no area identified); 3 Nephi 8:9, 9:4 (city of Moroni); 3 Nephi 8:14, (cities in the land northward); 3 Nephi 9:6–8, 4 Nephi 1:9 (various cities including Jerusalem); 3 Nephi 9:13 (persons sunk and buried); and 3 Nephi 8:13 (level roads spoiled).

It is important to note that subsidence can also occur on the flanks of a volcano during and after eruption, primarily from subsidence caused by emptying of the magma chamber, but this would only be a small local effect. Also, the burial of cities or persons should be differentiated from sinking, as the burial may have resulted solely from a volcanic effect or landslide. Similarly, references concerning the land northward to the changing of the "face of the land" and the land being "deformed" (3 Nephi 8:17) could be exclusively caused by the effects of a volcanic eruption and/or landslide, even though the quaking of the earth is also mentioned.

Similar to surface rupture, subsidence generally occurs within the fault zone or immediately adjacent, with some subsidence possible at distance due to liquefaction or lateral spreading. There are two cities mentioned in relationship to subsidence that have other corroborative geographical ties. The city Moroni was located "by the east sea" and sank into the sea, and is located in the land southward. It has been suggested that the destruction of Moroni could have been caused by a storm or hurricane surge (Sorenson, 1985,322), presumably with the sinking being referred to in the Book of Mormon being interpreted as beach erosion caused by the surge. Given the short duration of the storm (3 hours), a fast passage that would indicate a smaller hurricane, this explanation may not suffice even though hurricane storm surges have been documented to cause significant erosion in excess of 5 meters in the Gulf of Mexico where beach barrier spits or islands are involved (Stockdon, 2012, 11). Kowallis (1997, 162–65) has asserted that a tsunami may have been responsible for the sinking of the city of Moroni. Similar to a storm surge, a tsunami would have caused sinking by inundation erosion. The second city with scriptural references (under some textual interpretations) to sinking, Jerusalem, by corroborative geography from the Book of Mormon text according to the Sorenson model, is located far to the south in the land southward.

Indicators of the Location of the Fault Zone

As enumerated here and in previous chapters there are a number of conditions that the fault zone must meet:

1. The fault type must be capable of causing extensive surface rupture and fracturing, as well as subsidence, with the worst earthquake damage occurring in the land northward.
2. At least a portion of the fault zone must also be in the land southward or be located such that a large earthquake will cause significant damage in the land southward.
3. It must break up "the plains."
4. It must cause subsidence in areas that would subject cities to burial (as some cities were both sunk and buried), namely by eruptive volcanic deposition or landslide/mass movement.
5. The earthquake must have occurred in or near a populated area, or had significant effect in a populated area.

There are an additional number of preferential conditions that, if met, would provide strong indications of the fault zone where the 3rd Nephi earthquake took place:

1. The fault zone is capable of causing subsidence in the city of Moroni.
2. The fault zone is capable of causing subsidence in the city of Jerusalem.
3. Damage from the earthquake can be observed from a location within the land of Bountiful, and have a reduced damage level in Bountiful.
4. A volcano capable of causing the 3rd Nephi volcanic damage is located in or immediately adjacent to the fault zone.
5. The fault zone is capable of causing a tsunami in the east sea.
6. It must cause subsidence in areas that would subject cities to be covered quickly with water.

Best Fit Fault Zone

There are only two regional fault zones in the Isthmus, the Pacific Coast Subduction Zone and the Veracruz-Polochic/Motagua Strike-Slip Fault Province. The Veracruz-Polochic/Motagua province is divided into two segments, the Veracruz fault system and the Polochic/Motagua fault system. The two segments are separated (at the south end of the Veracruz and the north end of the Polochic/Motagua) by a "step-over area" where the fault systems have an offset in alignment. In applying the criteria above, the best-fit scenario appears to be strike-slip movement in the Veracruz-Polochic/Motagua Strike-Slip Fault Province, with the principal movement occurring in the Veracruz fault system.

Specifically, the criteria that is exclusively met by the Veracruz-Polochic/Motagua system is that strike-slip faults create more surface rupturing than the deeper Pacific Coast faults. In addition, the Veracruz fault system is located in the Gulf Coastal Plain, which stretches from Veracruz south to Tabasco and is the only significant plain located in the Isthmus of Tehuantepec. The Pacific Coastal plain is a narrow band from 5 to 20 kilometers in width; it was only lightly populated compared with the Gulf Coastal Plain. The other preferential conditions that are exclusively met by the Veracruz-Polochic/Motagua system are the ability to cause subsidence in the cities of Moroni and Jerusalem, the ability to cause damage observable from the city of Bountiful, a volcano that is in the fault zone (San Martín), and the ability to cause a tsunami in the east sea.

