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Archaeoseismology as an emerging science

Natural risks

Archaeoseismology involves the study of past earthquakes by analysing archaeological sites, furnishing previously unknown information on seismic events that might not even have been recorded in history. This data can help to ascertain the seismic danger of relatively stable areas with long return periods of highly destructive earthquakes, such as the Iberian Peninsula.

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Throughout the eighties and nineties of last century there was a stream of multidisciplinary research projects dealing with different aspects of archaeoseismology (Rapp, 1982; Stiros, 1988 a and b; Stiros and Jones, 1996; Nikonov, 1988; Guidoboni, 1989).

One of the main drawbacks of this relatively new science, however, is precisely that there is very little to go on as reference (excluding perhaps the work of Stiros and Jones, 1996). To fill this gap Rodríguez-Pascua et al (2009, 2011) made a bibliographic compilation of the main earthquake effects in archaeological sites of Europe and Asia, establishing a structured classification of the commonest seismic effects observable in archaeological sites (Earthquake Archaeological Effects or EAE for short) (Fig. 1).

Analysis of the seismic effects in archaeological sites or historical buildings is a multidisciplinary analysis (Fig. 2); it has to take into account fundamental aspects such as determination of the processes that might produce these deformations, the dating of the deformation structures or the available historical documentation.

Identification of Earthquake Archaeological Effects (EAE)

Identification of the damage is one the most important steps in the analysis, since it is the phase in which a suitable identification has to be made of all the possible earthquake effects. This necessarily involves a trawl through historical documentation to find out if the place to be analysed (archaeological site or historical buildings) bears an express relationship to any historical seismic event. If so, the most significant effects have to be culled and localised from the existing historical documentation and then analysed. In the case of old archaeological sites with no written record of any earthquakes, the archaeological dig reports need to be examined to document any possible archaeoseismological effects. Lastly, it is also a good idea to glean information on the most important works of archaeological restoration and consolidation to rule out repaired and restored zones from the analysis.

Archaeoseismology involves the study of past earthquakes by analysing archaeological sites, furnishing previously unknown information on seismic events that might not even have gone down in the historical record

The classification of earthquake archaeological effects (EAE) proposed by Rodríguez-Pascua (2009, 2011) (Fig.1) is used to identify the damage; this breaks down the effects into co-seismic effects, produced as a result of the direct, seismic-wave-induced earth movement (geological effects and effects on the building fabric), and post-seismic effects, meaning all effects occurring after the earthquake itself or measures taken by affected societies to repair past damage or ward off the effects of any future earthquakes. This identification has to take full account of all archaeological and historical studies of the area for two main reasons: firstly, to interpret the structures correctly and, secondly, to date them reliably and hence be able to assign them to a specific earthquake. Many of the recorded effects could have a multiple origin; this ambiguity can be ruled out by quantification of the deformation.

Likewise, the post-seismic effects can provide many insights to help us make sense of the visible deformation and its origin, even if it can no longer be analysed by means of deformation quantification techniques. There are localities where the occurrence of destructive earthquakes is still patently obvious in the buildings and post-quake repairs.

A classic example of a locality of this type is the city of Morelia (formerly Nueva Valladolid), state capital of Michoacán (Mexico), where systematic use has been found of earthquake-resistant construction methods in the reconstruction of masonry-block buildings. There are records of destructive earthquakes that affected large zones of Michoacán, including the city of Morelia, in the sixteenth and nineteenth centuries.

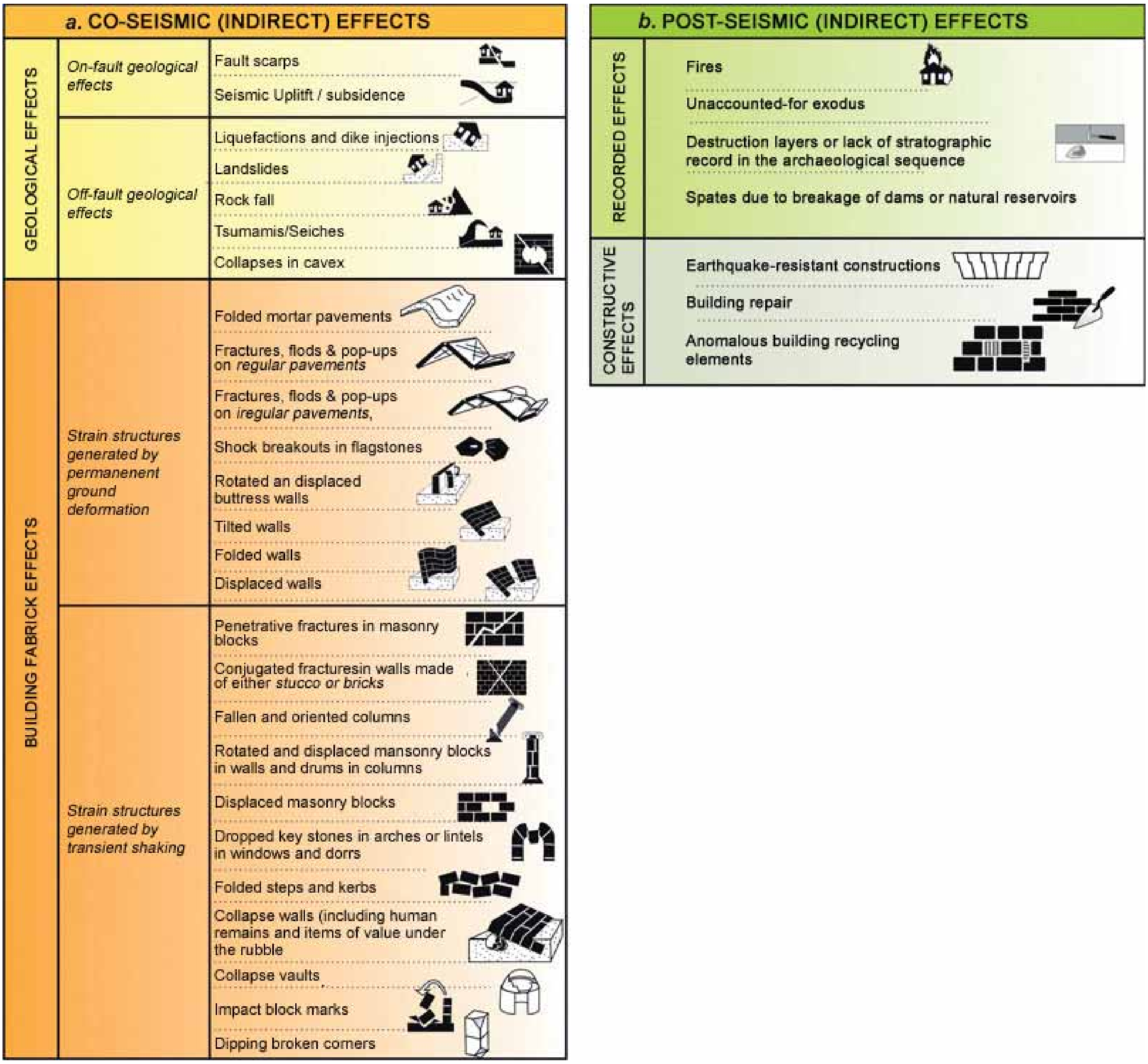

Figure 1. Classification table of the Earthquake Archaeological Effects or EAEs (modified from Rodríguez-Pascua et al, 2009 and 2011): a) co-seismic effects: effects produced directly by the seismic event (geological and in the building fabric); b) post-seismic effects: indirect effects of the earthquake aftermath, whether visible in the archaeological record (recorded effects) or in post-quake buildings (constructive effects).

In Morelia an inventory has been made of many examples of earthquake damage reconstruction and the use of interlocking masonry blocks (post-seismic construction effects) in seventeenth and eighteenth century buildings. Although this construction technique may in theory stem from various causes, some examples observed in this Mexican city show the true objective of using interlocking masonry blocks here: the reduction of infrastructure damage caused by horizontal charges of seismic origin.

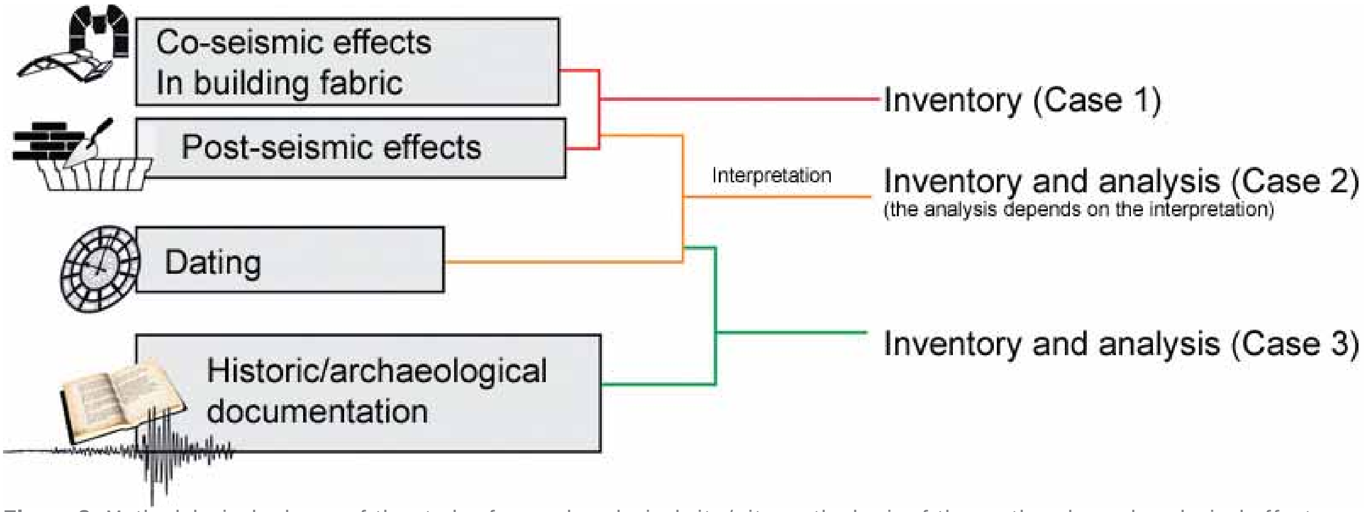

Figure 2. Methodological scheme of the study of an archaeological site/city on the basis of the earthquake archaeological effects (EAE), with inclusion of possible geological effects (primary and secondary) and possible determination of macroseismic scales (ESI-07), for seismic cataloguing of the event and calculating the seismic danger in the zone under consideration.

