

# Subsidence activity maps derived from DInSAR data:

## Orihuela case study

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## Abstract

A new methodology is proposed to produce subsidence activity maps based on the geostatistical analysis of **Persistent Scatterer Interferometry** (PSI) data. PSI displacement measurements are interpolated based on Conditional Gaussian Simulation (CGS) to calculate multiple equiprobable realizations of subsidence. The result from this process is a series of interpolated subsidence values, with an estimation of the spatial variability and a confidence level on the interpolation. These maps complement the PSI displacement map, improving the identification of wide subsiding areas at regional scale. At local scale, they can be used to identify buildings susceptible to suffer subsidence related damages. In order to do so, it is necessary to calculate the maximum differential settlement and the maximum angular distortion for each building of the study area. Based on PSI derived parameters those buildings in which serviceability limit state has been exceeded, and where in situ forensic analysis should be made, can be automatically identified. This methodology has been tested in

Orihuela City (SE Spain) for the study of historical buildings, damaged during the last two decades by subsidence due to aquifer overexploitation. The qualitative evaluation of the results carried in buildings where damages have been reported, shows a success rate of 100%.

## 1 Introduction

Subsidence caused by water withdrawal is a well-known phenomenon which affects worldwide areas. Structures built on these areas must withstand these vertical (and sometimes also horizontal) ground displacements, resulting in widespread damages when they cannot support differential settlements under their foundations (Skempton and MacDonald, 1956; Bjerrum, 1963; Burland and Wroth, 1974; Boscardin and Cording, 1989; Namazi and Mohamad, 2013). Thus the monitoring of the displacements affecting these structures plays an essential role on its serviceability and, exceptionally, on its safety. Classical surveying techniques (e.g. topographical techniques and extensometers) are commonly used for monitoring structures placed on subsiding areas (Poland et al., 1984; Galloway et al., 1999; Galloway and Burvey, 2011; Tomás et al., 2014). However, during the last decades, Differential SAR Interferometry (DInSAR) has become an alternative method for measuring infrastructures displacements showing a good capability for measuring ground surface displacements over wide areas (Galloway and Burvey, 2011; Tomás et al., 2014).

Initial single interferogram DInSAR techniques (Massonnet et al. 1993; Peltzer and Rosen 1995) evolved to advanced DInSAR techniques (A-DInSAR), which provide information on the temporal evolution of the ground displacement (Arnaud et al. 2003, Berardino et al. 2002, Ferretti et al. 2001 and 2011, Mora et al. 2003; Prati et al. 2010, Sowter et al. 2013). These techniques have been validated for subsidence monitoring with measurements obtained by classical survey techniques (Herrera et al. 2009a, b; Hung et al. 2011, Raucoules et al. 2009). These authors computed  $\pm 1$  mm/year and  $\pm 5$  mm errors for average displacement rate and cumulated displacements values along the Line of Sight (LOS) respectively.

Mostly, A-DInSAR techniques have been applied to monitor wide areas affected by ground surface movements associated with groundwater changes (e.g., Galloway et al 2007, Heleno et al., 2011; Raspini et al., 2012, Stramondo et al., 2008; Tomás et al., 2010; Tomás et al., 2014). Fewer works use these techniques to monitor singular urban structures and infrastructures and indicate its usefulness as a prevention tool (Karila et al., 2005; Bru et al., 2010; Herrera et al., 2010; Cigna et al., 2011 and 2012, Tapete et al., 2012, Arangio et al., 2013 and Sousa et al. 2013). Some authors (Cascini et al., 2007 and Tomás et al., 2012) go

further, and apply geotechnical criteria to A-DInSAR techniques in order to identify buildings where settlement induced damages could occur.

This work focuses on the utility of A-DInSAR techniques to monitor and characterize the phenomenon of subsidence both regionally and locally, adopting a geotechnical approach for the local scale. A preliminary analysis was shown in (Sanabria et al. 2014). In this paper, a much deeper analysis and discussion is presented. The ground surface settlements, caused by groundwater withdrawals, of Orihuela city are evaluated by ERS-1/2 and ENVISAT ASAR sensors covering two different periods July 1995–December 2005 and January 2004–December 2008. The A-DInSAR displacement data obtained are interpolated based on Conditional Gaussian Simulation (SGS) to generate subsidence activity maps both at regional and local scale. The SGS allows quantifying the spatial variability of the interpolation and provides a confidence level on the interpolation. From the interpolated maps, the serviceability limit states of 27 heritage buildings (XVI to XIX century) of the city of Orihuela (Fig. 1) are studied by means of geometrical-geotechnical criteria (i.e. differential settlements and angular distortions). A qualitative evaluation of the results is made with 10 buildings where damages have been reported. Finally, a comparison between the serviceability parameters obtained for Santos Justa and Rufina church and a detailed damage study (Tomás et al. 2012) is performed.

## **2 Description of the study area**

The city of Orihuela is located in the Vega Baja of the Segura River (VBSR) (province of Alicante, SE Spain). The basin is filled by Neogene–Quaternary sediments deposited by the Segura River. The substratum of the VBSR basin (Fig. 1a) consists on Permo-Triassic rocks and Tertiary sediments that outcrop in the north and south of the basin (Boer et al., 1982). These materials constitute the geotechnical substratum of Orihuela City, being the Pleistocene to Holocene sediments the most compressible ones. The spatial distribution of soft soils in the VBSR increases towards to the centre of the valley reaching a maximum thickness up to 50 m (Delgado et al. 2000). These data have been digitized and completed with the geotechnical information derived from new boreholes located at the west of Orihuela city and interpolated by kriging method (Matheron, 1963) to generate the soft soil thickness map (Fig. 4). Tomás et al. (2010) characterized these soft sediments as sediments with moderate to high compressibility, exhibiting compression indexes ( $C_c$ ) varying from 0.07 to 0.29 and with an average value of 0.18.

1 From a hydrogeological point of view the study area belongs to the Guadalentín–Segura  
2 aquifer system (IGME, 1986), which is divided in two units. The first one is an unconfined  
3 shallow aquifer with low conductivity (sand, silts and clays) with the water table a few meters  
4 below the ground surface. The deep aquifer is formed by gravels, usually interbedded with  
5 marls, showing a greater hydraulic conductivity than the upper aquifer (IGME, 1986).

6 In the past decades, recent subsidence phenomenon in the city of Orihuela is related to the  
7 excessive water pumping from the shallow and deeper aquifer during drought periods: 1993-  
8 1996 and 2006-2008 (Tomás et al. 2010). During these periods ground water extraction in  
9 authorized and illegal drought-wells increased while groundwater recharges were reduced due  
10 to low precipitations. This groundwater withdrawal caused an important piezometric level  
11 drop (Fig. 1b). During the years 1993-1996 the piezometric level dropped about 5 m as is  
12 shown in piezometer nº 4. For years 1998-2002 the decrease was about 5 to 8 m. Finally the  
13 more pronounced decline occurred during the years 2004-2008 where the piezometers 1 and 3  
14 show a drop of 18 m and 10 m, while piezometer 2 and 4 show a decline of about 8 m. The  
15 drop of piezometric level entailed an important soil consolidation due to pore water pressure  
16 decrease (Mulas et al., 2003; Tomás et al., 2007a, b; 2010), producing moderate damages to  
17 structures and infrastructures (Martínez et al., 2004) in the whole Segura River Basin.  
18 Subsidence related damages were reported in the western part of Orihuela city in 1995 by the  
19 local press. Furthermore, several heritage buildings affected by settlements have been repaired  
20 since 90s (Louis, 2005; Maciá, 2005; Louis et al., 2012). Recently, a subsidence damage  
21 assessment of a gothic church in Orihuela City, using advanced differential interferometry for  
22 the 1995-2008 period and field data, was performed by Tomás et al. (2012).

### 23 **3 Methodology**

24 In this section a new proposed methodology to obtain subsidence activity maps from  
25 Persistent Scatterer Interferometry (PSI) displacement estimates is described. A more detailed  
26 description of the PSI techniques can be found in Arnaud et al. (2003) and Duro et al. (2005).  
27 Sansosti et al. (2010) and Tomás et al. (2014) also present a review of PSI applications for  
28 subsidence research. In this work, ground subsidence measurements were obtained using a  
29 PSI technique called the Stable Point Network (SPN). The SPN software (Arnaud et al. 2003;  
30 Duro et al. 2005) uses the DIAPASON interferometric algorithm for all SAR data handling,  
31 e.g. co-registration task and interferogram generation. The SPN procedure generates three  
32 main products starting from a set of Single Look Complex (SLC) SAR images: (a) the

1 average deformation velocity along the line of sight (LOS) of a single Persistent Scatterer  
2 (PS); (b) a map of height error; and (c) the LOS displacement time series of individual PS.  
3 The proposed methodology is based on the third product, i.e. the total cumulated displacement  
4 over a period covered by a set of SAR images.

5 In the first stage the relation between ground displacement and the available geo-thematic  
6 layers is studied (Fig. 2-1<sup>st</sup> step). First at all, a spatial analysis is performed between the PSs  
7 and geo-thematic map. This analysis is performed in order to determine if different  
8 populations of PSs can be distinguished attending to geo-thematic layers. On the other hand,  
9 the Pearson correlation coefficient (i.e. a measure of the strength of a linear association  
10 between two variables, McCullagh and Nelder, 1989) is calculated between the PSs and the  
11 geo-thematic layers. This coefficient allows discriminating if the geo-thematic layers should  
12 be considered as a second input when performing the interpolation.

13 The second step consists on the interpolation of the cumulative displacement along the  
14 satellite Line of Sight (LOS); taking into account previously identified PS populations (Fig. 2-  
15 2<sup>nd</sup> step). For this task, geostatistical tools, coupled with Geographic Information System  
16 (GIS) (Burrough and McDonnell, 1998), allow to perform spatial interpolation of scattered  
17 measurements and to obtain an assessment of the corresponding accuracy and precision.  
18 Kriging (Matheron, 1963) is a geostatistical interpolation technique that considers both the  
19 distance and the relation between sampled data points when inferring values at unsampled  
20 locations (Journel and Huijberegts, 1978; Isaaks and Srivastava, 1989; Goovaerts, 1997). The  
21 kriging smoothing effect on the interpolated maps may be a disadvantage because the reality  
22 is expected to be more variable. As a consequence of this effect the variance of the estimated  
23 values is lower than the variance of the real values. Geostatistical simulation (Goovaerts,  
24 1997) allows generating multiple equiprobable realizations of the attribute under study, rather  
25 than simply estimating the mean. This is a key property of this approach, since a series of  
26 realizations representing a plausible range is generated, not just one best estimate. Hence,  
27 accuracy can be estimated through distributions of inferred values at unsampled locations  
28 using the series of simulated realizations. A large number of geostatistically-based algorithms  
29 exist for the simulation of realizations (i.e, Spectral Simulation, Sequential Gaussian  
30 Simulation Method, Boolean Simulation, Turning Bands, etc.). The Conditional Sequential  
31 Gaussian Simulation method (SGS) (Gómez-Hernández et al., 1993) has been used in this

work because of its long history and wide acceptance for environmental modelling applications.

First of all, each PS population is analysed and, if it necessary, transformed into a Gaussian or normalized distribution (Fig. 2-1<sup>st</sup> step). Then, for each normalized PS population, the experimental variograms (Goovaerts, 1997) are established. Variograms are widely used to quantify the spatial variability of spatial phenomena (e.g. Journel and Huijbregts, 1978; Armstrong, 1984; Olea, 1994; Goovaerts, 1997). In this work, the plot of the semivariances as a function of distance from a PS is referred to as variogram:

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^N [\delta(x_i) - \delta(x_i + h)]^2 \quad (1)$$

Where N is the number of PS pairs separated at a distance h,  $\delta(x_i)$  are PS cumulated displacement values and  $\delta(x_i+h)$  are all the PS cumulated displacement values at a distance h away from the PS  $x_i$ . The analysis of this function for different separation distances (“h” values) allows the characterization of the spatial variability of the PSs. After the calculation of the experimental variogram, a variogram model must be inferred. The parameters of the variogram model are used as input for the SGS. This interpolation method generates multiple equiprobable surfaces of the displacement reproducing the observed data at their locations. To preserve resolution of the satellite images, the chosen pixel size of the interpolated surfaces should be the same as the ground resolution of SAR images.

