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E. Ocaña, D. Stich, E. Carmona, F. Vidal, M. Bretón, et al.. Spatial analysis of the La paca, SE spain, 2005 seismic series through the relative location of multiplets and principal component analysis. *Physics of the Earth and Planetary Interiors*, 2008, 166 (3-4), pp.117. <10.1016/j.pepi.2007.12.005>. <hal-00532134>

HAL Id: hal-00532134

<https://hal.science/hal-00532134v1>

Submitted on 4 Nov 2010

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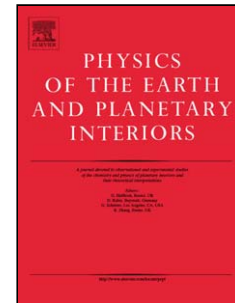


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Accepted Manuscript

Title: Spatial analysis of the La paca, SE Spain, 2005 seismic series through the relative location of multiplets and principal component analysis

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PII: S0031-9201(08)00027-7
DOI: doi:10.1016/j.pepi.2007.12.005
Reference: PEPI 4895

To appear in: *Physics of the Earth and Planetary Interiors*

Received date: 7-6-2007
Revised date: 28-9-2007
Accepted date: 3-12-2007

Please cite this article as: Ocaña, E., Stich, D., Carmona, E., Vidal, F., Bretón, M., Navarro, M., García-Jerez, A., Spatial analysis of the La paca, SE Spain, 2005 seismic series through the relative location of multiplets and principal component analysis, *Physics of the Earth and Planetary Interiors* (2007), doi:10.1016/j.pepi.2007.12.005

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SPATIAL ANALYSIS OF THE LA PACA, SE SPAIN, 2005 SEISMIC SERIES THROUGH THE RELATIVE LOCATION OF MULTIPLETS AND PRINCIPAL COMPONENT ANALYSIS

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Abstract

On January 29 2005, an M_W 4.8, I_{max} VI-VII, earthquake occurred near the village of La Paca, SE Spain. The aftershock sequence shows distinct heterogeneity, manifested in a non-uniform temporal decay of activity and different source mechanisms for the main shock and the largest aftershocks. We analysed 262 earthquakes of the seismic series in order to characterize the active seismic structures. Moving-window cross-correlation of the P- and S-waveforms recorded at local broad-band stations and the application of a selection algorithm have allowed to identify events with similar waveforms (multiplets) and to classify them into 16 clusters of 3 to 25 earthquakes each. In each multiplet cluster, events have been relocated with respect to a master event by the linear inversion of cross-correlation time lags for P and S-waves.

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Clusters show epicentral alignments with a predominant direction N145°E and two secondary directions: N6°E and N40°E. Spatio-temporal patterns of the seismicity have been analysed using Principal Component Analysis (PCA), upon the relocated epicentre distribution and we have obtained three trends, N42°E, N14°E and N145°E, present during all the sequence. These directions inferred from relative location and PCA are coincident with nodal planes of moment tensor solutions for the larger events within the series. They can be interpreted as the simultaneous activity of conjugate strike-slip faults under a N160°-170°E orientation of the principal compressive stress σ_1 .

Keywords: seismic series, multiplet analysis, master-event relative location, Principal Component Analysis.

Introduction

Retrieving the precise spatial distribution of tightly clustered earthquakes within a seismic series can help to image fault zone geometry and to associate seismic activity to a particular tectonic structure. Such results may provide important constraints to understand regional seismotectonics, and resolve the ambiguity between fault and auxiliary plane for point-source focal mechanisms. When the inter-spacing between clustered events is of the same order or less than single event location errors, the spatial distribution cannot be resolved by routine location procedures anymore. However, a more accurate location of them can be achieved through a relative

location approach, such as joint hypocenter determination (Douglas, 1967), the double difference technique (Waldhauser and Ellsworth, 2000) or the master event technique (e.g. Fitch, 1975). Furthermore, events originated along a single fault patch commonly generate similar ground motion at a seismic recording station, as they have similar source radiation patterns and nearby propagation paths through the heterogeneous earth (Geller and Mueller, 1980; Deichmann and García-Fernández, 1992). Those events with nearly identical waveforms are commonly referred to as doublets (if there is a pair of events) or multiplets (if there are more than two similar events). For seismic multiplets, we can exploit the waveform similarity to obtain an accurate relative timing of P- and S-phases between the different earthquakes by waveform cross-correlation or cross-spectral analysis of the respective arrivals (e.g. Scherbaum and Wendler, 1986), permitting a precise relative location with standard errors often in the range of a few tens of meters only. Such approaches are now frequently applied to resolve the seismotectonic fine structure in areas of intense local seismicity (recent studies e.g. by Scarfi et al., 2003; Moriya et al., 2003; Alparone and Gambino, 2003; Hemmann et al., 2003; Hurukawa et al., 2003; Schaff et al., 2004; Hauksson and Shearer, 2005; Mandal et al., 2006; Kraft et al., 2006; Massa et al., 2006; Ruiz et al., 2006).

Southern Spain shows a moderate level of seismicity in the context of oblique Eurasian-Nubian plate convergence at a rate of ~ 5 mm/year (McClusky et al., 2003; Serpelloni et al., 2007) as well as coeval extensional tectonics related to the formation of the Alboran Basin and Neogene intramountain basins in the Betic Cordillera (Lonergan and White, 1997; Galindo-Zaldívar, 1999). The complicated geodynamic setting is reflected in a widespread, diffuse distribution of earthquakes (Fig. 1) and

heterogeneous patterns in the orientation and faulting style of earthquake source mechanisms (Vidal, 1986; Bufo et al. 2004; Stich et al., 2006). An important portion of the seismic activity occurs within seismic series, including both (foreshock)-mainshock-aftershock sequences and extensive seismic swarms without a single dominating mainshock. Examples include the 1979 seismic series in the Granada basin, with 55 felt earthquakes with magnitude m_d up to 4.8, which lasted almost a year (Vidal, 1986), the 1985 seismic swarms near the town of Loja (~1500 earthquakes, $m \leq 3.9$, Posadas, 1991), the 1988-1989 Agrón seismic swarm (~400 earthquakes, $m \leq 4.0$, Saccorotti et al., 2002), the swarm occurred in the town of Antequera in June 1989 (Posadas et al., 1993) containing 158 earthquakes with magnitudes between 2.5 and 3.4, or the extensive aftershock sequence of the 1993-1994, M_w 4.8 and 4.9 Adra-Berja earthquakes with ~500 events (Stich et al., 2001).

88

Here, we analyse a seismic series in January and February 2005 near the town of Lorca, Murcia province, SE Spain. Following the M_w 4.8 mainshock on January 29 (Bufo et al., 2006; Cesca et al., 2006; Benito et al., 2007), important aftershock activity with more than 400 earthquakes was lasting for more than two weeks. We are interested in identifying the fault responsible for the main shock, which caused significant damage in the epicentral area, and to investigate apparent heterogeneity in the aftershock sequence, where a non-uniform temporal decay of the activity and differences between the source mechanisms for the main shock and the largest aftershocks suggest that two different rupture processes are involved (Benito et al., 2007). We use data from seven three-component broad-band stations out to ~100 km epicentral distance to perform (a) traditional single event relocation of the series, (b) cross-correlation of P- and S- waveforms between events to identify similar

100

earthquakes in the series, (c) cluster analysis (Maurer and Deichmann, 1995) to classify those similar earthquakes into groups or families of multiplet events, and (d) relocation of each multiplet cluster relative to a master event, based on the arrival time differences to each station between master and slaves as obtained from cross-correlation. Multiplet relocations are interpreted directly, as well as through a statistical analysis of their spatial and temporal distribution based in the Principal Component Analysis (PCA) (Michelini and Bolt, 1986; Posadas, 1991; Posadas et al., 1993; Saccorotti et al., 2002). Results are finally compared to the focal mechanisms for the larger earthquakes of the sequence and interpreted and discussed in the light of active tectonics in the area.

