Archaeoseismological approach in the Heartland of the Incas (Cusco, Peru). Potentialities and limitations for the current seismic hazard assessment and the past earthquake risk perception.

Andy Combey

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Andy COMBEY

Thèse dirigée par **Laurence AUDIN**, Chargée de Recherche IRD, Université Grenoble Alpes
et co-encadrée par **David GANDREAU**, Université Grenoble Alpes

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Madame Laurence AUDIN
DIRECTRICE DE RECHERCHE, IRD, Directrice de thèse

Madame Julia DE SIGOYER
PROFESSEUR DES UNIVERSITES, Université Grenoble Alpes, Présidente du Jury

Monsieur Chris GERRARD
PROFESSEUR, Durham University, Rapporteur

Monsieur Gerardo SUÁREZ
DIRECTEUR DE RECHERCHE, Universidad Nacional Autónoma de México, Rapporteur

Monsieur Daniel H. SANDWEISS
PROFESSEUR, University of Maine, Examinateur

Monsieur Rohit JIGYASU
DOCTEUR EN SCIENCES, ICCROM, Examinateur

Monsieur Thierry CAMELBEECK
DOCTEUR EN SCIENCES, Observatoire Royal de Belgique, Examinateur

Monsieur Klaus-G. HINZEN, Universität zu Köln, Invité

Monsieur David GANDREAU, ENSAG, Invité

"Tous les ouvrages péruviens portent le caractère d'un peuple laborieux qui aime à creuser le roc, qui cherche les difficultés pour montrer son adresse à les vaincre, et qui imprime aux édifices les plus chétifs un caractère de solidité d'après lequel on pourrait croire qu'à une autre époque il eût élevé des monuments plus considérables."

Humboldt (1801, p.443).

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Résumé

Approche archéosismologique dans le berceau des Incas (Cusco, Pérou). Potentialités et limites pour l'évaluation de l'aléa sismique actuel et la perception passée du risque tellurique.

Face à l'exposition croissante de nos sociétés aux tremblements de terre, une évaluation précise de l'aléa sismique s'avère être une impérieuse nécessité. Identifier les marqueurs de la sismicité dans le registre archéologique est désormais reconnu comme une approche pertinente afin de combler le fossé entre la paléosismologie et la sismicité historique/instrumentale. Pourtant, cette discipline demeure cantonnée au bassin méditerranéen.

A la différence de la frange Pacifique soumise aux fréquents et bien circonscrits séismes de subduction, la région de Cusco au Pérou est principalement affectée par une sismicité crustale modérée mais diffuse. Cette dernière représente un danger latent et un aléa très largement sous-estimé. La région est également le berceau de la culture inca et de son architecture en pierre monumentale, prétendument parasismique. Ce patrimoine offre donc une opportunité unique d'élargir le catalogue sismique, mieux comprendre la dynamique des failles régionales et améliorer notre compréhension de la perception/gestion des tremblements de terre à l'époque inca. Dans le cadre de ce travail de thèse original nous présentons les résultats de la première étude archéosismologique de grande ampleur en Amérique du Sud. Cette démarche transdisciplinaire inclue une prospection sur 17 sites incas, la conception/réalisation d'un système de collecte et de gestion des données de terrain et la réinterprétation d'un récit légendaire de la tradition orale précolombienne. En outre, nous avons élaboré une méthodologie permettant l'analyse vibratoire de structures massives en pierre, sur un cas d'étude en France lors de la crise sismique du Teil (2019) et avant son application à Cusco.

Avec plus de 3000 dommages sismiques identifiés, les résultats obtenus démontrent, en premier lieu, la capacité des édifices incas à enregistrer des séismes. Les données historiques suggèrent d'ailleurs un seuil de sensibilité proche de VIII en terme d'intensité sismique de ce type de construction. La grande majorité des déformations enregistrées dans le bâti en élévation témoigne donc de l'occurrence d'un, ou plusieurs, séismes plus violents que ceux recensés depuis 1650. L'interprétation combinée des données de terrain et des données ethnohistoriques supporte l'existence, d'au moins un séisme majeur ($M_w \geq 6.5$) durant la phase impériale inca (1400-1533 CE), associé à la rupture en surface du segment de faille Tambomachay-Pachatusan bordant le nord du bassin de Cusco. Enfin, notre travail souligne l'intérêt des méthodes de vibrations ambiantes pour caractériser le comportement dynamique des structures archéologiques et interroger la conception parasismique de l'architecture inca.

Compte tenu des résultats obtenus, ce manuscrit pose les bases d'une analyse renouvelée des interactions entre populations précolombiennes et sismicité, et plaide pour un développement accru de l'archéosismologie et de la paléosismologie dans les Hautes Terres andines, et à plus grande échelle en Amérique du Sud où cette approche n'a pas été encore mise en œuvre.

Mots-clés

Inca - Archéosismologie - Pérou - Cusco - Aléa sismique - Paléoséismes

Abstract

Archaeoseismological approach in the Heartland of the Incas (Cusco, Peru). Potentialities and limitations for the current seismic hazard assessment and the past earthquake risk perception.

Considering the increasing exposure of modern societies to earthquakes, an accurate assessment of the seismic hazard is of major significance. Identifying the earthquake evidence in the archaeological record is now considered a relevant approach for bridging the gap between palaeoseismology and historical/instrumental seismicity. However, this field of research remains confined to the Mediterranean area.

Unlike the Pacific margin, subject to frequent and well-defined megathrust earthquakes, the Cusco region in Peru is affected mainly by crustal seismicity, moderate but diffuse. The latter represents a latent danger and a significantly underestimated hazard. The region is also the heartland of the Incas and the focal point of their monumental stone architecture, allegedly earthquake-resistant. This heritage thus offers a unique opportunity to expand the seismic catalogue, better understand the dynamics of regional faults and improve our understanding of the perception/management of earthquakes in Inca times. In this pioneering PhD work, we present the results of the first large-scale archaeoseismological study in South America. The cross-disciplinary approach we conducted includes an extensive survey of 17 archaeological sites, the design/development of a field data collection-management system and the reinterpretation of a legendary story coming from the pre-Columbian oral tradition. In addition, we developed a methodology allowing the analysis of the dynamic response of massive stone structures, through a case study during the Le Teil seismic crisis (2019) in France, and prior to its application in Cusco.

First, with more than 3,000 earthquake features registered, the results show the potential of the Inca buildings to record earthquakes. Regarding the sensitivity threshold of this type of construction, the historical data suggest a seismic intensity close to VIII. The great majority of the damage recorded in the archaeological remains demonstrates thus the occurrence of one, or more, ground motions, stronger than those reported since 1650. Through the combined interpretation of field and ethnohistorical data, we demonstrate the existence of, at least, one major earthquake ($M_w \geq 6.5$) during the Inca imperial phase (1400-1533 CE), associated with the surface rupture of the Tambomachay-Pachatusan fault segment bordering the northern part of the Cusco Basin. Finally, our work emphasizes the interest of ambient vibration based techniques to characterize the dynamic behaviour of archaeological structures and question the earthquake-proof design of Inca architecture.

More broadly, this manuscript lays the foundation for a renewed analysis of the interactions between pre-Columbian populations and the seismicity, and argues for more refined development of the palaeo- and archaeoseismology in the Andean Highlands, and on a larger scale in South America where this approach has not yet been implemented.

Keywords

Inca - Archaeoseismology - Peru - Cusco - Seismic hazard - Palaeoearthquakes

Contents

List of Abbreviations

ACoR Atlas des techniques de la Construction Romaine
CBM Condition-based Maintenance
CDM Conceptual Data Model
CRED Centre for Research on the Epidemiology of Disasters
CVFS Cusco-Vilcanota Fault System
DBC Dipping Broken Corner
DMB Displaced Masonry Block
DRR Disaster Risk Reduction
EAE Earthquake Archaeological Effect
EQL Earthquake Lights
FDD Frequency Domain Decomposition
FDSN International Federation of Digital Seismograph Networks
GCI The Getty Conservation Institute
GTV The Gate Tower of Viviers
ICCROM International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOMOS International Council on Monuments and Sites
IEG Independant Evaluation Group
IGP Instituto Geofisico del Peru
INC Instituto Nacional de Cultura (prior to the creation of the Peruvian Ministry of Culture)
LH Late Horizon

LIP	Late Intermediate Period
M.M.	Modified Mercalli Intensity scale
MSK	Medvedev–Sponheuer–Karnik intensity scale
OMA	Operational Modal Analysis
OPUR	Outil Pour Unités de Réparation
PDM	Physical Database Model
RDBMS	Relational Database Management System
RDT	Random Decrement Technique
SHA	Seismic Hazard Assessment
SHM	Structural Health Monitoring
SVD	Singular Value Decomposition
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNISDR	United Nations International Strategy for Disaster Reduction
WHC	World Heritage Committee

General introduction

"The incidence of disasters is said to be increasing in the modern world, and consequently the amount of resources invested in the study and mitigation of natural hazards has increased dramatically. It is perhaps not surprising, then, that archaeological speculation about the impact of disasters in the ancient world has also become very popular."

Torrence and Grattan (2002, p.15)

Crustal seismicity, in stable continental regions, is the most deadly type of seismic hazard (England & Jackson, 2011). Interestingly, several factors that make it dangerous (i.e., diffuse hazard, long recurrence time, blind or unrecorded faults...) are also those that explain the difficulties in estimating it, predicting it and protecting against it.

In the Andes, the subduction process, which is the driving force of the Andean orogeny, is also a source of major, recurrent and often deadly earthquakes. This seismicity thus overshadows the crustal hazard that characterizes the Andean highlands and the sub-Andean area. The low levels of deformation measured during the recent period as well as the few palaeoseismological studies conducted in these regions suggest return periods greatly exceeding the instrumental (∼100 years) and historical (∼500 years) window. While the use of techniques such as palaeoseismology are promising to tackle this issue, the diffuse character of crustal seismicity underlines the magnitude of the challenge before us (number of faults to study) and argues for the development of complementary approaches.

Beyond its recent history, affected by destructive earthquakes, the region of Cusco was the cradle and the capital of the Inca Empire, which extended over a major part of the Andes until the Spaniards' arrival in the 16^{th} century. The Inca culture is famous, notably, for its dry-stone masonry comprising blocks finely cut and jointed perfectly, assembled sometimes in a jigsaw-like pattern. Considering the quality of execution and the level of expertise, some observers suggested even that the architecture resulted from an Inca earthquake engineering.

Archaeoseismology represents, therefore, a promising approach. By using the archaeological record as a marker of the seismic activity, this field of study consists in identifying and interpreting the direct or indirect consequences of earthquakes on any type of artefact produced by the human occupation (stratigraphy, material, architecture). Although archaeoseismology has experienced a real boom since the 1980s and 1990s, 1) the implemented methodologies are still subject to criticism, 2) the approach is often limited to the improvement of the local seismic catalogues and 3) the research topics remain confined to the Mediterranean area.

Bearing in mind the high vulnerability of Andean societies to earthquakes over the last 500 years (Degg & Chester, 2005), it is particularly striking that no studies have been conducted on this topic for the pre-Columbian period. This is all the more surprising given that numerous studies are currently addressing the impact of climate hazards (e.g., Binford et al., 1997; Sandweiss et al., 2001; Sandweiss, Solis, Moseley, Keefer, & Ortloff, 2009; Seltzer & Hastorf, 1990). In this project, we propose to move away from the traditional study areas and implement, for the first time, an archaeoseismological approach in the Andes.

Notwithstanding its exploratory nature, this unprecedented research work should be an opportunity to develop a holistic and renewed approach to archaeoseismology. Accordingly, we will address both the potentialities/limitations of our approach for the evaluation of the seismic hazard and the opportunities/challenges for the study of the past perception and management of earthquakes. To do so, we will try to answer the following four questions:

1. Do Inca stone architecture show evidence of ground motions?
2. Did the Inca stone buildings record the impact of “pre-historical” earthquakes?
3. What role did tectonic processes play in the lives of pre-Columbian populations?
4. What is the dynamic behaviour of the archaeological remains?

On the one hand, through the first two questions we will discuss the relevance of archaeoseismology in Cusco in extending the seismic catalogue and improving our knowledge on the seismic hazard. On the other hand, through the two last questions we will address the relationship that the Inca populations had with the seismic phenomenon. These two apparently distant topics are however complementary for the further development of an integrated management of the seismic risk.

Since the beginning of the 20^{th} century, the region of Cusco has experienced important and brutal socio-economic changes. Among them, the strong demographic growth and

the urban migration led to the resettlement of a growing number of people in the urban environment. This phenomenon has come with the development of informal settlements and increasing exposure and vulnerability of the most disadvantaged populations to earthquake risk. At the same time, Peru's economic growth has been based on tourism and the attractiveness of its historical and archaeological sites, while neglecting protective measures against earthquakes. From this point of view, the heritage of Cusco might be considered as a textbook case.
Hence, the use of innovative and cross-disciplinary approaches is all the more crucial to improve rapidly and significantly the assessment of the crustal seismic hazard and address more effectively the requirements in terms of heritage management and protection of populations. What can be the contribution of archaeoseismology in the construction of a more resilient Andean society?

This thesis is divided into four parts and seven chapters. The first part constitutes a state of the art of archaeoseismology and the settings of the study area. The first chapter provides a general introduction to the thesis, presenting the basic concepts associated with earthquakes and the main disciplines involved in the seismic hazard assessment. The chapter focuses on archaeoseismology and gives an overview of the methods and issues related to this approach. The second chapter describes the tectonic and archaeological context of the Cusco area. While the first section of the chapter is dedicated to the presentation of the active faults that go through the region and to the available data about the regional historical seismicity, the second section deals with the late pre-Columbian occupation and the description of the Inca architectural phenomenon. The singularity of the Inca stone masonry is a promising element for the implementation of an archaeoseismological approach.
In the second part, we present the method and results of the large-scale archaeoseismological survey conducted in 2019. Chapter 3 details the organization of the relational database developed to support the fieldwork and the recording of architectural strain features. It highlights the relevance that this tool has, both for the archaeoseismological approach and heritage preservation. This chapter has been published in the *Journal of South American Earth Sciences* in 2021. Chapter 4 presents the results of the statistical approach carried out on the earthquake-induced damage and the dating assumptions for the identified events. It includes a paper that deals with the data collected in the Cusco Basin and which has been submitted to *Quaternary International*.
The third part aims to broaden the scope of the thesis by addressing the knowledge and

coping strategies of pre-Columbian populations in the face of earthquakes. In Chapter 5, we propose a new interpretation of a story coming from the pre-Columbian oral tradition as an account of a surface fault rupture. This case study is an opportunity to examine the perception of earthquakes in Inca times. This chapter has been published in the *Journal of Archaeological Science: Reports* in 2020. Chapter 6 discusses the potential of ambient vibration measurements for the assessment and preservation of Inca finely carved stone buildings. The chapter presents the results of such instrumentation, carried out during the COVID-19 crisis, in a historic masonry tower in Ardèche (France). The French case study has been the subject of an article published in the *Bulletin of the Seismological Society of America* in 2022.

The last part and chapter are devoted to the synthesis of the results and existence of an Inca seismic culture. The limitations of the work are outlined and the main perspectives opened up by this project are discussed.

Introduction générale

La sismicité crustale, en régions continentales stables, constitue le type d'aléa sismique le plus meurtrier à l'échelle du globe (England & Jackson, 2011). Il est d'ailleurs intéressant de constater que plusieurs facteurs qui fondent sa dangerosité (i.e., aléa diffus, longs temps de récurrence, failles aveugles ou non répertoriées. . .) sont également ceux qui expliquent les difficultés à l'estimer, le prévoir et à s'en prémunir.
Dans les Andes, la subduction, moteur de l'orogène, est également une source de séismes majeurs, récurrents et souvent meurtriers. Cette sismicité éclipse donc l'aléa crustal qui caractérise les hautes terres andines et le domaine subandin. Les faibles niveaux de déformation mesurés au cours de la période récente ainsi que les quelques études paléosismologiques conduites dans ces régions suggèrent des temps de retour dépassant largement la période instrumentale (∼100 ans) et historique (∼500 ans). Si l'emploi de techniques telles que la paléosismologie s'avère prometteur pour faire face à cette problématique, le caractère diffus de la sismicité crustale souligne l'ampleur de la tâche à mener (nombre de failles à étudier) et plaide pour le développement d'approches complémentaires.
Au-delà de son histoire récente, jalonnée de secousses sismiques destructrices, la région de Cusco constitue le berceau et la capitale de l'empire inca, qui s'étendait sur une majeure partie des Andes à l'arrivée des Espagnols au XVIe siècle. La culture inca est notamment renommée pour sa maçonnerie en pierre sèche comportant des blocs finement taillés et parfaitement jointés les uns aux autres, assemblés parfois même à la manière d'un casse-tête. Cette qualité d'exécution et ce degré d'expertise suggérèrent même à certains observateurs que l'architecture inca résultait d'un savoir-faire parasismique.
L'archéosismologie constitue, à ce titre, une approche prometteuse. Visant à utiliser le registre archéologique comme un marqueur de l'activité sismique, ce champ d'étude consiste à identifier et interpréter les conséquences directes, ou indirectes, de séismes sur tout type d'artefact produit par l'occupation humaine (stratigraphie, matériel, architecture). Bien que l'archéosismologie connaisse un véritable essor depuis les années 1980-90, 1) les méthodologies mises en œuvre font encore l'objet de critiques, 2) l'approche est souvent

réduite à l'amélioration des catalogues sismiques régionaux et 3) les sujets de recherche demeurent cantonnés au monde méditerranéen.
Compte tenu de la très forte vulnérabilité des sociétés andines aux aléas telluriques au cours des 500 dernières années (Degg & Chester, 2005), il est particulièrement frappant qu'aucune étude n'ait abordé cette thématique pour l'époque précolombienne. Ceci est d'autant plus étonnant que de nombreux travaux sont aujourd'hui conduits sur l'impact des aléas climatiques (e.g., Binford et al., 1997; Sandweiss et al., 2001, 2009; Seltzer & Hastorf, 1990). Dans le cadre de ce projet, nous proposons de décentrer le regard et de mettre en œuvre, pour la première fois, une approche archéosismologique dans les Andes. Bien qu'exploratoire en raison de son caractère inédit, ce travail de recherche doit être l'occasion de développer une approche holistique et renouvelée de l'archéosismologie. En conséquence, nous interrogerons aussi bien les potentialités/limites de notre démarche pour l'évaluation de l'aléa sismique que les opportunités/défis pour l'étude de la perception et gestion passées des tremblements de terre. Pour ce faire, nous tenterons de répondre aux quatre questions suivantes :

1. L'architecture en pierre inca a-t-elle souffert de l'activité sismique ?

2. Les édifices en pierre inca présentent-t-ils des traces de séismes "pré-historiques" ?

3. Quelle place occupaient les processus tectoniques dans la vie des populations précolombiennes ?

4. Quel est le comportement dynamique des vestiges archéologiques ?

Tandis qu'au travers des deux premières questions nous aborderons la pertinence de l'archéosismologie à Cusco dans l'extension du catalogue sismique et l'amélioration de nos connaissances sur l'aléa, les deux autres questions nous permettront de discuter la relation qu'entretenaient les populations incas avec le phénomène sismique. Ces deux thématiques en apparence éloignées sont pourtant complémentaires dans l'optique d'une gestion intégrée du risque sismique.
Depuis le début du XXe s., la région de Cusco a expérimenté des changements socio-économiques importants et brutaux. Parmi eux, la forte croissance démographique et l'exode rural ont conduit à l'installation d'un nombre toujours plus grand de personnes en milieu urbain. Ce phénomène s'est accompagné du développement d'habitats informels, augmentant l'exposition et la vulnérabilité des populations les plus défavorisées au risque tellurique. En parallèle, l'essor économique du Pérou a reposé sur le tourisme et l'attrait

du public pour ses sites historiques et archéologiques, tout en négligeant les mesures de protection face aux tremblements de terre. De ce point de vue, le patrimoine de Cusco fait figure de cas d'école.

Le recours à des approches innovantes et transdisciplinaires s'avère donc d'autant plus crucial pour améliorer rapidement et significativement l'évaluation de l'aléa sismique d'origine crustal et répondre plus efficacement aux besoins en terme de gestion du patrimoine et de protection des populations. Quelle peut être la contribution de l'archéosismologie dans la construction d'une société andine plus résiliente ?

Cette thèse est divisée en quatre parties et sept chapitres. La première partie constitue un état de l'art des recherches en archéosismologie et des connaissances sur la région d'étude. Le premier chapitre propose une introduction générale à la thèse, présentant les notions de base associées au tremblement de terre et les principales disciplines dédiées à l'évaluation de l'aléa sismique. Le chapitre se concentre sur l'archéosismologie et offre une synthèse des méthodes et enjeux de cette approche. Le second chapitre détaille le contexte tectonique et archéologique de la région de Cusco. Tandis que la première section du chapitre est dédiée à la présentation des failles actives qui parcourent la région et aux données disponibles concernant la sismicité historique régionale, la seconde section porte sur l'occupation précolombienne tardive et la caractérisation du phénomène architectural Inca. Le caractère inédit de la maçonnerie en pierre inca constitue un élément prometteur pour l'implantation d'une approche archéosismologique.

La seconde partie est dédiée à la présentation de la méthode et des résultats de la prospection archéosismologique de grande échelle menée en 2019. Le chapitre 3 détaille l'organisation de la base de données relationnelle développée pour accompagner le travail de terrain et l'enregistrement des anomalies architecturales. Il souligne l'intérêt que cet outil comporte, aussi bien pour l'approche archéosismologique que la préservation du patrimoine. Ce chapitre a été publié dans le *Journal of South American Earth Sciences* en 2021. Le chapitre 4 présente, quant à lui, les résultats de l'approche statistique des dommages d'origine sismique et les hypothèses de datation des événements identifiés. Il inclue un article soumis à *Quaternary International* qui porte sur les données collectées dans le bassin de Cusco.

La troisième partie vise à élargir la portée de la thèse en abordant les connaissances et stratégies d'adaptation des populations précolombiennes face aux séismes. Dans le chapitre 5, nous proposons une nouvelle interprétation d'un récit tiré de la tradition orale précolombienne selon laquelle il s'agirait du témoignage d'une rupture d'une faille en sur-

face. Ce cas d'étude est l'opportunité de discuter de la perception des séismes à l'époque inca. Ce chapitre a été publié dans le *Journal of Archaeological Science : Reports* en 2020. Le chapitre 6 traite du potentiel des mesures de bruit ambiant pour l'évaluation et la préservation des édifices inca en pierre finement taillée. Le chapitre présente les résultats d'une instrumentation de ce type, effectuée durant la crise sanitaire, dans une tour en maçonnerie historique en Ardèche (France). Le cas d'étude français a fait l'objet d'un article publié dans le *Bulletin of the Seismological Society of America* en 2022.
Le dernier chapitre et dernière partie sont consacrés à la synthèse des résultats obtenus et à la discussion de l'existence d'une culture sismique inca. Les limites du travail y sont présentées et sont l'occasion d'évoquer les principales perspectives ouvertes par ce projet.

Part I

State of the art

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Chapter 1

Archaeoseismology: a recent contribution to the Seismic Hazard Assessment

"In short, archaeoseismology reflects far better the interests of palaeoseismologists than archaeologists and can be perceived as an ancillary discipline relegated to the gathering of historical seismic catalogues." Forlin and Gerrard (2017, p.95)

1.1 Introduction

Learning more about the seismic hazard means being better prepared and protected against it. As Chinese culture shows us, studying earthquakes has a long and complex history, going back over millennia[1]. In Europe, the theories proposed by the Classical Greek philosophers influenced during centuries the earthquake science. Based notably on the principles laid down by Aristotle in *Meteorologica* and the analogy with the "humours" of the human body, scholars saw in the earthquakes the outcome of a disequilibrium of the elemental forces (fire, water, earth and air) within the Earth (Adams, 1938). Regarded as the result of mysterious forces inside the crust, the telluric phenomenon was, therefore, out of reach for mankind. After the Middle Ages, during which it was widely accepted, the Aristotelian view was progressively challenged.

In 1755, the Lisbon earthquake constituted a turning point in the European history of science and marked the beginning of modern seismology. While the moving forces of the earthquake remained obscure, its manifestations became an object of study that needed to be described, measured and thus quantified. Six years after the Lisbon disaster, John Michell was the first to consider the ground motion as the propagation of elastic waves over great distances, paving the way for the location of the earthquake source (Adams, 1938). Then, the work of scientists like Robert Mallet and John Milne represented major contributions to the estimation of the focal parameters and the understanding of the underlying mechanisms. However, it was only with the development of the first instrumental networks and later with the creation of the Worldwide Standardized Seismic Network in the 1960s that the study of earthquakes turned into the study of the seismic hazard (Scholz, 2002). Thanks to the current network, researchers are able to monitor properly the seismicity anywhere on the planet. Regarding its assessment and prediction, the large set of seismic and geodetic data turns out, though, to be insufficient in large parts of the world and requires going beyond the traditional seismology. For more than a century, archaeoseismology has emerged as a promising but still neglected approach.

1.2 The earthquake hazards

1.2.1 The seismic phenomenon

The recent advances in seismology have contributed significantly in formulating the theory of *Plate Tectonics* (Isacks, Oliver, & Sykes, 1968; Morgan, 1968; Wegener, 2002). Such theory proposes a global framework that explains the genesis of the earthquakes and their distribution pattern. In the model, rigid plates of the lithosphere move with respect to one another over the underlying hotter and ductile asthenosphere. The relative movement of these rigid objects generates growing stresses at their boundaries where the deformation distribute over large geological discontinuities. These structures, called faults, accommodate elastically the deformation up to a certain limit. Above this threshold, the strain is released producing the earthquake. The stress drop takes, indeed, the form of heat (friction) as well as energy release (seismic wave) and results in a permanent (offset) and transient (ground shaking) deformation.

The seismic signal recorded by the seismometers highlights the existence of two main wave types (Oldham, 1900): the body and surface waves (fig. 1.1). While the former travels inside the Earth, the latter propagates across the surface. By propagating through compression/dilatation, the P-waves (primary) are faster than the shear S-waves (secondary). When reaching the surface, the P-waves might be transmitted in the atmosphere in the form of acoustic waves, known as "earthquake sounds".

Regarding the surface waves, they travel at a lower speed than the body waves (fig. 1.1) and their energy rapidly decreases with depth. However, at the ground-air interface their amplitude may be substantially higher than the P and S-waves. Among the surface waves

may be found, notably, the Love (horizontally polarized shear waves) and Rayleigh waves (ground roll).
Hence, the seismic shock felt at the surface is the result of a complex combination of body waves reflected and amplified at the surface leading to mainly vertical motions (upward and downward) as well as shear and roll motions corresponding to the surface waves. Buildings prove to be particularly vulnerable to the complex and extended motions generated by the surface waves (Hanks, 1975). Obviously, the ground motion will also depend on the frequency content of the seismic waves, which is function of the fault mechanics, local geology and distance from the source.

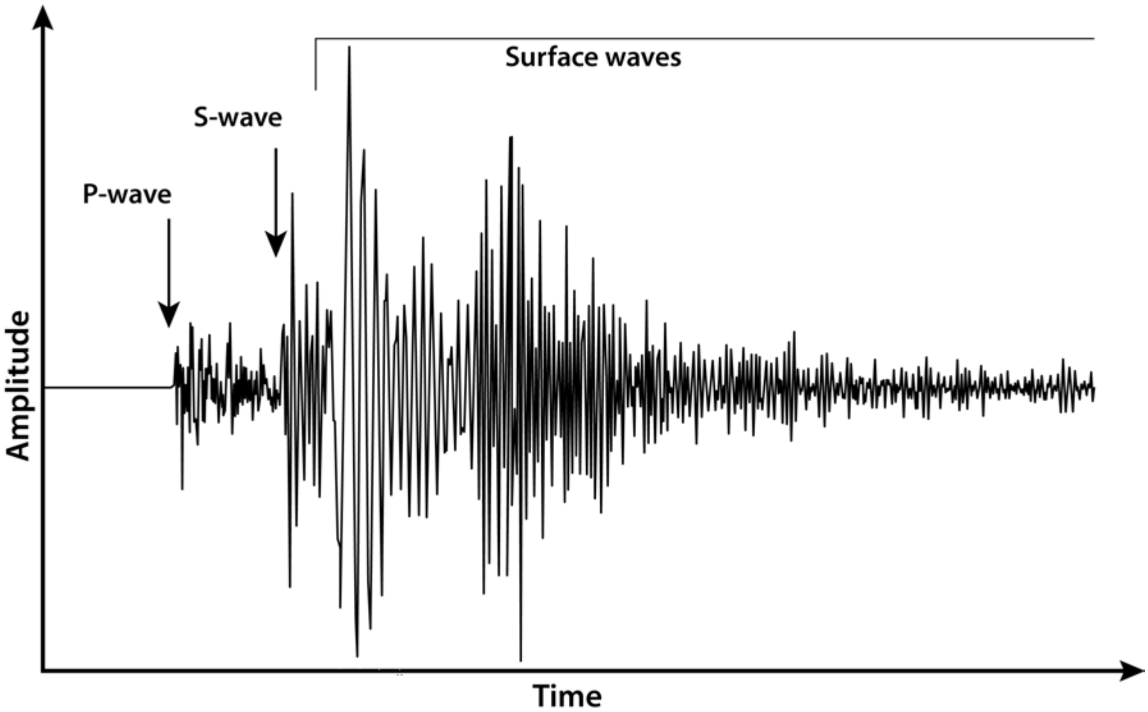

Figure 1.1: Seismogram (velocity) showing the different times of arrival of the body and surface waves caused by an earthquake (adapted from Michigan Technological University)

In addition to the propagation of elastic waves, the energy release during an earthquake comes with a permanent deformation and a sudden change in the stress regime that the current instrumental and geodetic data is able to quantify.
First formulated by Reid (1910) after the 1906 California earthquake, which ruptured no more than 450 km of the San Andreas Fault, the "elastic rebound theory" (fig. 1.2a) represents a true paradigm shift by emphasizing the cyclic nature of the seismicity. The

seismic phenomenon is thus conceived as the result of alternating periods of loading and unloading. In 1980, Shimazaki and Nakata (1980) completed the model by introducing two other scenarios (fig. 1.2b-c). In any case, the deformation dynamics are now regarded, in a simplified view, as periodic and characterized by three main phases: interseismic, co-seismic and postseismic.

During the interseismic period (1), the longest phase, the stress is increasing on the fault and the deformation is accommodated elastically. At a certain breaking point, i.e. the coseismic period (2), the energy stored is released leading to the fault rupture and a stress drop. This is followed by the intriguing postseismic period (3), during which relaxation processes within the lower part of the crust and the ductile part of the mantle dominate (afterslip) and aseismic slip occurs. Postseismic motions are commonly opposite to the coseismic ones. The duration of the postseismic phase varies greatly from one seismic event to another, lasting from some days to several decades (Scholz, 2002). The three periods form the seismic cycle and the fault recurrence is defined as the time needed to complete the whole cycle.

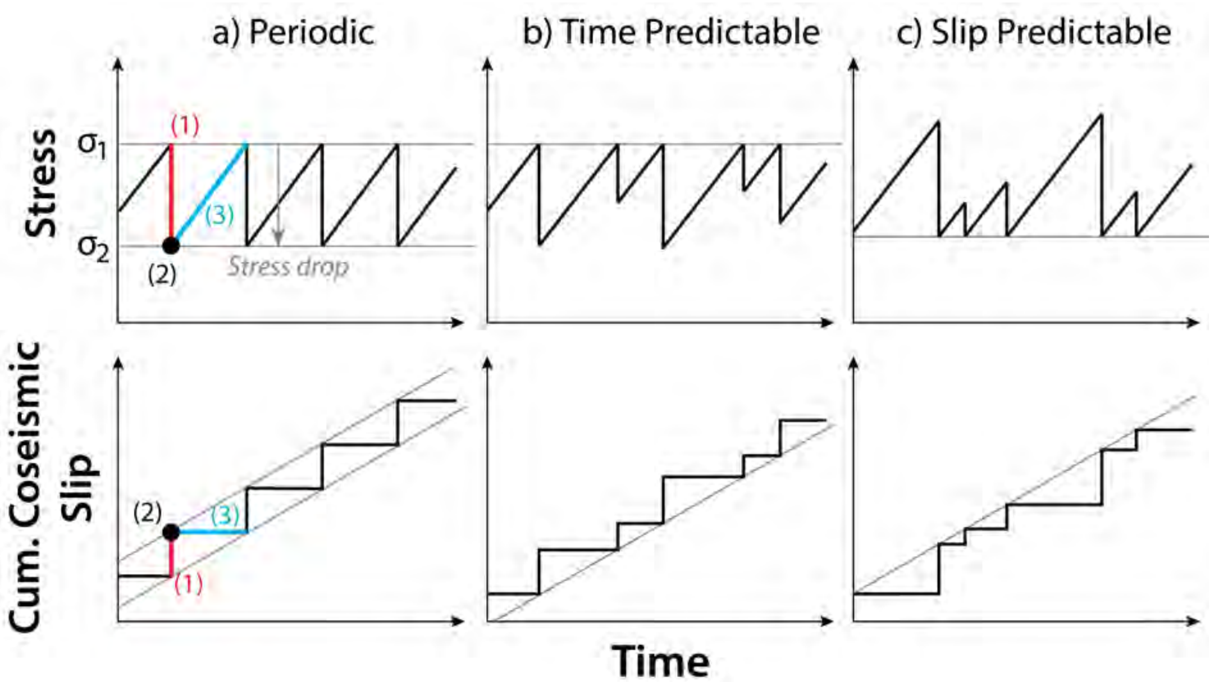

Figure 1.2: The three main earthquake recurrence models (adapted from Shimazaki & Nakata, 1980). Reid's model corresponds to the perfectly periodic one (a). On these diagrams, the coseismic (1), postseismic (2) and interseismic (3) periods are highlighted.

Although the models presented above (fig. 1.2) only constitutes a theoretical and ideal framework, they show how the data acquisition and monitoring of the fault dynamics might contribute to the seismic hazard assessment and prediction. Unfortunately, neotectonic studies highlight the great diversity of seismic settings on the planet and demonstrated the shortfall and insufficiency of modern observations to cover the entire seismic cycle, especially in intraplate contexts, where earthquakes constitute a major but still underappreciated threat for populations.

1.2.2 Limitations of the modern observations: the case of intraplate seismicity

According to the *Plate Tectonics* framework, we may distinguish three main types of seismicity:

- **Mid-oceanic ridges seismicity** generated principally by the spreading centres and transform faults;
- **Plate boundary earthquakes** clustered on active continental margins (convergence and subduction);
- **Intraplate seismicity** caused by crustal faults located on plate interiors and which accommodate regional tectonic strain.

Restricted mainly to the seafloor, the mid-oceanic ridges seismicity does not constitute the main focus of the seismic hazard studies and thus will not be further discussed. On the contrary, the plate boundary and intraplate earthquakes may occur in close proximity to inhabited areas and need to be properly assessed. Table 1.1 summarizes the distinctive features for both types of seismicity.
Plate boundaries are seismically active areas. A great part of the tectonic stress is accommodated by large well-known and well-mapped structures, leading to high and frequent seismicity. In various areas like the Pacific coast, the characteristic return period for large earthquakes ($M_w \geq 8$) is around 100 years (Rikitake, 1976). On the contrary, continental interiors are deemed to be stable. The regional residual strain is accommodated by a large network of crustal faults with recurrence rates from 1,000 to 10,000 years (Liu & Stein, 2016). Due to their extension, crustal faults are often unable to produce earthquakes larger than M_w=7-8.

MAIN CHARACTERISTICS	**PLATE BOUNDARY EARTHQUAKES**	**CONTINENTAL INTERIOR EARTHQUAKES**
SEISMIC SOURCE	Geographically well-constrained	Disseminated
RECURRENCE TIME	High (∼100 yrs.)	Moderate to Low (∼500-10,000 yrs.)
MAXIMUM MAGNITUDE	High (M_w>8)	Moderate (M_w<7.5)
IMPACTED AREA	Extensive	Local

Table 1.1: Main characteristics and differences between the two main seismic hazards.

Strikingly, in spite of the highest seismic activity at plate boundaries, earthquakes produced in continental interiors cause a far greater number of casualties (England & Jackson, 2011). Indeed, the magnitude and the energy released during the seismic event is not directly related to the number of deaths (fig. 1.3)[2]. This apparently paradoxical situation is aggravated by the high media exposure of recent examples of devastating subduction earthquakes (e.g., Sumatra–Andaman, 2004; Christchurch, 2011; Tohoku, 2011).

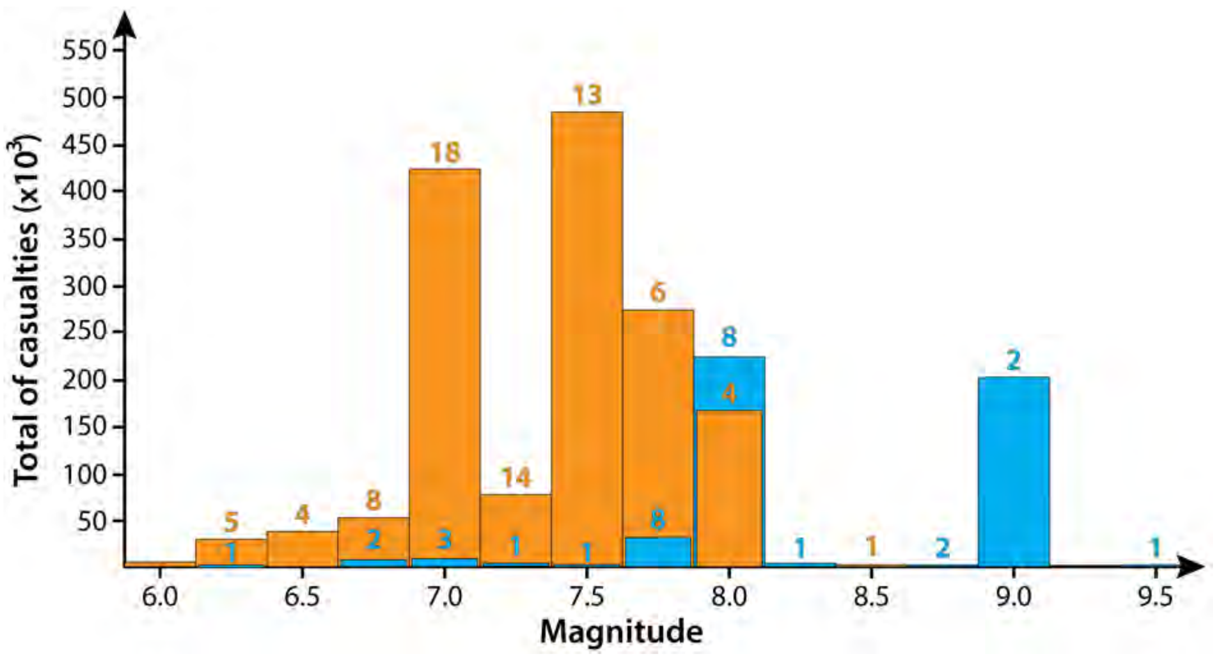

Figure 1.3: Number of deaths caused by earthquakes over the past century, according to the magnitude and the two main tectonic settings (in orange: intraplate seismicity and in blue: plate boundaries seismicity). The number of events is indicated above each bar. Modified from England and Jackson (2011, p.348).

Beside the human factors that may increase substantially the vulnerability in continental interiors (i.e., remote areas with isolated settlements, vulnerable traditional housing and populations poorly prepared), the high risk related to crustal earthquakes results from the great challenges specific to the assessment of this seismic hazard.
Assessing the seismic hazard requires answering where and when large earthquakes will occur and how large they will be. As early as 1944, Gutenberg and Richter proposed a law estimating the frequency of characteristic earthquakes based on the rate of smaller earthquakes:

$$log(N_M) = a - bM \tag{1.1}$$

Based on this relation, the number of events N_M with a magnitude greater than or equal to M is function of two constants *a* and *b*. The a-value varies according to the investigated region and represents the rate of seismic activity in this given area, while the b-value is regarded as universally close to 1. Hence, the accuracy of the Gutenberg-Richter law is directly related to the accuracy of the a-value estimation, which in turn depends on the level of seismicity and time span of earthquake recording. The smaller is the seismic activity, the longer the time of observation would be necessary to get significant results and assess properly the rate of the regional seismic activity.
Although the instrumental data do not cover the entire seismic cycle in many plate boundary contexts, the problem turns out to be even more acute in continental interiors where many faults are not necessarily considered as active due to their low to very low return period. Moreover, unlike for plate boundary earthquakes, the disseminated nature of crustal earthquakes hampers the identification and mapping of all potential seismogenic structures[3]. In such regions with a low to moderate seismicity, the ∼100 years of instrumental observations cannot be considered sufficient, at all, to extrapolate the a-value. Seismic hazard predictions must, therefore, consider and crosscheck other sources of data in order to extend the earthquake catalogue.

1.2.3 Moving beyond the instrumental era

Earthquakes that occurred before the rise of instrumental seismology and the development of the first seismological networks (~150 yrs.) are regarded as "palaeoearthquakes". This definition provides the advantage of encompassing the imprecise notions of historical and prehistoric seismicity, whose time boundaries vary from region to region according to the period during which written systems developed (even the period of development might be difficult to establish precisely in some regions).
Investigating earthquakes prior to quantitative observations also implies dealing with incomplete, sometimes confusing or even contradictory data. It requires, therefore, relying on a wide set of evidence coming from the historical, geological and archaeological records. As a result, three disciplines have developed: historical seismology, palaeoseismology and archaeoseismology. These approaches, which are characterized by complementary temporal scopes, differ mostly from a methodological point of view in their use of different types of sources (Caputo & Helly, 2008).

Historical seismology

Earthquakes leave often a deep imprint on people's minds and constitute thus a recurrent topic in human accounts. Scholars perceived early on the relevance of identifying and listing all the major historical earthquakes based on written (and even oral) accounts. In Europe, the first attempts to constitute earthquake catalogues go back to the 18^{th} century, as a consequence of the 1755 Lisbon earthquake (Fréchet, 2008). However, historical seismicity started sparking interest during the second half of the 20^{th} century with the construction of large and potentially vulnerable civil engineering structures, including power plants. Extending and completing seismic catalogues with pre-instrumental events has become crucial to assess more accurately seismic hazard, improve the ground motion predictions and size adequately the infrastructure. In addition, repeated efforts had been dedicated to the development of macroseismic intensity scales (MCS, MSK, MMI, EMS98…), i.e. to estimate the strength of the ground shaking based on the documentation and distribution of the earthquake effects on buildings and people. In theory, the historical approach enables registering all kinds of perceptible earthquakes, even those which did not produce any damage (M_w ~2-3 – fig. 1.4).
However, the historical approach suffers from several shortcomings (fig. 1.5). The volume and accuracy of data depend directly on the demographic and economic dynamics of the study region during the investigated period. Furthermore, the content of a document is,

first and foremost, an "act of communication" (Caputo & Helly, 2008) that needs to be taken into account. Its analysis and interpretation will always be a matter of debate. This also explains why the investigation remains too often limited to second-hand sources (Camassi & Castelli, 2004). Finally, the intent to get back to the focal parameters and conditions of an earthquake through the analysis of its consequences and implications is an extremely challenging task. In particular, the existing attempts to establish a relationship between the magnitude and the macroseismic intensity suffer from great uncertainties and none is satisfactory (D'Amico, Albarello, & Mantovani, 1999; Johnston, 1996).

Considering the historical account as much a subjective perception of the earthquake phenomenon as it is a factual description of the seismic event itself opens up though new perspectives. It aims to improve current earthquake hazard assessment and mitigation strategies through the analysis of previous human experiences (e.g., Bousquet, Dufaure, & Péchoux, 1984; Chester, Duncan, & Dibben, 2008; De Pascale, Bernardo, Muto, & Tripodi, 2015; Forlin & Gerrard, 2017; Walker, 1999).

Historical documents are often incomplete, difficult to access and sometimes unclear. This observation is all the more true as the investigated period is old (fig. 1.4). European catalogues are thus regarded as complete only for the last four or five centuries (Gisler, Fäh, & Kästli, 2004; Kázmér & Györi, 2020; Stucchi, Albini, Mirto, & Rebez, 2009). Even in countries where detailed references to earthquakes exist for thousands of years, like Japan or China, the collected data are not sufficient to assess properly the seismic hazard (Lee, Wu, & Jacobsen, 1976; Liu & Stein, 2016; Matsu'ura, 2017).

Palaeoseismology

As an offshoot of Quaternary geology, palaeoseismology covers a wider timeframe than historical seismology (fig. 1.4). It deals with the identification and analysis of earthquake-induced deformation features observed in different types of surficial geological deposits, i.e. from a stratigraphic unit to a whole landform (McCalpin & Nelson, 2009). Among these features may be found seismites, event deposits (e.g., rockfalls, landslide and seiche), liquefaction features, broken or deformed speleothems, colluvial wedges and uplift/subsidence indicators. It encompasses thus a wide spectrum of approaches ranging from excavations on the fault lines, and from the coring in lacustrine areas to geo-chemical and -morphological analysis of speleothems and tectonic structures (Meghraoui & Atakan, 2014).

Through the study of on- and off-fault deformations, palaeoseismology provides relevant information on the location and size of past ground motions. At a regional scale, the

dating and the stratigraphic correlation of a large set of coseismic features enable reconstructing the behaviour of seismogenic faults (recurrence time) and the pattern of seismicity (spatial distribution of the deformation) from the early Holocene (∼10 kyr.).
It is commonly assumed that earthquakes smaller than M_w=5 are not strong enough to rupture the surface (Wells & Coppersmith, 1994) and produce noticeable environmental effects[4]. Based on this assumption, the M_w=5 is regarded as the lower limit for detecting past seismic events (fig. 1.4). However, the intrinsic parameters of the earthquake (magnitude, focal depth and focal mechanism) do not constitute the only threshold for recording palaeoevents (Nelson, Kelsey, & Witter, 2006). The creation and preservation of unambiguous deformation features depends on the geological context (e.g., type of sediments/rocks) and taphonomic conditions (weathering, erosion, and compaction). Hence, the palaeoseismological potential will vary greatly from one region to another, and its application is still sparse in South America (Baize et al., 2015) or even Peru (Schwartz, 1988 – the USGS was the first to dig palaeoseismic trenches in Peru).
Besides the great incompleteness of the palaeoearthquake catalogue, the approach suffers from other limitations (fig. 1.5). Relating geologic evidence to instantaneous processes/earthquakes is a challenging task that requires good expertise and methodological tools (Wheeler, 2002). The interpretation process, ranging from the event dating to the magnitude estimation contains multiple uncertainties and remains subjective (Biasi, Weldon II, Fumal, & Seitz, 2002; Ken-Tor et al., 2001). Regarding the estimation of the magnitude, it depends, indeed, on the good identification and correlation of several coseismic indicators (Benavente et al., 2021; McCalpin & Nelson, 2009).