In the third step from the multiple equiprobable surfaces (Fig. 2-3<sup>rd</sup> step), variance and percentile surfaces are retrieved (mean, 68th percentile and 95th percentile). The percentile surfaces are analysed in order to generate the subsidence activity map. The subsidence activity map consists of two maps: the subsidence map and the variance map. The first one, the chosen percentile surface, is a subsidence interpolated surface with a confidence level on the interpolation. The second one, the variance, is an estimate of the spatial variability of the subsidence interpolated surface. Thus for every pixel, even for those areas in which there were not PS data, the method provides a subsidence value and an associated range of variation and a level of confidence of it.

In the fourth step (Fig. 2-4<sup>th</sup> step) subsidence activity maps are used to identify buildings that can be damaged by ground subsidence, according to the serviceability limit state criterion (SLS). The presence of damages mainly depends on the structure typology and the settlements magnitude and distribution. SLS are those conditions that make the structure unsuitable for its

projected use. In foundations design, the most common serviceability limit states are differential settlements ( $\delta_s$ ; i.e. unequal settling of a building's foundation that is computed as the maximum difference between two points from the foundation) and angular distortions ( $\beta_{\max}$ ; i.e. the ratio of the differential settlement between two points and the horizontal distance between them), which must be less or equal than the corresponding limiting value stated for them. A vast number of limiting criteria for settlements and angular distortion values are available in the geotechnical literature and standards (e.g. Terzaghi and Peck, 1948; Skempton and McDonalds, 1956; Burland et al., 1977; EN, 1990; CTE, 2006). In this work, considering the cohesive character of the available soils and the high rigidity of the heritage masonry building studied in Orihuela city, we have adopted the values shown in Table 1 for angular distortion and differential settlements following the aforementioned authors' recommendations. Note, that the limiting values established in the literature correspond to vertical displacements ( $\delta_{vs}$ ). Therefore, these vertical displacement values were multiplied by the cosine of satellite look angle ( $\theta=23^\circ$  for ERS and ENVISAT) (Fig .3), in order to compute the settlements projected along the LOS ( $\delta_{vs-LOS}$ ) for a direct comparison between A-DInSAR and settlement limiting values:

$$\delta_{vs-LOS_i} = \delta_{vsi} \times \cos(\theta) \quad (2)$$

Then, according to eq. (2) the vertical differential settlement ( $\delta_s$ ) between two pixels (i and j) can be expressed as:

$$\delta_s = |\delta_{vs-i} - \delta_{vs-j}| = \frac{|\delta_{i-LOS} - \delta_{j-LOS}|}{\cos \theta} = \frac{|\delta_{s-LOS}|}{\cos \theta} \quad (3)$$

Consequently, considering eq. (3) and an allowable vertical differential settlement ( $\delta_{s\max}$ ), the maximum allowable differential settlement between two pixels (i and j) along LOS ( $\delta_{s-LOS}$ ) is:

$$\delta_{s\max-LOS} = |\delta_{s\max} \times \cos \theta| \quad (4)$$

Additionally, the vertical angular distortion ( $\beta$ ) between two pixels (i and j) can be also computed by means of next expression:

$$\beta = \frac{|\delta_s|}{L_{i,j}} = \frac{|\delta_{vs-i} - \delta_{vs-j}|}{L_{i,j}} = \frac{|\delta_{i-LOS} - \delta_{j-LOS}|}{L_{i,j} \times \cos \theta} = \frac{|\beta_{LOS}|}{\cos \theta} \quad (5)$$



Consequently, considering eq. (5) and adopting a maximum allowable angular distortion caused by vertical settlements ( $\beta_{\max}$ ), the maximum angular distortion between two pixels (i and j) along LOS ( $\beta_{\max-LOS}$ ) can be expressed as:

$$\beta_{\max-LOS} = | \beta_{\max} \times \cos \theta | \quad (6)$$

The values provided by eqs. (4) and (6), considering the limiting vertical values shown in Table 1, are used as limiting values throughout the analysis. Note that the main advantage of projecting the maximum allowable settlement and angular distortion along LOS is that these values can be directly compared with the displacement values provided by DInSAR.

To calculate the angular distortion and the differential settlement along the LOS for a building, a buffer is performed around each building. The size of the buffer can be obtained by calculating the root square of the diagonal of a pixel. The buffer area is used to extract the cumulative displacement values from the subsidence activity raster maps, and represents the subsidence influence area of the building where damages can be induced. From the selected cumulative displacement values, both the maximum differential settlement and the maximum angular distortion (along the LOS) are computed for each building (Fig. 3) and compared with the maximum allowable values shown in Table 1.

## 4 Data analysis

In this section the above mentioned methodology is applied to the city of Orihuela, where SAR images covering two different periods from July 1995 to December 2005 and from January 2004 to December 2008 have been processed using SPN algorithm. First at all, the resulting PSI data for both processed periods are described. Then, following the first two stages of the methodology, the results obtained in Orihuela city for both periods are presented.

### 4.1 PSI data

PSI displacement maps were retrieved from the SPN processing of 110 C-band Single Look Complex (SLC) SAR images from descending orbits acquired by the European Space Agency (ESA) ERS-1/2 and ENVISAT ASAR satellites covering two different periods July 1995–December 2005 and January 2004–December 2008 (Table 2). A similar crop of about 20×8 km was selected from the 100×100 km SAR images, corresponding to the westernmost sector of the Vega Baja of the Segura River. Interferograms were generated from pairs of SAR images with a perpendicular spatial baseline smaller than 800 m, a temporal baseline shorter



than 6 and 3 years for the 1995–2005 and 2004–2008 periods, respectively, and a relative Doppler centroid difference below 400 Hz. The Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM) has been used. The PS selection for the estimation of displacements was based on a combination of several quality parameters including low amplitude standard deviation and high model coherence.

Even though the reference points used for both periods are not strictly the same, they were both located in nearby stable areas of Murcia City, 20 km west of Orihuela City. Considering the whole dataset for both periods, the average displacement rate of the PSs included within the stable lithologies (i.e. the mountain ranges) is below 2 mm/yr, which is the common stability threshold adopted in the scientific literature for C-band satellite sensors. Moreover, the validation experiments performed for these SPN datasets with the extensometric network of Murcia City (Herrera et al., 2009a,b; Tomás et al., 2011), provided a similar cumulative error ( $\pm 5$  mm) for both analysed periods. Thus, even though the reference point is different for each period, both datasets define the same unstable areas with the same error.

In both periods, 5730 and 4922 PS (Table 3) were detected within the City of Orihuela (280 km<sup>2</sup> area), measuring cumulated displacements between -119 mm and +67 mm (Fig. 4). Note that negative values represent subsidence and positive values surface uplift. Taking into account the validation experiment performed by Herrera et al. (2009 a, b) and Tomás et al. (2011), we define  $\pm 5$  mm as the stability range for cumulated displacements. Even if the cumulated displacements means are similar for both periods (Table 3), the displacement rate for the period 2004-2008 is almost double than for period 1995-2005 (Table. 3). Additionally, the statistical skewness (i.e. a measure of the degree of asymmetry in the distribution of sample data) reveals that the period 2004-2008 has a greater population of subsidence PS than the period 1995-2005. Hence, it can be concluded that subsidence phenomenon is more intense in the period 2004-2008.

## 4.2 Spatial analysis

Once the preliminary statistical analyses were completed, the relationship between the geo-thematic layers and the cumulative displacement was studied. Tomás et al. (2010) pointed out that the geology and the thickness of alluvial soft sediments were two important subsidence conditioning factors.

1 In order to discriminate if the geology is a factor to be considered for the A-DInSAR data  
2 interpolation, the PS data were classified in two different ways and then compared one to each  
3 other. The first one separates each period of PS in two normal populations (1st and 2nd  
4 components in Fig. 5). The probability of every PS to belong to the first or second component  
5 was computed through the Expectation-Maximization Algorithm for Mixtures of Univariate  
6 Normal function from the mixtools R package (Benaglia et al., 2009). This is an iterative  
7 process implemented in R software (R Development Core Team, 2010) which allows  
8 distinguishing the presence of sub-populations that follow a Gaussian distribution  
9 (components) within a global population. The second separates the PS located within the  
10 alluvial sediments (Holocene) and those located on the rock outcrops (Tertiary and Permo-  
11 Triassic) forming the edge of the basin (Fig. 5). In the period 1995-2005 the PS cannot be  
12 separated into two different populations attending to the component analysis (Fig. 5a), as the  
13 stable PSs are heterogeneously distributed over the study area. On the contrary, in the period  
14 2004-2008 two different normal populations can be separated (Fig. 5b) from the component  
15 analysis. The first component encloses stable PS on the stable rock outcrops, while the second  
16 component includes active PS on the younger and more compressible alluvial sediments.  
17 Consequently, through this analysis it is demonstrated that the geology is a subsidence  
18 conditioning factor. Therefore to perform PS data interpolations two different PS populations  
19 should be distinguished in each period: one in the stable sediments and another in the more  
20 deformable soft sediments.

21 The second conditioning factor pointed out by Tomás et al. (2010) was the thickness of  
22 alluvial soft sediments. Fig. 4 qualitatively shows an spatial correlation between soft soils  
23 thickness and cumulative ground displacements, in agreement with Tomás et al (2010)  
24 statements. Consequently, if a high linear correlation exists between the soft soils thickness  
25 and the ground displacements, the thickness could be used as a secondary variable to obtain a  
26 more accurate ground displacement interpolation. To evaluate if the soft soil thickness could  
27 be included as a secondary variable the Pearson correlation coefficient (McCullagh and  
28 Nelder 1989) was calculated between the displacements and the thickness of soft soils. For  
29 this purpose the elaborated soft soil thickness map described in section 2 was used. Note that  
30 the PSs not included within this map were not considered. The Pearson correlation coefficient  
31 is -0.22 and -0.52 for period 1995-2005 and 2004-2008, respectively (Appendix A). Using  
32 Kaiser's (1974) scale, the values obtained indicate that our variables have a poor linear  
33 correlation and/or other variables might also be involved. Therefore the thickness of the soft

soils cannot be considered as an additional source of information for improving the displacement data interpolation. The observed lack of high linear correlation can be explained considering that the ground displacements are the result of the combined and superposed effect of piezometric level changes and the soil thickness deformability that do not follow a linear relationship.

#### 4.3 Variogram analysis

Before obtaining the interpolation surfaces for each period, the experimental variograms and fitted models should be calculated. The libraries of R software (R Development Core Team, 2010) Gstat (Pebesma, 2004) and geoR (Ribeiro et al., 2001), combined with SGeMS software (Remy et al., 2009) were used for the displacement variogram visualization and analysis. The analysis of the experimental directional variograms, lead to the detection of anisotropy (N60E), which is assumed as the maximum spatial continuity direction. This direction coincides with the axis basin direction, this fact reinforces the idea that geology is a conditioning factor of subsidence.

The experimental and fitted variogram models obtained for the four PS populations previously defined are shown in Fig. 6 and described in Table 4. Experimental variograms for the 1995-2005 period present higher fluctuations around the sill than the ones computed for the 2004-2008 period. This behaviour can be attributed to the fact that during the period 1995-2005 the ground water level was under a recuperation phase. Hence measured subsidence rates are low and sparsely distributed and correspond to the residual consolidation of the 1992-1995 draught period. During the 2004-2008 draught period there was an intensive exploitation of the aquifer in the vicinity of Orihuela City, which induced a regional subsidence over the area. This process explains the lower spatial variability of PS displacement values, which corresponds to a lower slope of the variogram models near the origin during this period. Consequently, the analyses of the variogram models confirm a different subsidence spatial variability for each period, which corresponds to different phases (piezometric level recuperation and fall) of the subsidence phenomena.