The 2005 La Paca earthquake series

The eastern termination of the Betic Cordilleras in SE Spain is characterized by moderate seismic activity (Fig. 2). Historical records contain a number of relevant earthquakes that caused serious damage, most notably the 1829 Torrevieja earthquake in the province of Alicante ($I_{\max} = \text{IX-X}$, estimated magnitude $M_s = 6.9$, Muñoz and Udías, 1991). The region of Murcia experienced a dozen earthquakes with magnitude larger than 4 during instrumental times. Maximum intensity of VIII was reached for two earthquakes in 1911 (near Torres de Cotillas and Lorquí, estimated magnitudes M_s of 5.7 and 5.3, Bufo et al., 2005) and for the 1948 earthquake near Cehegin. The following 50 years produced less significant earthquakes, but in the recent eight years the region has experienced a notable succession of three seismic series: the first of them began on 1999 February 2 and had a main shock of M_w 4.8 located near the

village of Mula, the second one started on 2002 August 6 close to the village of Bullas with a M_W 5.0 event, and the third one occurred on 2005 January 29, M_W 4.8, close to the village of La Paca. The three shocks had shallow focii and predominately strike-slip focal mechanisms (Mancilla et al., 2002; Martínez-Díaz et al., 2002; Stich et al., 2003; Bufo et al., 2005; Bufo et al., 2006; Cesca et al., 2006; Stich et al., 2006; Benito et al., 2007).

The M_W 4.8 earthquake on 2005 January 29 (07:41:31) marked the beginning of the seismic series studied. The main shock was felt with a maximum intensity of VII and VI-VII (EMS 98) in La Paca and Zarzalla de Ramos close to the epicentre, causing surprisingly high damage for an event of this magnitude (Bufo et al., 2006; Benito et al., 2007). Several aftershocks were also felt by the population (January 29 (08:10:57, M_W 3.6), February 3 (11:40:33, M_W 4.2) and February 4 (01:09:41, M_W 3.9)). The seismic activity decreased from January 29 until February 3, when the M_W 4.2 shock drove up the rate of activity with 76 events recorded that day and 61 recorded on February 4 (Fig. 3), followed by a large number of aftershocks. While the overall evolution of the series appears complex, each of the two peaks alone satisfies Omori's law for the temporal decay of activity and the Gutenberg-Richter relation for the magnitude-frequency distribution, yielding b-value-estimates of 0.64 and 0.9 respectively (Benito et al., 2007). The duplication of patterns in the aftershock sequence and different moment tensor mechanisms for the main shock and largest aftershocks (Fig. 4) suggest that (at least) two different rupture processes are active during the seismic series.

For our study, we selected events that occurred between longitude 2.4° – 1.2° W and latitude 37.3° – 38.3° N, during the three-week period (from January 29 to February 20) of maximum activity in the series, from the seismic catalogue of the Instituto Andaluz de Geofísica. The initial date of our analysis coincides with the day when series started whereas the final date, February 20, was fixed taking into account that from that day the seismic activity clearly decreases and only sparse events occur (Fig. 3). With these criteria, 262 earthquakes were selected, with magnitudes between 1.2 and 4.8. For these earthquakes, we collected waveforms from seven seismic stations close to the epicentral area (~ 30 km to ~ 100 km distance, Fig. 4), which were operating during the sequence (ACLR, ASCB, SESP and VELZ from Instituto Andaluz de Geofísica, EMUR and ETOB from Instituto Geográfico Nacional, and CART from GEOFON/Real Observatorio de la Armada/Universidad Complutense). All of them are three-component broad-band stations and they offer a good azimuthal coverage of the earthquakes. We carefully hand-picked P- and S- arrivals in the seismograms, and obtained first hypocentral determinations for the 2005 series from single-event relocation (Hypocenter, Lienert and Haskov, 1995). The new locations group most of the seismicity very close to the main shock (Fig. 4), with most of the events located in the upper crust and showing a tendency to line up in approximately NW-SE direction. The main shock (37.84° N, 1.80° W) was relocated 5.5 km from the epicentre given by the Instituto Geográfico Nacional (37.88° N, 1.78° W) in the immediate proximity of Zarcilla de Ramos and La Paca, consistent with the highest macroseismic intensities observed there (Bufo et al., 2006; Benito et al., 2007). The difference in both locations reflects the different coverage of stations and velocity model used in our study.

Multiplet detection

Events with very similar waveforms at the same recording station are expected to be tightly clustered (Geller and Mueller, 1980), and are suitable for the relocation approach adopted in this study. In order to identify pairs of closely spaced earthquakes, a normalized moving-window cross-correlation analysis between pairs of seismograms was performed (Stich et al., 2001; Saccorotti et al., 2002; Kraft et al., 2006; Ruiz et al., 2006). The similarity between two waveforms was quantified as the maximum value of the cross-correlation coefficient, and the corresponding time lag of the traces was stored to obtain relative locations later on. Though multiplets should exhibit waveform similarity at all stations of a network, we decided to base multiplet detection in the single station VELZ, the closest one to the epicentral area, because it provides clearly the best signal-to-noise ratio for the smaller earthquakes of the series. We used time windows of length 2s starting 0.5s before our picked P and S onsets, and applied a bandpass filter between 1 Hz and 15 Hz. P-wave correlations were measured on the vertical component, and S-wave correlations on the horizontal components. Window length and filter band were adjusted by trial and error by evaluating the performance in the following cluster analysis.

To classify similar earthquakes into clusters or families of multiplets, we use equivalence class sorting (Press et al., 1992). It achieves its purpose by establishing that if element A is similar to B and B is similar to C, then all the three elements A, B and C are assigned to the same cluster. Aster and Scott (1993) introduced the method to multiplet detection, regarding as similar elements two earthquakes that exceed two

chosen threshold values imposed to the P-wave similarity (T_P) and to the S-wave similarity (T_S). A shortcoming of equivalence class sorting is that a single pair of similar elements is sufficient to collapse two formerly independent clusters into a single large one, even if other elements in the cluster show little similarity, which makes the fine-tuning of threshold values critical. We use the algorithm developed by Maurer and Deichmann (1995), which introduces a third threshold value named the cluster separation threshold (T_{SP}), to stabilize the cluster classification. It is imposed to the normalized scalar product of the corresponding rows of the S wave cross-correlation matrix, thus assuring that similar elements show similar trends in their cross-correlations with all other events inside and outside the cluster, and that a high level of similarity throughout the different elements of the same family is maintained.

We tested different values of these thresholds until finding a reasonable compromise ($T_P=0.7$, $T_S=0.8$, $T_{SP}=0.5$) between a possibly large number of clustered events and a high waveform similarity within all individual clusters. Not counting doublets, we obtained 16 clusters, composed of 3 to 25 multiplets (Fig. 5). They include a total of 118 earthquakes, 45% of the initial data set. Nearly all the clustered earthquakes occurred in the first ten days after the mainshock, following the evolution of activity over the seismic series. The first six clusters initiate within 24 hours after the first earthquake. A second phase of activity of seven clusters, starting within 24 hours after the second largest earthquake (M_W 4.2) on February 3, groups a higher number of earthquakes and contains the largest clusters no. 17 and 23 (25 and 23 events, respectively). The two largest aftershocks on February 3 and 4 show very similar waveform and are grouped together in cluster no. 8, starting shortly after the mainshock. At this stage, we also define absolute cluster locations, as a reference for

the relative location procedure, and to make another step towards a better spatial characterization of the series. Assuming that cluster extensions are small compared to the single-event location errors, we calculate absolute locations as the mean location of all multiplet events included in each cluster, thus averaging out random errors of the single locations (Fig. 6). Clusters group tightly around the mainshock and more than half of them are located less than 5 km away. An example for waveform similarity in a multiplet cluster (no. 3) is shown in Fig. 7.

Relative location of multiplets

Relative location of two events can be determined by P and S-wave arrival-time differences to a given station, which are explained by origin time difference and travel-times differences as waves travel along different length propagation paths. For each cluster, a master event has been chosen based on the signal-to-noise ratio of waveforms, and all other events (slaves) are located relative to it. For a pair of master-slave events with very similar waveforms, we can take advantage of that similarity to define highly accurate relative time delays from the time lag of their cross-correlation maxima. A polynomial interpolator was applied to resample the cross-correlation function for waveforms with different sampling rate (100/s at ETOB and EMUR, 50/s at ACLR, ASCB, SESP and VELZ and 20/s at CART), which allows estimating the position of the maximum with a formal precision about one order of magnitude beyond the original sampling rates. To obtain a common base line for all relative arrival times for a master-slave pair, the time lags were referenced to

the zero-lag position of the correlation windows and the GPS times of the first samples in the seismograms.