Earthquake Scenario

Finally, it will be useful to model a worst-case earthquake scenario for the Isthmus fault systems in order to project probable zones of Mercalli intensity for each fault system and see whether the results will also identify the probable fault zone. It is necessary to utilize the Mercalli intensity scale for pre-instrument historical earthquakes as it is based on the damage reports on the surface, not measurement by seismic instrument. It is an intensity scale that measures *felt intensity* not *monitored intensity*, based on eyewitness reports, felt shaking, and observed damage. When one is trying to 'recreate' an historic earthquake based on eyewitness reports, which is what we have in the Book of Mormon, it is the appropriate scale to use. Unfortunately, much of the description of damage in the Book of Mormon is regional damage with general damage descriptions, and because we don't have any specific locations for most of the cities mentioned in 3rd Nephi, we do not have geographic pinpoints to use. The only identifiable cities to work with under the Sorenson model are the cities of Zarahemla, Moroni, Bountiful, and Jerusalem, of which locations for Moroni, Bountiful, and Jerusalem are not really all that exact because more than one archeological location within a restricted area could meet the geographical descriptions mentioned in the Book of Mormon. We are principally dealing with eyewitness descriptions of destruction in larger areas like the "plains" and the "land northward" and the "land southward" that we can reliably identify. Be that as it may, there is enough information to determine which of the fault systems was the likely source of the earthquake, and we can model each of the faults to characterize the earthquake intensities for each fault system.

Earthquake modelling is not an exact science, and is highly dependent on the utilization of actual spatially concentrated seismic data collected over long periods of time. Faults like the San Andreas in California have had extensive data collection and detailed geologic mapping with millions of dollars spent to develop accurate models; such is not the case on the Veracruz fault or other faults in southern Mexico and Guatemala.

As this is just a general analysis, it is not necessary to have too much specificity on damage locations—some assumptions can be made. The first assumption is that the analysis will assume that the earthquake could have occurred anywhere along the entire Pacific Coast subduction fault system. In that way we should be able show the potential effects for movement along any section. Only the Veracruz segment of the fault will be examined as it is the only segment that is within the land northward. Again, the entire length of the segment will be looked at. The second assumption is that earthquakes did not occur simultaneously on both fault systems. While that is always a possibility, a rule of thumb for aftershocks from adjacent faults is that the aftershocks occur within the distance of the length of the initial fault rupture. Since the distance between the two fault systems ranges between 100 and 200 km, it would require a 100 km rupture surface on one or the other faults to trigger aftershocks. While that is definitely possible, the model is an attempt to identify the first or primary cause of the earthquake. The third assumption is that the depth of the earthquake is at an intermediate depth, in the range of 25 to 35 km, and that the time duration of the earthquake is the average for southern Mexico. Both of these parameters can affect the damage extent of the earthquake, the depth of the earthquake is a depth that seemed reasonable, especially for the strike-slip type of earthquake event. The attenuation factors we will need to utilize for southern Mexico were developed using a combination of data from multiple earthquakes, so some extent of averaging for the time duration of the earthquake is necessary.

1. Attenuation formula

The principle of earthquake attenuation is that the intensity of the ground shaking by an earthquake decreases as one gets farther away from the fault. There are exceptions to that premise when there are unique soil and sediment situations that can amplify ground shaking. Those amplifications are looked at on a case-by-case and geographical area basis. The attenuation of an earthquake is affected by the type of rock that the seismic waves pass through. There are general attenuation formulas, but it is better to use formulas developed based on data from a particular region. As one looks at more detailed data for smaller and smaller areas, these attenuation formulae can become quite complex. For the purposes of this exercise, given that the analysis is going to be regional, a simple regional formula will be used.