Take the example of the old *Convento de San Diego*, repaired after the 1856 earthquake of Pátzcuaro, with a recorded intensity of IX out of a scale of XII on the MSK scale.

This convent, dating originally from the mid eighteenth century (1768), was rebuilt in 1894 after the abovementioned earthquake. Its whole main front shows systematic use of interlocking masonry blocks, completely breaking up the horizontal tiers, especially on the ground floor (Fig. 3).

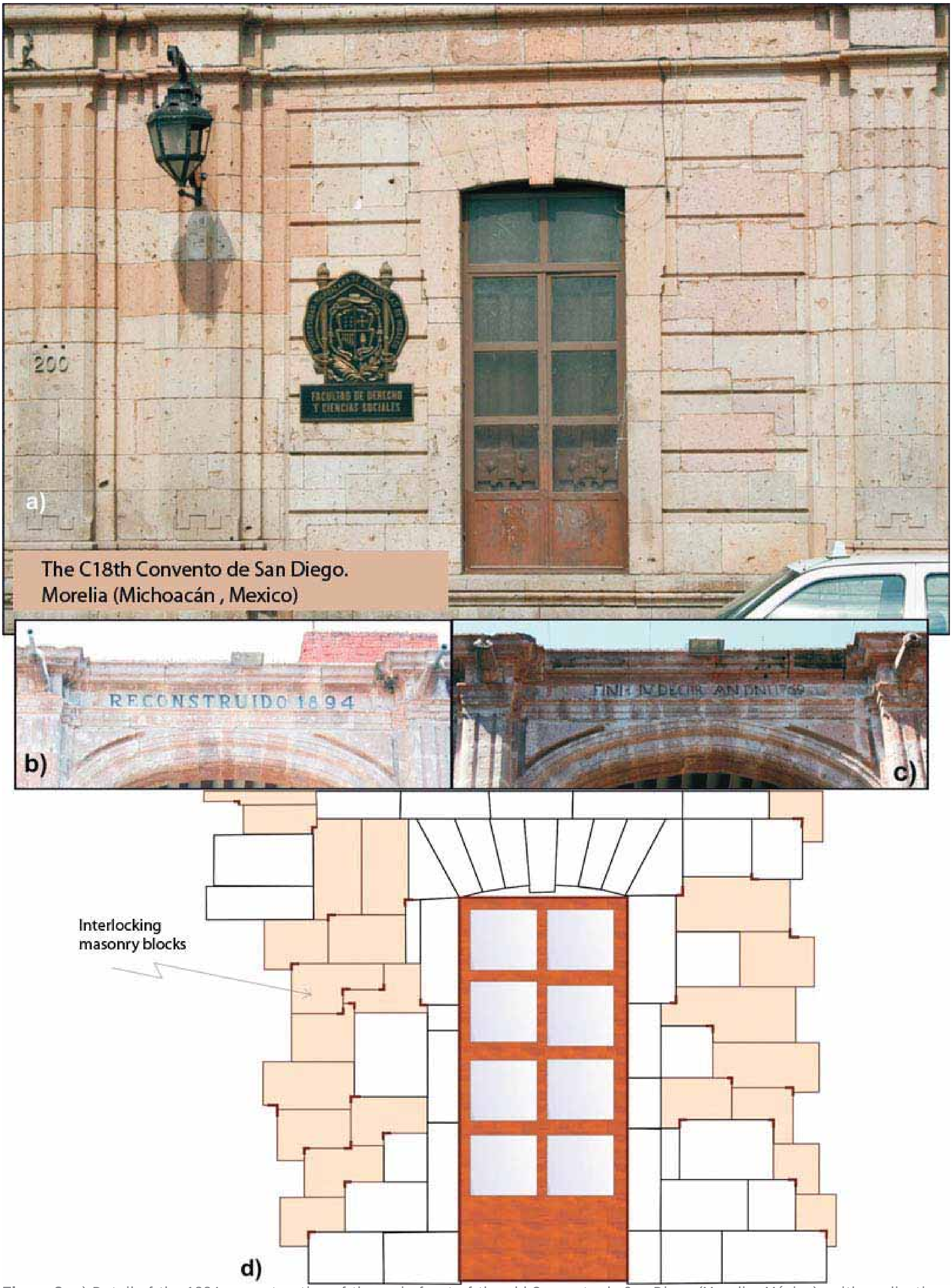

Figure 3. a) Detail of the 1884 reconstruction of the main front of the old Convento de San Diego (Morelia, México), with application of earthquake-resistant building techniques; (b) the reconstruction dates from the end of the nineteenth century (1895); (c) state after the great earthquake of Pátzcuaro (1856), which shook the towns of Pátzcuaro and Morelia. The main front reconstruction shows systematic use of interlocking masonry blocks (d).

Analysis of EAE deformation

Quantification of the deformation of the earthquake archaeological effects is based on analysis of the EAEs to gain insights into the deformation process produced or induced by the earthquake; i.e., the co-seismic effects: both the geological effects (a) and the building fabric effects (b) (see Fig. 1).

Classic structural geological techniques are used to ascertain the deformation of geological structures (a, geological effects). These enable us to establish the damage-causing deformation tensors.

Analysis of structures standing in different localities that have suffered damage from distant effects of the same earthquake enables us to analyse focal parameters of the earthquake in terms of the orientation and directionality of the observed damage

This article presents the methodology developed for quantifying the earthquake-induced deformation in building fabric. This study involves application of techniques similar to those used in structural geology. The study results enable us to establish the degree of uniformity present in the supposedly earthquake-caused deformation, thereby cutting down the uncertainty in the identification of the processes that have caused the recorded deformation.

The methodology applied to the analysis of earthquake-caused deformation in building fabric in archaeological sites is broken down into various phases (Giner Robles et al., 2009) (Fig. 4):

- Determination of the data type. Before analysing the observed deformation we need to consider a series of factors related to the data we are going to compile. These factors mainly involve definition of the analysable parameters to obtain deformation tensor data and ascertain properly the kinematics of the deformation.
- Quantification of the deformation in each structure analysed, applying geological structural analysis techniques. The orientation of the deformation tensor is defined, characterised by its two main axes in the strain field: ey (direction of maximum horizontal shortening) and ex (direction of minimum horizontal shortening).
- Analysis of the defined tensors for each one of the EAEs (a single result for each type of structure described on the archaeological site), thereby cross-checking the site-wide consistency of the data in due accordance with the type of structure.
- Joint analysis of the archaeological site to assess the uniformity of the results across the whole site and thereby ascertain the cause of the deformation.

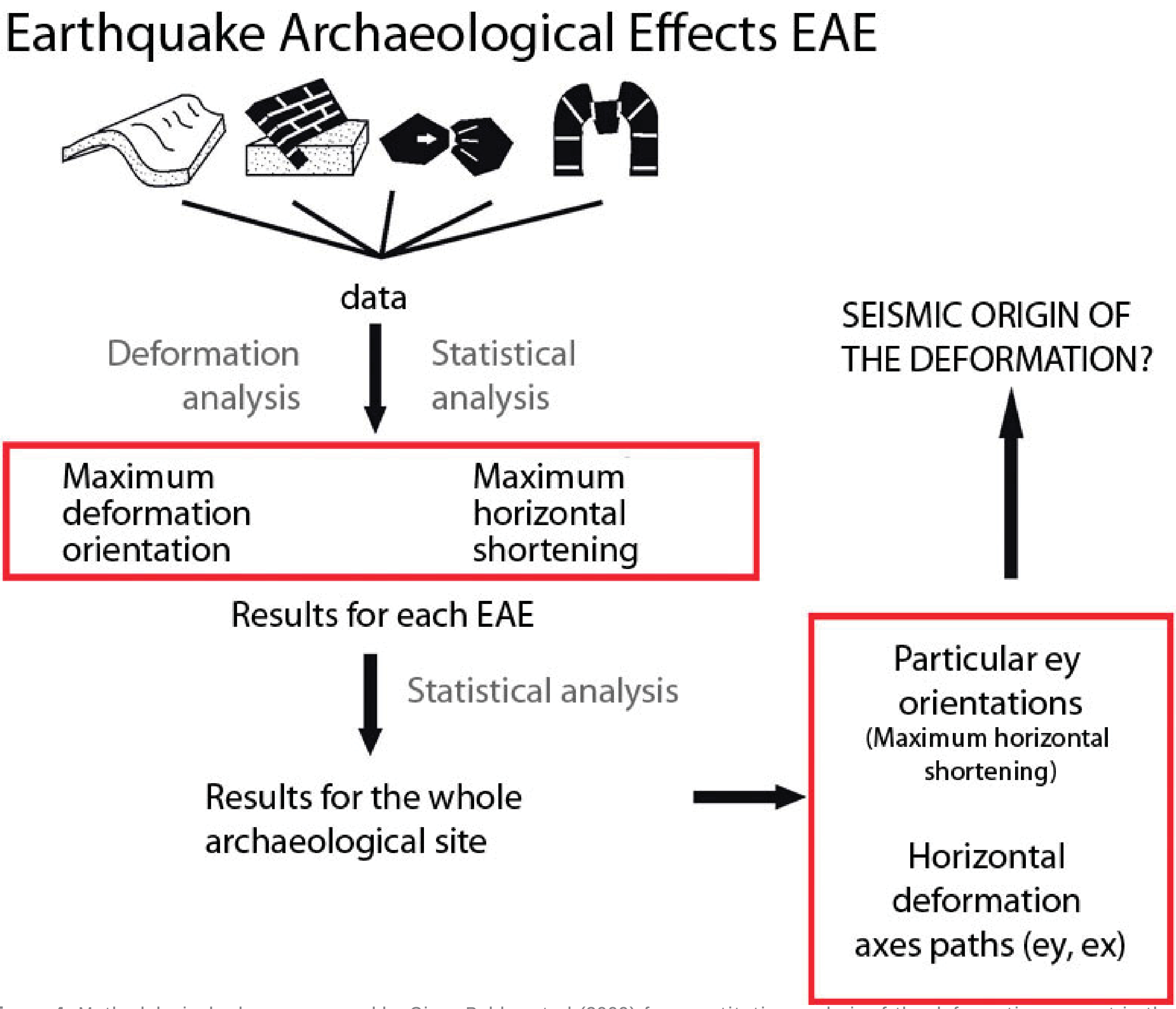

Figure 4. Methodological scheme proposed by Giner-Robles et al (2009) for quantitative analysis of the deformation present in the structures of an archaeological site (EAE) (Rodríguez-Pascua et al., 2009, 2011). Once the analysis has been made, the results are studied along with the rest of the information from the archaeological site: post-seismic effects, deformation dating, analysis of historical documents, etc. (see Fig. 2).

