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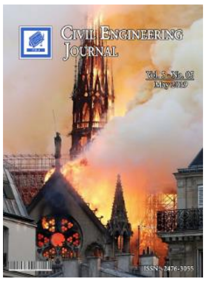

Peruvian Subduction Surface Model for Seismic Hazard Assessments

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Abstract

Throughout the years seismic hazard calculations in Peru have been developed using area sources models, having to date a great variety of models, however, since they are discretized planar models, they cannot adequately represent the continuity and subduction characteristics of the Nazca Plate. The main objective of this work is the developing of a surface subduction model (SSM), useful for seismic hazard assessments as well as the revision and control of previous models used in this sort of assessments. In this study a spatial interpolation was performed employing the Local Polynomial Interpolation method to capture short-range variation in addition to long-range trends. The data base is based on the compilation of seismic catalogs from Peruvian and international institutions such as the IGP, the USGS, the ISC and others, subsequently, in order to have independent events the elimination of duplicate events, aftershocks and foreshocks was carried out. Then, by interpolation of the focal depths of the independent events, a subduction surface model (SSM) was generated as well as a Standard Error Surface which supports a good correlation of the model. Furthermore, 14 transversal sections of the SSM was employed to compare with the hypocenter's distributions, evidencing a good correlation with the spatial distribution of the events, in addition to adequately capturing the subduction characteristics of the Nazca Plate. Finally, a comparison was made between 2 Peruvian area models for seismic hazard and SSM developed in the present research, evidencing that seismic source models of the area type have deficiencies mainly in the depths they consider, thus is recommended the use of the present model for future seismic hazard assessments.

Keywords: Subduction Surface Model; Seismic Hazard; Seismic Sources.

1. Introduction

Definition of seismogenic source are one of the most crucial parts in probabilistic seismic hazard assessments because it models the spatial distribution of earthquake events. Castillo and Alva [1] proposed the first seismotectonic model for seismic hazard assessments in Peru, his models was composed by 20 seismogenic area sources of which 12 were to model the subduction and the rest a continental sources. As a part of their work, the author developed the first national seismic hazard assessment in Peru. This model was extended employed, many years later, Bolanos and Monroy [2] developed an actualization of the national seismic hazard using this model.

Later, Gamarra [3] developed an actualized a model of 20 area sources, 14 of these were subduction sources. Some years later, Aguilar et al. [4] presented an actualization of the models trying to capture the spatial distribution of earthquakes that previous models could not adequately represent. This last model considers 29 area sources and 20 of them are used to model the intraplate and interface seismic zones. Although each time the models presented a greater discretization of the area, the sources in order to better represent the subduction characteristics, these do not necessarily

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fit into the characteristics of the Nazca Plate. Consequently, it is necessary to develop a model that can reveal the depth and distribution of the hypocenters of seismic events throughout Peru and that can be used with new trends in seismic hazard calculations, such as smoothed seismicity models.

The present work proposes the development of a subduction surface that can capture the neotectonics characteristics of Nazca Plate subduction, based on the interpolation of the hypocenters of a catalog that includes independent seismic events. This catalog was obtained after an elimination of foreshocks, aftershocks and duplicate events of a compilation of catalogs of several entities, such as the International Seismological Center (ISC), the Geophysical Institute of Peru (IGP), the United States Geological Survey, among others. Subsequently, a comparison of the resulting surface with the 2 seismotectonic models most used in the seismic hazard studies in Peru is made. Results show that the subduction model here developed, fits much better subduction mechanism than the previous ones.

2. Theatrical Background

2.1. Earthquake's Terminology

There is a range of terminologies used to describe the location of an earthquake, since it is the result of the rock breaking along a fault, which may involve several square kilometers of the fault plane surfaces. The point where the rupture begins is the hypocenter or the focus and the projection on the point on the surface is like the epicenter. The distance from the epicenter to the focus is known as hypocentral depth. The distance between the epicenter and an observer is the epicentral distance, besides, the hypocentral or focal distance is the corresponding distance between the focus and the observer [5], see Figure 1.

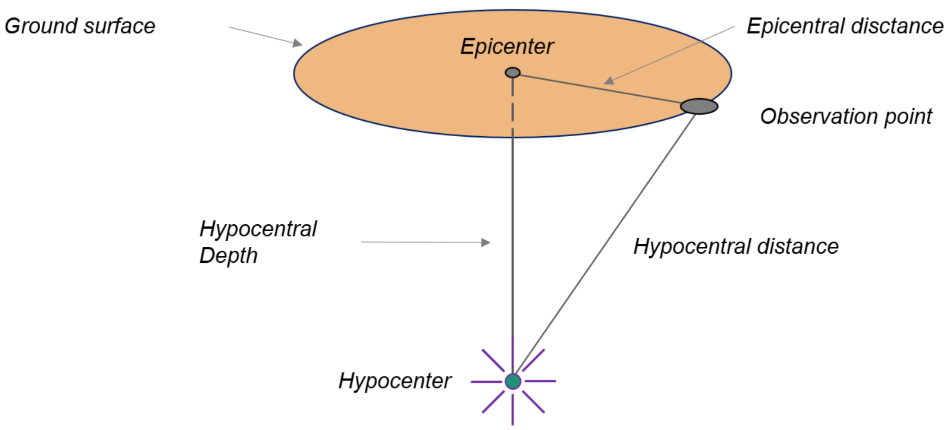


Figure 1. Spatial notation of earthquakes [5]

2.2. Spatial Distribution of Earthquakes in Peru

The seismicity associated with subduction events is concentrated throughout the interaction between the Nazca Plate and the South American Plate. The border between the Nazca Plate and the South American Plate in this region is demarcated by the Peru-Chile trench, which is 90 km west of the Peruvian coast. The seismic events from interface subduction are found in the western edge of Peru, mainly between the Peru-Chile trench and the coastal littoral, while the seismicity with focus at intermediate depth (60 km < h ≤ 350 km) is irregularly distributed beneath the continent.

