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ANALYSIS OF THE SEPTEMBER 2004 SEISMIC CRISIS IN THE AREA OF THE 1428 EARTHQUAKE (I_0=IX), EASTERN PYRENEES (SPAIN)

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SUMMARY

In the Eastern Pyrenees, at the same area of the 1428 destructive earthquake (I_0=IX, EMS-98), an Ml=4.0 earthquake took place on September 21st 2004. It was widely felt in the region and produced slight damage at the epicentral zone. This area is characterized by a continued moderate seismicity, with a few events of magnitude close to 4 reported in the last decades. For this most recent event the hypocentral localisation from the permanent seismological regional network of the Institut Cartogràfic de Catalunya (ICC) is 42.34º N, 2.17º E and 4 km depth. In the following two days the permanent network registered about 120 aftershocks, three of which were felt again in the epicentral zone. A temporary network of 6 portable three-component stations were installed during 35 days in the epicentral area, the network operated in continuous mode and allowed detection and location of about 800 aftershocks with magnitudes lower than Ml=2.0. The earthquakes have been located first with the Hypo71 code. A revaluation of the hypocentral parameters with a probabilistic, non-linear global search earthquake location in 3D structures method have been conducted and the selected earthquakes have been relocated using the double difference location method HYPODD code considering ordinary absolute travel time measurements. The results obtained are discussed in this paper, their gives a better knowledge of the seismotectonic features for an area of major historical seismic activity.

1. INTRODUCTION

During the XIV and XV centuries, a great number of large earthquakes occurred in Catalonia, (NE area of the Iberian plate), some of these earthquakes were felt up to a distance of 300 km [Olivera et al., 2006]. The seismic crisis that took place in Catalonia in 1427-1428 is one of the most important ones known in Western Europe, affecting wide areas of the Eastern Pyrenees. The 1428 event, with epicentral intensity I_0=IX EMSC is considered the most destructive of this seismic crisis. On the epicentral area of this event a moderate earthquake (Ml=4.0) occurred on 21 September 2004 at 17:48 (UTC). The event was felt over a very wide area from the Pyrenees to Barcelona, producing slight damages at the vicinity of the epicentral region. Their MSK intensity values ranges from V-VI to II at 120 km of the epicentral area. It was followed by a great number of small aftershocks, concretely, two days later by a magnitude 3.3, 2.7 and 2.5 earthquakes, also felt in the epicentral area. It is thus important to understand in what tectonic context they occurred, the analysis of the seismic crisis that followed the main event allow us specify the characteristics of the fault zone. At figure 1 are shown the instrumental seismicity in NE Iberian Peninsula for the period 1977-1997 together with the calculated focal mechanisms on a tectonic framework (ICC, 1999) the study area is marked with a rectangular box.

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In this paper we describe briefly the seismotectonic context of the Catalan Pyrenees and the seismicity of the area. Then we focus on the location and the focal mechanism of the September 21 earthquake and their aftershocks sequence. A probabilistic earthquake location with non-linear, global search method has been applied to the aftershocks sequence and the analysis of the probability density function and their uncertainties gives to a selection of the best events that have been relocated later with a double difference method.