Figures 5 and 6 show some examples of the kinematic interpretation of structures, allowing us to establish the orientation of the damage-causing deformation tensor.

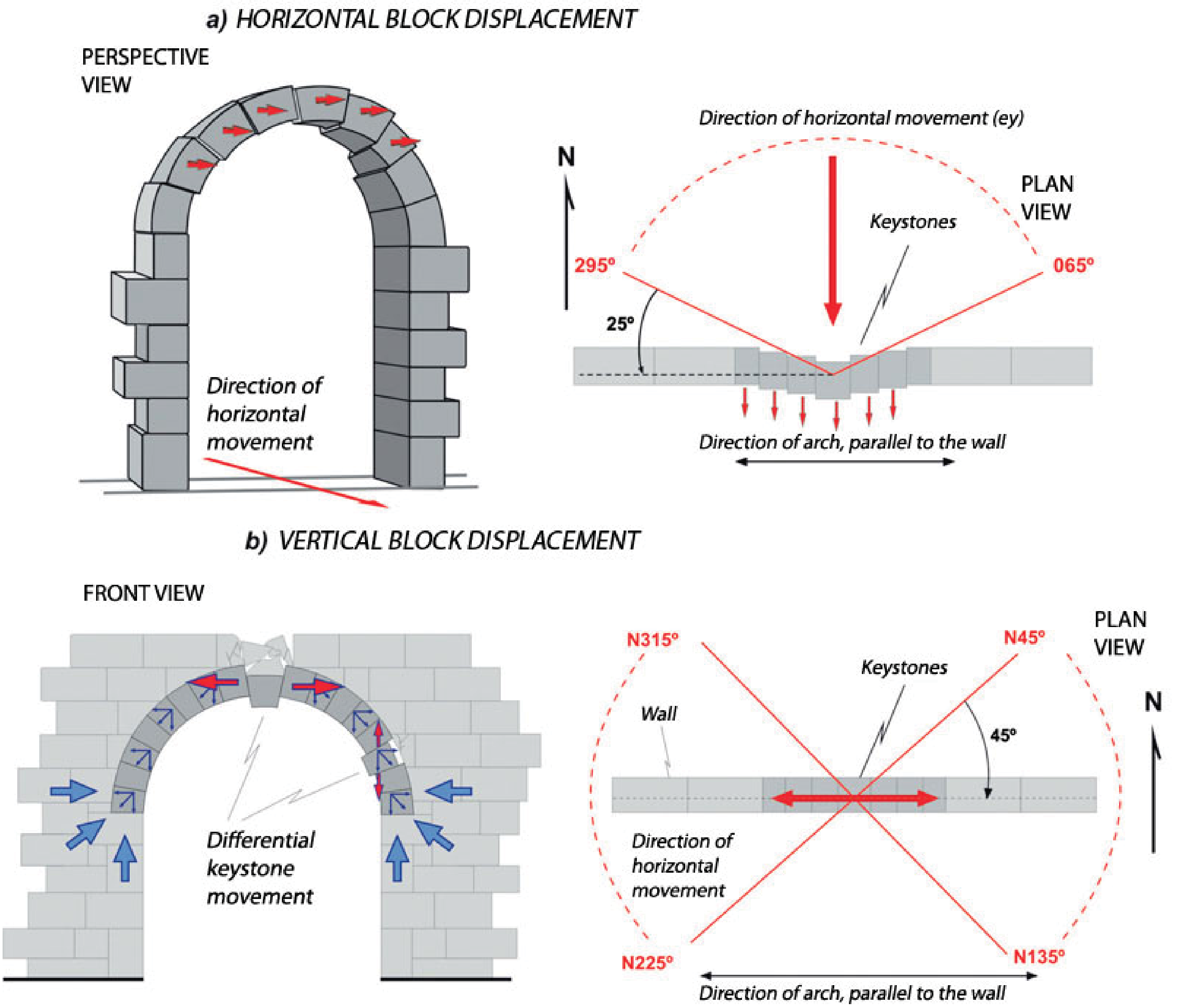

Figure 5. Idealised schemes of deformation analysis in arches and lintels. a) Deformation of seismic origin that shifted the keystones horizontally; the direction of maximum horizontal shortening (ey) is analysed in a similar way to that of titled walls. b) Deformation of seismic origin causing dropped keystones; the direction of ey lies at an angle of less than 45º vis-à-vis the plane of the arch-containing wall.

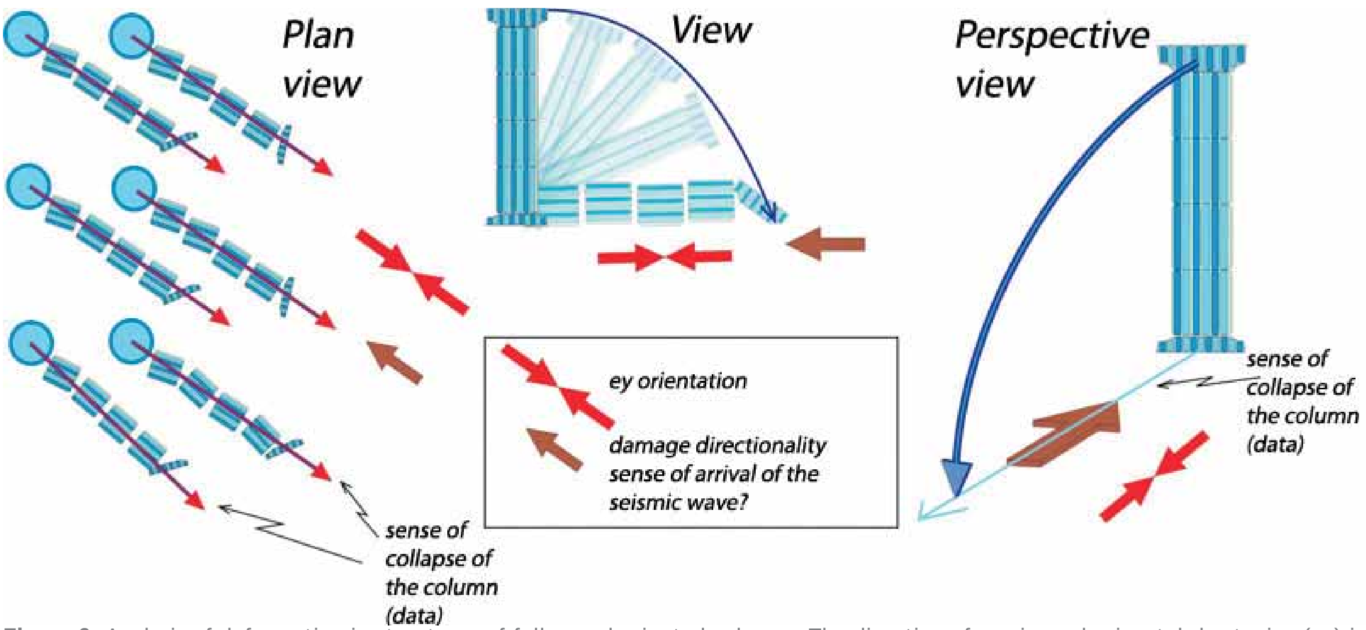

Figure 6. Analysis of deformation in structures of fallen and oriented columns. The direction of maximum horizontal shortening (ey) is parallel to the fall direction of the columns. In this case even the directionality of the damage can be established, defined by the column fall direction.

Examples of application of the methodology

A description is now given of some examples of application of the methodology in a few historical buildings and archaeological sites of the Iberian Peninsula (Giner-Robles et al., forthcoming)

Astorga Cathedral (León)

Building work on this cathedral began in the fifteenth century and it suffered severe damage as a result of the Lisbon earthquake of 1755. Copious damage is described in the missive sent by the *Alcalde Mayor* (chief magistrate) of Astorga to the court on 21 November 1755, 20 days after the earthquake struck (Martínez Solares, 2001).

Much of this damage is no longer visible because it was repaired in the past; the cloister, for example, was totally reconstructed after the earthquake. Some analysable co-seismic structures are still visible, however. Prime among them is the displacement of masonry blocks in the side columns holding up the nave (Fig. 7); there are in fact historical records of this damage. These shifts can be analysed as displacement vectors, directly determining the direction of maximum horizontal shortening (ey) (parallel to the vector), and even the directionality of the damage (in this case towards the southwest).

Another of the visible effects is the dropping of the upper keystones of a small rose window in the lunette of the northern chapel of the cathedral crossing (Fig. 7a).