### 5 Results and discussion

In this section, following the last two stages of the methodology presented in section 3, the regional and local subsidence activity maps are generated and discussed for both analysed periods in Orihuela city. First all, the different percentile maps are analysed. Then, the SLS

for 27 historical buildings are calculated and evaluated with the reported damages inventory. Finally a comparison is made between a damage study and the results obtained for Santas Justa and Rufina church.

## 5.1 Regional subsidence activity maps

The parameters of the four fitted models (Table 4) are introduced in the SGeMS software to generate one hundred equally likely realizations of subsidence by SGS method. As ground resolution of ERS1/2 and Envisat images is 20 m, the pixel size of the resulting surfaces has been set to 20 m. Subsidence activity maps are obtained from the SGS results. The mean of these simulations represents the expected subsidence value, which should be very similar to the result of the kriging interpolation (Figs. 7a and 8a). The spatial variability of the subsidence is evaluated calculating the variance for the 100 performed simulations (Figs. 7b and 8b). The confidence level for subsidence interpolated values is established calculating the percentiles from the 100 simulations. In our test site, 68th and 95th percentile maps are analysed for both periods (Figs. 7c, 7d, 8c and 8d). These maps display the threshold subsidence value for which there is a probability of 68% and 95%, respectively, that the true subsidence is greater or equal to that threshold. Note that greater subsidence means a more negative value. Visually during the period 1995-2005, 68th and 95th percentile maps are the same, being their average cumulated subsidence -17 mm. Note that the mean, which represents a 50% confidence level, exhibits an average cumulated displacement of -36 mm that is closer to the average of the PS dataset (-47 mm). This fact suggests that the mean is the best estimator to elaborate subsidence activity maps in this period.

Concerning the period 2004-2008, 68th and 95th percentiles differ substantially from each other, visually and numerically, with an average cumulated subsidence of -47 mm and -31 mm, respectively. The latter represents very low subsidence values compared to the -47 mm average cumulated subsidence of the PSs (sampled data), which is closer to the value of the 68th percentile map. Consequently, the 68th percentile is selected to elaborate the subsidence activity map during the period 2004-2008, providing a 68% confidence level, and the mean for the period 1995-2005 that provides a 50% confidence level on the interpolation.

Analysing the subsidence activity maps generated with the highest confidence level (Fig 7a and Fig 8c), a lower and a more localized subsidence is shown in period 1995-2005 than in period 2004-2008, when a greater and more extended subsidence occurred. This observation

is explained by the higher spatial variability (subsection 4.3) estimated during the first period (variance between 0 and 473.07 mm<sup>2</sup>) than during the second one (variance between 0 and 387.83 mm<sup>2</sup>). Overall, the geostatistical analysis agrees with the fact that during 2004-2008 there was a widespread subsidence due to water withdrawal, whereas for period 1995-2005 a more heterogeneous subsidence was due to the groundwater level recuperation.

## 5.2 Local subsidence activity maps

The purpose at this stage is to identify those building susceptible to suffer damage induced by subsidence based on subsidence activity maps. Following the service limit state (SLS) assessment methodology proposed in section 3, maximum differential settlements and maximum angular distortions along the LOS are calculated for the 27 historical building of Orihuela city and compared with allowable values. The buffer area used in this case study is 14 m as the pixel size of the subsidence activity maps is 20 m. Note that for this resolution only 5 pixels are considered for the SLS calculation of two buildings (22 and 23 in Table 5) due to their small area. In both cases, predictions might not be accurate enough and a higher resolution would be required. The results calculated for the remaining buildings indicate if the adopted SLS criteria exceed or not the values shown in Table 1. They represent the local subsidence activity map (Fig. 9). In these maps it is observed that the direction of both the maximum angular distortion (Fig. 9c and 9d) and the maximum differential settlement (Fig. 9a and 9b) is mainly radial to the Mesozoic reliefs dipping towards the thickest compressible sediments

According to SLS results (Table 5) expected damage in the period 1995-2005 affects almost twice the number of buildings than in the period 2004-2008. This is due to the more heterogeneous and variable spatial distribution of 1995-2005 displacements, which favours the existence of greater differential settlements and angular distortion. Unfortunately, the lower confidence degree (50%) obtained in 1995-2005 subsidence activity map could bias the calculation of the maximum differential settlement and the maximum angular distortion along LOS ( $\delta_{\text{max-LOS}}$ ,  $\beta_{\text{max-LOS}}$ ). On the other hand, the greater confidence degree (68%) and the lower variance obtained for the 2004-2008 subsidence activity map provides a more reliable calculation of the service limit state variables.

In the past two decades, damages have been reported at least in 10 historical buildings. For the rest of the buildings there is not available information about occurred damages. A

description of reported damages can be found in López (1992), Louis et al. (2005, 2012), Lara (2003), Maciá (2005) and Tomás et al. (2012). This damage description has been complemented with field visits to damaged buildings during the period 2011-2013. The year of the repairing and/or stabilization works (Table 5) is a key parameter because, after a repairing action previous damage cannot be identified in field surveys. Most of the repairing actions consist on the replacement of the pavement, the sealing and filling of cracks and the elimination of capillary ascent moistures and leaks (Louis et al., 2012; Lara 2003). However, these actions do not strengthen the foundation of the buildings and further settlements could reopen previous existing cracks or generate new ones. Taking into account that some buildings (e.g. buildings 1 and 6 in Table 5) have been completely or partially underpinned, thus, low displacements and damages are expected after the repairing action. Additionally, we have to consider that damages are repaired in different phases that can extend over years, acting on different parts of the building (e.g. in Santas Justa y Rufina church the foundation was only partially underpinned and part of the church is still supported by the old foundation). Considering the heterogeneity of the available information and the previously mentioned constrains that can distort the interpretation of the results, reported damages (Table 5) have only been used for a qualitative evaluation of local subsidence activity maps. Whatsoever, 100% of the buildings (over 10) where damages have been reported exhibit “medium” to “high” level of expected damages according to SLS calculations. Note that during the 1995-2005 period 90% of the buildings (over 10) exceeded the allowable SLS while for the 2004-2008 period this rate dropped to 50% of the buildings (over 10). In this context, damages observed on several buildings (2, 3, 4, 6, 9, 10, 13 and 20) can be attributed to cumulated subsidence during both periods, since no restoration activities have been performed. For these buildings subsidence activity maps show a good agreement with the observed damage, since the SLS threshold values were exceeded at least in one of both periods.

SLS values calculated for building 1 were only exceeded during the period 1995-2005 and coincide with reported damages on 2003 (Table 5). Recent field work permitted to attest that damages in this building did not persist in time since gypsum plaster markers located in the cracks have been intact since the building was underpinned. In the case of building 17, allowable SLS values were exceeded during both periods, even if a good overall condition was recognised during recent field work. This mismatch is explained by the building restoration in 2009. Additionally López (1992) recognized numerous damages that could be

related to “medium” and “high” expected level of damage calculated for 1995-2005 and 2004-2008 periods, respectively.

Analyzing those buildings where no information about their SLS state could be gathered, buildings 12 and 15 (Table 5) show in both periods, “high” or “medium” expected level of damage and should be considered as priority target in future field works. A second target would be formed by nine buildings (7, 8, 11, 15, 19, 21, 22, 25, and 26 in Table 5) with a “high” or “medium” expected level of damage. The remaining buildings (5, 16, 18, 23, 24 and 27 in Table 5) do not show potential of being damaged and should be inspected in the last stage. Thus with this methodology, two groups of problematic buildings could be identified, establishing priorities for further inspections.

### 5.3 Analysis of Santas Justa and Rufina church

A more detailed analysis of the local subsidence activity map is carried out in Santas Justa and Rufina church, where a forensic analysis is available. Santas Justa and Rufina church is located on the north bank of Segura River in the centre of Orihuela City (Fig. 7 and 8). It was declared a Spanish National Monument in 1971. During the last 20 years damages induced by regional subsidence are affecting the structural elements of this church (Fig. 10). Tomás et al. (2012) performed a detailed analysis of the damage suffered by the building summarized here. In the 70s the principal chapel suffered an important tilt (Fig. 10). In the 90s, important settlements affected the San José chapel and the foundation was reinforced in 2002 with micropiles. In the first decade of the present century, displacements affected the whole north zone of the church and the principal chapel area. Multiple cracks were identified in the north, west, and east walls, affecting as well La Comunión cupola (Fig. 10a), the sacristy and the antesacristy (Fig. 10c). Several plaster markers were placed in the cracks in 2006 and controlled in 2008 (Fig. 10b). Fig. 10 shows that multiple cracks grew up during this period as a consequence of the sinking of the foundation walls caused by ground subsidence.

Subsidence activity maps, maximum differential settlement and maximum angular distortion along the LOS, of Santas Justa and Rufina church are shown in Fig. 11. The average cumulated displacements are -39.2 mm and -31.9 mm for 1995-2005 and 2004-2008 periods, respectively, but a greater variance is appreciated for the first period. The maximum angular distortion shows medium (1995-2005) to high (2004-2008) values. Note that during the first period, the maximum angular distortion is located NE of the church, mainly affecting the



main chapel. On the other hand, it is observed that during the second period the maximum angular distortion is located SW of La Comunión chapel. The orientation of the two vectors representing the maximum angular distortion is E-W, which is in agreement with the location of reported damages (Fig. 11). Concerning the maximum differential settlement, the vector direction (NE-SW) is the same for both periods. This would indicate that the church would have tilted towards the SW and as a consequence the cracks direction (normal to tension stresses) are expected to be oriented from NW to SE, coinciding with the reported damages (Fig. 11). Even if the 23.01 mm threshold has been not exceeded in each period, and taking into account that the direction of both vectors is similar, the combination of them both yields a 34 mm maximum differential settlement. One can say that the reported damages match, spatially and temporally, with the calculated SLS.

## 6 Conclusions

This work proposes a novel method to produce subsidence activity maps based on the geostatistical analysis of persistent scatterer interferometry (PSI) displacement data. These maps permit to identify widespread subsiding areas and buildings where damages could be produced, providing a useful tool for local authorities planning and management activities. However derived results cannot be exploited in an isolated way. They need to be combined with in situ field data to confirm the potential levels of damage. The methodology has been tested in 27 historical buildings of Orihuela city (SE Spain), which have been damaged in the past decades due to subsidence triggered by ground water overexploitation.