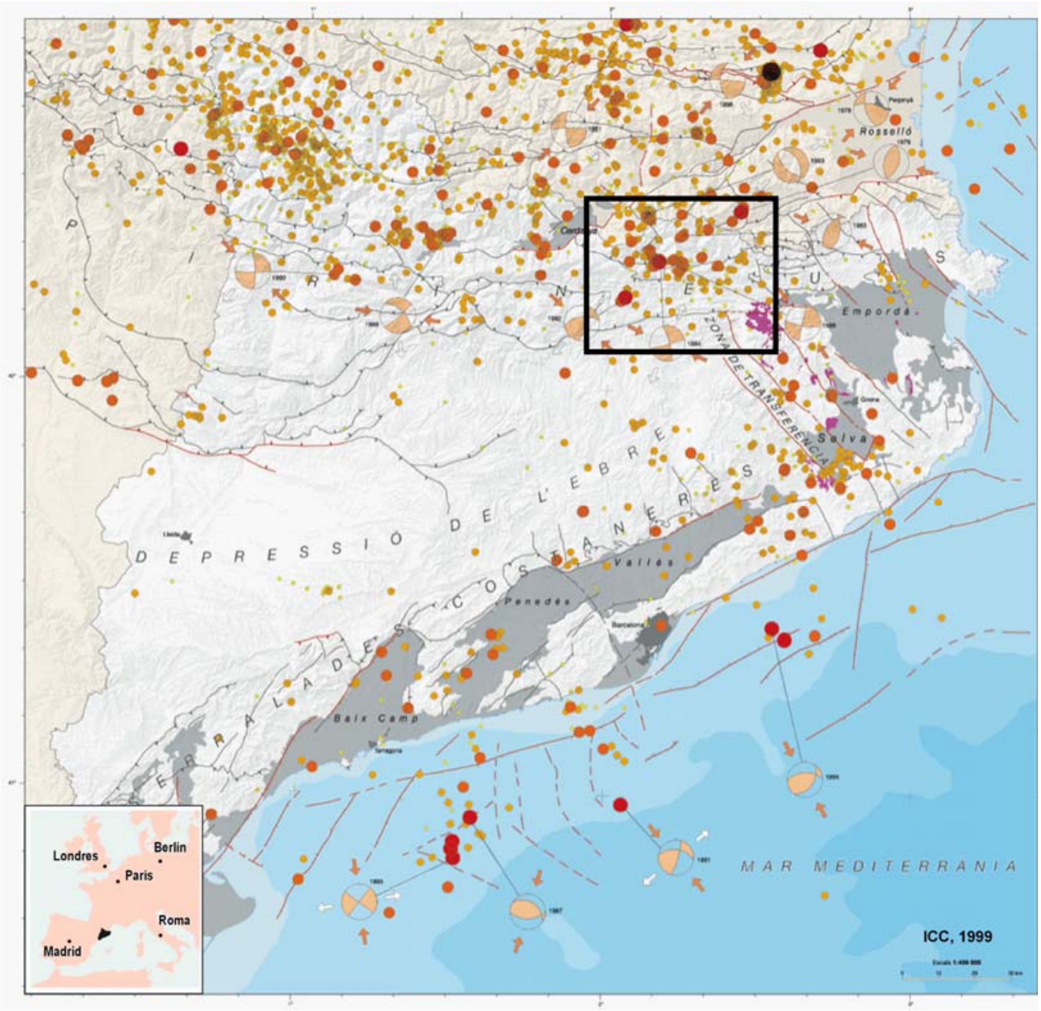

Figure 1: Instrumental seismicity in NE Iberian Peninsula (1977-1997), together with the calculated focal mechanisms on a tectonic framework. The study area is marked with a rectangular box.

2. SEISMOTECTONIC FRAMEWORK

2.1 Main tectonic features

Catalonia is located in the NE margin of the Iberia peninsula, at the NW area of the Mediterranean sea, just in the geodynamic context of the tectonic collision between the Eurasia and Africa plates. This collision has produced an increase of the thickness of the continental crust and the formation of the alpine orogeny and lately, the neogene thinning of the Valencia trough rift. The main catalan geologic units are the Pyrennes, Mediterranean system, the Ebro basin and the Transfer zone between the Pyrenees and the Mediterranean system. The Central and Eastern part of the Pyrenees chain, where is located Catalonia, is characterized by a thrusting system of an antiformal stack geometry that in the southward direction reaches the maximum shortening of 100 km. In this context, during the Upper Oligocene-Lower Miocene is developed the neogene intramountainous basin of the Cerdanya. Between the Pyrenees chain and the Mediterranean system is located the Transfer zone with reactivated alpine faults and new faults of the Pliocene-Quaternary age of NW-SE orientation. This system affects the eastern extremity of the Ebro basin. In this region are situated the Neogene-Quaternary volcanic area, the Emporda neogene basin and the Plio-Quaternary Selva basin. The study area is situated in the Pyrenees geological unit, concretely in the eastern axial zone characterized by a thrusting system (Ribes-Camprodon thrust, fig. 2) of an antiformal stack geometry that in the southward direction reaches the maximum shortening of 100 km. Their regional stress regime is characterised by a NW-SE oriented maximum compression axis, [Goula et al., 1999].