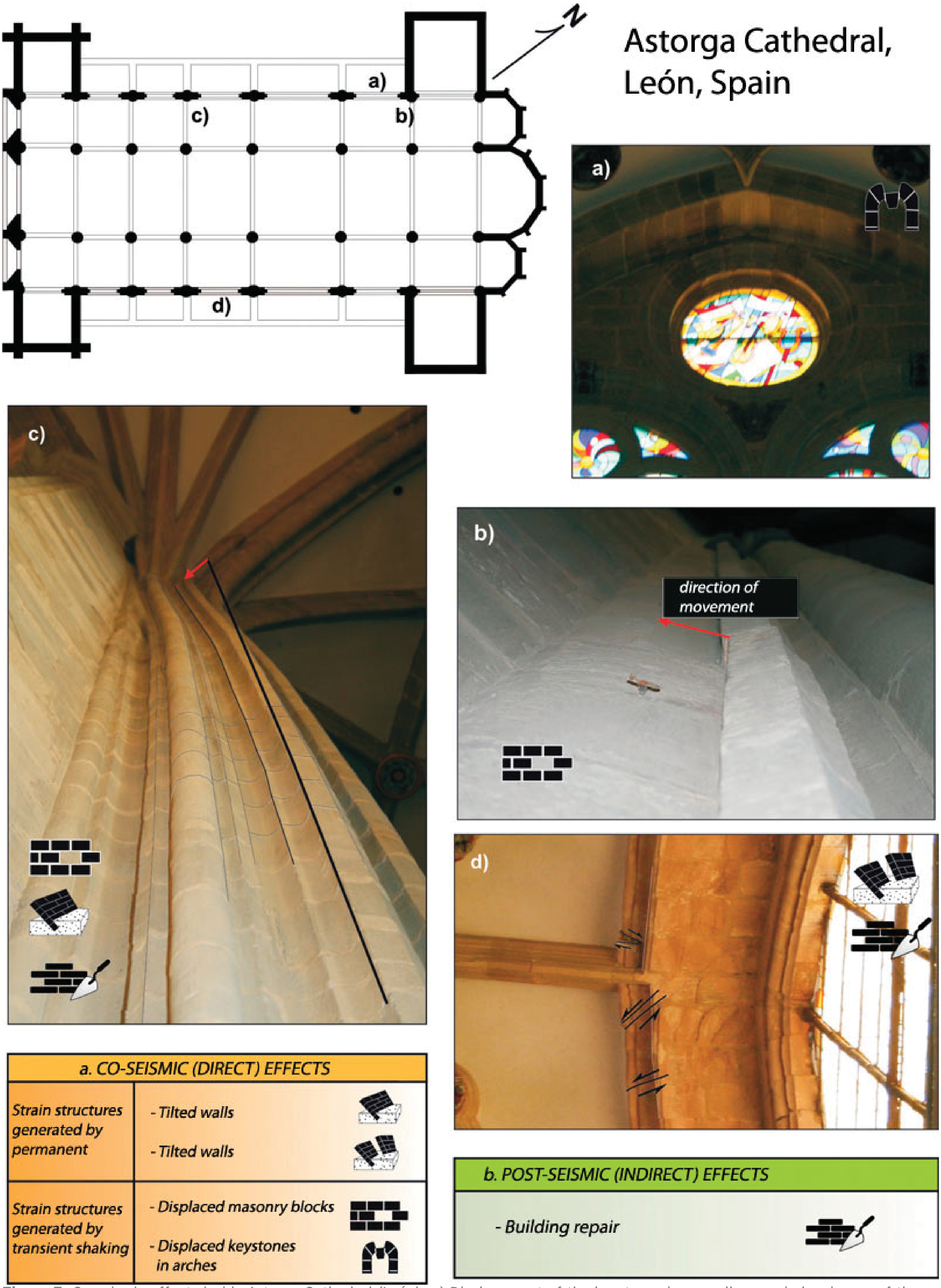

Figure 7. Co-seismic effects inside Astorga Cathedral (León). a) Displacement of the keystones in a small rose window in one of the side chapels. b) Decimetric displacement of the masonry blocks in one of the columns separating the crossing from the nave. c) Cumulative displacement of the masonry blocks making up one of the columns, visible displacement even with signs of thoroughgoing repairs. d) Masonry block displacement in the connection of the nave with one of the south facing windows.

Coria Cathedral (Cáceres)

The *Catedral de Santa María de la Asunción of Coria (Cáceres)*, built between the fifteenth and eighteenth centuries, suffered severe damage from the Lisbon earthquake of 1755.

In some cases the historical descriptions are so detailed that they enable us to reconstruct some earthquake-related events; these can then give many insights and even allow us to enhance the analysis of visible co-seismic effects.

In the case of this cathedral, the description of the collapse of the lantern roof and cupola of the tower clearly details the damage (letter from the Bishop of Coria to the court on 7 November 1755 describing cathedral damage) (Martínez Solares, 2001) (Fig. 8). The presence of rotated structures in some of the cathedral pinnacles (Martínez Vázquez, 1999) suggests that the collapse of the lantern was due to its rotation with respect to the cupola, bringing it tumbling down.

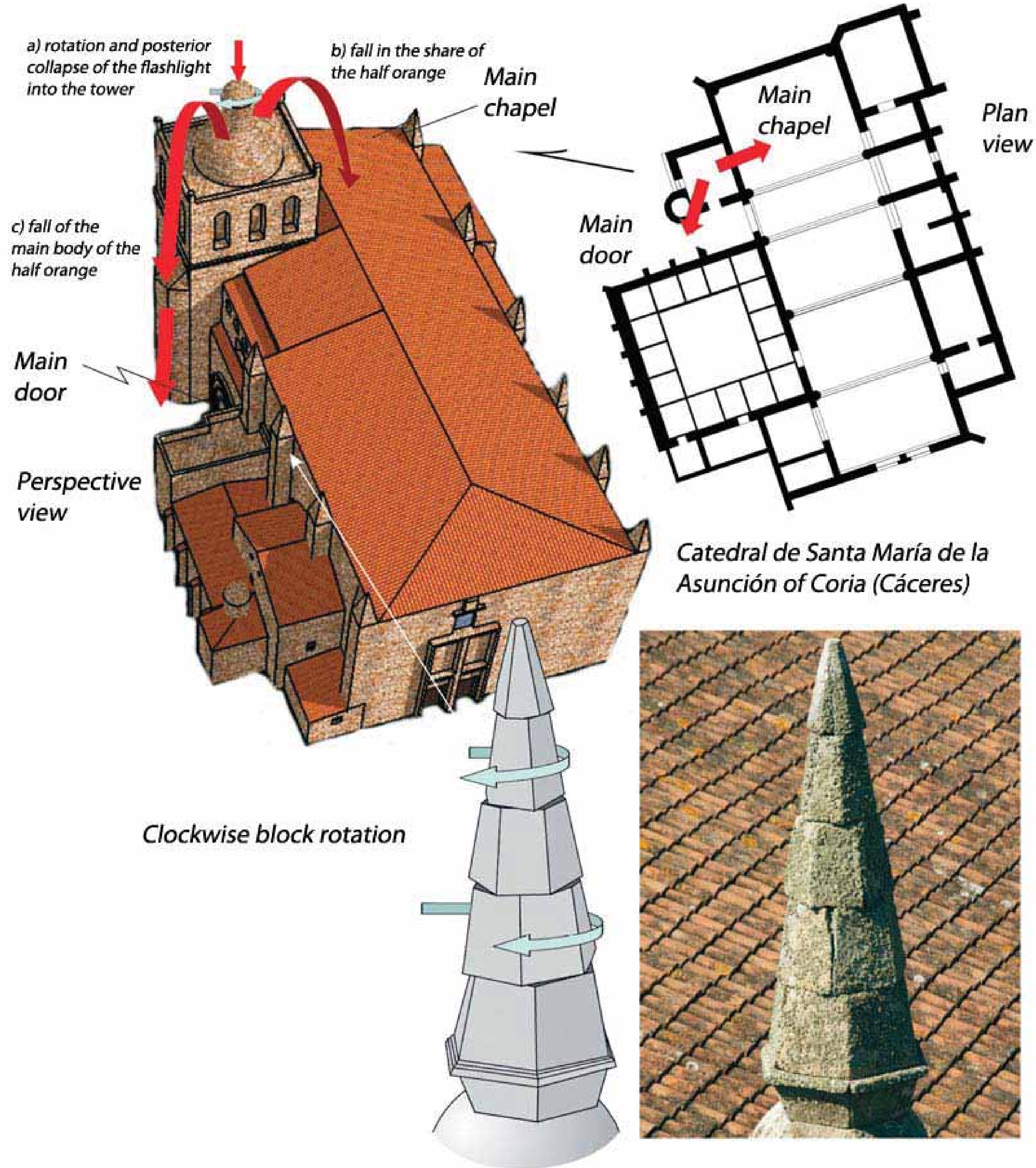

Figure 8. Interpretation of the damage suffered by the upper structure (lantern and cupola) of the tower of the Catedral de Santa María de la Asunción of Coria (Cáceres) as a result of the Lisbon earthquake. Without the historical description of the damage we would have been unable to determine the range of orientations of maximum horizontal shortening (ey) for this collapse, since post-quake repairs covered up all co-seismic effects, none of which are visible today. Detail of a rotation structure in one of the cathedral pinnacles (Martínez Vázquez, 1999). Note the lefthand (anticlockwise) rotation of the masonry blocks making up this pinnacle. The description of the collapse of the tower lantern suggest that it was due to the previous rotation of the lantern over the cupola.

Joint analysis of localities

Analysis of points or structures in different parts of Spain that suffered damage from distant effects of the Lisbon earthquake, as in the case of the above examples, enables us to study focal parameters of the earthquake with respect to the orientation and directionality of the observed damage (Fig. 9).

