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## **Reassessing the seismic hazard in the Cusco area, Peru: New contribution coming from an archaeoseismological survey on Inca remains**

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### **Keywords**

Archaeoseismology; Inca architecture; Earthquake damage; Seismic hazard; Heritage; Cusco

### **Abstract**

Devastated by two earthquakes in historical times (1650 and 1950 CE), the Cusco Basin is now characterized by dense and chaotic urbanization that makes it even more vulnerable. Unfortunately, the large recurrence intervals of the local crustal earthquakes, the shortness of the historical record (~500 yr) and the persistent lack of palaeoseismological studies hamper considerably the seismic hazard assessment. In such context, the outstanding archaeological heritage of the Cusco area turns out to be a relevant marker of past seismic activity.

We carried out a systematic archaeoseismological survey in nine Inca sites close to Cusco and registered almost 3,000 Earthquake Archaeological Effects. Thanks to a semi-quantitative approach, we show a clear anisotropic seismic deformation on the Inca fine stonework, consistent at the regional scale. In Cusco, the architecture exhibits the impact of two different and strong ancient seismic events (M.M. intensity >VII).

By combining these results with the analysis of historical photographs, our work supports, the occurrence of an unreported event during Inca times (~1400-1533 CE). More broadly, by providing new data on the destructive potential of past earthquakes, this study urges us to conduct further research on the faults near Cusco.

## **1. Introduction**

Crustal faults in continental interiors constitute a direct threat for millions of people around the world (Silva et al., 2017). Despite its harmfulness, this type of hazardous faults remains understudied and hence underestimated (England and Jackson, 2011; Liu and Stein, 2016). The diffuse and unpredictable nature of intraplate earthquakes as well as the related long return periods (1-10 kyr) hamper considerably the seismic hazard assessment (SHA) based on instrumental data. The SHA needs, therefore, to rely on complementary and innovative approaches (McCalpin, 1996) such as geomorphology, historical seismology, palaeo- and archaeoseismology.

Lying within the “Pacific Ring of Fire” and characterized by the subduction of the Nazca plate below the South American plate, Peru is particularly prone to earthquakes (Oliver-Smith, 1994; Petersen et al., 2018). Regarding the active margin, several seismic disasters have punctuated its recent history and affected the populations (Lima 1746: Walker, 1999; 2018; Arica 1868: Seiner Lizárraga, 2013; Ancash 1970: Plafker et al., 1971; Caruso and Miller, 2015; Pisco, 2007: D’Ercole et al., 2007). Since then, much work has been done on this topic, contributing to improving the SHA and to size the prevention strategies (e.g., Pulido et al., 2015; Villegas-Lanza et al., 2016; Aguilar et al., 2017; Das et al., 2020).

On the contrary, the Andean highlands that extend on a large portion of the Peruvian territory and are crossed by many active faults, lack studies (Dorbath et al., 1990; Costa et al., 2006). Besides the instrumental network coverage that remains sparse, the absence of writings during pre-Columbian times constitutes an aggravating factor. In contrast to the Mesoamerican area (Garduño-Monroy, 2016; Suárez and García-Acosta, 2021), we cannot, therefore, rely on comprehensible reports of earthquakes before 1533 CE. This results in an incomplete seismic catalog, limited to the last 500 years, i.e. insufficient to cover the entire seismic cycle of crustal faults. The consequences of modern crustal and strong earthquakes such as the  $M_S7$  1946 Ancash (Silgado Ferro, 1951),  $M_w5.6$  1986 Cusco (Cabrera and Sébrier, 1998) and  $M_w5.4$  2014 Paruro events (Tavera et al., 2014) urge for the development of innovative approaches in this part of the Andes.

The region of Cusco, which encompasses densely populated basins formed by the Quaternary tectonic activity, exemplify the vulnerability of the highlands to the crustal seismic hazard. This area is endowed also with rich archaeological and historical heritage. Such built heritage represents both an additional source of vulnerability and a unique opportunity to improve our

knowledge on the past local seismicity (Montabert et al., 2020; Kázmér et al., 2021; Dessales et al., in press).

Hence, archaeoseismology, i.e. the study of the earthquake-induced damage (and repairs) in the archaeological record (Noller, 2001; Ambraseys, 2006; Galadini et al., 2006), turns out to be a promising approach in Cusco. In this paper, we present the results of an archaeoseismological survey carried out in the Cusco area. This survey aimed at documenting Earthquake Archaeological Effects (EAEs - Rodríguez-Pascua et al., 2011), and more specifically primary effects (damage), on monumental Inca remains. Scholars soon regarded the Inca megalithic architecture as the product of pre-Columbian seismic-resistant knowledge (Calderón Peñaylillo, 1963). However, very few studies addressed yet the seismic behavior of those structures (Hinzen and Montabert, 2017) and their potential to register past ground motions (Rodríguez-Pascua et al., 2020; Combey et al., 2021).

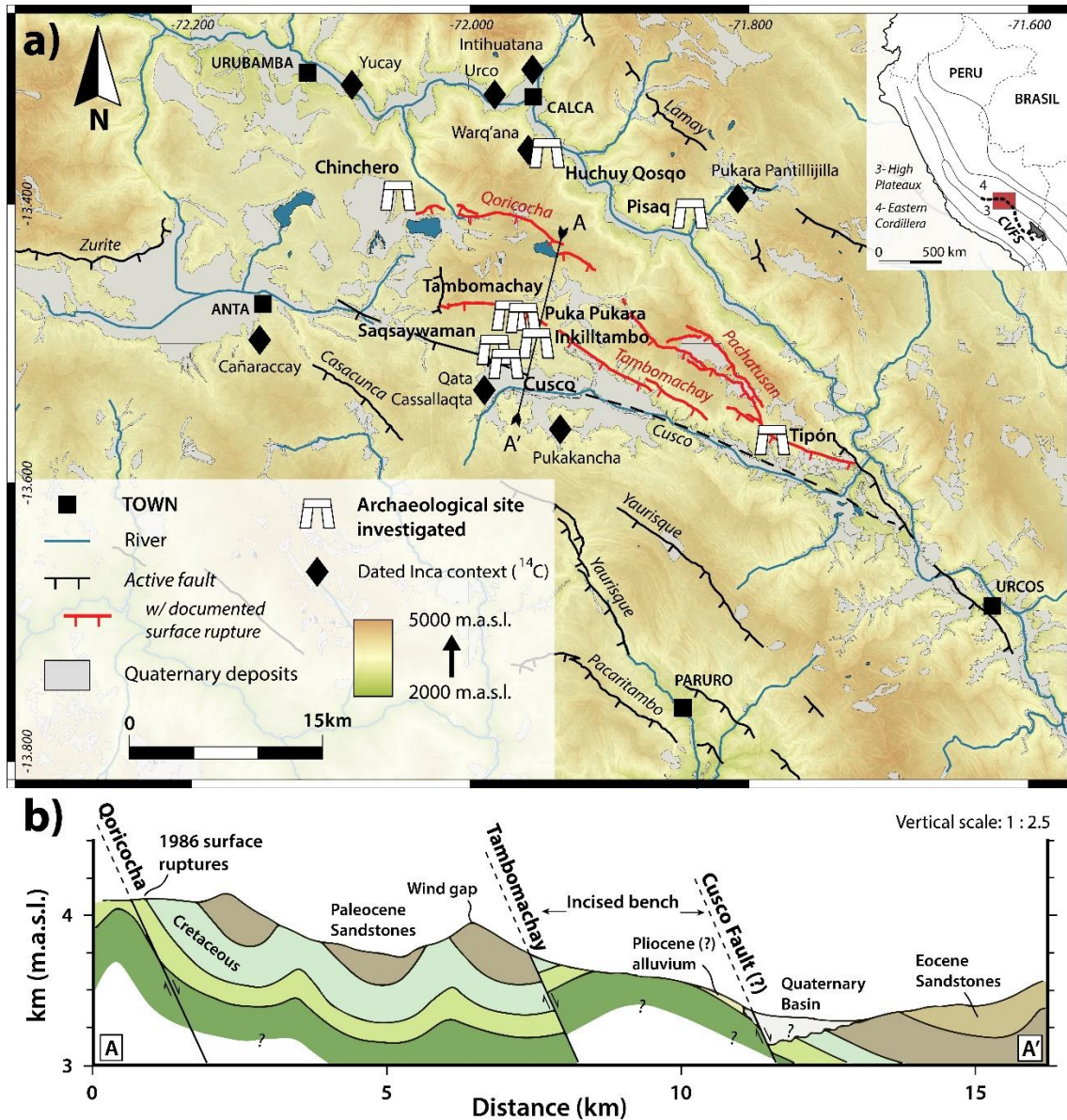
By combining a semi-quantitative approach on the EAE's orientation and a review of historical data, our work aims to provide new insights on ancient earthquakes (Sintubin, 2010) that struck the region of Cusco. We develop an alternative approach to the traditional EAE analysis based on the concept of anisotropy of the seismic deformation and the identification of damage patterns in Inca sites. We detail, first, the different types of earthquake-induced damage observed in nine archaeological sites around the Cusco Basin. We infer, then, the theoretical orientation of the ground movement using new statistical indicators and discuss the event(s) that may be responsible for the damage. The results support a limited impact of the 1950 Cusco ( $Intensity_{MAX} = VII$ ) earthquake and suggest instead a large impact of the 1650 event ( $Intensity_{MAX} = IX?$ ). Moreover, based on the consistency of the orientations of the ground movement on the regional scale and the clear difference of the damage patterns between colonial and Inca buildings, we hypothesize the impact of a seismic event prior to 1650, most probably during the late pre-Columbian period.

## **2. The Cusco area: tectonic and archaeological settings**

### **2.1. The Cusco Basin: an active tectonic landscape**

The Cusco region is located in the southeast of Peru and forms part of the Central Andes. The region extends on two distinct geomorphological units: the Eastern Cordillera to the north and the High Plateaus (*Altiplano*) to the south (Fig.1a). While Mesozoic sedimentary rocks associated with Cenozoic volcano-sedimentary units and magmatic intrusions form the High Plateaus (Fig.1b), the Eastern Cordillera is characterized mainly by metamorphic series and

igneous intrusions from the Paleozoic era (Cabrera et al., 1991). A major fault system known as the “Cusco-Vilcanota Fault system” (CVFS) separates these two domains (Cabrera et al., 1991; Carlier et al., 2005) and accommodates most of the current deformation of the High Andes in the area.



**Fig.1** a) Cusco regional map indicating the main active fault segments as well as the nine archaeological sites examined in the paper (in white). Black diamonds display the location of the dated Inca contexts presented in Fig.3a. Investigated faults with documented surface ruptures (historical and palaeoseismological studies) are highlighted in red. The geological zonation of the Andes is based on Dalmayrac et al. (1980); b) Cross section perpendicular to the Qoricocha, Tambomachay and Cusco faults in the west of the Cusco Basin (according to Wimpenny et al., 2020).



The geological investigations carried out around Cusco documented a large complex of active crustal faults (Sébrier et al., 1985; Cabrera et al., 1991; Benavente Escobar et al., 2013) that delimit the northern part of the intra-cordilleran basins, including the Anta-Chincheró and Cusco basins (Fig.1a). Being part of the CVFS, this active faulting is oriented NW-SE and predominantly extensional, with a normal motion roughly N-S (Sébrier et al., 1985; Cabrera, 1988; Mercier et al., 1992).