2.2 Eastern Pyrenees seismicity

Despite the moderate seismicity of the eastern Pyrenees, a destructive crisis occurred in the Middle Ages (1427-1428) suggesting that periods of low seismic activity are interrupted by destructive earthquakes, probably with long recurrence intervals. Instrumental seismic information before 1970's is very imprecise, the development of the seismic network of Catalonia, their collaboration with the Observatoire Midi-Pyrenées (OMP) the seismic survey of the Pyrenees on the French side and the recent update of the seismic network of Catalonia in the Institut Cartogràfic de Catalunya (ICC) with ten three component broad-band stations and real time satellite data transmission has permitted the detection and location of earthquakes, including those of small magnitude and define with precision the areas of current fragility. At present, the area is characterised by a continued, moderate seismicity, with a few events of magnitude close to 4 reported in the last decades. At figure 2 are plotted the epicentres for the 1977-2004 period in the study area. The distribution of the epicentres shows two remarkable clusters: one located near Pardines that corresponds to the February 2003 and June 2004 crises; and the other one, to the more recent event on September 2004, located at SW of Queralbs.

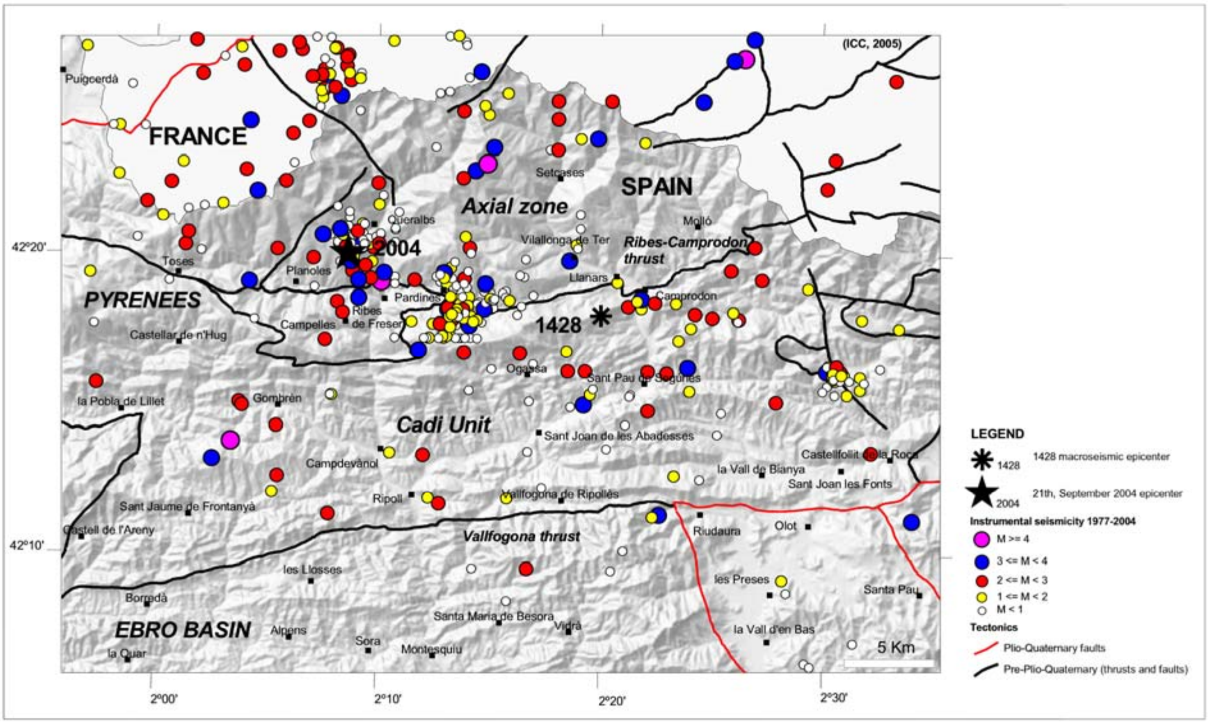

Figure 2: Instrumental seismicity in the study area (1977-2004) on a tectonic framework. The main shock is indicated with a black star and the 1428 epicenter with an asterisk.

