South Atlantic Anomaly Variations during Seasons

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ABSTRACT

This investigation searches the possible connections between deep and ultra-deep earthquakes in a subduction zone with unique characteristics known as Nazca-South America subduction. The earthquake events occurred in an area under the South Atlantic Magnetic Anomaly. The results pointed out that the cyclicity of earthquakes is independent of external factors and linked to internal unknown changes traced or associated with the lithosphere and upper mantle. The malleable minerals or unbreakable material could be due to a bulge of water between the two Nazca slabs sinking. The periodicity noticed from some events is opposite to the Solar Cycles, which means they enhance during the minima of cycles. Therefore, we concluded that these variations might be linked to internal causes below the crust into the lithosphere.

1. INTRODUCTION

The study focuses on the edge of the west of South America, as shown in **Figure 1**. This part of South America has the most giant earthquakes in subduction zones worldwide. The Figure shows the subduction zones on the border of South America (white line). The South American craton is marked with a yellow line. The first big earthquake occurred in 1906. We will discuss these events and how the earthquakes behaved between 2000 and 2022.

This paper's preliminary aim is to investigate the features of a specific subduction area in South America [1, 2]. Nazca is sinking under the continental plate. The deep-depth earthquakes in this place were addressed in another paper [3], especially for deep and ultra-deep tremors. The continental plate stratigraphy in the boundaries is formed by breakable material that triggers earthquakes in this area. The subducted oceanic plate is flattened beneath northern Peru instead of steeply sinking, called the Peruvian flat slab. The Nazca Plate is built on the west by the Pacific Plate and to the South by the Antarctic through the East Pacific Rise and the Chile Nazca Plate over several hotspots has created some volcanic islands as well as east-west running seamount chains subducting under South America. The break-up of the Farallon Plate formed Nazca. The Nazca plate motion is about 3.7 cm/year east, one of the fastest absolute motions

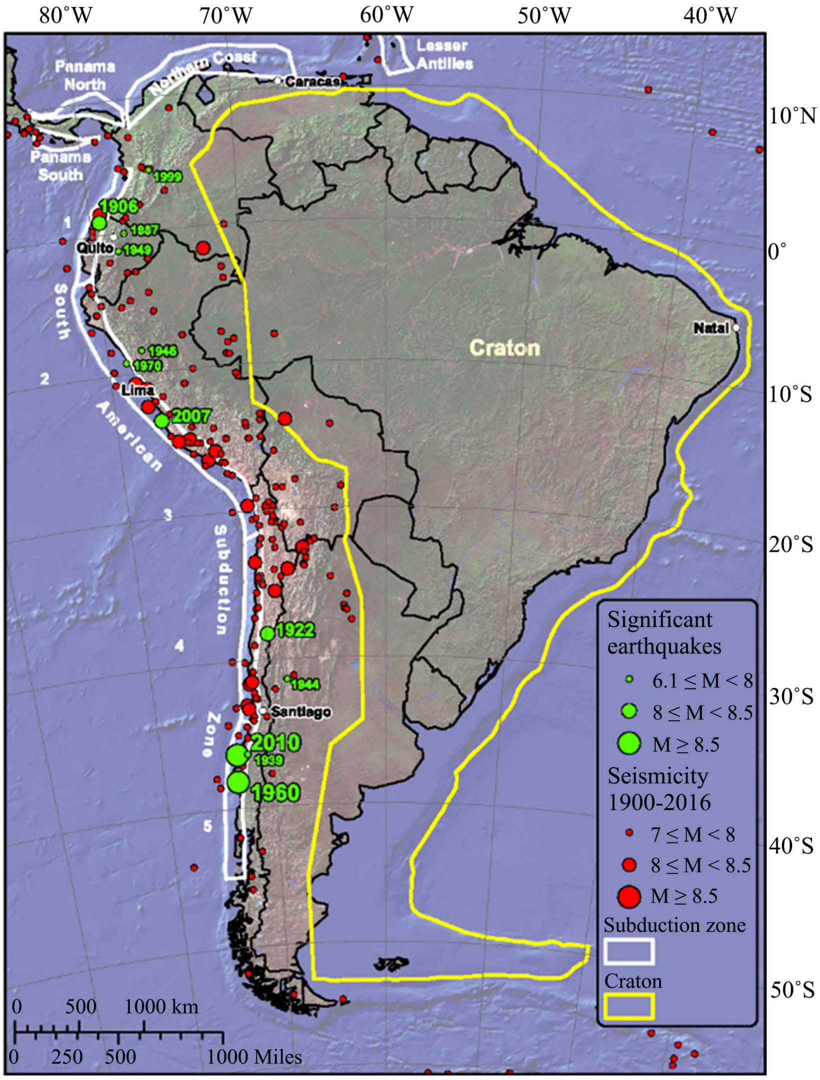

Figure 1. The west side of South America with several big earthquakes and seismicity range 1900-2016. (USGS).

of tectonic plates. The subduction has begun and continues to develop the volcanic Andes Mountain Range. The 1994 Bolivia earthquake occurred at a depth of more than 300 km, and its magnitude reached 8.2 M_w. The speed of the Nazca Plate is shown in **Figure 2**; the absolute motion of the Nazca Plate has been calibrated at 3.7 cm/year) east motion (88˚), one of the fastest absolute motions of any tectonic plate. The subducting Nazca Plate, which exhibits unusual flat slab subduction, is tearing and deforming as it is subducted. The subduction has formed and continues to develop the volcanic Andes Mountain Range. The Nazca Plate deformation even affects Bolivia's geography, far to the east. The 1994 Bolivia earthquake occurred on the Nazca Plate; this magnitude of 8.2 M, which at that time was the strongest instrumentally recorded earthquake occurring deeper than 300 km. Observe that the Nazca plate presents several boundaries with other poorly understood plates.

Finally, the region subduction is shown in **Figure 3**. The Nazca plate is sinking underneath the continental American platform in this Figure. The gap is marked as water in the picture since there is evidence of malleable material below the continent where no quakes happen. The second slab of Nazca hits the continent in a very deep depth. Approximately 500 km or more, and it is the exact location where earthquakes are happening on the continent.

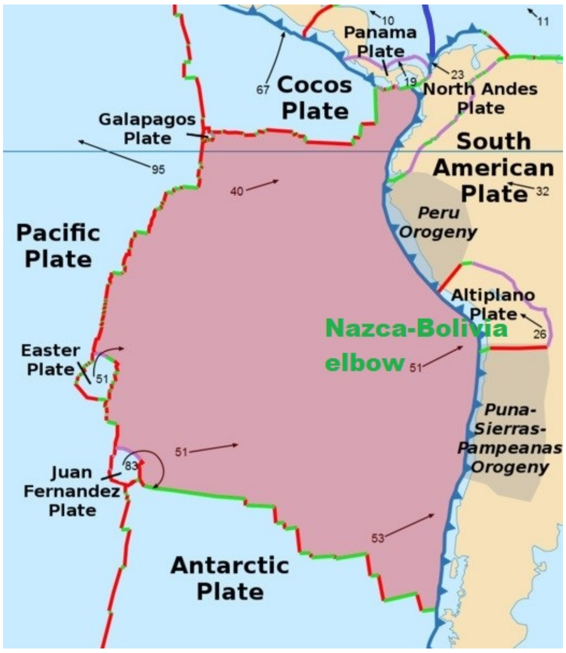

Figure 2. The Nazca plate collision with South America and the Nazca Elbow region, where deep earthquakes happened ≥300 km). Observe the location of Peru's orogeny.