Assuming that the hypocentral separation between multiplet earthquakes is small compared to the event-station distance, all ray-paths between the source volume and a common receiver are similar and leave the source volume practically parallel to each other. For parallel rays, arrival-time differences between master and slave at a given station depend linearly on the spatial offset between the two sources, and can be expressed by the origin time difference and the projection of relocation vector \mathbf{f} on the direction \mathbf{n} of the ray leaving the source volume:

$$\Delta t = \Delta T_0 - \frac{\mathbf{f} \cdot \mathbf{n}}{V} \quad (1)$$

where \mathbf{n} is the unit vector in the direction of the ray to the given station and v is the phase velocity at the cluster location of either P- or S-waves. This further implies the assumptions that P- and S-wave velocities are constant in the entire source volume of the cluster and during the period of occurrence of the multiplets. Strictly spoken, the changes in the stress field will probably change the velocity fields during observation, but such variations have been found to be small elsewhere (velocity variations and multiplets are treated in Poupinet et al., 1984; Haase et al., 1995). From m available time differences of P and S-phases to different stations, a system of m linear equations is set up, and four unknowns can be determined: the three components of the relocation vector (Δx , Δy , Δz) and the difference in origin time. The elements of the forward matrix connecting data and model parameters depend on the velocity model, cluster location and station geometry. Take-off angles and ray vectors \mathbf{n} were computed through ray tracing in a simple velocity model, consisting of a 2-km-thick layer ($v_p=5.4$ km/s, $v_s=3.1$ km/s) over a half space ($v_p=6.1$ km/s, $v_s=3.5$ km/s). The

problem of matrix inversion and model parameter determination was solved in a least-squares sense by singular value decomposition (Press et al., 1992). Errors of model parameters are described by the model covariance matrix that –in its diagonal form– gives us the orientation and the lengths of the principal error axes of the square standard deviations of the data (e.g. Lay and Wallace, 1996).

Examples of relocation of multiplets (clusters no. 17, 9 and 5) are plotted in Fig. 8. The by far largest axis of the error ellipsoid coincides approximately with the z-direction, representing vertical relocation error. Due to the recording geometry (the closest station is 32 km from the main shock) depth resolution is low (errors reach the order of kilometres) and will not be interpreted in this study. Relocated multiplets show very tight clustering of the epicentre distributions with typical horizontal dimension of about 500 m. Evidently, multiplet relocations collapse strongly in the vicinity of the average cluster location, compared to the distribution of the same earthquakes before being relocated, as is shown in panels (a) and (b) of Fig. 9, respectively.

Multiplets within a cluster are commonly expected to originate on the same fault plane to explain the coherency of seismograms. The local directions of those faults can be determined by fitting a plane to the relocated multiplet hypocentres within each cluster. The best-fitting planes were defined to minimise the L1-norm of distances of the relocated events to that plane (Stich et al., 2001). Dip directions are practically vertical (near 90°) but this is an artificial and unrealistic prolongation of the clusters in vertical direction due to the large scatter of the relocated events in depth. Azimuth values reveal a predominant trend with an average direction of

N145°±17°E which approximately corresponds to lineaments defined by clusters number 7, 17, 23, 31 and 36. This trend is considered the most important one as it represents 53% of the relocated multiplets. There are also two secondary groups of epicentre lineaments with approximate directions N6°±6°E (clusters number 8, 9, 21 and 28, which include 20% of the relocated multiplets) and N40°±7°E (clusters number 3, 4, 5 and 35, which include 17% of the relocated multiplets) (Table 1 and Fig. 10). Two of the clusters (no. 17 - Fig.8 - and no. 23) appear to show both NW-SE and SE-NW subrends, suggesting that they image intersections of both fault systems.

Principal Component Analysis

Principal Component Analysis (PCA) is a multivariant statistical method for reducing multidimensionality of a data set to a lower dimension. PCA has been applied here to the characterization of a system of active faults from our relocated hypocenters of earthquakes, in order to determine the local rupture ellipsoid and to retrieve the main planes along which earthquakes occurred (Michellini and Bolt, 1986; Posadas, 1991; Posadas et al., 1993). PCA represents a more general approach towards the identification and quantification of spatial trends, and differs from our previous interpretation in two other aspects. First, it takes into account the temporal occurrence of events and their proximity in time. Second, it was applied to the entire set of relocated multiplets instead of single clusters only, that is, it considers the multiplet distribution within clusters as well as the relative locations between clusters (Fig. 9b), which were obtained by collapsing the single event locations to their mean value (see

above). It thus merges two types of relative hypocenter locations with different accuracy, which we have to keep in mind when interpreting the results.

The point of departure for PCA is a set of N events written in a matrix form, whose rows are the earthquakes and whose columns contain hypocentral information relative to those earthquakes. The coordinates of hypocenters are used to define a scatter matrix S , whose elements are given by Cooley and Lohnes (1971):

$$S_{im} = \frac{1}{K} \sum_{j=1}^K (x_{ji} - X_{0i})(x_{jm} - X_{0m}) \quad i, m = 1, 2, 3 \quad (3)$$

where j is the event number, and x are the spatial coordinates of the hypocenters with the subscripts (i, m) taking values of 1, 2 and 3 corresponding to longitude, latitude and depth, respectively. X_0 are calculated by:

$$X_{0m} = \frac{1}{K} \sum_{j=1}^K x_{jm} \quad m = 1, 2, 3 \quad (4)$$

and represent the arithmetic average of the three Cartesian coordinates of the hypocenter. The scatter matrix is diagonalized, giving as eigenvectors the axes of an ellipsoid which best least-square fits the original cloud of hypocenters, and the length of these axes as the positive square roots of the eigenvalues λ_m . As this ellipsoid determines the fracture planes associated to earthquakes, Michelini and Bolt (1986) called it Local Rupture Ellipsoid (LRE). If the ratio between the largest and the smallest eigenvalue is less than 2.5, the LRE will be considered volumetric and will be rejected, else the two largest eigenvectors are assumed to define the rupture plane (Posadas, 1991).

To infer the evolution of the rupture process in time, the scatter matrix (S_{im}) is constructed by using subsets of K earthquakes, in temporal order of their occurrence.

A sliding window of K events is displaced along the whole set of earthquakes. We begin with the first one and take the following $K-1$, so if there is a set of N events, a total of $N-K+1$ LRE's will be available. The optimal value of K is that which makes the function $Q(N,K)$ constant (Ebblin and Michelini, 1986)

$$Q(N, K) = (N - K + 1)^{-1} \sum_{q=1}^{N-K+1} \frac{\lambda_2^q(K)}{\lambda_3^q(K)} \quad (5)$$

where q is the number of the window and λ_2^q and λ_3^q are the average and the smallest eigenvalues, respectively. Here, the optimal length of the sliding window was chosen as $K=31$ (Fig. 11). This analysis provides information about the number of LRE's constructed through K time-consecutive earthquakes having a predominant planar structure.

The most relevant planes obtained from our spatio-temporal analysis of the rupture process are reported sequentially in Table 2. From Table 2 and the stereographic projection (Fig. 12) the process shows an evolution of the rupture characterized by three principal trends active during all the series: $N145^\circ \pm 3^\circ E$ (projections (a), (d) and (k)), $N42^\circ \pm 4^\circ E$ (projections (b), (e) and (f)) and $N14^\circ \pm 4^\circ E$ (projections (c), (g) to (i), (l) and (m)). The dominant trends determined by the PCA method are in excellent agreement with the three orientations, $N145^\circ E$, $N40^\circ E$ and $N6^\circ E$, obtained from fitting planes to individual multiplets.