3. THE SEISMIC CRISIS: DATA ACQUISITION AND PROCESSING

3.1 The main event

The September, 21st 2004 earthquake was widely recorded in northern Spain and France, in particular by the stations of the seismic Network of Catalonia (ICC), the OMP and some stations of the Instituto Geográfico Nacional (IGN). This event has been located using Hypo71 program [Lee et al., 1975] with the P and S arrival times collected at all the available stations. The Hypocentre is located at 42.35º N, 2.15º E and 1 km depth [ICC, 2004], their local magnitude is 4.0. The focal mechanism of this event was computed from first motion data of 35 stations. In figure 3 we show the focal solution obtained, a dextral strike-slip movement with a normal component is observed.

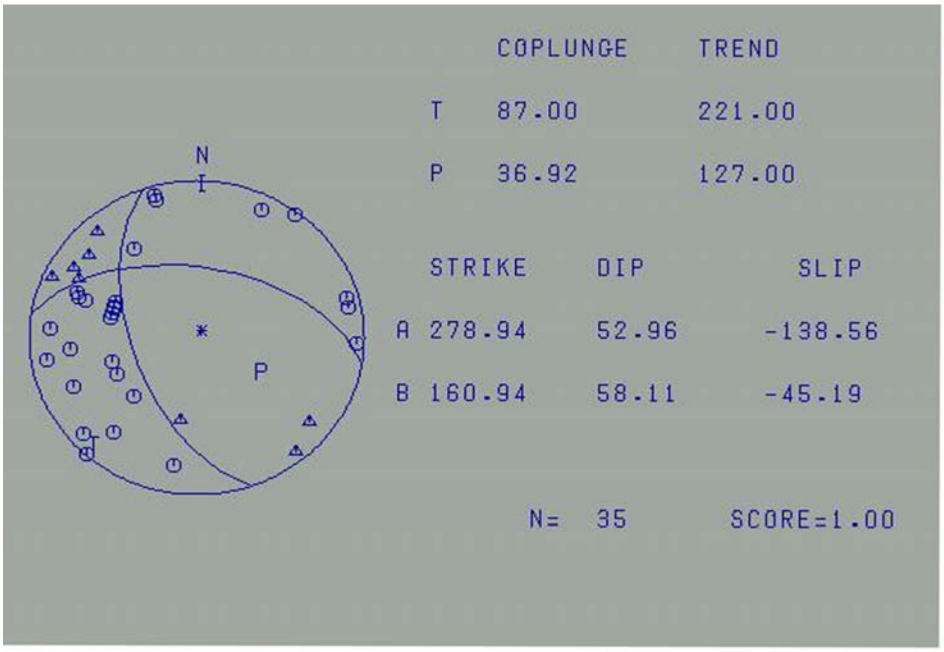

Figure 3: Focal mechanism and axis orientations for the September 21st 2004 event.

According to the dominant E-W geological structures in the epicentral area, a nearly E-W oriented nodal plane can be considered as the fault plane. The pressure axis is NW-SE oriented, which is coherent with the regional axis direction in the area.

In the following two days, the permanent network of the ICC registered about 120 aftershocks, three of which was felt again in the epicentral zone. The detailed aftershocks analysis may give us information about the fault geometry.

3.2 The aftershocks sequence

In order to monitor in detail the aftershock seismic sequence and to better constrain the seismotectonic pattern, 6 portable three-component stations were installed in the epicentral area during 35 days, between September 23rd and October 28th 2004. In this period, the portable network operated in continuous mode and allowed detection and location of about 800 aftershocks with magnitudes lower than 2.0 Ml. About 90 of these events were also recorded by the permanent regional network. In figure 4, the temporary evolution of the aftershocks located from the temporary and permanent network is depicted. The recordings in the portable network give us a better knowledge of the aftershocks sequence behaviour in the epicentral zone.