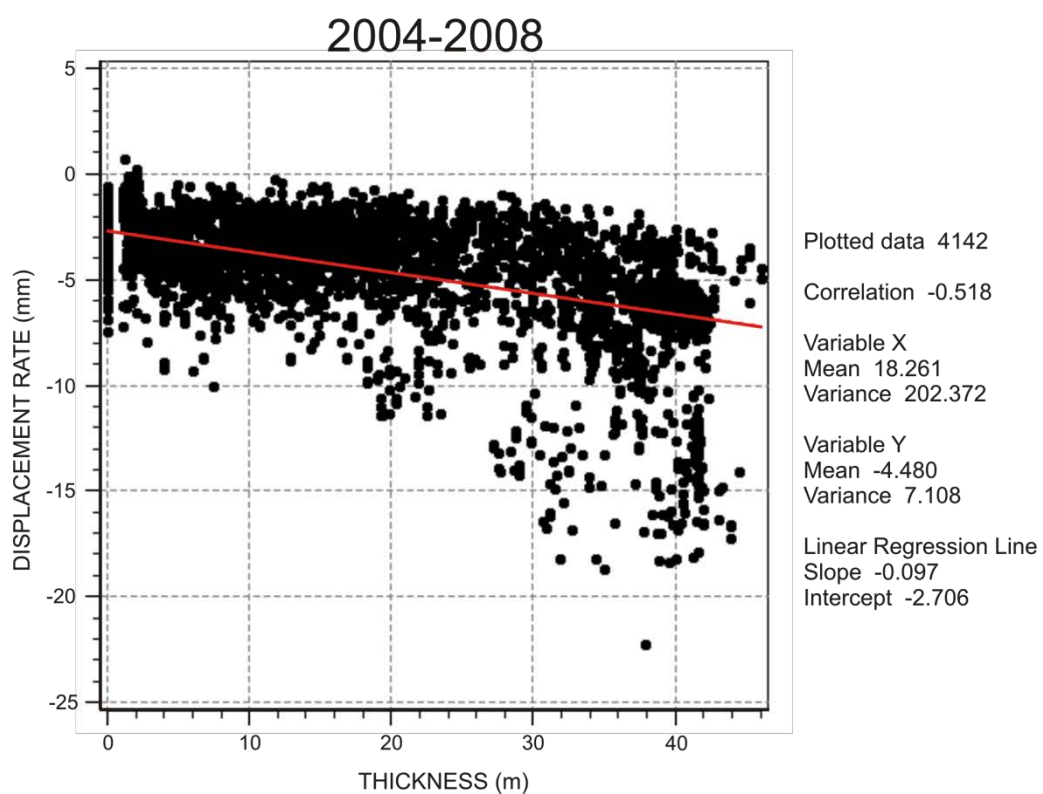
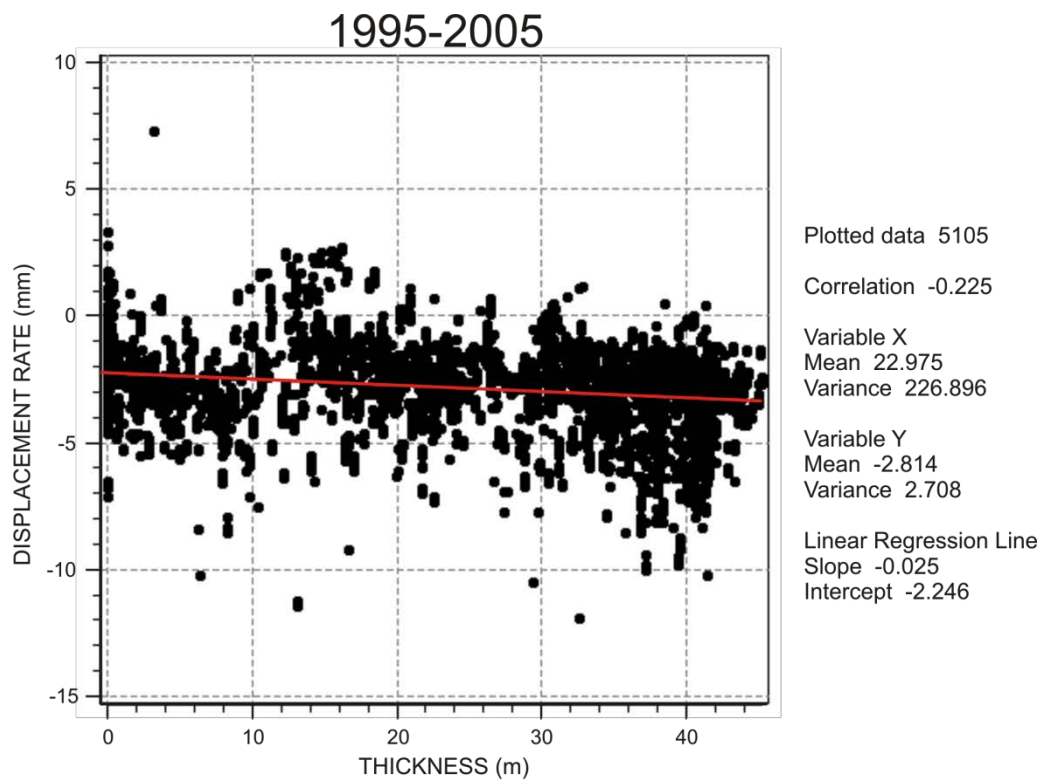
The spatial analysis and directional variograms revealed that geology is a subsidence conditioning factor that should be taken into account when performing a geostatistical analysis. The variograms fitted models differ for each period, confirming a different spatio-temporal subsidence behaviour, which is explained by groundwater level changes during droughts. The Conditional Sequential Gaussian Simulation (SGS) provided realistic subsidence estimations including the evaluation of its confidence degree level and its spatial variability.

In this case study, regional subsidence activity maps revealed a lower and heterogeneous subsidence for the period 1995-2005, being more intense and homogeneous for the period 2004-2008. On the other hand, local subsidence activity maps permitted to identify buildings susceptible to suffer damages through the calculation of the serviceability limit state (SLS) parameters: the differential settlement and the angular distortion. In 27 historical buildings of

1 Orihuela city, SLS results have been compared with reported damages and field checks  
2 available for 10 buildings, showing a 100% success rate. Additionally, SLS allowed for  
3 distinguishing two groups of potentially damaged buildings, permitting to establish an  
4 inspection priority in agreement with the expected level of damage.

5 The accuracy of the SLS prediction is limited by the satellite resolution and the area of the  
6 targeted buildings. Therefore, even though average resolution satellite PSI displacement data  
7 was used in this work (ERS & ENVISAT), better results are foreseen using high resolution  
8 satellite sensors (TerraSAR-X, Cosmo-SkyMed, Sentinel).

- 1 **Appendix A: Scatter diagrams between the average displacement and the soft**
- 2 **soils thickness for both periods.**



- 3
- 4

1 **Appendix B: List of processed SAR images.**

DATE	SENSOR	DATE	SENSOR	DATE	SENSOR	DATE	SENSOR
21/07/1995	ers1	18/12/1999	ers2	18/10/2003	envi	17/09/2005	envi
26/08/1995	ers2	22/01/2000	ers2	18/10/2003	ers2	22/10/2005	ers2
30/09/1995	ers2	26/02/2000	ers2	22/11/2003	ers2	26/11/2005	envi
04/11/1995	ers2	01/04/2000	ers2	27/12/2003	ers2	26/11/2005	ers2
26/04/1996	ers1	06/05/2000	ers2	31/01/2004	ers2	31/12/2005	envi
19/10/1996	ers2	15/07/2000	ers2	31/01/2004	envi	31/12/2005	ers2
23/11/1996	ers2	19/08/2000	ers2	06/03/2004	envi	11/03/2006	ers2
12/04/1997	ers2	23/09/2000	ers2	10/04/2004	ers2	15/04/2006	envi
17/05/1997	ers2	28/10/2000	ers2	15/05/2004	envi	20/05/2006	ers2
26/07/1997	ers2	02/12/2000	ers2	15/05/2004	ers2	24/06/2006	ers2
30/08/1997	ers2	06/01/2001	ers2	19/06/2004	ers2	02/09/2006	envi
04/10/1997	ers2	04/08/2001	ers2	19/06/2004	envi	07/10/2006	envi

08/11/1997	ers2	08/09/2001	ers2	24/07/2004	ers2	11/11/2006	ers2
17/01/1998	ers2	13/10/2001	ers2	28/08/2004	ers2	31/03/2007	envi
28/03/1998	ers2	17/11/2001	ers2	02/10/2004	ers2	31/03/2007	envi
11/07/1998	ers2	22/12/2001	ers2	06/11/2004	ers2	05/05/2007	envi
19/09/1998	ers2	02/03/2002	ers2	11/12/2004	ers2	18/08/2007	envi
28/11/1998	ers2	06/04/2002	ers2	11/12/2004	envi	05/01/2008	envi
13/03/1999	ers2	11/05/2002	ers2	15/01/2005	envi	09/02/2008	envi
17/04/1999	ers2	15/06/2002	ers2	19/02/2005	envi	15/03/2008	envi
22/05/1999	ers2	20/07/2002	ers2	19/02/2005	ers2	24/05/2008	envi
30/07/1999	ers1	24/08/2002	ers2	26/03/2005	envi	28/06/2008	envi
31/07/1999	ers2	28/09/2002	ers2	26/03/2005	ers3	28/06/2008	envi
03/09/1999	ers1	02/11/2002	ers2	30/04/2005	envi	02/08/2008	envi
04/09/1999	ers2	11/01/2003	ers2	04/06/2005	ers2	06/09/2008	envi
09/10/1999	ers2	22/03/2003	envi	09/07/2005	ers2	11/10/2008	envi

13/11/1999	ers2	26/04/2003	ers2	13/08/2005	ers2	15/11/2008	envi
		13/09/2003	ers2			20/12/2008	envi

1

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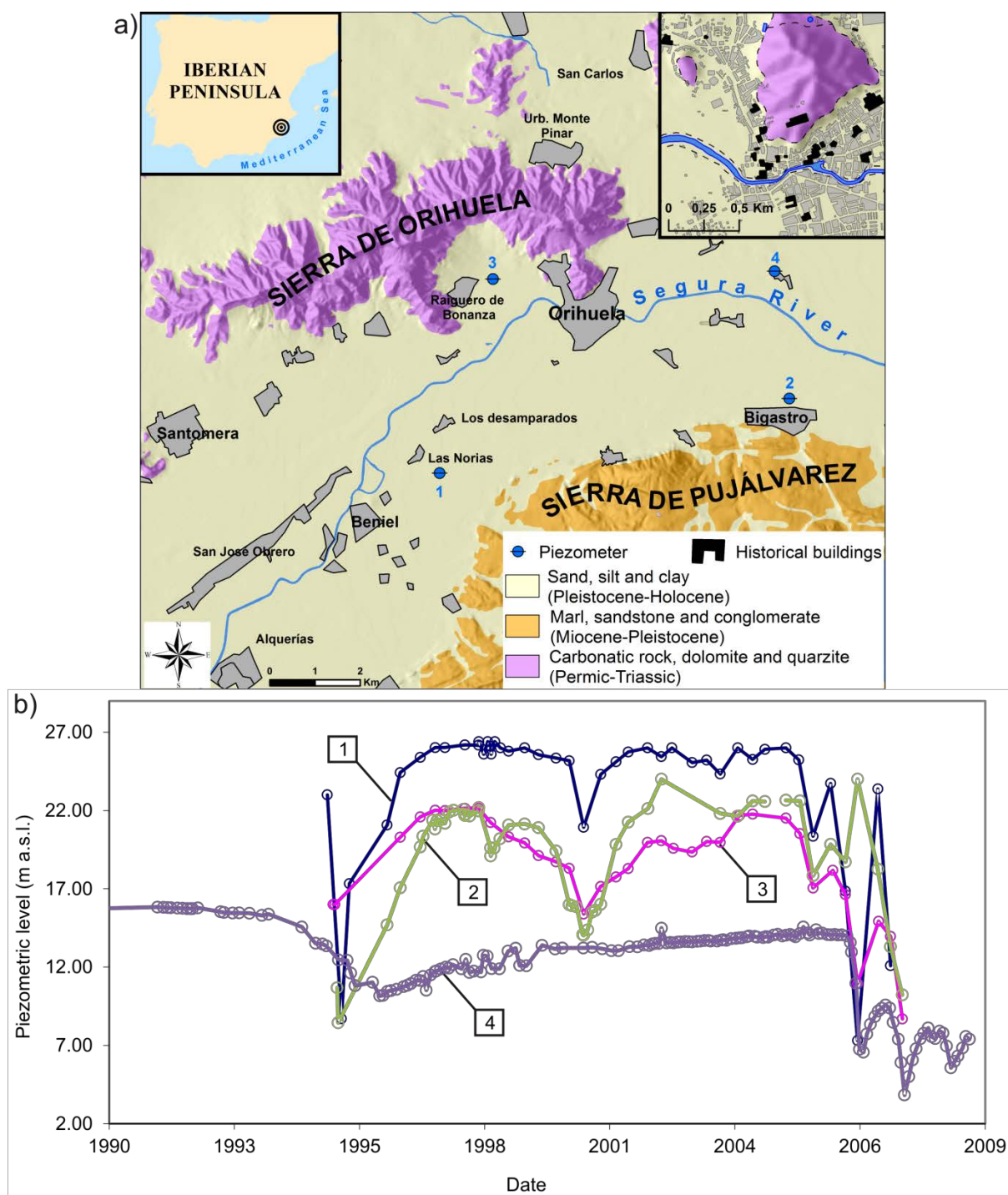
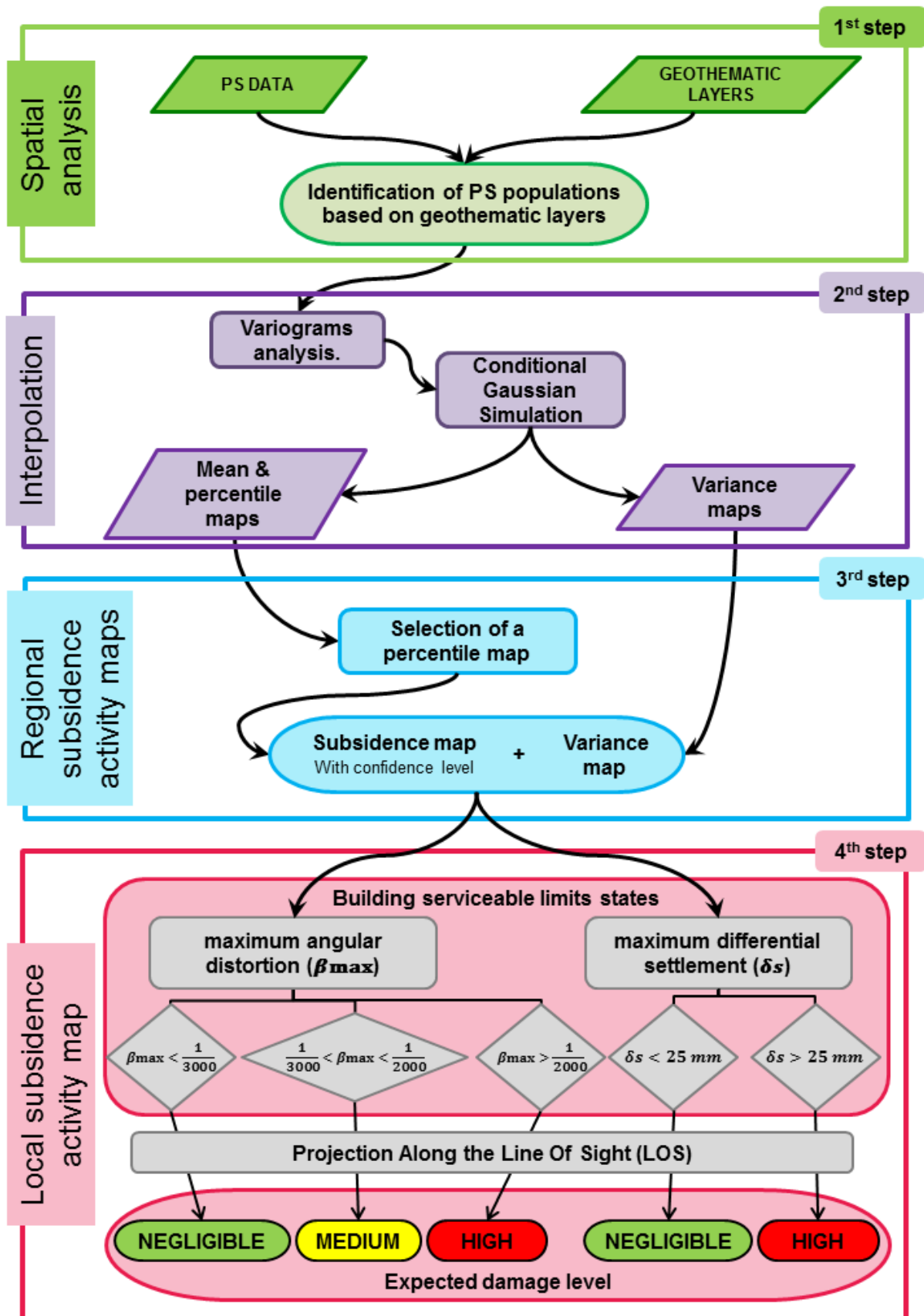