Conclusions

We analysed the 2005 La Paca (Southeastern Spain) seismic series, using a total of 262 earthquakes occurred during the three weeks posterior to the occurrence of the

M_w 4.8 main shock on January 29. Events have magnitudes from 1.2 to 4.8, and single event location depths mainly in the range 0-15km. We identified similar events, called multiplets, from moving-window cross-correlation analysis of waveforms recorded at VELZ station. The similarity between waveforms was quantified through the maximum cross-correlation, and events that exceed three thresholds applied to P-wave similarity, S-wave similarity and the normalized scalar product of the corresponding rows of the S-wave cross-correlation matrix were grouped through an equivalence class analysis. 16 clusters with 3-25 elements were detected, including nearly half of earthquakes involved in the analysis. Within each multiplet cluster, relocations relative to a master event were calculated by linear inversion of precise relative phase arrival times from cross-correlation analysis. Relative epicentres were obtained with an accuracy less than a few hundreds of metres whereas depth shows a higher uncertainty, with errors up to several kilometres, due to the lack of observations at short epicentral distance. As a consequence, dip values of the hypocenter distribution appear to be closer to 90° , and restrict the interpretation to the epicentre distribution and lateral trends of seismicity. The clear elongations of several multiplet clusters (Fig. 8) in fact suggest that most of the seismicity occurs along rather steeply dipping planes.

We quantified relative epicentre alignments in two different ways. First, planes are fit to the precise relocations within each individual multiplet, giving as the most relevant trend a $N145 \pm 17^\circ E$ orientation, and two more groups of clusters showing trends of $N6^\circ \pm 6^\circ E$ and $N40^\circ \pm 7^\circ E$ (Table 1 and Fig. 10). Second, the spatio-temporal pattern of the series is analysed through PCA, applied to the entire dataset of relocated multiplets. Here, the most relevant trends inferred have azimuths $N145^\circ \pm 3^\circ E$,

N42°±4°E and N14°±4°E (Table2). An entirely independent piece of information about the geometry of the seismic series is available from moment tensor source mechanisms, which were obtained from inversion of three-component intermediate-period seismograms at up to 12 near-regional stations (Stich et al., 2006, Benito et al., 2007). The three multiplet directions (N145°E, N6°E and N40°E), as well as the three main directions obtained from ACP (N145°E, N14°E and N42°E), are present in the focal mechanisms of the three largest shocks, showing nodal planes with trends of N132°E, N15°E, N11°E and N40°E (Table 3). This does not permit to identify the fault plane of the main shock as both nodal planes appear in the multiplet directions, but the excellent agreement from both types of analysis permits one to associate the N145°E and N6°E or N40°E multiplet clusters with right-lateral and left-lateral strike-slip faulting respectively (Fig. 13).

These sets of planes include acute angles towards North and South and kinematics involving opposite sense of shear, which characterizes them as conjugate faults. These faults form part of a major belt of distributed shear deformation that extends from southeastern Spain over the Alboran Sea. The orientation of N349°E of the maximum principal stress σ_1 in the shear belt (Stich et al., 2006) is close to the bisecting line of the acute angle between the N145°E and the N6°E multiplet faults, indicating a coincidence of local deformation and average regional stress conditions (Fig. 13). From Fig. 5 we see that activity on patches of either direction occurs simultaneously, a feature that has been occasionally identified in complex strike-slip faulting sequences (e.g. Smith and Priestley, 2000; Hauksson et al., 2002). This implies stress concentration at the intersection of the conjugate fault systems, which can contribute to the intensity of the aftershock sequence. We finally note that

multiplier results for the 2005 series are different from our initial intuitive notion of the spatio-temporal pattern: the two peaks in the seismicity evolution, accentuated by the occurrence of larger earthquakes of different focal mechanism at the onset of each peak, may appear consistent with a temporal succession of two different rupture processes, but the multiplier assignment confirms that the presupposed second rupture process is active from the very beginning of the series, and the presupposed first rupture process does even account for the majority of events in the second burst of activity.

Acknowledgements

We would like to thank the Instituto Geográfico Nacional (stations EMUR and ETOB) and GEOFON Program (station CART) for making available waveforms used in this study. We are very grateful to Editor George Helffrich and to two anonymous reviewers whose comments have helped us to improve and enrich the manuscript. We also appreciate the comments and suggestions proposed by Gerardo Alguacil. This study has been supported by the CICYT, projects REN2003-08159-C02-02 and CGL2007-66745-C02-01/BTE, and by the FPI program of the Spanish Ministry of Education and Science.

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Figure captions

Figure 1. Seismicity of S-Spain and surrounding area 1983-2007 ($m \geq 3.5$, Instituto Andaluz de Geofísica). The box in SE-Spain marks the study area where the 2005 sequence occurred.

Figure 2. Map with locations of the main historical events ($I_{\max} > VIII$) – triangles – and instrumental events with magnitude > 4 – circles – that affected the region of Murcia.

Figure 3. Time-frequency distribution of the 2005 La Paca seismic series. Arrows indicate the initial and final date for analysis in this study (January 29 to February 20).

Figure 4. Single earthquake relocations for 262 earthquakes of the La Paca sequence from January 29 2005 to February 20 2005 (circles, the location of the mainshock is marked by a star). Stations considered for the waveform analysis are represented by triangles while squares indicate the location of some of the villages near the epicentral area.

610 Figure 5. Organization of 118 multiplets (45 per cent of the initial data set) into 16
 611 clusters with a minimum of 3 members. Further, 20 doublets were obtained but they
 612 have not been included in the master relative location procedure.

613

614 Figure 6. Map showing the location of the 16 families with more than 3 members
 615 (circles); family numbers according to Fig. 5 have been labelled. Locations have been
 616 calculated as the mean location of all individual multiplets included in each of them.
 617 The depths of families are in the range 3-18km. The main shock of the seismic series
 618 has been represented by a star.

619

620 Figure 7. Example for waveform similarity within a multiplet family (normalized
 621 seismograms for cluster no. 3 at station VELZ) showing P- and S-arrivals.

622

623 Figure 8. Precise relative locations of multiplets within three clusters. The
 624 corresponding master events are represented by a star at relative coordinates (0,0).
 625 Horizontal planes of the 68.3% confidence ellipsoids have been plotted. The chosen
 626 examples show predominant average directions of epicentre distributions, of about
 627 N145°E (cluster no. 17), N6°E (cluster no. 9) and N40°E (cluster no. 5).

628

629 Figure 9. Map showing the location of the 118 multiplets included in some of the
 630 clusters (a) before being relocated and (b) after master relative location. A higher
 631 concentration of relocated seismicity can be observed. In both cases main shock has
 632 been represented by a star and the locations of some of the main villages near the
 633 epicentral area have been indicated by triangles. (c) Map showing the trends of planes

fitted to the relocated clusters, with predominant orientations around N145°E and N6°E and N40°E.

Figure 10. Equiareal projections of the best-fitting planes through relocated multiplet clusters. Clusters number 7, 17, 23, 31 and 36 show epicentre lineaments with an average direction of $N145^{\circ}\pm 17^{\circ}E$. There are also two secondary epicentre lineaments with approximate directions $N6^{\circ}\pm 6^{\circ}E$ and $N40^{\circ}\pm 7^{\circ}E$, which correspond, respectively, to clusters number 8, 9, 21, 28 and 32 and clusters number 3, 4, 5 and 35.

Figure 11. Plot of function $Q(N,K)$ versus the sliding window length K for the spatio-temporal PCA. The curve becomes near-constant for values of K around 30, and a sliding window of $K=31$ events was selected in this study.

Figure 12. Temporal evolution of the rupture process modelled by PCA. Equiareal projections of the planes are represented consecutive in time. Three principal directions are found: $N145^{\circ}\pm 3^{\circ}E$ (projections (a), (d) and (k)), $N42^{\circ}\pm 4^{\circ}E$ (projections (b), (e) and (f)) and $N14^{\circ}\pm 4^{\circ}E$ (projections (c), (g) to (i), (l) and (m)).

Figure 13. Trends of seismicity from multiplet analysis (black solid lines), from PCA analysis (black dotted lines) and trend of nodal planes of moment tensor mechanisms (from Benito et al., 2007, grey solid lines) concentrate along $\sim N10^{\circ}E$, $\sim N40^{\circ}E$ and $\sim N140^{\circ}E$ directions, with opposite sense of slip, showing the simultaneous activity of conjugate strike-slip faults. The regional maximum stress direction (grey arrows, from Stich et al., 2006) is consistent with local deformation.

