ANOMALOUS RECORDING OF EARTHQUAKES OCCURRING IN THE CENTRAL ANDES OF BOLIVIA

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ABSTRACT

To improve the location method of earthquakes occurred in the Central Andes of Bolivia, an automatic location model was proposed, developed on the basis of Red Neuronal in Radial Base Function; a second test was applied: Wavelet's method with the WDEN function (Aliaga, 2002; Minaya et al., 2003). Due to the signal complexity several processes were applied, such as WAVEDEC and WRMCOEF functions (MatLab), signal normalization and optimization to reduce the run time duration of the process as the signal needed to be adjusted (with left-to-right movements). The signals were introduced in the Neuronal Network. The final result of the process was successful up to a 78% rate in 36 seismic events.

The functionality of the model was proved by increasing the amount of samples from 36 to 83 earthquakes that occurred in the same region (central part of Bolivia). Once the model was applied the results were not satisfactory, mainly due to the presence of several phases among phases P and S and including the phases observed after phase S. These results obey to the complex structure of the crust under the Central Andes of Bolivia.

The 83 seismic signals split into four zones according to their waveform (envelope), and subsequently in sub-groups according to their specific characteristics that may be correlated to the geology, tectonic structures, crust structures, and status of the stress present at the study zone.

The analysis will continue in order to study the anomalous phases between P and S waves, and those that are recorded after the S wave, along with profiles balance to verify structures than could originate that anomalous phase. Once this research is finished, the automatic localization model will be applied.

OBJECTIVE

To improve the Neural Network Wavelet (NNW) Model to automatically locate earthquakes occurred in the Central Andes in Bolivia, applying other Matlab® functions when performing this step.

RESEARCH PERFORMED

ANALYSIS 1. Validation of the NNW model

In order to verify and to improve the results obtained with the NNW model, we selected events 2, 7, and 14, their waveform and location were correlated with events 3, 8, and 15 respectively, (circle, Figure 1). The same occurs for events 11, 18, 20, and 23, (in triangles, Figure 1) that display correlation with event 30 (Figure 1, closed square) without any correlation in location and waveform, thus the deficiency in results. Figure 1 shows locations obtained with the Geiger method after those previously obtained with the NNW. For the events with best results, (circles, Figure 1, Table 1) their final localization is noted in the triangle; for example, we remember that for event 7 the acceptable result with the NNW model is event 8, from which it inherits its localization parameters (latitude, length, and depth), and when we applied the Geiger method, the localization is close to both. This procedure is applied to the rest of the events analyzed in this stage.