Figure 1. (a) Location and geology of the study area. (b) Piezometric level evolution for the study period.



1  
2 Figure 2. Proposed methodology for the elaboration of subsidence activity maps

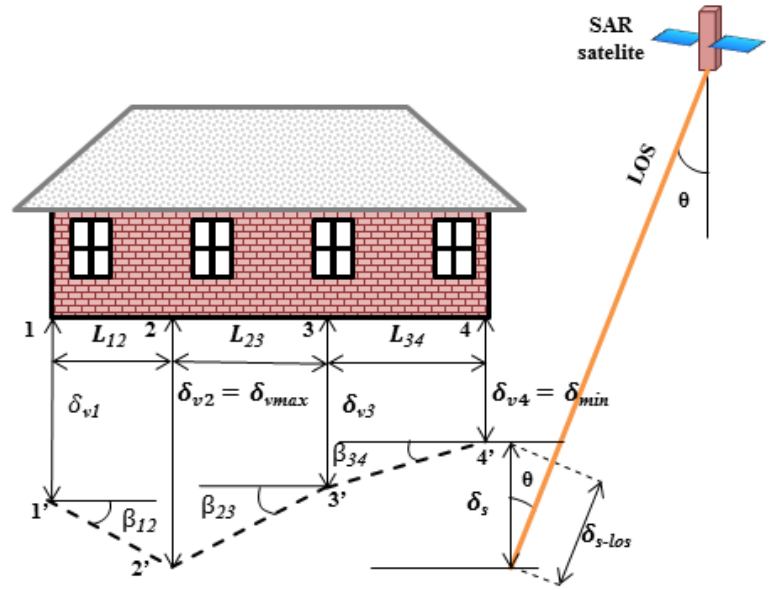
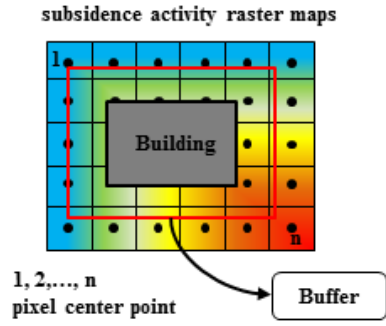
1 Table 1. Adopted SLS criterion for the performed analysis.

Expected structural damage level due to foundation settlements	Maximum angular distortion ( $\beta_{\max}$ )	Maximum differential settlement ( $\delta_{\max}$ )	Maximum angular distortion projected along the LOS, $\beta_{\max-\text{LOS}}$ (eq. (6))	Maximum differential settlement projected along the LOS, $\delta_{\max-\text{LOS}}$ (eq. (4))
Negligible	$<1/3,000$	$< 25 \text{ mm}$	$<. 3.07 \times 10^{-4}$	$< 23.01 \text{ mm}$
Medium	$1/3,000-1/2,000$	----	$3.07 \times 10^{-4} - 4.60 \times 10^{-4}$	----
High	$>1/2,000$	$> 25 \text{ mm}$	$> 4.60 \times 10^{-4}$	$> 23.01 \text{ mm}$

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2

3 Figure 3. Schematic explanation of the serviceability limit states parameters adopted in the

4 analysis.

5

- 1 Table 2. Main characteristics of the processed data stacks of the westernmost sector of the
- 2 Vega Baja of the Segura River:  $\lambda$ , wavelength;  $\theta$ , look angle; Desc, descending.

Data Stack	$\lambda$ (cm)	Orbit	$\theta$ (°)	Repeat cycle (days)	Ground range resolution (m)	Time interval	Number of scene	Processing technique	PS density (PS/km <sup>2</sup> )	Georeference accuracy (m)
ERS1/2	5.6	Desc	23	35	20	21/07/1995- 22/10/2005	84	SPN	117	5
ERS2 ENVISAT						31/01/2004- 20/12/2008	50		50	3

- 3
- 4

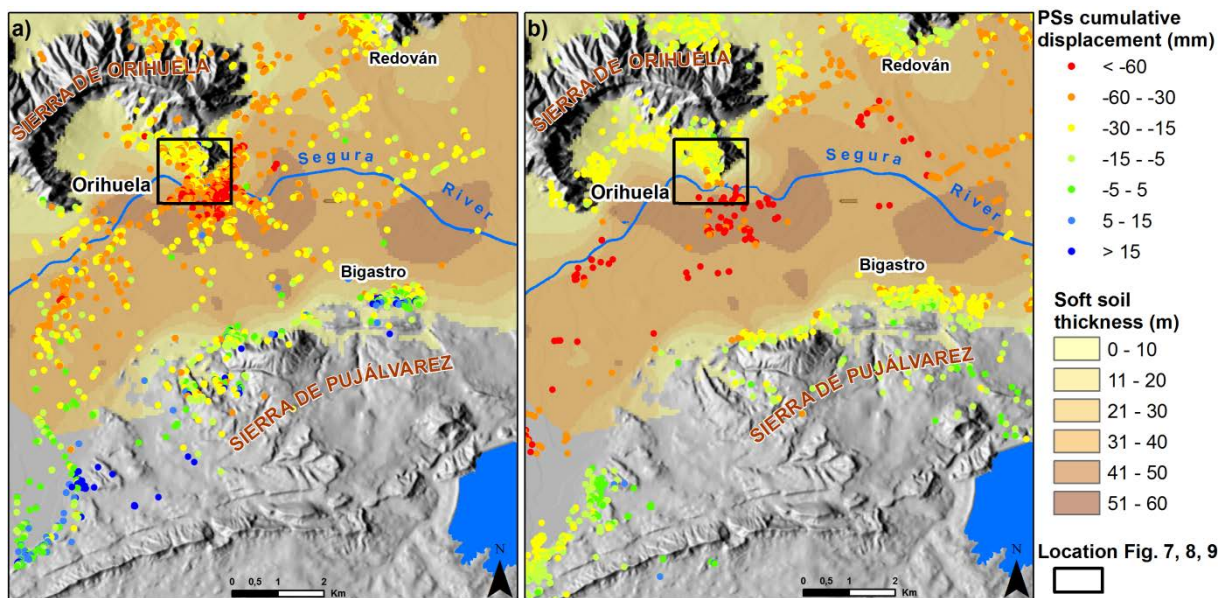


Figure 4. Cumulative displacement (mm) along the LOS superimposed to soft soil thickness for both processed periods: a) 1995-2005 and b) 2004-2008.

1

2 Table 3 Descriptive statistical measurements for both periods.

	N° of PS	PS density (PS/km <sup>2</sup> )	Minimum (mm)	Maximum (mm)	Cumulated displacements mean (mm)	Displacement mean (mm/yr)	Standard deviation (mm)	Skewness
1995- 2005	5730	20.46	-118.88	66.78	-24.91	-2.45	21.14	-0.07
2004- 2008	4922	17.58	-109.30	12.35	-20.76	-4.28	13.23	-1.85