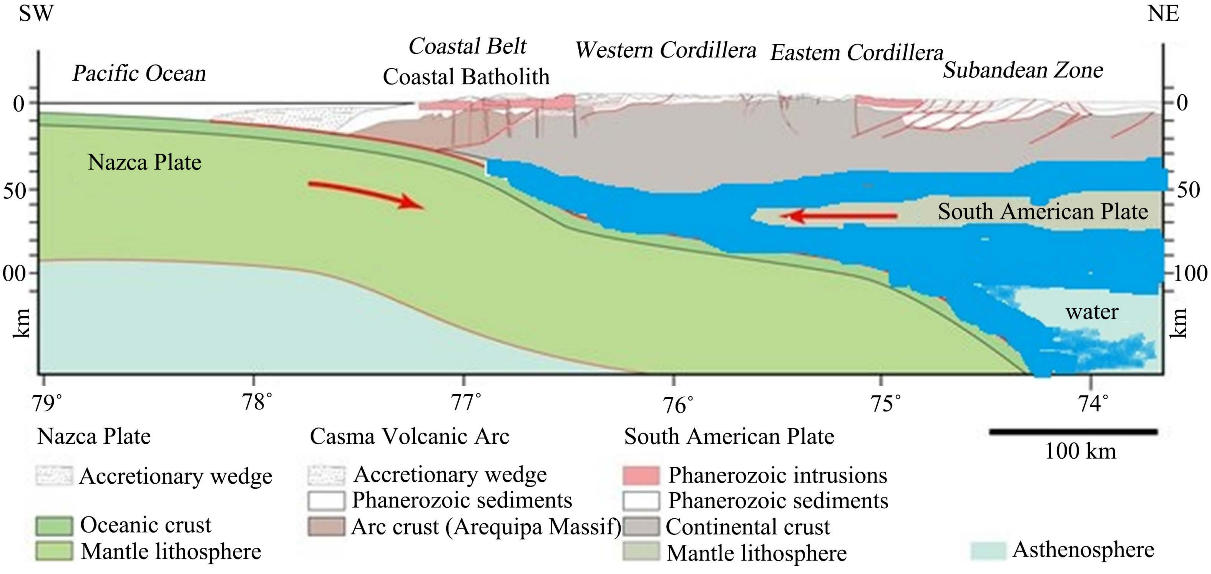

Figure 3. The region below the Nazca subduction, the picture was modified, and the unknown place was substituted by water, [1]-modified.

The well-known Pacific Ring of Fire is also a ring of mineral deposits, including deposits along western North and South America. Resources on the edge are base metals—copper, lead, zinc, and molybdenum (diamagnetic material)—and precious metals—platinum, gold, and silver(diamagnetic metals). Other metals, tin, tungsten, and antimony, all breakable, are detected in Bolivia. Some minerals on the continent are malleable as deposits include Copper-silver and gold veins, Porphyry copper-molybdenum deposits, Lead-zinc silver veins contact metasomatic deposits, and Tin deposits. Most of those minerals are diamagnetic and do not trigger earthquakes.

This mineralogy reflects the progressive melting of metals from the descending slab occurring under a depth of 300 km. The presence of this metal around Bolivia explains the triggering of great-depth earthquakes. The metals are sourced from the descending slab and overlying mantle. There are often associated geothermal regions [2].

Our last papers on the subject [3-5] worked on how the seasons could affect earthquakes worldwide, with an emphasis on subduction zones. Our last papers on the subject considered 1996-2018, comprising two solar cycles and two solar maxima in 2001 and 2014. The results indicated that Summer and Fall are the region's most important seasons for tremors. The quake evolution was considered under the South Atlantic anomaly. Also, another piece of information was that the Summer and Fall had the highest number of events in the year 2010, which is independent of the solar cycle. Other papers' investigations [6, 7] about the seasonality variability or periodicities for ultra-deep earthquakes worldwide pointed out that earthquakes M6 or above showed seasonality; however, it depends on the area searched. For example, in the inquiry on the Northern Hemisphere, the enhancements of events happened during Spring and Summer. In the Southern Hemisphere, it occurred during Fall and Winter. Nevertheless, the opposite seasons mean that it happened during the same months worldwide. Other observations were that ultra-deep earthquakes (depths ≥ 500 km) do not occur on the Northeast Pacific's side. We concluded that ultra-depth earthquakes showed seasonality only in the Northwest Pacific. Our paper now studies the deep seismicity in South America and how it could be connected with Solar Cycles. We shall define the variables that will be used in this paper. We choose the region defined by the South Atlantic Anomaly for future reference. The coordinates are 11.87N, −52.696S, −37.793E, −90.703W. The evolution events period is 2000-2022, the range with two solar maxima, 2001-2014. Depths are defined as deep and ultra-deep depths, as shown in **Table 1**. In this paper, we choose to work with deep-depth earthquakes because they are located below the crust, and many effects observed from those events come from the processes inside the Earth. However, we know that electromagnetic forces from the Sun are responsible for many observed hazard events, direct or indirect; therefore, it is necessary to consider the seasons and solar variations to check all the processes that can be involved in the phenomena studied.

The seasons analyzed in the Southern Hemisphere are in **Table 2**. With those variables, we will investigate the number of events in the Nazca-South America subduction zone for each depth and season. The table of seasons in the Southern Hemisphere is opposite to the Northern Hemisphere; therefore, having this on the paper is paramount. With these two tables, the earthquake events result during the range time defined before. The solar cycles mentioned in this paper are not necessarily complete; instead, we will focus on the two maxima, 2000 and 2014, and the minimum around them.

The variables considered here are coordinates, depths (**Table 1**), seasons (**Table 2**), and the time interval 2000-2022, allowing the construction of data files and maps for the entire region. The following section deals with the mathematical statistic methodology for earthquakes found. For the deepest depth events, events can use data with a more extended period since the occurrences and recorded quakes are much less in numbers.

Table 1. Distribution of depths for earthquakes.

Depths (consider deep (PE) and ultra-deep (UPE)
100 - 170 km (deep)
170 - 300 km (deep)
300 - 500 km (ultra-deep)
≥500 km (ultra-deep)

Table 2. Southern hemisphere seasons.

Seasons	Months
Winter	1 June-31 August
Summer	December 1-February 28
Fall	1 March-31 May
Spring	1 September-November 30

2. METHOD OF CALCULATIONS AND CLASSIFICATION OF EVENTS

To investigate a possible seasonality in deep (DE) or ultra-deep (UDE) earthquakes, we use the files from USGS (https://www.usgs.edu/) with data from the period 2000-2022, which has two solar maxima (2001, 2014). We will calculate the earthquake variations for several depths along the period, separating the data for seasons. The depths of 100 - 170 km and 170 - 300 km have similar occurrences, and we also make calculations with the two depths joined.

The last two depths are not similar, and the 300 - 500 km depth shows fewer occurrences than the ≥500 km. Those occurrences are in a narrower location in Bolivia in a place known as South America elbow. Both belong to our evaluation of ultra-deep quakes, and we will join them in one plot. We aim to determine if solar events, such as Solar Cycles or seasons, are essential for hazardous natural events on Earth—crust or under the crust.