Several factors may explain the peculiar tectonic setting and stress field observed in the Cusco region. Extension seems to be due, notably, to gravity and buoyancy forces exerted by the uplifted thick crust above its isostatic equilibrium depth in the Eastern Cordillera (Suárez et al., 1983) and the change in the subduction geometry at this latitude (Sébrier et al., 1985).

The onset of the extension is estimated at ~5-9 Ma (Kar et al., 2016). The first E-W extensive phase from the Pliocene is followed by a N-S compressive phase during the Early Pleistocene. The current N-S extensive regime, which controls the subsidence and the filling of the Anta and Cusco basins, started during the Middle Pleistocene (Gregory, 1916; Cabrera et al., 1991; Mercier et al., 1992). Besides the hundred-meter scarps due to the cumulative Quaternary offsets, normal faults cut moraine deposits from the Last Glacial Maximum and/or Younger Dryas (Cabrera, 1988; D’Arcy et al., 2019) creating smaller fresh scarps (~1-10 m) and supporting therefore their recent activity (Fig.1-2). Through tectonic landform dating (radiocarbon and cosmogenic nuclides), Wimpenny et al. (2020) estimate a global extension rate of around 1-4 mm/yr in the area. Moreover, palaeoseismological studies carried out on Tambomachay, Qoricocha and Pachatusan faults evidence several palaeo-surface ruptures (Fig.1a) and point at return periods of approximately 1-2 kyr (Rosell Guevara, 2018; Palomino Tacuri et al., 2021).

Despite the moderate deformation rates affecting the Cusco region, the large uncertainties and shortfalls regarding the mapping and characterization of the faults (seismogenic potential, recurrence interval, etc.) hamper an accurate assessment of the regional seismic hazard. Besides Cabrera (1988, p. 206) who estimated the maximal moment magnitude that can be generated by the faults near Cusco at  $M_w=7.2$ , the historical local seismicity reminds us that earthquakes with lower magnitudes had yet severe human and material consequences.

In 1650 (Villanueva Urteaga, 1970; Julien, 1995), 1744 (Anónimo, 1819) and 1950 (Ericksen et al., 1954), three particular earthquakes struck the Cusco Basin (Tab.1), triggering rockfalls, landslides and damaging the Cusco monuments. The limited distribution of damage during these earthquakes suggests near-field (i.e., crustal faults) rather than far-field earthquakes (i.e., subduction). Moreover, no instrumental subduction earthquake has ever caused significant

damage that far from the trench in the Central Andes (Dorbath et al., 1990; Seiner Lizárraga, 2009; 2016). Nonetheless, the exact source of the ground motions is still a matter of debate. Too few active faults were subject of palaeoseismological trenches (in red in Fig. 1a) to provide conclusive answers.

Date	Epicentral area	Magnitude	Intensity in Cusco
05/04/1986	NW of Cusco	5.3 (mb) - 5.6 ( $M_w$ )	VI (EMS98)
21/05/1950	SW of Cusco?	6.0 (estim.)	VII (M.M.)
18/09/1941			VI-VII (M.M.)
19/11/1744			
31/03/1650	South of Cusco?	7.2 (estim.)	IX (M.M.)

**Table 1** Damaging historical earthquakes (1533 CE to present) that affected the Cusco Basin. The table presents the computed (mb,  $M_w$ ) or estimated magnitude as well as their estimated intensity felt in the city of Cusco. Intensities are based on Ericksen et al. (1954), Silgado Ferro (1978) and Tavera et al. (2016).

## 2.2. The Inca occupation and the conundrum of the megalithic architecture

The particular tectonic setting of the Cusco region generated a great diversity of landscapes and ecosystems that fostered human occupation (King and Bailey, 2006; Force and McFadgen, 2012). The first hunter-gatherer's settlements go back to ~10 kyr (Bauer et al., 2006) and several hierarchical polities and complex cultures have developed successively since the Formative period (2200 BCE-200 CE) until the Spanish conquest (1533 CE). However, settled close to active faults (e.g., Puka Pukara site; Fig.2), the archaeological remains may have been seriously affected by ancient earthquakes and may have kept traces of these events. The special quality and durability of the Inca stone buildings make them good seismoscopes (Combey et al., 2021) and a suitable case study for archaeoseismological investigations.

From the 13<sup>th</sup> century CE, archaeological evidence depicts the transformation of a small polity from the Cusco Basin, the Incas, into a centralized state (Bauer and Covey, 2002; Covey, 2006; Vranich et al., 2014; Bauer, 2018; Hardy, 2019). The state formation process provided the necessary conditions to the development of the Inca empire (~1438-1533 CE), whose city of Cusco turned into the geographical and political center (Beltrán-Caballero, 2013; Christie, 2016). The imperial period is associated with an unprecedented, rapid territorial expansion (from Ecuador to Chile) and the appearance of multiple innovations in the field of metallurgy, irrigation, agriculture and architecture (Protzen and Nair, 1997; Covey, 2006; Wright, 2006).



This is the case of the Inca monumental and fine stonework that is commonly regarded as coeval with the political and territorial climax of the empire.



**Fig.2** View of the Tambomachay Fault from the Puka Pukara site.

Unfortunately, the chronology of the imperial phase remains highly dependent on a limited number of Spanish sources (e.g., Murúa, 1590; Garcilaso de la Vega, 1609; Cobo, 1890; Huaman Poma de Ayala, 1979). The suddenness and the relative brevity of the period raise serious issues regarding the use of absolute dating methods. Recent results from new radiocarbon analyses and statistical models (Marsh et al., 2017; Meyers, 2019; Burger et al., 2021) tend, nonetheless, to question – or even challenge – the traditional Inca chronology (Rowe, 1945) by suggesting an onset of the imperial expansion several decades earlier. This controversy raises serious questions about the factors of Inca expansion and the driving forces behind the development of megalithic architecture.

Currently, the few radiocarbon dates available (from different sources and of varying quality), do not enable the refinement of the chronology in the Cusco region and date precisely the onset of the imperial phase and architecture. The overview of the different dates provides, though, a relevant *terminus post quem* of the monumental stone masonry in the Heartland of the Incas. Figure 3a displays the radiocarbon dates – coming from sites around Cusco (Fig.1) occupied during the imperial phase that we recalibrated based on the Mixed Curve method detailed by

Marsh et al. (2018). While the largest and finest examples of imperial architecture (e.g., Chinchero, Pisaq, and Cusco) seem to be unique building projects initiated by Inca rulers during the second half of the 15<sup>th</sup> century according to colonial sources, the data indicate a lower bound of the monumental architecture at the beginning of the 15<sup>th</sup> century. The Inca monumental architecture and its different types of fine dry-stone masonry styles (Gasparini and Margolies, 1980; Agurto Calvo, 1987) seem to have, therefore, extended over ~150 years, until the fall of the Inca empire in 1533 CE. However, the peculiar stone cutting and laying techniques (Protzen, 1985; Protzen and Nair, 1997; Nair and Protzen, 2015) were not lost immediately after the Spanish arrival. Many colonial buildings in Cusco were indeed built by the Spanish elite in a mock Inca style, known as “neo-Inca” (Nair, 2003), until the late 16<sup>th</sup> century (Trever, 2005). The Inca architecture represents thus a unique opportunity to improve the earthquake catalog over a period of ~650 yr.

### **3. Methods**

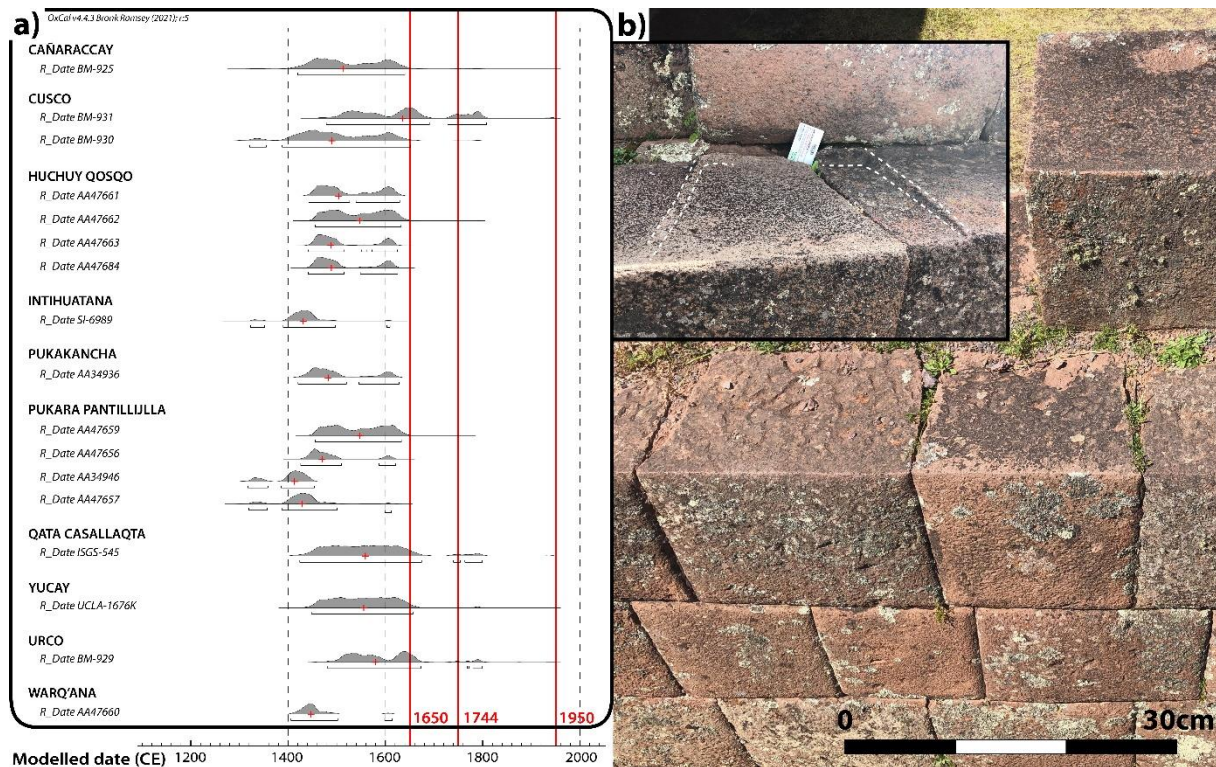
#### **3.1. Statistical analysis of the EAEs**

The seismic wave propagation and/or the ground deformation following a fault rupture generates several and distinctive types of strain structures in building fabrics. In archaeoseismology, an unequivocal characterization and quantification of such evidence turn out to be, a key step in proving or ruling out the occurrence of a seismic event (Rapp, 1986; Stiros, 1996; Ambraseys, 2006). In the framework of this research, we rely on the well-established “Earthquake Archaeological Effect” (EAE) classification established by Rodríguez-Pascua et al. (2011) and adapted to the Inca context by Combey et al. (2021).

In 2019, we carried out a large and unprecedented archaeoseismological survey of Inca sites in the Cusco region (Combey et al., 2021). The sites were selected based on their monumental and fine stone architecture that is well suited to register the impact of past earthquakes. In this paper, we focus on the data collected in the nine sites located within the Cusco Basin or close to it (Fig.1a - Supplementary). Those remains surround the Qoricocha-Tambomachay-Pachatusan fault complex and lie in close proximity to one other. Sharing the same tectonic environment, these sites are thus a good opportunity to compare the archaeoseismological results at a regional scale.