Archaeoseismology

Archaeoseismology, also called archaeoseismicity and earthquake archaeology, focuses on all types of anomalies observed in the archaeological record and related to the earthquake occurrence (e.g., Galadini, Hinzen, & Stiros, 2006; Sintubin, 2011). This includes therefore damage generated by ground motions (direct evidence) and repairs following seismic destruction (indirect evidence). By documenting these seismic "pathologies", archaeoseismology proves to be suitable for identifying even moderate earthquakes with a $M_w \geq 4$ (fig. 1.4). Particularly relevant during the last ∼3 kyr., the approach bridges the gap between the two different time frames covered by historical seismicity and palaeoseismology (fig. 1.4).
The research addresses all types of human artefacts, from preserved cultural heritage buildings to occupation levels and archaeological material uncovered during excavations.

The main challenges lie in identifying reliable seismic markers, gathering extensive and detailed archaeological literature and considering the geological, human and architectonical characteristics of the investigated context (fig. 1.5). Hence, the same limitations reported for palaeoseismology regarding the preservation and interpretation of earthquake evidence can also be applied to archaeoseismology (e.g., sparse studies, no specialists, no written accounts, interdisciplinary studies, lack of funding from the institutions,etc.).
Gathering a very broad spectrum of methods and specialities ranging from seismology, archaeology and architecture to earthquake engineering, this field of study constitutes a unique "scientific conglomerate", difficult to define.

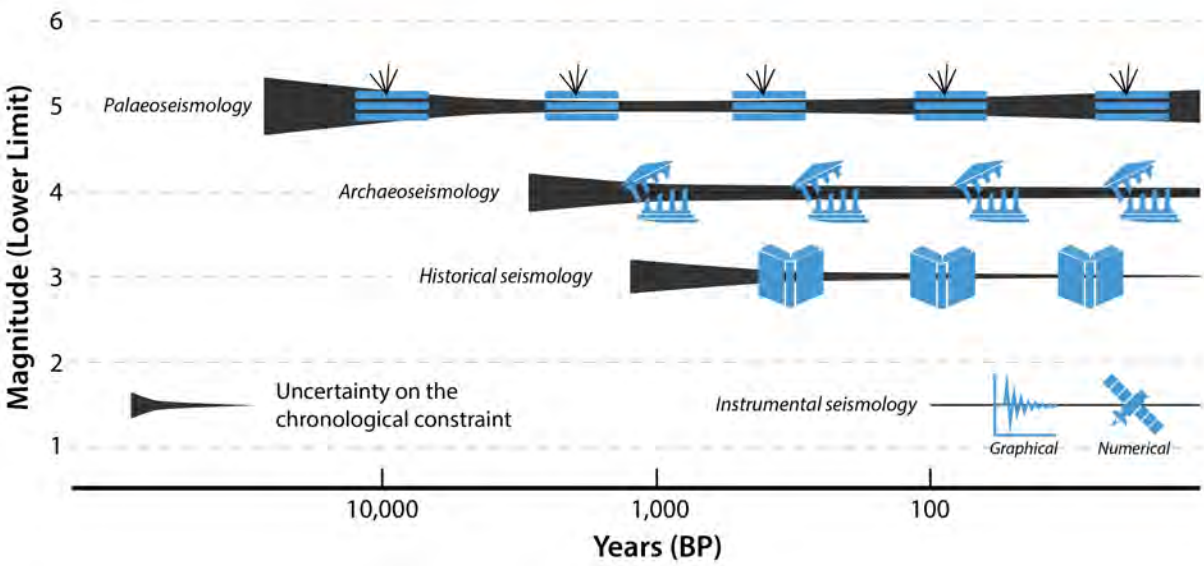

Figure 1.4: Temporal scopes of the different disciplines investigating the instrumental and pre-instrumental seismicity. These fields of study have distinct uncertainties regarding the chronological constraint of past events while the dating accuracy for each discipline may vary depending on the investigated period and context. Adapted from Levret (2002) and Galadini et al. (2006).

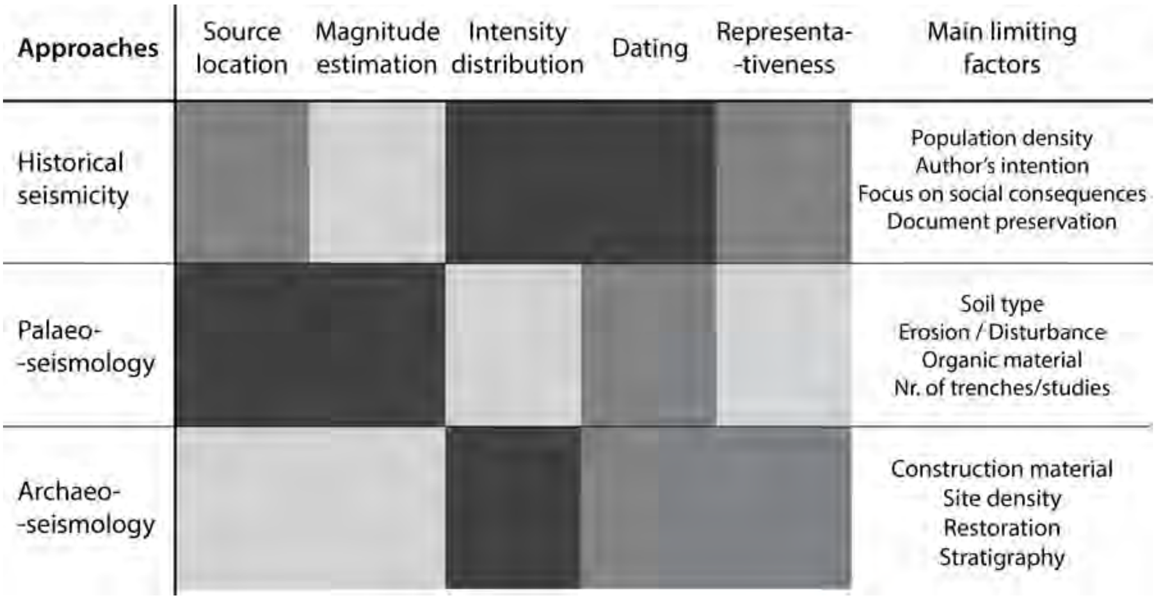

Figure 1.5: Potentials (in dark: high; dark grey: moderate; light grey: low) and limiting factors of the three fields of study regarding the reconstruction of the main parameters and characteristics of past seismic events.

1.3 100 years of archaeoseismology: a brief review

While the aforementioned section succeeds in defining, or rather outlining, archaeoseismology, it fails to convey the diversity of approaches and research problems that have emerged in the span of one century. In the following section, we propose a synthetic and comprehensive overview of the origins of the discipline, its main schools of thought and the evolutions it is experiencing. Far from being a proper epistemological analysis of archaeoseismology, this review will, on the one hand, recall the background of our research project, on the other hand, highlight the issues and challenges that articulate the thesis.

1.3.1 The origins (ca.1850-1980): between promises and "original sins"

The history of archaeoseismology is closely tied to that of modern seismology and historical seismicity. These fields of study emerged in the aftermath of the 1755 Lisbon seismic disaster, which triggered intense scientific discussions and called into question the established physical principles. The increasing interest for the seismicity and its properties led, during the second half of the 18^{th} c. and the first part of the 19^{th} c., to the compilation of the first national earthquake catalogues (e.g., Baratta, 1901; Gueneau de Montbeillard, 1761; Perrey, 1845; Sieberg, 1940). Regarding the South American region, Bandelier published in 1906 a pioneering work on the identification of historical and prehistorical telluric phenomena based on indigenous myths and oral traditions.

In addition to the characterization of past earthquakes, the strong seismic events of the 19^{th} c. became an object of research for scholars. In 1857, the civil engineer Robert Mallet was the first to consider the area devastated by ground shaking as a laboratory dedicated to the understanding of the earthquake characteristics and mechanisms. Thus, he documented precisely the damage to buildings and environmental consequences of the Basilicata earthquake (also called the Great Neapolitan earthquake) and suggested a location of the focus, as well as a magnitude for the event (Mallet, 1862).

Furthermore, the growing interest for archaeological and historical heritage, like Pompeii, and its preservation (*Monuments historiques* created in France in 1819) raised awareness on the harmfulness of the telluric hazards for the current and past societies. Following a traumatic personal experience in Crete, Sir Arthur Evans was the first scholar to assume, in 1928, the destructive impact of an earthquake in an archaeological site (Evans, 2013). Based on the destruction evidence registered during his excavations (fig. 1.5), the archaeologist postulated the dramatic role of seismic events in the collapse of the Minoan settlements from the Late Bronze Age. Although drastically reconsidered since then (Driessen, 2019; Jusseret & Sintubin, 2017), Evans' theory influenced many other archaeologists during the 20^{th} c. (e.g., La Rosa, 1995; Nur & Cline, 2000; Schaeffer, 1948). It fostered a catastrophist vision (fig. 1.6) in which the earthquake was considered as the sole explanation of entire societal and cultural changes.

Nonetheless, the documentation of earthquake-induced damage initiated by Mallet and the fad for the earthquake hypothesis in archaeology introduced by Evans constituted the starting point for the development of the archaeological reading of buildings (building archaeology) and the systematic identification of earthquake features (e.g., Dinsmoor, 1941).

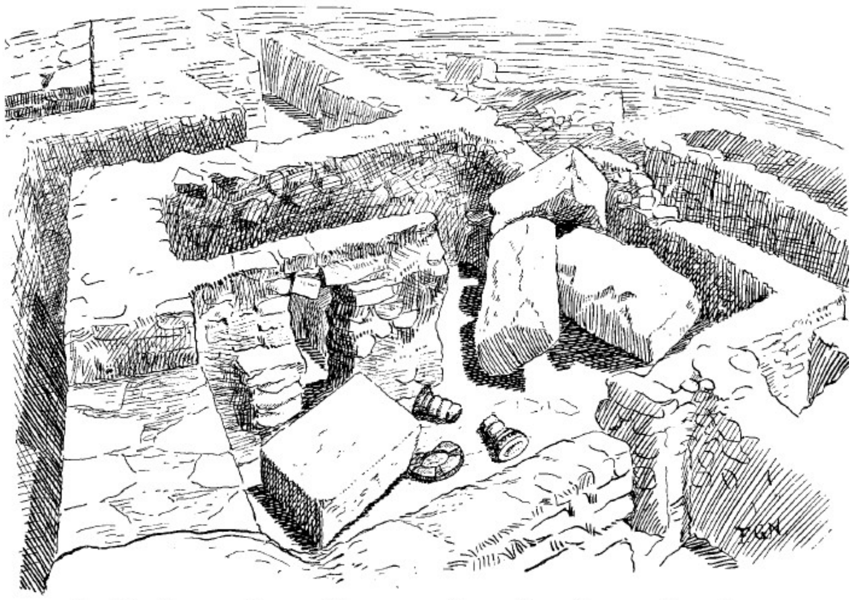

FIG. 173. BASEMENT ROOMS OF 'HOUSE OF THE FALLEN BLOCKS' SHOWING GREAT BLOCKS HURLED FROM SOUTH-EAST PALACE ANGLE. WINDOW OPENING TO LEFT.

Figure 1.6: Schematic representation of the destructive evidence documented in the so-called "House of the Fallen Blocks" in Knossos that Evans interpreted the consequence of an earthquake. Derived from Evans (2013, p.297).

1.3.2 A wide spectrum of methods and approaches

Diversification and formalization (1980-2010)

Despite the impetus given by the "Evans' school" during the first half of the 20^{th} c., archaeoseismology did not experience an immediate take-off. The intensive SHA research programs launched around nuclear power plants and industrial facilities in western Europe from the 1980s revitalized the whole investigation on palaeoearthquakes (Groupe APS, 2000; Postpischl, 1985; Vogt, 1991 – fig. 1.7). It gave new impetus for studying archaeological proxies and led to a gradual theorization of the archaeoseismological field of study and its principles (Barnes, 2010; Galadini et al., 2006; Noller, 2001; Sintubin, 2011). The renewing of the discipline and its diversification occurred hand in hand with the establishment of the first methodological guidelines (Ferrigni, 1990; Guidoboni & Santoro Bianchi, 1995; Noller & Lightfoot, 1997; Rapp, 1986; Sintubin & Stewart, 2008; Stiros, 1996). It was also at this time that grows the awareness of the limitations and pitfalls of this kind of investigation (Ambraseys, 2006; Buck & Stewart, 2000; Hinzen, 2009), using often the "catastrophism" as an example.
Numerous initiatives flourished and many specialists coming from different fields joined

up. The methods and approaches became more diverse, depending on the researchers' background and their area of expertise. Despite the formalization attempts mentioned above, the burgeoning research gave rise to a heteroclite terminology: "archaeoseismicity", "earthquake archaeology", "disaster archaeology", "geomythology" and "archaeoseismology". This growing terminology illustrates thus the numerous offshoots and movements of thoughts that emerged in the last decades of the 20^{th} c. (fig. 1.7).
Two strands of research constitute the most visible component of modern archaeoseismology. Focused on the analysis of the architecture and its earthquake-induced deformation, specialists of those strands should be regarded as the heirs of Mallet (fig. 1.7). The first strand refers to a scientific community that is primarily focused on the archaeological reading of buildings. Theorized by Ferrigni (1990) and Helly (1995) in the 1990s, the approach aims to address the vulnerability and resilience of past societies through the identification and dating of earthquake-induced damage and the subsequent repairs. As highlighted by Helly (1995, p.792) "vulnerability must be defined in terms of the social fabric, available resources and traditional cultural values. This introduces a historical dimension to vulnerability." Researchers developed the concept of "local seismic cultures". The stratigraphic reading of archaeological remains is also supposed to complement historical data and improve the regional earthquake catalogues (e.g., Poursoulis, Levret, Lambert, Rideaud, & Helly, 2006).
Seismologists and earthquake geologists, who played a very active part in the archaeoseismological revival in the 1990s, considered, like Mallet in 1857, man-made constructions as relevant witnesses of the past seismic activity and damage as a source of information for the location and characterization of palaeoearthquakes. This second strand (fig. 1.7) proposes a geomorphological reading of the architecture and deformation features (palaeoseismological approach). The relevance of damage does not lie in its archaeological and architectural context but rather in its type, shape and orientation. Several works might be considered as methodological handbooks to classify the earthquake "pathologies" and infer properly seismological/strain parameters (Guidoboni & Santoro Bianchi, 1995; Korzhenkov & Mazor, 1999; Rapp, 1986). These efforts have resulted in the widely accepted Earthquake Archaeological Effects (EAE) classification established by Rodríguez-Pascua et al. (2011). In a nutshell, the main objective of this community is the improvement of the local/regional seismic catalogues and the refinement of the current model of seismic hazard assessment (e.g., Berberian et al., 2014; Caputo, Helly, Pavlides, & Papadopoulos, 2006; Ellenblum et al., 2015; Karakhanyan, Avagyan, & Sourouzian, 2010; Meghraoui et al., 2003; Noller & Lightfoot, 1997; P. Silva et al., 2005).

Thanks to the development of digital technologies and the increase in computing capacity, a third approach emerged at the end of the 20^{th} c., commonly referred to as quantitative archaeoseismology (Galadini et al., 2006). Mostly coming from the field of civil and structural engineering, researchers designed and developed numerical models in order to (1) simulate the dynamic behaviour of cultural heritage buildings and/or material properties of such (pre)historic structures and (2) enhance our understanding on the damage mechanisms. Since it aims at confirming and validating the inductive reasoning based on field observations, this inverse approach (fig. 1.7) is, hence, closely related to the second strand (seismological and geomorphological perspective). Regarding this topic, Sinopoli (1991) and Kamai and Hatzor (2008) might be considered as pioneering initiatives. Since then, the modelling and computing community claims to be a necessary step towards the recognition of the archaeoseismological contribution and often turns out to be sceptic about the seismoscope properties of the destructive evidence (Hinzen, 2009, 2012).

At the turn of the century, the archaeological field seems thus to become disengaged from the archaeoseismic topic. The recent methodological discussions have brought discredit on the "catastrophist" vision leading to an apparent lack of interest for interactions between past societies and telluric hazards. Some cross-disciplinary research works open up, however, archaeoseismology to anthropological and social issues (fig. 1.7). We may cite De Boer and Hale (2000), Piccardi (2005) and Piccardi et al. (2008), who address the influence and impact of neotectonics on past settlements through the geological interpretation of myths, oral traditions and archaeological findings. Hence, the analysis of earthquake evidence in the archaeological record does not serve exclusively the understanding of tectonic settings but also the examination of past human behaviour and adaptation strategies.

As Noller (2001, p.144) pointed out correctly, the great diversity of methods and approaches developed in the archaeoseismological investigations emanates primarily from the great diversity of archaeological and geological settings that the scientist may encounter or focus on. However, the variety of approaches in modern archaeoseismology also illustrates the multiple specialities involved in the discipline (fig. 1.7). As a result, each strand of research mentioned above has its own perception and conception of archaeoseismology, deriving from the primary expertise or sole curiosity of the involved researcher and research team. The current challenge seems to lie in establishing a successful collaboration between those communities.

The challenge of cross-disciplinarity (2010-today)

While the Mediterranean region was traditionally the main focus of the archaeoseismological research, new areas started to be the subject of in-depth studies during the last decade (e.g., Berberian et al., 2014; Davis et al., 2019; Hoffmann, Kummer, Márquez, & Valdivia Manchego, 2019; Karakhanyan et al., 2010; Lin & Wang, 2017; Rajendran, Rajendran, Sanwal, & Sandiford, 2013; Rodríguez-Pascua, Pérez-López, Garduño-Monroy, Perucha, & Israde-Alcántara, 2017). This change in scope highlighted the growing need for interaction and collaboration between the different stakeholders involved in the discipline.

The research program conducted by Volant et al. (2009) on a French roman aqueduct marked the starting point towards promoting and fostering multidisciplinary studies in archaeoseismology. Notably, increasing efforts have been made to narrow the gap between "qualitative" and "quantitative" approaches. Several works combine, indeed, field observations/measurements and numerical predictions (Benjelloun et al., 2021; Hinzen, Schwellenbach, Schweppe, & Marco, 2016; Montabert, 2021; Pecchioli, Cangi, & Marra, 2018; Schweppe, Hinzen, Reamer, & Marco, 2021; Stiros, 2020). More broadly, most of the investigations in the archaeoseismological field include and benefit from electronic devices and digital applications such as remote sensing tools (Arrighetti, 2019; Forlin, Valente, & Kázmér, 2018; Yerli et al., 2010) or relational databases (Dessales, Cavero, & Tricoche, in press; Dessales & Tricoche, 2018) in order to facilitate the data acquisition and storage and improve their interpretation.

In addition, innovative approaches have been carried out regarding the past and current risk perception and management. Formerly limited to the discussion of the archaeological record, the "Earthquake Archaeology" (Jusseret, 2014) involves now a large set of methodological tools coming from social sciences (DezhamKhooy & Yazdi, 2010; Forlin & Gerrard, 2017; Parsizadeh, Ibrion, Mokhtari, Lein, & Nadim, 2015; Partida, 2016), earth sciences (Force & McFadgen, 2010; Kázmér, 2019; Stewart & Piccardi, 2017) and earthquake engineering (Hinzen & Montabert, 2017).

However, as highlighted by the current archaeoseismological map (fig. 1.7), the diversity of research axes and approaches are still a structuring element, hampering the implementation of true holistic approaches. Two main groups can still be distinguished: one dedicated to the reduction of the current physical vulnerability to earthquakes and the other one focused on the social vulnerability factors and strategies implemented by past societies to cope with the seismic hazard. The development of a unified archaeoseismology will only be achieved through enhanced dialogue and cooperation between these two complementary but segregated visions.

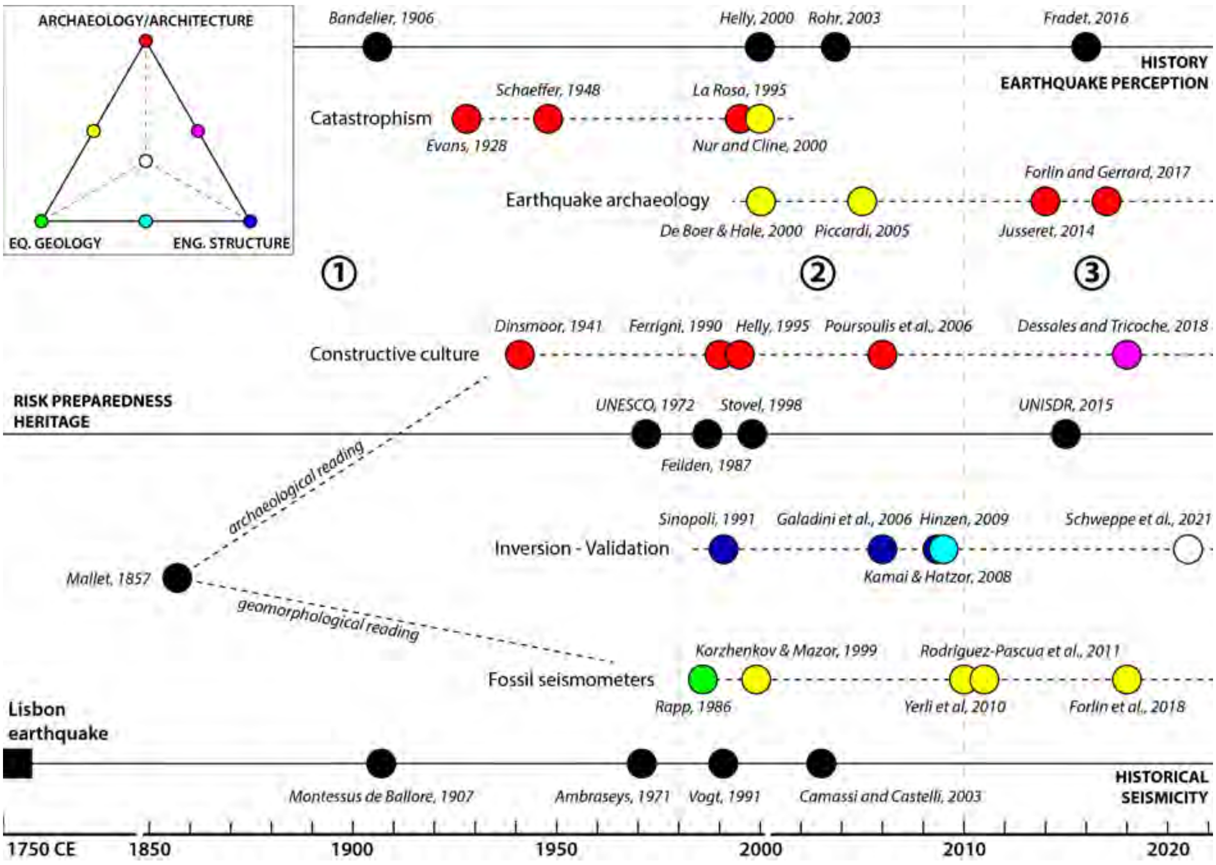

Figure 1.7: Chronology and cartography of the archaeoseismological research from its inception in the 19^{th} c. to the present time. The main research works are reported. Vertical dashed lines delimit the three main periods delineated in the text.

1.3.3 The Andes: starting from scratch

Despite the high seismic risk that characterized an overwhelming part of the Andes, the SHA studies remain based only on the short instrumental record (~70 yrs.) and the very incomplete historical data. The existence of written records since only the 16^{th} century, the strong depopulation of extensive regions during historical times and the document preservation issues explain, to a large extent, the deficiencies regarding the completeness of the historical record.

In Peru, recent efforts have been made to make up a reliable national earthquake catalogue (Seiner Lizárraga, 2009, 2016) and finalize the project initiated by Bandelier (1906) and Silgado Ferro (1978). In a similar manner, several works have started to address the incidence of strong ground motions on the colonial and republican societies (Gascón & Fernández, 2001; Oliver-Smith, 1994; Seiner Lizárraga, 2013; Simón Ruiz, Castro Castro, & Cortés Quintana, 2020; Walker, 2018). Those promising initiatives on historical seismicity, i.e. seismicity of the last 500 years, are though insufficient to get a comprehensive understanding of palaeoseismicity.

Densely occupied for thousands of years and endowed with significant cultural heritage buildings, the Andes have a great archaeoseismological potential. However, unlike the North-American and Mesoamerican areas, where several initiatives have already arisen (Fradkin, 1999; Garduño-Monroy, 2016; Hutchinson & McMillan, 1997; Noller & Lightfoot, 1997; Nur & Burgess, 2008; Rodríguez-Pascua et al., 2017; Suárez & García-Acosta, 2021), South America remains a "virgin land" with respect to the archaeoseismological research.

Several researchers have already claimed that pre-Columbian architectural features and techniques were earthquake mitigation strategies (Agurto Calvo, 1987; Brooks, Willett, Kent, Vasquez, & Rosales, 2005; Pozzi-Escot, Bernuy, Torres, & Aching, 2013; Torres, 2014 – fig. 1.8), sometimes without conclusive arguments. In contrast, very few archaeological studies report and document earthquake-induced damage (Berenguer & Salazar, 2017; Sandweiss et al., 2009). In such case, the earthquake hypothesis is rarely fully addressed and turns out to be a convenient explanation for unknown destructions and/or cultural upheaval (Franco Jordán, 2016; Kendall, Early, & Sillar, 1992; Lasaponara, Masini, Rizzo, & Orefici, 2011; Rick, 2008).

Ortloff, Moseley, and Feldman (1982) and Moseley (1983) appeared to have been the only ones to engage in an in-depth reflection on the implications of the tectonic processes on the development of the Andean societies. Unfortunately, the megathrust earthquakes associated with the subduction of the Nazca plate remains, too often, the only focus of archaeologists' interest. The works remained thus confined to the coastal cultures (fig. 1.8).

The Cusco-PATA project (2016-2018), which paved the way for this PhD work, was the first archaeoseismological initiative in the Peruvian Highlands. It led to the first robust data collection and to the publication of preliminary results about the famous Inca site of Machu Picchu (Rodríguez-Pascua et al., 2020).

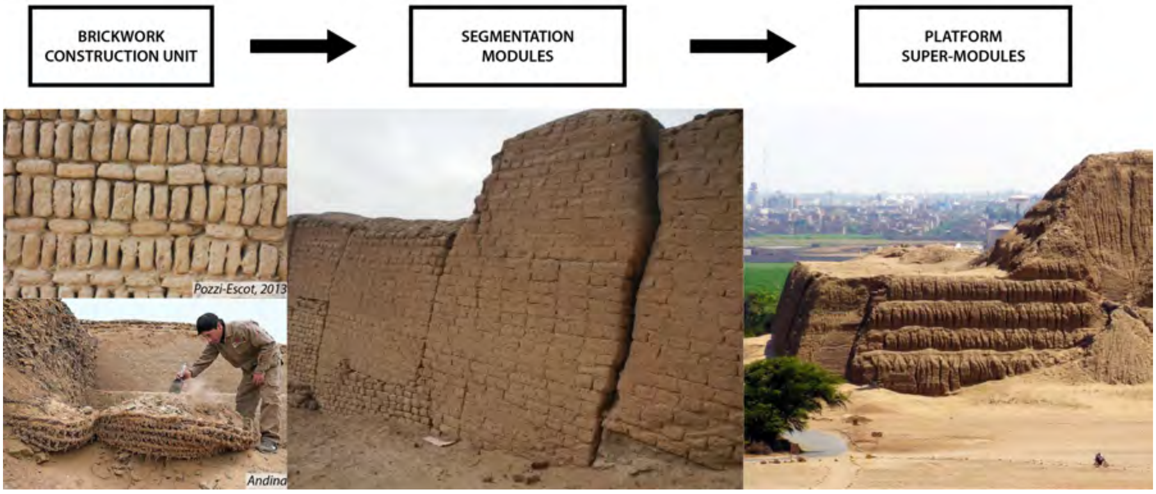

Figure 1.8: Coastal pre-Columbian architecture has a highly modularised nature. The pyramids, or "huacas", are the result of the assembly of several modules, on the scale of the brick, the wall or even the platform (super-module). Some Andean archaeologists regarded these construction features as the result of an earthquake-resistant design. Source: Andina.

1.4 Archaeoseismology: challenges and opportunities

As McCalpin and Nelson (2009) have rightly emphasized, recent deadly seismic events that occurred in 2001 in India (∼20,000 dead), in 2003 in Iran (∼30,000 dead), in 2005 in Pakistan (∼80,000 dead), in 2008 in Sichuan province, China (∼70,000 dead), or even in 2011 in Christchurch, New Zealand (∼200 dead) were all generated by faults for which no surface-rupturing earthquake was reported during the instrumental period and historical times. Increased efforts are thus needed to promote historical seismology, palaeoseismology and archaeoseismology as robust and essential approaches in earthquake sciences.

Among them, archaeoseismology remains definitely the most neglected and underappreciated research field. The review of its history and development enables outlining the main limits it needs to face and the main challenges it has to overcome in the near future:

- While the discipline was born as an attempt to explain and link the demise of past societies with strong earthquakes, the main objective of archaeoseismology has quickly become the identification, dating and quantification of past ground motions for the refinement of current probabilistic earthquake predictions. The issue of the interactions between past societies and the seismic hazard was thus progressively neglected in favour of seismological and earthquake engineering issues.

- The numerous non-concerted initiatives that characterized the beginnings of archaeoseismology have given way to a wide network of researchers agreeing on a common methodological framework. Meanwhile, the number of techniques and approaches has grown leading to the formalization of several specialities. Although the archaeoseismological work is now multidisciplinary, it mainly results in the involvement of different specialists and several methods supporting a single research axis. As an illustration, very few research papers have achieved to bring together the offshoots delineated in this chapter and their related research axes.

- Just like the first works carried out by Evans (2013), Schaeffer (1948) and Dinsmoor (1941), the archaeoseismological research is still strongly "Mediterraneocentric" (figs. 1.9 and 1.10). More than 70% of the papers published in international journals and reviewed in the framework of this project (n=84 - see Supplementary data) focused on the Mediterranean area, mainly in Italy, Greece, Turkey and the Levant. This heterogeneous distribution cannot be explained in terms of the level of the seismic hazard and risk. As highlighted by the two following maps (figs. 1.9 and 1.10), numerous regions across the world exposed to a strong earthquake hazard/risk might also be characterized by a rich archaeological heritage and have never been surveyed and studied.

Finally, the review, we carried out in this first chapter raises the question of the identity of archaeoseismology. Is it a recent burgeoning and distinctive field of study or the result of an accretion of multiple scientific approaches dealing with the same topic? We believe, based on the archaeoseismological history and literature summarized before, that archaeoseismology might still be regarded as a wide and heterogeneous spectrum of research projects. As recent projects demonstrated (e.g., Benjelloun et al., 2021; Montabert, 2021; Schweppe et al., 2021), it is now crucial to build stronger collaborations between the different delineated strands of research. It will be the first step towards the construction of more holistic approaches.
In this regard, archaeoseismology has a fundamental role to play in understanding the complex relationships established by past cultures with the seismic hazard. Geo-hazards often constitute a catalyst for societal changes and provide as much information on human behaviour and organization as on the underlying tectonic processes. Moreover, understanding how past human populations perceived and coped with the seismic hazard does not constitute a research topic completely disconnected from the concerns of the current

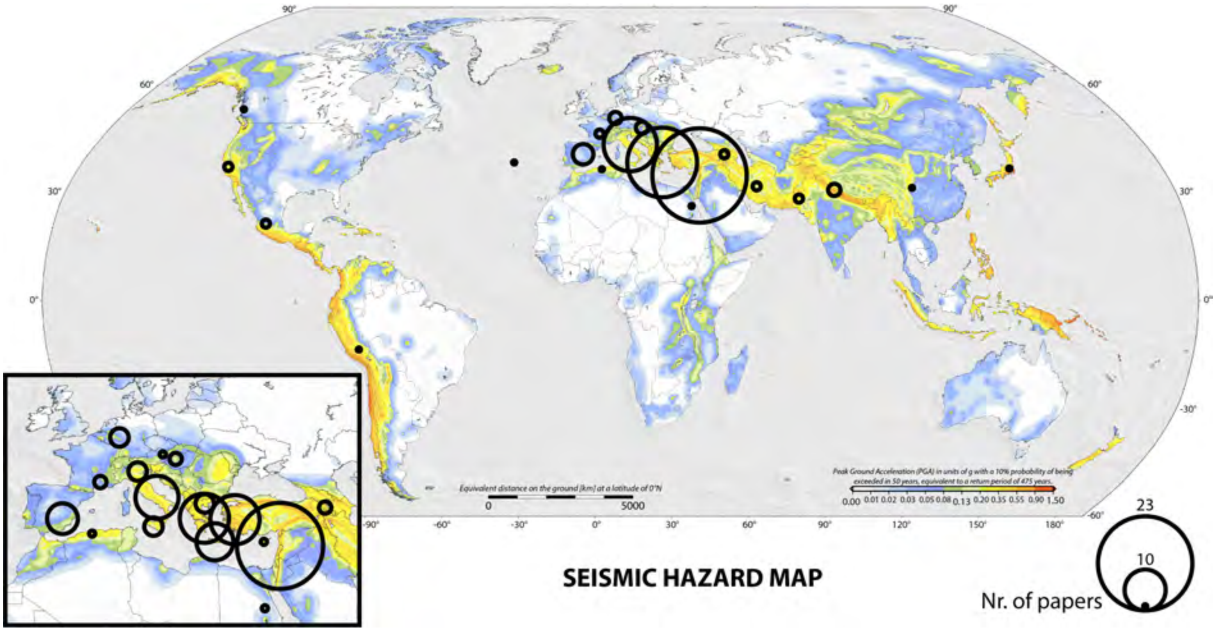

Figure 1.9: Distribution of the archaeoseismological studies, according to the research area, compared to the world seismic hazard map (Pagani et al., 2018 - GEM). The size of the circles is a function of the number of published papers reviewed. The inset on the bottom left corner is zooming on the European and Mediterranean areas.

SHA studies. Both objectives are complementary and may contribute to the development and design of more resilient lifestyles with respect to earthquakes. This requires, notably, taking into account the huge contrast of timeframe between the long-term archaeological processes and the instantaneousness of the seismological phenomena (Kovach & Nur, 2006). For that reason, we advocate for bridging the gap between the different sub-disciplines of archaeoseismology and for fostering true cross-disciplinary projects.

The persistent lack of studies on palaeoearthquakes in South America, and especially in the Andes, makes it a particularly promising area for implementing such innovative and comprehensive investigation. Through the case study in Cusco, our ambition is to reaffirm the relevant and prominent role that archaeoseismology may play in the broader fields of earthquake sciences and archaeology.

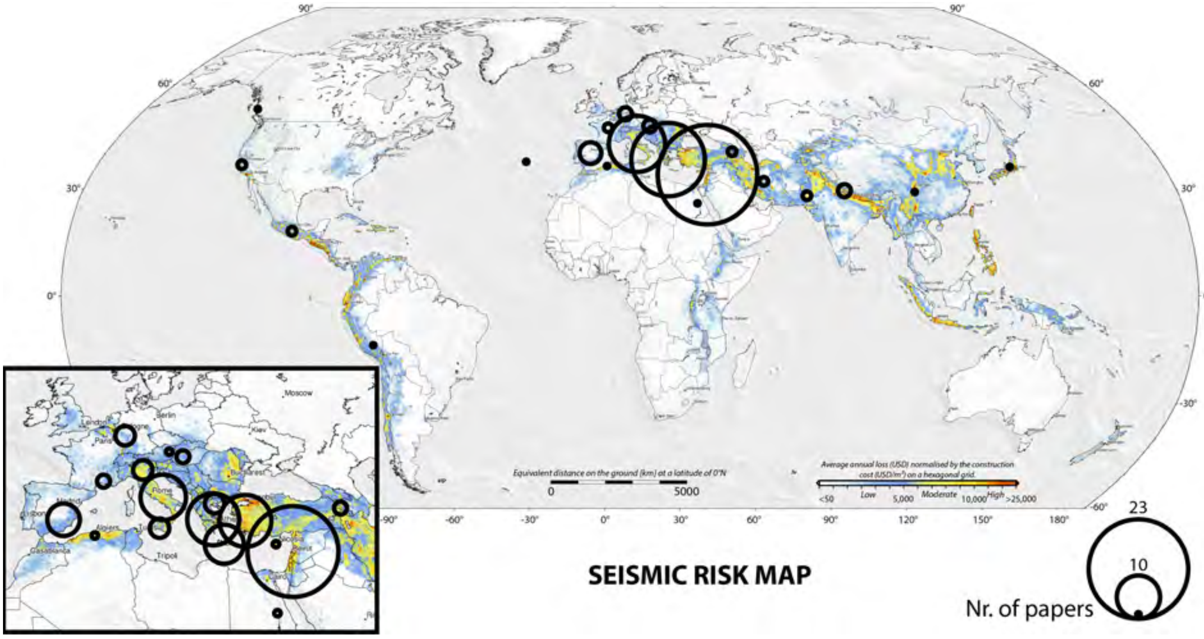

Figure 1.10: Distribution of the archaeoseismological studies, according to the research, area compared to the global earthquake risk map (V. Silva et al., 2018 - GEM). The size of the circles is a function of the number of published papers reviewed. The inset on the bottom left corner is zooming on the European and Mediterranean areas.

Notes

[1]According to Barnes (2010), the first seismograph was invented in China by Zhang Heng, a Han court mathematician who operated it during the 2^{nd} century CE.

[2]Several factors explain why crustal earthquakes are the most deadly, despite their limited magnitude. These include poor and difficult fault mapping (e.g., blind faults), their infrequent activity (e.g., long return periods), and the greater vulnerability of populations in intra-continental areas (e.g., difficulties to access, lack of emergency and health services, lack of housing with seismic standards, etc.).

[3]Many are blind faults or simply not (well) mapped due to the vegetation and/or their location in remote areas (difficult to access).

[4]The M_w4.9 Le Teil earthquake that struck the Middle Rhône Valley in 2019 has proved otherwise. The event that was very shallow (<1 km) was associated with a 5 km surface rupture (Ritz et al., 2020) and appreciable near-field geologic effects (Causse et al., 2021).

Chapter 2

The Cusco area: seismotectonic setting and archaeological occupation

"...Son tan frecuentes los temblores en esta ciudad [Cusco] que casi no pasa año sin que se sientan algunos." Esquivel y Navia (1980, II: 247)

2.1 Cusco, a testing ground for the SHA in the High Andes

Peru sits on the Circum-Pacific belt, commonly referred to as the "Ring of Fire". It is considered as one of the most vulnerable countries in South America for the seismic hazard (Stillwell, 1992; World Bank, 2012). An overwhelming part of the seismicity is the result of the convergence of the Nazca and South-American Plates and its distribution reflects a complex partitioning of the deformation within the Central Andes (Bevis et al., 2001; Chlieh et al., 2011; Villegas-Lanza et al., 2016). More broadly, the distribution of the instrumental seismicity (blue dots in fig. 2.1) allows the delineation of four basic seismogenic areas:

1. Interplate (<60 km) megathrust earthquakes located along the Pacific coast;
2. Deeper earthquakes occurring within the subducting Nazca Plate (60-300 km);
3. Very deep events (>300 km) that take place beneath the Amazonian lowlands;
4. Shallow crustal earthquakes generated within the overlying South American Plate. The latter occur mainly in the western margin of the sub-Andes (Suárez, Molnar, & Burchfiel, 1983).

The subduction process is the main source of seismicity and constitutes the main trigger of large destructive earthquakes, particularly in the southern and central parts of Peru. In this regard, we may note the major role played by the Nazca Ridge (fig. 2.1), corresponding to a change in the slab angle (Barazangi & Isacks, 1976; Stauder, 1975), in the segmentation of the subduction (Chlieh et al., 2011; Sparkes, Tilmann, Hovius, & Hillier, 2010). Characterized by recurrence times of about 100-300 years (L. Dorbath, Cisternas, & Dorbath, 1990; Kelleher, 1972), southern and central Peru are frequently hit by great and devastating earthquakes (e.g., Lima, 1746: Walker, 2018; Arica, 1868: Seiner Lizárraga, 2013; Pisco, 2007: D'Ercole, Chandes, Perfettini, & Audin, 2007). The megathrust earthquake hazard turns out, therefore, to be the main focus of the SHA studies (e.g., Z. Aguilar, Roncal, & Piedra, 2017; Chlieh et al., 2011; Das et al., 2020; Pulido et al., 2015).

Within the High Andes, the seismicity – defined by a complex pattern of deformation combining reverse, normal and strike-slip faulting – is surprisingly low over the last 50 years (fig. 2.1). The relative quiescence during that period does not reflect accurately, however, the seismic hazard, due to the low levels of deformation and significant return periods. Some isolated examples illustrate though the severity of the crustal seismic hazard (e.g., Ancash, 1946: Silgado Ferro, 1951; Cusco, 1986: Cabrera & Sébrier, 1998; Huaytapallana Fault: C. Dorbath, Dorbath, Cisternas, Deverchére, & Sebrier, 1990). Improving its assessment requires us to widen the time window and to build reliable historical earthquake catalogues.

Unfortunately, the number of historical events recorded, prior to the republican period (before 1821 CE - red dots in fig. 2.1) is strikingly low compared to the instrumental data. Considering the very active tectonic context, the scarcity of data can only be due to recording issues and biases in pre-instrumental times. Among them, we may mention, notably, the low density of population in large parts of the territory and potential loss of documents. Moreover, the absence of written accounts before the Spanish conquest explains the very low number of seismic events reported during pre-Columbian times (orange triangles in fig. 2.1).

The resulting heterogeneous and patchy distribution tends to "over-represent" the megathrust seismicity, in particular around the large colonial cities of Lima, Arequipa and Trujillo, situated on, or close to, the coast (fig. 2.1). Regarding the High Andes, only a few events are reported (fig. 2.1), making even more difficult a comprehensive assessment of the seismic hazard in this area.

In this respect, the region of Cusco (black frame in fig. 2.1) proves to be a notable exception. Whether it is an artefact, due to the dynamism of the city of Cusco during the colonial period, or the reflection of an abnormally high seismic activity, the density of colonial earthquakes in Cusco deserves to be addressed and the fault source to be identified. The availability of historical data combined with the presence of large tectonic structures represent a unique opportunity to better characterize this distinctive seismicity of the High Andes.

2.2 Active tectonics and seismic hazard in the Cusco region

2.2.1 The Cusco Vilcanota Fault System: description and current deformation

The Andes are the longest continental mountain range, extending over more than 7,000 km and bordering the entire western margin of the South American continent. Its great length and broad latitudinal gradient explain easily its division into three main zones: the Northern Andes (Venezuela, Colombia and Ecuador), the Central Andes (Peru and Bolivia) and the Southern Andes (Argentina and Chile). Located in the southeastern part of Peru (fig. 2.2), Cusco lies in the Central Andes. This region is divided, itself, into five main strips and geomorphological areas, perpendicular to the strike of the trench (Dalmayrac, Laubacher, & Marocco, 1980): the coastal zone, the Western Cordillera, the High Plateaus, the Eastern Cordillera and the sub-Andean fold and thrust belt. The previous division is the result of the long tectonic history, made up of successive phases of extension and convergence. Regarding the orogenic phases, the major ones have taken place during the Precambrian (<540 Ma, Ramos, 2010), the Paleozoic (~500-300 Ma, Dalmayrac et al., 1980) and the Meso-Cenozoic (from 250 Ma to the present time, Dalmayrac et al., 1980). Consequence of the subduction of the Nazca Plate below the South American Plate (Chen, Wu, & Suppe, 2019; Jaillard & Soler, 1996; Russo & Silver, 1996), the current orogeny has given rise to the Andean landscape that we know today.

The Cusco region is located approximately 350 km away from the Pacific coast, at the interface between the western Cordillera to the north and the High Plateaus to the south (fig. 2.2). A large inherited tectonic structure, the Cusco-Vilcanota Fault System (CVFS), separates these two areas. Most of the current deformation in the southern High Andes is thus accommodated at the boundary between these two distinct lithospheric blocks (Carlier et al., 2005; Ma & Clayton, 2014). In this respect, the most recent volcanic activity that took place in the area (since 7 Ma) was concentrated along this system (Bonhomme, Fornari, Laubacher, Sebrier, & Vivier, 1988; Carlier et al., 2005).