The area is only the location where the South Atlantic anomaly happens. The coordinates are 11.87N, −52.696S, −37.793E, −90.703W. The small area has unique characteristics, known as the South Atlantic Magnetic Anomaly. Many authors have studied the effects of the anomaly in several atmospheric events. Here, we investigate how the lithosphere works could be linked to the phenomena observed in the atmosphere. **Figure 4** shows earthquakes with 70 - 150 km depths and 150 - 300 km. The "shallow" depth follows the coastline, and the deeper events are displayed behind it. Observe that there are gaps in the area where there are no occurrences.

The following two figures are the variation in time of these occurrences. We took the first depth as 100 - 170 km to avoid the instabilities of the vast quakes between 70 and 100 km.

In **Figure 5**, earthquakes with depths 100 - 170 km show an approximately cyclic behavior. The evolution plot does not follow the Sun's periodicity of eleven years, and the maximum for earthquakes has no correspondence with Solar maxima. This Figure displays that during Summer, Winter, and Spring, the enhancement of events period 2001-2008 and decreased from 2009-2014, which happened during all seasons watched, but during Fall—after 2014, all seasons suffered small increases that persisted until now, with only one exception in Fall.

Notice that the maximum value of one Sun's event does not correlate with earthquakes maxima and vice-versa. The 2001 (November) solar maxima do not correspond to the maxima earthquakes in Spring. The seasons marked as most important for this level are Winter and Fall, with an anomaly in the Summer in 2000 (it is not shown in the plot)

The evolution of events for the following depth of 170 - 300 km shows the correlation between Spring/Summer, **Figure 6**. The same happens between Fall and Winter. It was a strong quake maximum in 2001; the corresponding season was the beginning of Summer in the Southern Hemisphere (November). There was a decrease in the events between 2007 and 2015 observed. It still correlates between Fall and Winter, as seen in **Figure 5**. There is no correlation between Spring and Summer.

Figure 6 shows that from this depth, the range 2001-2008 occurrences increased in the Summer, Winter, Fall, and Spring; they decayed 2008-2014, improving again after 2015, and now the seasons are enhancing the events again except for Summer.

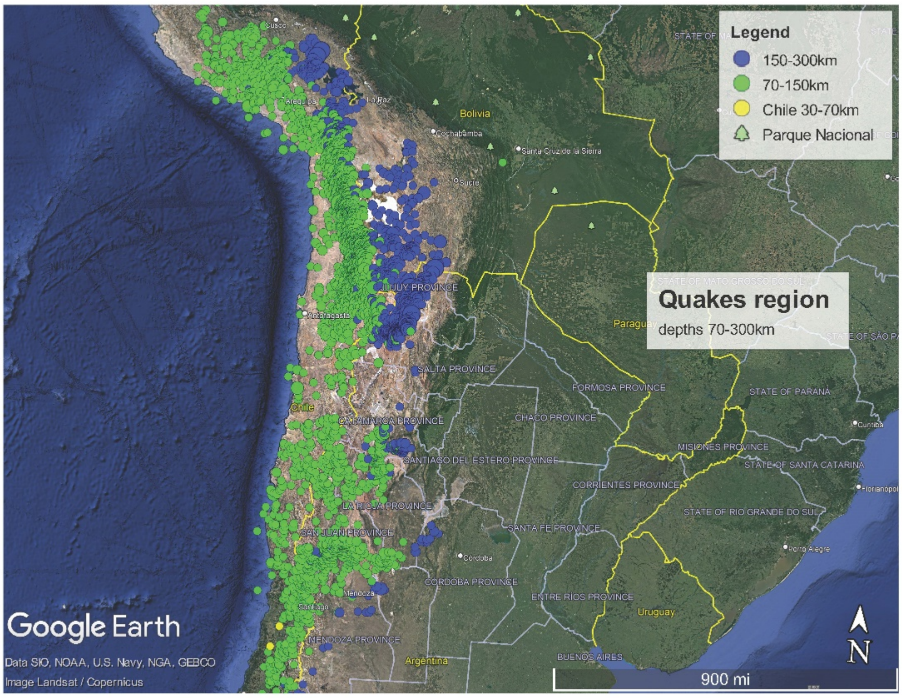

Figure 4. The area where occurrences of the first two depths are considered 70 - 150 km and 150 - 300 km.

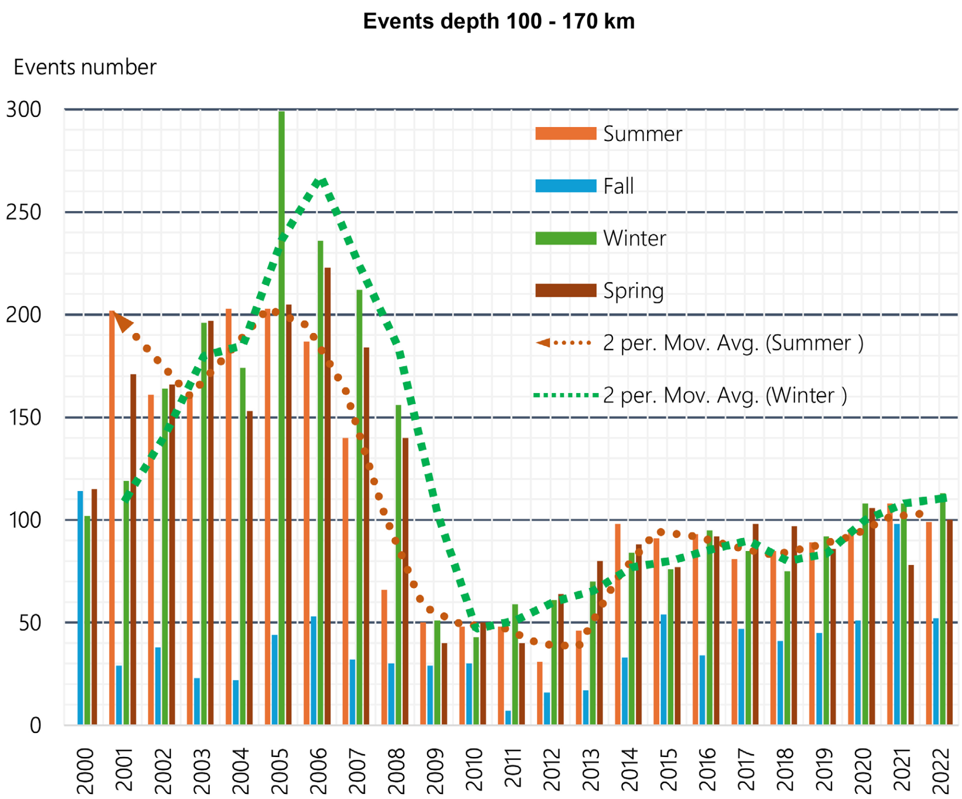

Figure 5. The earthquake occurrences depths of 100 - 170 km from 2000-2022. The first Summer value is omitted (2000) because of the anomaly (610 events).