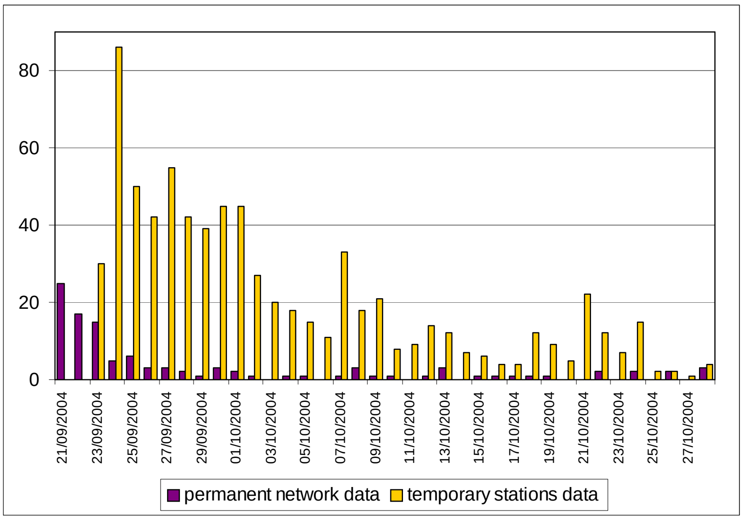

Figure 4: Mainshock (21/09/2004) and aftershocks sequence evolution in the permanent network and temporary stations.

The earthquakes have been located first with the Hypo71 code. The locations are performed considering datasets from either the permanent or the temporary networks. In figure 5 we can observe the hypocentral locations obtained, the results from the permanent array data are much more spread however, the hypocentres obtained from the temporary array are concentrating in a narrow NW-SE oriented band. The depths of the earthquakes are better constrained from the temporary array than the permanent one, nevertheless, in the hypocentral locations with the temporary array we observe an increasing number of aftershocks that are located southwards in a spread distribution.

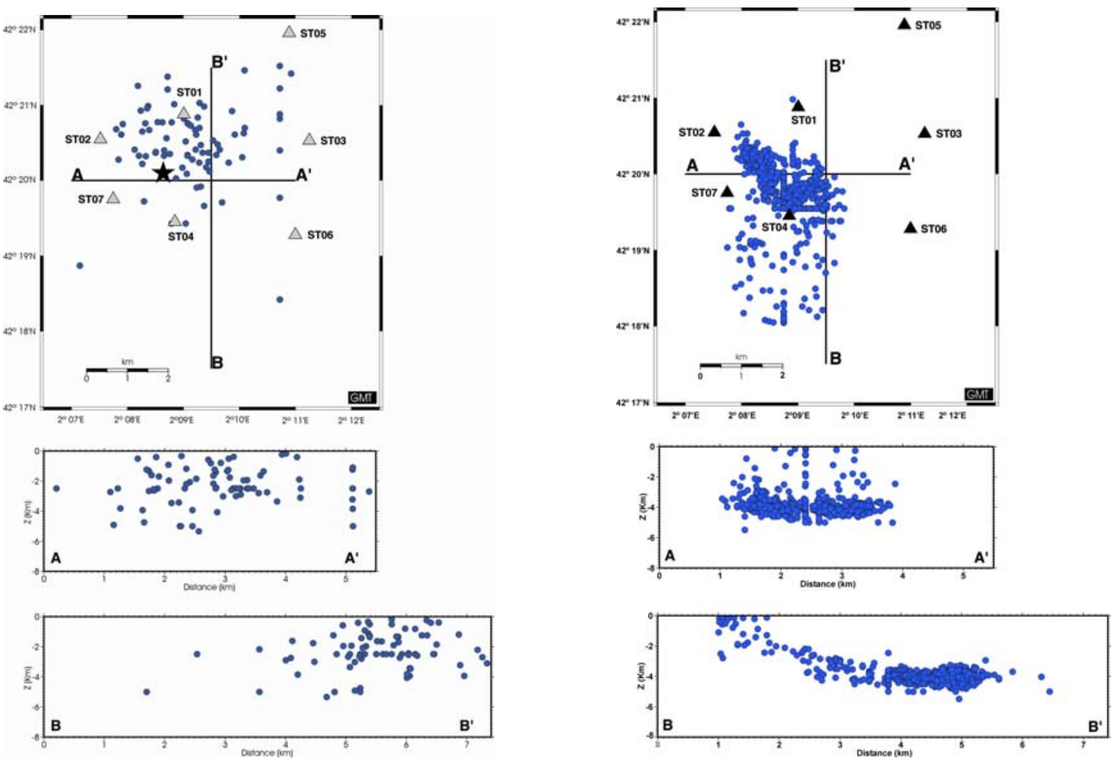

Figure 5: Aftershocks hypocentres located with Hypo71 from permanent regional network data (left) and from the temporary stations data (rigth), their location is indicated by triangles.