On the other hand, deep-focus earthquakes (h ≥ 350 km) occur at the edges of the submerged sheet that is in contact with the mantle material at great depths (hundreds of km); there this edge crumbles inside the mantle releasing seismic energy in the form of waves [6].

2.3. Tectonic Structures of the Nazca Plate

Several tectonic structures are found off the Peruvian coast, some of which influence the spatial distribution of earthquakes, such as the Carnegie Ridge and the Nazca Ridge. In Figure 2 the tectonic features of the Nazca Plate are shown.

The Carnegie Seismic Ridge is a high bathymetric Nazca Plate originated in the area of the Galapagos Islands, has an approximate direction EW, and enters the zone of subduction between 1°N and 2°S of latitude. The Ecuadorian continental margin rises along the Carnegie collision area with the trench [7].

The Grijalva escarpment, an old fracture zone N60ºE in the Farallon Plate, is interpreted as the southern half of the fault trace from which the Nazca Plate was detached. Additionally, exist an anomaly beneath northern Peru, called the Inca Plateau and it could be the responsible of a low seismicity activity in the northeastern of Peru [8, 9].

The Mendana fracture is one of the tectonic features of the Nazca Plate that is in the extreme west of the central region of Peru between latitudes 11 ° S and 15 ° S. It has a NE-SW orientation, that is, perpendicular to the line of the Peruvian-Chilean trench; with an approximate length of 1100 km, an average height of 1000 m above the oceanic crust and a width of approximately 80 km. Its origin is associated with an old zone of plate divergence [10].

The Nazca Ridge, is an old oceanic mountain range that is observed in the bottom of the sea, collides with the South American Plate and is located in the extreme NO of the South region of Peru in front of the department of Ica with great influence in the tectonic constitution of the western part. It has a NE-SW orientation perpendicular to the line of the Peruvian-Chilean trench between the latitudes 14 ° S and 16° S in such a way that its NE end is located in front of the department of Ica where it has a width of approximately 220 km above the 1.5 km elevation, however, its width and altitude gradually decrease towards its SW end [11].

At 450 km from the Nazca Ridge, the Nazca fracture is in front of the department of Arequipa, being the most remarkable bathymetric characteristic. The fracture zone has a depressed valley structure (~ 1.2 km depth) along the fault line [12], which is aligned in a NE-SW direction, perpendicular to the trench. Robinson *et al.* [13] link the fracture zone as a rupture barrier of the Arequipa earthquake in 2001.

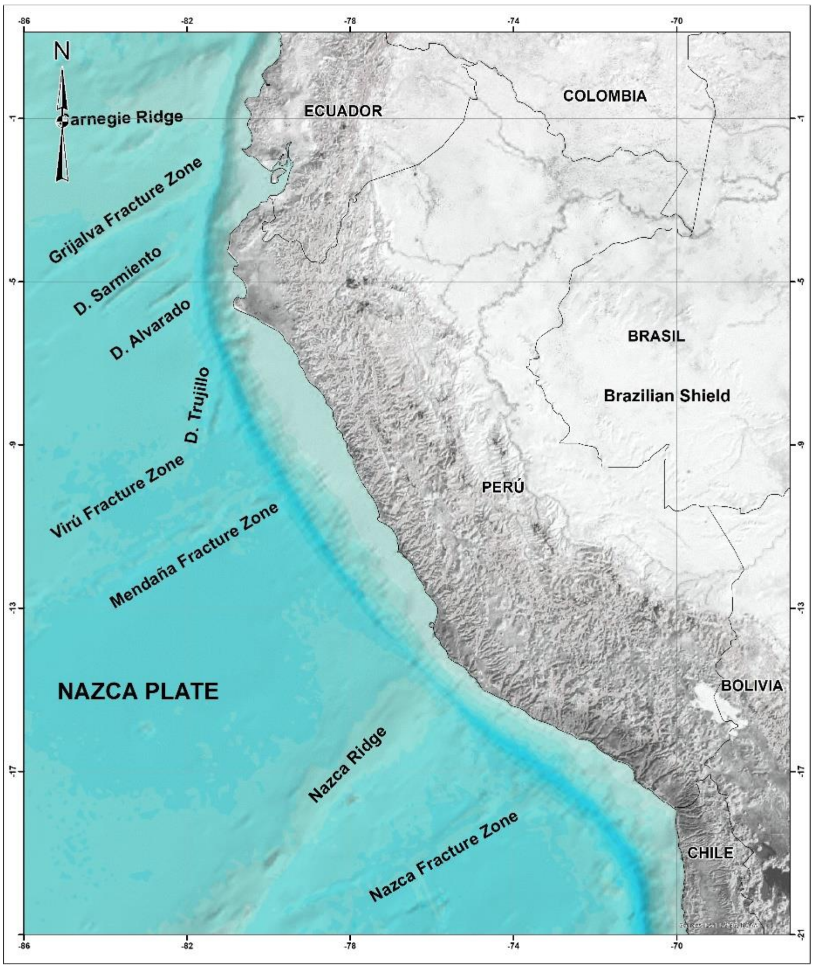


Figure 2. Tectonic structures of the Nazca Plate

3. Develop of a Subduction Surface Model

3.1. Hypocenters Data

In the present work, the information available from national and international catalogs such as the Geophysical Institute of Peru, International Seismological Center (ISC) (ISC), the United States Geological Survey (USGS), has been compiled. in English), the National Earthquake Information Center (NEIC), the National Oceanic and Atmospheric Administration (NOAA), the Global Centroid Moment Tensor of Harvard University (GCMT), among others, between the meridians 66 ° W and 84 ° W Greenwich and the parallels 4 ° N and 23 ° S in order to obtain the most complete seismic information from a magnitude Mw ≥ 4.0.