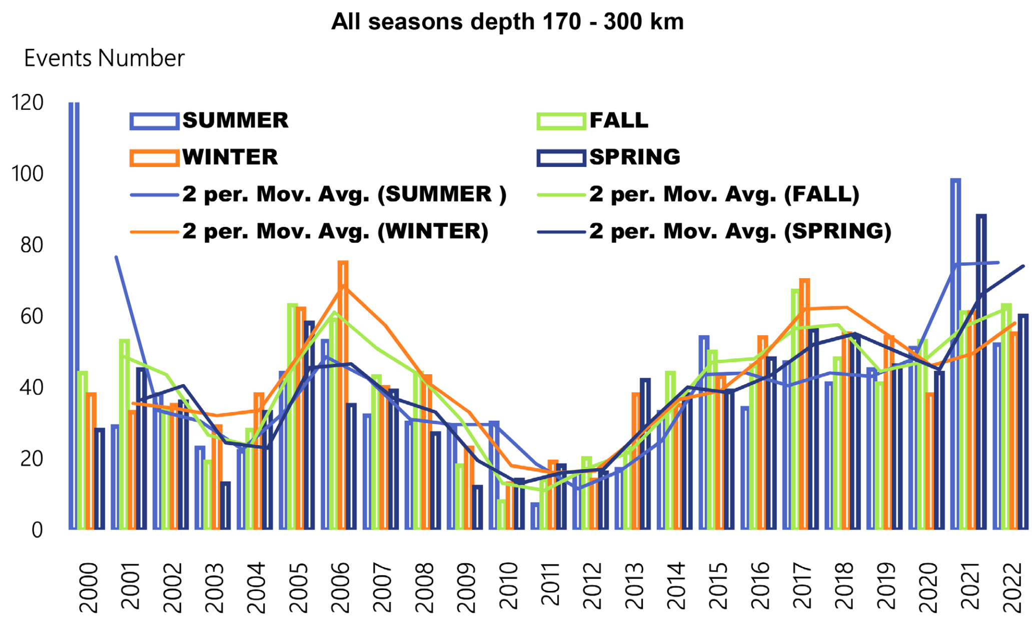

Figure 6. Variations of earthquake depths 170 - 300 km for all seasons 2000-2022; the anomaly is approximately the double value from other events displayed (as in Figure 5).

The following observations were to the depth of 300 - 500 km. The frequency of tremors at depths of 300 - 500 km near Bolivia. Figure 7 shows that 300 - 500 km earthquake depths are in one location and are not frequent. Most events occurred around one location, the South America elbow and near Bolivia. It was confirmed in this depth: a total absence of events from 2009-2017, Figure 7. An anomaly occurred in 2014 during the Spring with one event at this depth. Three years showed a continuing number of events during the Summer and Fall of 2017, 2018, and 2019; those years belong to the minimum of Cycle 24. The lack of tremors indicates that this region, but Bolivia, has a vast amount of non-breakable material. It could be terre rare, copper, argent, gold, and many other materials, even though it could be the presence of a bulge of water still non-detected by normal means. Finally, Figure 8 shows the ultra-deep earthquakes displayed inside the continental platform. Observe that there are several locations in the pattern.

Observe in Figure 8 the lack of deep quakes on the path. It is a strong indication due to the deposits spread on several locations of unbreakable materials.

That indicates the presence of malleable material in the Amazon craton region; it would be the reason earthquakes happen in a much deeper depth, as our research suggests. Figure 8 shows that the region where ultra-depth earthquakes occur is far from the coast. The only explanation is in Figure 3; the upper Nazca slab can trigger earthquakes 100 - 300 km deep. As shown in Figure 3, there is a bulge of water between the two slabs where the earthquakes cannot happen. However, the lower part of the Nazca plate is heavier, sinking and triggering earthquakes much deeper into the South American continent.

Now, Figure 9 displays a statistical plot with all events recorded in the period and their evolution.

Summer variations for 100 - 170 km showed an asymptotic behavior close to cyclical; however, it showed minima 2007-2014 and a continued increase afterward. The variations smoothed to the second depth of 170 - 300 km; however, between 2005 and 2014, there was a decrease and slow recovery.

We noticed that events in Summer and Spring are highly correlated; the enhancement of events starts in Spring and reaches a maximum during the Summer. Even though the Winter and Fall are less active, the number of events in the Fall seldom increases. Therefore, we concluded that Spring and Summer influences the majority of events. There is a strong anomaly in 2015, with 23 occurrences during the Spring. This exception points out internal causes unknown now that can propagate from an epicenter, multiplying several aftershocks.

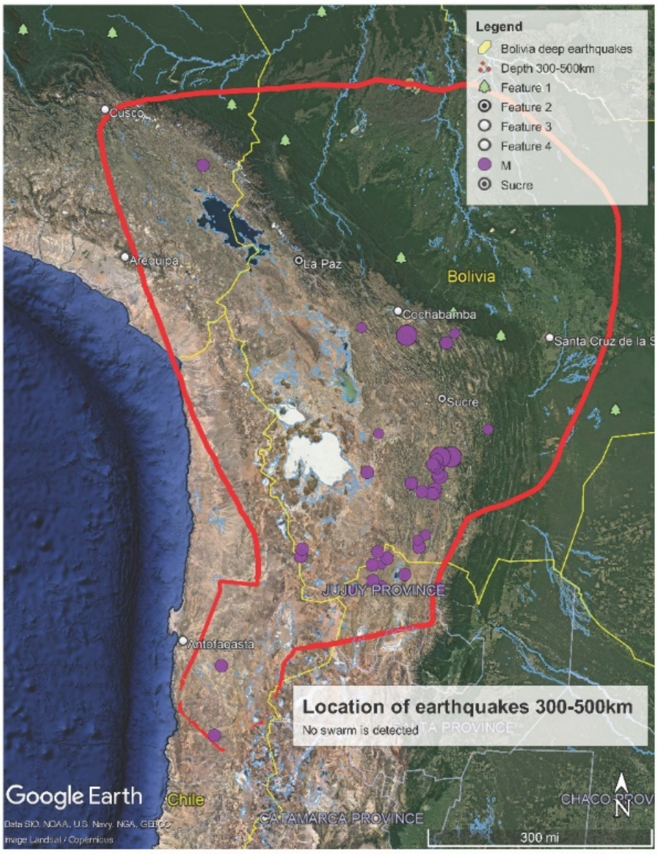

Figure 7. The region in the South American plate where the earthquake's 300 - 500 km depth occurs.

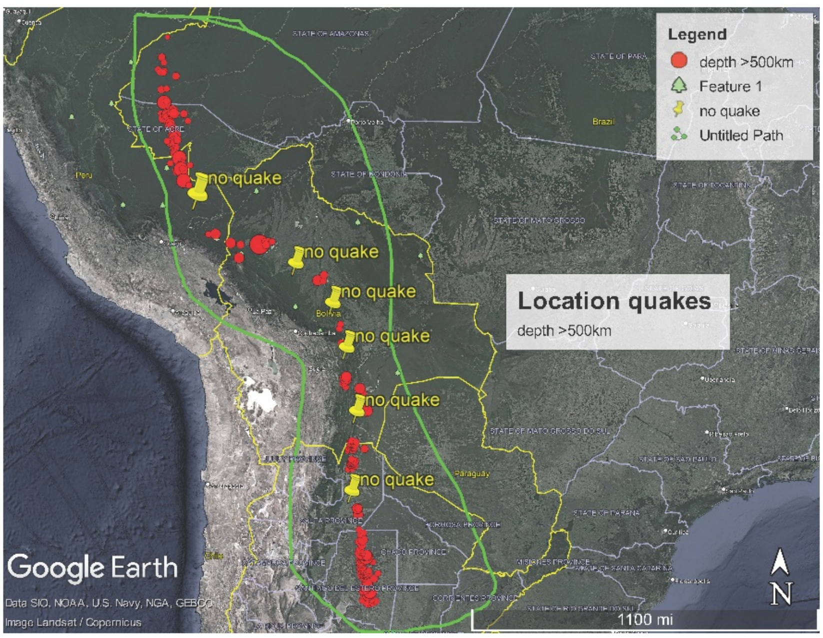

Figure 8. The occurrence of earthquakes with depth ≥ 500 km. All of them are in North Brazil to Southwest Argentina. Notice the gaps on the pattern marked in yellow. With no earthquake occurrences. (USGS).