As previously noticed by Combey et al. (2021), two types of off-fault effects constitute most of the EAEs registered during the archaeoseismological survey (~97%) and are numerous enough to carry out statistical analysis (see Supplementary): the Displaced Masonry Blocks (DMB) and

the Dipping Broken Corners (DBC). The latter are generated by vertical oscillatory movements of blocks and may occur everywhere in the masonry (embedded or in the free-ends of walls). While not prone to collapse due to their well-fitted stonewalls (Fig.3b), Inca fine dry-joint masonry can be damaged by strong ground shakings (Ericksen et al., 1954; Hinzen and Montabert, 2017). By exceeding the internal friction forces, strong transient vibrations generate strain structures like the DBC and DMB.

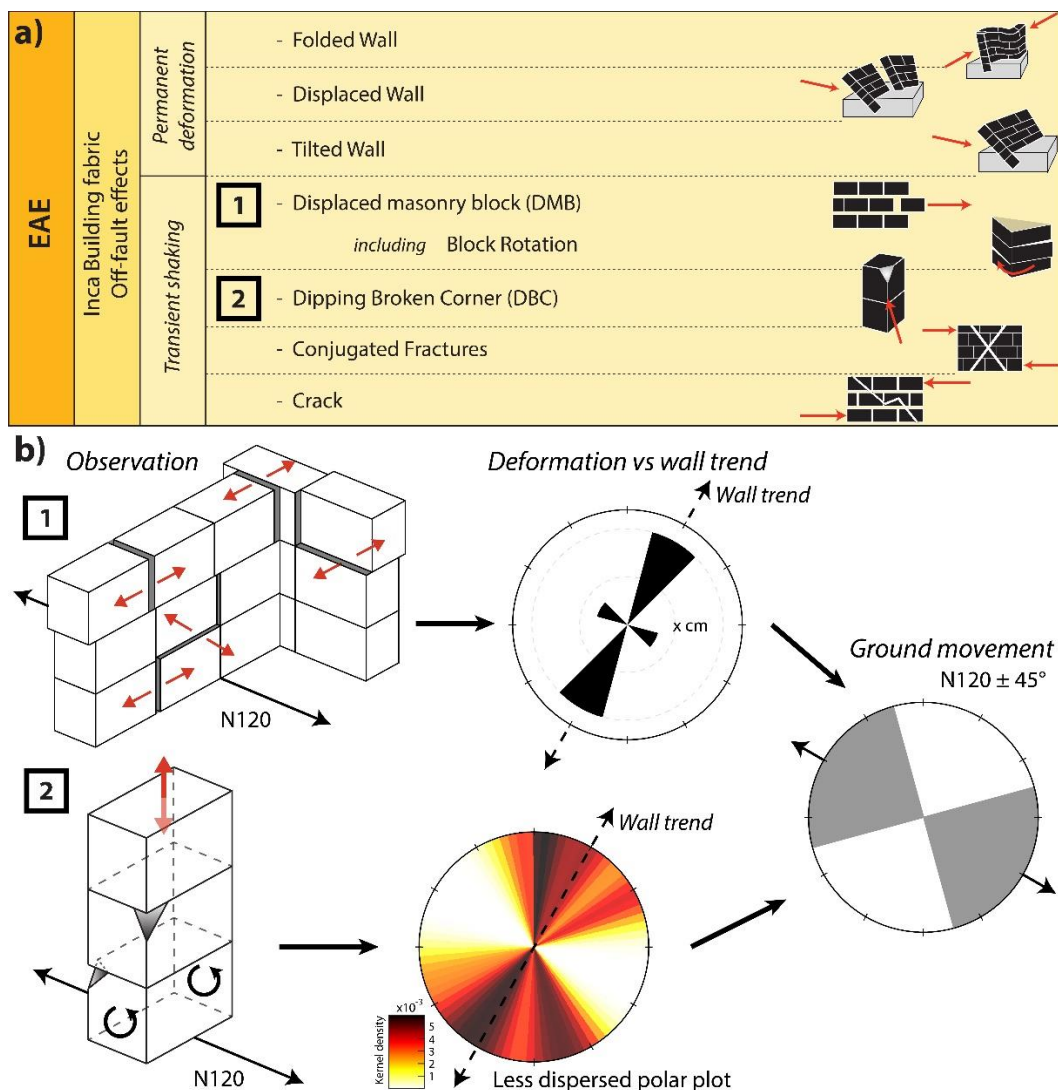


**Fig.3** a) Radiocarbon dates coming from 10 archaeological contexts of the Cusco region and belonging to the Inca Imperial phase (recalibrated with the mixed calibration curve using OxCal v5; Hogg et al., 2020; Reimer et al., 2020). The red crosses correspond to the median values. The red vertical lines indicate the three main damaging earthquakes that occurred in Cusco since the 16<sup>th</sup> century. No earthquakes are documented prior to 1650; b) The typical Inca coursed ashlar masonry (Pisac site). As shown by the stone footprints in the inset (dashed lines), each block was fitted individually to lay perfectly on the masonry course below, enhancing the whole stability of the structure.

Most of the EAEs (Fig.4a) are supposed to be “preferentially oriented” towards the direction of arrival of the seismic wave and their analysis was thus proposed to retrieve seismic sources. This assumption, which has only been tested on two instrumental earthquakes (Giner-Robles et



al., 2012; Rodríguez-Pascua et al., 2012), is still a matter of debate (e.g., Hinzen, 2009; Hinzen et al., 2016). Due to the complexity of real seismic signals, it is difficult to correlate the isolated behavior of architectural features in a given site to ground motion without taking into account additional factors such as geometry, friction or orientation of the structures, or even soil properties. It is, therefore, even more complex to associate the ground movement inferred at the scale of a building or site with the direction of the seismic wave because of the multiple factors involved (site effects, frequency content, etc. — e.g., Stiros, 2020).



**Fig.4** a) Main types of off-fault effects recorded in the Inca building fabric; b) Following an earthquake, the deformation features are not homogeneously distributed in structures. Diagrams summarize a hypothetical circular distribution of cumulative gap openings and DBC's dip directions in case of a seismic impulse oriented N120. Based on the field observations and the preferential deformation of walls oriented N030, the archaeoseismological approach enables to infer a ground movement oriented ~NW-SE (shaded area: N120 ±45°).

The objective of this paper is not to replicate the existing EAE analysis but to discuss and complete this approach. To do so, we found it necessary to take into account the results of numerical simulations. Considering, for instance, a ground shaking oriented mainly N120, structures oriented N30-210 would be the first to partially or completely collapse (Hinzen and Montabert, 2017). However, regarding isolated EAEs, such as block slides or Dipping Broken Corners, numerical results challenge some of the assumptions proposed in the EAE analysis (Hinzen, 2009; Caputo et al., 2011). The behavior is much more complex and is deeply influenced by external factors such as geometry, friction and structure orientation. Hence, a comprehensive EAE analysis is needed and new criteria must be established.

In Inca fine masonry, cut stones are closely fitted, meaning that there is ideally no gaps between them (Fig.3b). In this study, we consider therefore as anomalous any gap opening greater than or equal to 0.3 cm. Due to the two degrees of freedom of block displacements in masonry walls, seismic shaking can produce both in-plane (i.e. parallel to the wall trend) and out-of-plane (i.e. orthogonal to the wall trend) DMB. In a similar way as the direction of rotation of blocks (Hinzen, 2012), the complexity of the real ground motions seems to support a random distribution of in-plane and out-of-plane displacements. No direct correlation can be demonstrated between the occurrence of in-plane displacements, the wall trend and the orientation of the ground movement (Caputo et al., 2011). Numerical simulations on rectangular block walls and polygonal walls similar to Inca fine masonry (Hinzen and Montabert, 2017) supported, nonetheless, a differential vulnerability of the walls according to their orientation.

In other words, the walls orthogonal to the seismic impulse presented the largest amount of DMB, whether in-plane or out-of-plane. In this work, we assimilated this impulse to the local orientation of the ground movement. Assuming the seismic origin of the deformation features, we may thus expect, at the site scale, a preferential occurrence of block displacements in the wall trend (sub)orthogonal to the ground movement. Rather than a straightforward directivity of the EAEs, we address the broader concept of the anisotropy of the deformation, i.e. a differential vulnerability of the structures according to their orientation. We computed the cumulated amount of DMB (both in-plane and out-of-plane sliding) and sorted the result into four classes according to the wall's orientation in which displacements take place. We normalized, then, the cumulative gap openings, in each class, per 100 m of surveyed walls. We calculated the length of surveyed walls based on the following principle: we considered only the fine dry-stone masonry walls on which we identified at least one EAE (see Supplementary). Regarding wall's orientations, although the mean orientation of wall trends does not match perfectly with the cardinal directions (N0, N45, N90 and N135 – Tab.S1), we used likewise the

four previous classes (N-S, NE-SW, E-W and NW-SE) for the sake of convenience and simplicity. We plotted the cumulated amount of displacements according to the wall's orientation on a rose diagram. Based on the results of Hinzen and Montabert (2017), the impulse, or ground movement, was considered as (sub)orthogonal to the most affected wall trend ( $\pm 45^\circ$  – Fig.4b-1).

The number of Dipping Broken Corners (DBC) and the orientation of their fracture plane might also provide relevant insights on the direction of the ground shaking. However, contrary to the assertion from Rodríguez-Pascua et al. (2011), we consider that a statistical analysis of the DBC's dip directions is not sufficient to reach firm conclusions. At first sight, it seems, indeed, logical that the corners would fracture at an angle close to  $45^\circ$  with respect to the orientation of the wall and that this physical constraint represents a serious bias to the assumed directivity of the DBC. If so, the distribution frequency of the dip direction will be function of the proportion of the wall trends in the sample. In a similar fashion to the analysis of block displacements, we sorted the DBC into four classes according to the orientations of the walls in which they occur. We normalized, then, the number of chipped corners, in each class, per 100 m of surveyed walls.

Moreover, we plotted the frequency of DBC's dip directions for each class of walls. To this end, we computed the kernel density estimation of the DBC's dip directions with a bandwidth of  $10^\circ$  (Fig.4b-2). Stereograms were plotted by using the polarPcolor script developed by Cheynet et al. (2017) and available on Matlab (doi: 10.5281/zenodo.4463464). Thanks to the data smoothing, the kernel density estimation provides an unambiguous representation less dependent on the bin settings (centered or not, size) than the rose diagrams.

The outputs will enable us to address the following assumptions:

- Due to the elongated shape of the stone blocks (Fig.3b), the vertical oscillatory movement responsible for the chipped corners, is likely to occur as a roll motion of the blocks within the masonry (Fig.4b-2). This specific motion, and the chipping marks, might thus occur preferentially in the walls positioned perpendicular to the ground movement;
- Constrained by the wall's orientation, the dip direction of the DBC should be within a fixed angular range around the wall trend ( $\pm 45^\circ$ ). However, according to the first assumption, we may also expect a smaller dispersion of the dip directions within the walls (sub)orthogonal to the ground movement. This dispersion will be estimated by computing the proportion of dip direction within the range “*Wall azimuth*  $\pm 45^\circ$  & *Wall*



*back azimuth*  $\pm 45^\circ$  ( $\sigma_{50}$ ). In the case of a homogeneous distribution, the  $\sigma_{50}$ -value represents thus 50% of the sample. The higher is the indicator, the smaller is the dispersion with respect to the wall's orientation.