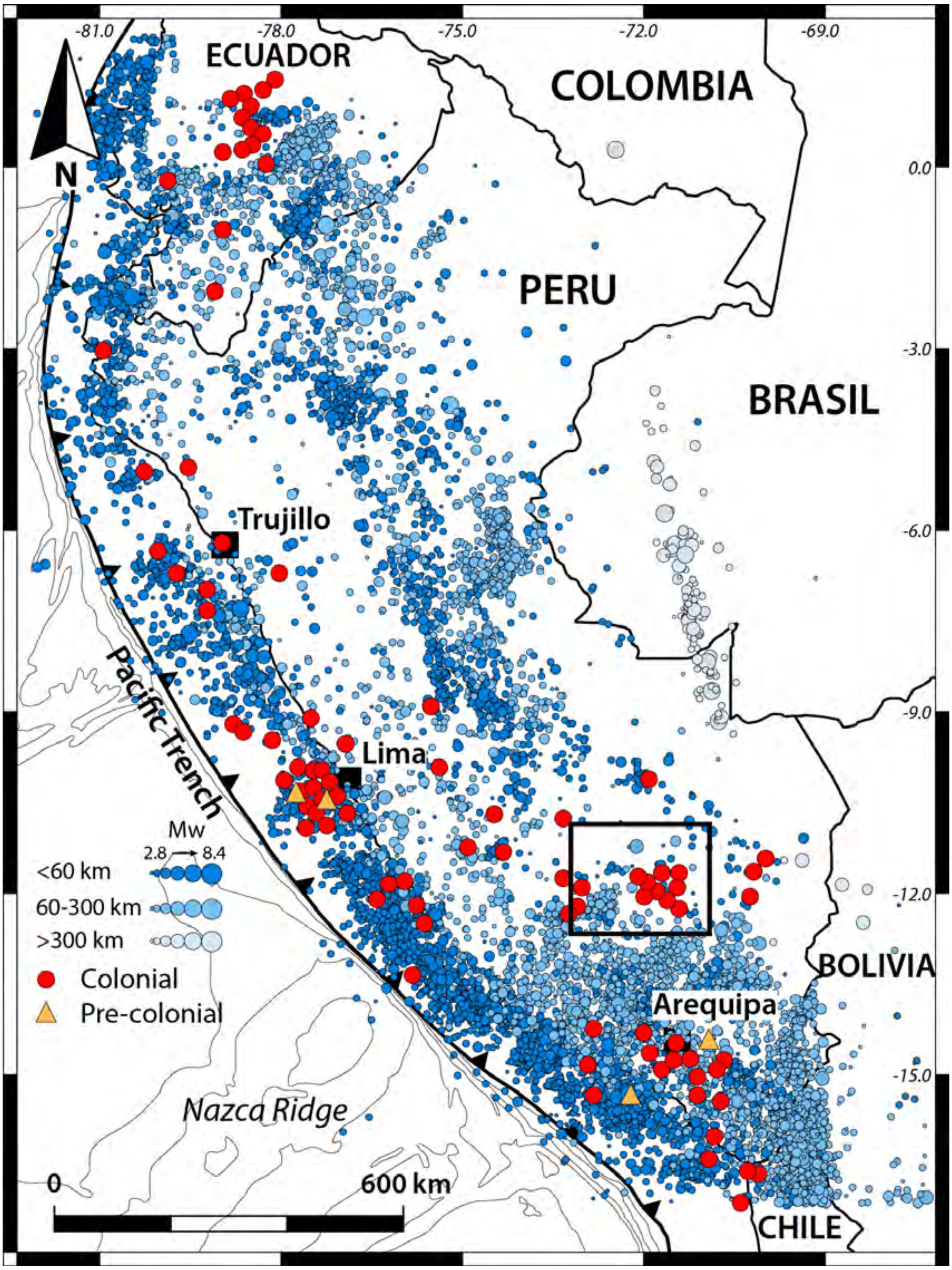

Figure 2.1: Comparison between the pre-Columbian/colonial (before 1821 – according to Cuadra et al., 2008) and instrumental seismicity (since 1970 – IRIS data) in Peru. The black frame indicates the study area.

More than 400 km long, the CVFS starts, on the west, on the southern edge of the Abancay Deflection (Gérard, 2020), which is characterized by a very rugged and incised topography. The CVFS crosses, then, the heart of the Cusco region and stretches up to the southern part of the *Altiplano* and Titicaca Basin. In the heart of the Cusco region, the CVFS splits into a large number of fault segments that delimit, to the south, the northern edge of the intra-cordilleran basins (e.g., Anta-Chinchero and Cusco Basins) filled with Pliocene and Quaternary sediments (Gregory, 1916) and leaves the room, to the north-east, to the sub-Andean fold and thrust belt (fig. 2.2). Although suspected by Gregory as early as 1916, the large and extensive network of crustal faults was documented, for the first time, by Suárez et al. (1983) and Sébrier, Mercier, Mégard, Laubacher, and Carey-Gailhardis (1985) and then extensively mapped by Benavente Escobar, Delgado Madera, Taipe Maquerhua, Audin, and Pari Pinto (2013). Oriented roughly NW-SE (fig. 2.2), the faults form significant topographic anomalies in the Cusco landscape. On one hand, triangular facets, sagponds and large scarps (fig. 2.3a), with heights up to 600 m, affecting Pliocene and Quaternary formations reflect the cumulative fault activity and support a motion mainly extensional since ∼5 Ma. On the other hand, small scarps (fig. 2.3), cutting and offsetting moraines and other quaternary deposits at the foot of the larger landforms, demonstrate a Holocene normal activity (Cabrera, Sébrier, & Mercier, 1991). A NNE-SSW trend defines the present-day extensional regime (Cabrera, 1988; Mercier et al., 1992). Based on the analysis of offset landforms, the horizontal extension slip rates have been recently estimated between 1 and 4 mm/yr. (Wimpenny et al., 2020).

Regarding the peculiar extensional setting and stress field in the Cusco region, several factors have been proposed but their contribution is still a matter of debate. Dated around 5-9 Ma (Kar et al., 2016; Mercier et al., 1992), the onset of the extension is contemporaneous with the flattening of the slab estimated at 7 Ma (Espurt et al., 2008) arguing for a decisive role of the slab geometry and the Nazca ridge (i.e., stronger coupling - Mercier et al., 1992; Sébrier et al., 1985). Mercier et al. (1992) highlighted, nonetheless, the existence of three distinctive regimes of stress since the Pliocene, including a compressional episode during the early Pleistocene. Accordingly, the pattern of extension in the High Andes may result from the interaction of several factors. Among them, Suárez et al. (1983) and Dewey and Lamb (1992) support the contribution of buoyancy and gravitational forces affecting the high relief, while Wimpenny et al. (2020) hypothesize that the timing of slip might be modulated by the seismic cycle of the subduction zone.

Despite the moderate deformation rates at the regional scale, the crustal seismicity recorded over the last 50 years confirms the activity of the fault system (fig. 2.2). Moreover, the focal mechanisms computed for the stronger recorded earthquakes vouch for the normal faulting. These include the Cusco April 6, 1986 earthquake, associated with the sole surface rupture in the region (Cabrera & Sébrier, 1998)[5], and the damaging Paruro September 21, 2014 event (Tavera, Flores, Fernandez, & Guardia, 2014). Estimated at M_w=5.3 and 5.0 respectively, both ground motions did not reach the maximal magnitude that might be generated by the local fault complex. Cabrera (1988) estimated it between M_w=6.0 and 7.2, depending on the segment length. What about the mean rate of occurrence of large crustal earthquakes at the regional scale?

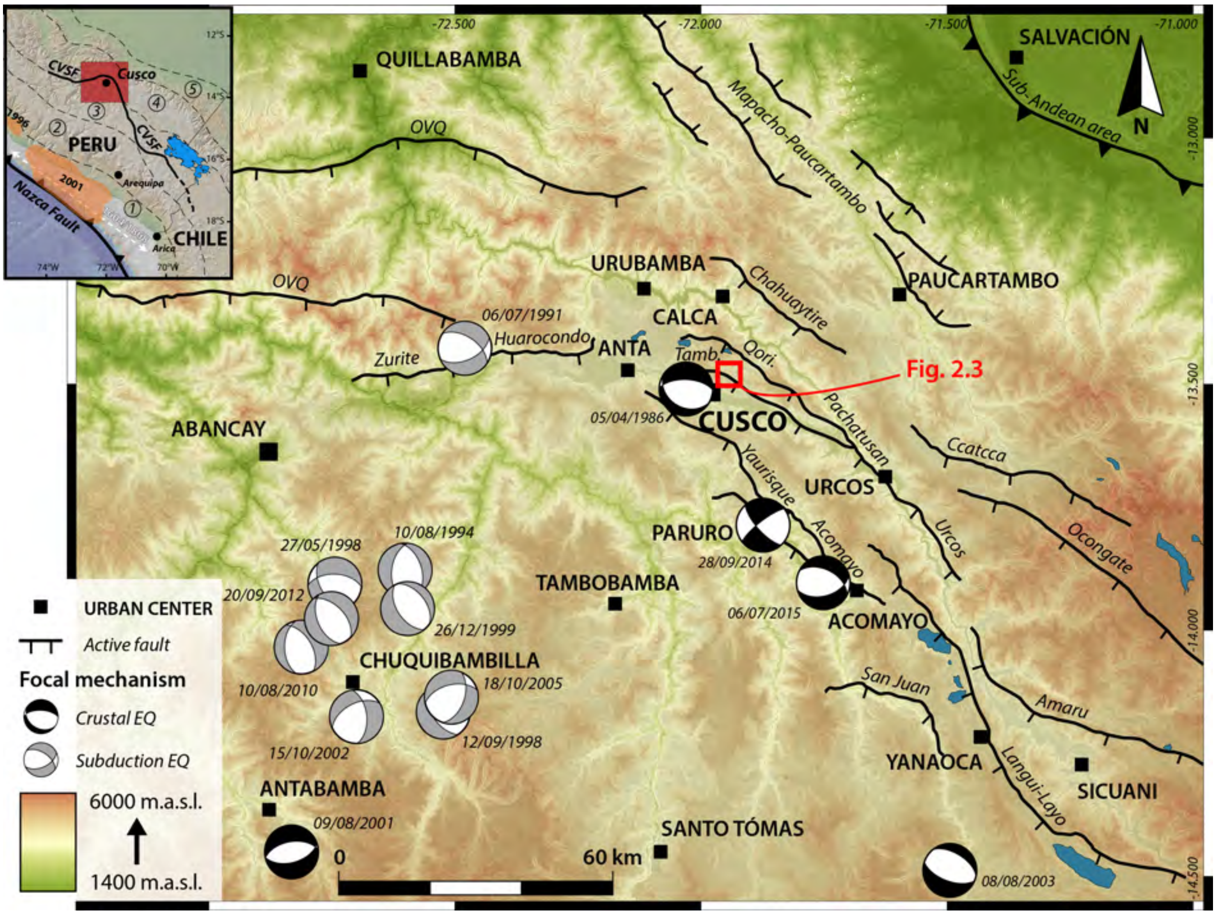

Figure 2.2: Main active fault segments and focal mechanisms of $M_w \geq 4.9$ earthquakes within the Cusco region between 1976 and 2017. Earthquakes and their focal mechanisms were extracted from the Global CMT catalogue (Dziewonski et al., 1981; Ekström et al., 2012) and the geographical coordinates were based on the IGP catalogue. Note that superficial earthquakes (<60 km) are correlated with the regional fault system. The geological zonation of the Andes, in the inset, is based on Dalmayrac et al. (1980).

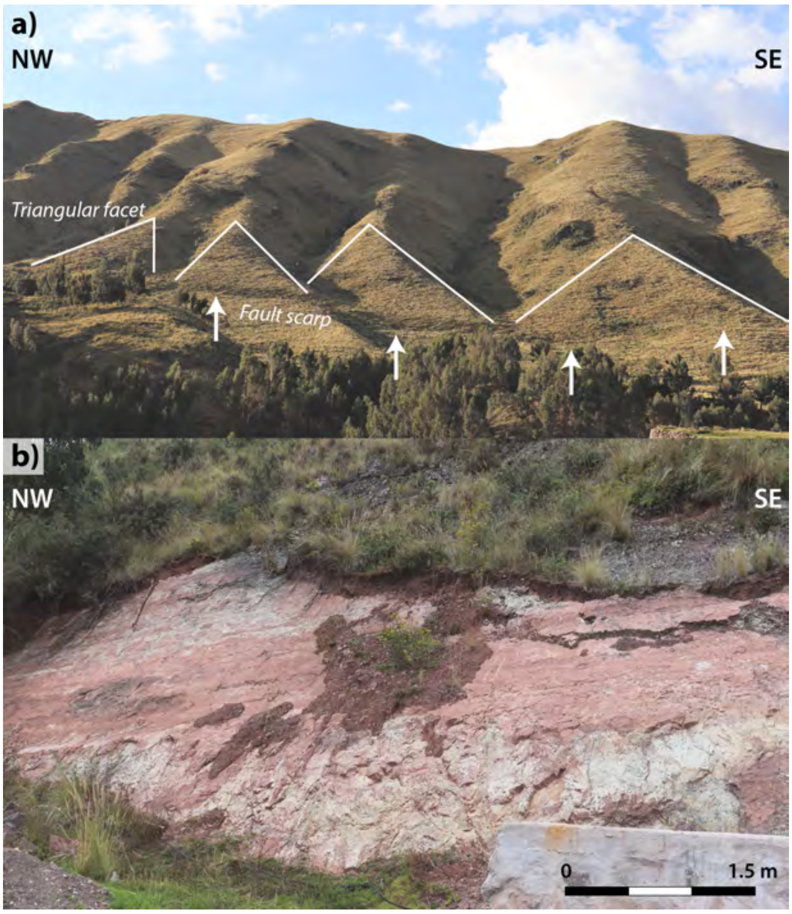

Figure 2.3: a) Holocene fault scarp located at the foot of triangular facets, evidencing the normal motion of the Tambomachay fault near Puka Pukara; b) Tambomachay fault plane in Pumamarca (north-east of Cusco).

We calculated the Gutenberg-Richter relationship (Gutenberg & Richter, 1944) by using the instrumental crustal seismicity recorded since 1960 and provided by the IGP catalogue (courtesy of H. Tavera)[6]. We considered only shallow earthquakes (depth<60 km) and we extrapolated the recurrence rate of $M_w \geq 7$ earthquakes based on the a- and b-values. Although the law is poorly constrained because of the narrow time window and the lack of high magnitudes, it provides a consistent b-value close to 1 (fig. 2.4). According to our extrapolation, the expected mean rate of occurrence is around 2,000 years. Regarding $M_w \geq 6.5$, the rate is close to 400 years. This result confirms the SHA issues related to crustal seismicity in Peru. It highlights, indeed, the inadequacy and shortfall of, not only, the instrumental but also historical data to cover the entire seismic cycle of such tectonic structures. Historical seismicity in Cusco turns out, though, to be particularly useful to improve our understanding of the local seismic hazard.

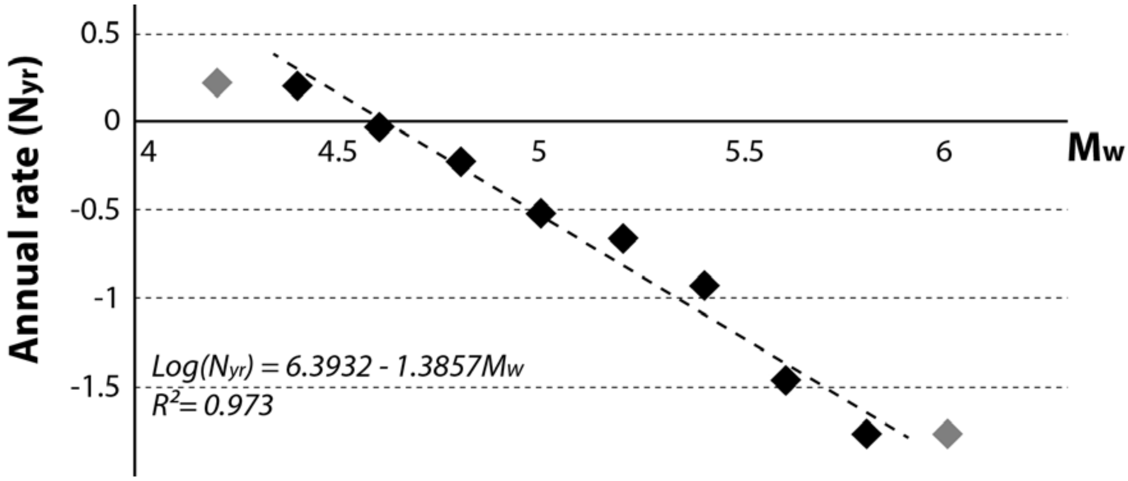

Figure 2.4: Magnitude-frequency relationship for crustal earthquakes in the Cusco area (geographical boundaries corresponding to the black frame in fig. 2.1, based on the seismicity of 1960-2019 (IGP catalogue). The inferred Gutenberg-Richter law is indicated on the top left corner. Outliers are displayed in grey.

2.2.2 Insights on the historical seismicity

As the inhabitants of Cusco noted in colonial times, tremors and earthquakes were frequently shaking the city and its surroundings (Esquivel y Navia, 1980). While no written description of seismic events exists before the Spanish Conquest, several damaging ground motions have struck the area before the installation of the first Peruvian seismological network (1980s – table 2.1).

Date	Epicentral area	Magnitude	Intensity in Cusco (M.M.)
21/05/1950 18:38	SW of Cusco?	5.6-5.9	VIII
18/09/1941 08:15	?		VI-VII
19/11/1744 06:30	Cusco Basin?		
24/03/1742 21:30	Cusco Basin?		
30/12/1702 14:00	Cusco Basin?		
31/03/1650 14:00	South of Cusco?	7.2?	IX

Table 2.1: Damaging historical earthquakes (from 1533 to 1960) that affected the Cusco Basin and their estimated intensity felt in the city of Cusco (Modified Mercalli intensity scale). Intensities are based on Silgado Ferro (1978) and Tavera et al. (2016). The two main events are shaded in grey.

Among them, two earthquakes, in 1650 and 1950, had particularly severe consequences in Cusco. On March 31, 1650, a ground motion of unprecedented violence devastated the Cusco region and leveled the colonial city. The earthquake triggered numerous land- and rockslides, cutting the axes of communication (Villanueva Urteaga, 1970). It also devastated many towns like Paucartambo, Yaurisque and Paruro (fig. 2.5). In the sedimentary basin of Cusco, the seismic event seems to have been associated with liquefaction processes[7], causing even more damage. According to contemporaneous observers, the ground motion was so strong that it was felt as far as Arequipa. This information falls probably within the numerous exaggerations of colonial texts and, based on the limited observations, it is most likely that the magnitude proposed by Silgado Ferro (1978) has been overestimated. No mentions of surface rupture is currently known but a local and shallow source is more than likely.

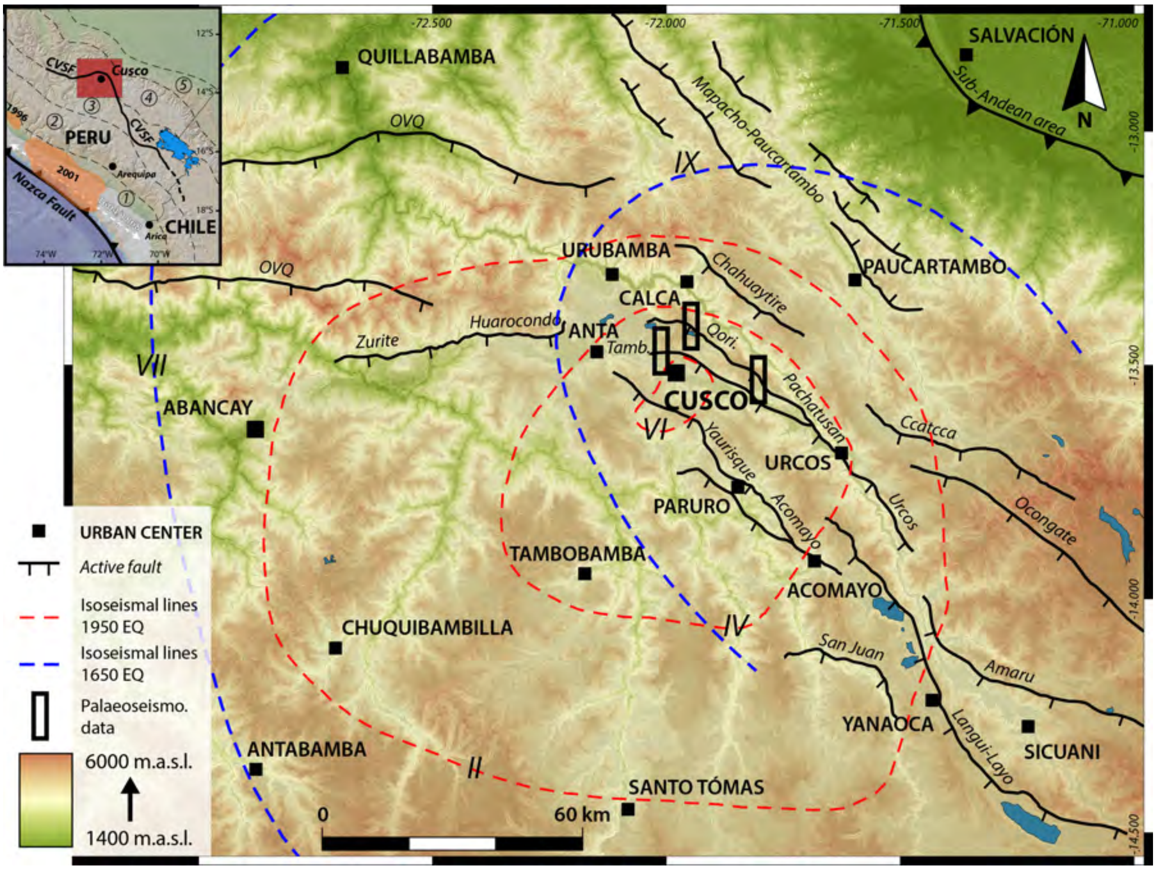

Figure 2.5: Regional map of the Cusco area showing the main active faults and the seismic intensity distribution of the 1650 and 1950 earthquakes (isoseismal lines) according to Tavera et al. (2016). The location of the palaeoseismological trenches is also reported.

The 1650 earthquake was estimated around IX in Cusco (fig. 2.5) on the Modified Mercalli intensity scale (M.M.). According to the inscription at the bottom of the Alonso Cortés de Monroy's canvas (fig. 2.6), the event "knocked down the churches, convents and houses of almost the entire city" and was followed by more than 1,600 aftershocks (Hajovsky, 2018, p.35). The southwestern sector of the Cusco Basin, in which the indigenous population was concentrated, was the most affected area[8]. Monroy depicts numerous fires and cracks in the buildings of the left side of its painting (fig. 2.6a), suggesting thus a stronger impact southwest of the Main Square (*Plaza de Armas* – fig. 2.6b).
Finally, while the reconstruction of the city seems to have been completed in approximately 10 years (Scaletti & Mazzanti, 2018), the event has left a deep imprint on inhabitants' minds and, more widely on the cultural life. On one side, the earthquake fostered the development of the Andean Baroque (Hajovsky, 2018). On the other hand, it causes the emergence of the cult of the Lord of the Earthquakes (*Señor de los Temblores* – fig. 2.6a), which remains the patron saint of Cusco nowadays.

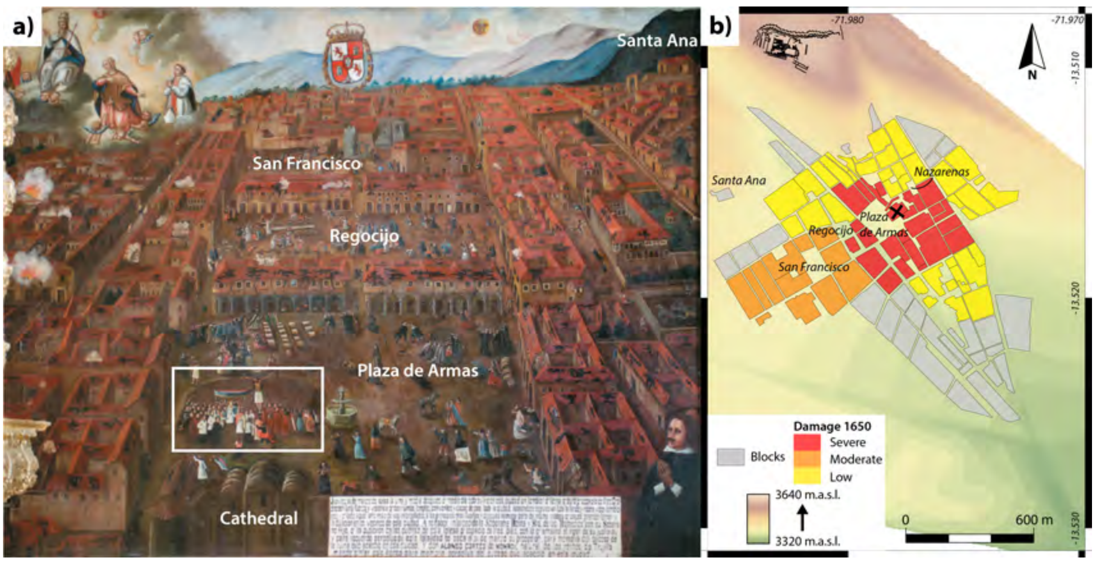

Figure 2.6: a) Painting of the 1650 Cusco earthquake exhibited within the Cusco Cathedral (Alonso de Cortés de Monroy). The white frame highlights the procession of the Lord of the Earthquakes; b) Damage distribution in the Cusco city after the 1650 earthquake according to Candia-Gallegos et al. (1993). The dark cross indicates the cathedral.

300 years later, an earthquake with an estimated surface magnitude between 5.6 and 5.9 (pers.comm. International Seismological Centre) struck again the Cusco Basin. This time, the damage was restricted to the Cusco Valley and did not extend beyond a radius of 20 km from the Cusco city (fig. 2.5). According to field observations, Ericksen, Concha, and Silgado (1954) locate the epicentral area in the western edge of the Cusco Basin.

On the contrary, Cabrera (1988) suggest the responsibility of the Pachatusan Fault in the 1950 earthquake, based on the detection of a fresh scarp on 1956 aerial photographs. Considering the absence of accurate instrumental data and the limited number of observations available, the identification of the source is complex and remains a matter of debate. In the city of Cusco, the May 21, 1950 earthquake caused serious damage (fig. 2.7a) and generated a seismic intensity from VII to VIII (M.M.), despite the moderate estimated magnitude. This is explained probably by a shallow fault rupture and strong site effects (fig. 2.7b-c).

Leaving 30 to 40,000 people homeless and causing the displacement of almost 20,000 inhabitants (Kubler, 1952), the seismic event constitutes a tipping point in the Cusquenan urban planning (Pinley Covert, 2019). The ground motion also triggered intense thinking about the historical heritage (Kubler, 1952; Ladrón de Guevara, 1967). Whether the tourism outreach or the serious issues regarding the uncontrolled urban expansion (Rey, 2007), both are the result of the decisions taken in the aftermath of the earthquake.

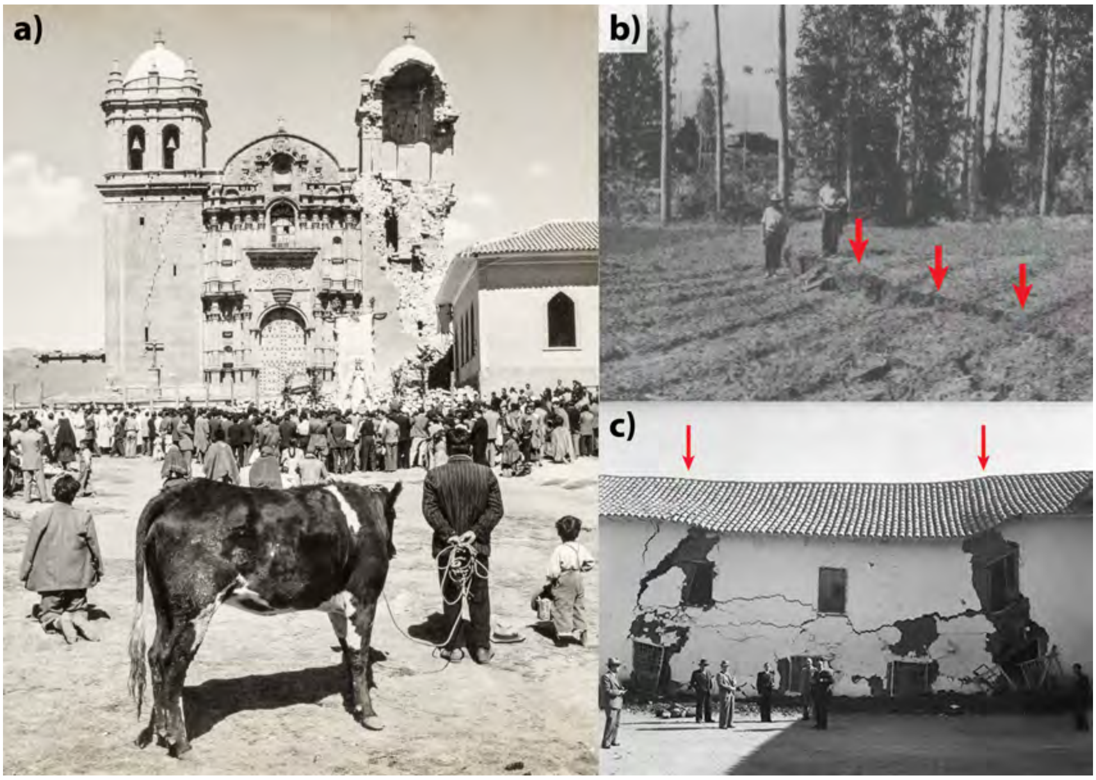

Figure 2.7: a) The church of Belén, as numerous colonial buildings, was severely affected by the ground shaking (credits: PUCP Repositorio); b) Ground fissure observed near the Huatanay River, east of Cusco (Ericksen et al., 1954); c) Collapsed and sunken house on the Nazarenas square suggesting liquefaction phenomenon (credits: Martín Chambí) .

These two events were thus seismic disasters for the city of Cusco and their multiple consequences in the socio-cultural and economic areas (Tamayo Herrera, 1981) had a considerable impact on its history and its inhabitants (Calvo, 1994; Gade, 1970). Unlike the instrumental period, the historical one (1533-1960) shows the severity and harmfulness of the regional seismic hazard. To the best of our knowledge, the last 500 years do not seem to have experienced, nonetheless, a major earthquake, i.e. corresponding to the rupture of the total fault length and reaching a magnitude greater than 6.5-7. In order to expand the time window, palaeoseismological studies were carried out in recent years.

2.2.3 First steps towards a palaeoearthquake catalogue

The first palaeoseismological trenches were excavated in the second half of the 1980s by Cabrera (1988). This pioneering work, at the scale of the Andes, showed three distinct deformation layers associated with three surface ruptures on the Qoricocha Fault (figs. 2.5 and 2.8) and ground motions stronger than the 1986 M_w=5.3 earthquake (Cabrera & Sébrier, 1998). However, the authors did not use absolute dating methods and concluded only on a recurrence time of a few thousand years for M_w>6 earthquakes.
Since then, other studies have been conducted on the Tambomachay and Qoricocha Faults (Rosell Guevara, 2018), as well as on two segments of the Pachatusan Fault (Palomino Tacuri et al., 2021 – fig. 2.5). The preliminary results suggest the occurrence of, at least, 10 surface ruptures during the Holocene (fig. 2.8), pointing at large return periods for each fault (∼1-2 kyr.). However, only two events, on the Tambomachay and Pachatusan Faults, were reported during the last 2,000 years and none of them seems to have occurred after the 10^{th} century CE (fig. 2.8). Considering the occurrence of only one strong event in Cusco over the last 500 years (1650) and the mean rate of occurrence calculated for the Cusco region in Section 2.2.1, it appears quite unlikely that no large earthquake(s) struck the area during the late pre-Columbian period, i.e. 1000-1533 CE.
Unfortunately, the number of trenched fault segments and palaeoseismological studies are still insufficient to characterize properly the fault dynamics and constitute a comprehensive catalogue of Quaternary earthquakes at the scale of the Cusco region. This is even more true since unknown active faults may still be discovered in remote parts of the Cusco region, difficult to access and to map. This short presentation of the seismotectonic setting of the Cusco region demonstrates thus the serious threat that represents the crustal seismicity in the High Andes. It stresses, nonetheless, the substantial lack of data that hampers an accurate assessment of the seismic hazard. There is an urgent need to both intensify and extend the palaeoseismological coverage and to use innovative complementary

approaches to address the seismicity in pre-Columbian times. The numerous settlements and buildings left by the Cusquenan populations may constitute a relevant marker of the past seismicity.

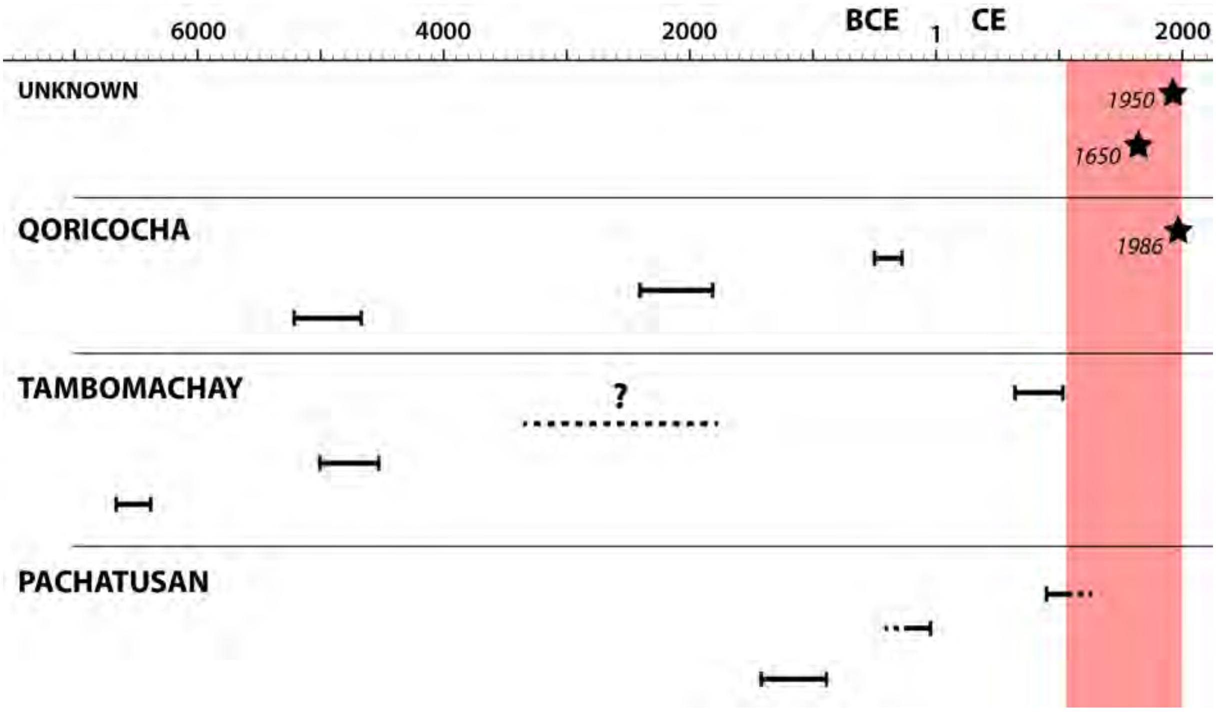

Figure 2.8: Surface ruptures documented in the Cusco Basin during the last 9 kyr. The dating of the seismic events and their associated uncertainties are based on Rosell Guevara (2018) and Palomino Tacuri et al. (2021). Moreover, the main historical events are reported (black stars). Aside from the 1650 earthquake, no large earthquake was reported for the period 1000-2000 CE (red strip).

2.3 Cusco: the Heartland of the Incas

2.3.1 The Incas: development and expansion

The pre-Inca occupation

The human occupation of the region (fig. 2.9a) goes back to the final retreat of the Pleistocene glaciers around 12,000 BP. The area is first colonized by hunters-gatherers during the Archaic period (∼10000 - 2500 BCE). Then, the semi-nomadic groups progressively settle and the earliest pottery styles appear (e.g., Marcavalle, Chanapata), giving way to the first hierarchical societies during the Formative period (2500 BCE - 200 CE – Bauer, 2018). Although the Early Intermediate Period (200 - 600 CE) is still poorly known, it seems to have been characterized by significant population growth, a clear change in the settlement pattern and the development of supra-regional networks of exchange. Meanwhile, we note the emergence of the Qotakalli ceramics that persist during the subsequent period, the Middle Horizon (600 - 1000 CE). This period constitutes a pivotal era in the human occupation of Cusco. Around 600 CE, two large sites, Pikillaqta (McEwan, 1996) and Huaro (Glowacki, 2002), are erected in the southern part of the Cusco region. The construction of these sites comes with the introduction of a new foreign pottery style coming from the Ayacucho region and the Wari polity. The archaeological investigations confirm the establishment of Wari people in the Cusco without supporting a real political and cultural shift at the regional scale (Bélisle & Bauer, 2020; Bélisle et al., 2020; Covey, Bauer, Bélisle, & Tsesmeli, 2013). The local groups interact nonetheless with the new player and the local elites take part in the pan-Andean networks of exchange of luxury goods (obsidian, ceramics, seashells . . .).

The State Formation

Around 1000 CE, the violent process of abandonment of the site of Pikillaqta (McEwan, 1996) highlights the sudden demise of the Wari influence in the region. This significant cultural change coincides with strong aridification of the climate (Binford et al., 1997; Chepstow-Lusty et al., 2009). The first part of the Late Intermediate Period (LIP: 1000 - 1400 CE) shows a clear settlement shift (i.e., the establishment of populations at higher elevation), a strong social differentiation between farmers and herders and a political/ethnical fragmentation (Bauer & Covey, 2002; Covey, 2008). However, during the second part of the LIP, the Killke culture and its related pottery style spread out at the scale of the entire Cusco Basin. According to the excavations of Brian Bauer and

Alan Covey (Bauer, 2018; Bauer & Covey, 2002; Covey, 2003), the Killke polity, established in the western part of the Basin, and notably in the current city of Cusco, seem to succeed in expanding politically and economically, through alliances and conquests. Notwithstanding the emergence of new pottery styles at the beginning of the 15^{th} century CE, the transition between the Killke and Inca polity seems to have been progressive and smooth. Moreover, ceramic analyses carried out in the Lucre Basin (30 km south-east of Cusco) support the influence of other ethnic groups in the development of the Incas (Ixer, Lunt, Sillar, & Thompson, 2014; McEwan, Chatfield, & Gibaja, 2002). In any case, a highly hierarchical and structured polity takes control, at the turn of the 15^{th} century, of the Cusco Valley and its surroundings (Paruro, Anta, Calca, Lucre). As a first step, the Inca control seems to have taken advantage of the pre-existing organization and cultural practices of the local groups (Hardy, 2019; Kosiba & Blanco, 2013; McEwan, Gibaja, & Chatfield, 2005; Quave, Covey, & Durand Cáceres, 2018).

The Late Horizon: chronicle of a pan-Andean empire

Benefiting from stable but dry climatic conditions throughout the 15^{th} century (Chepstow-Lusty et al., 2009), the Inca polity seems to have been able to produce surplus, unlike its neighbours. Based on a pragmatic, heterogeneous control of the numerous ethnic groups (Stanish, 2001) and the reward of the local submitted elites in exchange for large tolls (labor force and resources), the Inca polity quickly expands its control over large territories. Interestingly, this expansionism is, in itself, linked to the organization of the Inca state, forced to constantly find and exploit new lands to reward and sustain those local elites (Tantaleán, 2015). The singular tributary system and management strategies of the provinces organized from the Cusco capital come with the transformation of the landscape of the Andes, the construction of large axes of communication (Hyslop, 1984) and large (forced or not) movements of populations (Andrushko, Buzon, Simonetti, & Creaser, 2009; Bongers et al., 2020; Turner, Kamenov, Kingston, & Armelagos, 2009). The day before the Spanish arrival (1532 CE), the Inca empire is the largest pre-Columbian entity in history, extending from the southern part of Ecuador to the northern part of Chile and Argentina (fig. 2.9b).

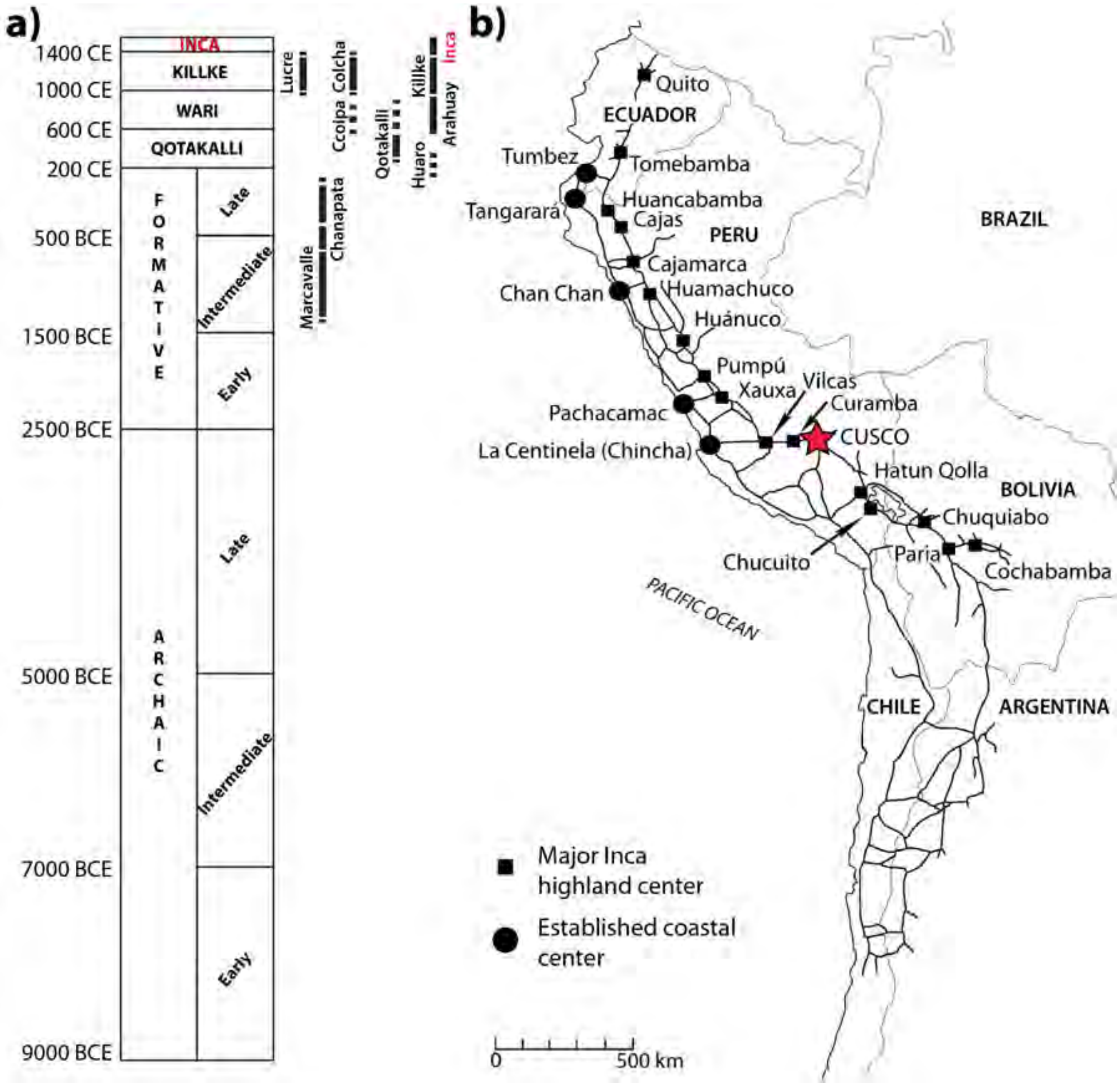

Figure 2.9: a) Chronology and ceramic sequence of the Cusco region (based on Bauer, 2018); b) Inca territory, road system and main centers before the Spanish Conquest (according to Covey, 2019).

2.3.2 Remodelling the Cusco landscape

A sacred landscape

Regarding the two founding myths of the Incas, one presents the site of Pacariqtambo as the place where emerged their ancestors (Bauer, 1987; Urton, 1989). Although this origin is purely imaginary, it justified and legitimized the appropriation of the Cusco area as a sacred landscape. Many cultural beliefs, ceremonies and celebrations of the Inca calendar take root in the landscape surrounding Cusco. Hence, numerous rock outcrops, springs and caves constitute holy places, or *wakas*. Within the Cusco Basin, the *ceque* system (Cobo, 1979) includes more than 300 shrines and defines a planned and complex ritual landscape (Bauer, 1998; Christie, 2008; Kosiba, 2015; Silva Gonzales & Loza García, 2007) that is intrinsically linked to the organization of the Inca State. More broadly, the Inca sites, themselves, become a vector of sacredness and authority, contrasting with the previous built environment (Kaulicke, Kondo, Kusuda, & Zapata, 2003; Kosiba & Blanco, 2013).

A new form of urban planning

The Inca State formation and the subsequent imperial phase results in densification and intensification of the human impact on the Cusco landscape (Covey, 2006). This coincides with numerous innovations in the fields of hydraulic engineering, agriculture and architecture. While the bottom and sides of the valleys, dedicated to maize cultivation, are carefully transformed thanks to monumental terraces and complex irrigation systems (Fairley Jr., 2003; Wright, 2006), the city of Cusco turns into the mirror and model of the Inca social organization and urban planning (Christie, 2016). In a similar manner to the Wari rectangular grid of Pikillaqta, the Incas design a geometric, highly standardized traffic network and build rectangular structures (Agurto Calvo, 1980, 1987; Alfaro, Matos, Beltrán-Caballero, & Mar, 2015; Beltrán-Caballero, 2013; Vranich, Berquist, & Hardy, 2014). The Inca architecture is thus articulated around an architectural nucleus, the *kancha*, which consists of a compound including one to four quadrangular buildings around a small plaza (fig. 2.10a). Through the replication of the basic *kancha*-pattern, large Inca settlements can be constructed quickly and in an orderly manner. In Cusco, the capital of the empire, the Incas develop what Agurto Calvo (1980) defined as an agrarian city. There, the geometric urban planning and the political-ceremonial complexes integrate sacred natural features and are embedded into a large complex of terraces and hydraulic infrastructures (Alfaro et al., 2015; Beltrán-Caballero, 2013 – fig. 2.10b).