The methodologies of elimination of foreshocks and aftershocks events used in this work correspond to the Reasenberg's second-order moment analysis [14] and the spatial, temporal and magnitude criterion developed by Maeda [15]. Furthermore, since it is a collection of events, there are cases in which the same event is registered by 2 or more different entities, for this reason an elimination of duplicate events was also carried out. The final seismic catalog consists of 11688 earthquakes with a magnitude Mw ≥ 4.0, Figure 3 shows the catalog with seismic events of magnitude greater than 5 Mw, where the size and chromatic scales represent the magnitude and depth range respectively.

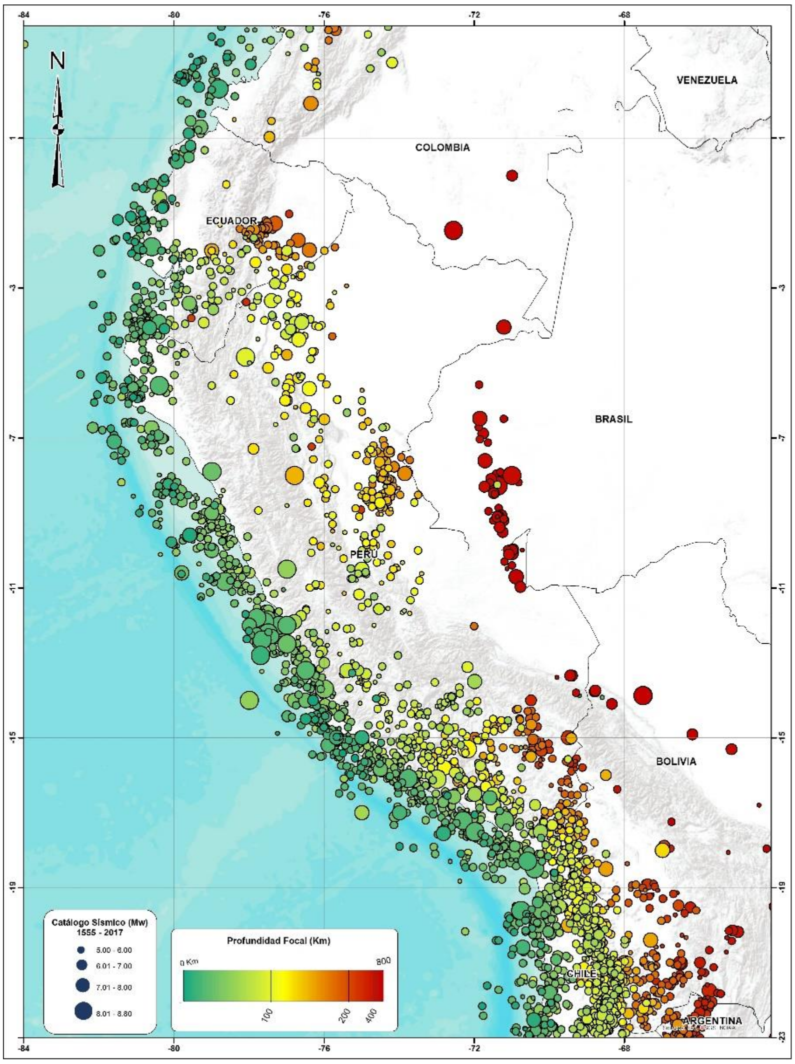


Figure 3. Seismic catalog of events 1555-2017 considering a magnitude Mw≥5

3.2. Spatial Interpolation

The interpolation tools make use of spatial and temporally distributed data about the phenomenon under study in order to make a prediction of the areas where no measurements have been recorded. Specifically, for the case of seismic events are distributed spatially by location of the epicenter and hypocentral depth. There are multiple methods for obtaining a prediction for each location. Local methods assume that each point influences the resulting surface only up to a certain finite distance. Values at different unsampled points are calculated by functions with different parameters, and the continuity condition between these functions is defined only for some approaches [16].

The local polynomial interpolation method performs a polynomial fit to the specified order using points only within the defined neighborhood. The neighborhoods overlap, and the value used for each prediction is the value of the adjusted polynomial in the center of the neighborhood. Figure 4 shows a surface that has a variable shape, a landscape that tilts, levels and slopes again, where multiple polynomial planes represent the surface with better precision compared to a global interpolation.

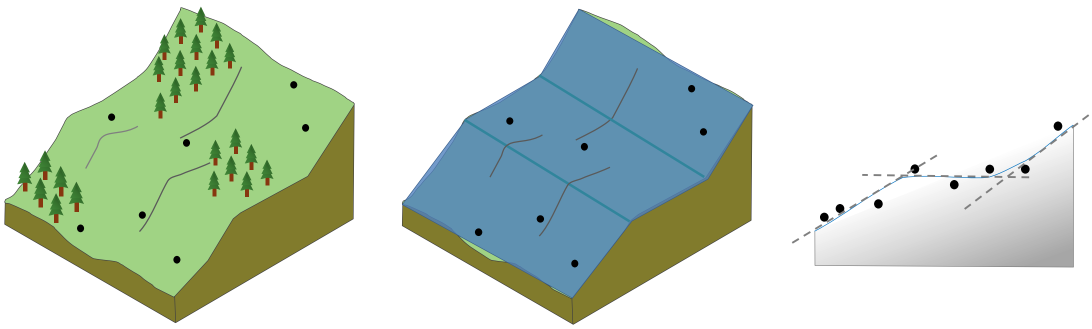


Figure 4. Spatial notation of earthquakes [16]

To obtain the subduction surface, the local polynomial interpolation algorithm of ArcGIS was chosen using the spatial distribution, latitude, longitude and focal depth corresponding to each event. The other parameters were chosen based on the recommendations of the software developers [16] and an iterative process, which are presented in the Table 1.