By combining the statistical results on the DMB (block displacements) and DBC (chipped corners), we will be able to discuss the damage distribution and pattern according to the wall trends, and propose a  $90^\circ$  angular range comprising the orientation of the ground movement generated by the earthquake (Fig.4b). We must point out that we are not yet able to associate the inferred ground movement with either the direction of the seismic ray (primary pulse) or the orientation of the wave front. Further research is required, particularly in the field of numerical modelling in order to test the latter. That is why no conclusion on the source location of the earthquakes can be drawn at this stage. The orientations of the ground movement on a regional scale are only used to detect potential discrepancies and thus discriminate between the impact of several earthquakes.

Thanks to the database used during the archaeoseismological survey, we assigned a qualitative level of confidence defining the probability of the seismic origin (“Low”, “Medium” and “High”) of each EAE identified. The criteria established to assign the levels of confidence are detailed in Combey et al. (2021). This paper examines the DBC and DMB with a robust level of confidence (“Medium” and “High”).

### 3.2. The use of historical photographs

Dating the EAEs, i.e. associating them to a specific seismic event, is often the most difficult part of the archaeoseismological approach, particularly in the Andes, where still few investigations have been made and where sources on (pre)historical crustal earthquakes are rare (Dorbath et al., 1990; Combey et al., 2021). Regarding modern seismic events, the photos constitute a relevant source of information for the reconstruction of the main earthquake parameters (Rodríguez-Pascua et al., 2017). In the region of Cusco, where successive strong ground motions occurred, the historical pictures may be a valuable way to assess the impact of the 20<sup>th</sup> century earthquakes and constrain chronologically the EAE occurrence.

Considering the recent historical seismicity of the Cusco region, we decided to review the rich collection of photographs taken during the first half of the 20<sup>th</sup> century by a Peruvian photographer (M. Chambí) and foreign travelers (M. Uhle, B. Hassel and F. Scherschel) and in the aftermath of the 1950 earthquake (Getty Conservation Institute, Life Pictures). We

concentrated our efforts on photos from the city of Cusco, which accounts for the greatest number of historical documents.

We identified first the EAEs and structural damage affecting Inca and neo-Inca buildings visible in pre-1950 pictures and compared then the results with post-1950 photographs. Although those documents are only one-off evidence of the damage caused by the last major earthquake that struck Cusco and its region, we considered them as a good indicator of the impact of this latter event on the Inca architecture.

## 4. Results

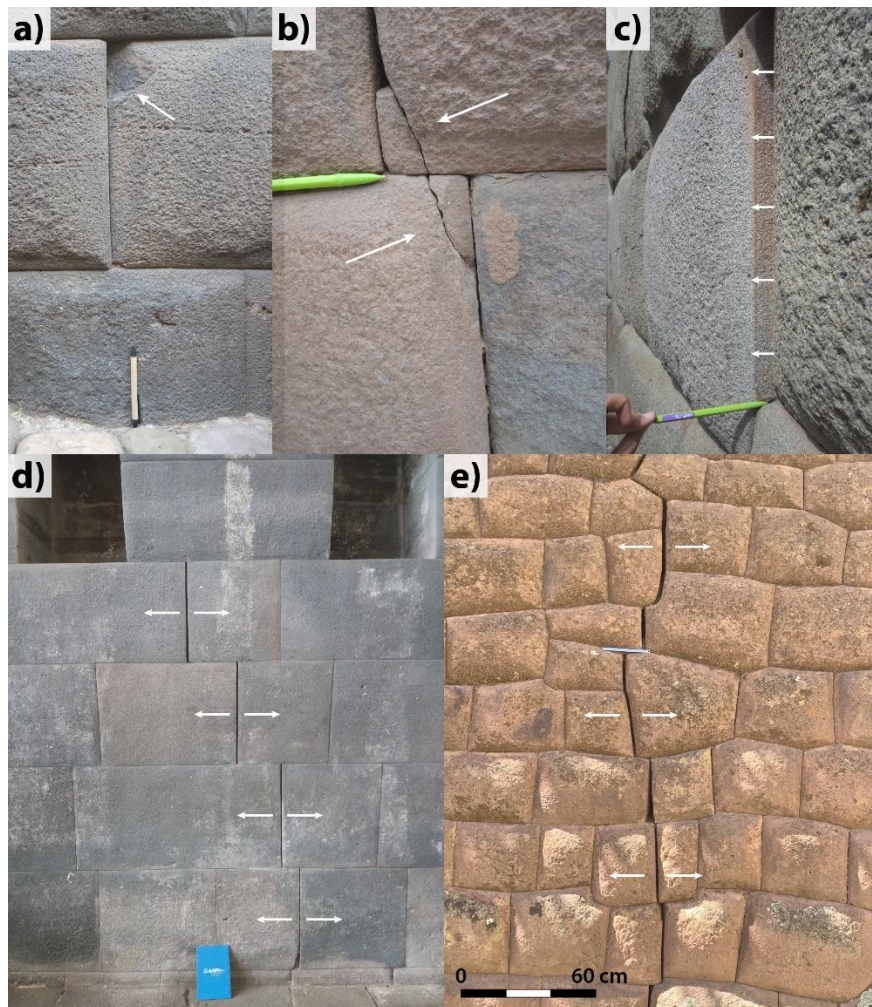
### 4.1. Assessing the anisotropy of the seismic deformation

We registered 2,980 EAEs in the nine archaeological sites (Fig.1a), including 2,907 DBC and DMB (Fig.5). Among those latter, 2,171 (~75%) were associated with a medium or high level of confidence regarding their seismic origin (see Supplementary). First, we should mention that the reduced number of EAEs identified in the sites of Inkilltambo, Tambomachay and Tipón as well as the reduced size of the surveyed areas in Inkilltambo and Tambomachay did not enable to get significant statistical results. Additionally, we were not able to estimate correctly the wall length in Tipón due to the great geographical dispersion of the EAEs collected. (Tab.2). Hence, although these three sites show clear evidence of a seismic impact, the data collected will not be further discussed.

Table 2 shows the number of Dipping Broken Corners as well as the cumulated amount of displacement with regard to the wall trend. At first sight, we note a great disparity in the results. In four out of six sites (e.g., Cusco, Chinchero and Puka Pukara), the largest number of DBC and the amount of displacement do not point at the same wall trend. However, as highlighted in Section 3.1, this disparity is mainly due to the unequal representation of wall classes (Tab.2), in terms of length surveyed.

The results are much more consistent when we normalize both indicators per 100 m of surveyed walls (Fig.6). In five out of the six remaining sites, we observe a good consistency between the wall classes affected by the greatest number of normalized DBC ( $DBC_{norm}$ ) and the ones affected by the largest normalized cumulated amount of DMB ( $DMB_{norm}$ ). In Puka Pukara, the apparent discrepancy is not relevant. The largest number of  $DBC_{norm}$  in the “N-S” class is probably due to the reduced length of N-S walls surveyed (Tab.2). The second largest value, belonging to the “NW-SE” class, is consistent with the largest amount of displacement (Fig.6). In a similar fashion to the Displaced Masonry Blocks, these results support, therefore, that the

DBC are heterogeneously distributed in structures and occur preferentially in walls sub(orthogonal) to the ground movement.



**Fig.5** Examples of EAAs registered on the field. The more common evidence are the DBC (a-b) and the out-of-plane (c) / in-plane DMB (d-e).

Located a few hundred meters from the site of Warq'ana (Fig.1a), where archaeological excavations have shown the consequences of an earthquake on early Inca structures (Kendall et al., 1992), the case of Huchuy Qosqo is particularly noteworthy. Figure 7 displays the frequency of the DBC's dip direction for the two main wall trends. The size of the polar plots depends on the number of DBC per 100m of surveyed walls. First, the orientation of the walls has a deep impact on the angular distribution of the DBC's dip direction. We observe, indeed, a high proportion of the dip directions in a range  $N000-060 \pm 180^\circ$  regarding the N-S walls (azimuth: N025), whilst the highest proportion lies within the range  $N060-130 \pm 180^\circ$  for the E-W walls (azimuth: N115), i.e., within the predicted angular range "wall azimuth  $\pm 45^\circ$ ".

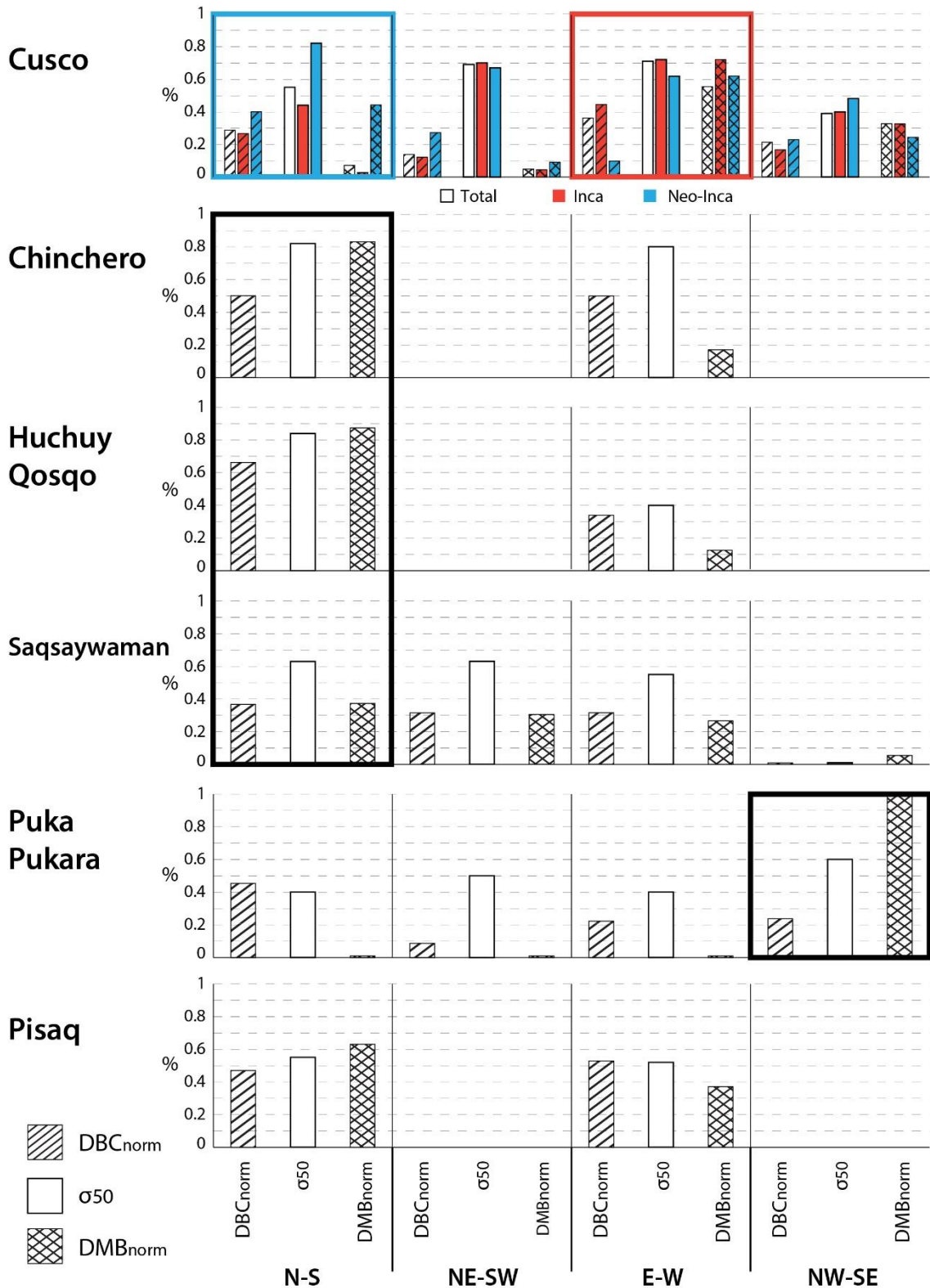
Sites	N-S			NE-SW			E-W			NW-SE		
	W. length (m)	DBC (n)	DMB (cm)	W. length (m)	DBC (n)	DMB (cm)	W. length (m)	DBC (n)	DMB (cm)	W. length (m)	DBC (n)	DMB (cm)
Cusco	362	114	10.5	1278	<b>186</b>	25.8	443	168	99.2	756	175	<b>102.2</b>
<i>Inca</i>	335	81	3.7	1209	129	22.2	374	<b>147</b>	<b>90.4</b>	640	94	86.1
<i>Neo-Inca</i>	27	33	6.8	69	57	3.6	69	21	8.8	116	<b>81</b>	<b>16.1</b>
Saqsay.	367	26	190.6	283	16	120.9	692	<b>40</b>	<b>258.4</b>	177	0	13.7
Chincheró	245	55	<b>60.9</b>				390	<b>85</b>	19.9			
Pisac	308	419	<b>73.7</b>				310	<b>474</b>	43.3			
Puka Pukara	8	5	0	86	10	0	49	<b>15</b>	0	30	10	<b>23.9</b>
Huchuy Q.	24	<b>21</b>	<b>157.5</b>				33	15	31.0			
Inkill.	20	5	18.4				54	16	0			
Tambom.	3	6	0	6	2	0	10	3	0	3	5	0
Tipón	0	28	0	0	0	0	0	8	0	0	1	0