659

660 **Tables**

661

662 Table 1. Best fitting planes through relocated multiplet clusters.

Cluster number	Number events	Azimuth (°)	Dip(°)
3	7	41	83
4	3	44	83
5	7	30	88
7	3	153	89
8	4	6	87
9	10	12	86
13	3	114	86
17	25	126	87
20	9	64	88
21	4	177	87
23	23	163	86
28	3	177	88
31	7	155	86
32	3	7	88
35	3	40	87
36	4	144	89

663

664

665 Table 2. Planes characterizing temporal evolution of rupture process.

666 NCP indicates the number of time consecutive planes used in the construction of the
 667 average plane and gives an idea of its relative importance. Other columns represent
 668 azimuth and dip values of the plane as well as spatial location (longitude, latitude and
 669 depth) of the ellipsoid.

PCA						
Plane	NCP	Azimuth (°)	Dip(°)	Long (°)	Lat (°)	Depth (km)
(a)	2	144	60	-1.785	37.821	10.0
(b)	2	44	70	-1.790	37.823	10.2
(c)	4	11	44	-1.792	37.824	10.1
(d)	5	147	35	-1.797	37.825	10.3
(e)	2	49	73	-1.807	37.827	10.5
(f)	5	39	84	-1.807	37.827	10.4
(g)	2	6	80	-1.807	37.827	10.0
(h)	2	9	89	-1.806	37.825	9.5
(i)	2	16	11	-1.803	37.829	9.3
(j)	4	173	88	-1.802	37.828	9.3
(k)	3	141	88	-1.799	37.827	8.9
(l)	12	17	90	-1.799	37.825	8.7
(m)	4	13	76	-1.793	37.822	8.4

670

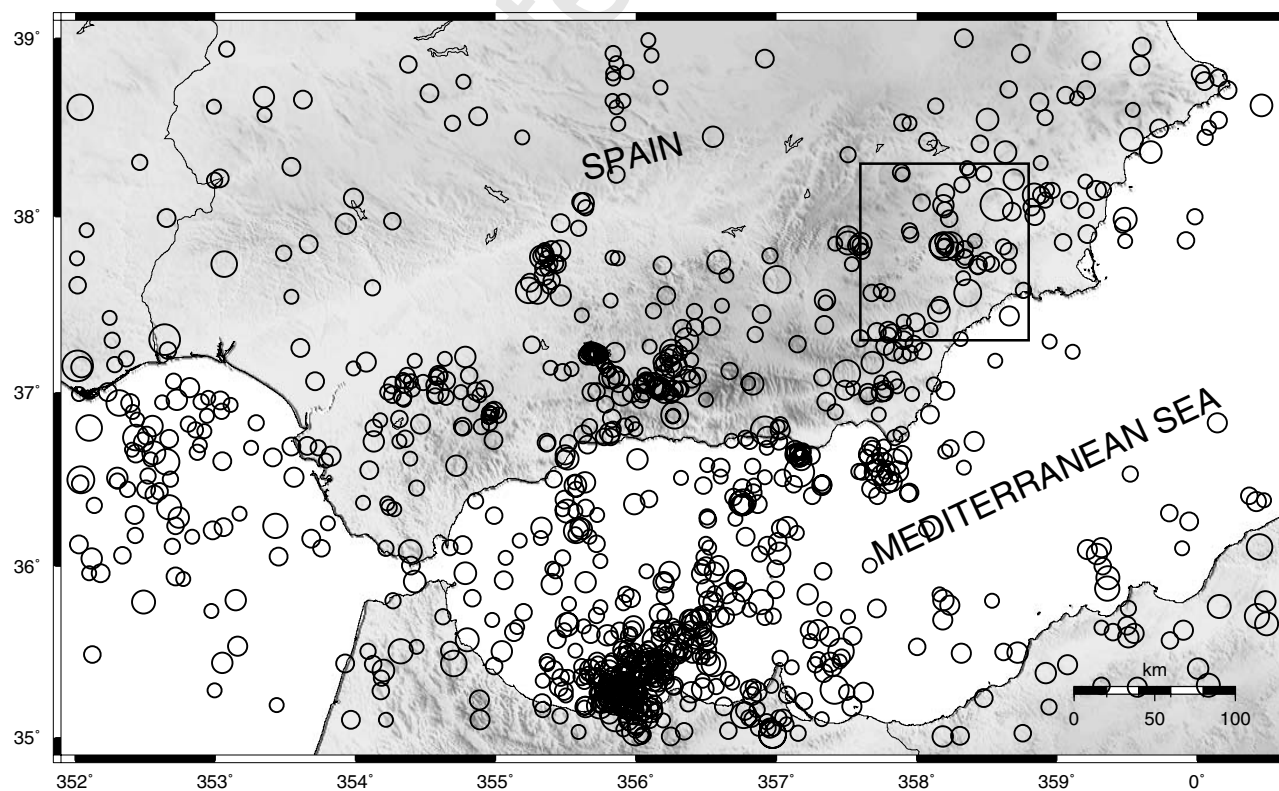
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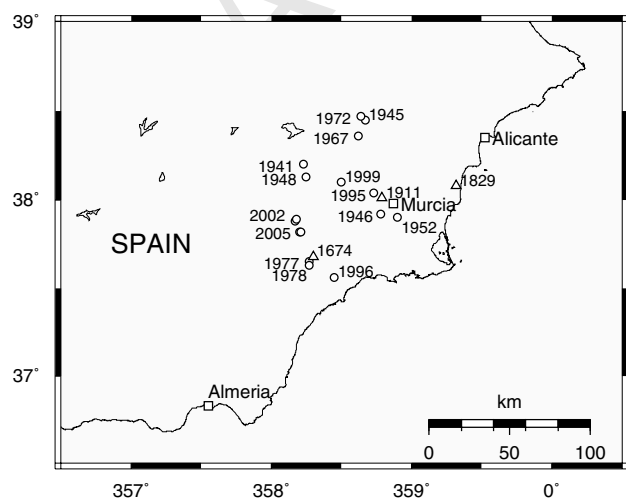
672 Table 3. Moment tensor solutions for the 2005 La Paca earthquake and the two
 673 largest aftershocks (from Stich et al., 2006, Benito et al., 2007). The double-couple
 674 component is represented by fault angle parameters for the two nodal planes. The

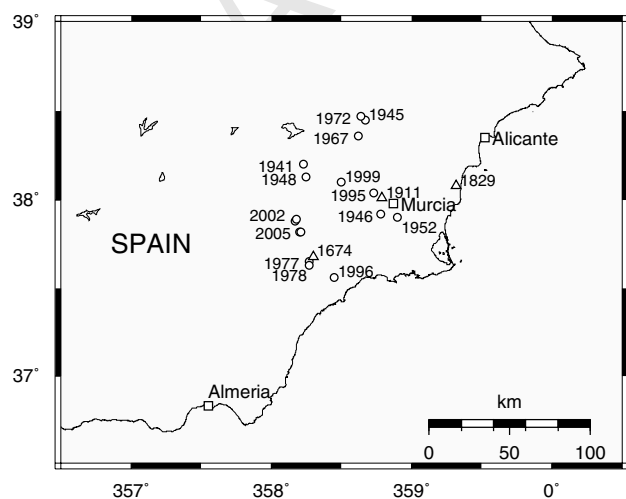
675 non-double-couple reminder (CLVD) is given in percent. M_0 is the seismic moment
 676 and M_w the moment magnitude.