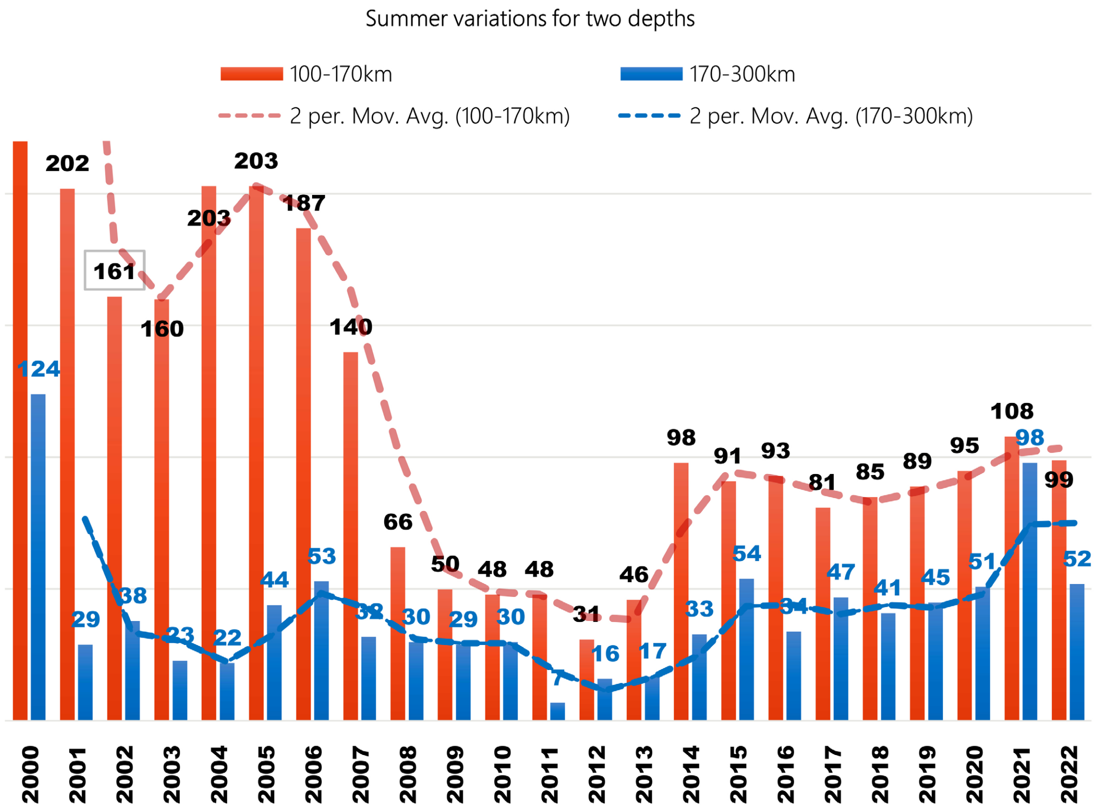

Figure 9. The Summer variation for shallower depths of 100 - 170 km and 170 - 300 km. The first 100 - 170 km value is an anomaly (610 events).

Resuming the year 2015 presented enhancements to the depth 170 - 300 km with a swarm created by an earthquake in February (Summer) with a magnitude of 6.7 M in Aguilar-Argentina, with a depth of 223 km; the other one happened in San Antonio de los Cobres; in November at the depth 192.1 km. There were other significant earthquakes in Inapari, Peru, 7.6 M, with depths of 606.2 km and 620.6 km. In the same month, two days later 26/11 occurred a big earthquake occurred in Tarauaca, Brazil, triggering three significant tremors and causing swarms and aftershocks at a depth of ≥500 km—Figure 10. The Figure shows an apparent chaotic behavior with sudden increases in 2012, 2015, and 2018 in Spring or Fall, which did not follow any external or a possible inner earth pattern. This Figure, with earthquakes with deepest depth ≥ 500 km, presents several cycles with small maxima at the start of the interval but increased after the 2012 Spring with 23 occurrences; the other two maxima were in 2012 and 2018 with nine incidences. The seasons with significant minimum values were Summer and Winter with constant null events. It also shows an apparent chaotic behavior with the sudden increase in 2012, 2015, 2018 during the Spring or Fall. It does not look to follow any pattern.

3. EARTHQUAKE VARIATION BY FOUR SEASONS

The data is now divided into depths of 100 - 300 km and 300 - 700 km. The aim is to know how they vary during each season and if there are any correspondences with the Solar events. First is Summer, 100 - 300 km depth, as Figure 11 shows.

The beginning of the period studied the variation of earthquakes during Summer to depths 100 - 170 and 170 - 300 km. Observe a periodicity of the events which is not linked to any solar variations or seasons. We noted a decrease in the events at the shallower layer 100 - 170 km, accentuating from 2008 until 2014. It had a sudden enhancement and slowly recovered until 2022.

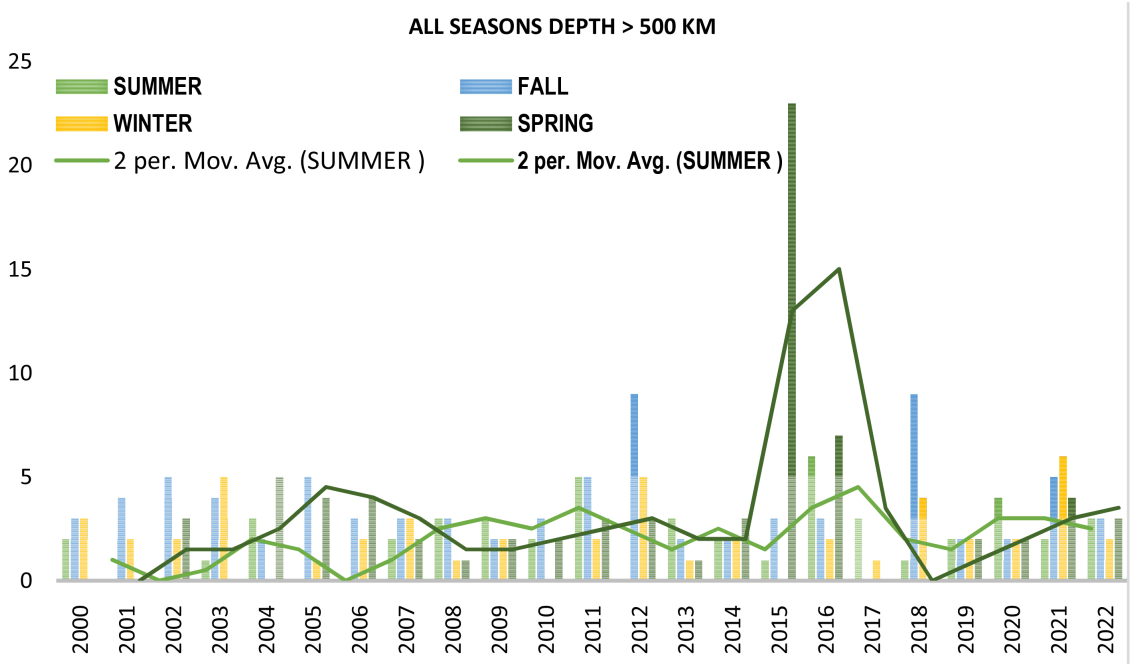

Figure 10. The earthquake evolution for depths ≥ 500 km during all seasons. Observe the anomaly in 2015 (23 events), sun minima.