**Table 2** Length of the surveyed walls for each class of wall’s orientation and each archaeological site compared to the number of DBC and the cumulated amount of DMB (High and Medium levels of confidence) sorted by the wall trend along which they occur. Highest values are highlighted in bold. Archaeological with no statistically significant results are shaded in grey.

Secondly, the angular distribution pattern seems to be distinct depending on the wall's orientation. In Huchuy Qosqo, the N-S walls affected by the greatest number of normalized Dipping Broken Corners and the largest normalized cumulated amount of DMB also show a smaller dispersion of the data around the wall azimuth. The  $\sigma_{50}$ -value is indeed two times greater for the N-S walls (0.84) than for the E-W walls (0.40 – Fig.6. and 7a-b). This observation tends to confirm the second assumption made in 3.1. The dip direction of the chipping marks is less dispersed in walls (sub)orthogonal to the ground movement. Such observation and the related damage mechanism will require to be clarified by theoretical deformation models.

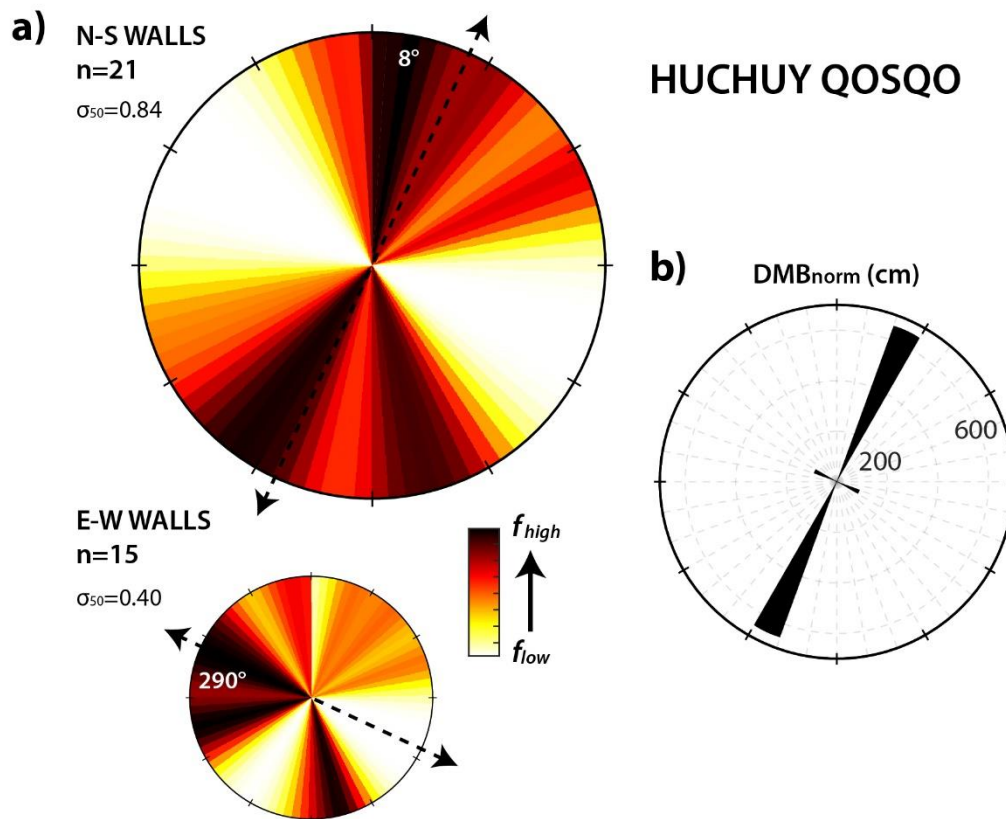
Regarding the other sites, the results of the  $\sigma_{50}$ -value demonstrate a good consistency with the  $DBC_{norm}$  and  $DMB_{norm}$ -values (Fig.6). Only the site of Písaq shows inconclusive results. We may highlight nonetheless the great homogeneity of the EAE distribution with respect to the wall's orientation. The case of Písaq will be discussed more thoroughly in the following section.





**Fig.6** Percentage of the normalized number of DBC (hatched bars) and normalized cumulated amount of DMB (crosshatched bars) according to the wall's orientation. The  $\sigma_{50}$ -value (solid bars) is also reported. Classes with the highest rates are highlighted in boxes. Only the six archaeological sites with statistically significant results are represented. Detailed information is provided in Tab.S2-S3.





**Fig.7** a) Polar plots displaying the kernel density function of the DBC's dip direction in the site of Huchuy Qosqo. The size of the plots is function of the  $DMB_{norm}$ -value. The dotted arrows indicate the wall trends; b) Normalized amount of displacement according to the wall trends.

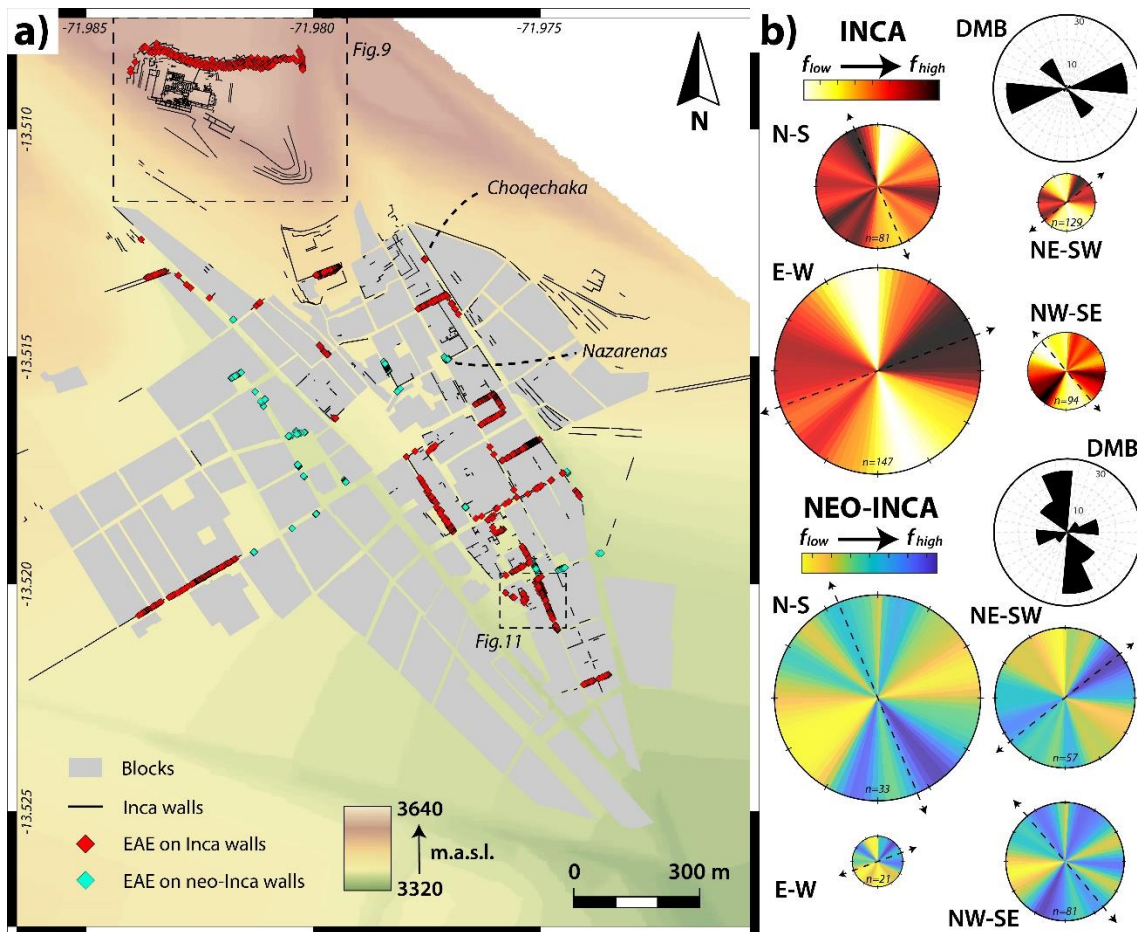
#### 4.2. EAE analysis at a local and regional scale

Six investigated archaeological sites present a number and density of EAEs sufficient to derive the orientation of the ground movement. Comparing the results provides a valuable opportunity to improve our knowledge on the Cusco (pre)historical seismicity. According to the degree of consistency of the inferred ground movement on the local and regional scales, we may hypothesize the impact of one or more damaging seismic events on the Inca settlements.

Before 1533 CE, the Inca settlement of Cusco included both the current city and the ceremonial complex of Saqsaywaman (Beltrán-Caballero, 2013; Bauer, 2018 – Fig.8a). We decided here to present the results separately due to the different geological contexts and architectural layouts.