The “royal estate” phenomenon

Developed in Cusco, the model of “agrarian settlement” reached its climax with the construction of extensive royal estates in several places of the Cusco Basin and Urubamba Valley. Residences of the Inca rulers and then of their lineages, these estates are, according to the chronicles, royal properties including agricultural and residential sectors and

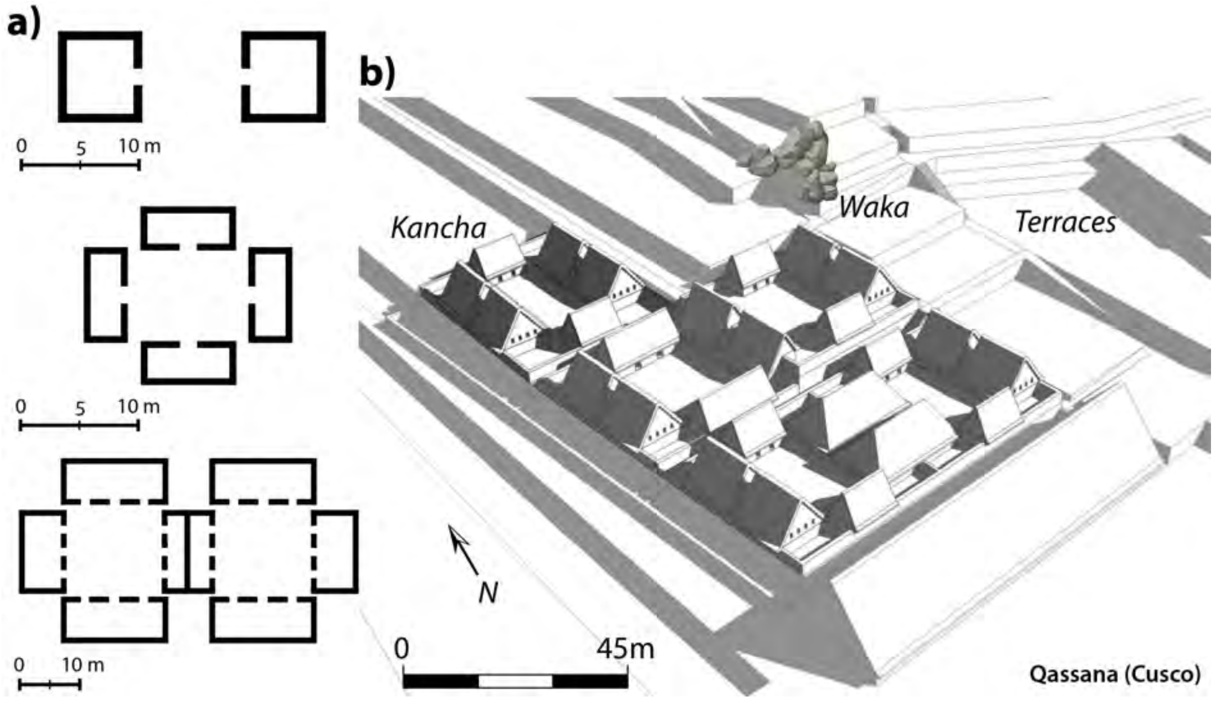

Figure 2.10: a) The *kancha* is the basic Inca architectural unit (top to bottom: model with two or four buildings and combination of two groups of four buildings; modified from Bouchard, 1983, p.71); b) 3D reconstruction of an Inca compound in Cusco (according to Beltrán-Caballero, 2013). Its shows how Inca settlements were designed, by combining geometric planning, supporting walls, terraces and sacred places.

ceremonial buildings. As the emperors succeed one another, the number of royal estates increases dramatically until reaching the minimum number of 19 in 1533 CE (Covey, 2003 – fig. 2.11). Based on the information provided by Spanish chroniclers, these extensive private estates represent planned constructive projects, undertaken over a short period of time that have required an important workforce. Hence, they were prestigious projects aiming at emphasizing the power of the ruler and the State (Nair, 2015). Among others, we may mention Huchuy Qosqo (Bauer, 2018) considered as the formal residence of Viracocha Inca (ca.1410-1438 CE), Chinchero (Alcina Franch, 1970) constructed allegedly by Tupac Yupanqui (1471-1493 CE) as well as Pisaq (Kaulicke et al., 2003), Ollantaytambo (Protzen, 1993) and Machu Picchu (Burger, 2004; Rowe, 1990; Wright & Zegarra, 2000) regarded as estates of Pachacuti Inca Yupanqui (1438-1471 CE). Those sites present numerous high-status buildings with fine stone masonry styles that amazed both the Spaniards and the current visitors.

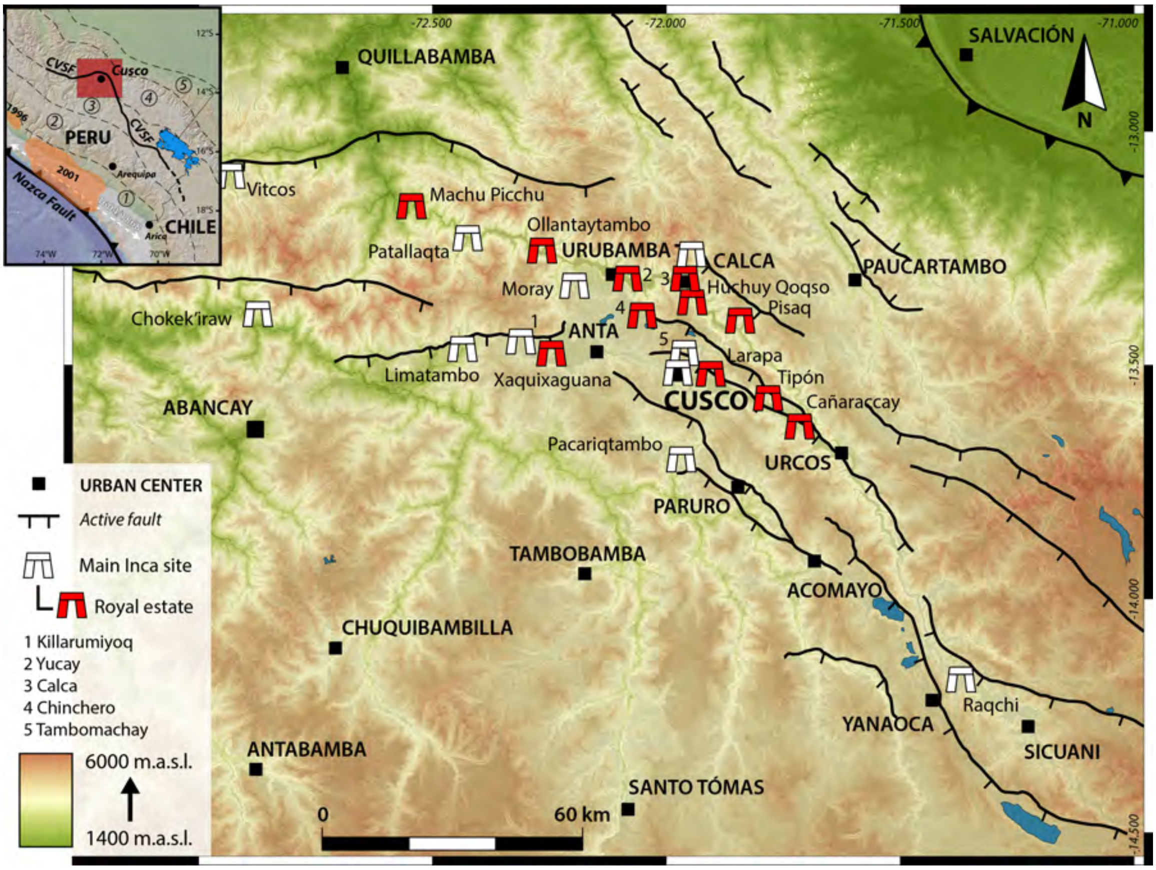

Figure 2.11: Regional map of the Cusco area displaying the main Inca settlements. The royal estates, generally associated with monumental and fine stone masonry styles, are represented in red (only the main estates and those mentioned in the manuscript are reported). Note the close proximity of those sites with the active tectonic structures.

2.3.3 The Inca stonework

Main characteristics and construction techniques

A large number of recurrent features characterizes the Inca architecture, giving the impression of a uniform and standardized design. Through the replication and combination of a small range of basic and geometric forms, the Incas were, nonetheless, able to make subtle variations (Agurto Calvo, 1987; Farrington & Zapata, 2003; Gasparini & Margolies, 1980; Protzen, 2018). The Inca stonework exemplifies this elementary and modular approach[9].

Based on the works of Agurto Calvo (1987) and Gasparini and Margolies (1980) it is possible to identify five main types of bonds in Inca stone masonry [10](fig. 2.12):

- **Rustic**: it consists of natural or poorly cut stones joined with mortar, earth and/or rubblework (*blocage*). Stones vary greatly in size and shape. Rustic walls are often built using limestone and sandstone blocks and are preferentially used as terrace walls;

- **Cellular**: so-called because of its alveolar aspect, this style can be likened to a cell network. Cellular walls are generally composed of well-fitted limestone or andesite blocks, of medium/large size. However, the walls are of widely varying quality. Pentagonal or hexagonal in shape, the stone blocks are characterized by smooth/rounded corners;

- **Imbedded-Polygonal**: in these walls, stones are arranged in a jigsaw-like pattern. Andesite, diorite or even basalt blocks, of varying sizes, show a very large number of corners and fit perfectly in each other. The imbedded-polygonal style is mainly used in terrace/retaining walls of high-status buildings;

- **Cyclopean**: this style of stonework stands out for the size of the blocks. Cyclopean walls are made up of large to giant stone blocks (>1 m), roughly cut but closely fitted. Among the few examples of cyclopean walls, most of them were built as retaining walls, using limestone blocks;

- **Sedimentary**: this style consists of regularly coursed walls, where precisely cut stones in parallelepiped shape (i.e., ashlar masonry) are laid out in horizontal rows without mortar. Built using limestone, andesite or even granite blocks, the size of the ashlars is usually decreasing from bottom to top. Unlike the three previous dry-stone masonry types, well known for their "pillow-faced" style, the surface of sedimentary walls is almost polished and flat. This style was used for most of the Inca high-status and sacred buildings.

The three latter are the most common fine masonry styles, which puzzled and amazed the Spaniards and European travelers. Any observer may wonder how a society that had almost exclusively stone tools to its disposal was able to cut stones so precisely and fit them so closely. Regarding the cyclopean style, the first *conquistadores* questioned even the human agency (Dean, 1998). The Inca architecture is, however, the result of well-organized human labor. Despite many unknowns regarding the technologies and processes that enabled the quarrying, cutting, transport, shaping and laying of blocks, it is possible to give an overview of the production line designed by the Incas, notably in the Cusco region (fig. 2.13).

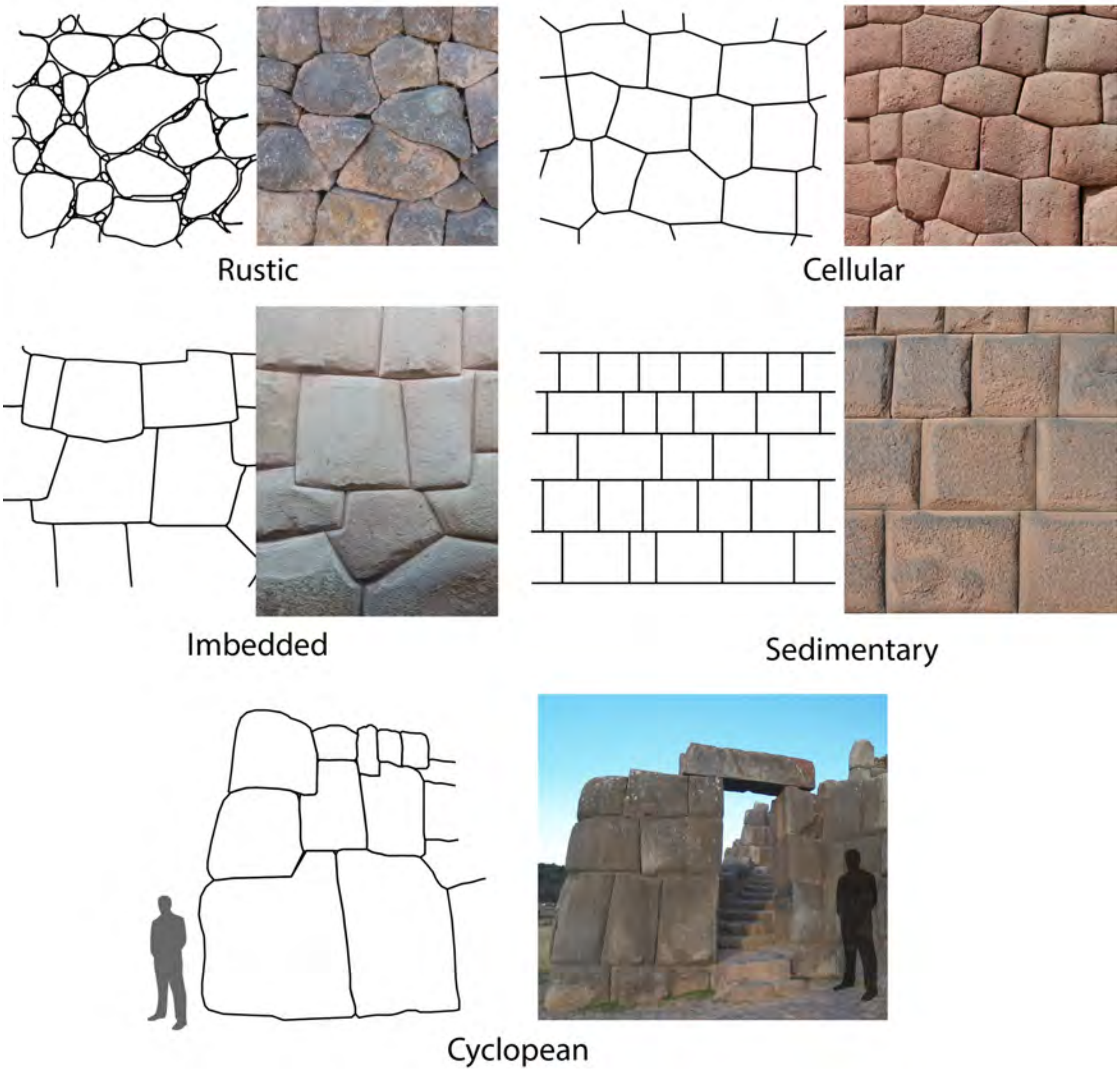

Figure 2.12: Five main types of Inca stone masonry styles (modified from Agurto Calvo, 1987)

First, the source of the stone seems to have been carefully selected by the Incas, who extracted blocks in specific quarries around Cusco (Hunt, 1990; Protzen, 1985). In these places, rocks were broken off from the quarry face and squared up thanks to metal chisel and large hammerstones. Depending on the situation, blocks were, then, roughly to finely cut in situ. All the flaking process, which allowed giving the desired shape to the blocks, was done with cobbles (Protzen, 1985). How the workers lifted and transported the blocks from the quarry to the construction site remains a matter of debate. Some scholars supported the use of ropes and wooden logs (Agurto Calvo, 1987; Protzen, 1993). In any case, this handling phase seems to have required a lot of human labor and led

to significant changes in territory planning through the design of large roads and the construction of loading ramps (Protzen, 1993). The ultimate phases of dressing and polishing were carried out when the blocks reached their destination. There, the shape of the blocks was adjusted to their intended location within the masonry. This specific assembling and laying process, where each architectonical element must fit the shape of the previous one, allows precise tracking of the constructive sequence of buildings (Protzen, 1985). Aside from the sedimentary style in which the stone blocks were erected course by course, the other types of Inca walls may have been built differently. Protzen (1987) showed evidence of several vertical sections (i.e., distinct wall segments) that were constructed concurrently and connected afterwards. Finally, contrary to common beliefs, archaeological experiments demonstrate that all the constructive process might have been achieved “with little effort and in very short time” (Protzen, 1985, p.175).
It is commonly assumed that Inca stonecutting skills faded away with the Spanish conquest and the related population decline. However, the dry-stone architecture did not disappear suddenly in 1533 CE. The interaction between indigenous masons and Spanish elites led to the construction of colonial houses in Cusco and Chinchero in a mock Inca style, known as the neo-Inca style (Nair, 2003). The European influence was associated, notably, with the development of zoomorphic carvings. The neo-Inca style came to an end in the second half of the 17^{th} century (Trever, 2005).

Political dimension and symbolism

Commonly associated with the development of the Inca State, the fine stone architecture turns out to be as much the reflection of the Inca social and ritual organization as a vector of ideological discourse and an instrument of domination.
First, the construction of high-status buildings seems to have contributed to an increase of the social cohesion and the reinforcement of the control exercised by the State upon its subjects. According to that model, the architectural achievements were the remnant of the required stonework and acted as a reminder of the massive and intensive labor force mobilized by the political elite (Dean, 2010). As such, the long-distance transportation of finely cut stone blocks (from Cusco to Saraguro: Ogburn, 2004 or to Pachacamac, pers.comm. L. Enciso) is the ultimate expression of the elite capacity to mobilize the human force, supporting even an Inca “philosophy of submission” through work (fig. 2.14a). The constructive projects are, therefore, at the service of a broader strategy that intends to organize the whole society (from the family unit to the supra-local entities) and ensure its perpetuation.

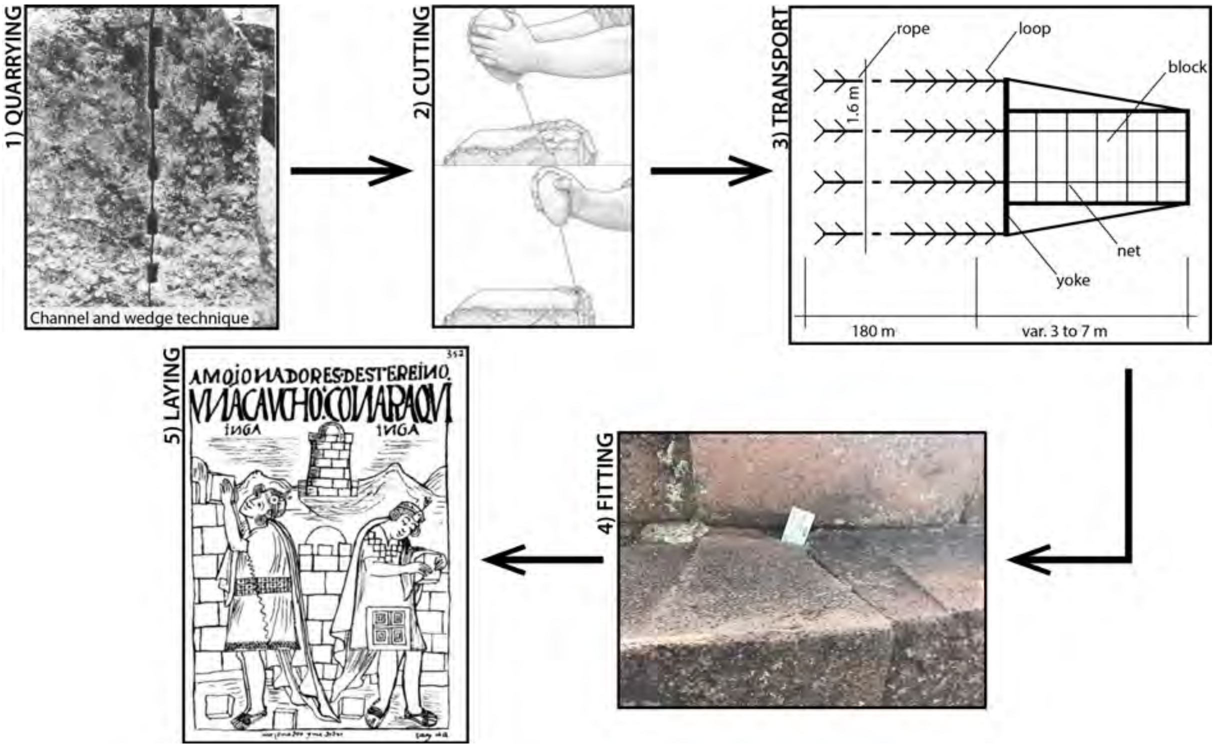

Figure 2.13: Simplified *chaîne opératoire* for the construction of stone buildings. It includes five main steps: the splitting of blocks in the quarry, the dressing/cutting, the transport, the shaping/fitting and the laying of the blocks (credits: Huaman Poma de Ayala, 1979; Protzen, 1985, 1993).

Moreover, one of the distinctive features of the Inca stone architecture is its close association, and even symbiosis, with the environment (fig. 2.14b). As summarized by Protzen (1987, p.155), the objective is to "integrate the man-made within the natural". By rooting in a sacred landscape (Nair, 2015), the Inca stonework aims at conveying a message on the Inca cosmogony and the prevalence of its culture and ancestors (Kaulicke et al., 2003). In a precursory way, the Inca organic architecture was already a constructive approach that focuses on natural surroundings and sustainability.
The fine stone masonry is thus an integral part of the political and ideological discourse of the Inca State. It turns out that the stone is directly related to the imperial power and the legitimation of the elites and their mythical origins. Besides the transportation of buildings blocks several hundreds of kilometers from the Cusco region (Ogburn, 2004), which aims to make visible the power of the sovereign in the provinces, Bauer (1987) sees the singular architectural style of the site of Pacariqtambo (fig. 2.11) as a symbolic way

for the Incas to claim their mythical origin from the Lake Titicaca. Finally, we should emphasize that the most highly qualified masons that supervised the construction of the finest walls were part of a selected group attached to the exclusive service of the Inca emperor (Cobo, 1890).

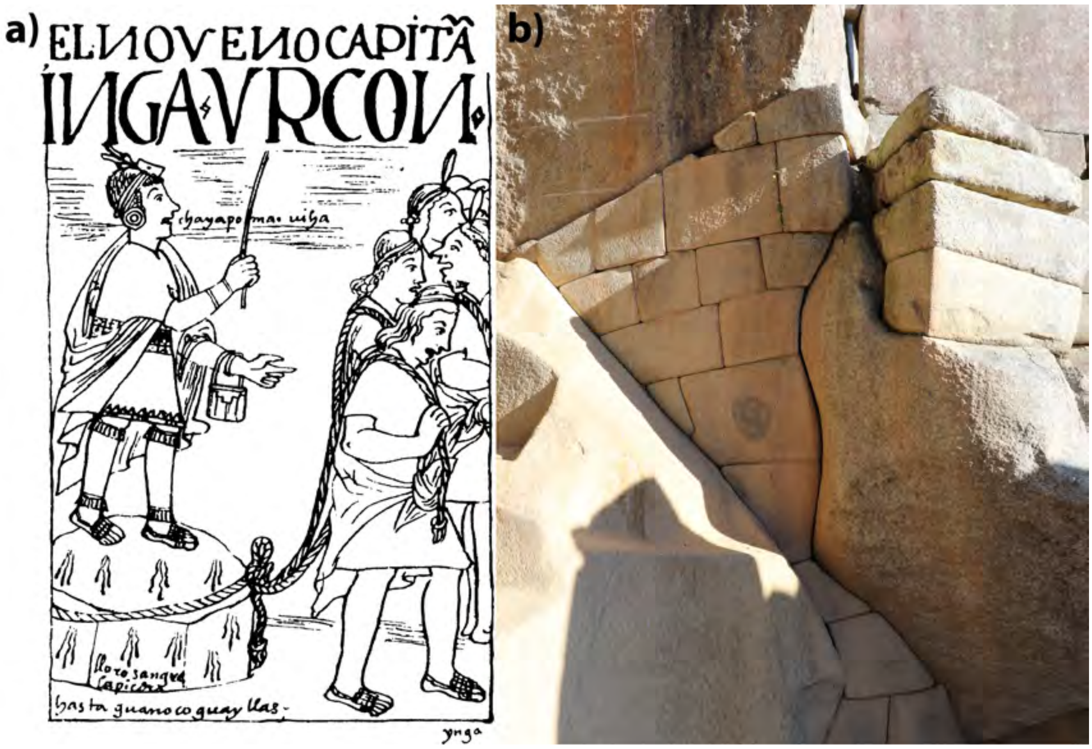

Figure 2.14: a) Inca leader supervising the dragging of a large stone block with ropes ("*El noveno capitán, Inga Urcon / Chayapoma Uisa / lloró sangre la piedra / hasta Guánuco, Guayllas*" – Huaman Poma de Ayala, 1979, p. 159); b) Well-fitted stone blocks filling a gap between two rock outcrops in Machu Picchu, below the Temple of the Sun.

Chronological and filiation issues

The Inca empire has always intrigued scholars by its quick development, its rapid geographical extension and its sudden demise[11]. The shortness and suddenness of the imperial phenomenon (∼150 yrs.) continue to feed the discussions regarding the onset and expansion of related cultural traits, notably the fine stone masonry styles. The very short lifespan combined with the distinct indigenous perception of the world raises, indeed, serious issues about the dating accuracy of the Inca archaeological contexts. In 1945, Rowe worried yet that "we will probably never be able to date the Incas exactly, for the reason that the Cuzco Indians took no interest in the passage of years" (Rowe, 1945, p.276).

Unfortunately, the entire Inca chronology is inextricably tied to the story and portraits of the sovereigns drawn up, among others, by Garcilaso de la Vega (1609); Huaman Poma de Ayala (1979) and Murúa (1590). These chronicles served thus as a basis for the establishment of the absolute chronology of Rowe (1945) that still constitutes the reference framework. However, as early as 1979, Duviols called into question our conception and interpretation of the Inca political system and, accordingly, its chronology. Nowadays, several independent lines of evidence tend to challenge the chronology of Rowe. Whether from the Titicaca region (Pärssinen & Siiriäinen, 1997), the Eastern Bolivia (Meyers, 2016) or the northern part of Chile and Ecuador (Marsh, Kidd, Ogburn, & Durán, 2017; Ogburn, 2012), the ceramic analyses and radiocarbon dating suggest an earlier expansion than stated by the Spanish chronicles. It is thus necessary to take a critical look at the absolute chronology of the Late Horizon (1400-1533 CE) and take a step back from the personification of the conquests and political changes within the empire. This applies, in particular, to the figure of the emperor Pachacuti Inca Yupanqui (1438-1471 CE), often depicted as the first great reformer (Rostworowski, 2001) and instigator of the expansionist Inca State.

In Cusco, the stone architecture, commonly associated with the imperial phase of the Inca chronology, suffers from a lack of published archaeological resources. This lack of data from excavated contexts maintains confusion about the origins, emergence and intentions of the Inca fine stonework. To the best of our knowledge, the only architectural contexts dated directly are located in Ollantaytambo (Bauer, 2018), Pumamarca (Bauer, 2018), Pukara Pantillijilla (Covey, 2006) and Raqchi (Sillar, Dean, & Pérez Trujillo, 2013). The other dates come from the dating of occupation levels allegedly related to the architecture and not as reliable as the former ones. Although several attempts were made to date stratigraphically (Agurto Calvo, 1980; Vargas P., 2007)[12] or stylistically (Kendall, 1985) the different masonry styles, there is little information that may support the existence of a true constructive sequence. As Protzen (1993, p.264-265) noted, the distinctive types of stonework have probably co-existed and did not disappear with the death of an Inca ruler. In a similar fashion, it is hardly likely that the large royal estates mentioned in the chronicles, such as Pisaq, Ollantaytambo (*Tampu*), Machu Picchu or even the capital Cusco might have been the result of a unique constructive project decided by one Inca ruler (Alcina Franch, 1970; Burger, Salazar, Nesbitt, Washburn, & Fehren-Schmitz, 2021; Ziólkowski et al., 2020).

The origins and filiation of the Inca stonework are unclear too. While some chroniclers (Cieza de León, 1554; Cobo, 1890) and archaeologists (Gasparini & Margolies, 1980) have referred to the influence of the Tiahuanaco culture and the stone craftsmanship of the populations from the Titicaca Basin, the evidence remains weak. To this day, only cultural goods coming from this region and belonging to workers and masons involved in the construction of large Inca complexes (INC, 2007) might support this hypothesis. On the contrary, Protzen and Nair (2016) saw no clear relation between the masonry styles and building techniques. They even support the existence of two opposite constructive philosophies, since the Incas based their architecture on the one-on-one fitting whereas the Tiahuanaco relied on standardized architectonical elements. The (ethno)historical and archaeological data turns out, hence, to be contradictory and do not allow, at this stage, to formulate a robust hypothesis. Unfortunately, the investigations carried out on the Inca culture and the human occupation of Cusco still suffer from the past strategies of excavations, too often conducted without scientific questioning (Farrington, 2010).

2.4 Concluding remarks

The Cusco area is crossed by a large fault system that accommodates the main part of the regional deformation associated with the Andean orogeny and forms noticeable scarps and discontinuities in the Holocene to Historic landscapes. In the light of the instrumental seismicity only, the faults do not seem to represent an imminent threat to the populations. However, the historical documentation itself enables us to refute this misguided assumption. The 1950 and, above all, the 1650 earthquakes were, indeed, two seismic catastrophes, which illustrated the seismological potential of the local crustal faults as well as the vulnerability of the area. These two events, though, do not apparently reach the maximum magnitude that may be generated by the rupture of an entire fault segment, suggesting the occurrence in the past, and in the future, of even more violent ground motions.

The Cusco area is the cradle of the Inca culture and the core of the empire, which encompassed a large part of the Andes at the beginning of the 16^{th} century. There, the Incas built large settlements, extensive estates and developed a distinctive fine stone architecture. Demonstrating unique expertise and true technical skills, the Inca fine masonry amazes us as much as it puzzles scientists regarding its origins and motives. Scholars quickly hypothesized the earthquake-resistant property of the polygonal and closely fitted stone blocks, without mortar, and supported even the existence of an Inca earthquake engineering (Calderón Peñaylillo, 1963). This assumption remains very common in scientific publications although very few works addressed the topic properly.

Whether or not designed as earthquake-resistant features, the massive and well-arranged layout of the Inca architecture benefited undeniably to the Inca architecture, contributing to its durability. Due to the close proximity of large Inca remains with tectonic structures, we may legitimately wonder if those structures do constitute neglected markers of the crustal seismicity of Cusco.

In 2017, Hinzen and Montabert have carried out numerical tests on two types of dry-stone masonry walls (with rectangular and polygonal blocks), whose characteristics are very similar to the Inca fine masonry styles. The walls were subjected to 24 real earthquake signals with the objective to establish a diagnosis of their damage state. Figure 2.15 displays the statistical distribution of two input earthquakes' parameters – the PGA and the magnitude – related to each damage level described on the structures. Although the study dealt only with freestanding walls[13], it yields interesting findings on the necessary conditions to damage Inca fine masonry. First, the worsening of the structural state seems to correlate with the increase of the PGA and the magnitude. Besides their so-called earthquake resistant design, the Inca walls might be affected at low PGA values (fig. 2.15a). More strikingly, the internal deformations seem to occur at a magnitude superior or equal to 5.5 (fig. 2.15b). Regarding the onset of partial and total collapse, the results indicate a magnitude around 6.5 and 7, respectively.

Considering the seismotectonic setting presented at the beginning of this chapter, the numerical simulations allow establishing that the Inca architecture is vulnerable enough to exhibit internal deformation or partial collapse if a nearby strong fault rupture ($M_w >$ 5.5) takes place, even with low local levels of acceleration. Hence, the high-status Inca architecture with closely fitted stone blocks turns out to be a promising "recording medium" of the uncommon but damaging crustal earthquakes within the Cusco area, and this for almost 600 years. In the following chapters, we will confront this assumption with the field data and will present the contributions and limitations of our archaeoseismological approach.

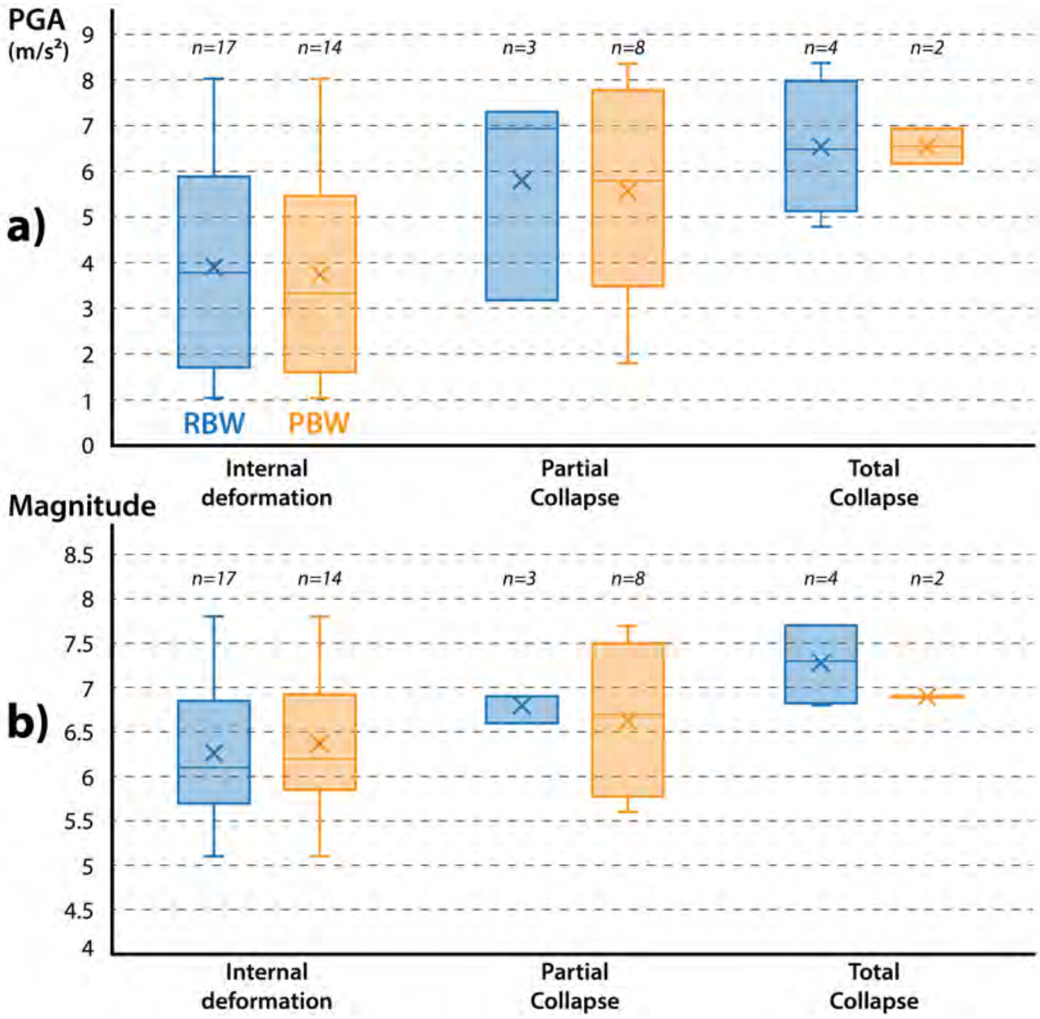

Figure 2.15: Statistical distribution of the a) PGA of the signal and b) the magnitude of the earthquakes associated with three distinct levels of damage of two typical Inca masonry types (RBW: Rectangular Block Wall in blue and PBW: Polygonal Block Wall in orange). Those box plots are based on the results of the 24 numerical tests computed by Hinzen and Montabert (2017) on walls with a 5.4 height/width ratio.

Notes

[5]More recently, one of the rare surface rupturing earthquakes occurred in 2016 on the southernmost and unknown fault in Parina, Department of Puno (M_w6, Aguirre et al., 2021).

[6]Most of the time, the Gutenberg-Richter law includes historical seismicity. In this particular instance, we preferred to calculate the law by taking into account only the unified instrumental catalogue provided by the IGP. As highlighted in section 2.2.2, there is no magnitude estimation for most of the historical earthquakes and there is no information on the calculation method regarding the others. Including the historical dataset seemed, therefore, difficult to justify methodologically speaking. Moreover, the lack of

completeness for a wide range of magnitudes and the issues in terms of magnitude estimation may have affected in a negative way the computation of the law.

[7] *"los campos y caminos se han abierto, y hecho grandes socabones, brotando por ellos bolcanes de agua colorada, y en otras partes embuelto con gran cantidad de arena."*
"the fields and trails opened, and made great sinkholes, volcanoes of red water sprouting from them, and in other parts covered with a lot of sand." (pers. trad. from Villanueva Urteaga, 1970, p.214)

[8] *"Y luego se visitaron las dichas cassas de los yndios particulares, las quales estan todas arruynadas y caydas al suelo, que no ay ninguna de provecho, porque paresçe que el dicho temblor llegó con mas biolençia a esta dicha perroquia [Belén], pues ninguna cassa quedó en pie."*
"And then they visited the houses of the Indians, which are all wrinkled and fallen to the ground, that there is nothing left, because it seems that the said tremor came with more violence to this parish [Belén], because no house was left standing." (pers. trad. from Julien, 1995, p.362)

[9] Although Inca architecture is often synonymous with stone masonry, it should be pointed out that the stonework represents only a small part of the Inca construction. It is commonly involved in high-status buildings or large agricultural and hydraulic infrastructures. On the contrary, an overwhelming part of the traditional housing and vernacular architecture is built thanks to the *tapia* technique or with adobe bricks. There is also mixed construction techniques including both earth and stone materials. Unlike their stone counterpart, earth and mixed vernacular architectures involve low levels of technology and constitute frugal strategies in terms of material and labor. The associated construction techniques derive though from centuries of trial and error and reflect equally past sustainable and resilient practices (Caimi, 2014; Ortega, Vasconcelos, Rodrigues, Correia, & Lourenço, 2017). Considering that stone architecture is the focus of this work, only this category is examined in this section.

[10] Obviously, this classification is a simplification of reality that created invented categories. In fact, the boundaries established between them are fluid. Inca walls may show, thus, bond systems at the transition between two different styles.

[11] It is of great importance to distinguish the Inca empire from the Inca polity. The Inca polity predates the imperial phenomenon, which is defined by a highly hierarchical political structure and its expansionism. While the Inca polity seems to originate from the Killke polity (Bauer, 2018; Covey, 2006) and develop from the beginning of the 14^{th} century (ca. 1300-1533 CE), the empire classically begins with the reign of the ruler Pachacuti Inca Yupanqui (i.e. 1438-1533 CE). It is the chronology of the empire that is now the subject of debate and might be moved forward by several decades.

[12] Based on a limited number of observations and excavations carried out in Cusco, where they reported cellular walls in limestone overlaying imbedded walls built using diorite, both authors supported that the former style chronologically preceded the latter one.

[13] The paper by Hinzen and Montabert (2017) is the only detailed study simulating the seismic behaviour of complex dry-stone masonries. The sole use of freestanding walls is obviously one of the main limiting factors. Complete structures show non-linear responses that cannot be addressed by considering freestanding walls. The building geometry and the connections between walls (or between walls and other structural elements) considerably affect the seismic performance of the structures (Ortega, Vasconcelos, Rodrigues, & Correia, 2018). Nevertheless, this work demonstrates that complex block geometries do not prevent internal deformations, including at low levels of loadings.

Part II

An innovative contribution to the seismic hazard assessment

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Chapter 3

Methods: designing and implementing an archaeoseismological database in Cusco

"Surveying and mapping an archaeological site is an art, verifying the cause of damage is science." Ambraseys (2006, p.1015)

Monumental Inca remains and past seismic disasters: A relational database to support archaeoseismological investigations and cultural heritage preservation in the Andes.

Andy Combey[a], Agnès Tricoche[b], Laurence Audin[a], David Gandreau[c], Carlos Benavente[d], José Bastante[e], Hernando Tavera[f] and Miguel Ángel Rodríguez-Pascua[g]

a Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IGE, ISTerre, 38610 Gières, France.
b CNRS UMR 8546, AOROC, École normale supérieure, 75230 Paris, France.
c Ecole Nationale Supérieure d'Architecture de Grenoble, AE&CC - CRAterre, 38000 Grenoble, France.
d Geología Ambiental, Instituto Geológico Minero y Metalúrgico (INGEMMET), Av. Canadá 1470, San Borja 15034, Lima, Peru.
e Director of the Archaeological Park of Machu Picchu, Cusco, Peru.
f Instituto Geofísico del Perú (IGP), Calle Badajoz 169, Lima 15012, Peru.
g Geological Survey of Spain (IGME), Geosciences Research and Prospective Department, Madrid, Spain.

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Abstract As recent dramatic and numerous examples demonstrate, earthquakes still constitute a significant threat to cultural heritage (Bam 2003, L'Aquila 2009, Haiti 2010, Nepal 2015). By damaging the historical legacy, telluric phenomena affect economic and touristic incomes and alter regional identities and collective psyche. In the Andes, as in other emerging regions across the globe, deficient seismic hazard assessments, constant lack of resources, and inadequate maintenance programs are additional challenges for cultural heritage management. As part of our archaeoseismological investigation in the Cusco area (Peru), we developed a relational database, which seeks to identify, record and inventory seismic damage in pre-Columbian architecture. This work presents the main characteristics of the structure and design of the RISC ("Risque sismique, Incas et Société à Cusco") database and its contribution in supporting the fieldwork organization and facilitating the data acquisition. The collected architectonical evidence constitutes the first large archaeoseismological dataset in South America and will provide valuable complementary data in Peru to regional seismic hazard studies. We here aim to demonstrate that an ergonomic and user-friendly interface has a role to play in supervising and preserving the cultural heritage in active seismic areas. By converting *ad-hoc* surveys into routine inspections, RISC could become an effective low-tech monitoring system, providing relevant support for disaster risk reduction plans in archaeological sites conservation. We stress the necessity of adopting cost-effective and easy-to-implement tools for cultural heritage monitoring in emerging countries through this case study. Our database may represent a relevant methodological background and template for further initiatives in both fields of archaeoseismology and cultural heritage protection.

Archaeoseismology, Database, Seismic Hazard, Cultural heritage, DRR, Cusco

3.1 Introduction

As a social, cultural and symbolic act, architecture and, more specifically, the built heritage is an integral part of the collective memories and traditions (Caimi, 2014; Garnier, Moles, Caimi, Gandreau, & Hofmann, 2013; Ortega et al., 2017). In 1972, during the General Conference of the UNESCO, State parties agreed on the necessity of "ensuring the identification, protection, conservation, presentation and transmission to future generations of the cultural and natural heritage" (UNESCO, 1972, Art.4). To do so, the international organization proposed several guidelines related to seismic hazard mitigation (UNESCO, 2007, p.173): "reducing risk through ensuring maintenance", "strengthening

buildings", "improving earthquake warning systems" as well as "developing comprehensive earthquake plans." The creation and development of monitoring systems thus represent a prerequisite to follow those preparedness guidelines correctly.
Identifying earthquake evidence and damage in archaeological remains has long been seen as a re-active investigation. Archaeoseismologists intervened "after" a seismic event with the objective to improve the seismic catalogue and thus better assess the regional seismic hazard. Hence, ancient human settlements and monuments have turned out to be valuable markers of past seismic activity, providing complementary information to the traditional geomorphological and palaeoseismological studies and filling the gap between prehistorical and instrumental seismology (Karakhanyan et al., 2010; Noller, 2001; P. Silva et al., 2005; Similox-Tohon et al., 2006). The recent shift from qualitative to (semi)quantitative methods not only strengthens the archaeoseismological methodology and its scientific basis (Ambraseys, 2006; Galadini et al., 2006; Sintubin, 2013) but also provides a great opportunity to connect the research field to pro-active strategies such as risk management and disaster risk reduction (DRR) programs in the context of cultural heritage protection (Jusseret, 2014; Sintubin, 2011). Indeed, the large-scale registration of Earthquake Archaeological Effects (EAE – Rodríguez-Pascua et al., 2011), the use of remote sensing tools (Lidar, photogrammetry – Forlin et al., 2018; Yerli et al., 2010) as well as the construction of seismic deformation simulation thanks to 3D models (Hinzen, Cucci, & Tertulliani, 2013; Hinzen & Montabert, 2017; Pecchioli et al., 2018) constitute important steps towards monitoring strategies of archaeological remains. Addressing the impact of past earthquakes on cultural heritage has turned into an emerging priority, particularly in the Mediterranean area (Marchetti, Redi, Savini, & Trizio, 2017; Montabert et al., 2020; Remondino & Rizzi, 2010). However, in South America and across the High Andes, research is still at its early stage (R. Aguilar et al., 2015; Briceño et al., 2018; Noel, Moreira, Briceño, López-Hurtado, & Aguilar, 2019). In Peru, considered as the most vulnerable country of the continent in terms of seismic hazard (Stillwell, 1992; World Bank, 2012), increasing the risk preparedness and resilience of built heritage requires innovative and multipurpose approaches. To fill this gap in the Cusco region, we propose the implementation of a new database designed to characterize the level of damage of the cultural heritage facing earthquake threats (or even broader natural disastrous events).

3.2 Research aim

The Cusco area stands out for its rich pre-Columbian and colonial heritage. While the area and its monuments were severely affected by past ground shaking episodes, the current seismic hazard remains poorly assessed and its implications in terms of heritage vulnerability sometimes even overlooked (Carlotto, Cárdenas Roque, & Fidel Smoll, 2007; Noel et al., 2019). In the framework of the archaeoseismological project RISC ("Risque sismique, Incas et Société à Cusco"), we developed a user-friendly database, whose aim was to keep a record of potential seismic effects observed in Inca remains (ca.1300-1533 CE). Initially designed as an ephemeral data collection tool, the RISC database has turned into a permanent platform for data mining. Taking into account the main challenges that South America has to face in terms of cultural heritage preservation (Gamboa, 2016; ICCROM, 2004), we consider the use of large and organized datasets in archaeoseismological studies as a particular promising resource to improve the seismic vulnerability assessment and management of numerous touristic archaeological sites. Through this case study, we hope to offer a valuable database template, easy to use and adapt for future research.

3.3 Theory

3.3.1 Seismic risk in the Andes

Social vulnerability to earthquakes is a crucial challenge in the coming years, exacerbated by the constant and rapid urbanization processes (Jackson, 2006). The increasing exposure is probably even more acute in South America and especially all along the Andes. Actually, the mountain range that borders the western part of the continent concentrates an overwhelming majority of the current seismic strain and deformation rate (Costa et al., 2006; Dewey & Lamb, 1992). The Andean region is also marked by a high density of population compared to the rest of South America, hosting mega-cities like Santiago, Lima, Quito or Bogota. Recent seismic risk assessment evaluates that more than one-third of the total population of the continent "may experience strong ground shaking in a 50-yr period (2% probability of exceedance in 50 yrs)" and 30 millions of people "reside in areas of high hazard where earthquakes are quite likely (50% in 50 yrs)" (Petersen et al., 2018). Anarchic urban sprawl, informal settlements and deficient building standards are aggravating factors that alter the capacity of Andean societies to cope with violent ground motion episodes.