In 1988, Mario Chavez and Raul Castro derived attenuation formulas to predict the attenuation of Modified Mercalli Intensity (I) with distance (D) for Mexican earthquakes:

$$\ln I = B_o + B_1 \ln (D/D') + B_2 (D-D') + B_3 \ln M_s$$

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M_s is the earthquake surface-wave magnitude, D and D' are distances related to the maximum intensity (I) mapped for an earthquake. The coefficients B_i, i = 0, 1, 2, 3 were obtained by utilizing a least-square method from the information contained in the intensity maps of 32 earthquake events. The events were classified in three groups according to their epicentral location, focal mechanism, and depth. The three groups are the Mexican Pacific subduction-zone intermediate-depth earthquakes, the south-central Mexico intermediate-depth earthquakes, and the shallow crustal events along the Trans-Mexican Volcanic Belt. For the profiles in the Isthmus, the Veracruz and the Polochic/Motagua fault segment earthquakes were considered to be equivalent to the south-central Mexico earthquakes.

For this model, an earthquake that would generate a magnitude of 11 was assumed. This level would be comparable to some of the worst earthquakes documented in modern times. Graphs developed by Chavez and Castro for some standard earthquakes were used to extrapolate the following attenuation profiles and zones:

Pacific Coast Subduction Zone earthquake

Mercalli Intensity	Distance from fault (km)
11	0
10 to 11	0-7
9 to 10	7-22
8 to 9	22-36
7 to 8	36-79
6 to 7	79-139
5 to 6	139-172
4 to 5	172-307

Veracruz and the Polochic/Motagua earthquake

Mercalli Intensity	Distance from fault (km)
11	0-6
10 to 11	6-14
9 to 10	14-29
8 to 9	29-50
7 to 8	50-100
6 to 7	100-157
5 to 6	157-172
4 to 5	172-257

Figure 59 is a map showing the result along each fault line. The shaded area shows all areas that would have experienced a Mercalli intensity of 7 or higher. As previously discussed, a Mercalli intensity of 7 would cause considerable damage in poorly built or badly designed structures. On the Pacific Coast, the fault trace used was where most of the earthquakes appear along the subduction zone; some do occur further inland, but even moving the earthquake fault line inland 50 km would not affect the conclusion of the analysis.

Figure 59. Areas subject to Mercalli 7 intensity or higher for an 11 intensity earthquake at the fault line

2. Adjustment for soil and sediments subject to amplification

The characteristics of geologic material at or just beneath the surface is a critical factor affecting earthquake shaking intensity. Deep, loose soils tend to amplify and prolong the shaking. If any of these types of soils are located at or relatively near a regional fault system, this would also be an additional indicator of the 3rd Nephi regional fault system. The worst soils are the loose clays and filled areas. The type of rock that least amplifies the shaking is granite. I was unable to locate any calculations in the Isthmus area of amplification due to the soil types. An area in the United States that has been intensely studied with regards to soil amplification is the San Francisco Bay area, which seems to have similar characteristics (strike-slip fault, muds, and clays) as the Isthmus. Factors in the San Francisco area have been determined by actual measurements that indicate the added factor of intensity when an earthquake occurs in a particular soil type (Perkins and Boatwright, 2010). The increment factors identified in San Francisco based on the type of soil/sediments are:

Material Properties	Predicted Intensity Increment Increase
Clay and silty clay, very soft to soft	2.4
Clay and silty clay, medium to hard	1.8
Sand, loose to dense	1.6
Sandy clay-silt loam, interbedded coarse and fine sediment	1.4
Sand, dense to very dense	1.1
Gravel	0.7