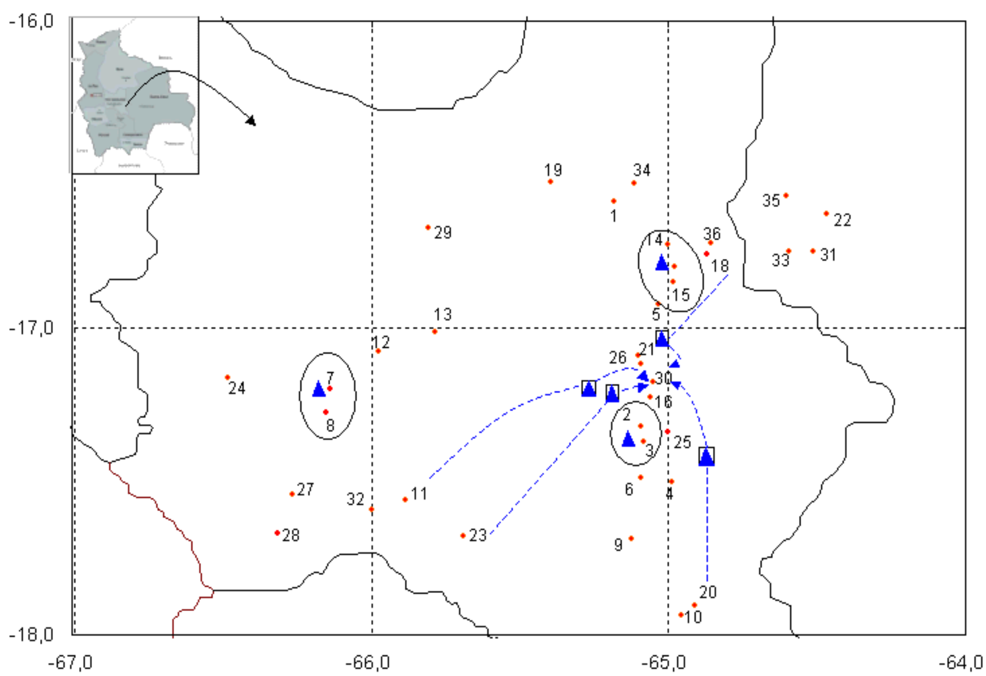

Figure 1. Localization obtained with the Geiger method, in regard to the preliminary localization

Table 1. Locations obtained with the Geiger method for events 2, 7, 11, 14, 18, 20, and 23.

	Original location				Final location			Difference in location		
No.	No.	Lat. (°)	Lon. (°)	Dep. (km)	Lat. (°)	Lon. (°)	Dep. (km)	Lat. (°)	Lon. (°)	Dep. (km)
2	3	-17.369	-65.083	65.00	-17.365	-65.139	54.00	0,004	0,056	11.00
7	8	-17.275	-66.154	40.00	-17.210	-66.185	45.00	0,065	0,031	5.00
11	30	-17.178	-65.052	35.00	-17.185	-65.371	20.00	0,007	0,319	15.00
14	15	-16.851	-64.985	31.00	-16.800	-65.051	8.00	0,051	0,066	23.00
18	30	-17.178	-65.052	35.00	-17.036	-65.025	8.00	0,142	0,027	17.00
20	30	-17.178	-65.052	35.00	-17.452	-64.933	49.00	0,274	0,119	14.00
23	30	-17.178	-65.052	35.00	-17.203	-65.271	55.00	0,025	0,219	20.00

As we remember, the parameter of event 30 (Figure 1) is the same for events 11, 18, 20, and 23. Consequently, they inherit their parameters of localization and when applying the Geiger method a new locations for events 11 18, 20, and 23 are obtained, (Figure 1, framed triangle). It should be remarked that data event 30 data have influenced the located events final result. Consequently, results are not acceptable.

To analyze the events with deficient results (11, 18, 20, and 23) a verification of original signs has been made with events that were close. For example, in Figure 1 the event 11 is in the same zone as events 23, 27, 28, and 32, and not in the same zone as event 30. In Figure 2 it is shown that event 11 does not correlate to the events of the same zone, like the characteristics of the analyzed events. Therefore, it would not be possible to obtain a positive result for this event. The opposite goes for events 23 and 32, which apparently have similar waveforms and locations.

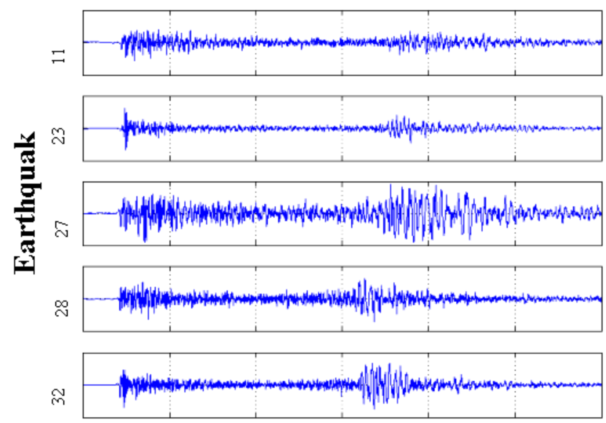

Figure 2. Signals of events 11, 23, 27, 28 y 32 located in the same area but with a difference in waveforms.

ANALYSIS 2. Wden Function

The variations obtained applying the WDEN function affected the results of the Neural Network, as differences between signal amplitude in regard to each other were made in parallel.