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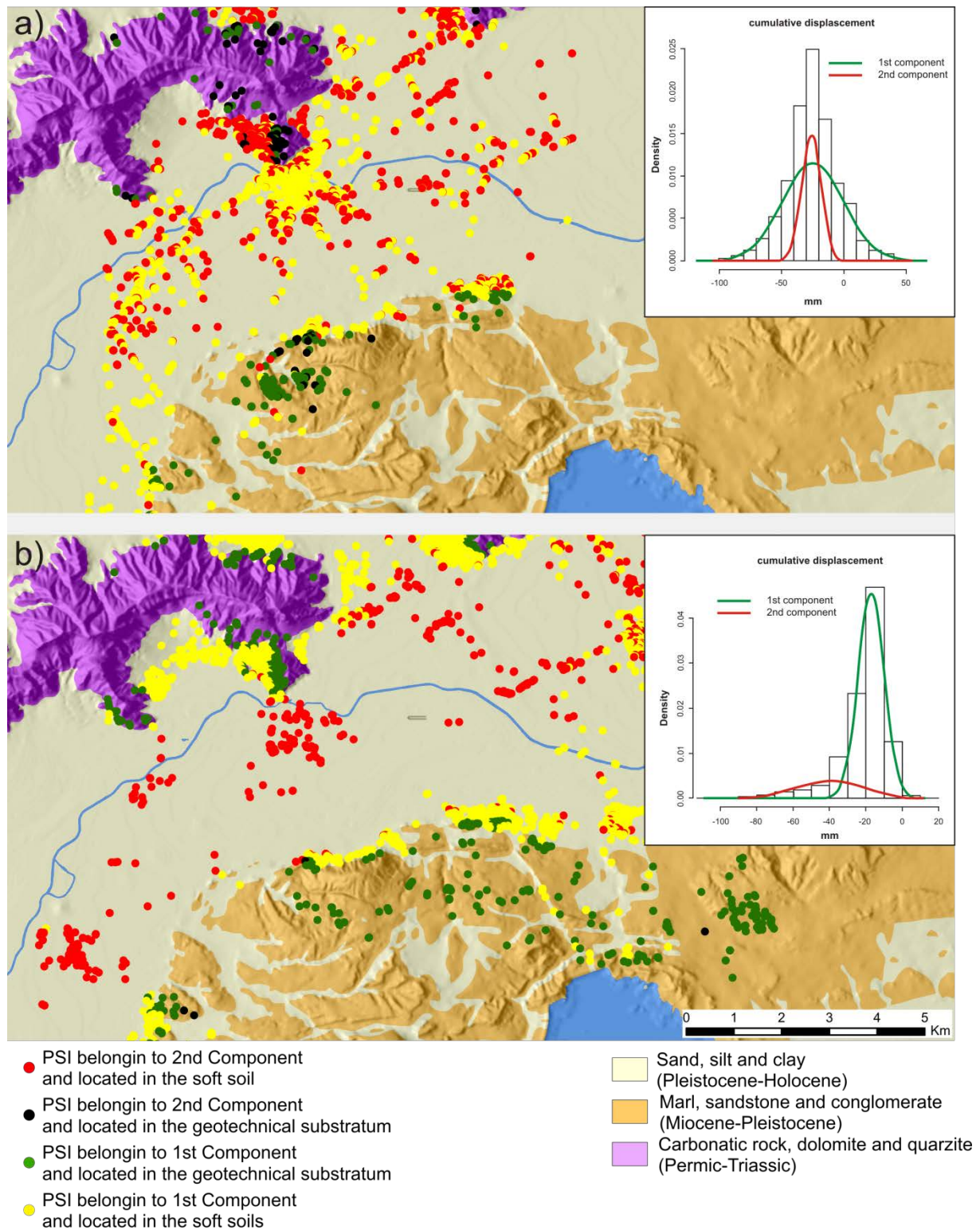
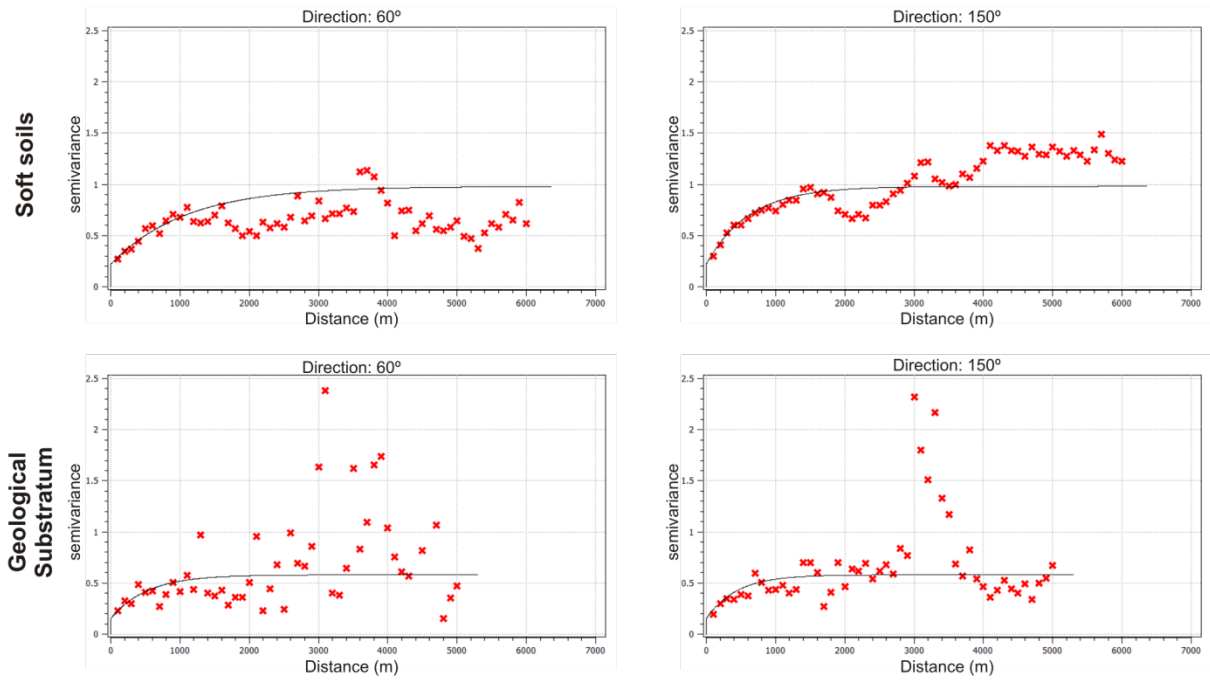
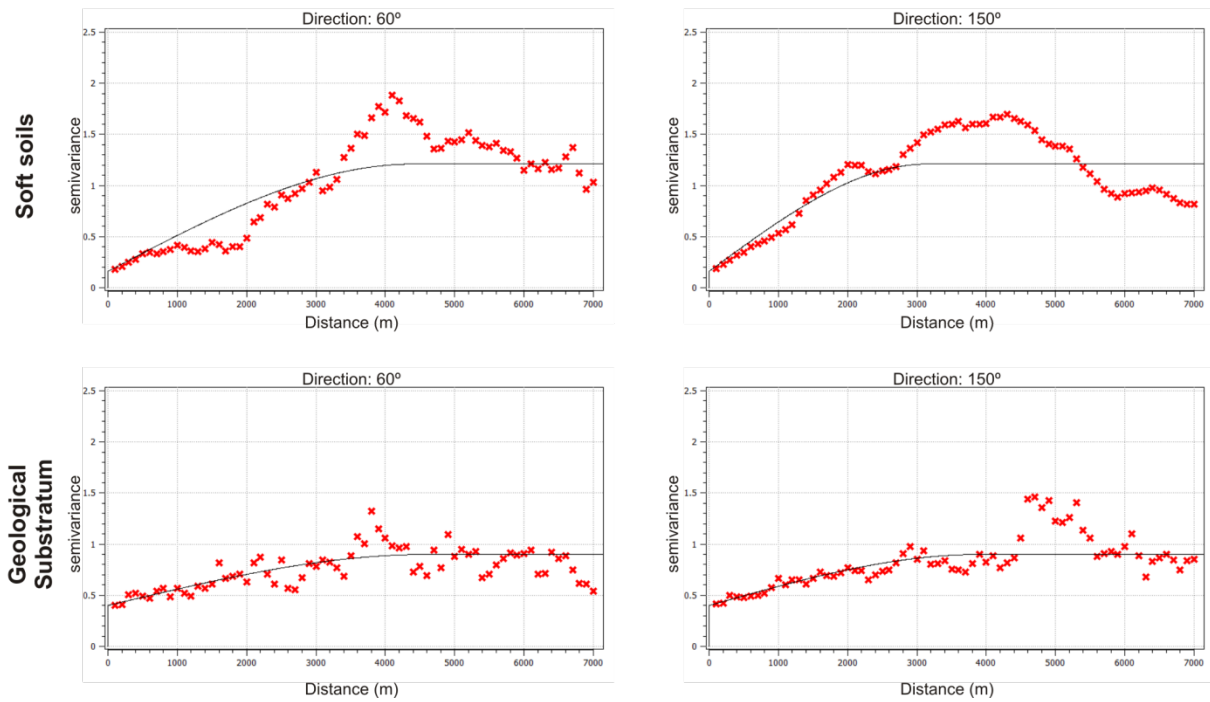


Figure 5. PS classification according to normal distributions (1st component and 2nd component) and geological criteria for both studied periods: a) 1995-2005 and b) 2004-2008.

## Period 1995-2005



## Period 2004-2008



1

2 Figure 6. Experimental variograms with fitted theoretical model in 60° and 150° direction  
3 (angles are counted from the North increasing clockwise).

4

1 Table 4. Parameters of the variogram models for each normalized PS data group.

Period	Geology	Model	Nugget	Partial Sill	Effective Range 60°	Effective range 150°
1995-2005	Soft soils	Exponential	0.22	0.76	3240	1860
	Geotechnical Sustratum	Exponential	0.15	0.43	1550	1300
2004-2008	Soft soils	Spherical	0.16	1.05	4410	3150
	Geotechnical Sustratum	Spherical	0.4	0.5	4620	3920

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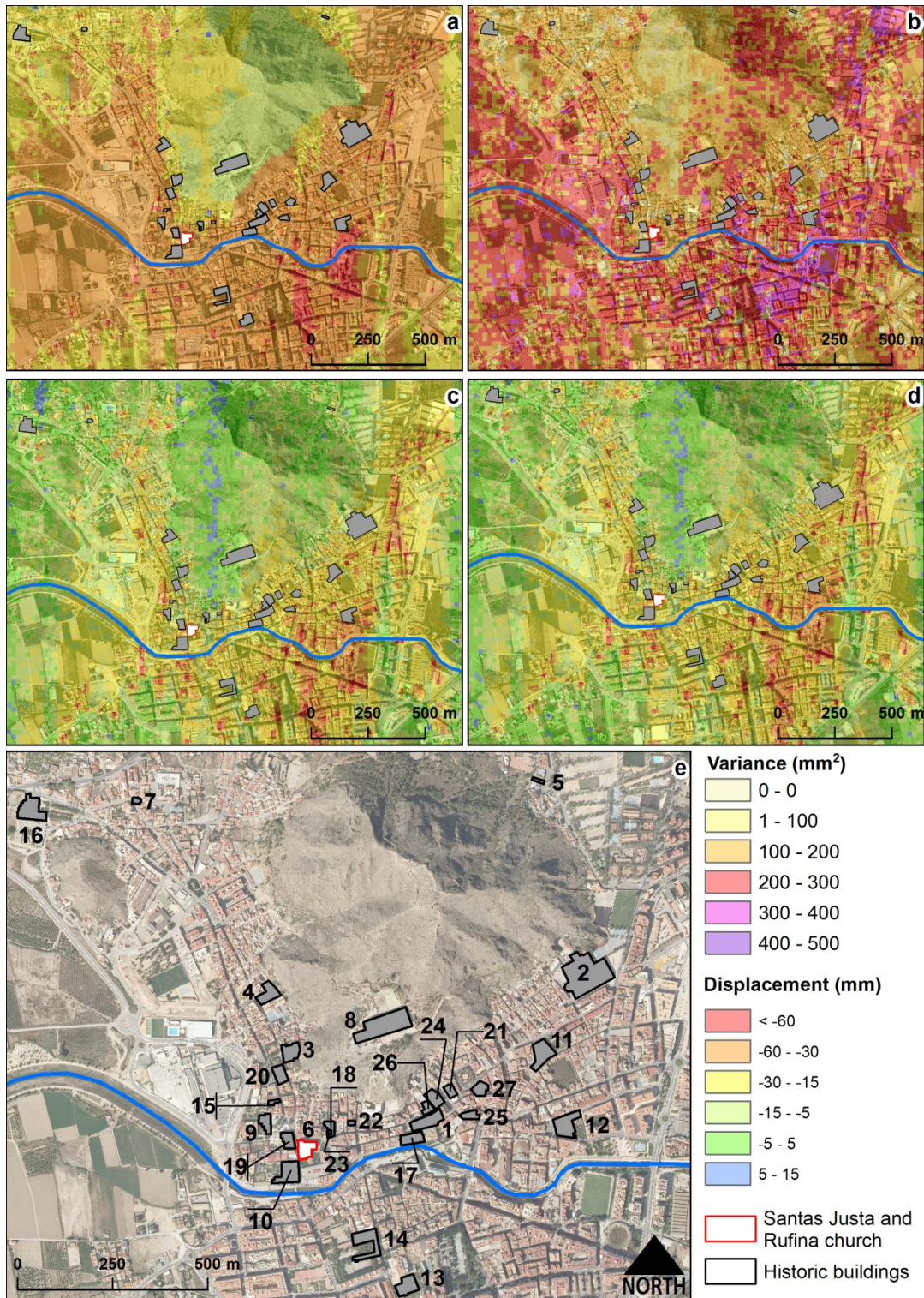


Fig. 7. Sequential Gaussian conditional simulations results for 1995 -2005 period: a) Mean; b) Variance; c) 68th percentile; d) 95th percentile; and e) location of historic buildings listed in Table 5.