Table 1. Parameter of the local spatial interpolation

Parameter/Conditions	Value/Description
Interpolation Field	Hypocenter depth
Output Cell Size	0.02
Order of Polynomial	3
Search	Neighborhood type – Smooth Circular
Smoothing Factor	0.2
Function Kernel	Exponential
Spatial Condition Threshold Number	Yes

3.3. Surface Subduction Model

The elevation views of the obtained subduction surface model (SSM) is shown in Figure 5, while in Figure 6 a plan view with isolines spaced each 1km of depth, can be appreciated. At first sight, the subduction model allows to differentiate different zones whose subduction has peculiar characteristics. While in the north and center of Peru the subduction has a low slope, in the south it becomes more abrupt, generating a marked transition zone between the limits of the central and southern zones, a more detailed description will be made in the following sections.

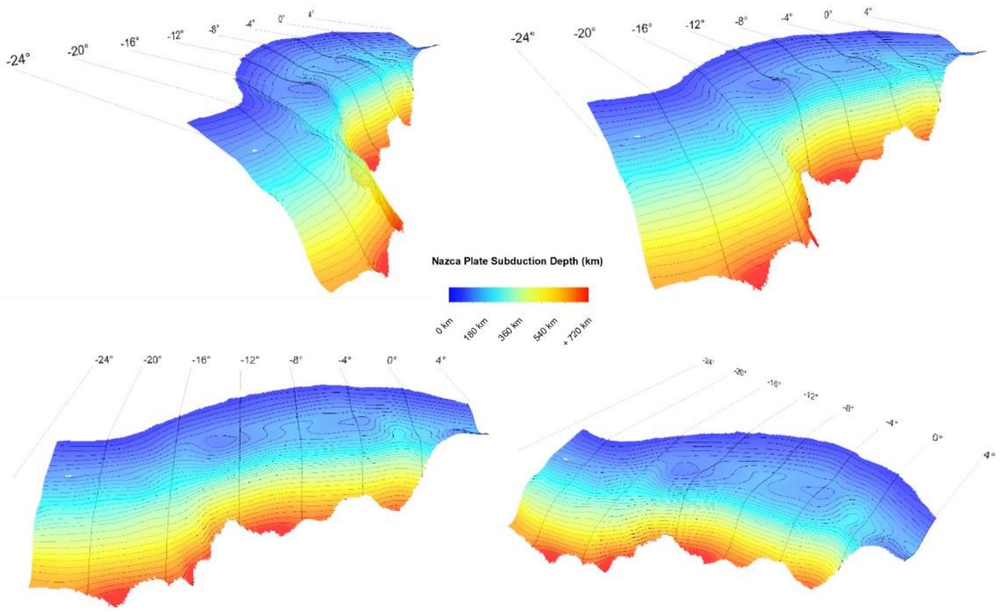


Figure 5. Three-dimensional views of the subduction surface

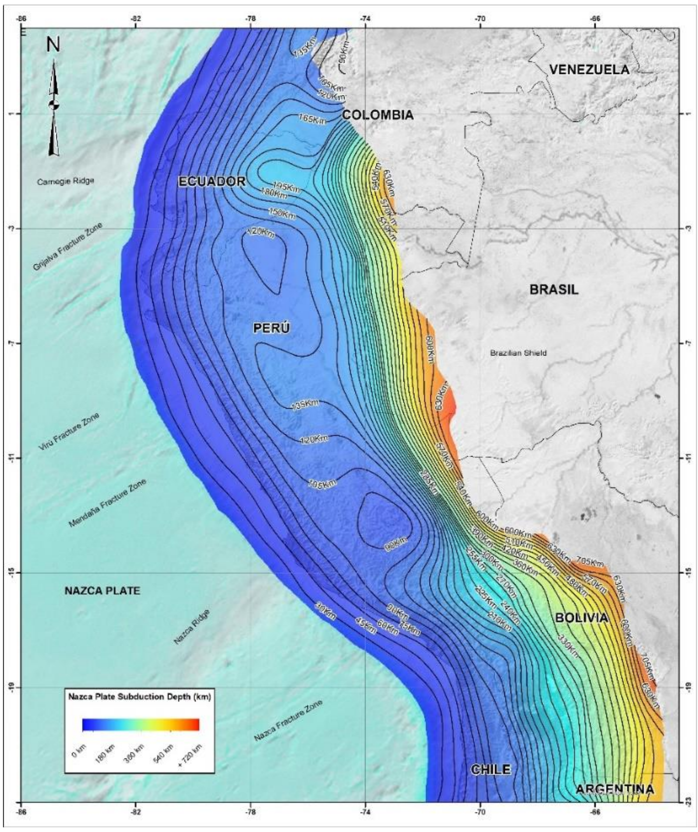


Figure 6. Plan view of the obtained subduction surface

In order to know the precision of the prediction, a prediction standard error surface was created (Figure 7), which indicate the uncertainty associated with the value predicted for each location. As it could be noticed, the standard error of the SSM is lower than 10 km which means a strong correlation of the model with the spatial distribution of the hypocenters, except when the prediction reaches high depths in zones where information of the events is lower.