In order to justify the invalidity of the WDEN function, a complex signal displaying amplitude variations is analyzed, corresponding to an earthquake occurred in Peru and registered in the station BBOE occurred on 22/08/2000 (Figure 3). A duration of 120 seconds was considered for each event. The original signal and the transformed one after applying the WDEN function are shown in Figure 3. The cause of this variation is due to the WDEN function that executes the convolution product and the algorithm of soft-thresholding. The WDEN function obtains zeros at the beginning of the Pn phase and in some points of the signal, when making several decompositions, which is shown with the overlay of the transformed and original signals, Figure 3. This is the reason it is difficult to use the Wden function. The weighting of some values in the coda of the transformed signal are more marked that others, giving estimations that do not work for signal models. In order to solve this problem it is necessary to apply the Transformed Wavelets so that the coda of the transformed signal is approximated, and some values are not emphasized.

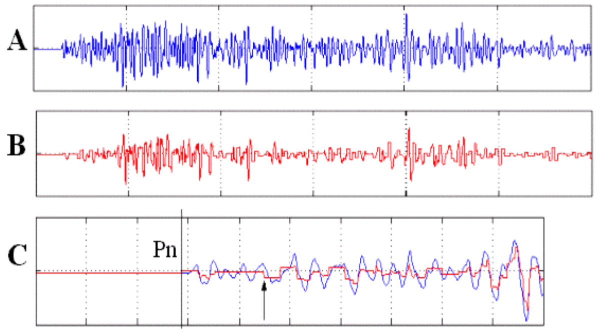

Figure 3. Event occurred on 22/08/2000, the original signal (A), transformed (B) and (C) overlay of original signal (blue) and transformed (red), the line on phase Pn and the arrow show the variation of signals when the WDEN function is applied.

ANALYSIS 3. Wavelets Transformed in the Neural Network

In this analysis the objective is to apply Wavelet Transform and a Neural Network to a sample of 36 earthquakes.

The Wavelet Transform allows a better management of WAVEDEC and WRMCOEF functions (MatLab, 1999), in view that the Neural Network gets better results if the signal pattern is generic, not detailed. The procedure corresponds to a sequential methodology according to the process that must be realized by the transformation.

Step 1: An interval should be considered at the beginning and end of the signal in each event.

Step 2: The main idea is not to plan the events on a map and group them, but to classify them according to their likeness between signals.

This classification according to similarity is not only made with signal filtering, or with filters as the Fast Transformed Fourier, or algorithms of reduction of the Wavelet noise (soft-thresholding), that provide the identification of phases in the coda if the signal, allowing a grouping of events according to their characteristics, but hen this is applied to the Neural Network, the classification made by comparisons results in “details,” which is not advisable. The Discreet Wavelet Transform is applied to the waveform signal, that allows the modeling of a signal as “generics” for regions that have their own peculiarities.

Step 3: Once the transformation is done event by event a cutting of the signal is made from a new "beginning," defined by the Haar Wavelet up to the end of coda, as it is observed in the Figure 4. When the Wavelet is applied to the beginning of the Pn phase in the original signal, it is “moved” towards the right approximately an average of 1.30 seconds, which does not affect the MSE value to a great extent.

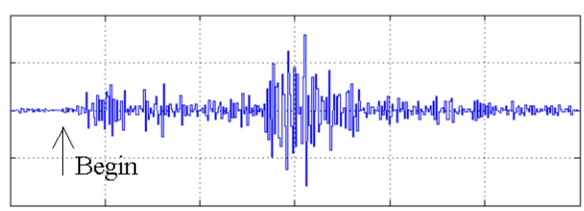

Figure 4. Beginning defined by the transformed Haar Wavelets.

Step 4: In order to test the functionality with the Wavelets and Neural Network, an event is taken from the 36 total events, to classify it with the 35 remaining events, and successively perform the same process with each one of the 35 events.

The data in Table 2 shows the results obtained once the Wavelets and the Neural Network were applied giving a rate of 64% that corresponds to acceptable results.

ANALYSIS 4. Signal Transform and Cropping

After the transformation of the 36 signals, an entrance signal is taken and at least one training signal, repeating this process with the remaining events. In the next step the cropping of the signal is made, that consists of the selection of only one common beginning for the signals that are being treated, the Pn will, be called “Pn assumed,” as it is in Figure 5, for two transformed signals (events 7 and 8, Table 2).