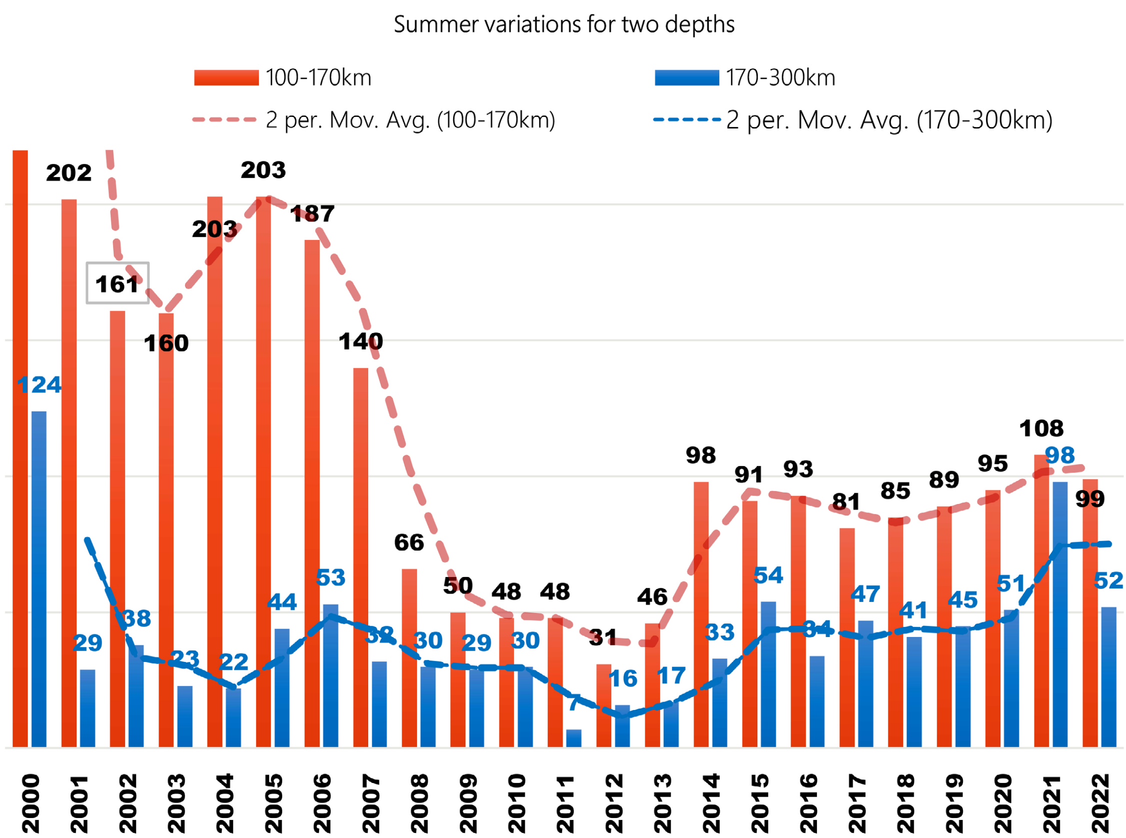

Figure 11. Summer variations for shallower depths 100 - 170 km and 170 - 300 km. The first value in 100 - 170 km is an anomaly (610 events).

Figure 12 shows the Spring variations during the same period and the same 100 - 300 km depths. The first eight years of data showed an enhancement of tremors with a slight decrease during the minimum (solar) 2004 and 2008; after that is a noted depression from 2009-2019 and recovery so far. The Figure shows a trendline for the maximum and minimum years. Now, the number is smaller for the depth of 170 - 300 km, and a significant depression in 2008-2016, recovering in 2017. Observe that the occurrence frequency is higher than the next depth at the first depth of 100 - 170 km. However, the locations where those events are occurring are remarkably close (observed on the map, Figure 4).

The following picture is the Winter variation for the same depths as before. The winter performance shows an entirely new scenario (Figure 13).

There are periodic variations independent from the season or the Solar cycles; there is a maximum in 2005, a depression in 2008-2016, and a minor enhancement for depths 100 - 170 km.

The other depth observed is 170 - 300 km, and a cyclic variation displaying more evidence with at least three cycles and slight increases in 2006, 2017. Comparing the last two plots for Spring and Winter, we observed that the behavior during seasons is more substantial than by Solar cycles. Spring and Winter share the enhancements during 2005 and 2006. They followed extended minima after 2006, and it lasted until 2015.

Figure 14 shows the Fall variation for two different depths. All those years, a maximum surge in 2002, 2006, 2016, and 2020 belong to the solar minimum performances. The 170 - 300 km analysis demonstrates three minimum events in 2004, 2010, and 2019.

Those plots showed a configuration of a cyclicity; however, it would take longer to recover the same number of events in a former earth's cycle. Figures 9-12 explain what happens for all seasons' variation, delineating the similar cyclicity. Summer and Spring variation displays a faster recovery if it is compared with the Fall and Winter. Comparing Summer, Spring, and Fall, Figure 14 shows a maximum during 2005, 2006, and 2007, which are equally essential maxims. The rest of the path is like the other seasons and depths analyzed.