4. REEVALUATION OF HYPOCENTRAL PARAMETERS

Seismicity analysis for the study of tectonic processes, earthquake recurrence, and earthquake interaction requires knowledge of the precise relative locations between earthquake hypocenters. The accuracy in the earthquake locations and the realistic estimates of their uncertainties are key factors in the seismotectonic and seismic risk studies [Waldhauser et al. 2000]. The aftershocks sequence of the September 21, 2004 event has been reevaluated by applying first a probabilistic, non linear, grid-search earthquake location method in order to make a selection of the best well constrained aftershocks. Then, they have been relocated by applying a double-difference earthquake location algorithm.

4.1 Application of a non-linear earthquake location probabilistic method

In order to make a selection of the aftershocks with "optimal" hypocenters we apply the NLLoc program [Lomax et al., 2000]. The program is based in a probabilistic earthquake location methodology that produces comprehensive uncertainty and resolution information represented by a probability density function (PDF) over the unknown hypocentral parameters. The errors in the observations (phase time picks) and in the forward problem (travel-time calculation) are assumed to be Gaussian. This assumption allows the direct, analytic calculation of a maximum likelihood origin time given the observed arrival times and the calculated travel times between the observing stations and entire model volume. A grid search algorithm performs successively finer, systematic grid-searches within a spatial volume to obtain a misfit function, an optimal hypocenter and an estimate of the posterior PDF for hypocenter location. In figure 6 is depicted an example of the result obtained in the application of NLLoc method for one of the aftershocks by considering: only permanent network data; only temporary network data; and of the combination of data of the two networks. As can be seen in figure 6, the best result is obtained in the last case.