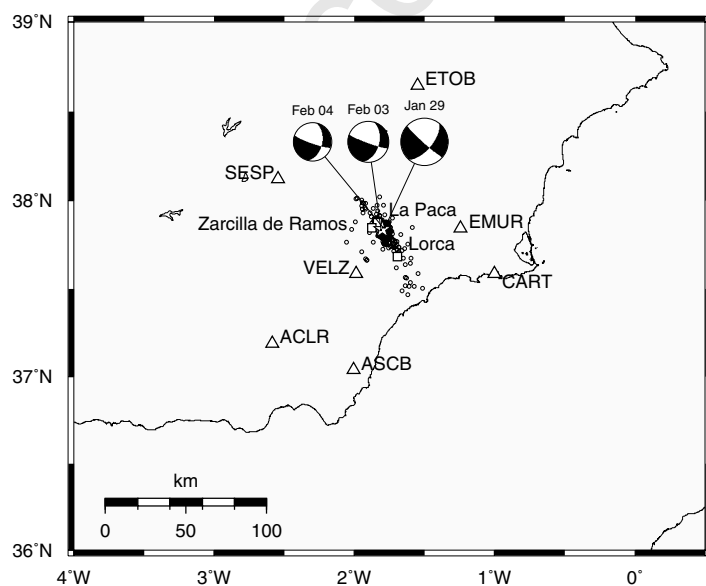
Date	time	fault angle parameters	clvd	M_0 [Nm]	M_w
y/ m/ d		(strike/ dip/ rake)	[%]		
2005/01/29	07:41:31	132/ 85/ -153; 40/ 63/ -5	3	$1.62 \cdot 10^{16}$	4.8
2005/02/03	11:40:33	110/ 84/ -136; 15/ 46/ -7	6	$2.44 \cdot 10^{15}$	4.2
2005/02/04	01:09:41	109/ 82/ -136; 11/ 47/ -10	3	$8.65 \cdot 10^{14}$	3.9

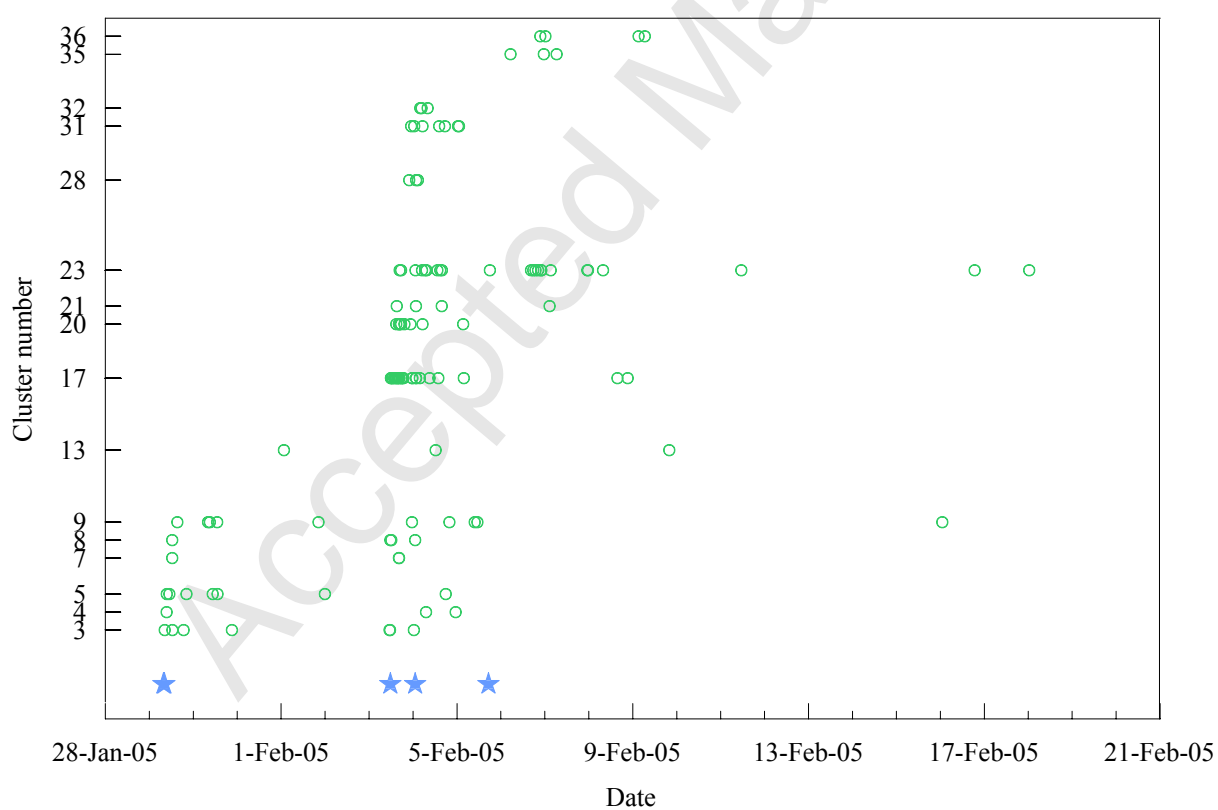
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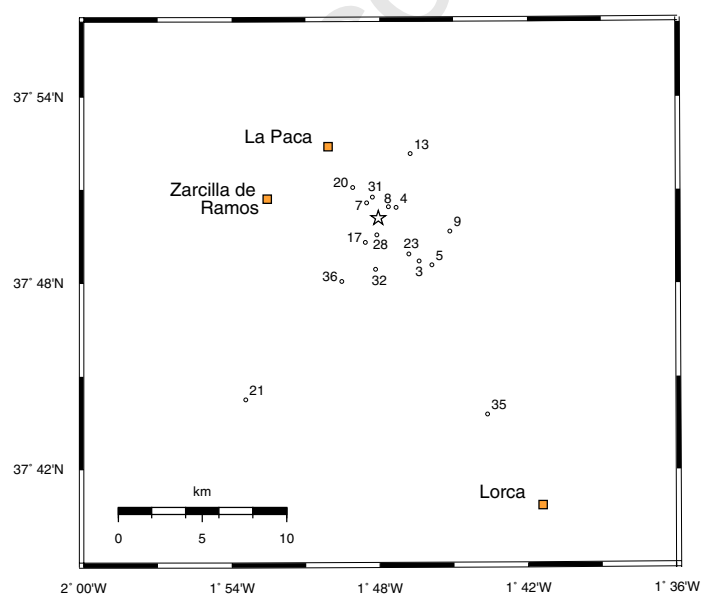