The cropping made in the transformed signal coincides with the Pn phase of the original signal (Figure 6). Nevertheless in some cases the Pn phase is assumed after the Pn phase of the original signal (Figure 7). This happens when the amplitude of the beginning of the original signal is small and comes near zero, when applying the transformed one.

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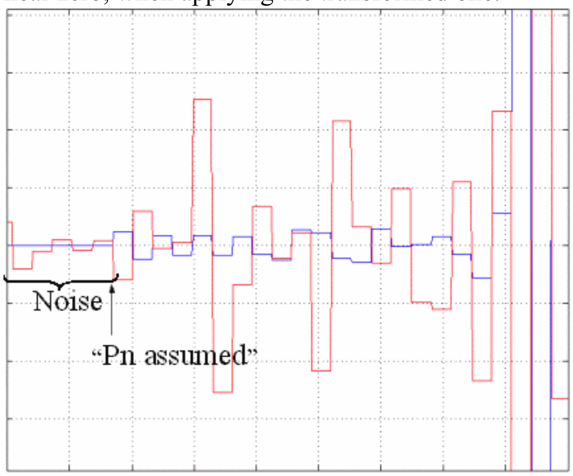

Figure 5. Cutting selection a common beginning for events 7 (blue) and 8 (red)

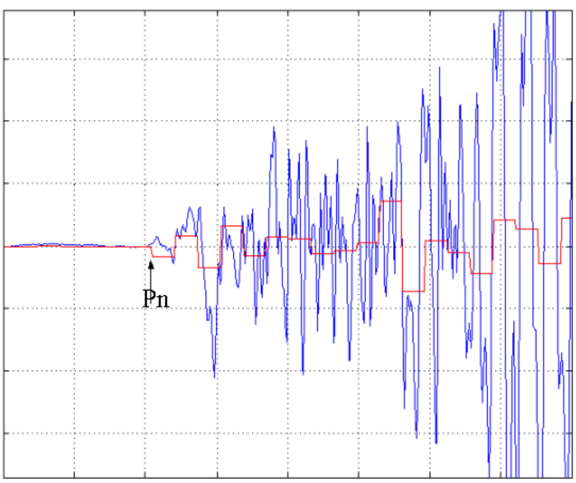

Figure 6. Original signal (blue), Transformed signal (red), both phases (original Pn and "Pn" assumed) coincides, event 17 Table 2.

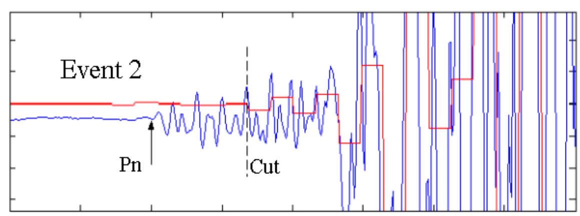

Figure 7. Cutting after the Pn phase is shown in an overlaid picture of the original signal (blue) and transformed signal (red).

Transformed Signal Normalized

Normalization of the transformed signals may be considered as a waiting room for the adjustment of the Neural Network.

Step 1: Once the cropped transformed signals are obtained, they take initial values from zero, followed of by positive and negative values (Figure 4) and then absolute values are obtained (Figure 8).

Step 2: 80 seconds are taken from the beginning of the cropping because in this time period, the characteristics of the region could be recorded.

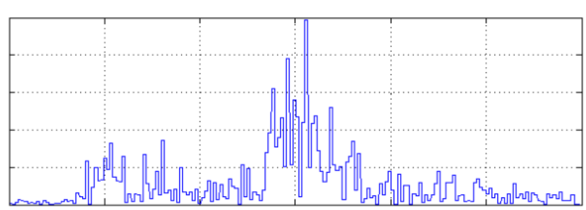

Figure 8. Absolute transformed signal of event 1.

Step 3: For each one of the 36 transformed signals, the maximum threshold is found. Then the minimum threshold is chosen, so that normalization of the signals is made with the minimum threshold.

Step 4: The maximum thresholds are divided by the minimum threshold, these are values to be standardized. Later the signal is standardized dividing each point by that value. Once these steps conclude, the signal transformed is obtained and the 36 events are standardized, with approximate characteristics but without details of the phases of coda of the signals, that at the time of applying the neural network are not considerable.