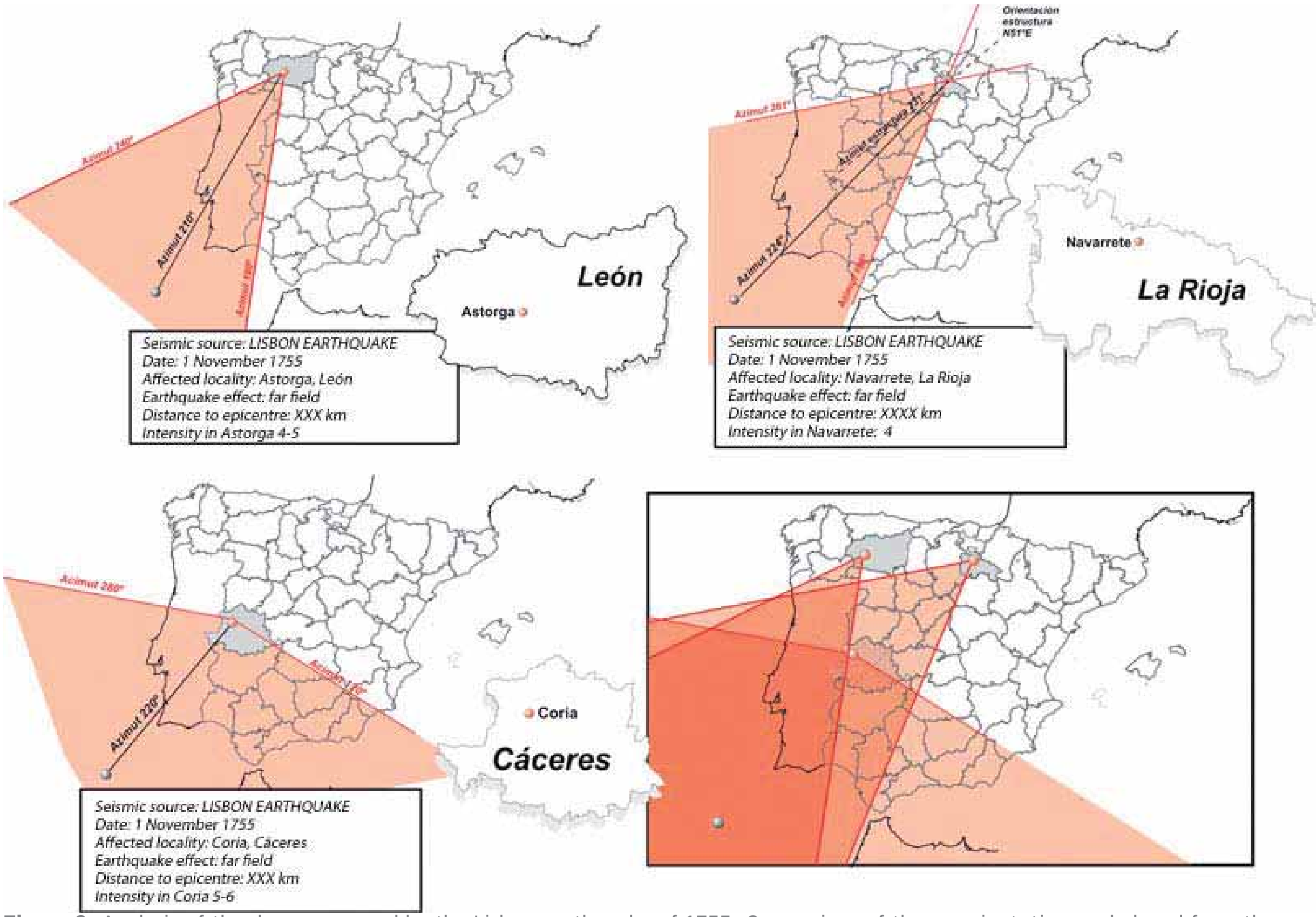

Figure 9. Analysis of the damage caused by the Lisbon earthquake of 1755. Comparison of the ey orientation as deduced from the particular results in three different locations: Navarrete (La Rioja), Astorga Cathedral (Astorga, León) and Coria Cathedral (Cáceres). The results are consistent with the most probable position of the Lisbon earthquake (grey circle).

In this case, however, there is too little far field data to draw trustworthy conclusions from; taken together, however, the ey orientations deduced from analysis of the archaeoseismological effects in these localities do allow us to deduce the main orientations of the earth movements during this earthquake.

Roman archaeological site of Baelo Claudia *(Cádiz)*

Identification and recording of the effects of ancient earthquakes in the historical and archaeological heritage can raise public awareness of seismic danger

In the Roman archaeological site of Baelo Claudia (Cádiz) previous studies had defined the occurrence of two earthquakes with no historical records in the period running from the 1st to 3rd century BCE. (Silva et al., 2005). This archaeological site was analysed by means of multidisciplinary collaboration between various experts (archaeologists, historians, geologists, architects, etc); this collaboration brought out diverse damage and effects that seem to have been caused by nearby earthquakes; this is especially true of the archaeological data (e.g. abandonment of parts of the city, presence of destruction layers, etc.).

Identification and recording of the effects of ancient earthquakes in the historical and archaeological heritage can raise public awareness of seismic danger

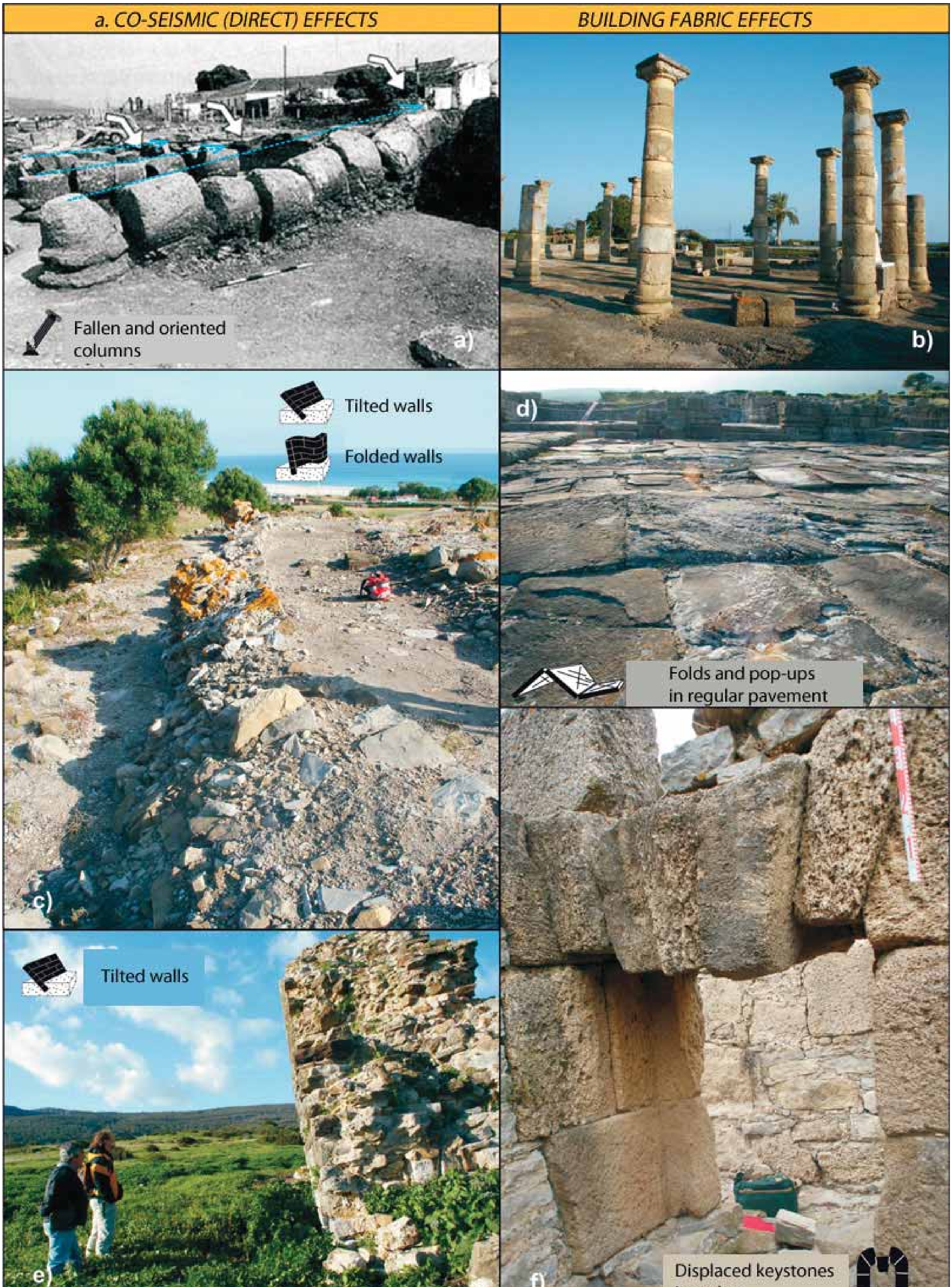

Figure 10. Co-seismic effects in the building fabric as recorded in the Roman archaeological site of Baelo Claudia (Cádiz). a) Fallen and oriented columns affecting the walls of the basilica in the forum area of Baelo Claudia (Silleries, 1997). In many cases the original material of the archaeological digs has to be checked to define the different effects correctly. b) In this case the basilica zone has been restored and the columns located in their original pre-collapse position. c) Fragment of the eastern wall of the city, folded and titled. On some occasions we might find two effects on the same structure. d) Folds and pop-ups in the regular pavement of the forum plaza. e) Fragment of the eastern tilted wall. d) Dropped and displaced keystones in a linteled window in one of the public buildings of the forum

The EAE deformation found on this archaeological site was analysed to quantify this deformation and thereby confirm the hypothesis of past destructive earthquakes on this site, as suggested by other multidisciplinary techniques and analyses (Silva *et al.*, 2009).

Application of the deformation analysis to *Baelo Claudia* focused, firstly, on recording all EAE in the site zone. Once all the apparently earthquake-related deformation had been recorded a determination was then made of the orientation of the maximum horizontal shortening direction (*ey*) of each one of the individual structures. An analysis of deformation for each type of EAE was then carried out for the whole site (Fig. 11).