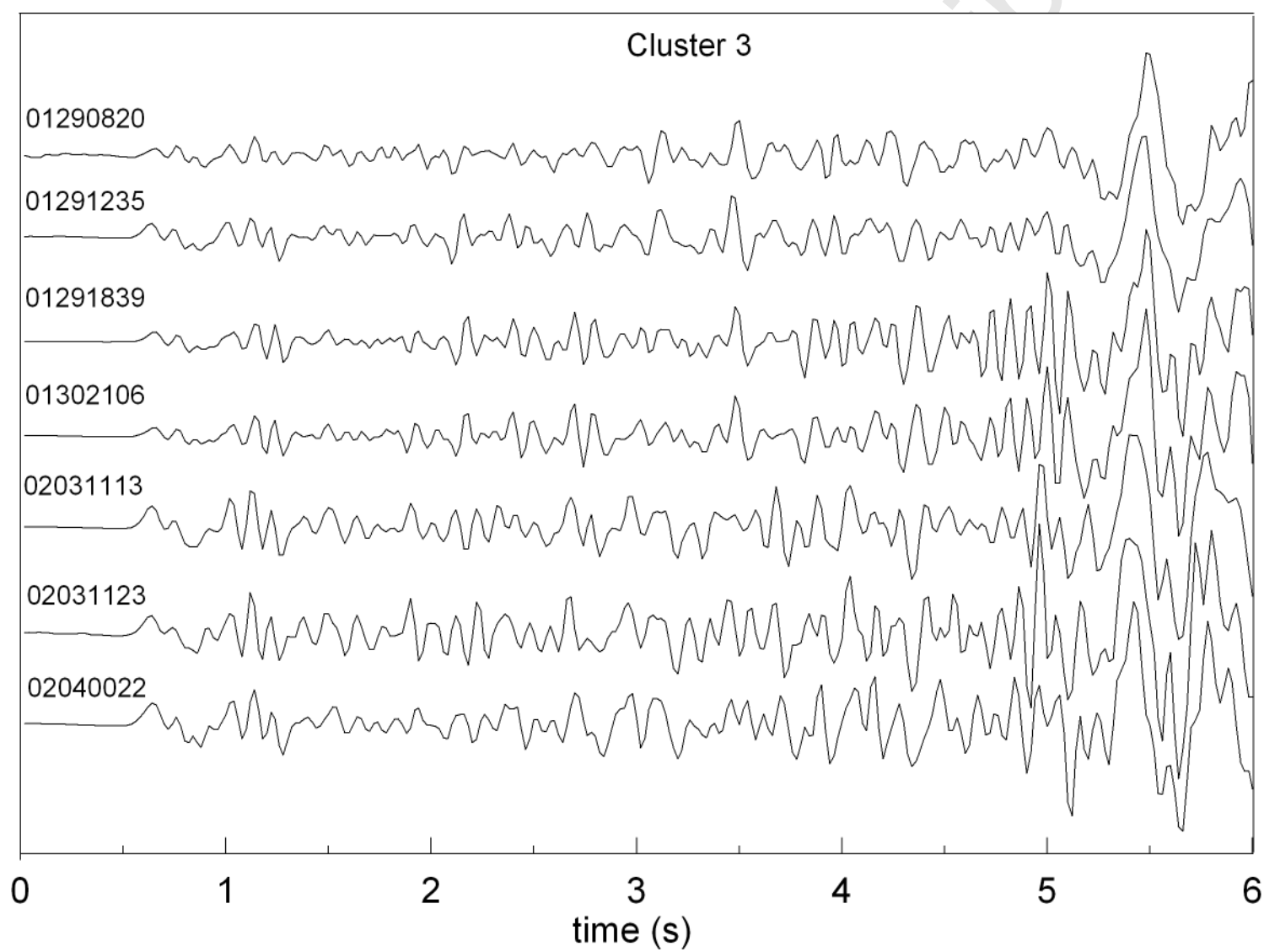


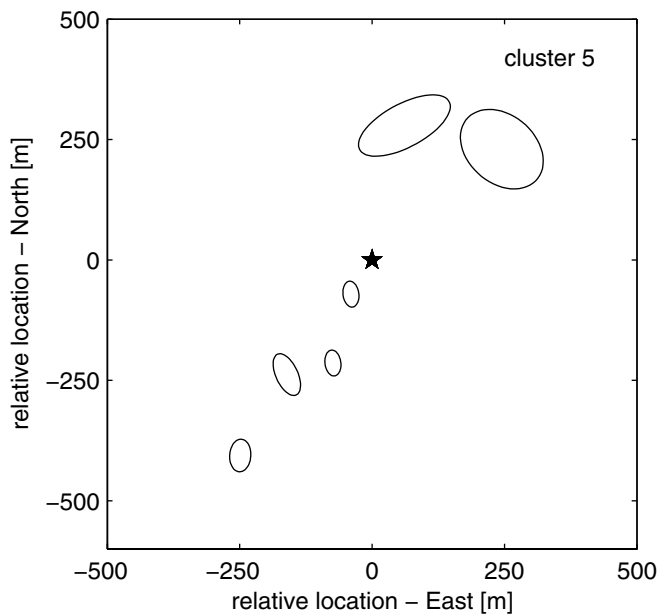
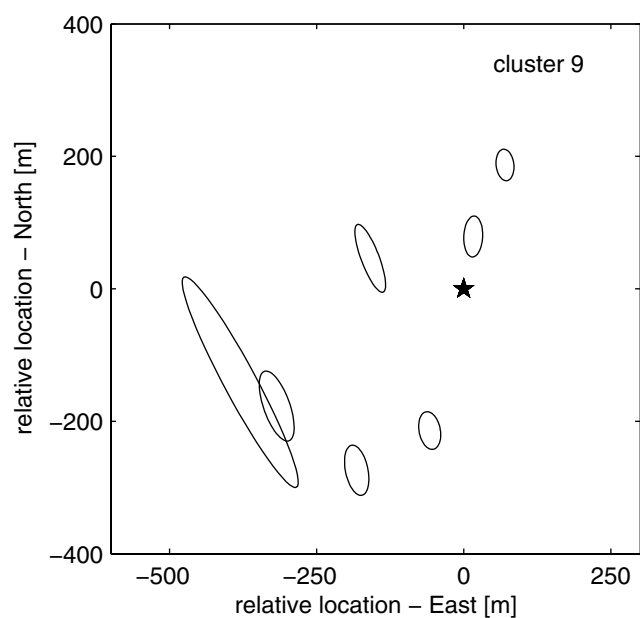
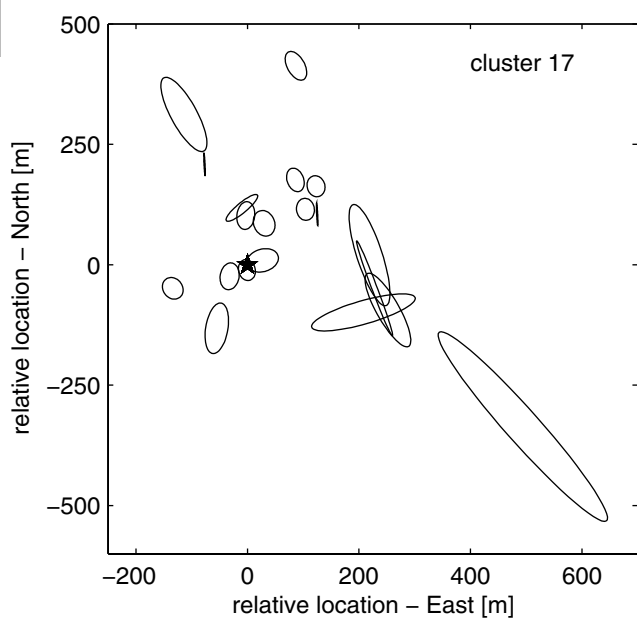