The results of this analysis gave a rate of 61% successful when the signal is transformed and normalized (Table 2). the normalization is the cause of reduction of the percentage of successes, because it allows the comparison of signals of equal amplitude, a situation that is not possible when there are earthquakes of different magnitudes, for example between earthquakes with magnitudes 3 and 5. Consequently, normalization of signals is a necessary process.

ANALYSIS 5. Optimization and Adjustment

In this analysis two processes are introduced to improve the Neural Network results, but before doing the adjustment process, one first step is necessary to improve the values of Neural Network: optimization.

Optimization

The signals have a duration of 80 seconds that correspond to 4000 points. The adjustment of those points and Neural Network to obtain the MSE are executed in an excessive period of time. Due to this situation the signal was reduced from 4000 to 125 points. As the decomposition of level 5 is used, it is possible to reduce the signal taking a value of32 points each conserving the signal waveform (Figure 9). An optimized signal is shown in Figure 10 with the absolute values of the amplitude. It should be noted that when this process is made it tends to lose some beginnings of the transformed signal, because their amplitude comes near to zero.
A second step is necessary make an adjustment to the signal. In this process the points are moved from the left to the right.

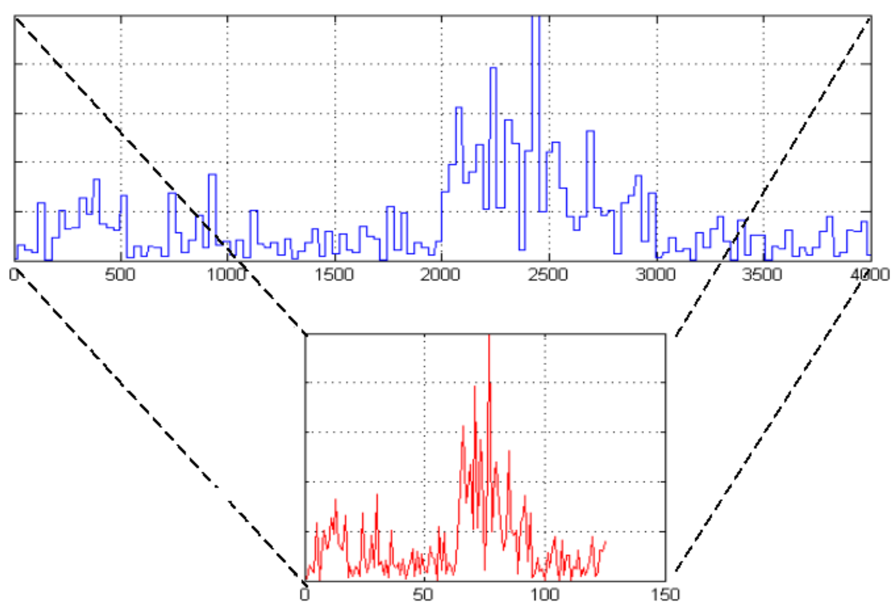

Figure 9. Reduction of size of event 1, from its transformed signal of 4000 points to an optimised signal of 125 points.

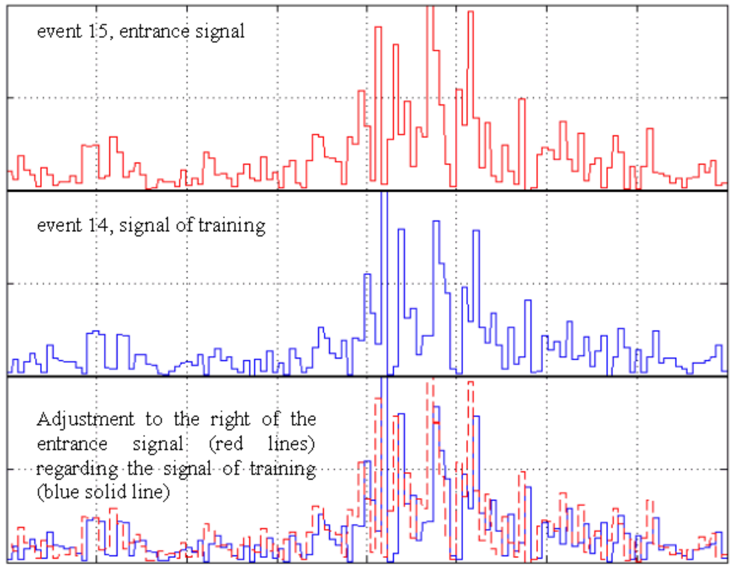

Figure 10. Adjustment process between events 15 and 14, Table 2.