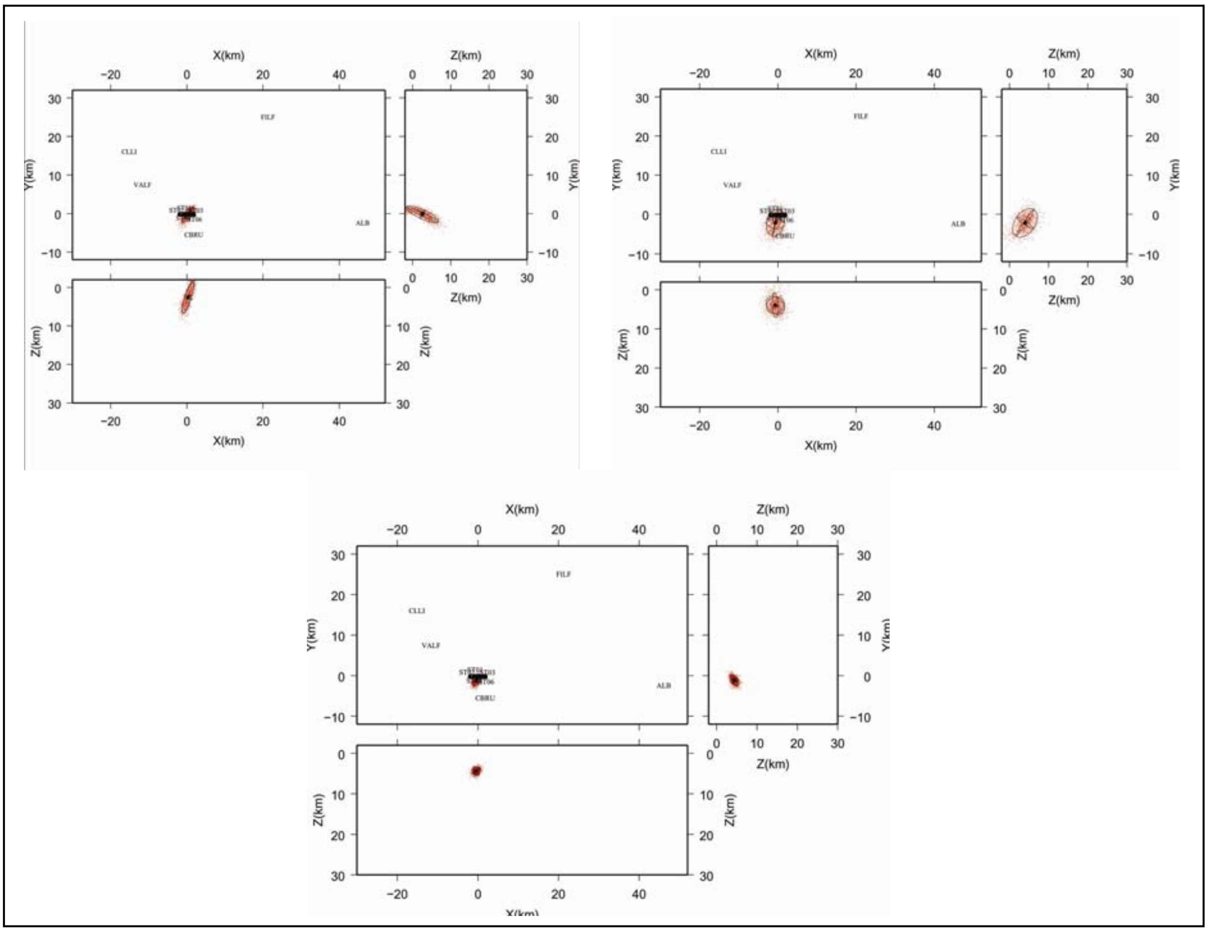

Figure 6: PDF obtained from the NLLoc method by considering permanent network data (top left), temporary stations data (top right) and combination of the two (bottom).

4.2 Double-difference hypocenter locations approach

From the application of the NLLoc location algorithm to the aftershocks of the 2004 earthquake we have extracted a subset of 107 events that are well recorded and located. We have applied to these earthquakes the double-difference location method hypoDD of Waldhauser [2000] in order to obtain more precise relative locations of the earthquake sequence. On a first stage we have used catalog-derived differential data (obtained from analyst phase picks). Currently we are obtaining differential data using cross-correlation of waveforms recorded on the same station for different earthquakes, which will be significantly more. However the results presented here correspond to the catalog-derived differences.

In Figure 7 are presented the hypocentral locations of the aftershocks sequence obtained with Hypo71 code (left), NLLoc program (centre) and relocation with HYPODD (right). With NLLoc and HYPODD the epicentres delimited well the fault plane. Two clusters are observed in depth with HYPODD relocations that can be associate a one discontinuity in the 1D model considered.