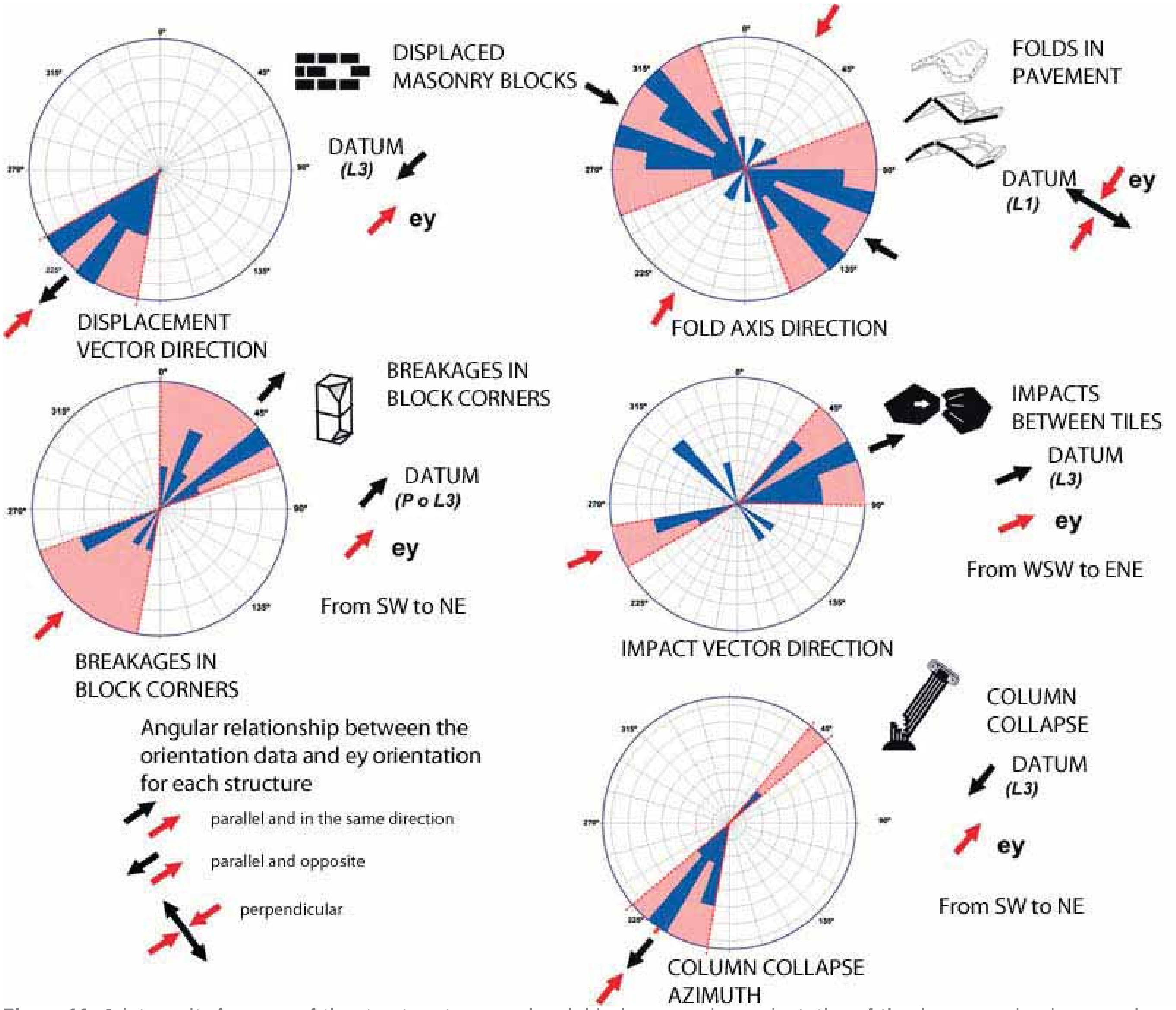

Figure 11. Joint results for some of the structure types analysed: black arrows show orientation of the damage and red arrows show the orientation of maximum horizontal shortening (ey) deduced for each structure. Note that the orientation of the damage is not necessarily parallel to or in the same direction as the ey orientation as deduced from its analysis. The angular relation between the orientation of the damage and the ey orientation deduced from its analysis depends on the theoretical kinematic interpretation of each one of the structures.

Finally, a joint analysis was made of the ey orientations in the whole site. Once other processes had been ruled out, this analysis established the seismic origin of the deformation. The results also chime in with those obtained by other authors (Silva et al., 2005 and 2009). This type of analysis also allows us to define zones in which deformation paths have been reoriented due to the presence of structures such as pipelines, foundations, etc.

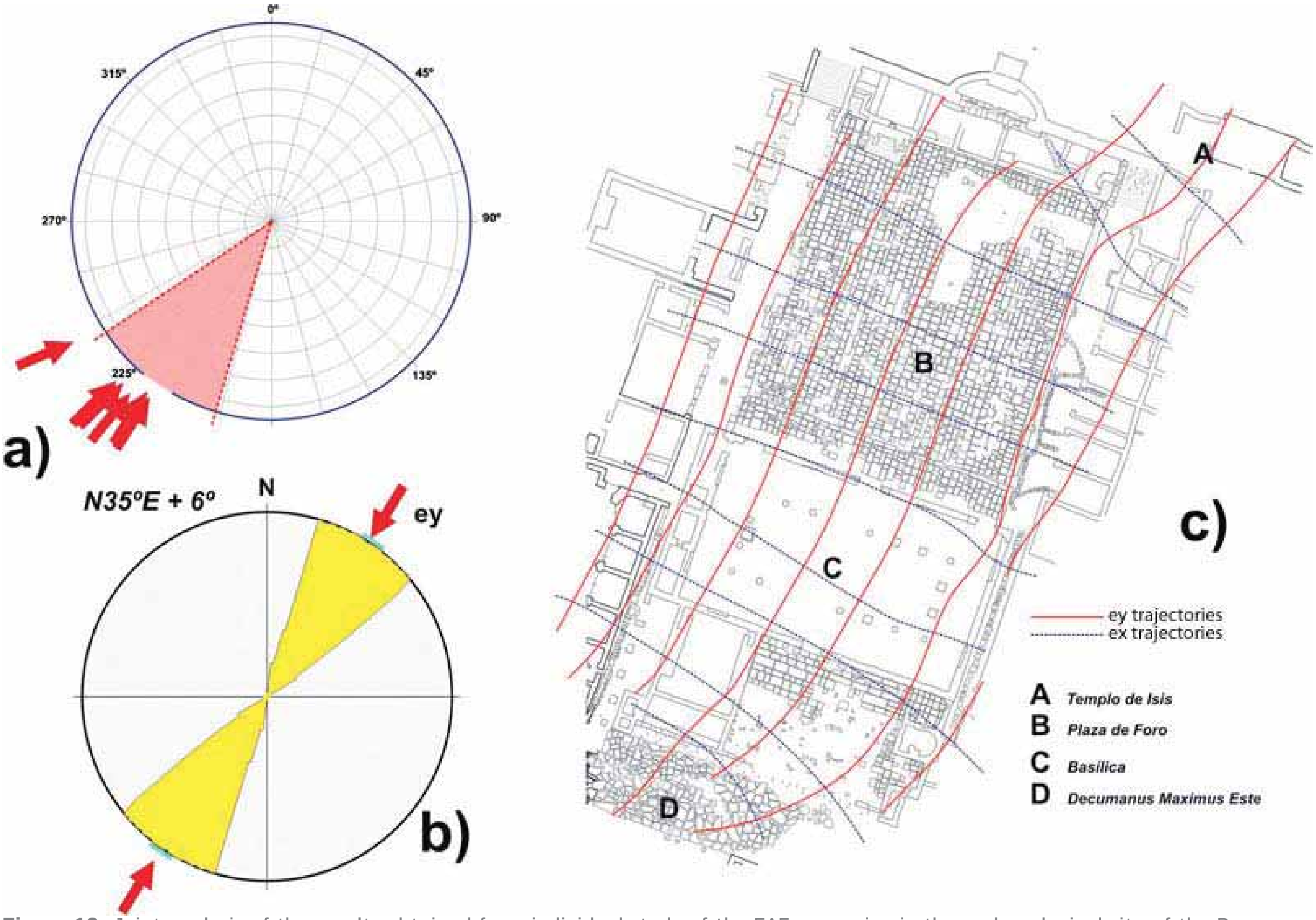

Figure 12. Joint analysis of the results obtained from individual study of the EAE appearing in the archaeological site of the Roman city of *Baelo Claudia (Cádiz).* a) Representation of the orientations of maximum horizontal shortening (ey) as deduced from individual EAE analysis. b) Common result of the ey orientation for the whole site. c) Representation of the deformation paths (ey red lines; ex blue lines) in the city's forum area. These results show a clear uniformity, bearing out the reoriented paths in: the area of the *decumanus maximus* (D), caused by underground drainage; the area of the forum plaza (B), caused by the existence of regular pavements; and the zone of the Temple of Isis (A), related to a very superficial co-seismic gravitational process affecting this part of the archaeological site (Silva et al., 2009).

Instrumental earthquake analysis

Most of the structures and effects considered in this classification have been described in various archaeological sites as a result of earthquake-caused damage. Nonetheless many of these effects can be observed in historical buildings affected by instrumental earthquakes (Fig. 13).

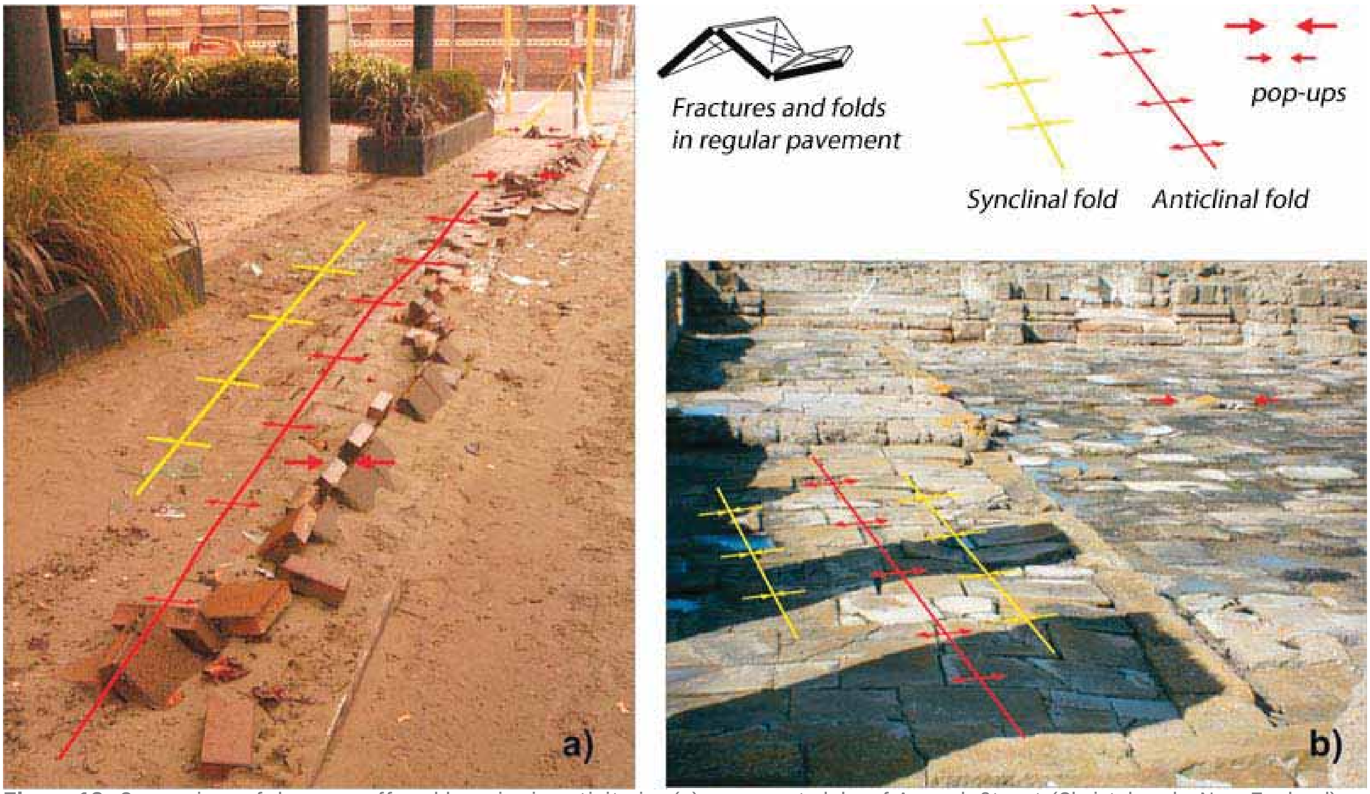

Figure 13. Comparison of damage suffered by seismic activity in: (a) pavement slabs of Armagh Street (Christchurch, New Zealand) (earthquake of 22 February 2011) (Photo: Juan Miguel Insúa Arévalo); b) pavement of the forum of the Roman archaeological site of Baelo Claudia (Cádiz), a city affected by an earthquake in the third century (Silva et al., 2009). In both cases the pavement is seen to buckle into anticlinal and synclinal folds with pop-ups. In the case of the Christchurch earthquake structure this deformation is associated with liquefaction process of underlying sand.