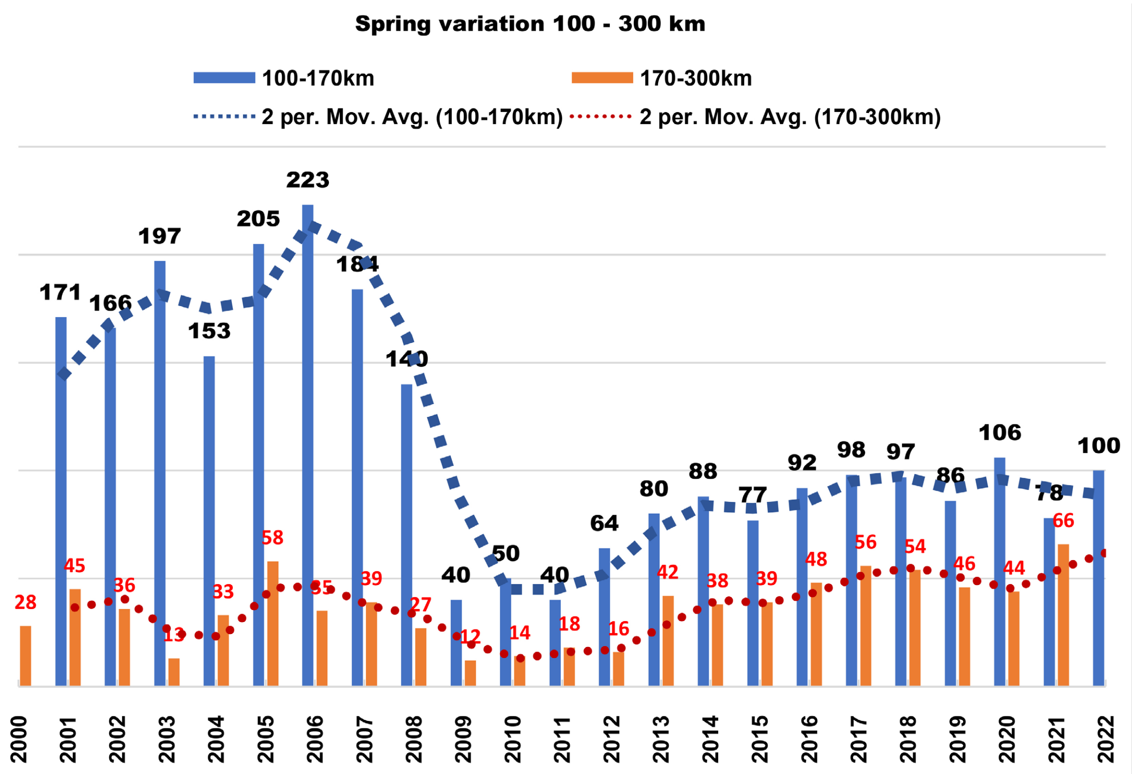

Figure 12. **The spring variations during the period 2000-2022.**

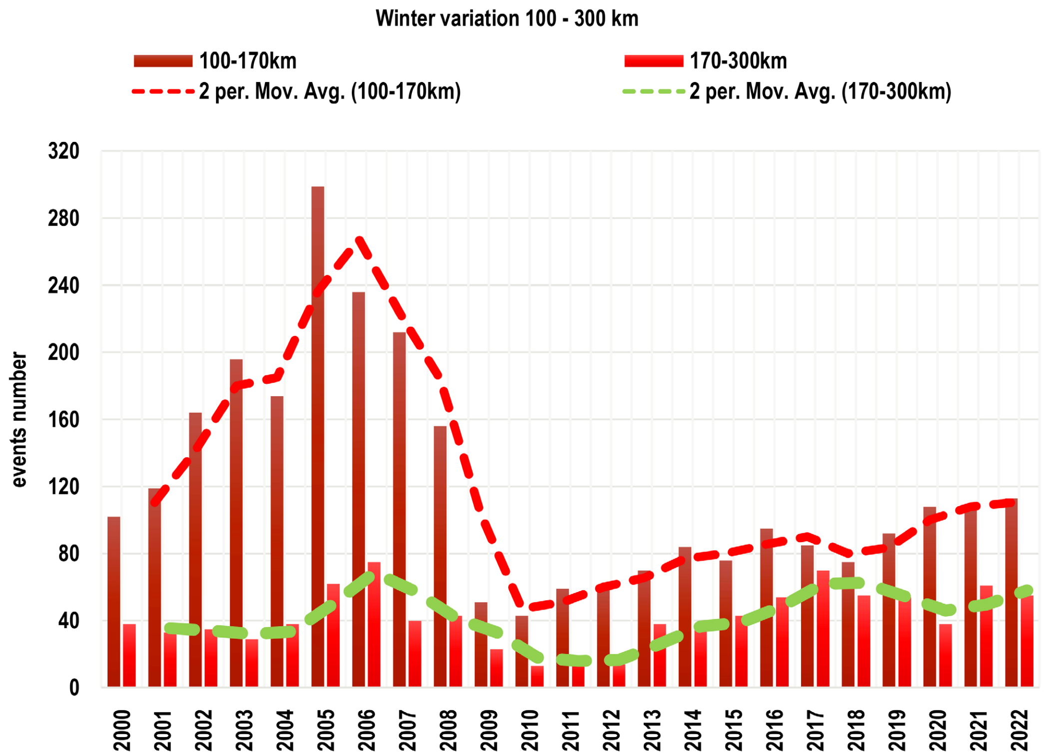

Figure 13. The winter variation for the 170 - 300 km depth. Maxima in 2005 (299 events).

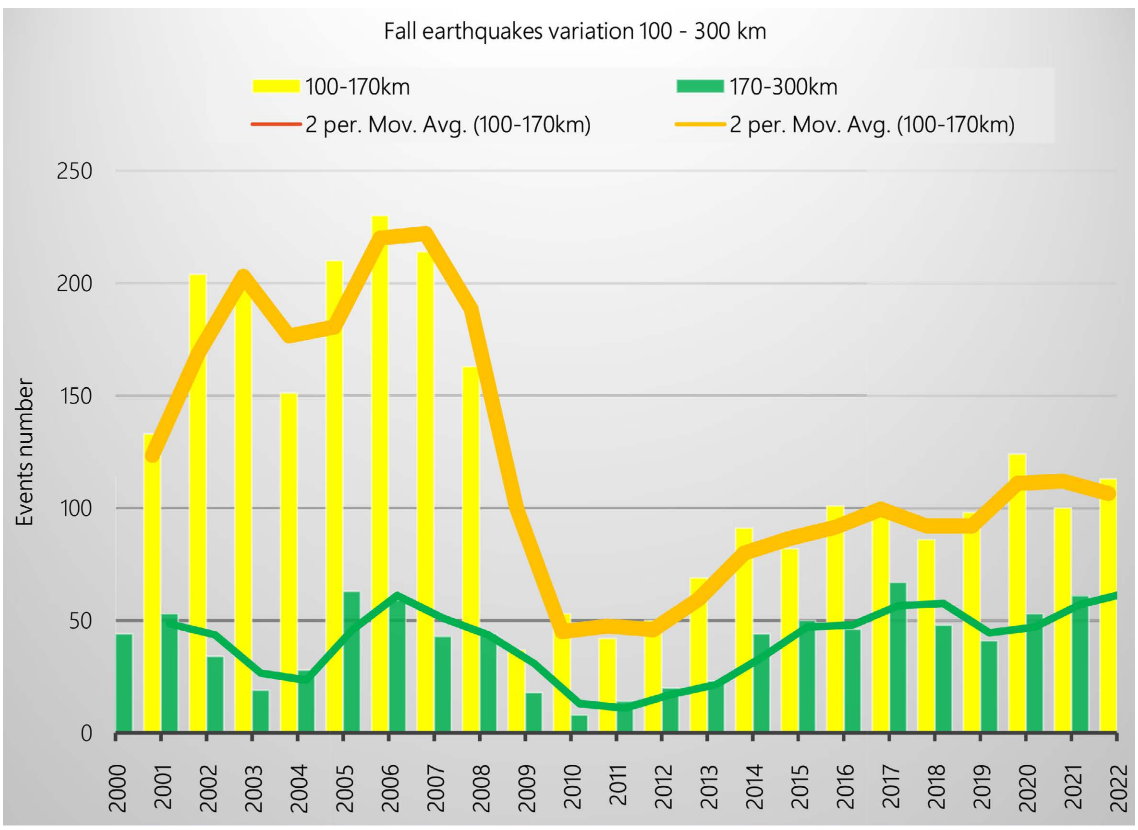

Figure 14. Fall variations with two different depths 100 - 170 km and 170 - 300 km, period 2000-2022.