Unfortunately, little is still known on the quaternary deformation and associated seismic

activity (Costa et al., 2006). Suffering from huge discrepancies between inter-plate and intra-plate seismicity (England & Jackson, 2011), the current global seismic risk assessment remains heterogeneous and too poor in many regions distant from the active tectonic margins. Unlike the well-monitored subduction seismicity, scattered active crustal faults in continental interiors are not sufficiently mapped and characterized (motion type, return period, strain rates… – Petersen et al., 2018). Local and regional models for seismic hazard assessment, first attempt to set up a scientific basis for political decision-making, are still in their infancy (Das et al., 2020; Leyton, Ruiz, & Sepúlveda, 2009) and few are the ones that consider shallow crustal seismicity (Z. Aguilar et al., 2017; Asociación Colombiana de Ingeniería Sísmica, 2010; Beauval et al., 2018; Yepes Arostegui, 2015).
In such active tectonic areas, traditional approaches (e.g., instrumental seismology, tectonic geomorphology and palaeoseismology) appear to be insufficient to assess properly the seismic hazard and risk. The lack of intelligible written sources before the Spanish Conquest (mid-sixteenth century) diminishes the potential of historical seismic studies substantially. Cross- and multi-disciplinary approaches are therefore needed to improve the regional seismic catalogue and get an appropriate resolution to the moderate-low return period associated with crustal faulting (Blumetti, Grützner, Guerrieri, & Livio, 2017; Liu & Stein, 2016). Archaeoseismology has demonstrated to be particularly well suited to address this issue and link accurate instrumental data from the last century with long-time sedimentological/limnological records (Caputo et al., 2006; Meghraoui & Atakan, 2014; Sintubin, 2013; Stiros, 1996). The built archaeological heritage of South America, whose history spans at least the two last millennia, represents a promising marker of past seismic activity. Results may complement scanty colonial accounts and improve the dating of poorly constrained seismic events evidenced in palaeoseismological trenches.
As the result of centuries of building experiments, the cultural heritage reflects a long empirical learning process with regard to seismic hazard. However, given its complex history and our inability to manage it properly, this legacy constitutes one of the most vulnerable sectors with respect to earthquakes and thus requires special attention. Unfortunately, it remains too often a second-ranking priority for emerging economies.

3.3.2 Challenges of the conservation of the cultural heritage

While cultural heritage and particularly archaeological sites play a crucial part in the identity construction process of southern American countries (national symbol, self-esteem, touristic income), the lack of financial resources hampers ambitious conservation plans (ICCROM, 2004; Sevieri et al., 2020). Governments dedicate most of their funding legitimately to reduce poverty and support the productive economy and are thus not able to preserve adequately their cultural assets (Heras et al., 2013; ICCROM, 2004). A lack of institutional memory in public institutions and authorities as well as issues in terms of formation of the persons in charge of the conservation work are two supplementary factors that explain dysfunctions in the cultural heritage preservation policies (Jokilehto, 2015). Despite the recent effort to overcome those problems, a report requested by the World Heritage Committee in 2006 stated that "most world heritage properties, particularly in developing areas of the world, do not have established policies, plans and processes for managing risk associated with potential disasters" (World Heritage Committee, 2006, p.1). However, cultural heritage buildings are even more at risk because of their great age as well as the several constructive phases and the inadequate human interventions that may have affected them (Díaz Fuentes, Laterza, & D'Amato, 2019; Despotaki, Silva, Lagomarsino, Pavlova, & Torres, 2018; Ferrigni, Helly, & Rideaud, 1993; GCI, 2015).
Regarding the seismic risk, one main interrogation is nonetheless raising: how do we protect the cultural heritage from a natural hazard that is intrinsically unpredictable and uncontainable? In case of an earthquake, it is impossible to remove the causative factor of damage, but it is possible to mitigate it (Feilden, 1987). The main organizations and institutions involved in the conservation field advocate for preferring a pro-active (preventive) approach to a re-active (curative) one (Feilden & Jokilehto, 1998; Jokilehto, 2000; UNESCO, 2010; Van Balen, 2017). Considered as the best-cost-effective strategy, the preventive approach aims to maintain authenticity by reducing the building's vulnerability and limiting the potential destruction. That results in expensive retrofitting works but also in more modest monitoring devices and condition assessment surveys to assess the seismic vulnerability of the buildings (UNESCO, 2010). Monitoring is based on the concept of time and change and supposes the existence of constantly updated documentation about the heritage of interest and the potential vulnerability factors (Gandreau & Delboy, 2012; Paolini et al., 2012; Van Balen, 2017). Archaeological and historical buildings need, therefore, to be considered in a long-term perspective (Stovel, 1998). Earthquakes experienced by the buildings in the past as well as their consequences, are particularly helpful in making the best diagnosis. Prerequisite to any conservation decision (ICCROM, 2004),

monitoring has to rely on a multi-sectoral and collaborative approach (UNISDR, 2015). Databases appear to be well-suited to organize large sets of data and ensure standardized and harmonized methodologies. As it has been previously demonstrated, they are particularly helpful for supervising cultural heritage (Berg, 2007; Zerbini, 2018) and supporting systematic processes of damage assessment (UNESCO, 2010). How can the system be nevertheless more useful for safeguarding the heritage? An archaeoseismological database may provide relevant input data for future risk reduction.

3.4 Material and methods

3.4.1 Overview of the RISC project

Famous worldwide for its cultural heritage, including notably the Cusco city and the Machu Picchu archaeological site inscribed both on the World Heritage List, the Cusco region (Peru) is less known for its recurrent and potentially destructive seismicity. As various Andean regions distant from the subduction trench and as explained in Section 3.3.1, the Cusco area suffers from a poor understanding of its crustal seismicity. The concise historical catalogue (Silgado Ferro, 1978; Tavera et al., 2016) available, coupled with still scarce palaeoseismological studies (Benavente Escobar et al., 2013; Cabrera & Sébrier, 1998; Palomino Tacuri et al., 2021; Rosell Guevara, 2018), does not allow to assess properly the return period of the numerous active faults of the region, which triggered damaging earthquakes in historical (1650, 1950, 1986) and pre-historical times (Combey et al., 2020). We decided thus to develop the RISC project, whose objective is to improve the seismic hazard assessment by implementing the first large archaeoseismological survey in South America. Due to their particular and massive megalithic architecture, monumental Inca settlements of the Cusco and Sacred Valley constitute well-suited "seismoscopes" (Sintubin, 2013) that may have recorded large ground motion events since the fourteenth century (Rodríguez-Pascua et al., 2020). The location of numerous Inca sites in seismically active areas during the instrumental period (since 1960) as well as their distribution near active normal faults, emphasize their archaeoseismological potential (fig. 3.1a). We surveyed 17 monumental archaeological sites of the region (fig. 3.1a) with the objective to identify and register EAE, i.e., architectural damage, direct consequences of seismic activity (fig. 3.2).

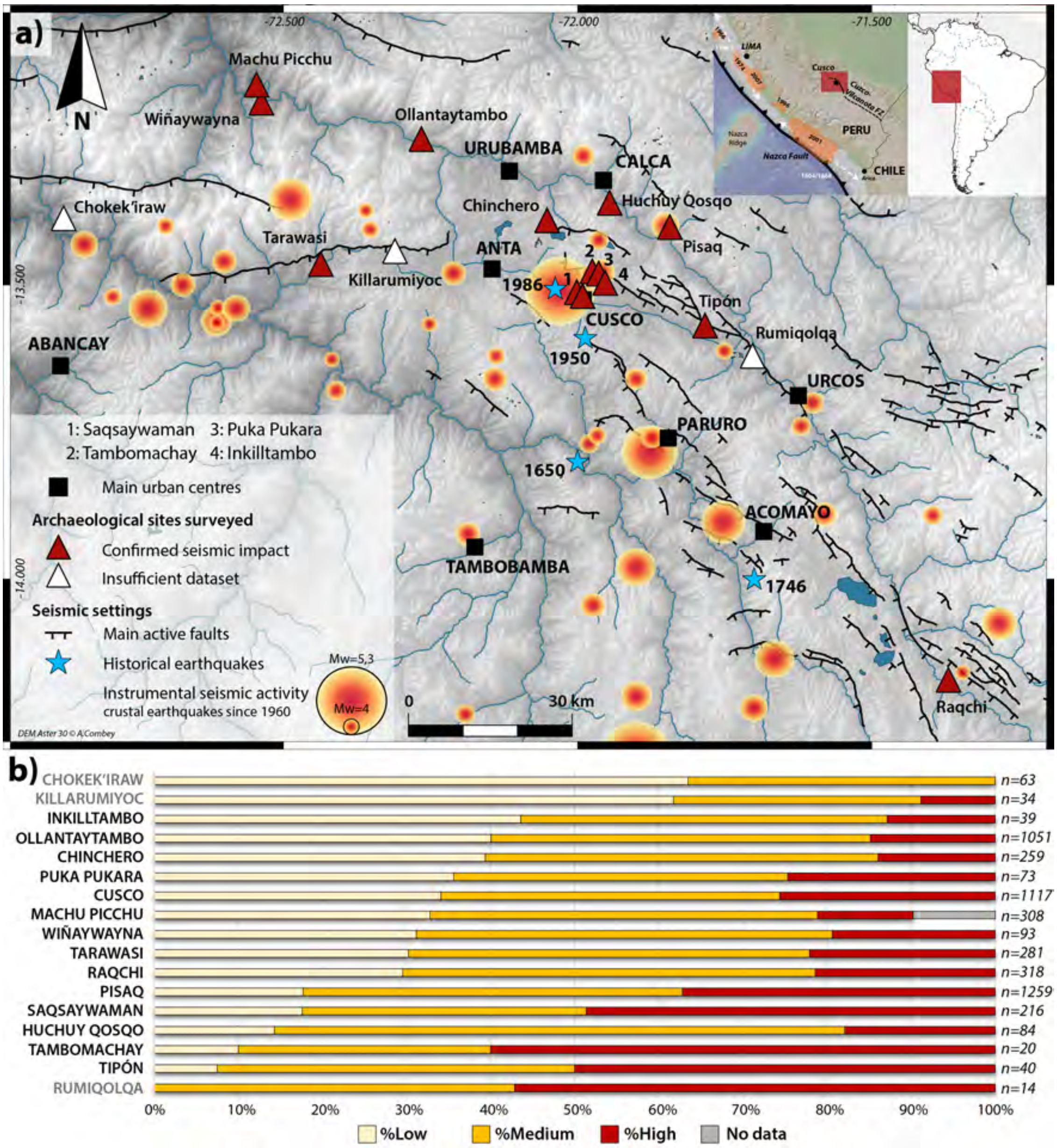

Figure 3.1: a) Cusco regional map displaying the main active seismic areas during the last 60 years (instrumental seismicity) and the location of the 17 archaeological sites surveyed during the RISC project. The size of the buffer zones depends on the estimated rupture length for each seismic event (see Supplementary data). Information on historical earthquakes (blue stars) is based on Ericksen et al. (1954); Silgado Ferro (1978); Tavera et al. (2016); b) Proportion of High, Medium, and Low levels of confidence of EAE records for each archaeological site. The chart displays the results of the previous database version, i.e., the level of confidence is only based on the assessment of the seismic origin. Sites with an insufficient dataset are reported in grey.

The management of a large amount of observations was soon understood as the main challenge of the archaeoseismological fieldwork leading to several issues in terms of methodology and data analysis. Therefore, we decided to build a database that would allow storing the data in an orderly manner. A database speeds up indeed considerably the real-time data acquisition, facilitates its management and processing, guarantees the homogeneity of all of those input values (Anichini, Fabiani, Gattiglia, & Gualandi, 2012; Gattiglia, 2018), and reduces the risk of loss. The structure of the database itself enables faster researches and data mining. We based our program on the pioneer initiatives of the ACoR (Atlas des techniques de la Construction Romaine – Dessales, 2020) and OPUR (Outil Pour Unités de Réparation) databases (ANR Recap), which aimed to register and characterize roman building techniques and ancient postseismic repairs in Pompeii site (Dessales & Tricoche, 2018). While adopting a starkly different approach by focusing on damage, RISC benefited considerably from those previous projects, especially in terms of data structuration and data entry. The main objective was to conceive a database structure that would closely fit fieldwork requirements.

3.4.2 A field-designed database with a single front-end user interface

We used the proprietary FileMaker Pro 16 software, which has the advantage of providing both the data storage and the user interface. Easy-of-use and ergonomic, thanks to its customizable interface, this Database Management System (DBMS) provides a particularly well targeted solution to meet investigation needs. Thanks to the FileMaker Go extension, freely available in any iOS device, database models are easily transferable and adaptable to the two main types of mobile devices (smartphone or tablet). The main advantage of those devices is to provide an interface wide enough to allow a direct digital entry during the fieldwork (Gattiglia, 2018). The use of a mobile device as the main tool for data collection required rethinking deeply the design of the user interface to address the specific fieldwork requirements (accuracy, simplicity, rapidity). We built, therefore, a straightforward database organized around one main table, the "Damage" table (Supplementary data), and characterized by a sober and intuitive display. "Damage" gathers the main information relative to the core of the investigation topic, i.e., the EAE registered on the archaeological heritage (fig. 3.2). Moreover, we integrated basic information relative to the geographical and architectural context of the EAE.
The most suitable and easiest way to make RISC operative for users was to create one form composed of three distinct tabs (fig. 3.3). The first one, entitled "Context" includes

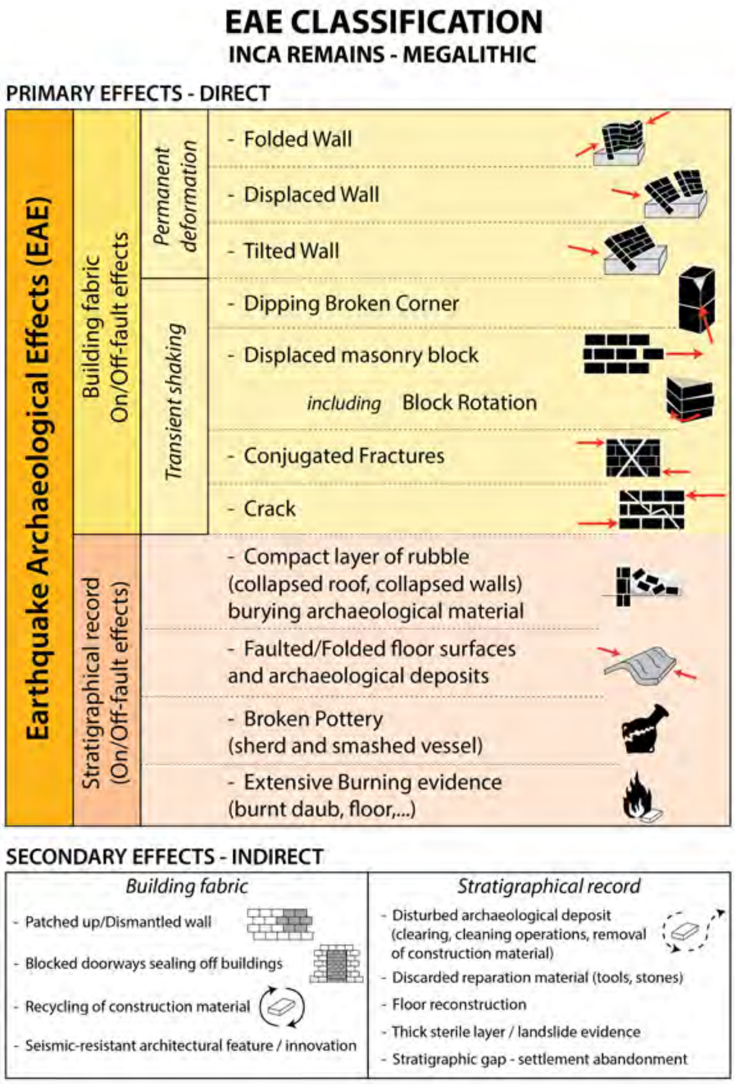

Figure 3.2: EAE chart adapted to Inca megalithic architecture (modified from Rodríguez-Pascua et al., 2011). Our fieldwork focused on the EAE affecting the building fabric, and due to off-fault effects.

basic data on the geographical and architectural environment of the EAE (fig. 3.4). The second tab focuses on the EAE description and characterization. Finally, the third one is dedicated to the illustration of the registered EAE (any type of visual representation). By means of those three tabs, the present form reproduces and supports the three main steps of the EAE record. It has turned into a single front-end user interface, simplifying the data entry. We made some other adjustments to make the interface as user-friendly as possible:

- A widespread use of thesauri and dynamic lists of values reduce the risk of data heterogeneity and the entry time. Four interdependent values lists, which feed into each other as data is entered, were inserted in the "Context tab", enabling the database user to fill the tab according to a hierarchical tree (fig. 3.4 – Supplementary data). Standardizing the dataset avoid creating future accidental discrepancies and speeds up hence the data analysis thanks to efficient queries;

- The automatized data entry for some metadata fields. Among others, that is the case for the dates of creation and modification of each record. They are directly managed by FileMaker and do not need any supervision;

- Script-writing dedicated to task automation such as the taking of picture or the GPS coordinates acquisition (Supplementary data).

The current structure and design of the RISC database do not prohibit or impede future evolutions or extensions. The flexible nature of the database opens the door to substantial adjustments, providing solutions to other scientific needs and questioning.

3.4.3 An adaptable and customisable tool enhancing the archaeoseismological methodology

Fieldwork procedures and methodologies are still too often unreported in the archaeoseismological literature, and it is therefore difficult for the reader to understand how the EAE and evidence were identified, ranked and interpreted (Galadini et al., 2006). The development and design of a database in the framework of the project RISC came with an automation of the data recording and enabled, thus the creation of additional fields that may improve substantially the data quality and its assessment.

Recording architectural damage referred to as "Earthquake Archaeological Effects" does not mean in any way that the potential non-seismic causes are completely ruled out from the scientific discussion. That is the global quality of the dataset and level of confidence in the archaeoseismological observations, as a statistic assessed through metadata fields, that allows discussing the potential impact of past earthquakes at the scale of an archaeological site or even a region (Giner Robles et al., in press; Giner-Robles et al., 2011 – fig. 3.1b). That is why such a database would be an important first step towards studies on palaeo- or historical earthquakes on a peculiar architecture such as the Inca monuments.

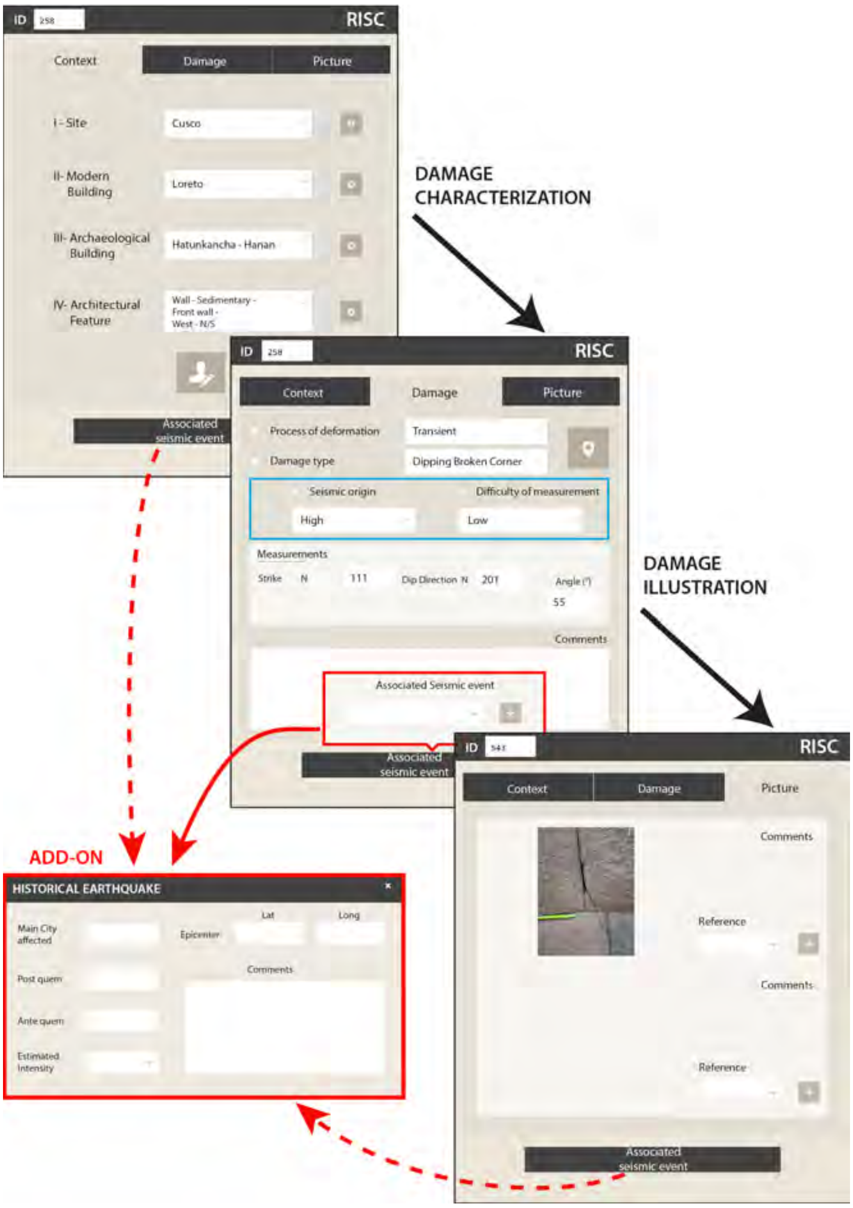

Figure 3.3: The RISC front-end user is organized around three tabs: “Context”, “Damage” and “Picture”. Those three sections reproduce the three main steps during the data acquisition. In blue: the two metadata fields to assess the data quality. In red: the database extension, which allows relating one EAE with a particular seismic event.

To meet the requirements of both data assessment and fieldwork, we considered a qualitative assessment based on clear and simple criteria as the most adapted and effective solution. We created two metadata fields (fig. 3.3) based on a list of values and containing four probability and confidence levels (“Low”, “Medium”, “High” and “Certain”). We originally created one metadata field, whose objective was to assess the level of confidence

Figure 3.4: "Context" tab of the RISC front-end user interface. You may note the user-friendly structure based on interdependent values lists.

in the seismic cause of the damage (fig. 3.1b – 1 in table 3.1). We introduced then a new one related to the difficulty of characterizing the recorded EAE. This field addresses the different measurement biases and gives the reader a qualitative estimation of the uncertainty of the measurements and observations.

The filling of the second metadata field (2 in table 3.1) is based on a limited number of criteria (accessibility to the architectural feature, presence of vegetation cover as well as alterations, posterior to the damage that makes difficult the observation and characterization). On the other hand, the interpretation of the seismic cause of the damage (1 in table 3.1) depends on several indicators:

- The masonry type (rustic, cellular, cyclopean, polygonal and sedimentary - Agurto Calvo, 1987). Those different categories are directly related to different rock types (calcareous/andesite/granite) and distinct layouts (forms and types of courses). They have therefore different vulnerabilities to slow deterioration processes. For instance, the rustic masonry type in Inca architecture is highly vulnerable to a large spectrum of deterioration processes (dissolution, vegetation growth, physical weathering and alteration) that makes it more difficult to distinguish effects related to climatic processes from damage induced by seismic shaking;
- the damage aspect and dimension;
- the petrological and geological contexts (water ingress in the architecture, slope instability, soil and rock properties and structural weaknesses);
- the management of the archaeological site (site history and large restoration works).

Based on the presence or absence of "positive" criteria, it is possible to assign a specific level of confidence for each recorded EAE. This method allows assessing quickly the quality of the archaeoseismological data at the site and regional scale.

Due to the unpredictable and changing nature of the fieldwork, the database has to be adjusted and improved frequently following an iterative process. Those improvements originate principally from the trial and error process (back and forth between field and laboratory). However, the DBMS offers great flexibility making it possible to cope easily with superficial and structural changes. Database extensions do not alter the current functioning and do not necessarily induce large modifications of the front-end user interface. The particularity of FileMaker databases, able to run on both fixed and mobile devices, constitutes a great opportunity to imagine and test new database versions on a computer without modifying the operative version available on tablets during the survey work[1]. As an example, we developed the first extension to indicate a potential causal relationship between one particular seismic event and the recorded EAE. This add-on takes form through an additional and optional button in the bottom part of the main interface. Clicking on this button will lead the user to select one existing seismic event related to the architectural damage recorded if or when known or will guide him to create a "new" event responsible for the damage (fig. 3.3). Besides its utility in distinguishing EAE produced by distinct past earthquakes (the chronological assumption will require bibliographical and/or historical sources – Rajendran et al., 2013), the extension may prove to be particularly relevant during a survey carried out immediately after a future destructive seismic

event (Cancino, 2011; Davis et al., 2019). This particular case demonstrates how much the current RISC database might be enlarged and upgraded in the near future to address new scientific issues.
Regarding RISC perspectives, we should consider several shortcomings and feasible improvements. The creation of a well-organized dataset of earthquake-induced damage on archaeological sites of the Cusco region has one fundamental implication: the reproducibility of the archaeoseismological investigation enabling the periodical update of the information while keeping track of previous recordings as an indicator of potential changes (Van Balen, 2017). Taking into account this change in outlook induces a substantial widening of the database scope and opens the door to interesting adjustments. We could only mention some of them: new fields dedicated to the qualitative estimation of the global state of conservation of the architectural feature and indices assessing the level of structural risk caused by the EAE. Furthermore, we may consider enhancing the temporal dimension of the EAE recording as a means to make the database even more suitable for periodic archaeoseismological surveys.

We developed RISC as a user-friendly program to support and strengthen our archaeoseismological project. The intrinsic properties of databases, coupled with the results of the archaeological survey, suggest a broader interest covering several DRR stages in the cultural heritage conservation program.

EAE	Level of Conf.	1-SEISMIC ORIGIN					2-MEASUREMENT BIAS
		Masonry Type	EAE characteristics	Aspect	Geological Context	Human Context	
Dipping Broken Corner	Low	Rustic Cellular Cyclopean Polygonal Sedimentary	Plane<cm Dip angle$<25°$ Ultimate course of masonry	Plane hardly definable	Pre-existing rock fractures within the blocks	Cleaning works	Difficult to access Irregular plane Low dip angle Vegetation
	Medium	Cellular Cyclopean Polygonal Sedimentary	Plane>cm Dip angle$>25°$	Clean plane	X	Cleaning works	Irregular plane
	High	Polygonal Sedimentary	Plane>cm Dip angle$>25°$	Clean plane	X	X	X
	CERTAIN	DOCUMENTED DAMAGE (pictures or scientific literature)					
Displaced masonry block	Low	//	Small and unique Ultimate course of masonry Non constant displacement	Mortar masonry	Slope instability Water ingress	Restoration work Unfinished structure	Heterogeneous displacement
	Medium	//	Non constant displacement	Dry joint masonry	Water ingress	Restoration work	Heterogeneous displacement
	High	//	X	Dry joint masonry	X	X	X
	CERTAIN	DOCUMENTED DAMAGE (pictures or scientific literature)					
Fracture - Crack	Low	Rustic Cellular Cyclopean Polygonal Sedimentary	Affecting 1 rock	//	Slope instability	Large-scale repairs	Non-apparent fracture plane Irregular plane Vegetation
	Medium	Cellular Cyclopean Polygonal Sedimentary	Affecting more than 1 rock	//	X	X	X
	High						
	CERTAIN	DOCUMENTED DAMAGE (pictures or scientific literature)					
Block rotation	Low	//	Ult. course of masonry	//	Slope instability	Unfinished structure	Small movement ($<2°$)
	Medium	//	X	//	X	X	X
	High						
	CERTAIN	DOCUMENTED DAMAGE (pictures or scientific literature)					

Table 3.1: Two metadata fields, providing a level of confidence in 1- the seismic origin of the damage and 2- the measurement precision and difficulty, were added to the database interface. This table summarizes the main criteria used for the most common EAE types registered during our survey. Those criteria determine the level of confidence based on a qualitative scale ranging from "Low" to "Certain". '//': the criterion does not apply to this EAE type 'X': no "positive" criterion In grey: confidence level not registered.

3.5 Results and discussion

3.5.1 Facilitating archaeoseismological survey

The archaeoseismological survey carried out within the Cusco area involved nine persons during two field campaigns. Those two campaigns of three months in total led to the inventory of more than 5,000 architectural features in 17 archaeological sites (fig. 3.1a). The implementation of a tailor-made database contributed to improving significantly the speed and efficiency of the fieldwork. Three semi-automatized and multifunctional entry processes were particularly useful: the creation of several dynamic lists of values, the connection between several tablet functions and the database (GPS, camera. . .), and the possibility to duplicate the DBMS on several tablets without affecting the data homogeneity. Working in pairs was particularly well-suited and productive. As an illustration, one pair was able to register more than 100 EAE in only a half day of work in Pisaq settlement. Even if it depends obviously on the density of seismic damage in Inca buildings, it shows how RISC brought powerful support to the data acquisition (detailed and accurate).

The database not only fastens the entry time it also allows a standardized data quality assessment. Although qualitative, both metadata fields we imagined to assess the data quality enable evaluating the archaeoseismological potential for each site visited as well as the precision for each single EAE record (measurements and observations). At the time of the archaeoseismological survey, the database included only one metadata field (see Section 3.4.3). The results of the data quality provide interesting results about the relevancy of the archaeological sites datasets. In three of the 17 archaeological examined, the sample was too small (n<20) and/or involved an insufficient proportion of medium and high-quality indices (<50% - in grey in fig. 3.1b). Although we considered, in the frame of our study, those three sites as irrelevant for the archaeoseismological interpretation, all the data will be stored and will remain available for future purposes. The confidence indexes represent valuable feedback for future investigations in the same area, necessary to carry out better-targeted surveys.

Archaeoseismological methodologies are particularly dependent on the type of architecture and thus EAE that professionals may encounter. The typologies as well as the identification criteria have to fit the geographical and cultural context and the research needs, influencing the database content and interface. While the database conception needs to be tailor-based, we consider that the structure of our database may be a helpful template for other researchers in South America and an off-the-shelf system in case of an earthquake.

3.5.2 Re-assessing the seismic hazard in the Cusco region

The archaeoseismological approach carried out in Cusco highlighted numerous seismic damage on Inca architecture along the Sacred and Cusco valleys. Through statistical and qualitative analysis detailed in Section 3.5.1, survey records stored in RISC were quickly processed. We concluded on the undeniable presence of EAE in 14 archaeological sites of the area (fig. 3.1). Although further research is required to date the EAE registered and assess earthquake recurrence; preliminary results demonstrate an unexpectedly large impact of ground motions. The wide distribution and common occurrence of EAE argue for a drastic reappraisal of the (pre)historical seismicity in that region, seismicity that was underappreciated before. Several Inca remains located in the Sacred valley display seismic damage (e.g., Machu Picchu, Ollantaytambo, Huchuy Qosqo and Pisaq), contrasting indeed with the low level of seismic activity during the instrumental era (fig. 3.1a – Supplementary data) and contradicting past statements on the seismic vulnerability of Machu Picchu (Carlotto et al., 2007).

The dating of EAE is still a critical point when dealing with poorly contextualized remains. It requires crossing approaches to complement the archaeoseismological data. That is why we develop additional detailed tables, including architectural, archaeological and seismological information. Those linked tables do not only contextualize EAE in their build environment, they also foster the multidisciplinary collaborative effort around this specific topic. Immediately after the archaeoseismological survey or during the post-processing, the user has the possibility to add data about the dating and characteristics of archaeological buildings or past seismic events found in the scientific literature. This accretionary process of data input/storing increases substantially the cross-disciplinary potential and leads to a better involvement of archaeological, architectural, and palaeoseismological results into the final interpretation.

Finally, the RISC database contributed substantially to the reassessment of the seismic hazard in the area thanks to its spatial dimension. The GIS compatibility of the database outputs (spreadsheet files) enables quick visualization of the EAE distribution at a regional scale and within a studied site. Looking at the global distribution and density of EAE exhibits a clear pattern: a stronger seismic impact in the Eastern part of the Sacred Valley and the core of the Cusco valley (fig. 3.1a). Refining this data will allow maybe to identify a common seismic source responsible for the damage. Similarly, the precise maps derived both from the geolocation (fig. 3.5a) and the detailed architectural context available for each record are the starting point for in-depth inspection of damage. Including complementary data on the previous restoration works as well as indications

on surveyed/non surveyed areas, we might consider identifying sectorial patterns. Understanding what buildings were the most affected and for what reason will open the door to the identification of vulnerability factors and local site effects (Brando et al., 2019). The organized and comprehensive dataset gathered by the database enables, even, a precise mapping of the EAE at the building scale (fig. 3.5b). This multi-scale analysis enhances considerably the archaeoseismological interpretation and constitutes a prerequisite for periodic inspections.
As we demonstrated in Sections 3.5.1 and 3.5.2, RISC was designed as a powerful tool to support two main phases of the seismic hazard assessment: the data collection and the past earthquake characterization. Bearing in mind that the most profitable way to assess the vulnerability of a historic building is the analysis of the consequences induced by the previous earthquake in its fabric (Cancino, 2011; Feilden, 1987), the database may have a crucial role in strengthening the risk preparedness in archaeological heritage programs.

3.5.3 Monitoring the archaeological heritage

Initially, our archaeoseismological survey was conceived as an *ad hoc* data acquisition, i.e. responding to an academic project completely disconnected from current heritage vulnerability issues. Archaeoseismologists have developed though a specific expertise in architecture that can benefit considerably to heritage stakeholders and curators.
Considering converting the "casual" survey into a systematic and periodic inspection requires taking into account preservation concerns and rethinking completely the whole potential of our approach. Although the current objective of RISC is to record and inventory seismic damage only, this type of structural alteration may constitute important weaknesses in the building fabric, sensitive to other destructive processes (erosion, landslides, human actions . . .). The dataset obtained in the framework of an archaeoseismological research project turns out, therefore, to be an *ad hoc* condition assessment of the archaeological heritage (fig. 3.6). It brings valuable information on the state of conservation of the buildings and calls for a regular implementation of such analysis. The database is, in that sense, a promising tool for monitoring the state of conservation of the building and preventing potential deterioration of the structure. As previously mentioned in Section 3.4.3, the database structure might be easily improved to take into account this temporal dimension in the data acquisition.

According to previous studies, some 50 percent of the damage during an earthquake is directly related to the lack of maintenance (Feilden, 1987). If this figure does not

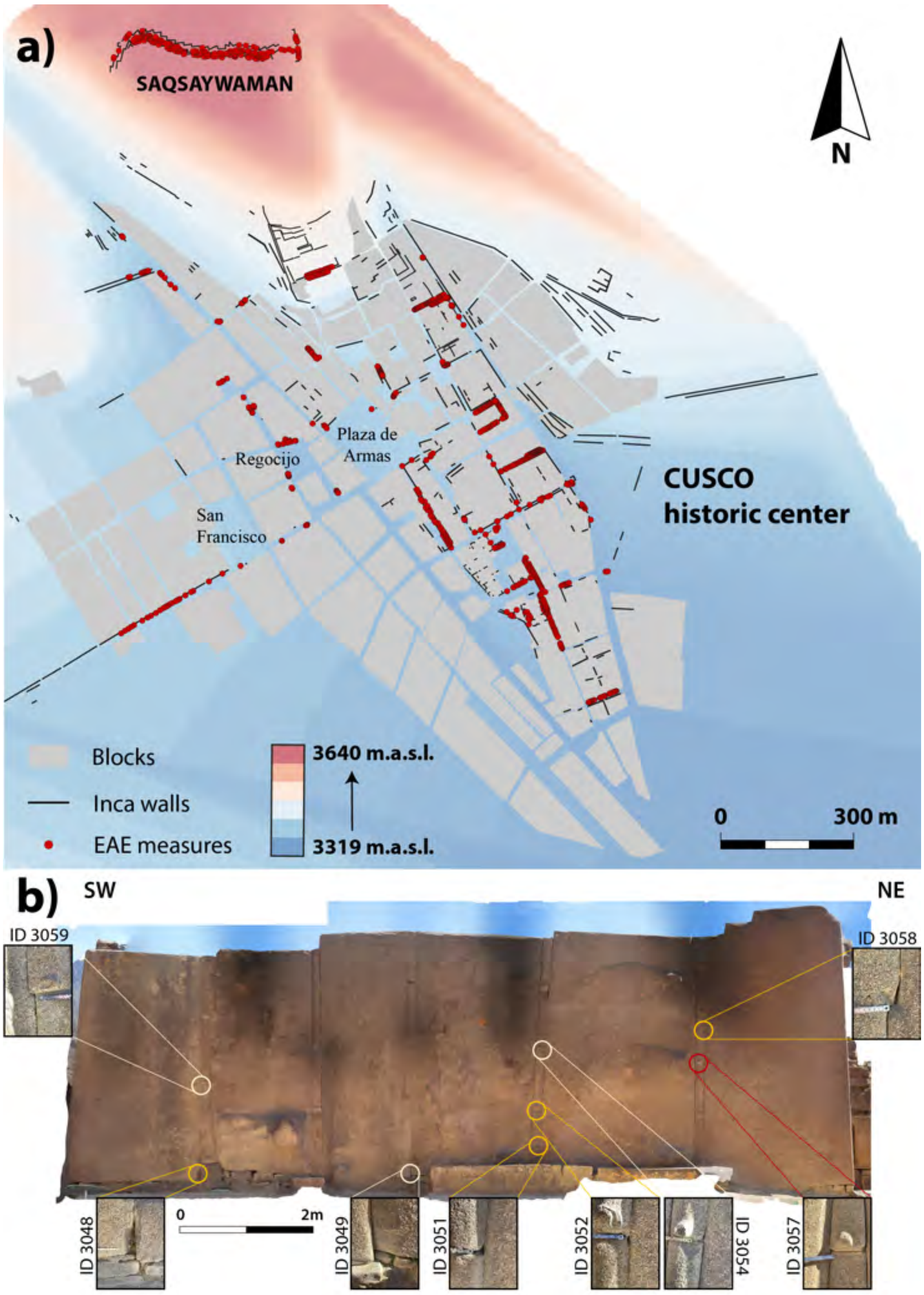

Figure 3.5: a) Spatial distribution of the EAE (red dots) in the archaeological settlements of Cusco and Saqsaywaman. Credits DEM and Inca walls: Instituto Nacional de Cultura, Center for Advanced Spatial Technologies (Univ. of Arkansas) & Cotsen Institute for Archaeology (UCLA); b) Distribution of the EAE on the Sun Temple of Ollantaytambo. The color indicates the probability of the seismic origin (beige: Low; orange: Medium; red: High).

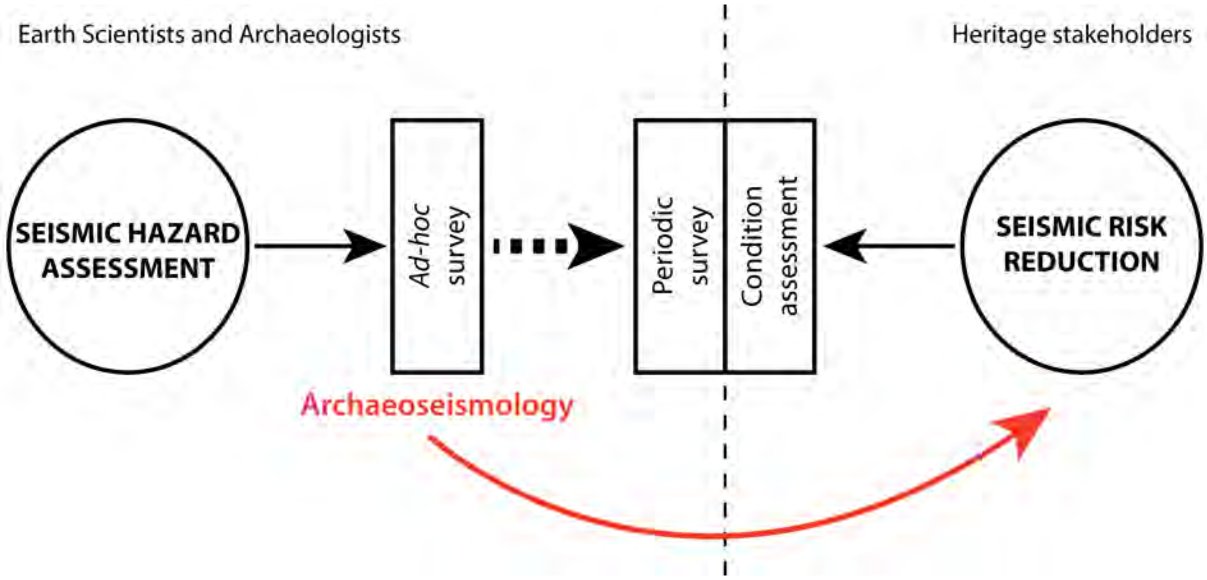

Figure 3.6: Diagram summarizing the theoretical disconnection existing between two worlds: heritage conservators and academic scientists. From our point of view, archaeoseismology can provide an interesting tool to engage collaboration and dialogue.

address the situation for the cultural heritage, in particular, the incidence of too scarce and/or inappropriate conservative works was yet emphasized as a major vulnerability factor (Brando et al., 2019; Cancino, 2011). Based on the frame of reference that constitutes the *ad hoc* inspection and based on the seismic hazard data provided by the archaeoseismological approach, two critical DRR phases may benefit from the present methodological tool: the monitoring pre- and post-intervention (fig. 3.7). Once a large dataset has been collected and has been made available, it converts into relevant support for assessing the evolution of the archaeological remains state and for proposing new conservation plans. Similarly, the inspections conducted with the database will contribute to evaluate the positive or negative impact of potential retrofitting works. We are thus convinced that an archaeoseismological database like RISC has a role to play in helping to quantify the threats, scaling the prevention measures and controlling their effects (fig. 3.7).
In heritage conservation, vulnerability analysis results too often in complex and resource-consuming procedures (Canuti et al., 2005; Ravankhah et al., 2019), leading to an ever-widening gap between academics and heritage curators/decision-makers. In emerging economies like Andean countries, for which cultural expenditure may represent a low priority investment, it is even more essential to select the most appropriate and frugal mitigation option, resulting from a subtle balance between implementation/maintenance

costs and benefits (ICCROM, 2004; Paolini et al., 2012). Minimally invasive, easily and quickly implementable, low-cost strategies and low-tech devices represent a pragmatic way to cope with immediate and urgent conservation threats, as yet acknowledged for photogrammetry (Abed, Mohammed, & Kadhim, 2017; Dhonju et al., 2017; Remondino & Rizzi, 2010). The good cost-benefit ratio that generally characterized those methods contributes thus to reopen a fruitful dialogue and collaboration between parties with divergent concerns. We believe that RISC database is one relevant example of a multi-functional, flexible and easily replicable assessment strategy that could be implemented in archaeological sites throughout the Andes. The great amount of information accumulated during the monitoring process facilitates the prioritization of the interventions (Sevieri et al., 2020) and serves as comprehensive support for decision-making. The international community now considers risk preparedness and DRR as a priority (UNISDR, 2015). Hence, databases like RISC have to play a role in transforming heritage conservation into a day-to-day effort, financially sustainable.

As Feilden (1987, p.19) pointed legitimately: “after an earthquake, a precise knowledge of every historic building and its contents is one of the most crucial factors in making an accurate assessment of the damage and conservation work required”. We strongly support that archaeoseismological databases represent a relevant tool to acquire, store and process this type of architectural and structural knowledge. RISC established that organized datasets might be particularly helpful during three specific steps of the Seismic Risk Management cycle: condition assessment, past seismicity characterization and heritage supervision.

3.6 Conclusions

Despite the challenges and difficulties, there is an absolute necessity to involve more deeply science in risk assessment topics and better communicate results to the public and decision-makers (Stewart, Ickert, & Lacassin, 2018). Research methodologies and approaches may contribute notably to raise awareness about the seismic threat on cultural heritage and support adapted DRR programs. Monitoring archaeological site has turned to be a key stage in implementing pro-active measures to face the seismic hazard. It also constitutes a meeting ground for a wide spectrum of specialists and an excellent opportunity to carry out integrative and multi-disciplinary analysis (ICCROM, 2004; Stovel, 1998; UNISDR, 2015).