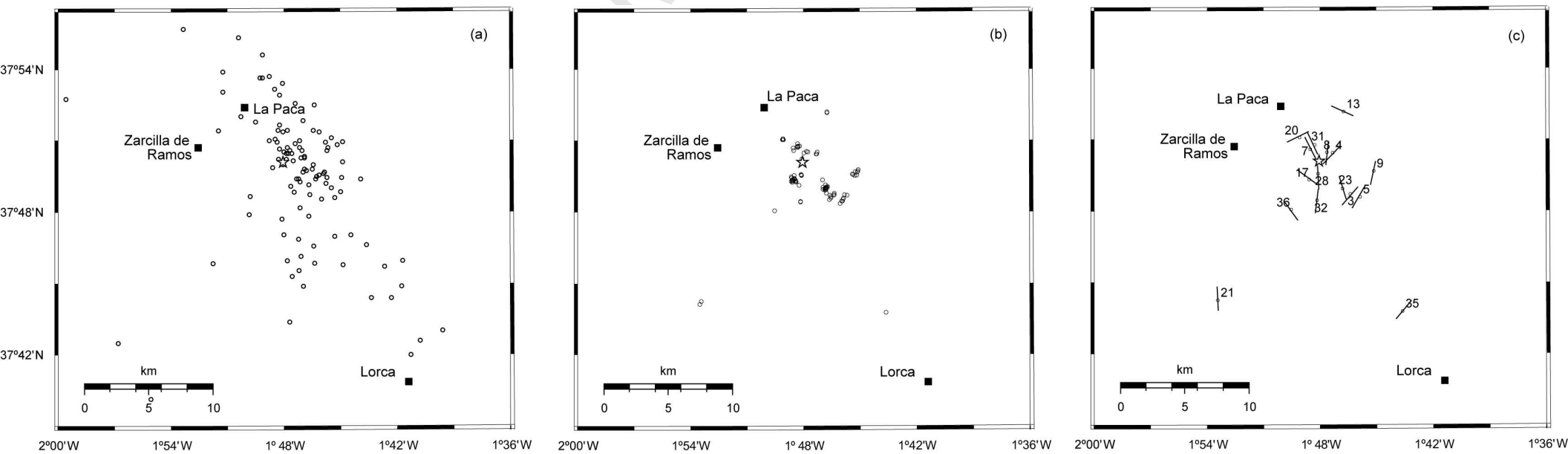


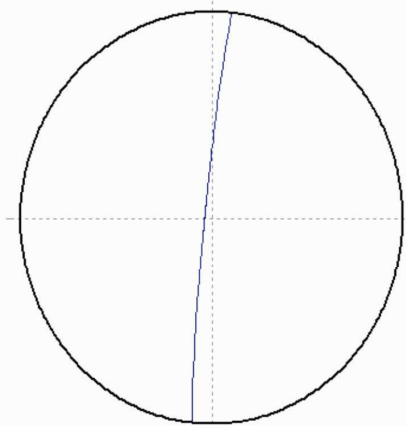




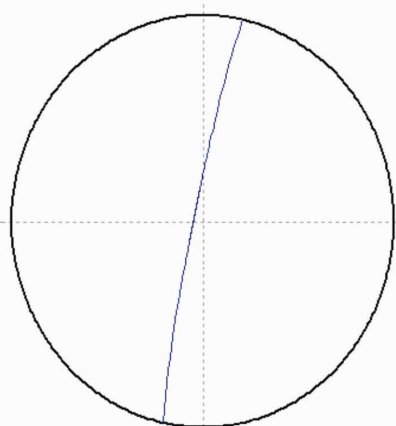




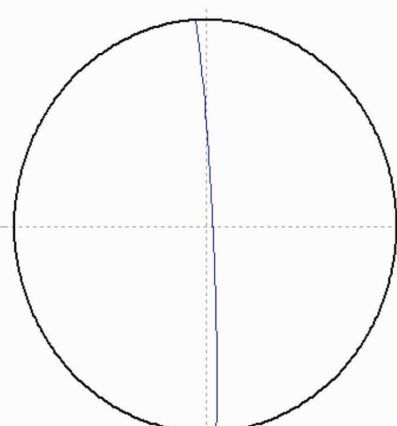




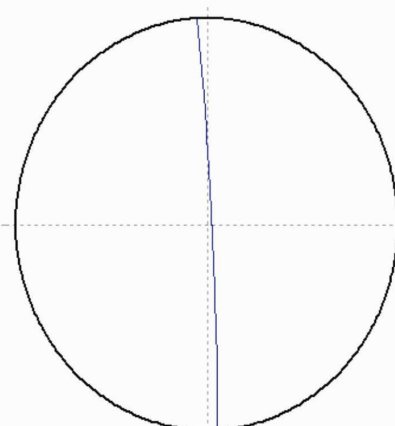
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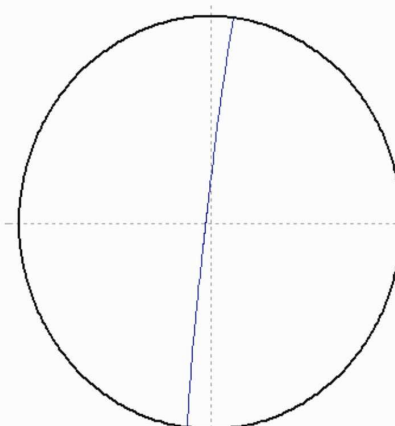
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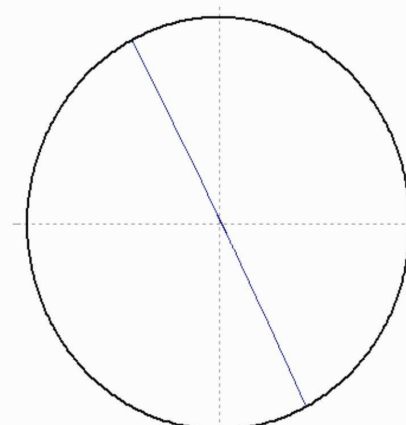
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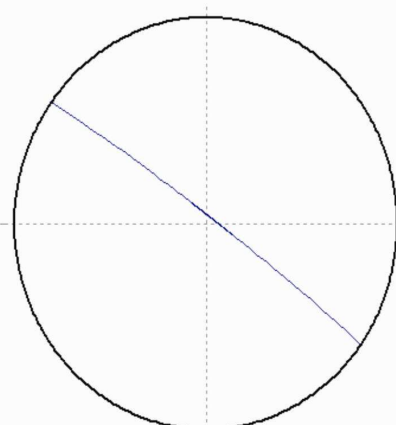
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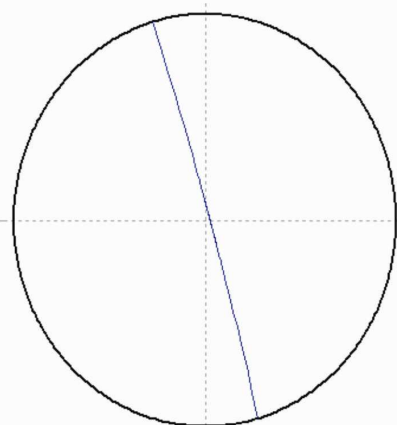
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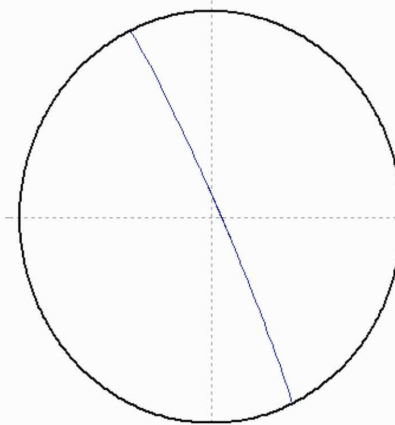
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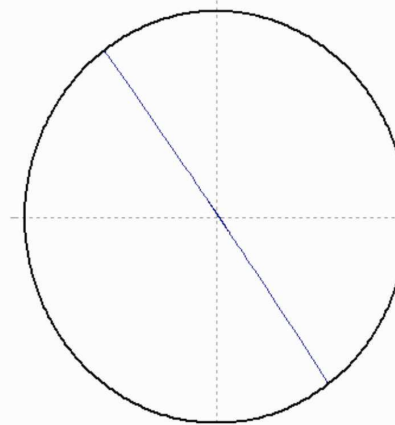
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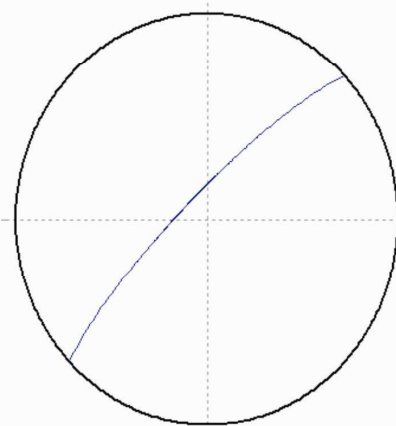
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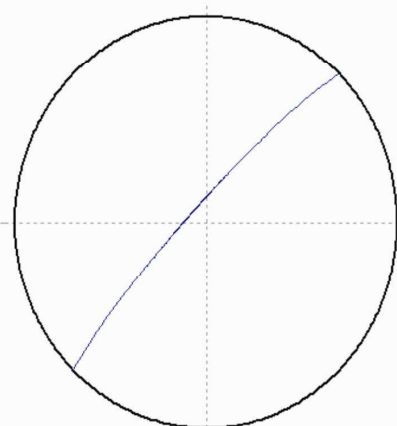
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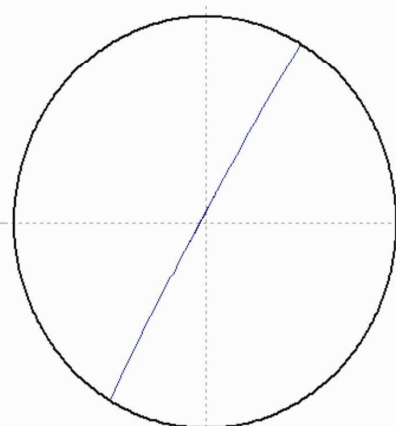
cluster 36



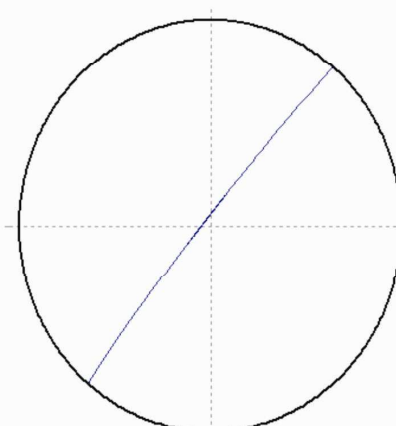
cluster 3



cluster 4



cluster 5



cluster 35