Adjustment

In Figure 10, an example of the adjustment process is shown. Event 15 was considered like the input signal and event 14 like the signal of training, whose maximum thresholds are out of phase (lower part of Figure 10). Event 15 is shown by dashed lines, which will be adjusted by moving it to the right, so that the maximum thresholds agree with the maximum thresholds of event 14.

The example described allows observation of the difference of the result with analysis 4. Event 15 is associated with event 34, whereas in this analysis its relation is with event 14, obtaining a similar result as with the initial analysis. In order to be able to fit an optimized signal, it is necessary to know which points are moved at the beginning and at the end of the signal. These tests were made taking into account the movement of the points to the left and to the right. This is if the movement to the left eliminated a point, and it was duplicated one point, to maintain duration of the signal.

The result using the movement of 10 points (left and right), concludes that it is better to consider movements of 3 points (in both ends). Consequently, the positive results reach 78% (Table 2). This is acceptable. Notice that the percentage with respect to the results to analysis 4 has improved the locations. For example, event 5, with analysis 4 gave event 22 and with new analysis gave event 18. The same happens with events 1, 13, 14, 15, 16, 17, 22, 24, 28, 33, and 36.

ANALYSIS 6. New Validation

A new validation of the process is realized incrementing the data from 36 to 83 seismic events, the results were not successful. The principal cause should be because signals are complex; several probable phases are observed among phases Pn and Sn. In addition, an evaluation of the waveform was performed looking for the details registered in that interval. The results permitted division of the region of study into four zones according to their general characteristics (Figure 11) and each of them was subdivided according the details more relevant.

The four zones apparently keep more relation with general geology of the region and the subdivisions have direct relation with Tectono- Stratigraphic dominions. They are been studied and will allow us to get more information about the actual deformation that causes this superficial seismic activity in the region. This analysis is relevant to determine the relation of the complex crust with anomalous phases observed in earthquakes with epicenters in the Central Andes (the anomalous phases would not correspond to phases normally registered). The importance of this situation is due to the fact that the seismic activity of the region of study is only in the crust (without proofs in the surface). The intermediate seismic activity (depths about 300 km to 400 km), that corresponds to the Nazca Plate is absent.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained with different analysis performed to improve the Automatic Locate Model using Wavelets and Neuronal Network are summarized as follows:

The test to validate the Model, on the basis of correlation among seismic signals according to waveform and position, permitted the detection of expected results. Several cases were deficient due to the similarity among signals was not effective at either location.

The WDEN function determines the details of the signal, in the coda of the phase Pn, generating zeros before the same phase, in other points of the signal, and highlighting the amplitude of others. Aspects that do not favour the results when is applied to the Neuronal Network since this uses generic signals and no detailed signals.

For the above, the WDEN function is discarded and the application of Wavelet Discrete Transform is introduced, using WAVEDEC and WRMCOEF functions, and modelling generic signals necessary for the Neuronal Network.

Other artifices are needed in the models that permit a best development in Neuronal Network process. One of these is cutting the signal because some signals register emerging beginnings that can be mixed up