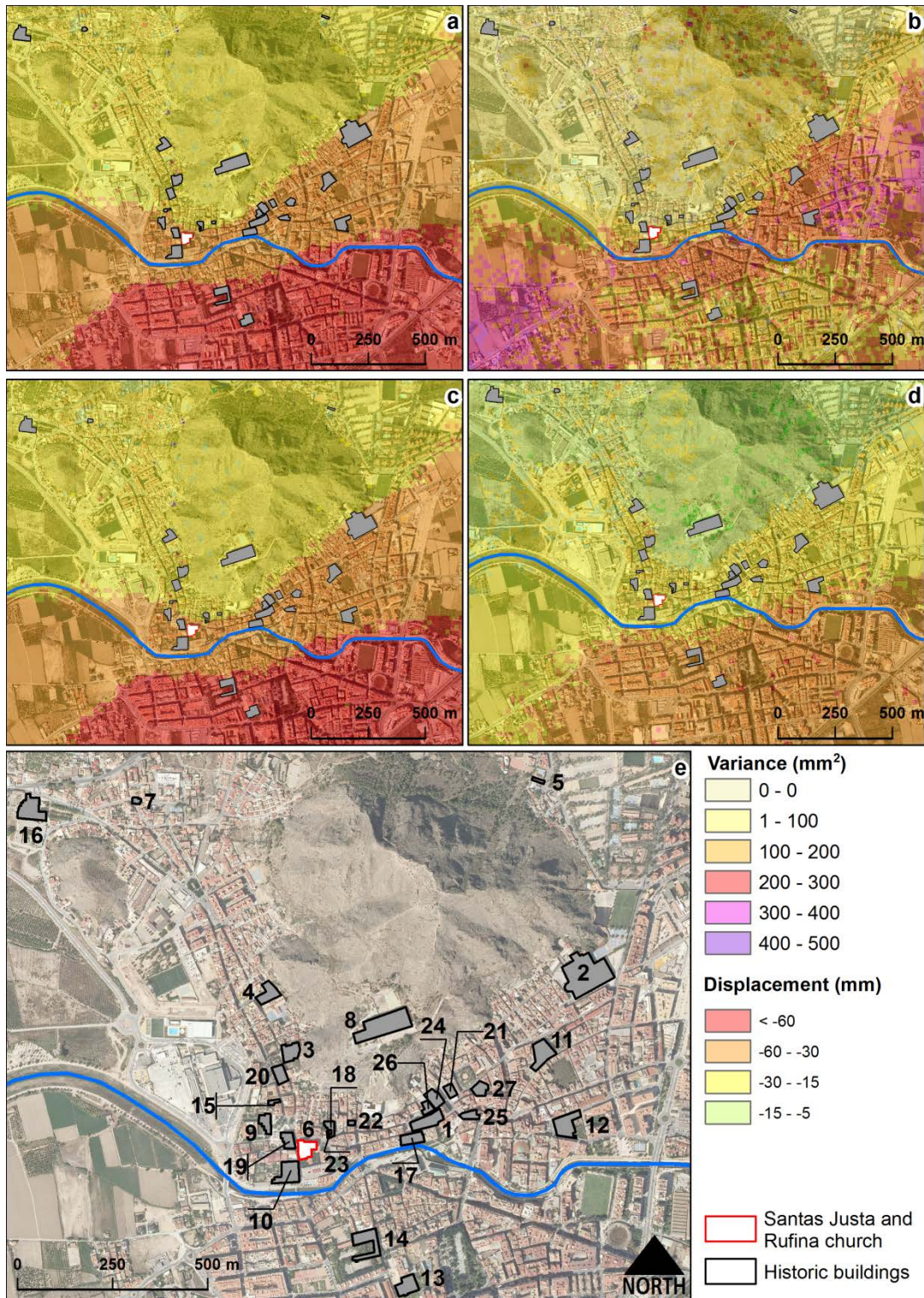


Fig. 8. Sequential Gaussian conditional simulations results for 2004-2008 period: a) Mean; b) Variance, c) 68th percentile; d) 95th percentile; and e) location of historic buildings listed in Table 5.



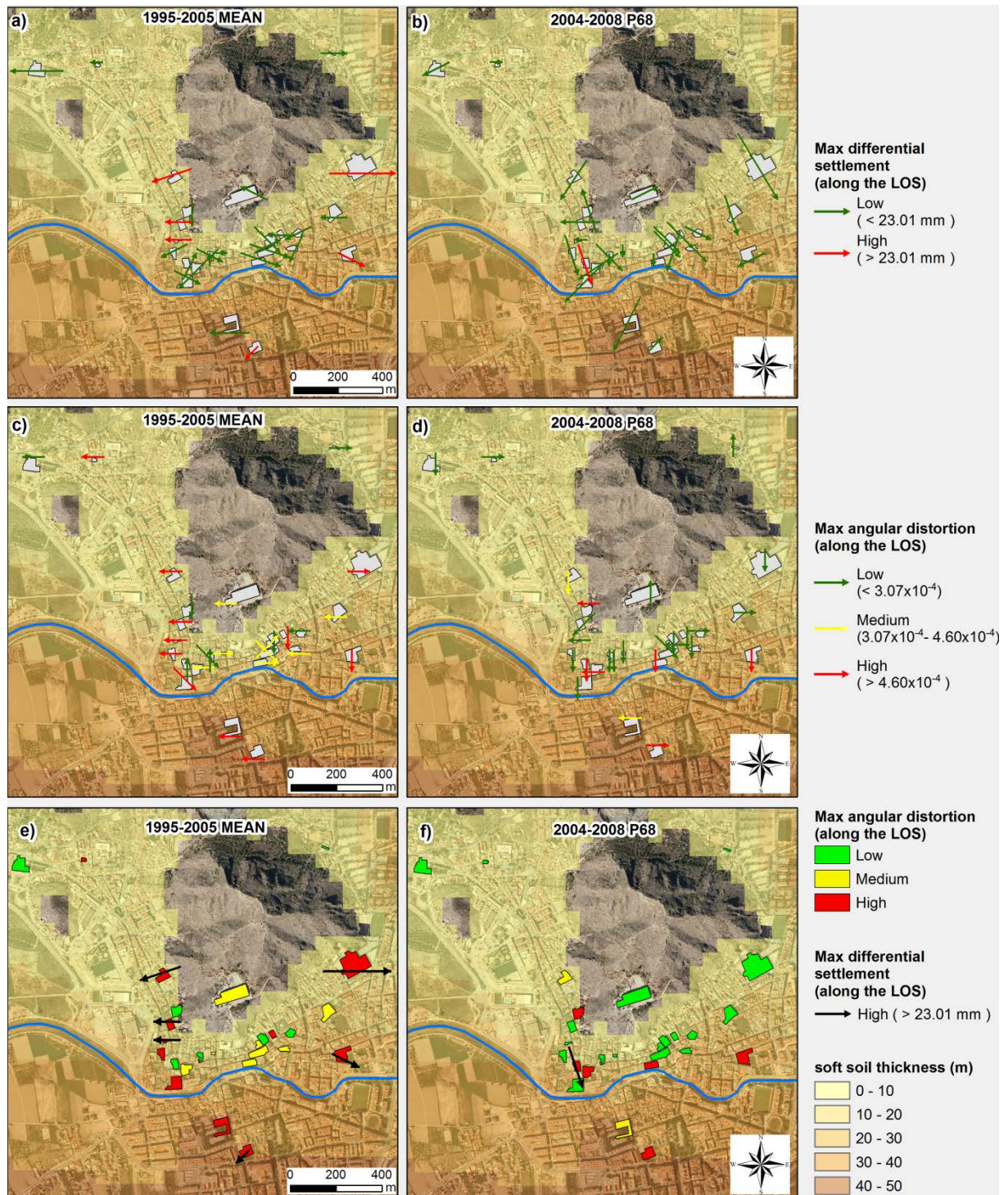


Figure 9. Local subsidence activity maps for both studied periods. Notice that the used interpolation surfaces are the mean and the 68th percentile for 1995-2005 and the 2004-2008 periods respectively.

1 Table 5. Inventory of historical buildings from Orihuela city. See buildings location in figure 8. Note that angular distortions ( $\beta_{\max\text{-LOS}}$ ) and  
2 ( $\delta_{\max\text{-LOS}}$ ) values provided by InSAR for both periods have been classified using a traffic light colour scale according to Table 1. NA: Not  
3 available; R: Renaissance; G: Gothic; B: Baroque; N: Neoclassical; U: Unknown. (\*) Total or partial underpinned foundation.

Id (Figs. 7 and Fig. 8)	Name of the building	Century	Style	Area (m <sup>2</sup> )	PERIOD 1995-2005		PERIOD 2004-2008		Structural damage general description (performed between 2011 and 2013)	Year of repairing and / or stabilization works	Reference
					$\delta_{\text{s-LOS}}$ , mm (Mean)	$\beta_{\max\text{-LOS}}$ (Mean)	$\delta_{\text{s-LOS}}$ , mm (P68)	$\beta_{\max\text{-LOS}}$ (P68)			
1	Santa Iglesia Catedral del Salvador	XIV	G, R	2473.53	15.62	$4.43 \times 10^{-4}$	6.32	$1.77 \times 10^{-4}$	Cracks (up to 2 cm width) in internal and external walls, in the ceiling and in a cupola. There are uncracked plaster markers. The S and W façades exhibit apparently ancient tilts.	1990, 2002(*)	Lara (2003) and field work
2	Colegio Diocesano Santo Domingo	XVI	R	9962.95	27.51	$9.43 \times 10^{-4}$	9.42	$1.89 \times 10^{-4}$	Cracks in internal and external walls of the cloister (up to 6 cm in the refectory). Most of the cylindrical vaults from the corridors also present milimetric to submilimetric fissures. The annexed church presents a clearly ancient tilt. Some plaster markers placed in the cloister in 2000 are uncracked.	2002 (only the Comunión Chapel was repaired)(*)	Lara (2003), Maciá (2005) and field work
3	Iglesia Parroquial de Santiago Apostol	XV	G	1881.50	4.96	$1.94 \times 10^{-4}$	16.35	$7.63 \times 10^{-4}$	Good overall condition. Most of the damage are located on the SW corner and consists on cracks and fissures affecting the walls and the ceiling.	1993, 2002 (*)	Lara (2003) and field work
4	Santuario de Nuestra Señora de Monserate	XVII	B	2031.75	26.97	$7.54 \times 10^{-4}$	14.43	$4.34 \times 10^{-4}$	Cracks on the bell towers, the internal and external walls, in the vaults and cupolas.	None	Field works
5	Iglesia Parroquial de	XVIII	B	263.88	5.64	$2,27 \times 10^{-4}$	0.63	$3.17 \times 10^{-5}$	NA	NA	