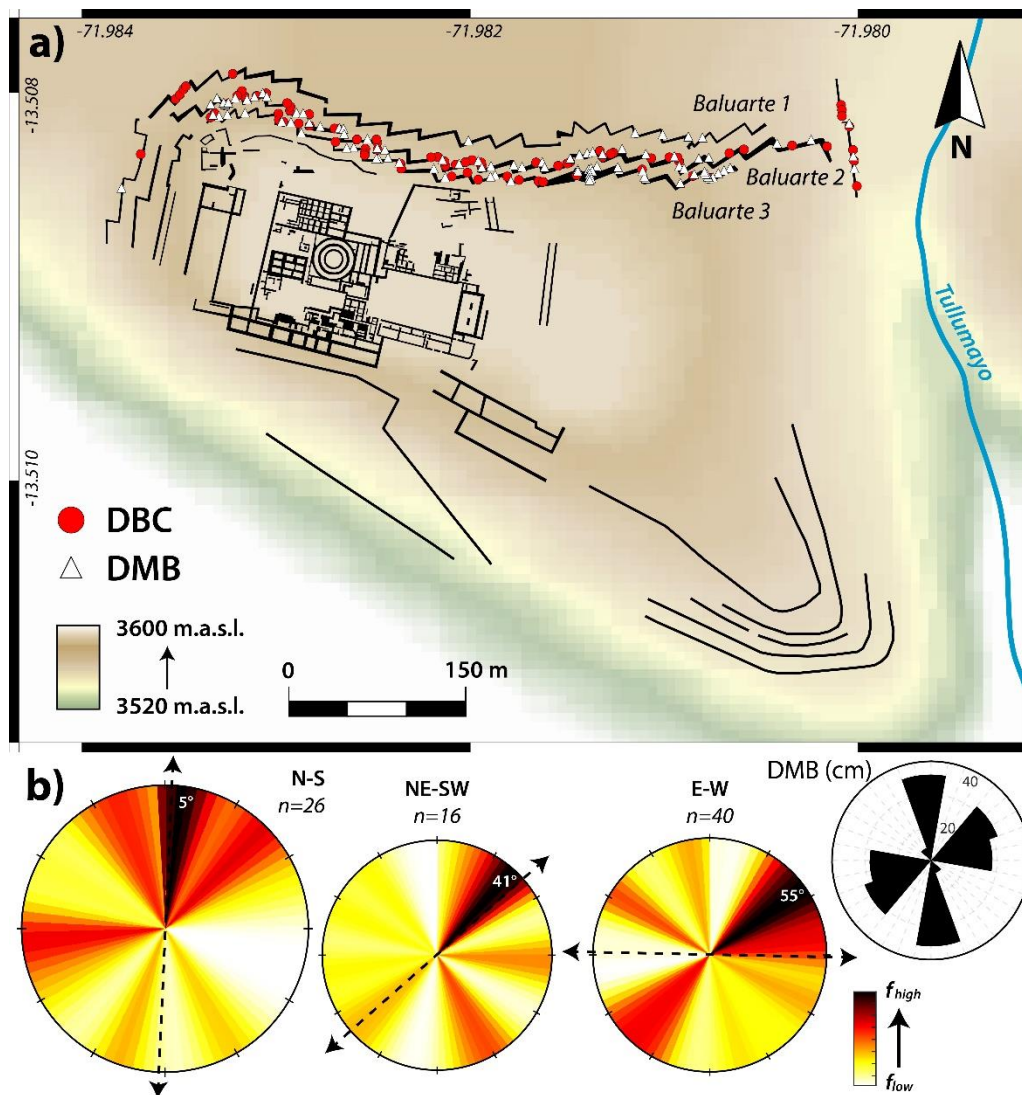
In the historic city center of Cusco, 643 DBC and 64 DMB were registered. By taking into account the length of the surveyed walls, the greatest number of Dipping Broken Corners occurs in the E-W walls (N075/255). The normalized amount of displacement ( $DMB_{norm}$ ) gives similar

results (white bars in Fig.6). However, we registered EAEs on two types of buildings with fine stone masonry styles that dot the city of Cusco, the Inca and neo-Inca (colonial) ones. By splitting the data based on this criterion, we observe a marked discrepancy in the results (red and blue bars in Fig.6). On neo-Inca structures (blue diamonds on Fig.8a), the N-S walls (N160/340) are preferentially affected by the DBC and DMB (Fig.8b). In contrast, the E-W trend is even stronger in the Inca remains (red diamonds in Fig.8a) than in the whole dataset (Fig.6 and 8b). While the distribution of the deformation in neo-Inca buildings supports a ground movement oriented ~E-W, the distribution of the damage in Inca buildings indicates rather a N-S impulse. This sharp difference suggests the impact of, at least, two distinct seismic episodes on the Cusquenian architecture.



**Fig.8** a) EAE distribution within the city of Cusco. Damage on Inca and neo-Inca walls are represented respectively in red and blue; b) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to the wall's orientations on Inca and neo-Inca walls. Polar plots are sized based on  $DBC_{norm}$ . Credits DEM and Inca walls: Instit. Nacional de Cultura, Center for Advanced Spatial Technologies (Univ. Of Arkansas) & Cotsen Institute for Archaeology (UCLA).

In Saqsaywaman, we surveyed mainly the three cyclopean terraces (*baluartes* in Spanish), which border the site to the north (Fig.9a). These structures have four distinct orientations: N005/185 (N-S), N050/230 (NE-SW), N090/270 (E-W) and N140/320 (NW-SE). While the  $DBC_{norm}$ -value is slightly greater in the N-S walls and the distribution of the dip directions ( $\sigma_{50}$ ) is less scattered in the N-S and NE-SW orientations, the normalized cumulated amount of Displaced Masonry Blocks points towards the N-S orientation (Fig.6 - Fig.9b). We may assume, therefore, a ground shaking oriented E-W. The results do not match thus with the data presented in the Inca remains of Cusco, in spite of their close proximity.



**Fig.9** a) EAE distribution in Saqsaywaman (walls based on Beltrán-Caballero, 2013); b) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to the wall's orientations. Polar plots are sized based on  $DBC_{norm}$ . Credits DEM: Instit. Nacional de Cultura, Center for Advanced Spatial Technologies (Univ. Of Arkansas) & Cotsen Institute for Archaeology (UCLA).

Outside Cusco, four sites have a statistically relevant dataset: Puka Pukara, Chinchero, Huchuy Qosqo and Písaq (Fig.10 - Fig.S2-S3-S4). Settled on a top of a hill, Puka Pukara (Fig.2) shows a non-orthogonal layout and thus a great diversity of wall trends. The greatest  $DBC_{norm}$ -value corresponds to the walls oriented N-S (Fig.6). However, the very short length of surveyed walls in this class (8 meters) introduces a statistical bias. The second greatest value, in the NW-SE orientation, also coincides with the largest cumulative gap openings (79.7 cm/100m) and the highest  $\sigma_{50}$ -value (0.60). The deformation occurs thus preferentially in the NW-SE walls and indicates an impulse oriented approximately NE-SW (N050/230).

The archaeological site of Chinchero shows an equal normalized number of DBC for both classes of wall's orientations (Fig.6). The  $\sigma_{50}$ -value is, though, slightly greater in the N-S group and the  $DMB_{norm}$ -value is significantly higher in the same orientation (Fig.6). We postulate, therefore, a preferential distribution of the deformation generated by a ~E-W impulse (N095/275).

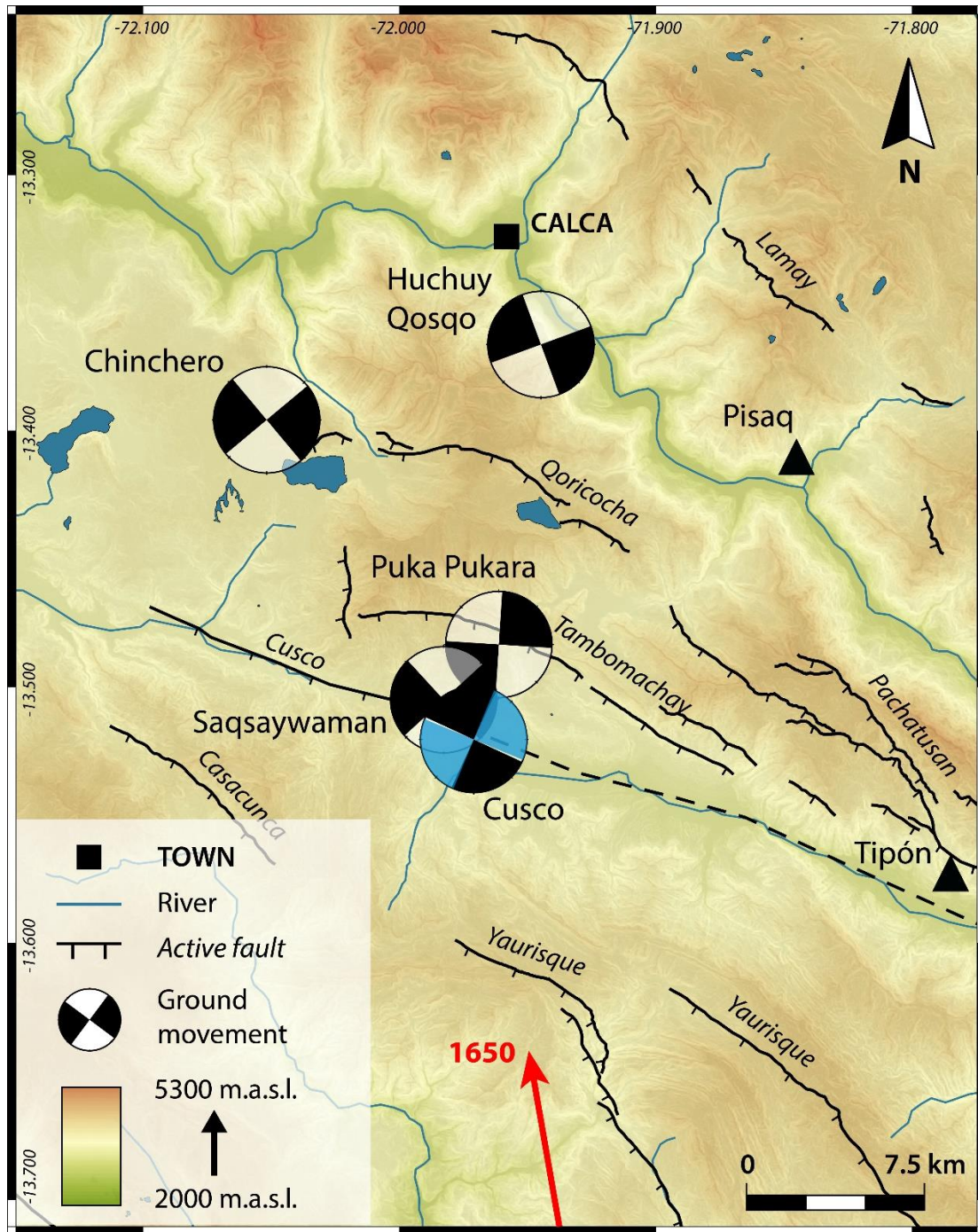
As previously outlined in Section 4.1, the surveyed Inca architecture of Huchuy Qosqo is characterized by a strong anisotropy of the seismic deformation. The three studied criteria (Fig.6) point all to a ground movement oriented E-W (N115/295).

Finally, the results obtained in Písaq (Intiwatana sector – see Supplementary) are less conclusive. Very similar for both wall trends, the  $DBC_{norm}$ , the  $\sigma_{50}$  and the  $DMB_{norm}$ -values do not point at a preferential distribution of the deformation (Fig.6 - Fig.S3). We may raise the four following reasons:

- 1) The seismic deformation results from a unique seismic event. The main impulse associated with this event was almost “bisecting” the two main wall trend, i.e. N050/230, inducing isotropic deformation of the buildings;
- 2) The sector investigated is situated on a crest oriented N-S, artificially flattened during pre-Columbian times. We may suppose a peculiar topographic effect in case of ground shakings generating isotropic deformation of the buildings;
- 3) The damage results from two or more events, leading to a more complex deformation pattern. These events would have occurred prior to the construction of the other Inca sites or would have not reached a sufficient local intensity in the other places to generate substantial damage;
- 4) The heterogeneity may result from the instability of the slopes on which the remains are located. In Písaq, the geomorphological hazard is high and several landslides occurred nearby (Carreño Collatupa, 2006; Vílchez Mata et al., 2020).