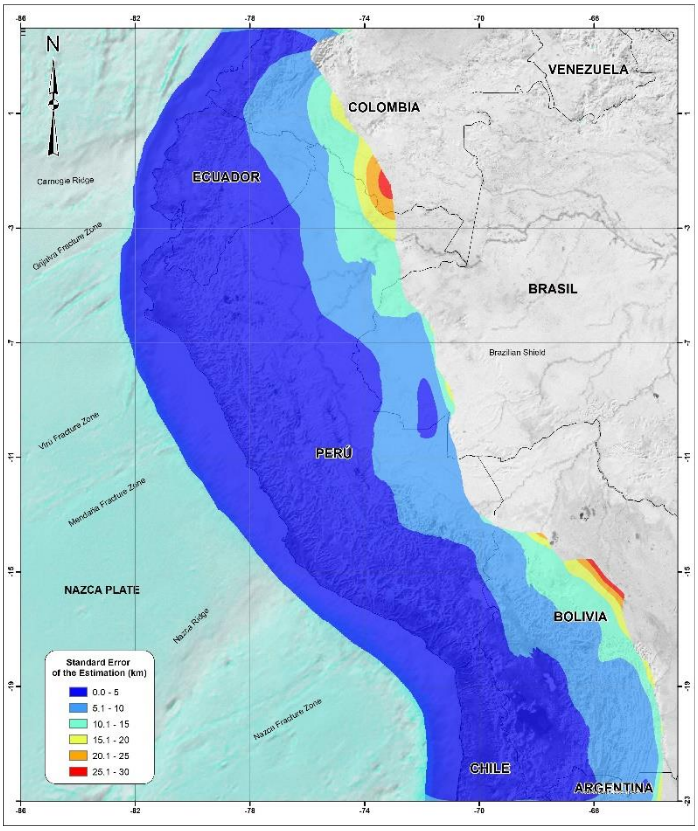


Figure 7. Standard error of the subduction surface model.

Additionally, in order to verify the quality of the adjustment, 14 sections with a width of 1º have been made, which in turn are grouped into 4 zones which are shown in Figure 8, the subduction region near Ecuador (red lines), the northern zone (purple lines), the central zone (green lines) and the southern zone of Peru (blue lines). The spatial distribution of hypocenters and the Surface subduction Model (SSM) shows a strong correlation and let appreciate the different ways in which Nazca Plate subducts the continental crust.

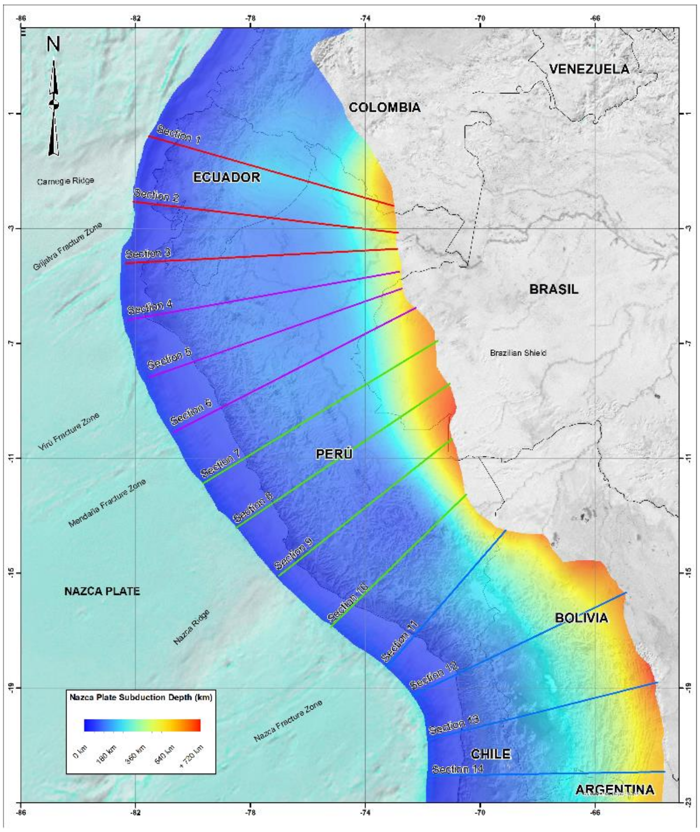
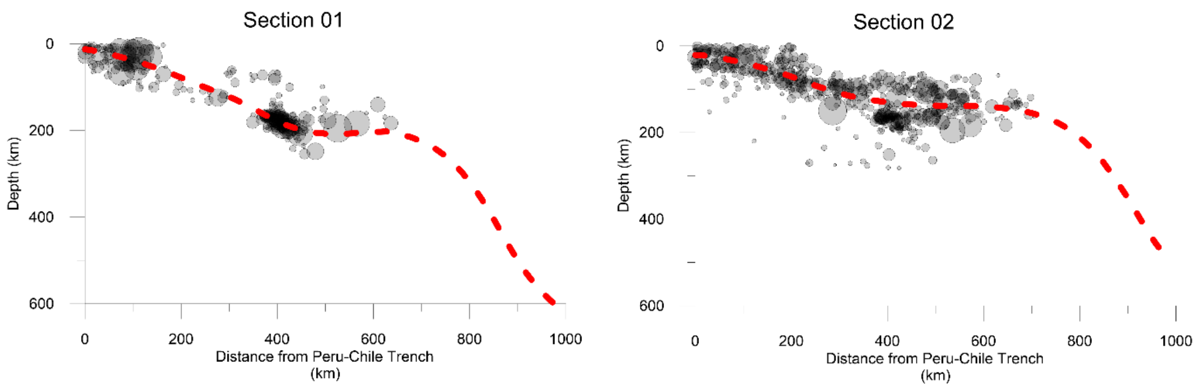


Figure 8. Selected Cross Sections

3.4. Northern Zone of Ecuador

In the northern zone of Ecuador represented by section 1 (See Figure 9), it can be seen that there is a continuous subduction up to 200 km depth with an angle between 25 and 30 ° and a distance of 400 km from the trench, this behavior gradually varies towards the southern part of the equator becoming a subduction with an angle of 20 to 25 ° as shown in sections 2 and 3. This behavior is consistent with what has been described by several authors [17-19], who determine a subduction angle in the range of 25 to 35 ° between the parallels 1.5 ° N and 2.5 ° S, which subducts continuously up to around 200 km. In central part Ecuador, between 4°S and 1°S, the Nazca Plate undergoes a sharp contortion similar to that observed in southern Peru where at ~15°S, this is because the presence of the ancient Farallon Plate [20].