The analysis of damage caused by instrumental earthquakes such as that of Lorca (Murcia), which occurred on 11 May 2011, could be key in the interpretation of seismic damage in archaeological sites (Figs. 14 and 16). The preliminary analysis of the effects of this earthquake enables us to calibrate the developed methodology, establishing the margins of error in calculating the deformation parameters.

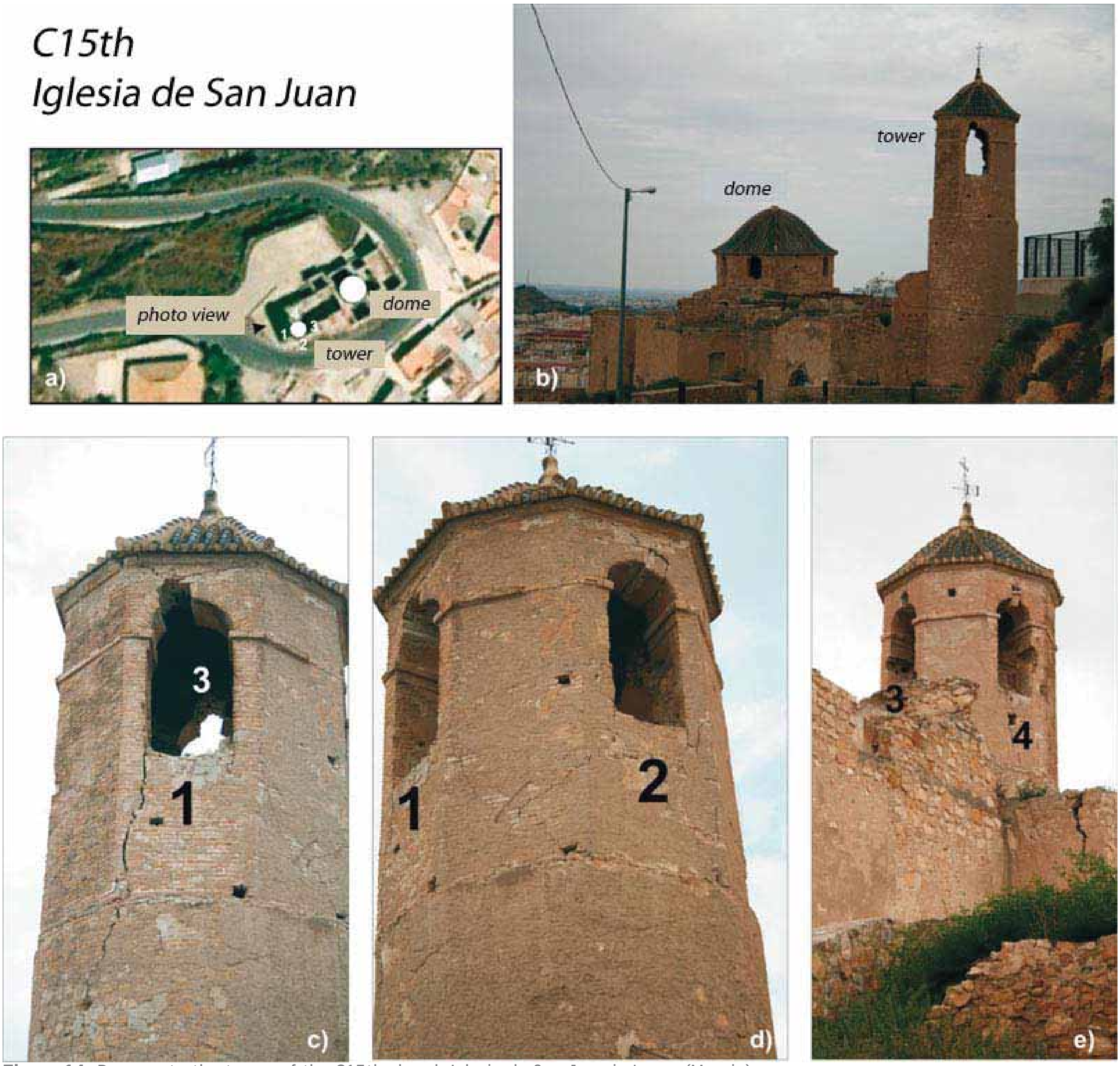

Figure 14. Damage to the tower of the C15th church Iglesia de San Juan in Lorca (Murcia).

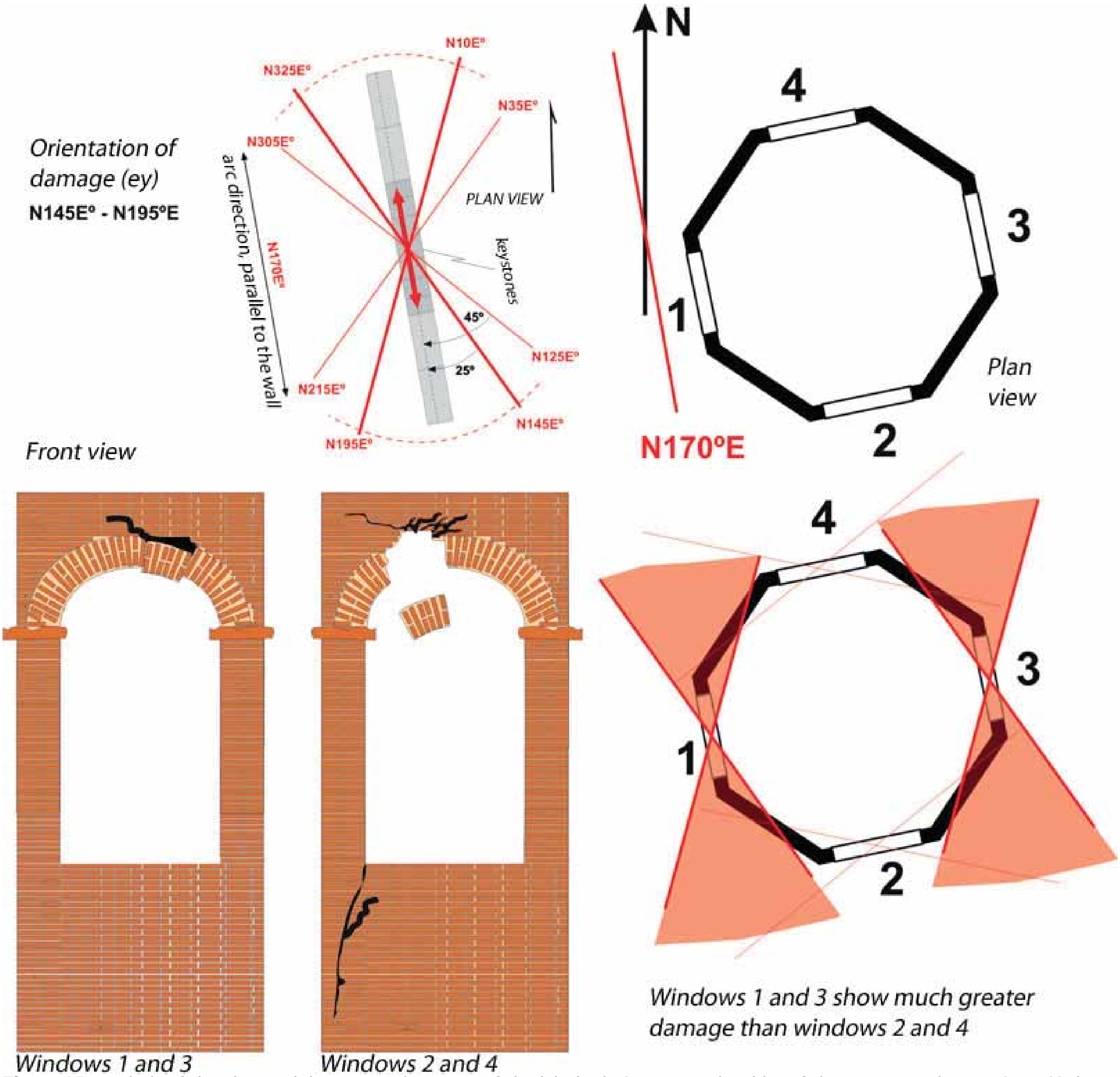

Figure 15. Analysis of the observed damage to the tower of the iglesia de San Juan. The sides of the tower running NW-SE 170º show more damage than those running in other directions. Determination of these orientations enables us to quantify the earthquake-caused deformation.

In the case of the Lorca earthquake, two historical buildings of the city were chosen: the church called Iglesia de San Juan (Figs. 14 and 15) and the St. Clare Nunnery (Monasterio de las Clarisas) (Figs. 16 and 17).