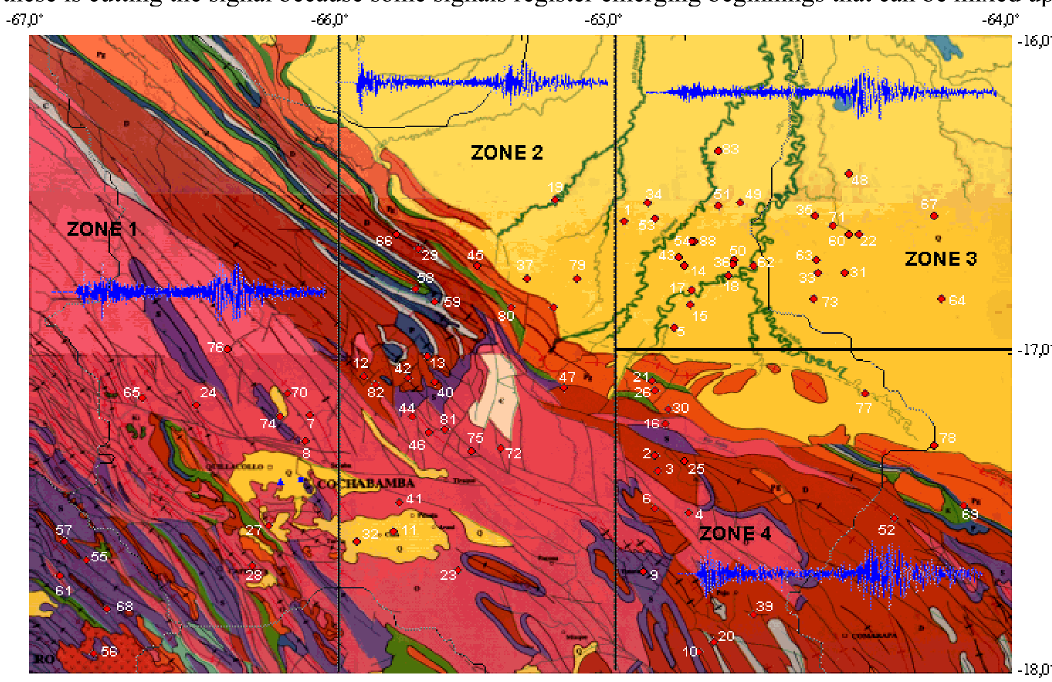

Figure 11. Study region with the geological and structural map, division in four zones according to their waveform, 83 seismic events (red dots) and temporal station (blue triangles).

Table 2. Results of the analyses

Event No.	Date (dd/mm/yy)	Hour (HH:MM:SS.mm)	Lat. (°)	Lon. (°)	Dep.(km)	MI	Analysis 3	Analysis 4	Analysis 5
1	16/01/00	10:55:11.775	-16.588	-65.183	65.00	3.32	19	2	36
2	20/01/00	23:05:39.860	-17.323	-65.091	65.00	4.13	3	14	18
3	21/01/00	03:35:16.869	-17.369	-65.083	65.00	4.19	2	25	2
4	21/01/00	05:34:56.200	-17.502	-64.990	16.06	3.14	6	6	21
5	24/02/00	23:28:59.762	-16.921	-65.032	15.00	3.48		22	18
6	25/02/00	11:02:57.937	-17.489	-65.093	45.00	3.51	4	34	18
7	07/03/00	03:57:30.910	-17.197	-66.140	16.95	3.71	8	8	8
8	07/03/00	03:59:36.234	-17.275	-66.154	40.00	3.57	7	32	32
9	21/03/00	00:22:12.273	-17.687	-65.125	65.00	3.52	6	25	1
10	22/03/00	19:47:53.374	-17.907	-64.913	30.00	3.18	20	34	22
11	29/03/00	21:50:00.221	-17.559	-65.887	20.00	3.14		27	25
12	04/04/00	06:31:32.980	-17.076	-65.978	50.00	3.76	8	7	32
13	25/04/00	23:21:28.667	-17.013	-65.786	42.00	3.71	29	27	29
14	03/05/00	11:19:09.060	-16.730	-65.000	10.00	3.10	15	18	15
15	03/05/00	15:44:17.249	-16.851	-64.985	31.00	3.28	14	34	14
16	05/05/00	01:41:16.831	-17.224	-65.060	30.00	3.69	21	1	26
17	07/05/00	07:43:58.882	-16.803	-64.978	8.00	4.16	18	26	18
18	24/05/00	09:16:37.859	-16.761	-64.869	10.00	3.75	17	14	22