We are convinced that archaeoseismology, situated at the crossroads between seismic and vulnerability studies, has to take part in this multi-sectoral approach in heritage preser-

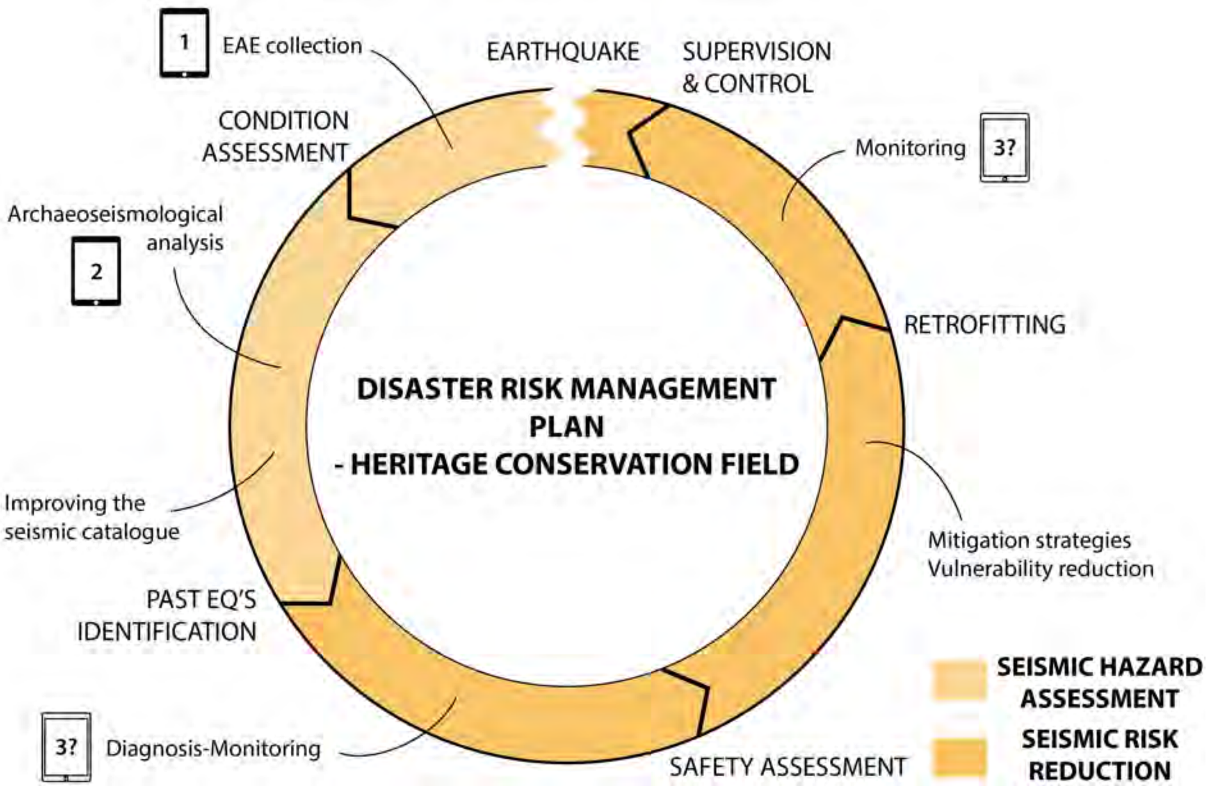

Figure 3.7: Graphical representation of the Disaster Risk Reduction program applied to heritage conservation and inspired on the Preventive Conservation Cycle (principles formulated by the ICOMOS Charter, 2003). RISC project demonstrates the role that may play database systems during four stages of this cycle.

vation. By providing all the necessary information about the RISC database, we hope to share a relevant template for future archaeoseismological investigations in the Andes, and more broadly, in all emerging countries. This user-friendly way of storing and organizing data improves the data entry and processing and considerably facilitates data sharing (Labrador, 2012).

RISC database does not represent only advancement in implementing large semi-quantitative approach in the Andes. It also demonstrates how a basic data collection system might become a relevant interface for a systematic and periodic condition assessment. A properly selected and organized dataset may play a central role during archaeological remains supervision and may serve as a basis for disaster risk management (GCI, 2015; Heras et al., 2013; Paolini et al., 2012). Given the humanitarian stakes during a seismic crisis, in-depth assessments of built heritage integrity are usually carried out at the end of the emergency phase. However, quick on-site damage analysis allows the identification of risks posed to both cultural heritage and the populations in the aftermath of a disaster. Easy to deploy after a seismic crisis, such a database would constitute a unique asset that would benefit any immediate action undertaken to inventory damage in endangered cultural heritage and evaluate the effects of those emergency measures prior to retrofitting works. Hence, easy to implement and customize, our database prototype seems to be a promising complementary tool to monitor archaeological sites, especially in emerging countries where low-tech devices constitute the most appropriate and cost-effective solution (GCI, 2015).

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Notes

[1]We are aware that the usability of proprietary software such as FileMaker Pro may represent a limit to the promotion of the RISC database, especially in developing countries. However, only one license is needed to design the database that may be then replicated freely in as many iOS portable devices as necessary (FileMaker Go is a free app). Furthermore, based on the conceptual and physical models of the database presented in detail in this work (Supplementary data), any reader interested in building a similar database will be able to do it as an open-source option.

Chapter 4

Analysis of earthquake-induced damage in Inca sites, Cusco

"...las gracias que se deben dar a Dios de que no haya tragado la tierra toda esta ciudad como sucedió en tiempo del inga con otros temblores y se sabe por tradición de los antiguos y se ven los edificios cuando se abren algunos cimientos."

Villanueva Urteaga (1970, p.206)

Introductory words

Preliterate, the pre-Columbian societies of the Andes did not leave written sources describing their life or the earthquakes they experienced. Apart from the still limited palaeoseismological data available, the earthquake catalogue in Peru is confined, therefore to the last 500 years, i.e. from the Spanish Conquest (1532-1533 CE) up to now. This catalogue is even more deficient given that historical records of earthquakes are often incomplete (Camassi & Castelli, 2004; Galadini & Galli, 2001; Kázmér, Al-Tawalbeh, Györi, Laszlovszky, & Gaidzik, 2021) and the related information cannot be taken for granted. Hence, using the archaeological record as a proxy for the earthquake identification turns out to be particularly promising and critical to expand the time window and improve the seismic hazard assessment. This situation is even more acute in the earthquake prone area of Cusco, characterized by a diffuse and poorly understood seismicity.
The large archaeoseismological survey we carried out in the Cusco region in 2019 constitutes, thus, a pioneer initiative at the scale of the Andes. In this chapter, I present the main results of the analysis of earthquake-induced damage documented in Inca remains. Based on a robust methodology developed in the previous chapter, the semi-quantitative

approach enables to infer the local ground movement generated by past earthquakes at multiple scales (building, site, and region) and provides new data on the (pre)historical seismicity of the region. The archaeoseismological data suggests, notably, the occurrence of unreported events, which affected among others the sites of Cusco and Machu Picchu. First, we discuss the data collected within the core of the study area, the Cusco Basin. This part corresponds to an article submitted to *Quaternary International*). In the second part, we complement this overview by presenting the results coming from additional archaeological sites located in surrounding areas.

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

Andy Combey[a], Laurence Audin[a], David Gandreau[b], Carlos Benavente[c], Lorena Rosell[c] and Léo Marconato[a]

a Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IGE, ISTerre, 38610 Gières, France.
b Ecole Nationale Supérieure d'Architecture de Grenoble, AE&CC - CRAterre, 38000 Grenoble, France.
c Geología Ambiental, Instituto Geológico Minero y Metalúrgico (INGEMMET), Av. Canadá 1470, San Borja 15034, Lima, Peru.

Submitted to *Quaternary International*

Abstract Devastated by two earthquakes in historical times (1650 and 1950 CE), the Cusco Basin is now characterized by a 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 yrs.) 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 the 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 the Inca empire (∼1400-1533 CE). More broadly, by providing new data on the destructive potential of past earthquakes, this study urges to conduct further research on the faults near Cusco.

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

4.1 Introduction

Crustal faults in continental interiors constitute a direct threat for millions of people around the world (V. Silva, Yepes-Estrada, & Weatherill, 2017). Despite its harmfulness, this type of hazardous faults remains under-studied and hence underestimated (England & Jackson, 2011; Liu & 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: Caruso & Miller, 2015; Plafker, Ericksen, & Concha, 1971; Pisco, 2007: D’Ercole et al., 2007). Since then, much work

has been done on this topic, contributing to improve the SHA and to size the prevention strategies (e.g., Z. Aguilar et al., 2017; Das et al., 2020; Pulido et al., 2015; Villegas-Lanza et al., 2016).

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 (Costa et al., 2006; L. Dorbath et al., 1990). 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 & García-Acosta, 2021), we cannot, therefore, rely on comprehensible reports of earthquakes before 1533 CE. This results in an incomplete seismic catalogue, 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_s 7 1946 Ancash (Silgado Ferro, 1951), M_w 5.6 1986 Cusco (Cabrera & Sébrier, 1998) and M_w 5.4 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 (Dessales et al., in press; Kázmér et al., 2021; Montabert et al., 2020).

Hence, the archaeoseismology, i.e. the study of the earthquake-induced damage (and repairs) in the archaeological record (Ambraseys, 2006; Galadini et al., 2006; Noller, 2001), 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. The aim of this survey was to document 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 a pre-Columbian seismic resistant knowledge (Calderón Peñaylillo, 1963). However, very few studies addressed yet the seismic behaviour of those structures (Hinzen & Montabert, 2017) and their potential to register past ground motions (Combey et al., 2021; Rodríguez-Pascua et al., 2020).

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 detail, first, the different types of earthquake-induced damage observed in nine archaeological sites around the Cusco Basin. We propose new statistical indicators to document the damage patterns in Inca sites and assess the anisotropy of the seismic deformation. We discuss, then, the event(s) that may be responsible for the seismic damage. The results support a limited impact of the 1950 Cusco earthquake (*Intensity*$_{MAX}$=VII) and suggest instead a large impact of the 1650 event (*Intensity*$_{MAX}$=IX?). Moreover, based on the consistency of the damage orientation pattern on the regional scale and the clear difference of EAE's orientation between colonial and Inca buildings, we hypothesize the impact of a seismic event prior to 1650, most probably during the late pre-Columbian period.

4.2 The Cusco area: tectonic and archaeological settings

4.2.1 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. 4.1a). While Mesozoic sedimentary rocks associated with Cenozoic volcano-sedimentary units and magmatic intrusions form the High Plateaus, 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.
The geological investigations carried out around Cusco documented a large complex of active crustal faults (Benavente Escobar et al., 2013; Cabrera et al., 1991; Sébrier et al., 1985) that delimit the northern part of the intra-cordilleran basins, including the Anta-Chinchero and Cusco basins (fig. 4.1a). Being part of the CVFS, this active faulting is oriented NW-SE and predominantly extensional, with a normal motion roughly N-S (Cabrera, 1988; Mercier et al., 1992; Sébrier et al., 1985).
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 fill-

ing of the Anta and Cusco basins, started during the Middle Pleistocene (Cabrera et al., 1991; Gregory, 1916; 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. 4.1-fig. 4.2). Through tectonic landform dating (radiocarbon and cosmogenic nuclides), Wimpenny et al. (2020) estimates a global extension rate 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. 4.1a) and point at return periods of approximately 1-2 kyr. (Palomino Tacuri et al., 2021; Rosell Guevara, 2018).
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 (Julien, 1995; Villanueva Urteaga, 1970), 1744 (Anónimo, 1819) and 1950 (Ericksen et al., 1954), three particular earthquakes struck the Cusco Basin (table 4.1), triggering rockfalls, landslides and damaging the Cusco monuments. The source of these ground motions is still a matter of debate. Too few active faults were subject of palaeoseismological trenches (in red in fig. 4.1a) to provide conclusive answers.

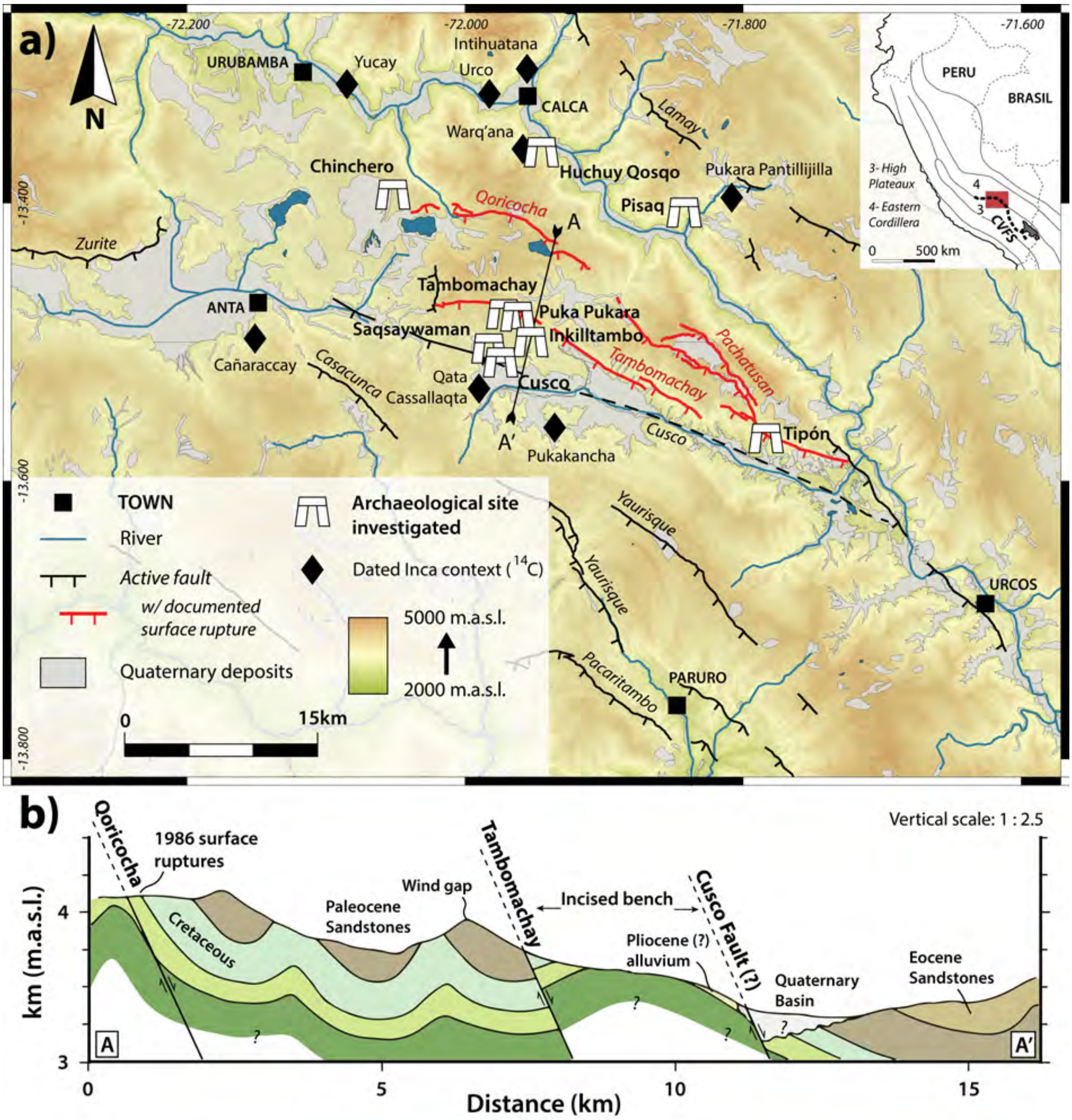

Figure 4.1: a) Cusco regional map indicating the main active fault segments as well as the nine archaeological sites examined in the paper (in white). Black diamonds display the location of the dated Inca contexts presented in fig. 4.3a. Investigated faults with documented surface ruptures (historical 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)

Figure 4.2: View of the Tambomachay Fault from the Puka Pukara site.

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 4.1: 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 Silgado Ferro (1978) and Tavera et al. (2016). The two main events are shaded in grey.

4.2.2 The Incas 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 (Force & McFadgen, 2010; G. King & Bailey, 2006). While the first hunter-gatherer's settlements go back to ~10 kyr. (Bauer, 2018), several hierarchical polities and complex cultures have developed successively since the Formative period (2200 BCE-200 CE) and until the Spanish conquest (1533 CE). From the 13^{th} century CE, archaeological evidence depicts the transformation of a small polity from the Cusco Basin, the Incas, into a centralized state (Bauer, 2018; Bauer & Covey, 2002; Covey, 2006; Hardy, 2019; Vranich et al., 2014). 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 (Covey, 2006; Protzen & Nair, 1997; Wright, 2006). Regarding the Inca monumental and fine stonework, it is commonly regarded as contemporaneous with the political and territorial climax of the empire. Unfortunately, the chronology of the imperial phase remains highly dependent on a limited number of Spanish sources (e.g., Cobo, 1890; Garcilaso de la Vega, 1609; Huaman Poma de Ayala, 1979; Murúa, 1590). 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 (Burger et al., 2021; Marsh et al., 2017; Meyers, 2019) tend, nonetheless, to question – or even challenge – the traditional Inca chronology (Rowe, 1945) by suggesting an onset of the imperial expansion several decades earlier.

Currently, the few radiocarbon dates available (from different sources and varying quality), do not enable to refine 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 4.3a displays the radiocarbon dates – coming from sites around Cusco (fig. 4.1) 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 example of the 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^{th} century according to colonial sources, the data indicate a lower bound of the monumental architecture at the beginning of the 15^{th} century. The Inca monumental architecture and its different fine dry-stone masonry styles (Agurto Calvo, 1987; Gasparini & Margolies, 1980) 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 (Nair & Protzen, 2015; Protzen, 1985; Protzen & Nair, 1997) 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 16th century (Trever, 2005).

The Inca fine stone buildings constitute large seismoscopes (Combey et al., 2021), which may have been affected by ancient earthquakes, due to their proximity to active faults (e.g., Puka Pukara site; fig. 4.2).

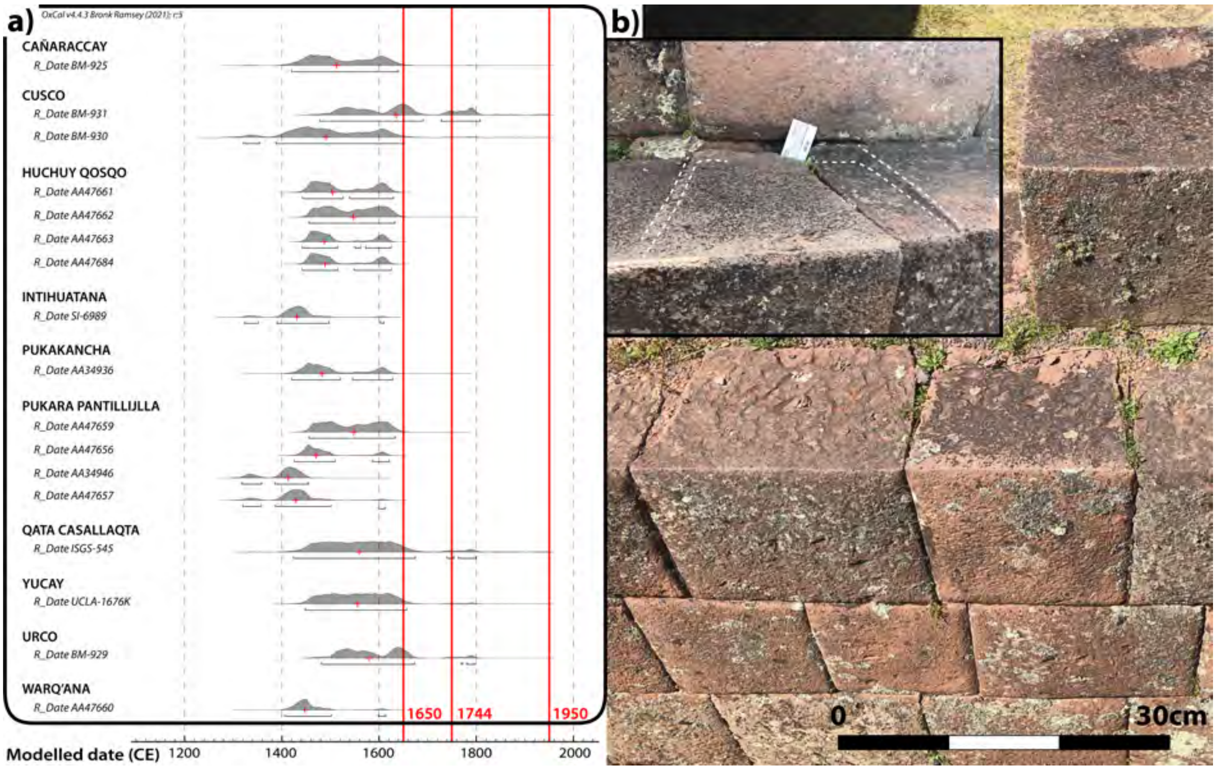

Figure 4.3: a) Radiocarbon dates coming from 10 archaeological contexts of the Cusco region and belonging to the Inca Imperial phase (recalibrated with the mixed calibration curve using OxCal v5; Hogg et al., 2020; Reimer et al., 2020). The red crosses correspond to the median values. The red vertical lines indicate the three main damaging earthquakes that occurred in Cusco since the 16th century. No earthquakes are documented prior to 1650; b) The typical Inca coursed ashlar masonry (Pisaq 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.

4.3 Methods

4.3.1 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 (Ambraseys, 2006; Rapp, 1986; Stiros, 1996). 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. 4.2 – Supplementary data). 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 a statistical analysis (Supplementary data): the Dipping Broken Corners (DBC) and the Displaced Masonry Blocks (DMB). While not prone to collapse due to their well-fitted stonewalls (fig. 4.3b), Inca fine dry-joint masonry can be damaged by strong ground shakings (Ericksen et al., 1954; Hinzen & Montabert, 2017). By exceeding the internal friction forces, strong transient vibrations generate strain structures like the DBC and DMB.
Most of the EAEs (fig. 4.4a)are supposed to be "preferentially oriented" with respect to the ground motion and their analysis was proposed to retrieve seismic sources. This assumption, which has only been applied on two instrumental earthquakes (Rodríguez-Pascua, Pérez-López, Martín-González, Giner-Robles, & Silva Barroso, 2012), is still a matter of debate (e.g., Hinzen, 2009; Hinzen et al., 2016). In any case, the documentation of the EAEs provides relevant information about the local properties of an ancient earthquake. Considering, for instance, a ground shaking oriented mainly N120, structures oriented N30-210 would be the first to partially or completely collapse (Hinzen & Montabert, 2017). Regarding isolated EAEs, such as block slides or Dipping Broken Corners, their behaviour is much more complex (Caputo et al., 2011; Hinzen, 2009) and is deeply influ-

enced 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. 4.3b). In this study, we consider thus 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, a 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 & 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. 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 (Supplementary data). Regarding wall's orientations, although the mean orientation of wall trends does not match perfectly with the cardinal directions (N0, N45, N90 and N135 - table C.1), 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 ground movement was considered as (sub)orthogonal to the most affected/deformed wall trend ($\pm$ 45° – fig. 4.4b-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. The dip

directions are indeed constrained by the wall's orientation and their distribution frequency will be function of the proportion of the wall trends in the sample. In 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° (fig. 4.4b-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. 4.3b), the vertical oscillatory movement responsible for the chipped corners is likely to occur as a roll motion of the blocks within the masonry (fig. 4.4b-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 (± 45°). 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 directions within the range "*Wall azimuth* ± 45° & *Wall back azimuth* ± 45°" (σ_{50}). In the case of a homogeneous distribution, the σ_{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 anisotropy of the deformation, i.e., the damage distribution and pattern according to the wall trends, and to propose a 90° angular range comprising the orientation of the ground movement generated by the earthquake (fig. 4.4b). We must point out that this shaking axis does not necessarily correspond to the orientation of propagation of the seismic waves. Depending on the most damaging wave type, the movement will be parallel or orthogonal to the seismic wave propagation. That is why no conclusion on the source location of the earthquakes can be drawn at this stage.

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").

4.3.2 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 (Combey et al., 2021; L. Dorbath et al., 1990). 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^{th} 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^{th} 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 on 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.

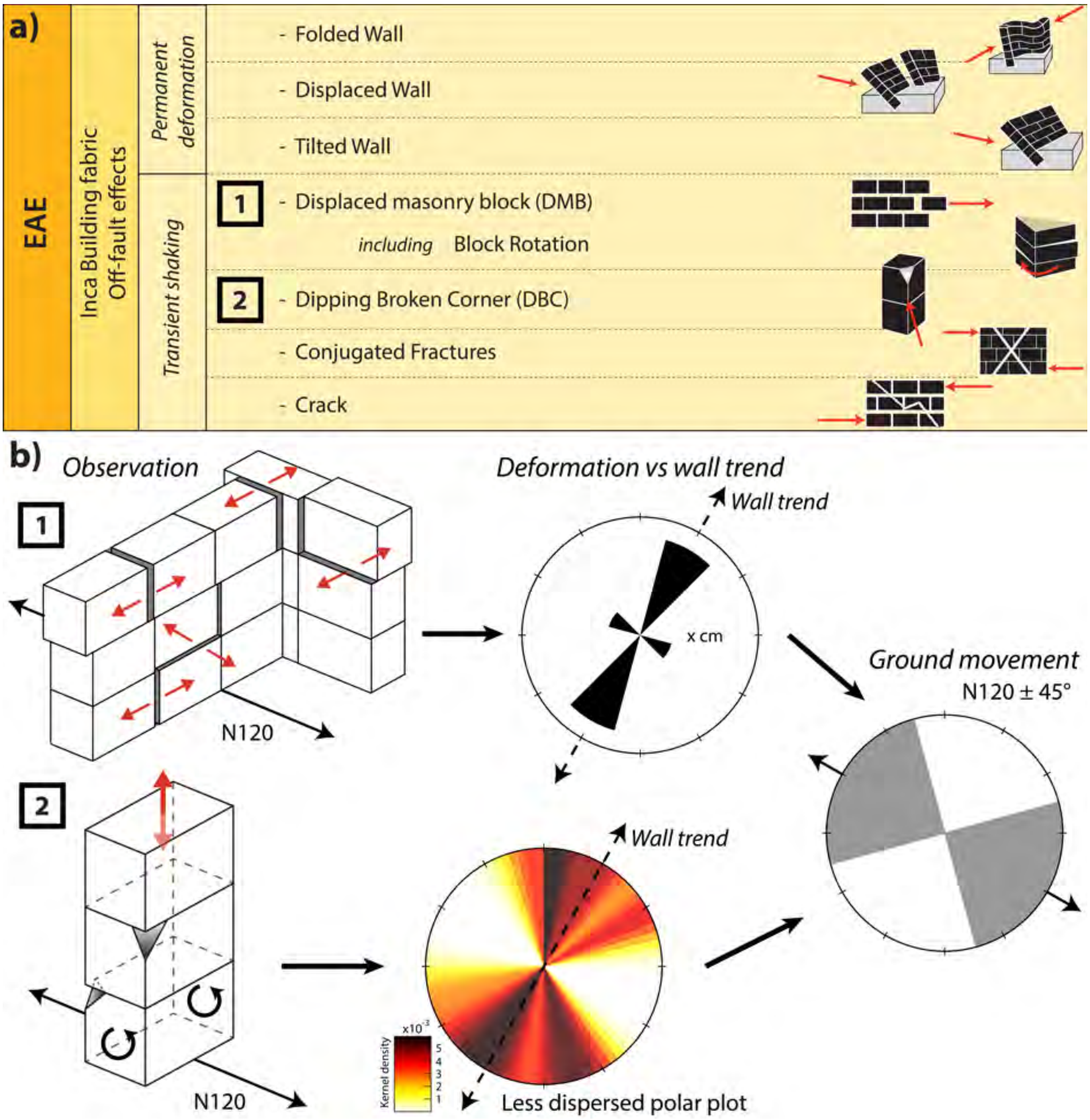

Figure 4.4: a) Main types of off-fault effects recorded in the Inca building fabric; b) Following an earthquake, the deformation features are not homogeneously distributed in structures. Diagrams summarize a hypothetical circular distribution of cumulative gap openings and DBC's dip directions in case 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°).

4.4 Results

4.4.1 Assessing the anisotropy of the seismic deformation

We registered 2,980 EAEs in the nine archaeological sites (fig. 4.1a), including 2,907 DBC and DMB (fig. 4.5). Among those latter, 2,171 (∼75%) were associated with a medium or high level of confidence regarding their seismic origin (Supplementary data). 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. (table 4.2). Hence, although these three sites show a clear evidence of a seismic impact, the data collected will not be further discussed.
Table 4.2 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 of 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 4.3.1, this disparity is mainly due to the unequal representation of wall classes (table 4.2), in terms of length surveyed.
The results are much more consistent when we normalize both indicators per 100 m of surveyed walls (fig. 4.6). 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 (table 4.2). The second largest value, belonging to the "NW-SE" class, is consistent with the largest amount of displacement (fig. 4.6). In 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.
Located a few hundred meters from the site of Warq'ana (fig. 4.1a) – 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 4.7 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

± 180° regarding the N-S walls (azimuth: N025), whilst the highest proportion lies within the range N060-130 ± 180° for the E-W walls (azimuth: N115).
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 σ_{50}-value is indeed two times greater for the N-S walls (0.84) than for the E-W walls (0.40 – fig. 4.6 and fig. 4.7a-b). This observation tends to confirm the second assumption made in Section 4.3.1. The dip direction of the chipping marks is less dispersed in walls (sub)orthogonal to the ground movement.
Regarding the other sites, the results of the σ_{50}-value demonstrate a good consistency with the DBC_{norm} and DMB_{norm}-values (fig. 4.6). Only the site of Pisaq shows inconclusive results. We may highlight nonetheless the great homogeneity of the EAE distribution with respect to the wall's orientation. The case of Pisaq will be discussed more thoroughly in the following section.

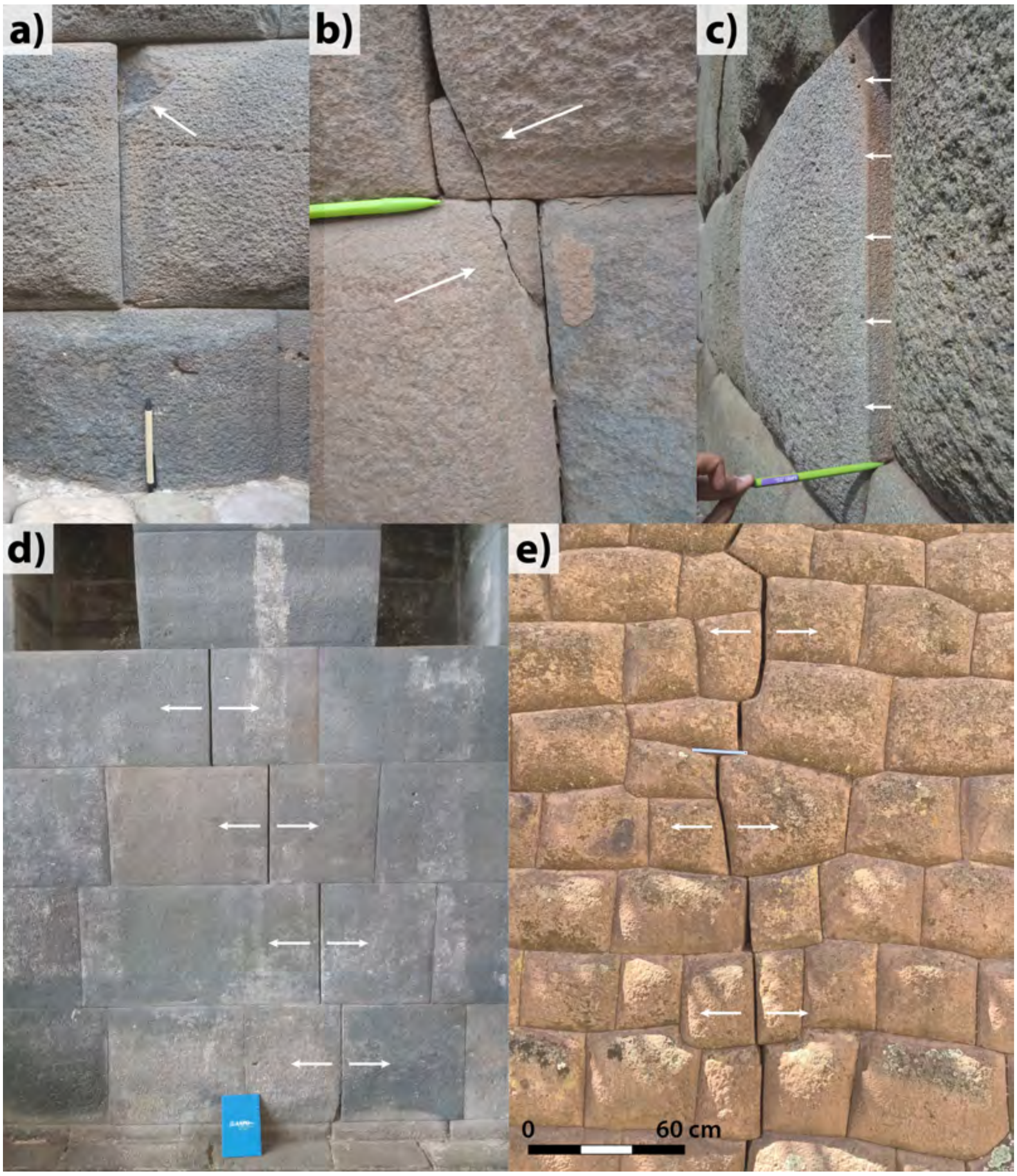

Figure 4.5: Examples of EAEs registered on the field. The more common evidence are the DBC (a-b) and the out-of-plane (c) / in-plane DMB (d-e).

Sites	**N-S**			**NE-SW**			**E-W**			**NW-SE**		
	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)
Cusco	362	114	10.5	1278	**186**	25.8	443	168	99.2	756	175	**102.2**
Inca	335	81	3.7	1209	129	22.2	374	**147**	**90.4**	640	94	86.1
neo-Inca	27	33	6.8	69	57	3.6	69	21	8.8	116	**81**	**16.1**
Saqsay.	367	26	190.6	283	16	120.9	692	**40**	**258.4**	177	0	13.7
Chinchero	245	55	**60.9**				390	**85**	19.9			
Pisaq	308	419	**73.7**				310	**474**	43.3			
Puka Pukara	8	5	0	86	10	0	49	**15**	0	30	10	23.9
Huchuy Q.	24	**21**	**157.5**				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 4.2: 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.

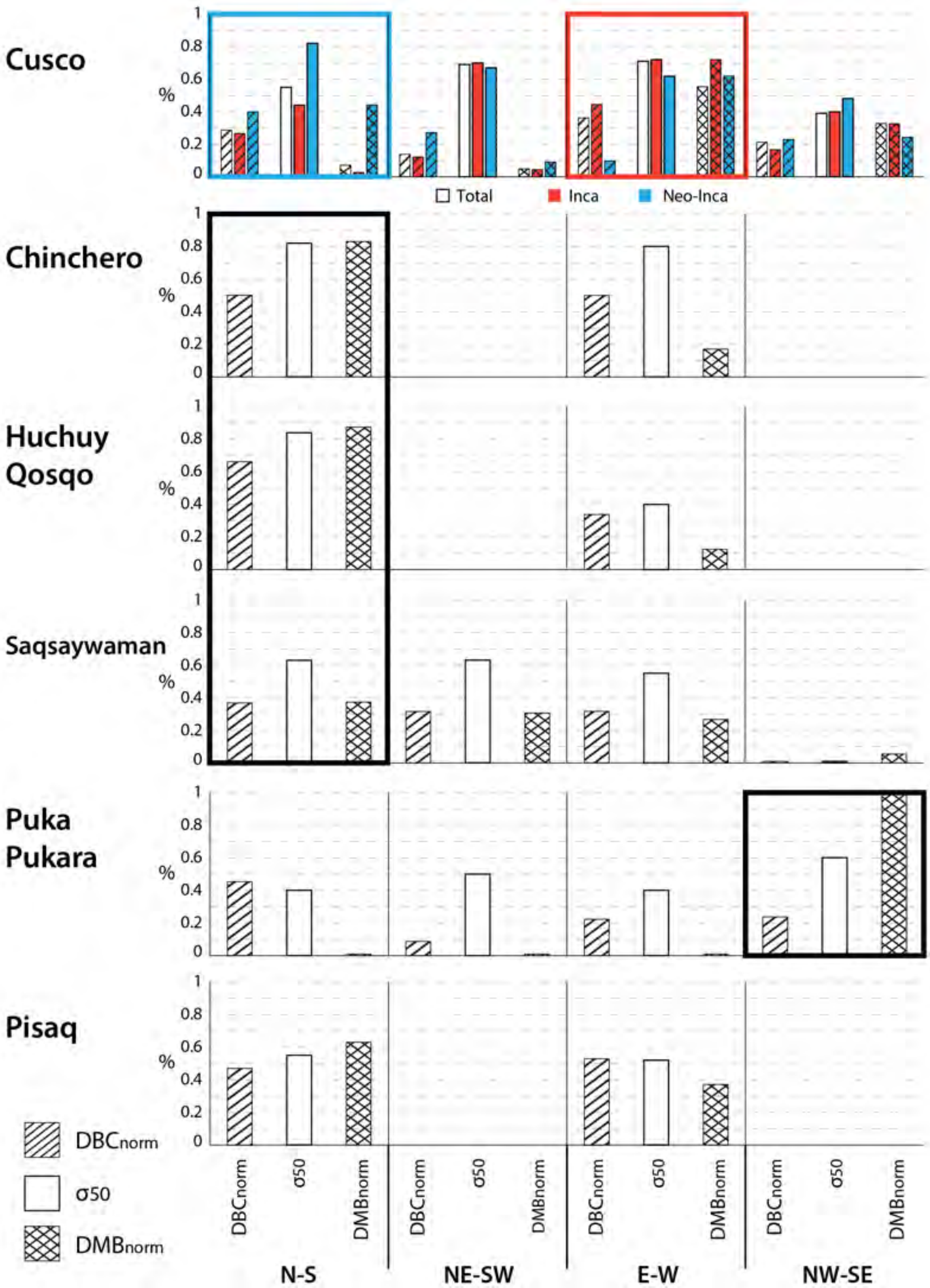

Figure 4.6: Percentage of the normalized number of DBC (hatched bars) and normalized cumulated amount of DMB (crosshatched bars) according to the wall's orientation. The σ_{50}-value (solid bars) is also reported. Classes with the highest rates are highlighted in boxes. Only the six archaeological sites with statistically significant results are represented. Detailed information is provided in Tables C.2 and C.3.

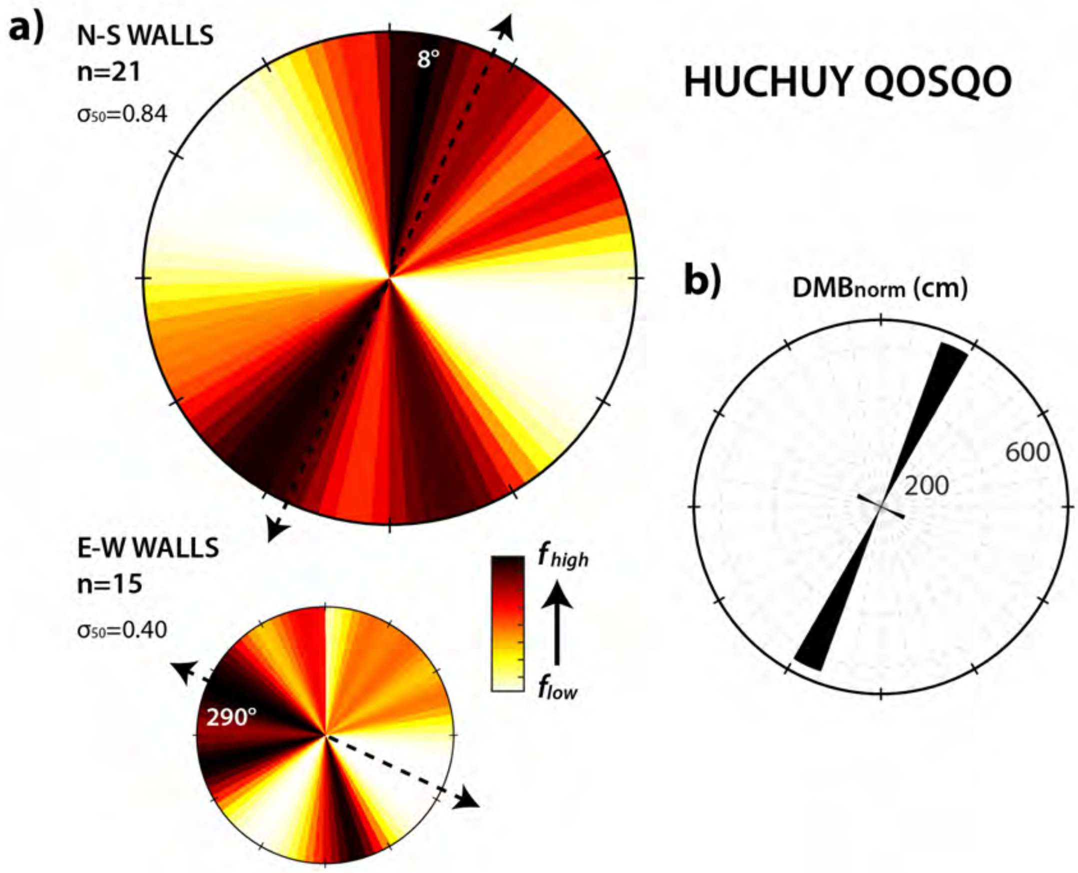

Figure 4.7: a) Polar plots displaying the kernel density function of the DBC's dip direction in the site of Huchuy Qosqo. The size of the plots is function of the DBC_{norm}-value. The dotted arrows indicate the wall trends; b) Normalized amount of displacement according to the wall trends.

4.4.2 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 (Bauer, 2018; Beltrán-Caballero, 2013 – fig. 4.8a). We decided here to present the results separately due to the different geological context 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. 4.6). However, we registered EAEs on two types of buildings with fine stone masonries 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 of the results (red and blue bars in fig. 4.6). On neo-Inca structures (blue diamonds on fig. 4.8a), the N-S walls (N160/340) are preferentially affected by the DBC and DMB (fig. 4.8b). In contrast, the E-W trend is even stronger in the Inca remains (red diamonds in fig. 4.8a) than in the whole dataset (fig. 4.6 and fig. 4.8b). 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 Cusquenan architecture.
In Saqsaywaman, we surveyed mainly the three cyclopean terraces (*baluartes* in Spanish), which border the site to the north (fig. 4.9a). 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 (σ_{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. 4.6 - fig. 4.9b). 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.

Outside Cusco, four sites have a statistically relevant dataset: Puka Pukara, Chinchero, Huchuy Qosqo and Pisaq (fig. 4.10 - figs. C.3 and C.4). Settled on a top of a hill, Puka Pukara (fig. 4.2) 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. 4.6). 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 σ_{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. 4.6). The σ_{50}-value is, though, slightly greater in the N-S

group and the DMB_{norm}-value is significantly higher in the same orientation (fig. 4.6). We postulate, therefore, a preferential distribution of the deformation generated by a ∼E-W impulse (N095/275).

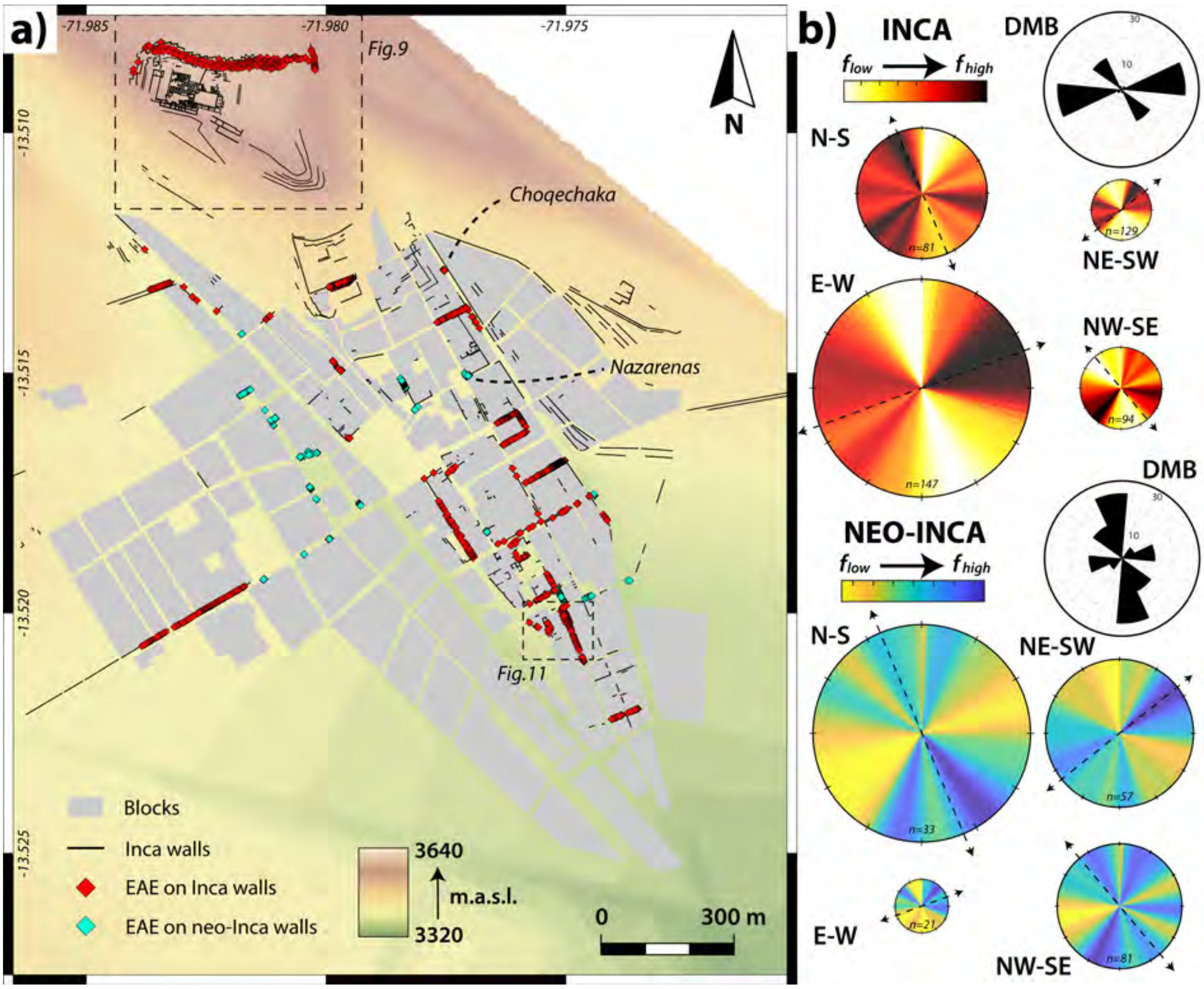

Figure 4.8: a) EAE distribution within the city of Cusco. Damage on Inca and neo-Inca walls are represented respectively in red and blue; b) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to wall's orientations on Inca and neo-Inca walls. Polar plots are sized based 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).