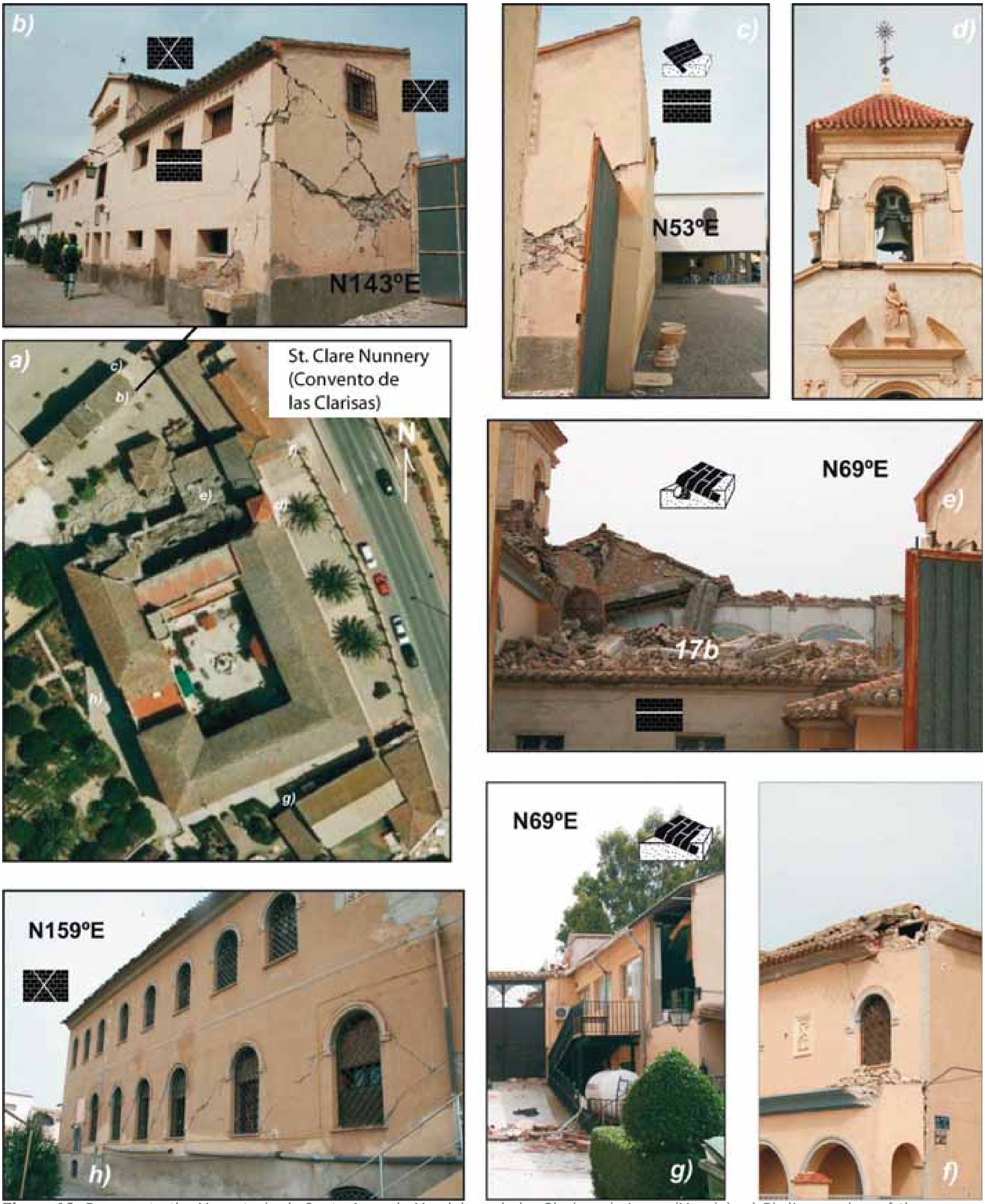

Figure 16. Damage to the Monasterio de Santa Ana y la Magdalena de las Clarisas, in Lorca (Murcia). a) Bird's eye view of the nunnery buildings and location of the main damage. (b) and (h) Conjugated fractures in walls of various buildings of the nunnery; c) Fracture and displacement of the NW wall of a building annexed to the church; fallen and oriented walls in different structures: (d) in a small belltower; (e) in the NW wall of the nunnery church; (g) in a building annexed to the church, and in one of the corners of the main front (g).

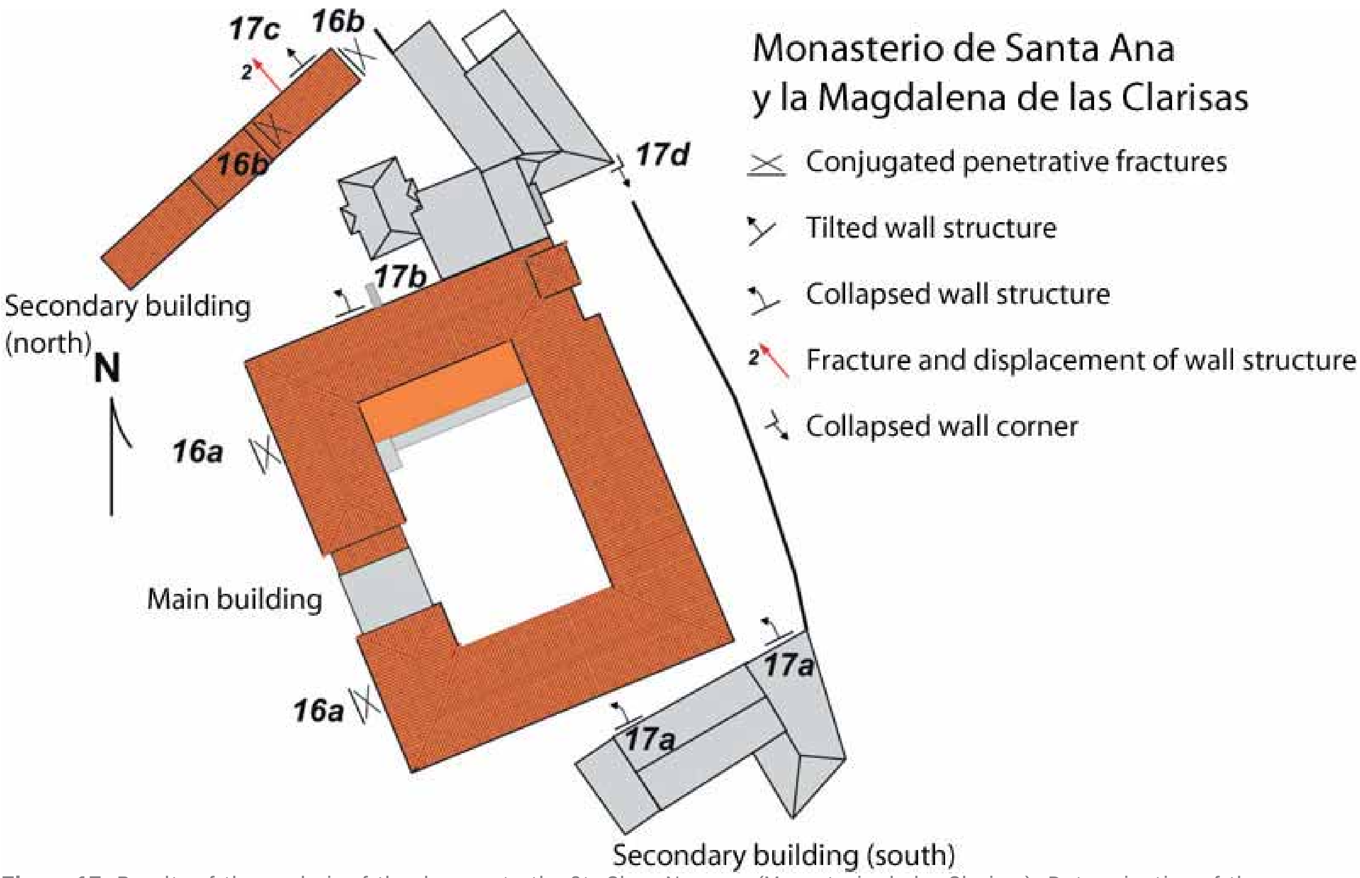

Figure 17. Results of the analysis of the damage to the St. Clare Nunnery (Monasterio de las Clarisas). Determination of the kinematics and damage orientation enables us to systematise the data culled and represent it for subsequent analysis. In the case of this historical building, results show that the damage has a clear NW-SE 140º orientation. Even the collapse direction of the wall of the various nunnery buildings is uniform according to 320º; this same orientation is repeated in practically all the historical buildings affected by this earthquake

The C15th Iglesia de San Juan (siglo XV) shows diverse damage to the tower windows, varying in degree according to their orientation (Fig. 14). Due to the collapse of the arch (see Fig. 5), the windows running NW-SE 170º show greater damage than those running at right angles to them (Fig. 15); this tells us the main orientation of the damage-causing deformation tensor (orientation of ey).

In the case of the St. Clare Nunnery, fairly severely damaged by the earthquake (Fig. 16), the analysis shows a uniform orientation of ey in the direction NW-SE (Fig. 17), chiming in with the results obtained in over 80 analysis points throughout the town.

Conclusions

The archaeoseismological analysis of archaeological sites and historical buildings can give us crucial insights for calculating seismic danger.

Analysis of observable deformation in the various effects recorded on site, with application of classic geological structural analysis methodologies, enables us to quantify the deformation present on the site.

Analysis of damage in instrumental earthquakes such as that of Lorca (Murcia), which struck on 11 May 2011, could be key in the interpretation of seismic damage in archaeological sites

The results of the archaeoseismological analysis of the deformation related to the surface seismic-wave propagation front facilitates analysis of the consistency of the deformation with respect to probable seismogenic sources, whether known or unknown active faults.

Analysis of the effects of recent earthquakes recorded instrumentally in historic enclaves or archaeological sites furnishes a great deal of information about the kinematics of the processes involved. Instrumentation tells us the focal parameters of the earthquake; this then makes it possible to calibrate the EAE, which, applied inversely to palaeoseismological and archaeological earthquakes, enables us to reduce the degree of uncertainty of the analysis and even consider such parameters as epicentre location and maximum intensity. These parameters can then be used in calculating seismic danger, implementing the results in macroseismic scales based on the geological and environmental effects of these earthquakes, such as the macroseismic scale ESI-07 (Environmental Seismic Intensity – 2007; Michetti et al., 2007).

Results of the archaeoseismological analysis of the deformation help to weigh up the consistency of the deformation with respect to probable seismogenic sources, whether known or unknown active faults

Archaeoseismological analysis is now another arrow in the quiver for ascertaining and heading off seismic risk in areas of long return periods such as the Iberian Peninsula. In these slow areas the return periods of big quakes means that the public is not really aware of the seismic danger of the area they live in. Such a long lapse of time dampens public perception of the danger and limits society's preparation against event of this type.

In our opinion the identification and analysis of earthquake effects and EAE in the historical and archaeological heritage could help to make the public more aware of the existing seismic danger in certain areas of the Iberian Peninsula and also the degree of exposure to destructive earthquakes.

This information on the seismic danger as perceived by the population is of great help not only in mitigating possible damage but also establishing emergency plans by the public authority.

All too often historical architecture restoration programmes completely eliminate these seismic effects. We consider these effects to be of great historical and didactic importance, however, and they could even be said to form part of our cultural heritage

Effects of destructive earthquakes, such as the Lisbon 1775 quake, are still visible in many historical buildings and archaeological sites in Spain. All too often historical architecture restoration programmes completely eliminate these seismic effects. We consider these effects to be of great historical and didactic importance, however, and they could even be said to form part of our cultural heritage.

TO FIND OUT MORE

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