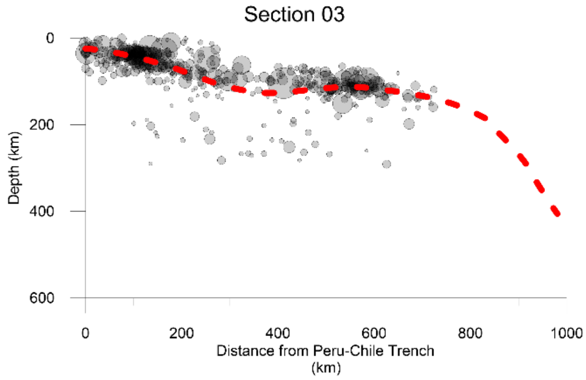


Figure 9. Cross sections in the northern zone of Ecuador

3.5. Northern Zone of Peru

In the northern zone of Peru according to sections 4 through 6 of Figure 10, the subduction advances with an angle of ~ 20°, reaching an average depth of 150 km, depth at which it becomes a subduction horizontal sub to the 700 km from the trench.

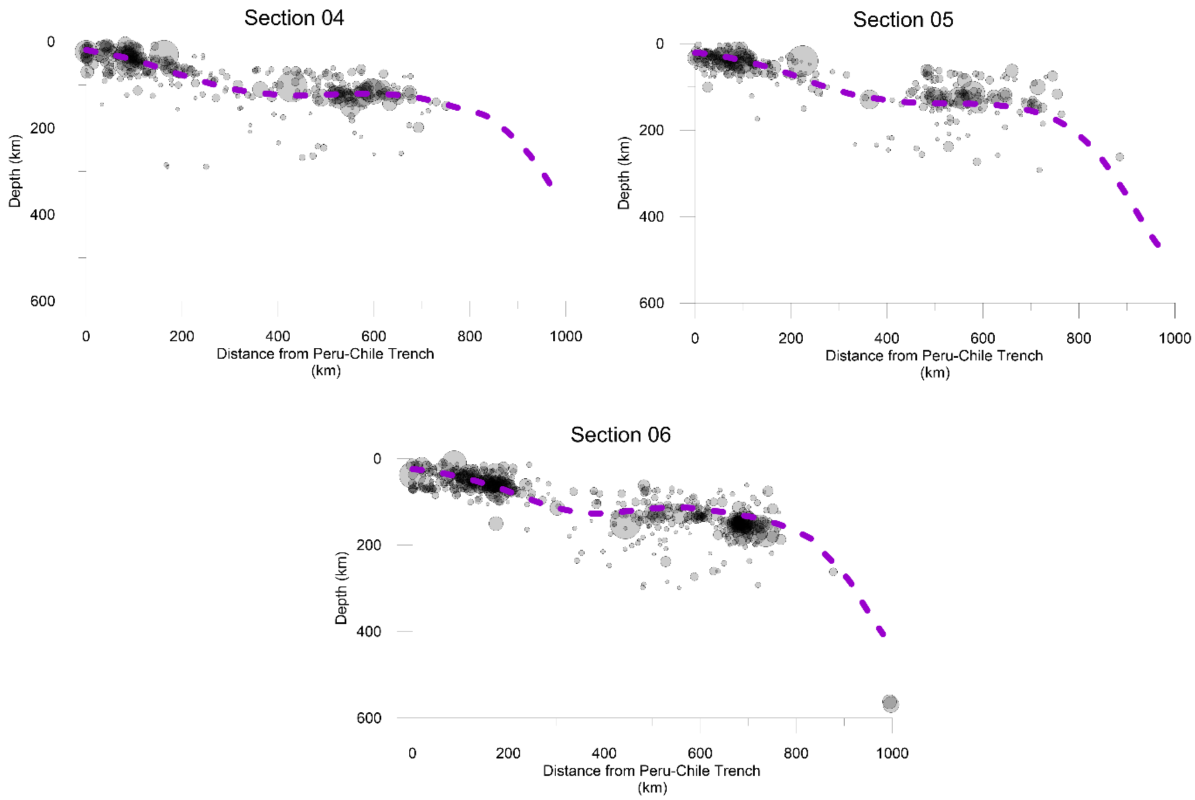


Figure 10. Cross sections in the northern zone of Peru

The model captures the characteristic of flat subduction, that previous studies have proposed a broad flat slab of relatively uniform depth [21-23]. It should be mentioned that between the range of distances of 200 and 400 km from the trench there is not many events, however, from 400 to 600 km there is evidence of a high deep intraplate seismicity. The northward extent of the flat slab may be due in part to the subduction of the Inca Plateau [8].

3.6. Central Zone of Peru

The central zone of Peru maintains the subduction tendency of the northern zone, with the difference that the zone of initial subduction that advances with an angle of ~ 20°, reaches a depth of 100 km at distances between 200 and 250 km from the trench, from where it becomes a sub horizontal subduction until 500 and 600 km from the trench, where the subduction increases its slope, to then reach depths in the range of 600 and 700 km, where a deep seismicity is the product of the contact with the Brazilian shield, allowing to extent the model until these depths, it can be appreciate in sections 7 to 10 of Figure 11.

Previous studies have shown that subduction of the Nazca Plate occurs at an approximate angle of 18º, reaching a depth of 100 km, from which it remains constant for about 300 km to subsequently resume its descent [12, 22], so the model developed is consistent with the subduction characteristics of the area.