Therefore, the seasons are essential for the events. For the time interval considered in this study, the events number varies for each season picked. There were two cycles for Summer and Spring and three for Winter and Fall. Reminding the events occurred in the depths of 100 - 300 km. A particular range of depths 300 - 500 km presented rare events; however, the location's occurrences (Bolivia) were stable. The last analysis is ≥500 km, showing the increase of events unaware of Solar Cycles, instead indicating internal causes that must be investigated in triggering earthquakes to this depth. Figure 15 is the Summer earthquake variations.

The results for these depths showed much fewer occurrences than in the first range studied (100 - 300 km). The two seasons that showed some responses were Summer and Fall. However, although they also display some periodicity, most for depths ≥ 500 km do not connect with solar cycles or directly with seasons. However, they are so scarce during Spring and Winter that we did not make them plots. Getting data from a longer timeline would be necessary to know precisely what is happening for those depths. These two depths are difficult to interpret, 300 - 500 km producing few events most in the Summer, and this is not a possible prediction based on the few events.

4. DISCUSSION OF RESULTS

This paper considered several aspects of deep and ultra-deep earthquakes—the evolution of events by deep depths during two solar cycles and seasons. This paper defines deep depths as 100 - 170 km, 170 - 300 km, 300 - 500 km, and ≥500 km in the Nazca-South America subduction zone. We constructed several maps defining the locations where the events appeared.

The differences in the areas with ≥500 km were inside the continental platform. It was also observed that 300 - 500 km occur in a small area known as South America elbow in Bolivia, presenting few tremors where swarms eventually happen, Figure 5 and Figure 6.

Evidence shows that most of the area is formed by malleable material, leading to a lack of tremors.

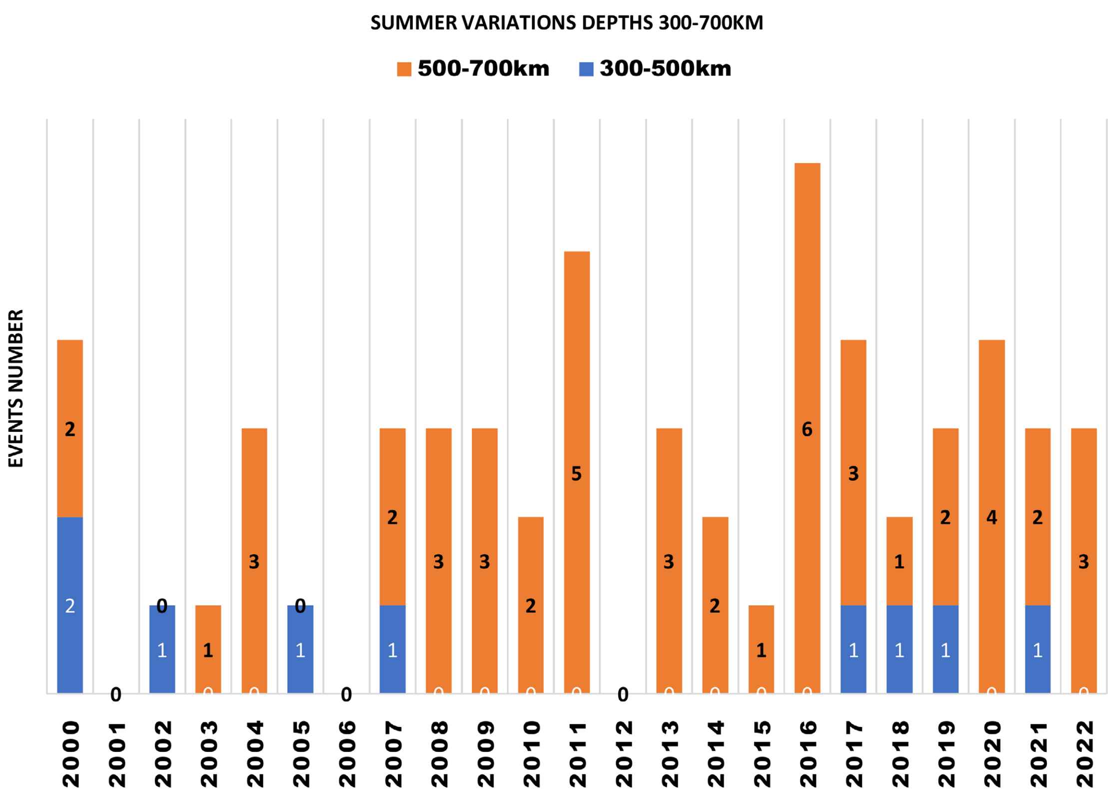

Figure 15. Variation during summer for depths 300 - 700 km.

The earthquakes ≥ 500 km are in a path inside the continent, more frequent than the 300 - 500 km depths. The second part of this paper showed how earthquakes in the region vary with Solar Cycles or seasons. **Figure 5** and **Figure 6** display 100 - 170 km depths and 170 - 300 ms during all seasons. It was an indication that these events are periodically independent of external variations.

It would mean that maximum earthquake events occur during the solar minimum period. See **Figures 9-12**. For ultra-deep depths ≥ 300 - 700 km, the Summer is the only season with enough data to analyze. However, it presents maxima during 2011 and 2016 for depths ≥ 500 km. The shallower values were inconclusive, with insufficient data available, **Figure 15**.

The substantial variation in earthquake measures during seasons indicates that it plays a role in their occurrence. The most affected seasons are Spring and Summer depths varying from 100 - 170 km to 170 - 300 km. The deepest 300 - 700 km did not show enough data during the period analyzed and would request an interval range larger. Most results predicted that the events will enhance during the Solar minima.

Therefore, all the changes observed must be linked to unknown causes located in the lithosphere and below the crust. We can nominate it as Earth's cycles, independent of solar cycles but connected with seasons. It relates to the Sun maxima since there were events with sudden enhancements for the first solar maxima reported in 2001.

5. CONCLUSIONS

Our paper concluded that in the Nazca-South America subduction zone, the deep and ultra-deep earthquakes showed variations independently from the Solar Cycles. The periodicity of deep events looks connected with internal causes below the Earth's surface. In the 100 - 300 km range, those cyclical variations are more apparent during the Summer and Spring seasons. The first two depths found the most critical variations, considered 100 - 170 km and 170 - 300 km. For the range 300 - 500 km, the data recorded were not enough for delineating a behavior, and only Summer brought data enough to quake ≥ 500 km, bringing a brief discussion.

The possible connections with solar cycles were not registered; we witnessed enhanced events during the solar minima. Overall, results pointed out internal variations in this region that need to be better understood. It is necessary to analyze other subduction areas to investigate the possibility of cyclical variations in other places. The several gaps in the areas observed in the pattern of ultra-deep depth earthquakes with spots showing no tremors, there may be malleable elements in those places, and there would be a possibility of stagnant bulge of unbreakable material as water. It is impossible to link this particular result to worldwide connections. Several factors will modify the results, including whether the boundary studied is convergent, divergent, or transform. Other issues indicate that the results here are restricted to this region. Therefore, the results found here can only be applied worldwide with further research. Catalogs used in this paper are [8-10].

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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