At this stage of our investigations, we are unable to choose between these four hypotheses.



**Fig.10** Map of the Cusco Basin showing the orientation of the ground movement (black) inferred for the Inca remains surveyed. The ground movement assessed for the neo-Inca architecture is displayed in blue. The red arrow indicates the direction of the 1650 ground shaking mentioned in colonial sources (Villanueva Urteaga, 1970).

#### 4.3. A limited impact of the 1950 earthquake

The last earthquake that severely struck the city of Cusco and its surroundings occurred on May 21, 1950. At that time, the first seismological network was not yet installed in Peru hampering any precise location and characterization of the ground motion. Field campaigns and architectural surveys were, nonetheless, conducted quickly after the earthquake to inventory and map the main consequences and to assess the seismic intensities (Ericksen et al., 1954). Interestingly, several observers pointed out the slight impact of the earthquake and the post-seismic sequence on Inca remains (d'Harcourt, 1950; Kubler, 1952; Ericksen et al., 1954). Comparing the photographs taken after the 1950 earthquake with the pictures from the early 20<sup>th</sup> century is a unique opportunity to check the previous statements and address the impact of a local seismic intensity (estimated around VI-VII on the M.M. scale) on the Inca fine masonry. We present here the result of the analysis of historical pictures of two Inca and one neo-Inca structures of Cusco (Fig.8a): respectively the Qorikancha, an Inca doorway in Choqechaka street and the House of the Snakes (*Casa de las Serpes*).

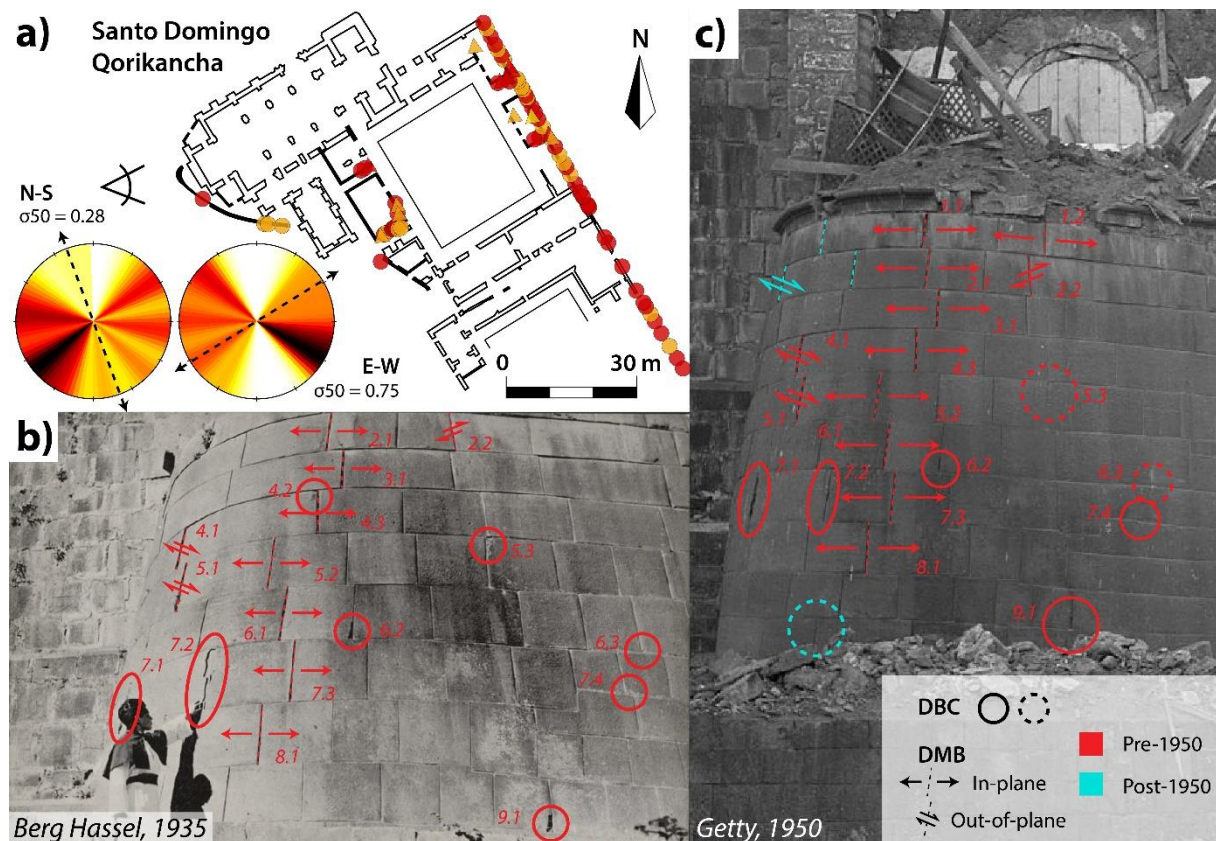
Regarding the Qorikancha (Santo Domingo Convent), Ericksen et al. (1954, p. 101) noticed that, unlike the majority of “the stone walls and doorways constructed by Incaic artisans” were “nearly all intact and show no effects of the earthquake”, “at the Iglesia (church) of Santo Domingo a few large Incaic stones were cracked, corners of others were chipped, and others rotated as much as a centimetre from their original position.” Moreover, in his report on the restoration works carried out by UNESCO immediately after the 1950 earthquake, Kubler (1951, p. 2) also noted the pre-existence of large cracks and openings on the famous curved wall of the Qorikancha (Fig.11c). He ascribed the damage to the seismic activity and the weight of the colonial convent built upon it.

The photo from Berg Hassel in 1935 (Fig.11b) confirms the pre-existence of many of those strain structures. We identified, indeed, only four new features on the building after the 1950 earthquake out of the 23 EAEs (Fig.11c - Fig.S9-S10). A large majority of the Displaced Masonry Blocks affecting the curved wall since the early 20<sup>th</sup> century occurred at the northern extremity where we may observe a change in the terrace's orientation (Fig.11).

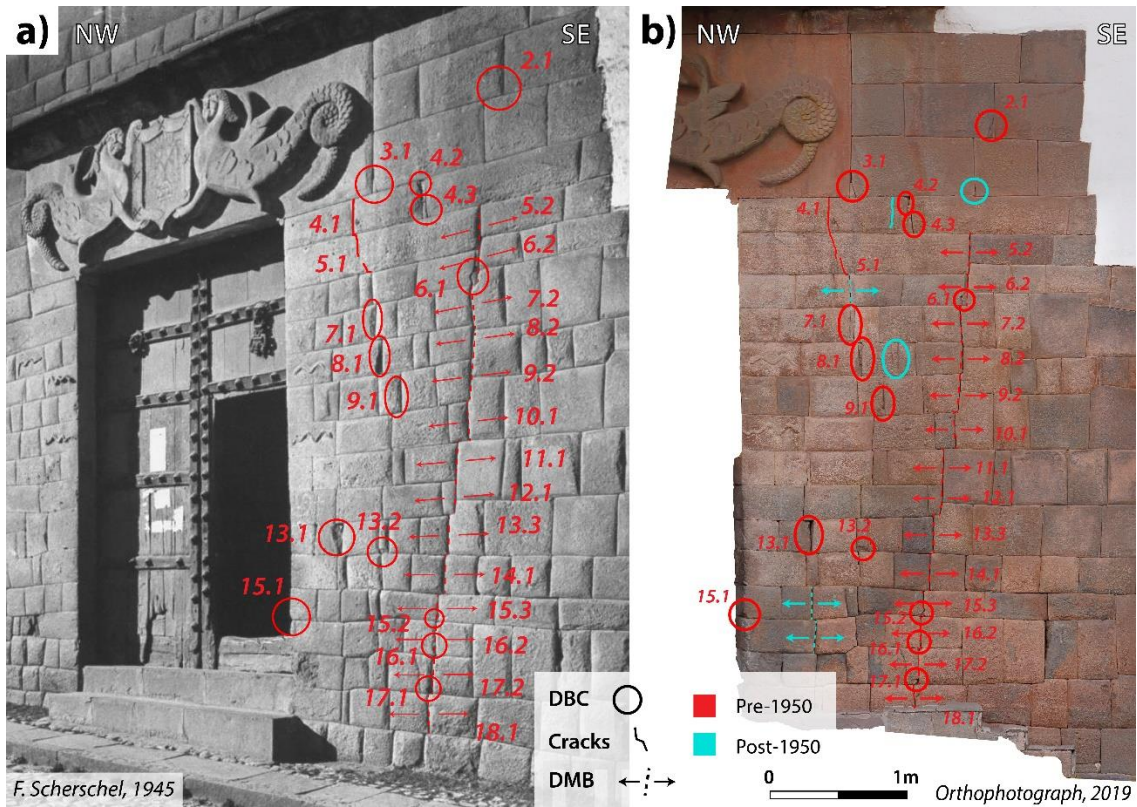
The pre-existence of earthquake-induced damage on Inca and neo-Inca stone architecture does not seem to be limited to the Qorikancha as demonstrated by Figures 12 and 13. Regarding the *Casa de las Serpes* on the Nazarenas square, several DMB and DBC affecting the western façade and registered during the archaeoseismological survey appear to date, at least, from the 1940s (Fig.12). Besides the evidence of restoration of the Inca doorway in Choqechaka Street,



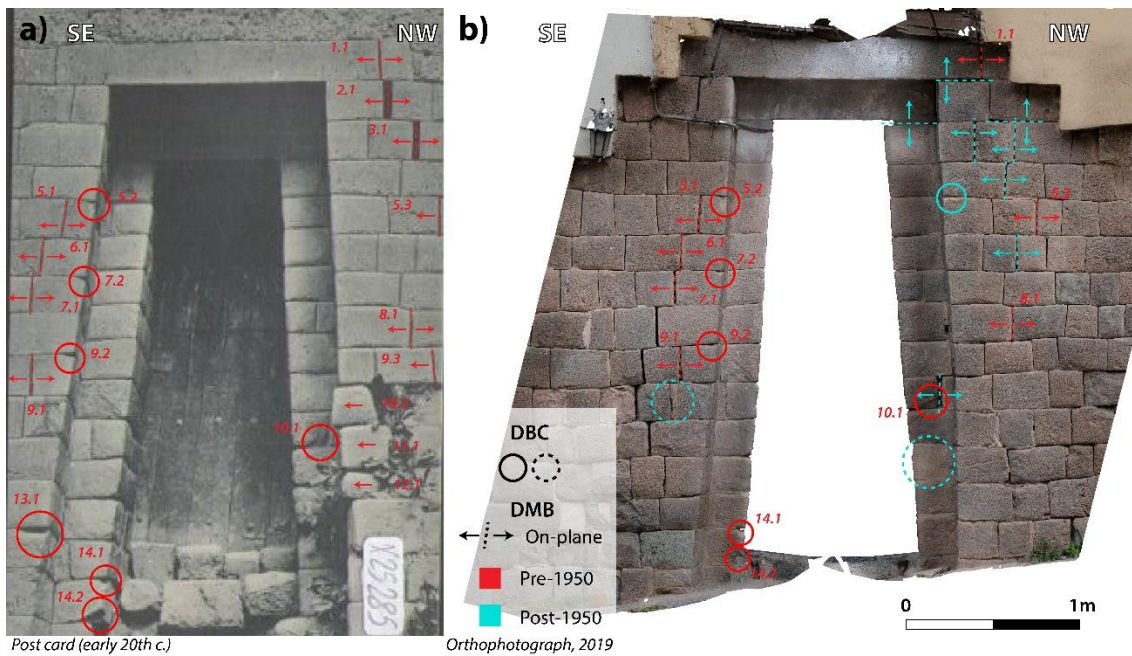
the reader may clearly see the 7 Displaced Masonry Blocks and 6 Dipping Broken Corners yet present on the structure in the first half of the 20<sup>th</sup> c. (Fig.13). In total, only ~20% of the EAEs identified in the three distinct structures might be caused by the 1950 ground shaking. Hence, this line of evidence as well as complementary pictures (see Supplementary) support a very limited impact of such event on the fine stone masonry. The results also suggest a low vulnerability of this kind of architecture to intensity levels inferior or equal to VII, i.e. corresponding to the maximum seismic intensity felt in Cusco in 1950.