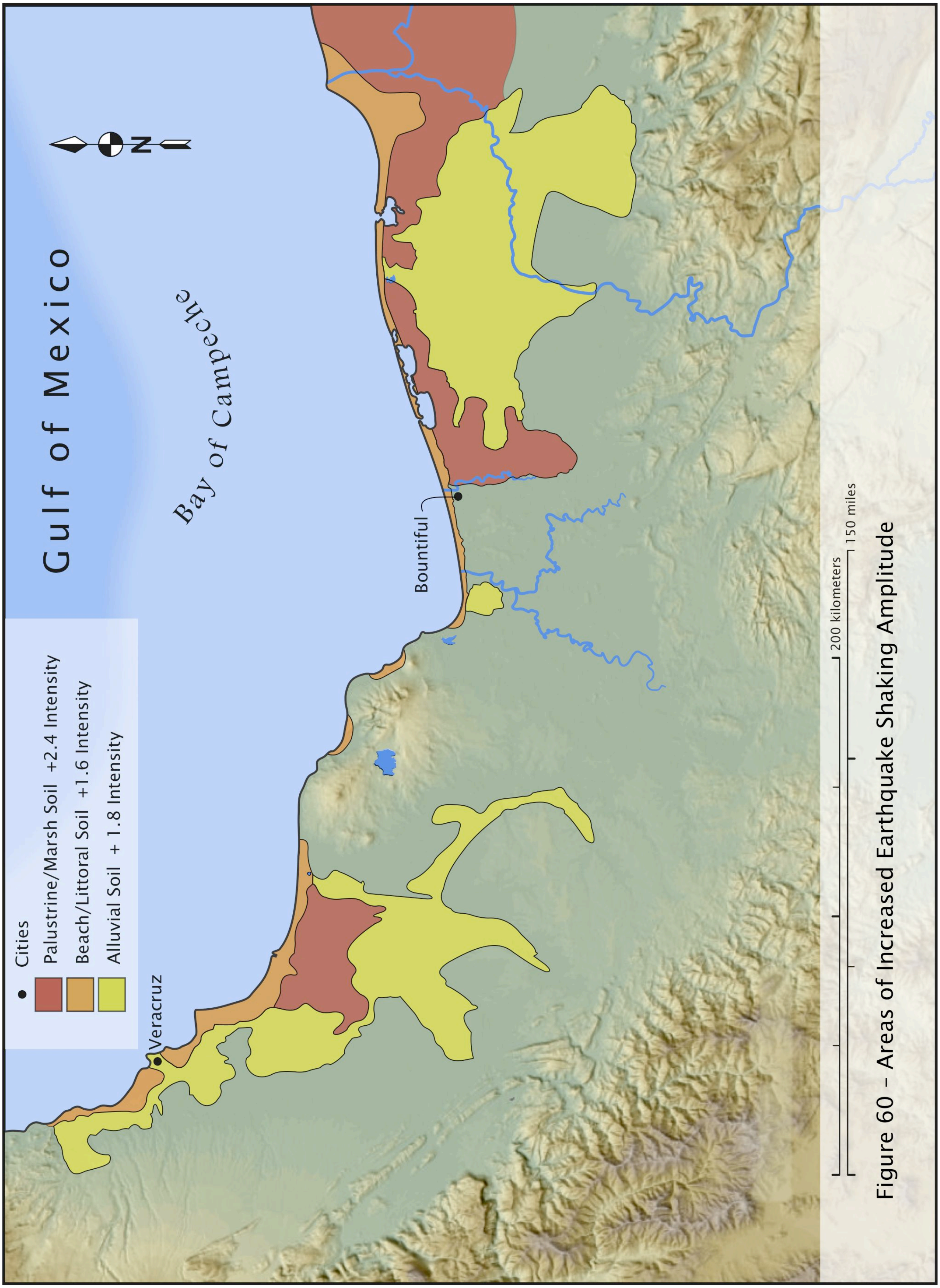

Figure 60 – Areas of Increased Earthquake Shaking Amplitude

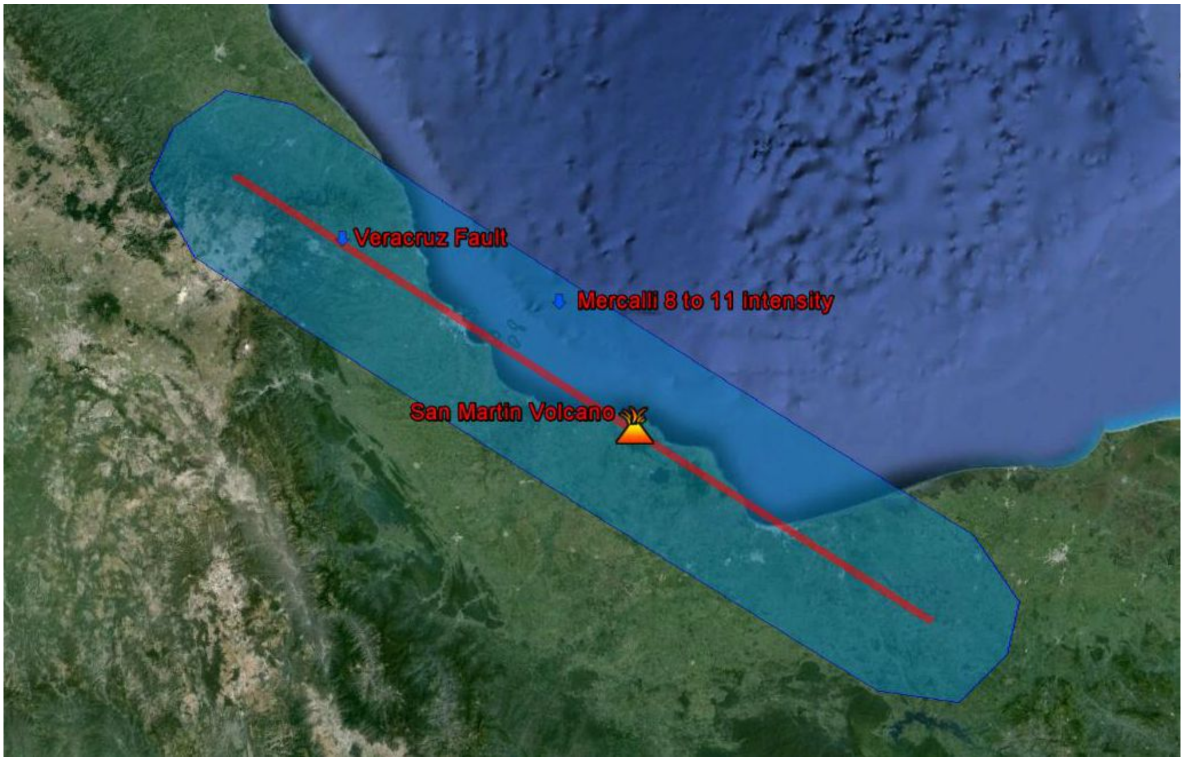

Figure 61. Areas subject to Mercalli 8 intensity or higher for an 11 intensity earthquake at the fault line where most fissuring, subsidence, lateral spreading, liquefaction, and earthquake induced landslides would be expected.

Now that the Veracruz fault is determined to be the primary regional fault, it is appropriate to determine some general zones of damage. Figure 59 shows all areas that would have been subject to an earthquake intensity of 7 or greater without local amplification; these would be the areas that would have significant or complete structural damage. Generally speaking, for most large earthquakes, the surface damage (ruptures, fissuring, settlement, subsidence/elevation, lateral spreading, and liquefaction) occurs in areas subject to earthquake intensities of 8 or greater. In the case of landslides, larger landslides can generally be triggered by intensities greater than 8, smaller landslides with intensities greater than 7. Figure 61 shows the areas potentially subject to an intensity level of 8 or greater along the Veracruz fault. It is important to note that figures 59 and 61 use a center line for the fault entire fault system when in actuality, the fault system consists of multiple faults many of which do not occur on the center line. As a result, it must be recognized that the damage areas indicated in the figures could be expanded to the southwest or northeast if one of the faults on the edge of the system is the one that experienced the most movement. In strike-slip fault earthquakes, one earthquake event will typically include movement on many faults within the fault system. Figure 60 shows the areas of amplification of effects due to soil and/or sediment conditions, which can occur both inside and outside of the zones shown in figures 59 and 61. The factors shown in figure 60 indicate the increase in whatever earthquake intensity is already present, meaning that the factor added to the modelled earthquake intensity will be the actual earthquake intensity expected in the problematic soil areas.