Event No.	Date (dd/mm/yy)	Hour (HH:MM:SS.mm)	Lat. (°)	Lon. (°)	Dep.(km)	Ml	Analysis 3	Analysis 4	Analysis 5
19	03/06/00	15:36:49.793	-16.523	-65.397	25.00	3.20	1	33	33
20	14/07/00	01:06:52.358	-17.936	-64.956	30.00	3.61		18	21
21	28/07/00	18:57:09.935	-17.089	-65.102	15.00	3.56	16	26	36
22	29/07/00	13:30:02.771	-16.628	-64.468	10.00	3.13		5	36
23	16/08/00	13:33:06.738	-17.680	-65.692	65.00	3.09		13	33
24	22/08/00	19:52:28.232	-17.165	-66.485	51.00	3.02		12	8
25	25/08/00	19:43:32.564	-17.338	-65.001	40.00	3.08	26	30	36
26	08/09/00	05:23:24.860	-17.118	-65.090	15.00	3.06	25	21	36
27	15/09/00	19:38:23.284	-17.542	-66.267	21.00	3.81		7	13
28	20/09/00	04:47:15.985	-17.669	-66.314	65.00	3.40		11	27
29	21/09/00	05:06:07.212	-16.676	-65.810	23.99	3.31	12	12	8
30	27/09/00	03:06:03.683	-17.178	-65.052	35.00	3.26	25	34	18
31	01/10/00	09:34:52.154	-16.750	-64.512	50.00	3.70		34	21
32	03/10/00	15:00:43.571	-17.592	-65.997	65.00	3.35		8	8
33	03/10/00	17:46:26.885	-16.750	-64.593	65.00	3.19		19	36
34	12/11/00	05:44:50.738	-16.529	-65.115	20.00	3.26	1	30	26
35	30/11/00	15:44:54.595	-16.570	-64.604	65.00	3.83		22	18
36	04/12/00	06:30:10.883	-16.724	-64.856	30.00	3.05		30	22

with noise. Normalization is applied because the signals of the sample do not have the same magnitude, but this application showed that can be a complex wave in many cases. The last step permits the adjustment of the signal, especially when there is a small displacement in the same point of the signals. Optimization was introduced to reduce the run time of the process.

Finally, a new test was made increasing the sample from 36 to 83 earthquakes that occurred at the same zone, but the process was deficient, and results confirm that the analysis of the waveform is not enough. Also, the signal cannot be considered generic due to the complexity of the presence of these anomalous phases registered in many of the seismic events of the sample.

Individual characteristics are associated with geological, tectonic structures observed in several cortical continental structures as those present in the Central Andes. These characteristics correspond to the details that are not admissible in the process of the Neural Network but now must be considered in the model.

According to those characteristics of detail, the region of study was split into four zones correlated to geology in general: each zone was subdivided in groups according to special natures of earthquakes analyzed that would be related directly with the Tecto – Stratigraphic domains and sub-domains, which must be related to the complex crust present underneath the Central Andes.

The analysis will continue to obtain a structure that could explain the origin of the anomalous phases that correspond to characteristics and details observed in the coda of earthquakes that occurred in the Central Andes.

This process will have to apply to each one of the stations of the seismic network because these are on places with different structures to prove if any of those anomalous phases originate by the structure under the station.

Finally, other functions will have to be introduced in the Automatic Location Model on the basis of the results obtained this analysis.

The objective of Wavelets and the Neural Network methodology is to obtain one previous localization, and later to apply the Geiger localization method in order to complete the cycle of the model of localization.

REFERENCES

Aliaga, H. P. (2002), Modelo de Localización Sísmica con Parámetros Sismológicos Aplicando la Red Neuronal con Funciones de Base Radial y la Metodología de Geiger, *Tesis Universidad Catolica Boliviana*, La Paz –Bolivia.

MatLab (1999), *The MathWorks, Inc.,* MatLab 5.3 release notes, Chapter 34.

Minaya E., P. Aliaga, G. Avila, C. Condori, and A. Córdova (2003), Neural network and wavelets model in seismic location for the Central Andes of Bolivia, in *Proceedings of the 25th Seismic Research Review—Nuclear Explosion Monitoring: Building the Knowledge Base,* LA-UR-03-6029, Vol. 1, pp. 248-258.