**Fig.11** a) Map of the Qorikancha (Cusco) showing the location of the EAEs identified during the survey and the frequency of the DBC's dip direction; The curved wall pictured in b) in the first half of the 20<sup>th</sup> c. and in c) on the aftermath of the 1950. Several DMB (dotted lines) and DBC (circles) affected already the structure before 1950.



**Fig.12** a) Picture of F. Scherschel of *La Casa de las Serpes* dated 1945 and b) 2019 orthophotograph of the southern side of the doorway (credits: the authors). DBC and DMB are highlighted in red and blue.



**Fig.13** Comparison of the EAEs affecting the Inca doorway in Choqechaka Street based (a) on a photo taken before 1950 and (b) an orthophoto made in 2019 (credits: the authors). DBC and DMB are highlighted in red and blue.



## 5. Discussion

Usually, EAE analysis is applied to find probable sources for earthquakes. However, such a hypothesis is based on the concept of directivity of the damage with respect to the ground motion. Our results are not congruent with the traditional EAE analysis and demonstrate that the orientation of structures has a very strong impact on the damage mechanisms and distribution, i.e. EAE are not straightforward indicators of the seismic wave propagation. By integrating new criteria and taking into account results from Physical modelling, this statistical approach addresses rather the anisotropy of the deformation. The differential vulnerability and behavior of walls enable us to infer an empirical direction of the ground movement. As we stressed in Section 3.1, data are still too scarce and complex to assimilate this shaking axis to a specific ground motion phenomenon. Given such limitations, we consider it highly speculative to make assumptions on the location of the seismic source and prefer to limit the discussion to the differentiation and dating of the seismic events based on the consistency of the ground movements.

As shown in Section 4.3, the comparison of historical photographs agrees well with the observations made in the aftermath of the 1950 earthquake and supports a very limited impact of this event on the Inca fine architecture of Cusco. Therefore, we can statistically neglect the consequences of the event on the EAE analysis. The large majority of the EAEs identified during our survey would have been caused by previous ground shakings with a local seismic intensity greater than the maximum intensity produced by the 1950 earthquake (VII on the M.M. scale).

Among the historical earthquakes that have generated known damage in the Cusco Basin prior to 1950, we could mention the 1941 event, three seismic events during the 18<sup>th</sup> century (1702, 1742 and 1744) and the 1650 earthquake (Silgado Ferro, 1978). Regarding first the 1941 event, the seismic intensity felt in Cusco was estimated between VI and VII (M.M. scale), i.e. significantly lower than the intensity of the 1950 earthquake. While some strain structures were registered on colonial buildings (Ericksen et al., 1954; Silgado Ferro, 1978), it is very unlikely that Inca structures would have been affected. The ground motion in 1941 is used to be considered as one of the main aggravating factors explaining the disastrous impact of the 1950 earthquake on colonial buildings. If the 1941 event had been capable of generating appreciable strain structures on the Inca remains, the consequences of the 1950 earthquake would have been more acute. Moreover, as demonstrated by the historical pictures in Santo Domingo (Fig.11a)

and complementary evidence from Nazarenas (Fig.S11) many EAEs were already present in the early 20<sup>th</sup> century, i.e. before 1941.

The three mainshocks in 1702, 1704 and 1744 seem to have affected seriously only one colonial convent of Cusco (fractured walls/vaults – Anónimo, 1819; Esquivel y Navia, 1980). While the seismic intensities reached in Cusco during those three seismic sequences are unknown, the very brief historical descriptions of the episode suggest a limited impact of the ground shakings in Cusco.

On March 31, 1650, a strong earthquake occurred in the area that devastated the city of Cusco and marked a turning point in its urbanism and cultural life (Altez, 2017; Hajovsky, 2018). The numerous Spanish accounts mentioned huge induced landslides around the capital of the Incas as well as liquefaction phenomena within the Cusco Basin (Villanueva Urteaga, 1970; Julien, 1995). Despite the traditional overstatements of the colonial documents, the extent and severity of the damage, particularly on colonial temples recently built, argues for a higher seismic intensity than the 1950 earthquake (Tavera et al., 2016). This natural disaster represents, therefore, a credible explanation for the EAEs collected on colonial buildings (neo-Inca style) in Cusco and in Inca sites in its surroundings. As highlighted in Section 4.2., the archaeoseismological data collected in the city of Cusco show two distinct patterns of deformation. While the Inca structures evidence a ground movement oriented N-S, the neo-Inca buildings seem to have suffered from a ground shaking preferentially oriented E-W. Based on the arguments detailed above, we consider the strain structures on colonial buildings (neo-Inca style) as generated by the 1650 earthquake. Spanish accounts report that “this first ground shaking, which caused the damage on the temples seems to have come from Arequipa” (personal translation from Villanueva Urteaga, 1970, p. 204), i.e. an orientation ~N170/350 (Fig.10), not consistent with the archaeoseismological results. However, as emphasized in Section 3.1, the orientation of the ground movement does not match necessarily with the direction of propagation of the seismic waves.

Besides, the sharp difference between the results on Inca and neo-Inca remains in Cusco also suggests the impact of at least one other strong seismic event, before 1650. Considering the absence of strong earthquake reported between 1533 and 1650 CE, we postulate that the deformation observed in the Inca architecture is the result of a prehistorical event that occurred during the Inca imperial phase (1400-1533 CE). Interestingly, such an event might correspond to the large fault rupture hypothesized through an ethnohistorical analysis (Combey et al., 2020).

At the regional scale, the ~E-W impulse inferred from the data of Puka Pukara, Saqsaywaman, Huchuy Qosqo and Chinchero are particularly consistent (Fig.10), arguing for the identification of EAEs associated with the same seismic event. However, these results do not match with the orientation inferred from the Inca architecture in the Cusco city. Strikingly, the results of the four sites north of Cusco agree rather with the orientation inferred from neo-Inca buildings. To explain this observation, we put forward four main hypotheses:

- 1) The damage affecting the sites close to the city of Cusco corresponds to the impact of the 1650 earthquake, also responsible for the E-W movement inferred from neo-Inca buildings of Cusco. If so, it would endorse the regional dimension of the 1650 event and its severity;
- 2) The preferential occurrence of EAEs in N-S walls demonstrated in the four Inca sites and in E-W walls in the Inca architecture of Cusco correspond to the same seismic event that would have occurred prior to 1650. In such a case, the dissimilar patterns of deformation might be explained by the peculiar location of Cusco, within a large sedimentary basin prone to substantial site effects (Ericksen et al., 1954; Rosell Guevara, 2018);
- 3) The four sites located north of Cusco may have suffered the impact of a distinct (pre)historical earthquake that caused no damage in Cusco or whose impact in the city whose blurred by the two other following events;
- 4) A combination of the first and third hypotheses, i.e. the deformation observed in the closest sites from Cusco (Saqsaywaman and Puka Pukara) may evidence the consequences of the 1650 earthquake while Chinchero and Huchuy Qosqo suffered from the impact of another strong earthquake, not documented.

At this stage of our research, we are not yet able to choose between these options. The lack of information on the location of the historical earthquakes and their related source parameters constitutes a major constraint. At least, the hypothesis of near-field earthquakes is the most likely with regard to the limited damage distribution of the historical events. Testing the empirical ground movements in the archaeological sites will require thus the modelling of a set of potential ground shakings in the Cusco Basin with different seismic sources and local intensities (Benavente Escobar et al., 2013). Nonetheless, the third and fourth hypotheses seem unlikely. Considering the close proximity of Cusco and the four other archaeological sites (less than 1 km between Cusco and Saqsaywaman), it seems difficult to assume no impact of the 1650 earthquake on those sites. Similarly, the long return periods of the faults, of approximately

1000-2000 yr (Cuadra et al., 2008; Rosell Guevara, 2018; Palomino Tacuri et al., 2021) and the small number of strong earthquakes during the historical period make the hypothesis of multiple devastating earthquakes affecting the Cusco Basin between the 14<sup>th</sup> and 16<sup>th</sup> centuries quite unlikely.

## **6. Conclusions**

The seismic hazard in the Cusco area remains understudied and largely underappreciated. As we emphasized, this lack of knowledge is mainly due to the short and incomplete historical record of the regional seismicity (~500 yr). Hence, developing complementary and innovative approaches based on the analysis of indigenous oral traditions, palaeoseismology and archaeoseismology turn out to be critical. This archaeoseismological survey carried out in the Cusco region led to the acquisition of the first large dataset of earthquake-induced damage affecting pre-Columbian remains. The results on the monumental Inca architecture prove the relevance of this work to increase the regional seismic record by approximately 150 years.

First, by refining the semi-quantitative EAE analysis proposed by Rodríguez-Pascua et al. (2020), we prefer addressing the anisotropy of the seismic deformation at the site scale than the directivity of the EAE. The damage analysis performed on five well-preserved but seismically exposed Inca settlements around Cusco enables inferring a consistent ground movement oriented E-W and suggests the impact of, at least, one strong regional ground motion. Within the city of Cusco, the EAE analysis brings to light two different patterns of deformation, arguing for the identification of two damaging earthquakes since the 15<sup>th</sup> century.

The joint analysis of historical pictures conducted in this paper provides, for the first time, some pieces of evidence regarding the dating of the damage. The comparison of modern and historical photographs in Cusco enables us to neglect the consequences of the 1950 earthquake on fine dry-stone masonry and suggests a substantial impact of two damaging and more ancient earthquakes.

In short, this work supports a significant impact of the 1650 earthquake at a regional scale and advocates for the occurrence of an unknown strong motion prior to 1650 and probably during pre-Columbian times. Finally, we claim that a local seismic intensity greater than VII (M.M.) represents a lower limit to the EAE detection on the Inca fine stonework based on the impact of the 1950 earthquake. Complementary seismic engineering testing must now further assess the resistance of Inca structures. Beyond the implications that those results may have in the



local SHA, we think that this work paves the way to future discussions and investigations on pre-Columbian perception and adaptations to the seismic hazard.

## Data availability

Dataset related to this article is available at <http://dx.doi.org/10.5281/zenodo.6078514>, an open-source online data repository hosted at Zenodo (CERN).

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