Analysis and Conclusion

The Veracruz fault segment satisfies all of the necessary conditions given in the Book of Mormon as the primary earthquake fault system. It is a strike-slip fault, which typically generates surface ruptures, fractures, and subsidence. It is located in the land northward where the worst damage occurred. Part of the fault segment is in the land southward and could cause damage in the land southward. It is located on and adjacent to the coastal plains. It occurs in areas that had significant population at the time.

The Veracruz fault system also satisfies most of the preferential conditions. It has a major volcano sitting directly on the fault system, the volcano San Martín. It occurs within parts of the land of Bountiful. Part of the fault system sits under water in the Gulf of Mexico and could potentially generate a tsunami. It possibly could cause effects triggering subsidence in the city of Moroni. There are major rivers and some lakes and lagoons on or adjacent to the fault, which could quickly fill areas of subsidence. The only preferential criteria that does not appear to be met is the ability to cause subsidence in the city of Jerusalem (located near Lake Atitlán in the Sorenson model), as the intensity felt at a distance of 400 km from the southern reach of the Veracruz fault would not be enough to cause any direct subsidence (at a level III on the Mercalli scale), and although possible, would not be expected to trigger landslides at that distance and intensity. However, the destruction at the city of Jerusalem may have involved non-earthquake related events, so this condition is not critical.

The Veracruz fault segment is the ‘best fit’ for the primary location of the regional earthquake that occurred at the time of 3rd Nephi.