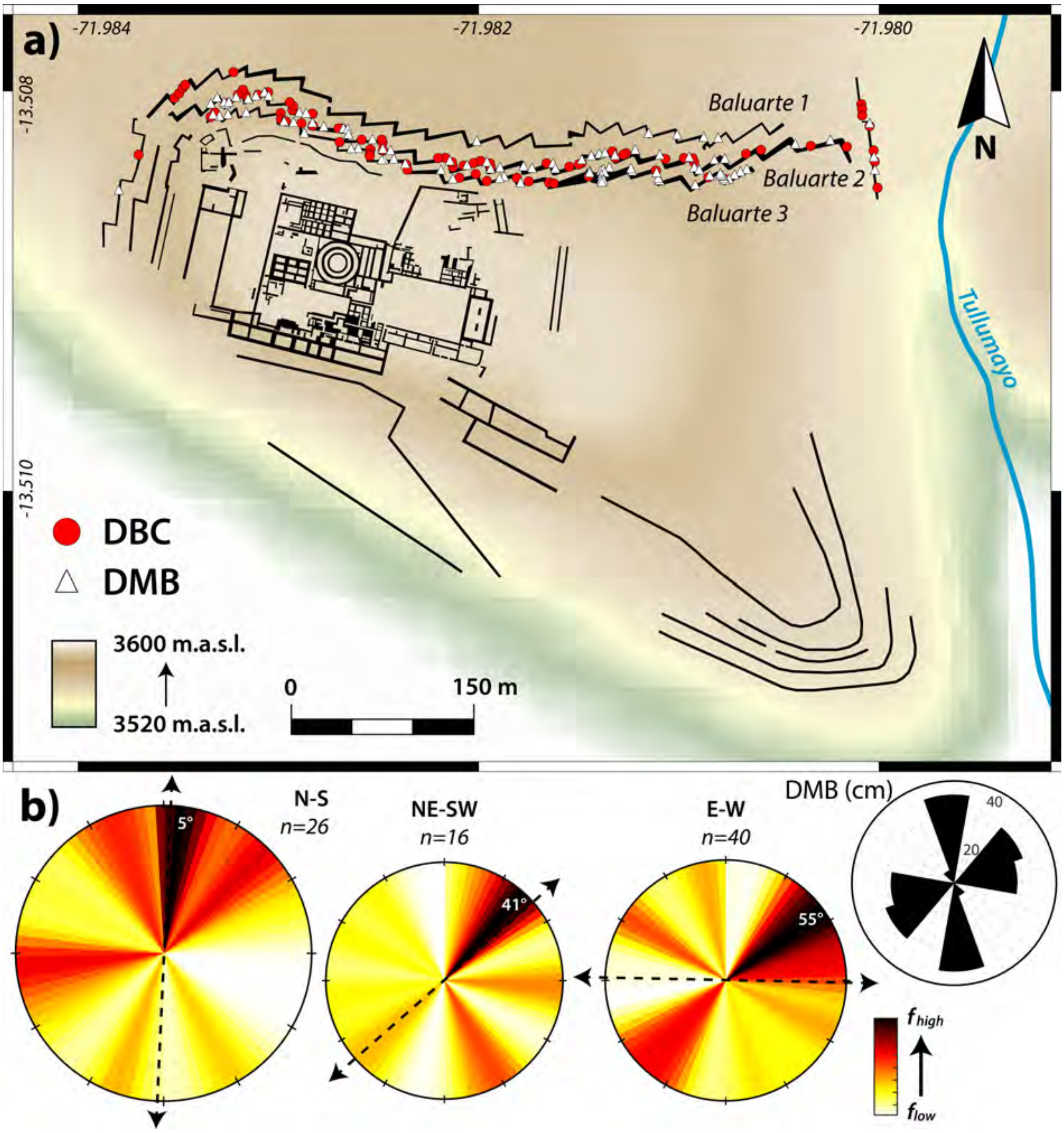

Figure 4.9: a) EAE distribution in Saqsaywaman (walls based on Beltrán-Caballero, 2013); b) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to wall's orientations. Polar plots are sized based on DBC_{norm}. Credits DEM: Instit. Nacional de Cultura, Center for Advanced Spatial Technologies (Univ. Of Arkansas) & Cotsen Institute for Archaeology (UCLA).

As previously outlined in Section 4.4.1, the surveyed Inca architecture of Huchuy Qosqo is characterized by a strong anisotropy of the seismic deformation. The three studied criteria (fig. 4.6) point all to a ground movement oriented E-W (N115/295).
Finally, the results obtained in Pisaq (Intiwatana sector – see Supplementary data) are less conclusive. Very similar for both wall trends, the DBC_{norm}, the σ_{50} and the DMB_{norm}-values do not point at a preferential distribution of the deformation (fig. 4.6 - fig. C.4). We may raise the four following reasons:

1. The seismic deformation results from a unique seismic event. The impulse associated with this event was almost "bisecting" the two main wall trend, i.e. N050/230, inducing an 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 an 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 Pisaq, the geomorphological hazard is high and several landslides occurred nearby (Carreño Collatupa, 2006; Vílchez Mata, Sosa Senticala, Pari Pinto, & Peña Laureano, 2020).

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

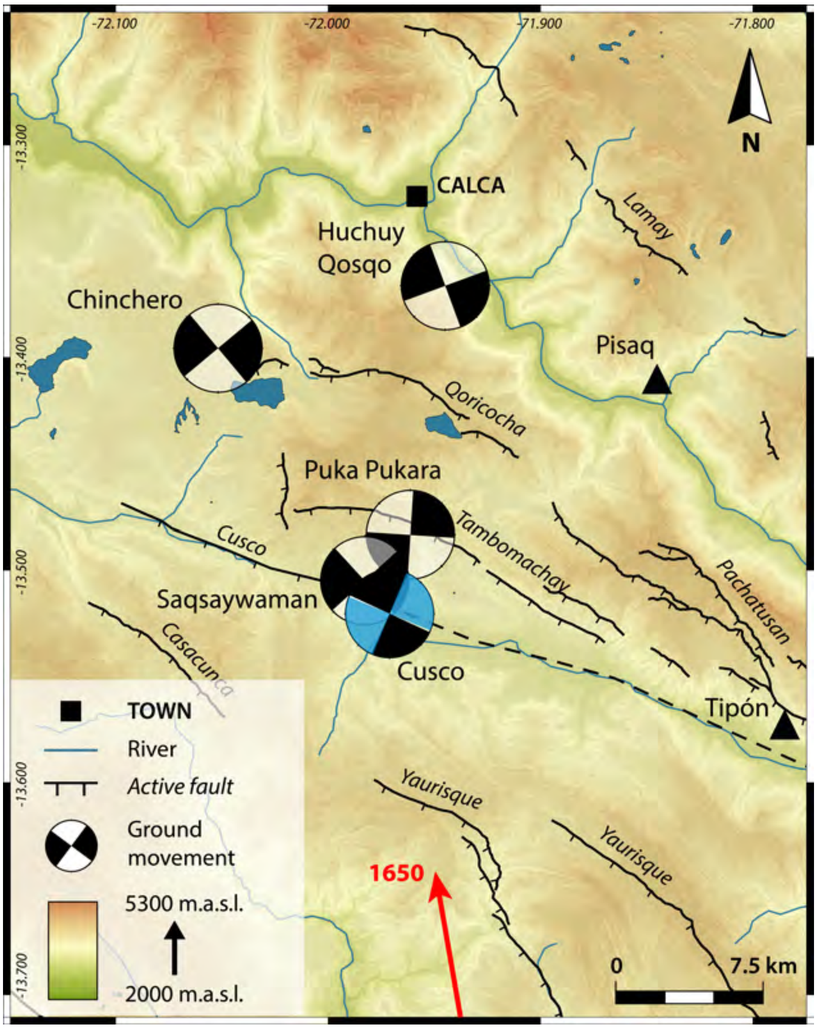

Figure 4.10: Map of the Cusco Basin showing the orientation of the ground movement (black) inferred for the Inca remains surveyed. The ground movement assessed for the neo-Inca architecture is displayed in blue. The red arrow indicates the direction of the 1650 ground shaking mentioned in colonial sources (Villanueva Urteaga, 1970).

4.4.3 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 postseismic sequence on Inca remains (d'Harcourt, 1950; Ericksen et al., 1954; Kubler, 1952). Comparing the photographs taken after the 1950 earthquake with the pictures from the early 20^{th} 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. 4.8a): respectively the Qorikancha, an Inca doorway in Choqechaka street and the House of the Snakes (*Casa de las Sierpes*).

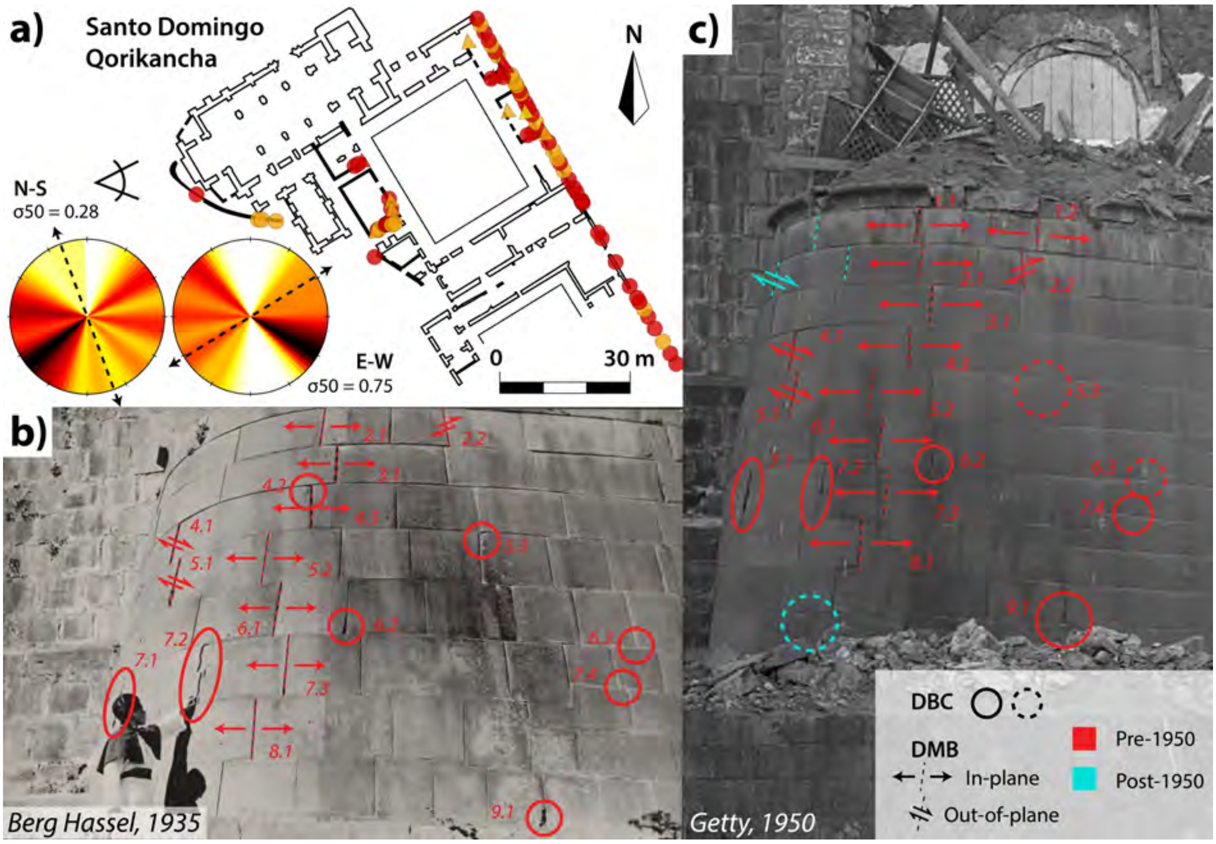

Figure 4.11: a) Map of the Qorikancha (Cusco) showing the location of the EAEs identified during the survey and the frequency of the DBC's dip direction; The curved wall pictured in b) in the first half of the 20^{th} c. and in c) on the aftermath of the 1950. Several DMB (dotted lines) and DBC (circles) affected already the structure before 1950.

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 the 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. 4.11c). He ascribed the damage to the past seismic activity and the weight of the colonial convent built upon it. The photo from Berg Hassel in 1935 (fig. 4.11b) 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. 4.11c - figs. C.12 and C.13). A large majority of the Displaced Masonry Blocks affecting the curved wall since the early 20^{th} century occurred at the northern extremity where we may observe a change in the terrace's orientation (fig. 4.11).

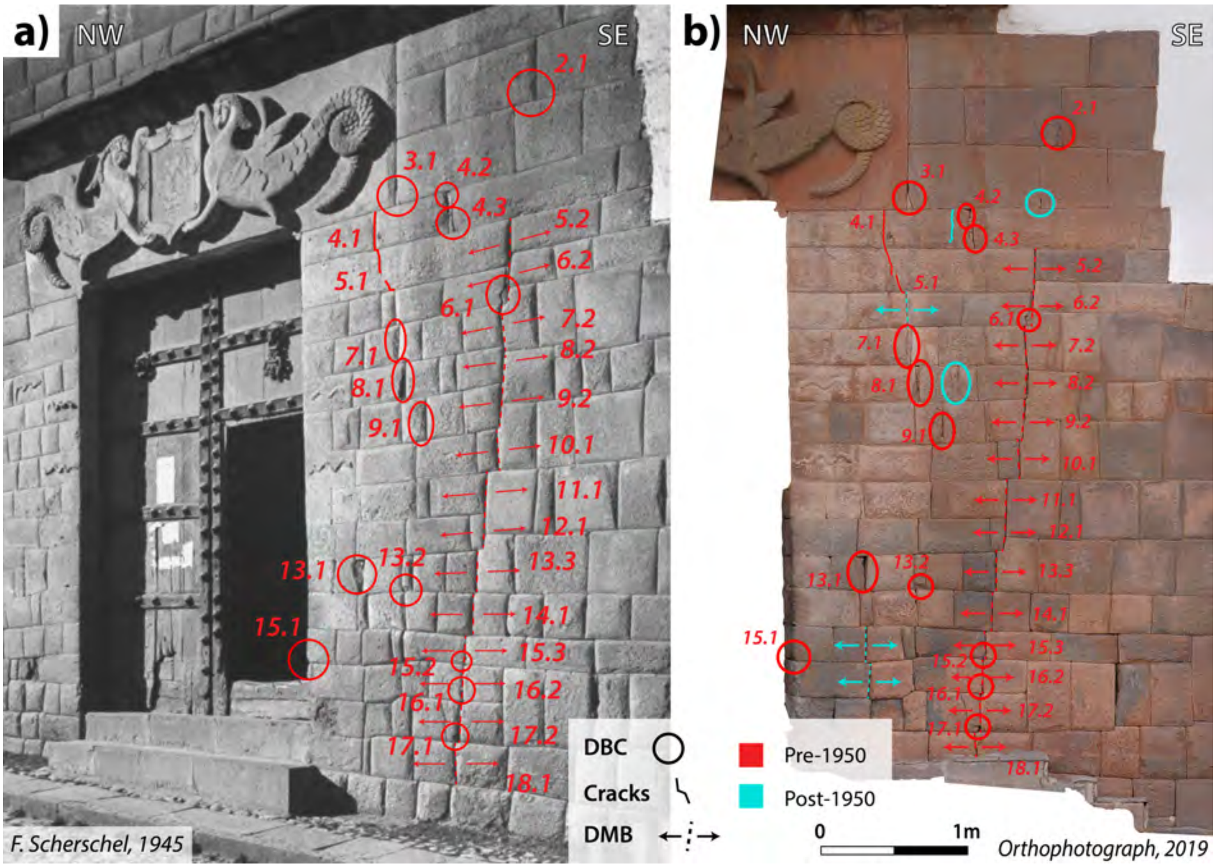

Figure 4.12: a) Picture of F. Scherschel of *La Casa de las Sierpes* dated 1945 and b) 2019 orthophotograph of the southern side of the doorway (credits: the authors). DBC and DMB are highlighted in red and blue.

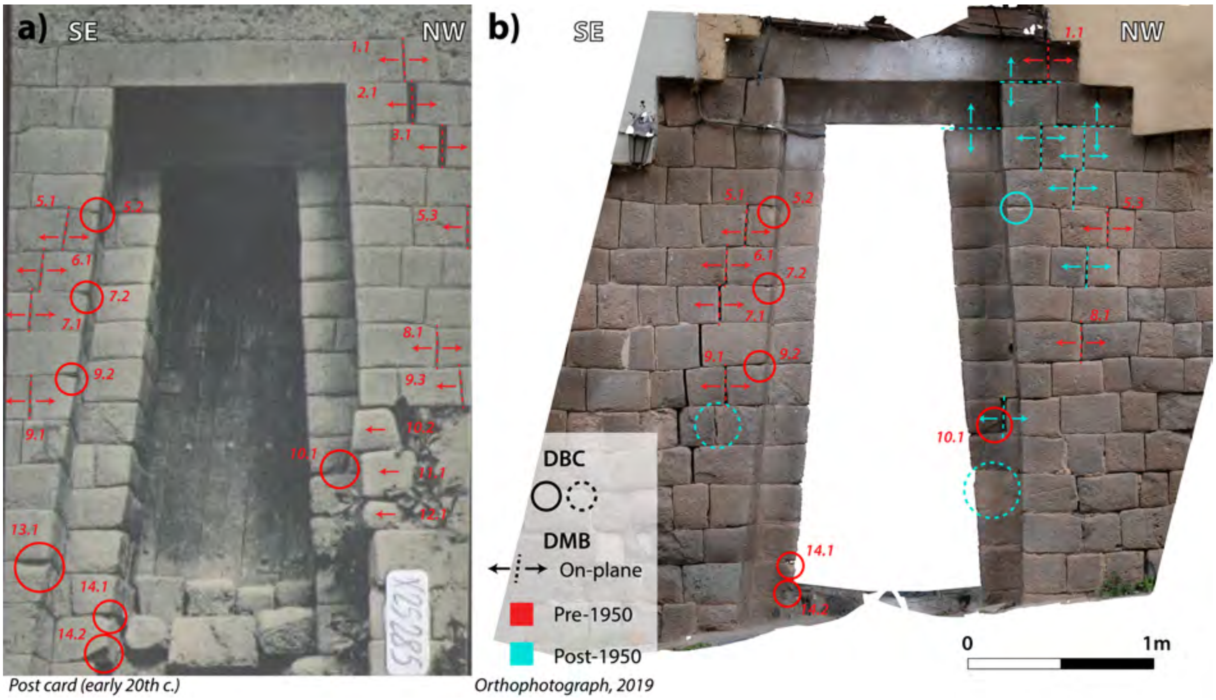

Figure 4.13: Comparison of the EAEs affecting the Inca doorway in Choqechaka Street based (a) on a photo taken before 1950 and (b) an orthophoto made in 2019 (credits: the authors). DBC and DMB are highlighted in red and blue.

The pre-existence of seismic damage on Inca and neo-Inca stone architecture does not seem to be limited to the Qorikancha as demonstrated by the Figure 4.12 and Figure 4.13. Regarding the *Casa de las Sierpes* 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. 4.12). Besides the evidence of restoration of the Inca doorway in the Choqechaka Street, the reader may clearly see the seven Displaced Masonry Blocks and six Dipping Broken Corners yet present on the structure in the first half of the 20th c. (fig. 4.13). 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 (Supplementary data) 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.

4.5 Discussion

As showed in Section 4.4.3, 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. We may therefore consider that 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 VII (M.M. scale) and that we can statistically neglect the impact of the 1950 earthquake on the EAE analysis.

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^{th} 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 damage 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 factor 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. 4.11a) and complementary evidence from Nazarenas (fig. C.14) many EAEs were already present in the early 20^{th} 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 sequence 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 (Julien, 1995; Villanueva Urteaga, 1970). Despite the traditional overstatements of the colonial documents, the extent and severity of 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 4.4.2, 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. 4.10), not consistent with the archaeoseismological results. However, as emphasized in Section 4.3.1, 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 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. 4.10), 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 hypothesis, 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. This will require the modelling of potential ground shakings in the Cusco Basin with different seismic sources and local intensities. Nonetheless, the third and fourth hypothesis 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 in those sites. Similarly, the long return periods of the faults, of approximately 1000-2000 yrs. (Cuadra et al., 2008; Palomino Tacuri et al., 2021; Rosell Guevara, 2018) and the small number of strong earthquakes during the historical period makes the hypothesis of multiple devastating earthquakes affecting the Cusco Basin between the 14^{th} and 16^{th} centuries quite unlikely.

4.6 Conclusion

The seismic hazard in the Cusco area remains under-studied 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 yrs.). Hence, developing complementary and innovative approaches based on the analysis of indigenous oral traditions, palaeoseismology and archaeoseismology turns 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 highlight the anisotropy of the seismic deformation at the site scale. 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^{th} 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. Complementary seismic engineering testing must now further assess the resistance of Inca structures. Beyond the implications that those results may have in the local seismic hazard assessment, we think that this work paves the way to future discussions and investigations on pre-Columbian perception and adaptations to the seismic hazard.

Acknowledgments This paper and the research behind it would not have been possible without the cooperation of the Decentralized Department of the Ministry of Culture from Cusco. We thank Peter Molnar, Sara Neustadt, Fabrizio Delgado and Xavier Robert for their precious assistance during the field campaigns. We are grateful to Krzysztof Gaidzik and Hélène Dessales who provided expertise and comments that greatly assisted the research. This work was part of the CuscoPATA project (006-2016-FONDECYT) and of the inter-institutional agreement between the IRD (Institut de Recherche pour le Développement) and the INGEMMET (Instituto Geológico, Minero y Metalúrgico del Perú). This work has been realised in the framework of the IDEX CDP Risk@Univ. Grenoble Alpes as part of the program “Investissements d’Avenir” overseen by the French National Research Agency (ANR-15-IDEX-02). The project has received, as well, financial support from the CNRS through the MITI interdisciplinary programs and from the IRD.

4.7 Outside the Cusco Basin

Apart from the nine archaeological sites located in a 20 km radius around Cusco and presented above, the archaeoseismological survey led to the identification of seismic evidence in five other sites. Four of them were situated in the western part of the Cusco region (more than 50 km away from the regional capital), including three in the lower part of the Urubamba Valley (Machu Picchu and Wiñaywayna) and one in the upper part of the Apurimac catchment (Tarawasi). The fifth site of Raqchi is located 100 km southeast of Cusco.

We registered and documented 1,987 EAEs in the five sites (see Supplementary data), including 1,771 DBC, 142 DMB and 65 Cracks/Fractures. Among them, 1,266 EAEs have a Medium or High level of confidence (∼64%). We assigned a robust level of confidence ("Medium" and "High") to 1,132 DBC (64%), 91 DMB (64%) and only 36 Cracks (55%). The reduced number of Cracks prevented the implementation of any statistical analysis. As done in the Cusco Basin, we examine, thus, the DBC and cumulated amount of DMB with a High and Medium level of confidence. Following the methodology presented in detail for the Cusco Basin, we classified the DBC and the cumulated amount of DMB according to the wall's orientation (table 4.3) and normalized the values per 100m of surveyed walls. We detail hereinafter the archaeoseismological results according to the three distinct areas:

Sites	**N-S**			**NE-SW**			**E-W**			**NW-SE**		
	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)	Wall length(m)	DBC (n)	DMB (cm)
Machu Picchu	97	**73**	65.5				60	52	**288.4**			
Wiñaywayna	25	**46**	**4.5**				5	10	2.2	6	4	0
Ollantay.												
Residential sector	*426*	***114***	***12.9***				*615*	*101*	*10.2*			
Temple Hill	*66*	*27*	*0*	*56*	*24*	*0.7*	*109*	*71*	*0*	*201*	***256***	***0.8***
Tarawasi				131	**82**	63.3				99	63	**163.6**
Raqchi	91	**102**	0				23	29	0			

Table 4.3: 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. Not statistically significant data (limited wall length and/or reduced number of EAE) are shaded in grey.

The western part of the Urubamba Valley (Sacred Valley)

Discovered scientifically in 1911 by Hiram Bingham, Machu Picchu is located on a narrow N-S granitic crest dominating the Urubamba River and surrounded by rainforest. The crest was artificially flattened during the Inca period (Carlotto et al., 2007) and its flanks covered with numerous terraces.
In the framework of our archaeoseismological field campaign, we were able to survey only a small part of the archaeological site (in red in fig. 4.14). We targeted Inca buildings characterized by a fine stonework, slightly restored and with a special interest, such as the Temple of the Three Windows (1 in fig. 4.14b) and the Intiwatana sector (2 in fig. 4.14b). In total, we registered 125 DBC and more than 350 cm of DMB with a robust level of confidence (table 4.3).
The normalized number of DBC is slightly greater in the walls oriented E-W (n=87). This observation is consistent with the smaller dispersion of the DBC's dip directions around the wall axis (σ_{50}) in the E-W orientation (fig. 4.14b - table C.3). In a similar fashion, the E-W walls are the most affected by gap openings (fig. 4.14b). The results support, therefore, the occurrence of, at least, one earthquake associated with a ground movement oriented ~N-S (N150/330).

Nowadays, the site of Ollantaytambo is renowned for its megalithic Inca constructions and the monumental terraces that cover the lower part of the rocky hill west of the modern town of Ollantaytambo. However, the former Inca settlement was bigger and divided by the Patakancha River into two main sectors (fig. 4.15a): the Temple Hill, which assumed probably a ceremonial function and the residential sector (Gasparini & Margolies, 1980; Protzen, 1993), located on the eastern bank of the river. In the framework of our study, both sectors were considered part of the same site. We discussed, though, separately the results of the two distinct sectors.
Regarding the archaeoseismological data collected in the ceremonial sector, we did not register robust evidence of DMB (<2 cm) despite our extensive survey. The large number of DBC identified in the Temple Hill demonstrates, though, a seismic impact (table 4.3). The DBC_{norm}-value is significantly larger in the NW-SE walls (n=127) than in the rest of the dataset (n≤65). This indicator is inconsistent with the dispersion indicator of the DBC's dip direction. The σ_{50}-value shows a high data dispersion in the NW-SE class and points rather towards a preferential deformation of the NE-SW and E-W walls (fig. 4.15). Considering the very low σ_{50}-value (0.33) and the reduced number of normalized DBC computed in the N-S walls (n=41), we assume, nonetheless, a strong anisotropy of the seismic deformation despite the inconsistency of the two previous indicators (fig. 4.15b).

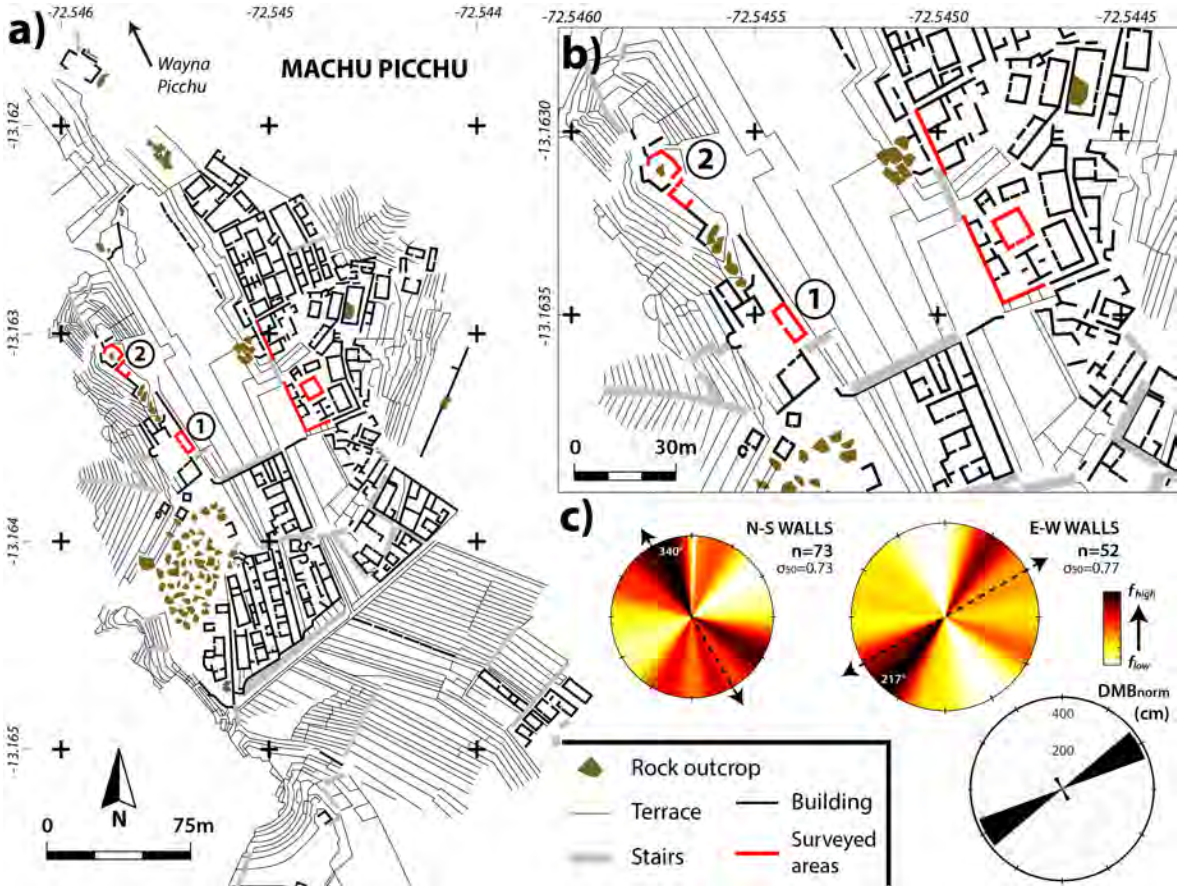

Figure 4.14: a) Map of the Machu Picchu site indicating the surveyed remains (in red); b) Zoom on the area of interest; c) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to the wall trends. Polarplots are sized based on the DBC_{norm}-value.

Hence, we hypothesize a ground movement oriented somewhere between N145 and N225, i.e. orthogonal to the wide spectrum of the NE-SW/E-W and NW-SE walls.

Planned in a regular grid, the walled-in habitation compounds of the residential sector are still forming the blocks of the city centre of Ollantaytambo. Due to this geometrical layout, wall trends can be divided into only two classes: N-S (N025/205) and E-W (N105/295). Combining the statistical analysis of the DMB and DBC, we are not able to identify a clear preferential pattern of deformation. While the N-S walls seem to be the most affected by the DBC (fig. 4.15b), there is only a slight difference regarding the σ_{50}-value and cumulated amount of displacement between the two wall trends (fig. 4.15b - table C.3). We assume, therefore an isotropic deformation at the scale of the residential sector of Ollantaytambo.

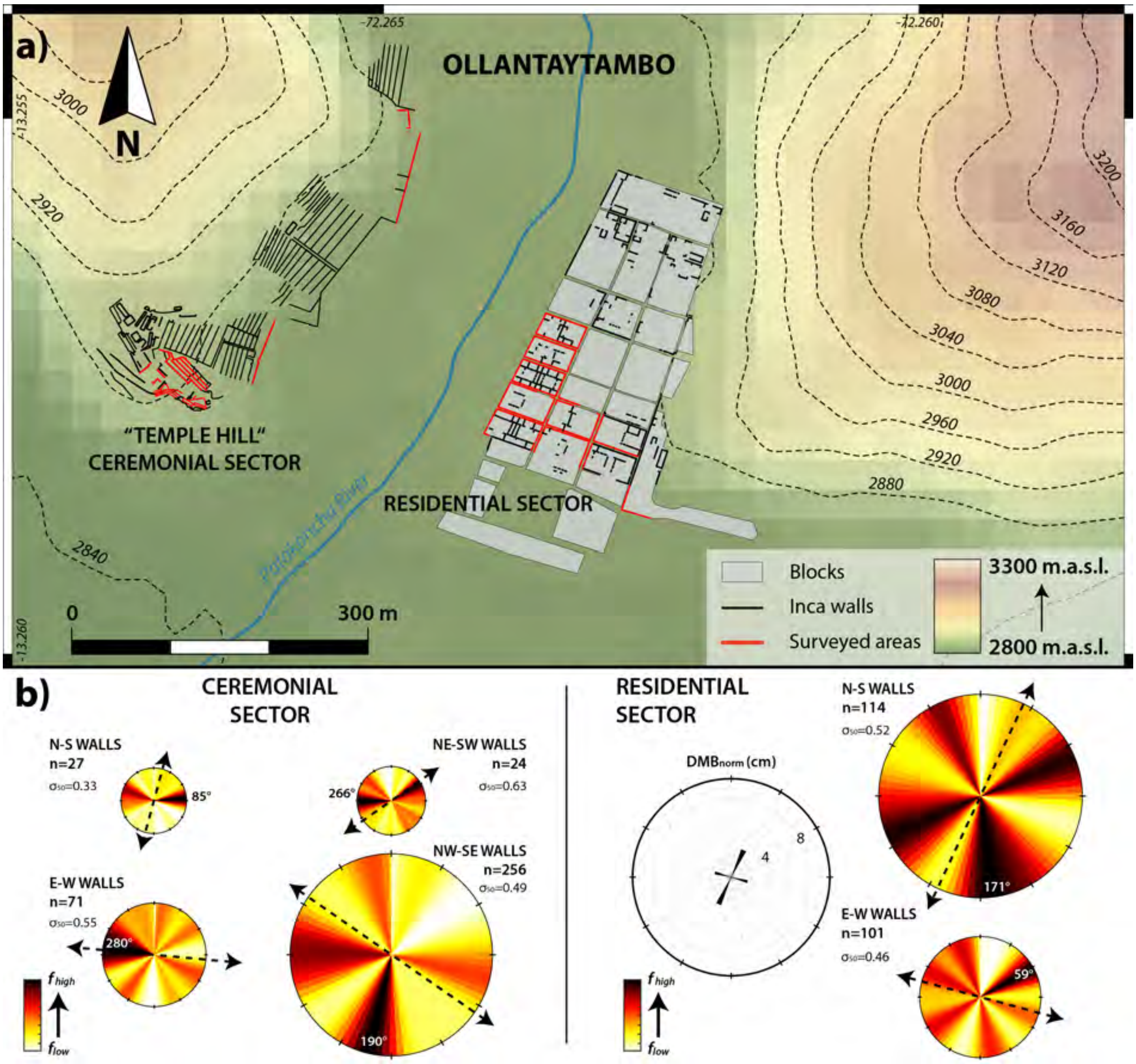

Figure 4.15: a) Location of the investigated remains (in red) in the ceremonial and residential sector of Ollantaytambo (Inca walls based on Protzen, 1993); b) Frequency of the DBC's dip direction and normalized cumulated amount of DMB according to the wall trends. Polarplots are sized based on DBC_{norm}.

Located along the Inca trail, Wiñaywayna is a 7 km walk from Machu Picchu. The site is nestled halfway up a steep hillside overlooking the Urubamba River. The site consists of two sectors – an upper and lower – of houses and terraces connected by a staircase. We focused our investigation on the upper sector (*hanan*), which has the finest and most preserved architecture. Unfortunately, due to time constraints, we surveyed only a small part of this sector and examined very shorts segments of E-W and NW-SE walls (table 4.3). Regarding these two classes of orientation, the three indicators suffer from a significant statistical bias (table C.2 and fig. C.6) and cannot be compared to the values along the N-S orientation. Consequently, the archaeoseismological data collected in Wiñaywayna is still insufficient to bear a solid conclusion regarding a preferential pattern of deformation.

Tarawasi

Tarawasi is a small Inca site in the upper catchment of the Apurimac River, close to the town of Limatambo. The current Inca remains are composed of a succession of five preserved levels terraces (Heffernan, 1989), surmounted by a fine monumental platform called *ushnu*. In the framework of this study, we surveyed the last level of terrace wall and the *ushnu*. Both structures were built using the fine cellular masonry style.
On the one hand, the DBC_{norm}-value is similar in the NE-SW (n=63) and NW-SE (n=64) orientations. On the other hand, the DBC's dip directions are less scattered in the NW-SE walls and the normalized cumulated amount of DMB is significantly larger in those same walls (fig. C.7). The archaeoseismological results indicate thus an anisotropic deformation pattern with the NW-SE (N140/320) walls preferentially affected. This suggests a ground movement oriented $\sim$N050/230.

Raqchi

Located 100 km southeast of Cusco in the upper part of the Vilcanota Valley, Raqchi was an important ceremonial site for pre-Columbian populations. The site was occupied, at least, from the Middle Horizon (600-1000 CE) but acquired a regional dimension under Inca dominion. The site turned into an important centre of pilgrimage (Sillar et al., 2013) with the construction of the Viracocha Temple (mid-15th c.). Built in adobe with a $\sim$2m finely cut stone base, this huge two-story roofed structure is one of the most prominent Inca buildings preserved in the Cusco region. We focused our survey on the temple and the polygonal masonry that constitutes its base (fig. 4.16a). Unfortunately, only the N-S central wall is still standing and well preserved. Most of the work was, therefore, limited to this structure and the majority of EAEs was recorded on this unique orientation (table 4.3). However, we identified also strain structures on the column bases situated on both sides of the central wall. Due to their circular shape, these structures are supposed to be a good indicator in case of a ground motion. Not constrained by the structure's orientation, the distribution of the DBC's dip directions enables to infer the ground movement.

The statistical analysis performed on the DBC affecting the N-S (N025/205) and E-W (N115/295) walls of the temple does not produce satisfactory results (fig. 4.16b). The normalized number of DBC in the two orientations is similar and, above all, the σ_{50}-value is particularly low in both classes of walls ($\sigma_{50} \leq 0.45$). Furthermore, we did not identified robust evidence of DMB. In contrast, the outputs of the DBC collected on the column bases are consistent and show a clear NW-SE orientation (N130/310 – fig. 4.16c). Based on this assumption, we may question the great dispersion of the DBC's dip direction in the E-W walls, which have a similar orientation as the deformation inferred from the columns. We may tentatively explain it by a statistical bias due to the reduced length of E-W walls surveyed and the limited number of DBC collected on these structures (table 4.3). We support that the Raqchi remains were affected by an impulse oriented approximately N040-220.

Discussion

Outside the core of the Cusco region, the limited number of archaeological sites surveyed and the great distance between them makes any regional discussion difficult. This is all the more true since only small areas were investigated in four out of the five sites, i.e. apart from Ollantaytambo. Is the earthquake-induced damage affecting those sites the result of one or multiple strong seismic events? At this stage, it is impossible to give a definitive answer. However, besides Wiñaywayna for which the dataset was insufficient, the semi-quantitative approach enables us to address several items related to the seismic impact in these peripheral regions.

First, our work shows robust evidence of earthquake-induced damage in the site of Machu Picchu and confirms thus the observation of EAEs made by Rodríguez-Pascua et al. (2020). Although the largest part of the cumulated amount of DMB in E-W walls is recorded along the same orientation as the slope direction (in-plane gap openings >90%), we consider that the displacement cannot be fully explained by creep phenomena. Regarding the DBC, generated only by cyclic-shear stresses, their largest number and the smallest dispersion of the dip directions also occurs in the E-W walls. This preferential deformation of the E-W walls demonstrates, therefore, the responsibility of a seismic impulse oriented ∼N150/330. The presented data contradicts previous statements on the

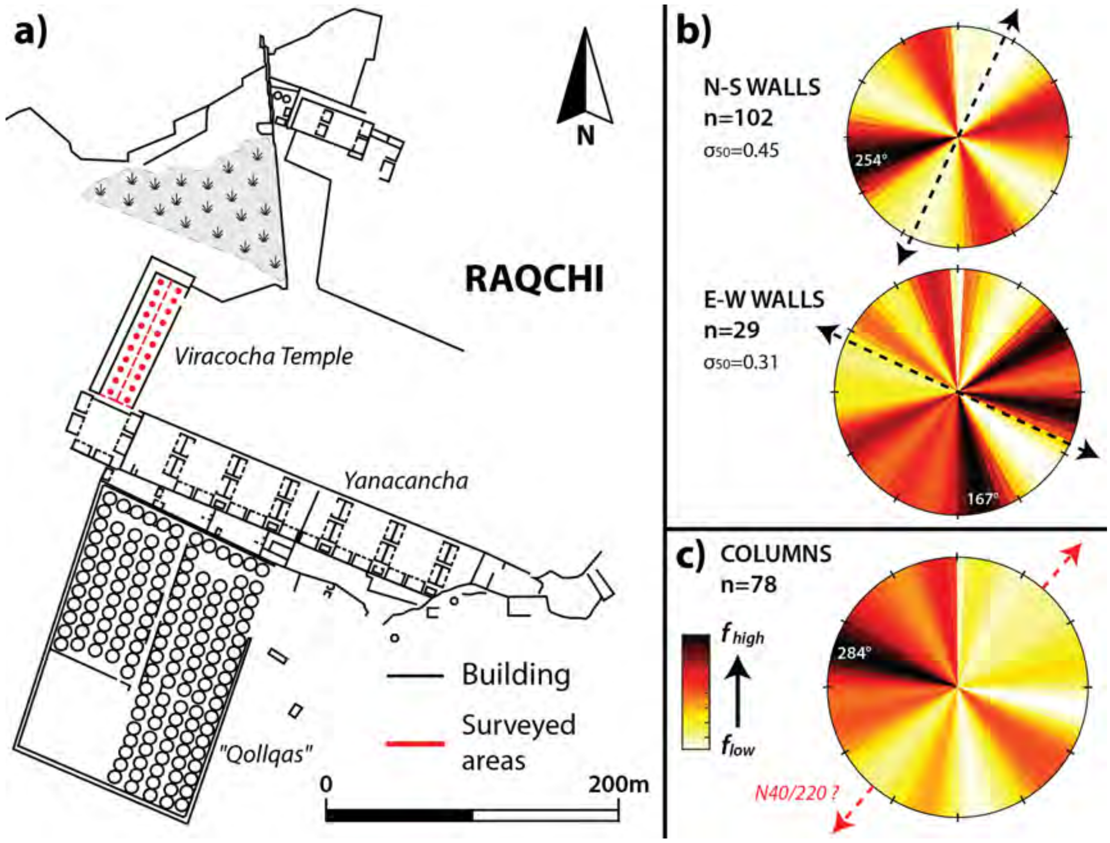

Figure 4.16: a) Map of the Raqchi site (according to Sillar et al., 2013) indicating the surveyed remains (in red); b) Frequency of the DBC's dip directions in both wall's orientations. Polarplots are sized based on the DBC$_{norm}$-values; c) Frequency of the DBC's dip directions computed for the column bases. The red dotted arrow indicates the inferred ground movement.

level of the seismic risk affecting the site (Carlotto et al., 2007) and stresses the need to reconsider the seismic hazard in this region (Cuadra et al., 2008; Fujisawa & Sudo, 2001), where no significant earthquake was recorded during the instrumental period. The consistent pattern of deformation inferred from our survey challenges, though, the hypothesis of two seismic episodes defended by Rodríguez-Pascua et al. (2020). We claim that the orientations mentioned by the previous study are biased by the wall's length and wall's trend, and do not, therefore, provide sufficient information to support the existence of two seismic events. Although a comprehensive survey of the fine stone masonry of Machu Picchu is required to confirm those results, our analysis demonstrates the need to consider further parameters than just the EAEs' orientation to assess the anisotropy of the earthquake damage.

Regarding Ollantaytambo, the isotropic deformation reported within the residential sector appears to be inconsistent with the N-S ground movement inferred from the data of the ceremonial sector. However, both sectors differs greatly in terms of lithology. Unlike the "Temple Hill", which is built on a rocky outcrop, the eastern part of the site lies on a large alluvial fan of the Patakancha River. The presence of unconsolidated and water-saturated sediments, as well as the specific geometry of the soft deposits below the residential sector (the sector is located at the basin edge may lead to complex amplification and reverberation phenomena of the surface waves (e.g., Galetzka et al., 2015). In such context, site effects can be regarded as a plausible cause of the isotropic nature of the seismic deformation.

At the regional scale, we may notice that the Inca remains from Machu Picchu and from the ceremonial sector of Ollantaytambo exhibit a consistent ground movement oriented N-S (fig. 4.17). Considering the geographical proximity (located only 30 km apart), we might suspect the responsibility of a single strong earthquake. Built both on a narrow crest oriented ∼N-S, we cannot rule out, however, that the preferential pattern of deformation in both sites result from a topographic effect, the crests acting as a waveguide.

As the unique archaeological site investigated in the southeastern part of the Cusco region, 100 km away from the Cusco Basin, Raqchi was probably not affected by the same events that damaged the other investigated sites. Despite the inconclusive dataset coming from the E-W and N-S walls, we demonstrate an anisotropic seismic deformation thanks to the analysis of circular column bases. Interestingly, the N040/220 impulse inferred from the DBC's dip direction in these architectural features turns out to be orthogonal to the strike of the main local active faults (fig. 4.17).

In short, based on the present analysis we formulate the two following assumptions:

– Due to the great distance between Raqchi and the four other sites (∼150 km), the earthquake(s) that caused the EAEs in Raqchi had most likely distinct sources;

– Considering the relatively low-to-moderate and infrequent seismicity recorded during the instrumental period in the lower part of the Urubamba Valley and the low sensitivity of this region to the seismic activity of the Cusco Basin (Carlotto et al., 2007), it is unlikely that numerous damaging earthquakes had occurred in this region since the 14^{th} century. Based on the consistency of the results in Machu Picchu and the ceremonial sector of Ollantaytambo, we may tentatively assume that no more than two earthquakes were responsible for the damage recorded in the four sites west of Cusco (fig. 4.17).