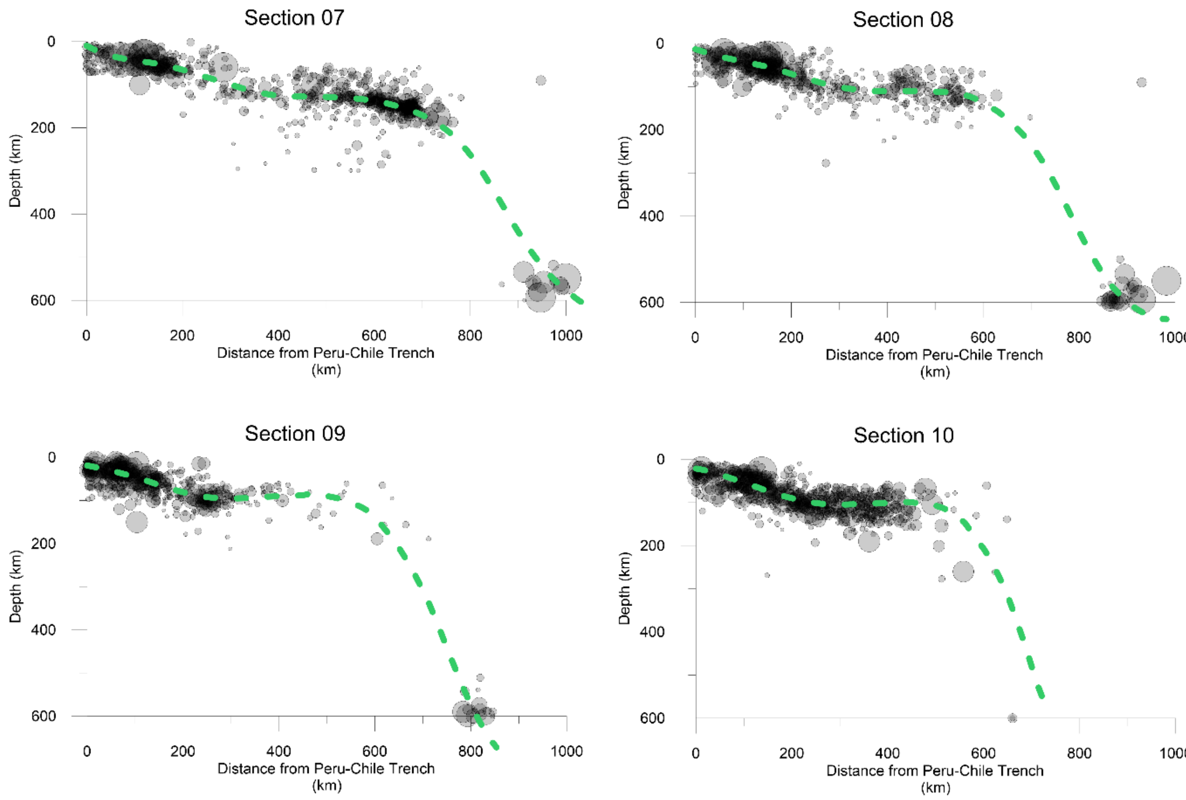


Figure 11. Cross sections in the central zone of Peru

Furthermore, it can be noticed that the model presents a practically flat subduction that moves away from the trench between the parallels 11º S and 16º S, which coincides with the entrance of the Nazca ridge to the coast and maintains a homogeneous depth between the 90 and 105 km deep. This behavior is consistent with other models, Phillips *et al.* [12] propose that the Nazca ridge reaches a constant depth of 100 km, while Antonijevic *et al.* [24] developed a model based on cutting wave velocities in addition to a conceptual model of dorsal formation, concluding that it subducts to a depth of 90 km.

3.7. Southern Zone of Peru

The marked difference between sections 10 and 11 denotes an abrupt change in the form of subduction is observed, coinciding with the intersection of the Nazca Ridge with the Peru Chile trench as was described in other studies [12, 21, 23, 25, 26]. Moreover, in this transition zone a decrease in seismicity is observed in the model, according to Dougherty and Clayton [25], this decrease in seismicity suggests a change in the structure of the plate between the normal subduction in the southeast and the sub horizontal in the northeastern zone. This variation in seismicity is likely related to the overthickened crust of the Nazca Ridge, compared to the normal oceanic crust on either side of the ridge [26].

The southern zone has a steeper subduction with an angle of 30 ° to 300 km depth which is consistent with that of previous studies [21, 22, 25]. As observed in sections 11 and 12 of Figure 12, earthquakes occur up to a distance of 450 km from the trench, while for sections 13 and 14 of the same figure, there is a large number of seismic records at distances from the trench of 550 km on average.