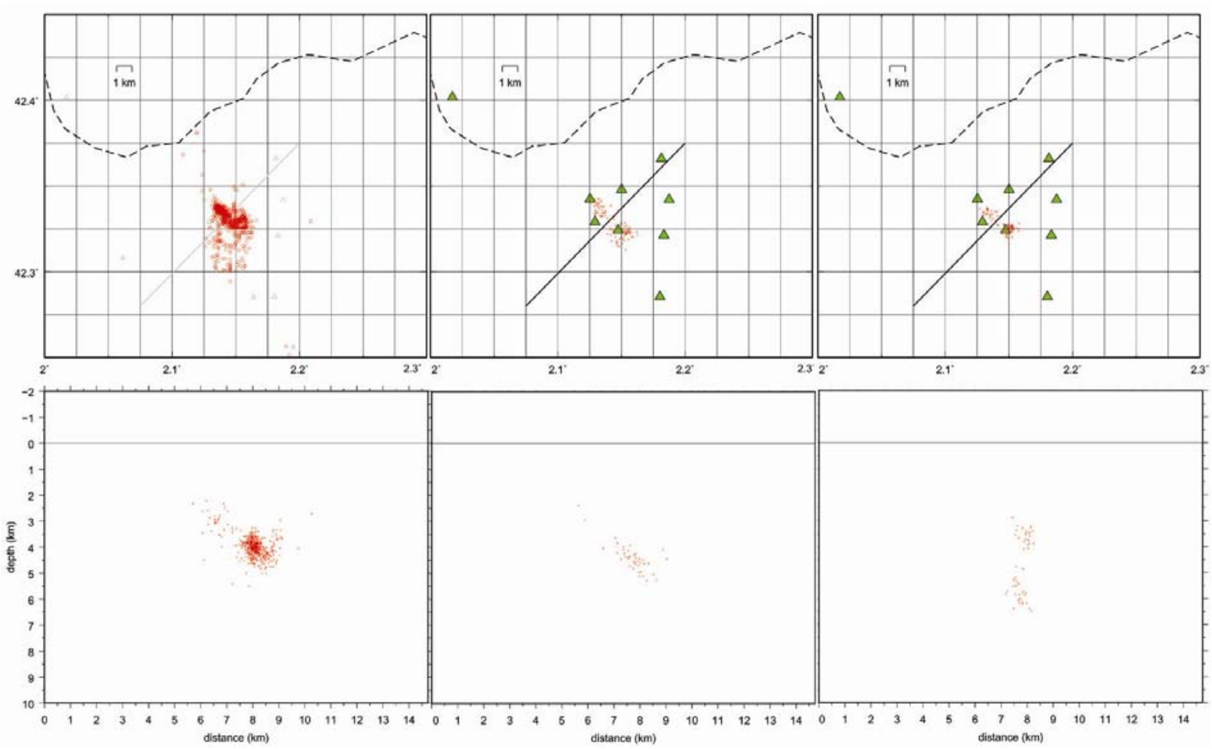

Figura 7: Hypocentral aftershock sequence locations, (epicentres at top and depths at bottom). Hypo71 (left), NLLoc (centre) and HYPODD (right).

5. DISCUSSION

The studied seismic crisis occurred in a region with at present day moderate seismicity but with major historical seismic activity. Thus it is of interest to relate the seismic dataset with the structure in depth in order to constraint the knowledge of the seismotectonic features of the area. In figure 8, the seismic crisis of September 2004 is represented together with a N-S geological cross-section of the region. By integrating surface geology and seismic information, as well as information from industry oil wells drilled in the area, the N-S geological cross-section has been constructed [Vergés, 1999].

The depicted active structure is a fault plane that deepens from SW to NE, in agreement with the N-S geological cross-section in this area, that shows a S-directed vergence, N-dipping thrust fault interpreted as the basal thrust of the Tertiary Pyrenean fold and thrust belt system. The seismic crisis of September 2004 is represented in the cross-section, the mainshock with this error ellipse (dashed line) together with the aftershocks hypocenters. A better precision on the hypocentral locations from the relocations carrying out by cross-correlation of waveforms is expected.

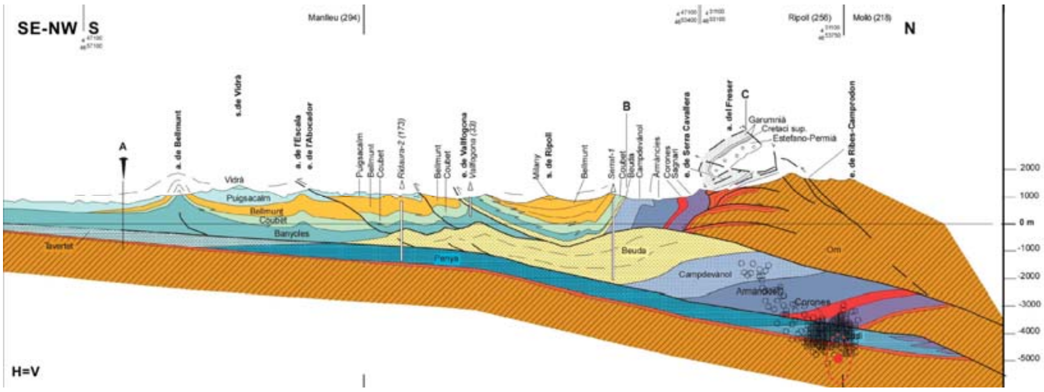

Figure 8: N-S geological cross-section together with the mainshock with this error ellipse (dashed line) and aftershocks hypocenters

6. REFERENCES

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