	San Antón										
6	Santas Justa and Rufina church	XIV	G	1880,13	15.18	$3.99 \times 10^{-4}$	19.16	$6.41 \times 10^{-4}$	Millimeter to centimeter cracks on the internal and external walls from the main building. The eastern wall presents an ancient tilt. The cupola from the Comunión chapel presents a centimetric crack.	1970, 2002, 2010(*)	Lara (2003) and Tomás et al. (2012)
7	Ermita del Santo Sepulcro	XVII	B	348,74	9.65	$4.82 \times 10^{-4}$	1.60	$8.00 \times 10^{-5}$	NA	NA	
8	Seminario Diocesano de San Miguel	XVIII	B	6933,81	9.99	$3.53 \times 10^{-4}$	5.50	$2.42 \times 10^{-4}$	NA	NA	
9	Iglesia y convento del Carmen	XVIII	B	1230,62	19.41	$4.98 \times 10^{-4}$	4.08	$1.49 \times 10^{-4}$	Cracks on the external walls from the main building. The number of cracks (with a submillimeter width) increases in the internal face of the walls. Most of the cylindrical vaults present submillimetric-milimetric fissures. There are some uncracked plaster markers placed in 2007.	1986, 2004	Field works
10	Real Monasterio de las Religiosas Salesas	XVIII	N	2895,02	20.10	$5.67 \times 10^{-4}$	6.78	$2.08 \times 10^{-4}$	45º cracks (with a subcentimetric width) on the façades from the main building coinciding with the windows corners. Inside the building, Louis (2005) described important irregularities caused by ground settlements in the pavement of the convent which were repaired in 2008.	2008	Louis (2005) and field work
11	Monasterio de San Juan Bautista de la Penitencia	XV	B	2840,28	14.72	$4.43 \times 10^{-4}$	6.10	$1.98 \times 10^{-4}$	NA	NA	
12	Monasterio de la Santísima Trinidad	XVI	R	3110,35	33.52	$1.62 \times 10^{-3}$	15.10	$4.79 \times 10^{-4}$	NA	NA	
13	Monasterio de San Sebastián	XVI	R, B	2254,29	23.50	$1.11 \times 10^{-3}$	13.78	$5.51 \times 10^{-4}$	Cracks in the cylindrical vaults, the copulas from the main building and the walls repaired in 1987. Local settlements of the pavement. (Data	1978, 1987, 2008	Louis et al. (2012); Lara (2003)



									reported in 2008 by Louis et al. (2012))		
14	Colegio de Jesús-María	XIV	G, N	3140,66	15.67	$5.31 \times 10^{-4}$	13.44	$3.21 \times 10^{-4}$	NA	NA	
15	San Juan de Dios	XVI	B, N	307,32	27.50	$1.10 \times 10^{-3}$	1.49	$7.45 \times 10^{-5}$	NA	NA	
16	Convento de San Francisco	XVI	B	3323,43	7.98	$2.71 \times 10^{-4}$	2.21	$8.82 \times 10^{-5}$	NA	NA	
17	Palacio Episcopal de Orihuela	XVIII	B	1649,61	9.86	$3.13 \times 10^{-4}$	17.78	$8.89 \times 10^{-4}$	Cracks in internal and external walls from the main building and the cloister. Some tilts can be recognized in the cloister (Data reported in 1992 by López (1992)). Currently the building shows a good overall condition after 2009 general restoration.	2001, 2003, 2009 (*)	Field works
18	Palacio del Conde de La Granja	XV	B	708,13	8.96	$2.76 \times 10^{-4}$	7.01	$1.45 \times 10^{-04}$	NA	NA	
19	Palacio Marqués de Arneva	XIX	B	1236,88	7.25	$2.87 \times 10^{-4}$	28.72	$1.12 \times 10^{-3}$	NA	NA	
20	Palacio de los Marqueses de Rubalcaba	XX	U	1376,06	38.79	$9.86 \times 10^{-4}$	1.84	$5.92 \times 10^{-5}$	Cracks in the external façades. The building is currently The building is closed by collapse risk.	2008	Field works
21	Palacio del Marqués de Rafal	XIX	U	801,23	12.93	$6.41 \times 10^{-4}$	6.69	$2.12 \times 10^{-4}$	NA	NA	
22	Palacete de los Mejías	XIX	U	205,53	7.55	$3.77 \times 10^{-4}$	4.48	$2.24 \times 10^{-4}$	NA	NA	
23	Palacete de los Condes de Chele	NA	N	75,88	0.70	$3.48 \times 10^{-5}$	2.59	$1.30 \times 10^{-4}$	NA	NA	
24	Palacio del Duque de Pinohermoso	XVI	G	1493,12	6.84	$2.27 \times 10^{-4}$	7.20	$2.61 \times 10^{-4}$	NA	NA	
25	Palacio de los Condes de Luna	XVIII	B	906,88	10.14	$4.07 \times 10^{-4}$	4.65	$1.49 \times 10^{-4}$	NA	NA	
26	Palacio de Portillo	XVIII	B	771,63	13.24	$4.22 \times 10^{-4}$	5.24	$1.46 \times 10^{-4}$	NA	NA	
27	Palacio del Barón de la Linde	XVIII	B	1174,34	7.89	$2.59 \times 10^{-4}$	5.52	$1.65 \times 10^{-4}$	NA	NA	

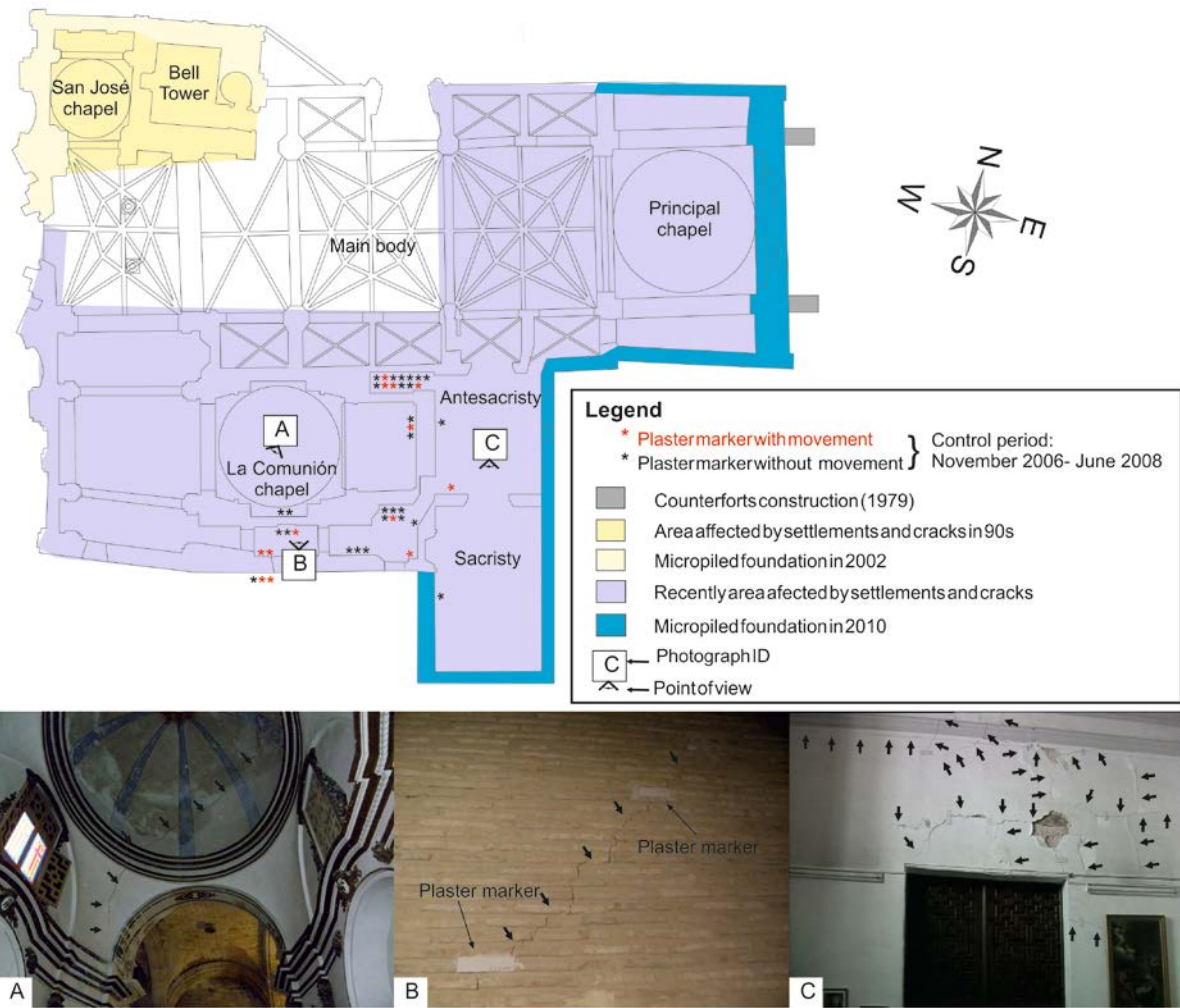


Fig.10. Location of the structural damage and restoration and reinforcement actions performed on Santos Justa and Rufina church (modified from Tomás et al., 2012).

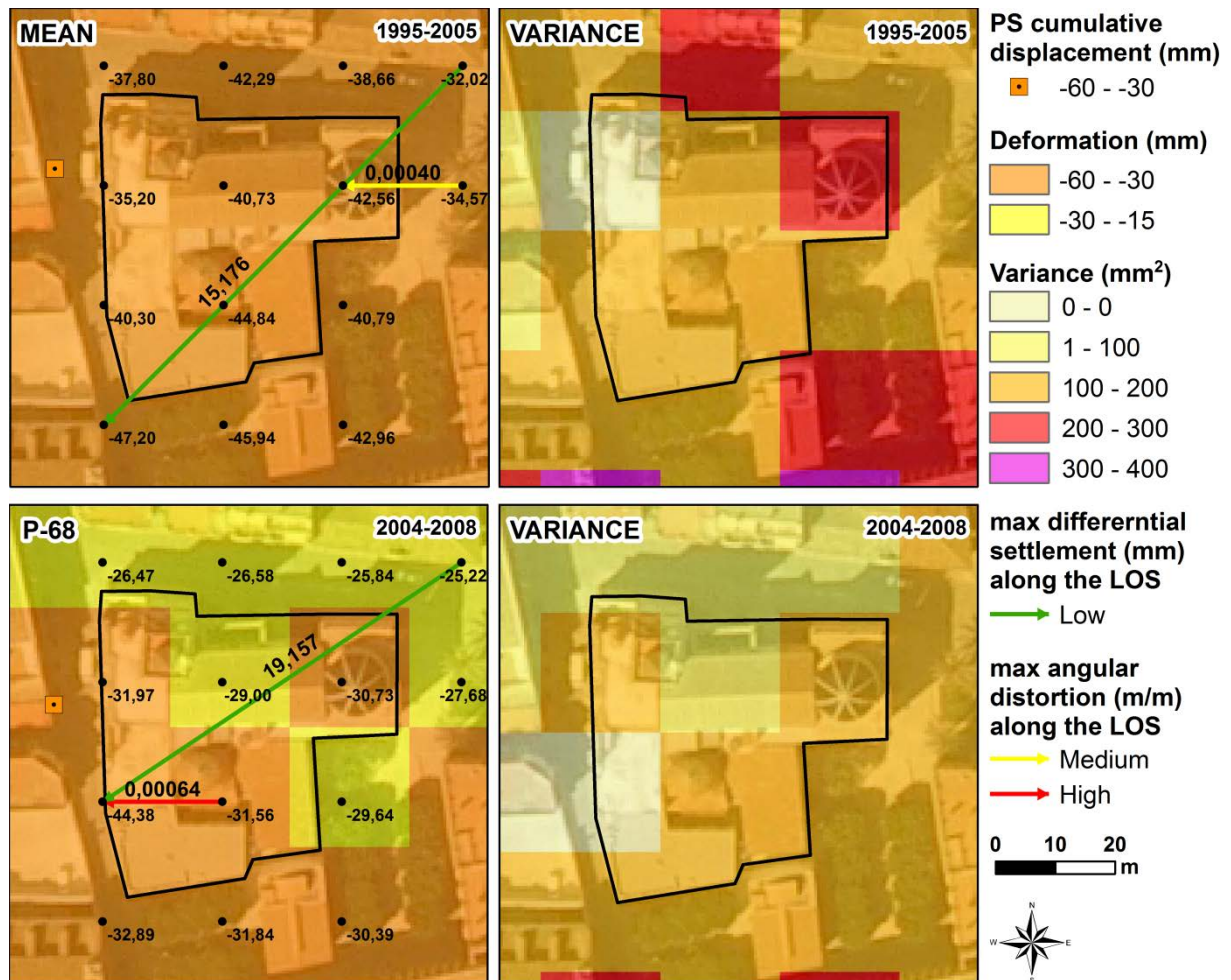


Figure 11. Mean (1995-2005), 68th percentile (2004-2008) and variance for both studied periods in the vicinity of the Santos Justa and Rufina church.