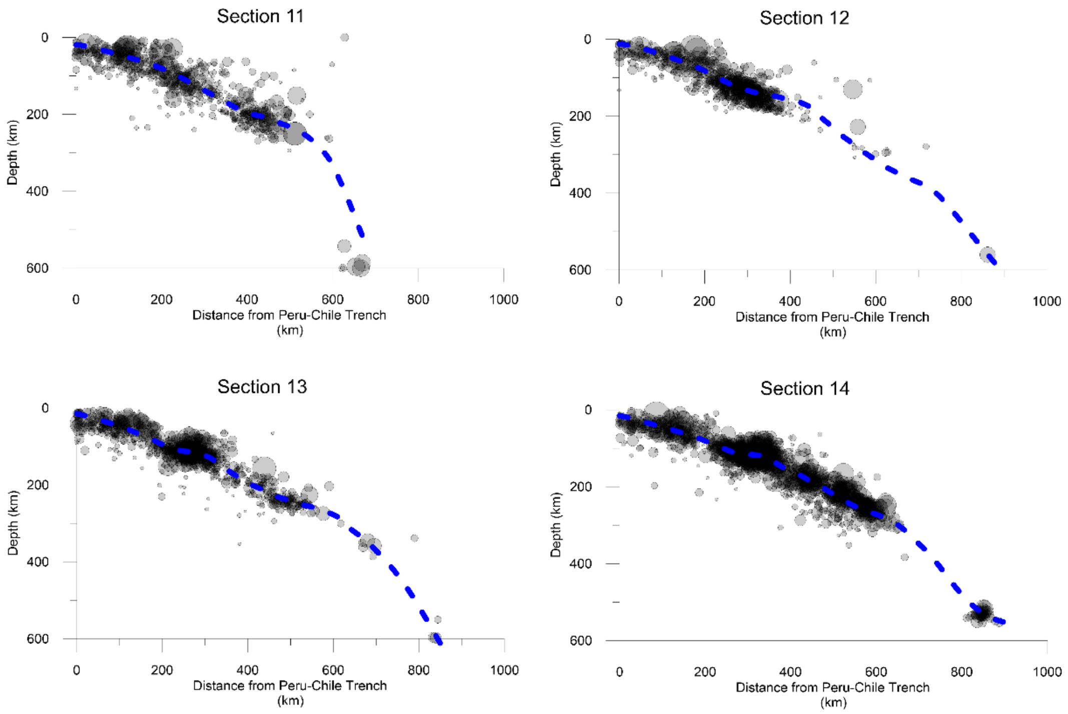


Figure 12. Cross sections in the southern zone of Peru

It should be mentioned that the locations of the earthquakes usually provide a first-order estimate of the geometry of the oceanic trench, however, currently there are more advances, but complicated methods that allow to study in a more adequate way the upper and lower limits of the subduction zone [12, 23, 25, 28], however, for seismic hazard assessments the SSM developed in this work can be used adequately.

4. Comparison of Seismotectonic Models

Seismogenic source are one of the most crucial parts in probabilistic seismic hazard assessments because it models the spatial distribution of earthquake events, Castillo and Alva [1] proposed the first seismotectonic model for seismic hazard assessments in Peru, his models was composed by 20 seismogenic area sources of which 12 were to model the subduction and the rest a continental sources. Gamarra [3] developed new seismotectonic model of 20 area sources, 14 of these were subduction sources which in contrast to Castillo and Alva [1] model, discretized better the subduction zone. Some years later, Aguilar *et al*. [4] present an actualized of the models trying to capture the spatial distribution of earthquakes that previous models could not adequately represent. This last model considers 29 area sources and 20 of them model subduction seismic zones, being the model that discretizes more than other the Nazca Plate subduction.

Figure 13 shows the comparison of the subduction surface generated with the sources of Gamarra [3] and Aguilar et al. [4], As can be seen in the figure, both models show deviations from the SSM of the present investigation, however, Aguilar's sources adjust much better than those of Gamarra. Although the area sources proposed by Aguilar *et al.* fits better to the SSM in comparison to Gamarra’s source, for further works in seismic hazard assessments, the use of subduction surface models such as the one generated in the present investigation is recommended.

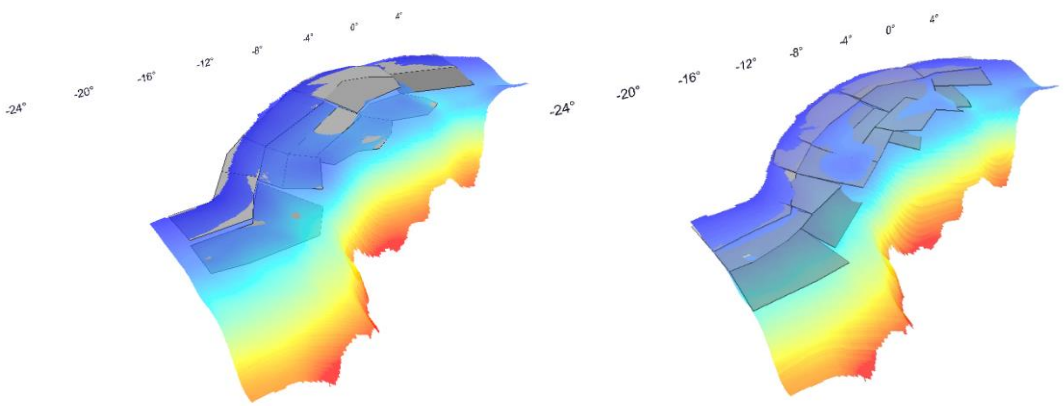


Figure 13. Spatial comparison between SSM and Peruvian seismotectonic models for seismic hazard assessment. On the Left side Gamarra [3], on the right Aguilar et al. [4]

5. Conclusion

The subduction model developed in this research allows to estimate the distribution of earthquakes in areas where there is not enough data of earthquakes, being of great help both for the control of the geometries of seismogenic sources and for the generation of smoothed seismicity models, thus allowing the performance of seismic hazard assessments in a more reasonable way than simply use geometrical area sources.

The geometry of the resulting subduction surface represents adequately the tectonic features of the Nazca Plate, such as the Inca Plateau and Nazca ridge, both responsible for a markable flat subduction zone in the north and central zone in Peru, the last also divides the central and southern subduction zone of the Peruvian coast, the former having a sub-horizontal subduction and the second, a continuous subduction with an angle of 30° to reach considerable depths, all of these patterns we observe are consistent with the stated by several authors, as was detailed in the previous sections.

The seismicity of deep focus, product of the contact with the Brazilian shield, allows to suggest a geometry of subduction to great depths, nevertheless, for the purposes of estimation of the seismic assessments they do not have greater relevance.

6. Funding

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7. Conflicts of Interest

The authors declare no conflict of interest.

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