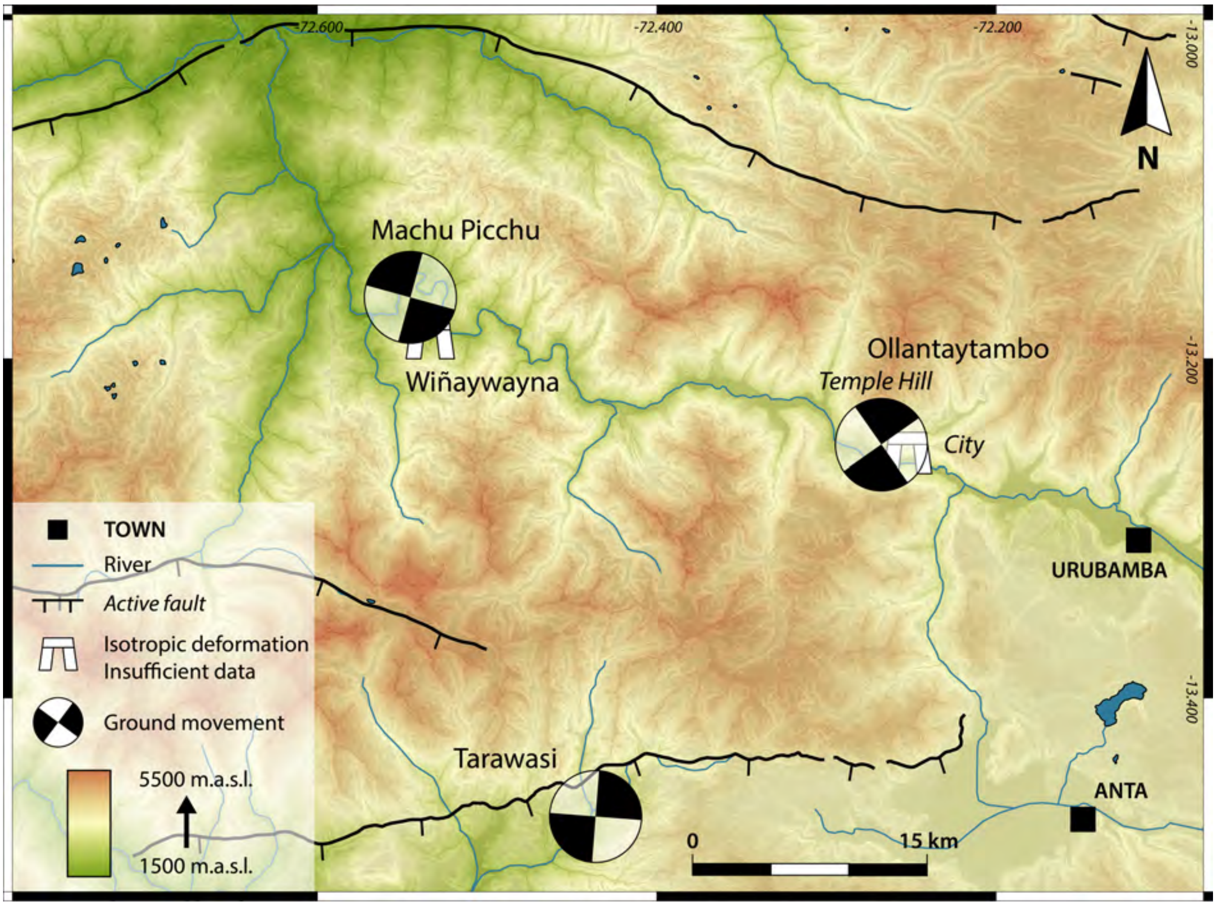

Figure 4.17: Map of the western part of the investigated area showing the ground movements (in black) inferred from the archaeoseismological data.

4.8 Overall summary

Through this first large archaeoseismological survey carried out in the Cusco region, we identified and registered more than 3,400 seismic deformation features in 14 Inca monumental sites located in four distinct areas: the Cusco Basin and its surroundings, the upper part of the Apurimac catchment, the upper Vilcanota Valley and the lower part of the Urubamba Valley (fig. 4.18).

First, the semi-quantitative approach we implemented in the core of the study region highlights a consistent E-W ground movement in several Inca sites and suggests the regional impact of one strong seismic event in the western part of the Cusco Basin between the 14^{th} century and 1950. Locally, the results on the Inca and colonial architecture of Cusco show two distinct orientations of deformation, indicating thus the occurrence of, at least, two damaging earthquakes in the city. Thanks to the analysis of historical photographs, we were able to highlight the marginal impact of the 1950 earthquake on the fine dry-stone masonry styles of Cusco and support a major role of two previous ground-shaking episodes: the 1650 earthquake and an unreported pre-1650 event. The earthquake evidence recorded seem to have been generated by ground motions exceeding the local seismic intensity of VII (M.M. scale).

Second, the detailed statistical analysis of the EAEs in the periphery of the study region shows preferential patterns of deformation in four sites and confirms, thus, the occurrence of damaging earthquakes in regions with a supposedly low seismicity. That is the case, notably, of the lower part of the Sacred Valley of the Incas (Machu Picchu and Ollantaytambo), where no noticeable seismic event is reported in earthquake catalogues. The great distance between the investigated sites and the lack of historical information constitutes, nonetheless, major challenges to the interpretation of the results at a regional scale.

Considering the whole archaeoseismological dataset, one main conclusion can be drawn. Besides the great distance between the sites of the peripheral zones and those of the core of the study region, the orientations of the ground movement in the former seem to be inconsistent with those of the Cusco Basin. Based on this observation, three clusters, at least, can be distinguished (fig. 4.18). These clusters might sketch the seismic sensitivity of the Inca fine architecture, i.e. the geographical area in which a strong earthquake is likely to be recorded. Our data argues for a limited area of sensitivity. The Inca stone masonry was probably affected by strong ground shaking with nearby sources ($\sim$50 km). This observation turns out to be crucial for future archaeoseismological studies in the area and for targeting further fault trenches.

In other words, the seismic deformation recorded in the five sites far from the Cusco Basin is most probably the result of earthquakes triggered by very close crustal faults (fig. 4.18), poorly mapped and barely studied. The results of this archaeoseismological survey urge, therefore, to conduct new palaeoseismological investigations on the Cusco fault complex in order to detect ancient earthquakes.

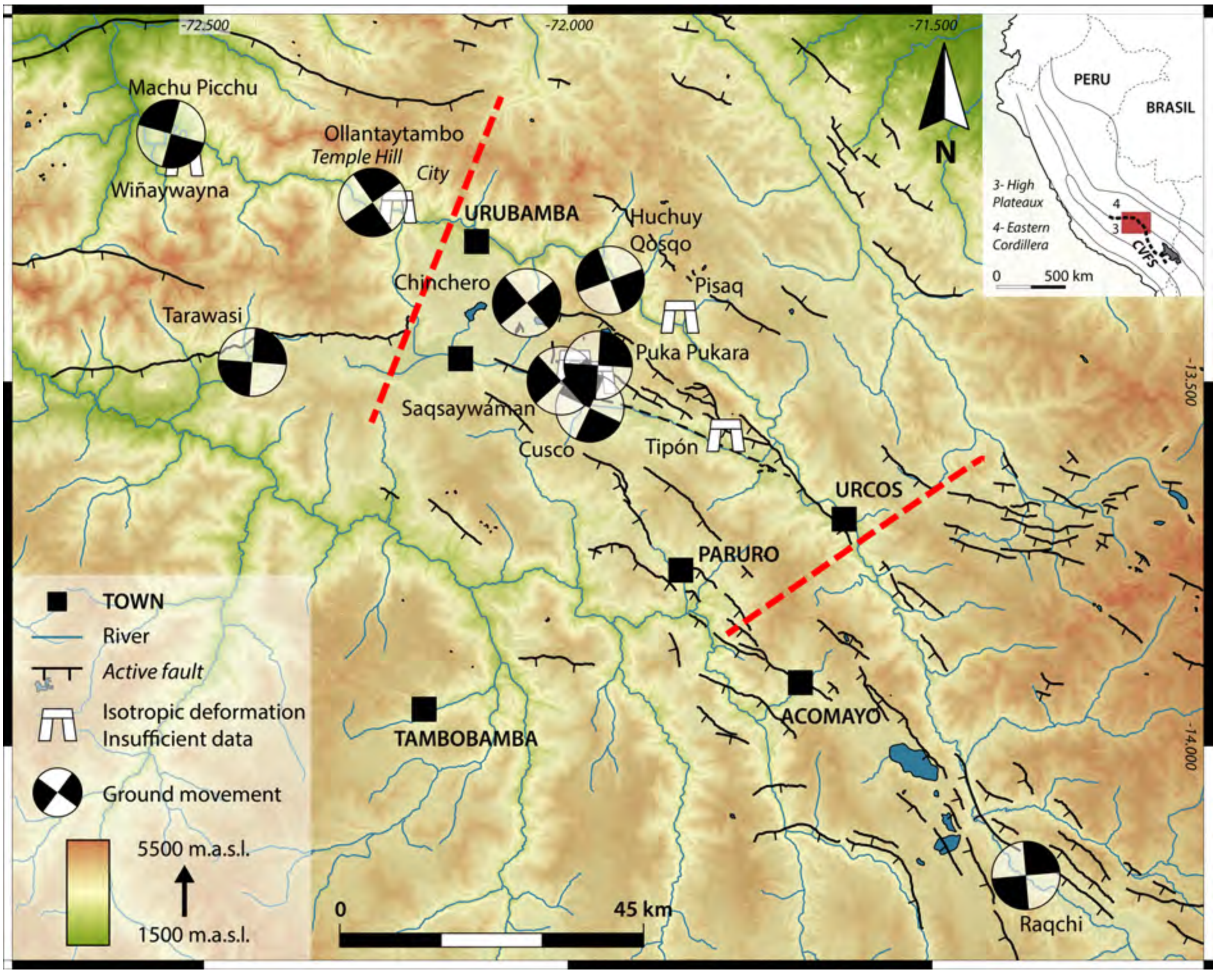

Figure 4.18: Map of the Cusco region indicating the 14 archaeological sites with attested seismic evidence. We displayed the orientation of the ground movement (in black) inferred from the nine archaeological sites presenting anisotropic deformation. Regarding the consistency of the orientations, three clusters might be hypothesized (red dotted lines).

Part III

The Incas and the earthquakes: between myths and reality

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Chapter 5

Evidence of a large "prehistorical" earthquake during Inca times? New insights from an indigenous chronicle (Cusco, Peru)

"The residents of the Sacred Valley believe that the Urubamba River (also called the Sacred River) absorbs the force of the earthquakes and so protects the valley from harm."

Howell and Lott (1980, p.337)

Introductory words

In the region of Cusco, the tectonic processes have contributed as much to provide favourable conditions for the human settlement (G. King & Bailey, 2006) as they have affected and disrupted the societies during ground shaking. The populations have, thus, always interacted with the seismic landscape (Michetti, Audemard M., & Marco, 2005), elaborating myths, stories and also constructive practices/strategies in relation with this potential threat. In a nutshell, they have taken possession of their environment and attempted both to make sense and cope with its natural phenomena.

Modern archaeoseismology (see Chapter 1) has long been the prerogative of the Earth scientists, and more particularly the seismologists (Helly, 2000). The social and archaeological dimension of this discipline have been neglected in favour of a quantitative vision focused on the assessment and prediction of the seismic hazard (Forlin & Gerrard, 2017). However, understanding the perception and, ultimately, the strategies of ancient societies regarding the earthquake threat might be critical to increase our current preparedness (e.g., Chester et al., 2008; De Pascale et al., 2015; Oven & Bankoff, 2020; Parsizadeh et al., 2015; Wachinger, Renn, Begg, & Kuhlicke, 2013) and enhance the protection of our architectural heritage. In Peru, and more broadly in the whole Andean region, where the pre-Columbian societies were preliterate, the historical approach turns out to be insufficient to address the interaction between indigenous populations and the tectonic processes. In this chapter, we present an example of cross-disciplinary research in the Cusco Basin, which allows tackling this issue. The case study consists in the reinterpretation of a mythological tale of pre-Columbian origin and transcribed by a local indigenous chronicler in the seventeenth century. Through a joint analysis of geomorphological, seismotectonic, ethnohistorical and archaeological data, we suggest that the emergence of a snake-like creature above Cusco during Inca times reported by the oral folklore alludes to a surface rupture associated with the activation of the fault system located north of Cusco. Beyond the potential identification of a major earthquake close to Cusco before the Spanish Conquest, this work investigates the meaningfulness of the noticeable fault scarps in the area for the Incas and their link with the sacred places north of Cusco. This analysis stresses the importance of a broader and unifying archaeoseismological approach, involving the human sciences.

Evidence of a large "prehistorical" earthquake during Inca times? New insights from an indigenous chronicle (Cusco, Peru)

Andy Combey[a], Laurence Audin[a], Carlos Benavente[b], Thérèse Bouysse-Cassagne[c], Léo Marconato[d] and Lorena Rosell[b]

a Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IGE, ISTerre, 38610 Gières, France.
b Geología Ambiental, Instituto Geológico Minero y Metalúrgico (INGEMMET), Av. Canadá 1470, San Borja 15034, Lima, Peru.
c CNRS UMR 7227, IHEAL CREDA, Campus Condorcet, 93322 Aubervilliers, France.
d Master Student, Ecole Normale Supérieure de Lyon, Department of Earth Sciences, 69342 Lyon, France.

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Abstract A colonial chronicle written by the indigenous Peruvian author Pachacuti Yamqui Salcamaygua ([1613?]) relates a legend of the sudden appearance of a huge animal – kilometres in length and approximately 4 m in width – and described as the Andean snake-like deity *amaru*. Pachacuti Yamqui alleged that this fantastic event occurred on the day that the sovereign Pachacuti Inca Yupanqui's eldest son was born around 1440 CE, and was named "Amaru". We suggest that the underlying event was an earthquake, and that the propagation of the surface rupture across the landscape resembled a sudden appearance of a snake-like being wriggling over the mountains and leaving an undulating surface trace. The concordance between the snake's route and the layout of a major fault complex above Cusco, as well as several ethnographic testimonies, support this hypothesis. Although little is known about pre-1532 CE seismicity, the current tectonic settings of the Cusco area point to seismic awareness of the Incas (ca. 1300–1533 CE). Independent results from architectural and palaeoseismological fields in the Cusco area corroborate a significant impact of large earthquakes on local societies. In Peru, without pre-Hispanic written sources, the oral folklore and traditions preserved in Spanish chronicles offer a relevant, but still underexploited resource for identifying palaeo-extreme events. Combining multidisciplinary geomorphic observations, archaeological evidence and historical sources, we revisit this legendary episode and its possible implications.

5.1 Introduction

What could be the nature and degree of influence of thousands of years "long-term" geological dynamics on decade-scale, "short-term", human expansion and evolution? Without considering and adopting a deterministic perspective, this question remains nevertheless worthy of debate (Force & McFadgen, 2010; G. King & Bailey, 2006; Nomade et al., 2016). Severely affected by floods, climate variations, volcanic eruptions, and earthquakes, the Andes appear to be suited well for assessing the influence of natural phenomena on past human societies. In Peru, particularly, numerous studies have demonstrated correlations between climatic events and the emergence or demise of archaeological settlements (Binford et al., 1997; Chepstow-Lusty, Frogley, Bauer, Bush, & Herrera, 2003; Chepstow-Lusty et al., 2009; Christol et al., 2017; Sandweiss, 2003; Sandweiss, Richardson III, Reitz, Rollins, & Maasch, 1996; Sandweiss et al., 2009). Volcanoes and sudden eruptions have also had a great impact on the worldview and organization of the pre-Columbian cultures (Bouysse-Cassagne, 2006; Bouysse-Cassagne & Bouysse, 1984; Chávez Chávez, 2001; Reinhard, 1983). Few academic investigations, however, seem to have focused on the impact of earthquake activity, and almost exclusively in the Mesoamerican world (Garduño-Monroy, 2016; Garduño Monroy et al., 2020). Although valuable work has been carried out in the aftermath of devastating earthquakes that struck the Peruvian coast during colonial and modern times (D'Ercole et al., 2007; Seiner Lizárraga, 2013; Walker, 1999, 2018), little has yet been done regarding pre-Hispanic seismic risk management and perception. Beyond megathrust earthquakes that affect mainly coastal areas, crustal faults within the Andes present a major threat for local populations as demonstrated by the 1946 Ancash (Silgado Ferro, 1951) and 1950 Cusco (Kubler, 1952) earthquakes. It therefore seems unlikely that earthquakes large enough to rupture the earth's surface did not affect local inhabitants before the Spanish Conquest (1532 CE).

In the absence of an intelligible pre-Columbian writing system, indigenous oral tradition and folk tales preserved in colonial chronicles represent a particularly relevant source of information for the identification and perception of past disastrous events. Often disregarded for their lack of scientific rigor and chronological context, transgenerational oral memories originate, however, from empirical environmental knowledge that may describe true natural events in an alternative narrative system (Cohen, Mark, Fallon, & Stephenson, 2017; D. King, Goff, & Skipper, 2007; Masse & Masse, 2007; McMillan & Hutchinson, 2002; Nunn, 2014; Troll et al., 2015). Through a geological, archaeological and ethno-historical reading, we argue in this paper for a reinterpretation of an extract from Pachacuti Yamqui Salcamaygua's chronicle (1993). Recounting seemingly a mythological event, a passage from the *Relación de antiguedades deste reyno del Piru*, written in the mid-seventeenth century, alludes to the activation of the major fault system crossing the Cusco Basin. Dated around 1440, it might be the oldest seismic event reported by written sources in South America.

5.2 Background

5.2.1 Incas and ground motions

While earthquakes have frequently shaken the Cusco region (Peru) in the last 500 years, Spanish chronicles are surprisingly quiet about the occurrence of any seismic event during Inca times (ca.1300–1532 CE). The only references to earthquakes before the Spaniards arrived are imprecise and come from secondary sources (Garcilaso de la Vega, 1609, p.477-Lib IX, CAP XIV; Silgado Ferro, 1978). This situation is all the more striking because Bernabé Cobo mentioned in his *Relación de las guacas del Cuzco* (1979, p.16 – Ch-2:1) the existence of a powerful Inca shrine, Guaracince, whose location was considered as the focal point of ground shakings. Convinced of the occurrence of destructive “prehistorical earthquakes” in the Cusco area, Bandelier (1906) was the first to address the issue of the perception of natural hazards by pre-Columbian societies. He demonstrated the relevance of examining and interpreting pre-Columbian legends and myths to assess the volcanic risk at this period, for the Quinsachata and Misti eruptions.

In spite of abundant evidence of destruction (burnt daub, collapsed walls, smashed vessels) registered in archaeological sites from the Late Intermediate Period (LIP: 1000–1400 CE) and Late Horizon (LH: 1400–1532 CE) around Cusco (Covey, 2006; Kendall et al., 1992; McEwan et al., 2005; Quave et al., 2018; Vargas P., 2007), very few were interpreted as consequences of earthquakes[1] (fig. 5.1). The extended layer showing collapsed structures within the site of Warq’ana, near Huchuy Qosqo, constitutes unique evidence of a hypothesized seismic event in the Cusco area (Kendall et al., 1992, p.224). Even recognizing that earthquakes do not provide the sole explanation of such types of evidence (instead, for example, of war, raiding, or ritual behaviour), the small number of inferences of earthquakes as the potential cause of destruction is particularly striking.

Recent palaeoseismological and archaeoseismological research carried out within the Cusco region may shed new light on this topic. The palaeoseismological trenches excavated in only two segments of the Cusco Fault System (Palomino Tacuri et al. 2021; Rosell Guevara 2018 – fig. 5.1) indicate at least four large and crustal seismic events (M_w>6) during the last three millennia, and argue for a reappraisal of the seismic impact on Cusquenan populations. Although in its infancy, the results of an archaeoseismological survey in Machu Picchu attest to the occurrence of at least one major and regional earthquake during the occupation phase (Rodríguez-Pascua et al., 2020). Sudden and violent, this type of natural hazard may have generated stress and panic in the population, leaving its imprint in the pre-Hispanic worldview.

5.2.2 The amaru entity in the Andean worldview

In contrast to common snakes called *mach’aqway* in Quechua (Santo Tomás, 2003, p.285), *amaru* describes a mythological and chthonian serpent-like monster (likened to the European dragon in the first Spanish description). Based on colonial definitions, the *amaru* was associated with snakes of great dimension (Gonçález Holguín, 2007, p.408) and coming from the hot and humid Amazonian lowlands (Garcilaso de la Vega, 1609, p.196, 221; Huaman Poma de Ayala, 1979, p.190). This deity, particularly important in the Andean pantheon, and having inspired names of Inca and indigenous leaders, as well as the appel-

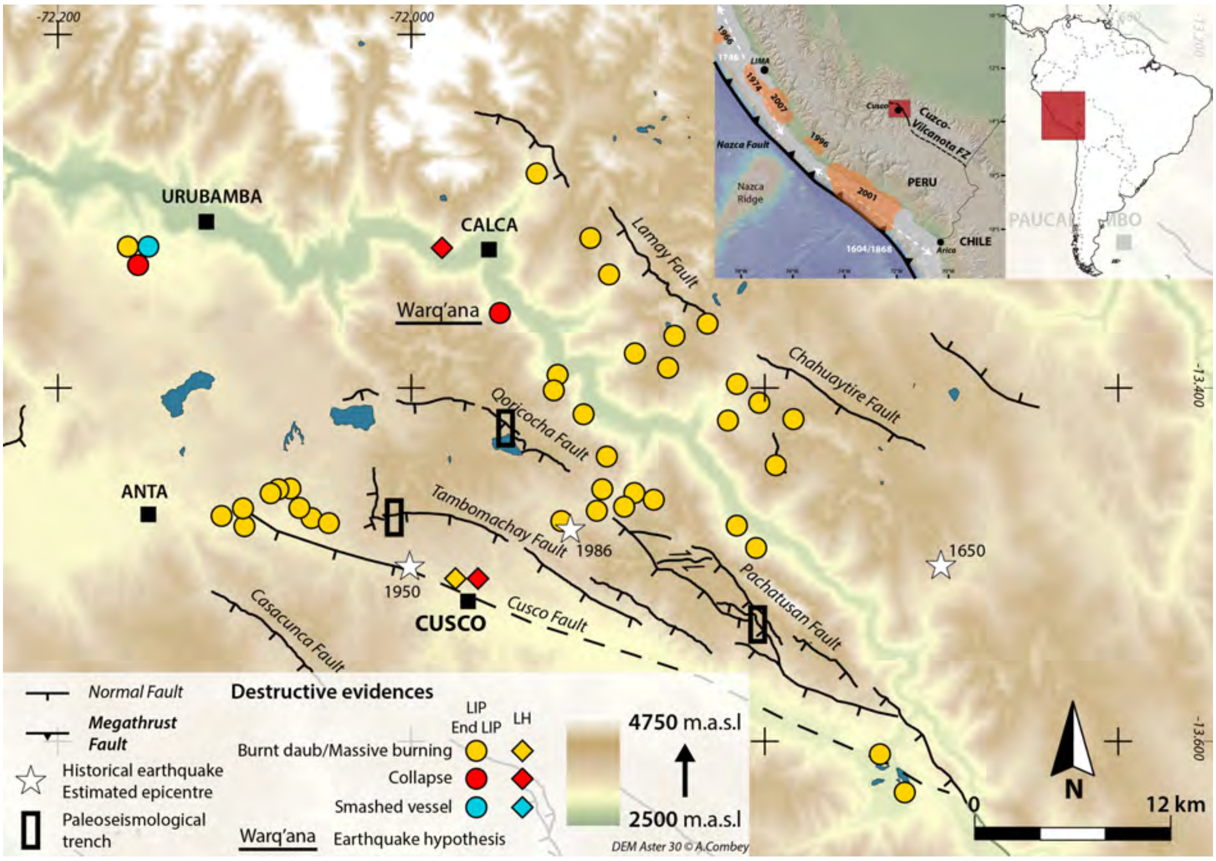

Figure 5.1: Map listing the archaeological evidence of destructive events (without a determined origin) dated from the Late Intermediate Period and the Late Horizon in the Cusco area (Covey, 2006; Kendall et al., 1992; McEwan et al., 2005; Quave et al., 2018; Vargas P., 2007). The earthquake hypothesis was only alleged in one case.

lation of the large Inca compound of Cusco, the Amarukancha, seems to have covered a wide spectrum of meanings and cosmologic notions. Urton (1981) described it as a double-headed and rainbow serpent whose extremities are anchored in water sources. Its relation with meteorological processes may have been much broader, such as associations of the *amaru* with the wet season, with water streaming or lightning (Boelens, 2014). Finally, as Hocquenghem (1989, p.212-213) explained, the rupture of equilibrium in the Andean conception of the world, called a *pachacuti*, is often synonymous with the liberation of an *amaru* and its subsequent petrification. Several phenomena could have triggered this disequilibrium: war, epidemics, floods, and earthquakes.

Snakes and earthquakes are commonly linked in human folklore, all around the world. The animal is often described as a reptile, a serpent, or even a dragon of great dimensions living underground (Ludwin et al., 2007, p.88). Ground shaking, as occurs during earthquakes, is hence explained as the direct consequence of the movement of the serpent-like animal (Kirikov, 1992 – fig. 5.2). The Chumash Indians that inhabited the south coast of California believed in the existence of two underground snakes that were responsible of the frequent ground shaking produced by earthquakes on the San Andreas Fault (Fradkin, 1999, p.70). Although less common in Mediterranean legends, the snake or the dragon appears, nonetheless, as a secondary character (Piccardi, 2005, p.98,103; Piccardi, 2007)[2]. If this quick overview does not demonstrate a widespread representation of earthquakes by serpent-like entities in past human societies, it reveals at least a common association between this animal and the seismic phenomenon, based probably on environmental and ecological observations. Several references to the snake in the Andean mythology seem to endorse this assumption.

According to Martín de Murúa, a snake called *chipiroque* or *pichiniqui* appeared to the Indians some time before the Huaynaputina eruption (1600 CE) to warn them about this subterranean punishment (Bouysse-Cassagne & Bouysse, 1984, p.58). In the Huarochirí manuscript (Ávila, 1980), the appearance of an *amaru*, created by the pre-Hispanic deity Huallalu Carhuinchu during his legendary struggle with Pariacaca, is also accompanied by intense ground shaking. Similarly, a Jesuit text of 1624 (Polia Meconi, 1999, sec.37) describes how the arrest of a sorceress that was breeding snakes in her house triggered lightning strikes and tremors. As a chthonian creature, related to the underground world, the serpent seems to be frequently related to earth motions in the Andean worldview (M. Gentile, 2017; Hocquenghem, 1989).

5.3 The study area: the Cusco Valley and its seismic setting

At an elevation of 3,400 m.a.s.l., Cusco lies in the south-eastern part of Peru, in the Eastern Cordillera. The region displays a long human occupation that dates back to, at least, 10,000 BP. Characterized, until the end of the Middle Horizon (MH: 600-1000 CE) by small-clustered polities, the Cusco Valley experienced then a gradual state formation process throughout the LIP (Bauer, 2018; Covey, 2006) that turned it into the geographical centre and political core of the Inca empire during the fifteenth century. Densely inhabited since the Formative Period (∼2000 BCE-400 CE), the Cusco Basin has resulted from the continuous action of active tectonic processes, which probably foster human settlement.

The Cusco Basin is an intra-montane valley bounded along its northern margin by a complex of active crustal faults. Trending mainly NW-SE, the Qoricocha, Tambomachay,

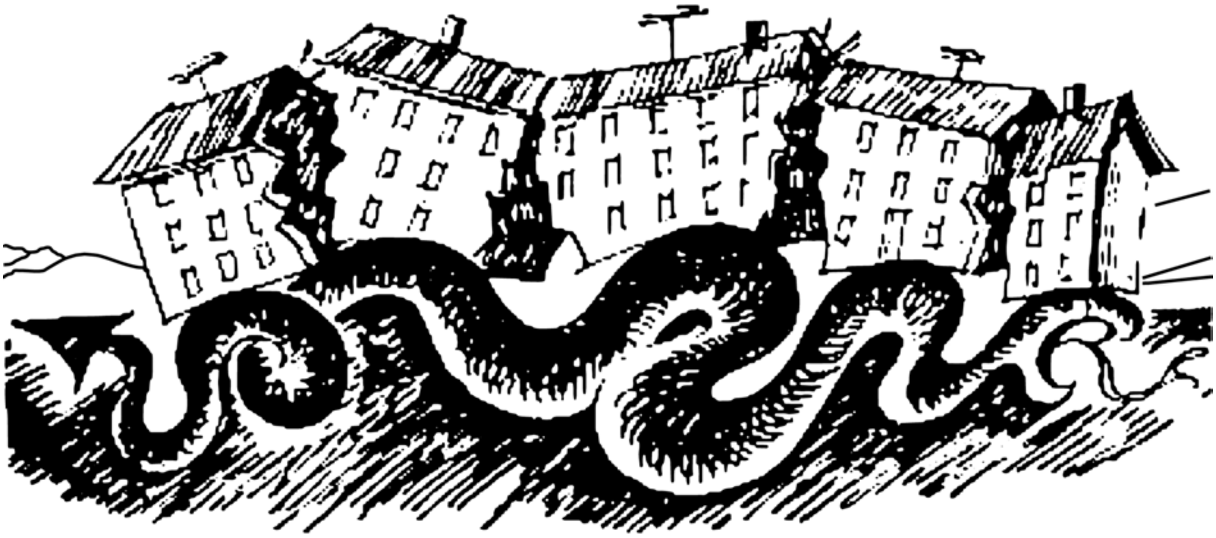

Figure 5.2: Wiggling of a Dragon-like creature as a metaphor of the ground motion during an earthquake: "let us resort to some imagination to fancy the picture of ground motion under a structure during an earthquake. In my opinion, it can be best illustrated by an image of a gigantic snake-like dragon moving under the building by throwing its body into vertical loops" (see Kirikov, 1992, p.11).

Pachatusan and Cusco normal faults control the subsidence and the filling of the basin (Benavente Escobar et al., 2013; Cabrera, 1988; Cabrera & Sébrier, 1998 – fig. 5.1). Overlying the Cenozoic and Mesozoic basement is a thick, extensive layer of unconsolidated lacustrine and fluvial sediment of Quaternary age (Gregory, 1916; Marocco, 1978). Suitable for water retention and farming activity that unconsolidated sandy sediment also amplifies seismic waves, producing major site effects and making the area more sensitive to ground motions than where rock is solid. Indeed, the lake deposits are $\sim$300 m thick and show deformed sedimentary structures (seismites), which are secondary effects of earthquakes (Benavente Escobar et al., 2013, p.27-44).
The active tectonic structures crossing the Heartland of the Incas are part of the Cusco Vilcanota fault system (CVFS) that generates frequent seismic activity (fig. 5.1). Historical documents refer regularly to *temblores* (slight shakings) that cause stress and panic (Esquivel y Navia, 1980; Gade, 1970; Palma & Nacional, 1901). Two violent *terremotos* (devastating earthquakes) in 1650 (Julien, 1995; Villanueva Urteaga, 1970) and 1950 (Ericksen et al., 1954; Kubler, 1952) led to these acute reactions. In terms of structural impacts, and despite their limited scope, both earthquakes destroyed buildings in the city

of Cusco, and the main colonial structures in particular. The high level of amplification of the soft sediment lying in the Cusco valley-bottom explains a large part of the severity of the damage.
In terms of cultural impact, the high frequency of ground shaking (Silgado Ferro, 1978) has caused a persistent trauma in inhabitants' minds since the Spanish Conquest, while both maintaining and fostering a collective seismic concern. The Lord of the Earthquakes (*Señor de los Temblores*) cult, still celebrated each Holy Monday in Cusco, is one of the most salient examples. The intense devotion attached to the patron saint originated in the 1650 earthquake, but may have taken root in a pre-Columbian belief (Calvo, 1994; Gade, 1970; Hajovsky, 2018).

5.4 Methods

5.4.1 Historical material

Juan de Santa Cruz Pachacuti Yamqui Salcamaygua was an indigenous chronicler living during the seventeenth century. We know little about him, for his own writings constitute the only source of information. Native of the Canas-Canchis region, approximately 130 km southeast of Cusco, he claims a direct familial ascendency in the local *curacas* of Guaygua Canchi, which soon converted to Catholicism. Through his *Relación de antiguedades deste reyno del Piru*, Pachacuti Yamqui (1993) claims to have written about the main events that shaped the history of Peru. Imbued with catholic references (Duviols, 2017), his text is, arguably too often, regarded exclusively as an early indigenous Christian worldview. Because of the direct influence and contribution of the oral tradition in his work, we consider this source particularly valuable for studying mythological stories coming from the local collective memory. In his presentation of the Inca sovereign Pachacuti Inca Yupanqui, Pachacuti Yamqui wrote about a fantastic event that allegedly occurred the day of birth of the eldest son of the emperor.

> In that time, they say that news arrived of a miracle in Cuzco, consisting of something like a *yauirca* or *amaru* [snake in Aymara or Quechua, respectively[3]] that had emerged from the mountain of Pachatusan, a very fierce beast, half a league long and thick, of two and a half fathoms in width, and with ears and fangs and whiskers. And it came by Yuncay Pampa and Sinca, and from there it entered the lake of Quibipay, and so, two sacacas of fire came out of Aosancata, and [one] passed Pontina of Arequipa; and the other came down

> to and passed Guamanca, where there are three or four very high mountains covered with snow, those in which they say that there are animals with wings and ears, and tails and four feet, and on top of their backs many spines like a fish, and from afar they say that it appeared to them [to be] all fire. (f.21-21v / Translation modified from Bauer & Dearborn, 1995, p.148)[4]

The extract cited above reports the sudden appearance of a snake-like animal, commonly called *amaru* in the Andean mythology. Due to the importance of the event, the Inca Pachacuti decided to name his son Amaru Tupa Yupanqui. The supernatural entity had impressive dimensions: 2.75 km long and almost 4.2 m thick[5]. The quoted text describes the pathways of the snake to different key places along the traces of active faults that define the geologic landscape of Cusco. The snake appeared at Pachatusan (point 1 on fig. 5.3), the highest mountain in the Cusco valley and considered sacred by the Incas (Silva Gonzales & Loza García, 2007). The animal continued westward along the ridge crest that borders Cusco to the north. It crossed "Yuncay Pampa" known currently as Yuncaypata (point 2 on fig. 5.3), a small locality 4 km north of Cusco, and then passed through "Sinca" that corresponds to the Sinqa Mountain (point 3 on fig. 5.3). It finally vanished in the Quibipay lagoon (point 4 on fig. 5.3).

The exact location of the latter remains unknown, up to now. Mentioned a second time in the book by Pachacuti Yamqui, the place was defined as a flat area where Atahualpa gathered the main ethnic leaders of Cusco after the final battle against the Huascar's army (Pachacuti Yamqui Salcamaygua, 1993, p.178 f.42). Others placed it one league, i.e. approximately 5 km, from Cusco (Mendiburu, 1902, p.74), west of Cusco behind the Sinqa Mountain (Zuidema, 1974, p.215), or north-east of Cusco (M. Gentile, 2017, p.310).

5.4.2 Geomorphological analysis

We combined the analysis of the historical source with a geomorphological and neotectonic investigation. Topographical data from the Cusco Basin were processed using two Digital Elevation Models (DEM). The creation of a high-resolution DEM (1.5 m) based on Pleiades images and covering the western part of the Cusco Basin allows us to relate the location of the Quibipay lake with a classic feature of tectonic geomorphology. To this end, topographic features were studied thanks to basic GIS analysis including a slope map, hill shadings, and topographic profiles.

Based on a larger ASTER DEM (30 m) we executed a "visibility analysis" from the archaeological site of Amaru Marka Wasi, settled on a calcareous plateau above Cusco (AMW on

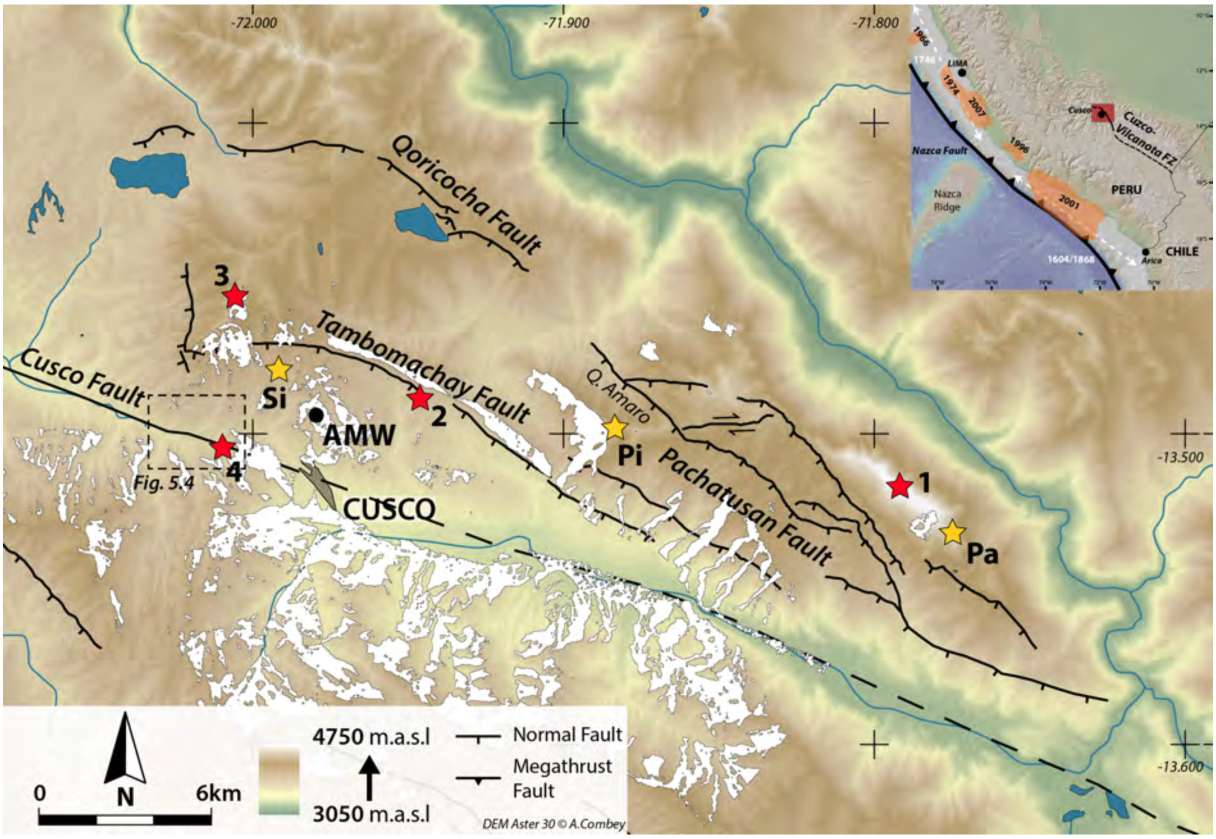

Figure 5.3: Map of the Cusco valley showing the layout of the Pachatusan-Tambomachay-Cusco Fault System as well as the geographical places (red stars) mentioned in the Pachacuti Yamqui's text. 1- Pachatusan; 2- Yuncaypata; 3- Sinqa summit 4- Cruz Verde de Quehuepay. "Pa" refers to the Paukarcancha site, "Pi" to the Picol summit and "Si" to the Sinqa waka. White areas show what can be seen from the Amaru Marca Wasi site (black point, AMW) and therefore highlight that large segments of the fault system are visible from that spot.

fig. 5.3). Composed mainly of rocky outcrops containing carvings this site was the seventh shrine of the first ceque of the Antisuyu (An 1:7 in Bauer, 1998, p.76). Considered to be the former residence of the eldest son of the sovereign Pachacuti Inca Yupanqui, the site most probably was dedicated to ceremonial activities. Due to its sacred character, its geographic proximity with the localities mentioned in the story, and its direct relation with Amaru Tupa Yupanqui, we considered it worth questioning the link that may have existed between the outcrop and the Amaru story. The "visibility analysis" realized thanks to Global Mapper software allows us to display the area visible from the summit of the outcrop. This particular GIS analysis highlights the main features of the environment visible from the site and provides some indications of its ceremonial purpose. We fixed as initial parameters an observer of 1.65 m tall and, a visibility radius from 20 km, and we kept the standard value of atmospheric correction (1.333 - Brunner, 1984). Field reconnaissance carried out around the archaeological site allowed to validate the region visible from the site. Finally, the GIS platform enabled us to cross check the results with places mentioned in the text and distribution of the main faults (Benavente Escobar et al., 2013).

5.5 Results and discussion

5.5.1 Archaeological places as "geolandmarks"?

The present analysis led us to identify a small community now belonging to the extended agglomeration of Cusco, Cruz Verde de Quehuepay (Point 4 on fig. 5.3), as the former Quibipay plain and lagoon mentioned in the text of Pachacuti Yamqui. As commented in 5.4.1, this place seems to have held a special significance for the inhabitants of the Cusco region, since it is the place chosen by the sovereign Atahualpa and his court to speak to the main kin groups and to request their obedience after he defeated his brother's army. The etymological similarity of Quehuepay and Quibipay as well as its distance from the Cusco historic centre (less than 4 km westward) strongly support the placement of the Quibipay lagoon in Cruz Verde de Quehuepay. In spite of the present dense urbanization, the new high-resolution DEM clearly highlights two important facts. First, Cruz Verde de Quehuepay occupies the flattest part of the area (∼2% of declivity) and lies against the Cusco fault scarp (CVQ on fig. 5.4). Second, the small lagoon seems to have formed as a sag pond, a classic feature of tectonic geomorphology (Burbank & Anderson, 2011) that develops where ruptures bend or where fault segments are offset from one another; in either case the floor of the pond drops with respect to surroundings during recurrent seismic rupturing (fig. 5.5).
Hence, the Quibipay plain, as well as the other toponyms mentioned in the legend, can be associated directly with active tectonic structures and supports a seismic interpretation of the Pachacuti Yamqui's extract. Three large fault segments run through the region where the legend takes place (the Cusco, Tambomachay and Pachatusan faults) and match with the Amaru's route (fig. 5.3).

The "visibility analysis" computed from the high-resolution DEM at Amaru Marka Wasi enhanced the observation that standing atop the rocky promontory it is possible to

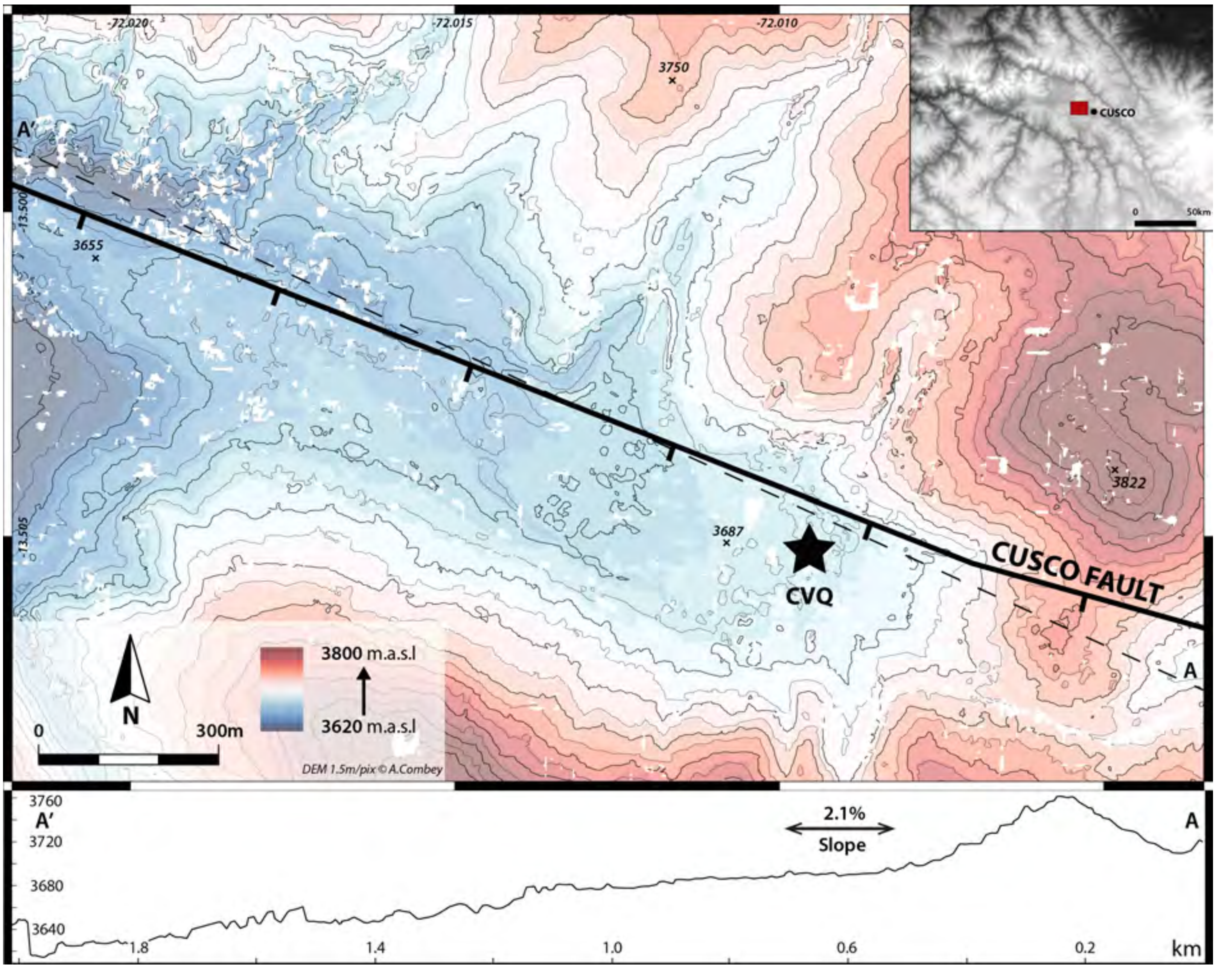

Figure 5.4: Topographic map of the Quehuepay area. The black star marks the location of Cruz Verde de Quehuepay (CVQ). The gentle slope illustrated in the topographic profile (AA') explains easily the former name Quibipay pampa and its ability to retain water.

see each of the places mentioned by Pachacuti Yamqui (fig. 5.3). Instead of providing an overview on the Cusco valley bottom and the Inca city, the archaeological site offers a wide panorama of the mountain ridges bordering the northern part of the Cusco Basin. The Tambomachay fault, which runs all along the mountainside, marks a clear topographic anomaly and forms the most salient element of the landscape (fig. 5.6).

It is even more striking that all the sites mentioned in the legend and settled along the fault segments contain important venerated places. Pachatusan, Picol and Sinqa were three of the six most important sacred mountains in the Cusco region and hosted places of worship. Not only was Paukarcancha (Pa in fig. 5.3), an important ceremonial and pilgrimage site displaying Inca material, built on the top of Pachatusan (Bauer, 1998,

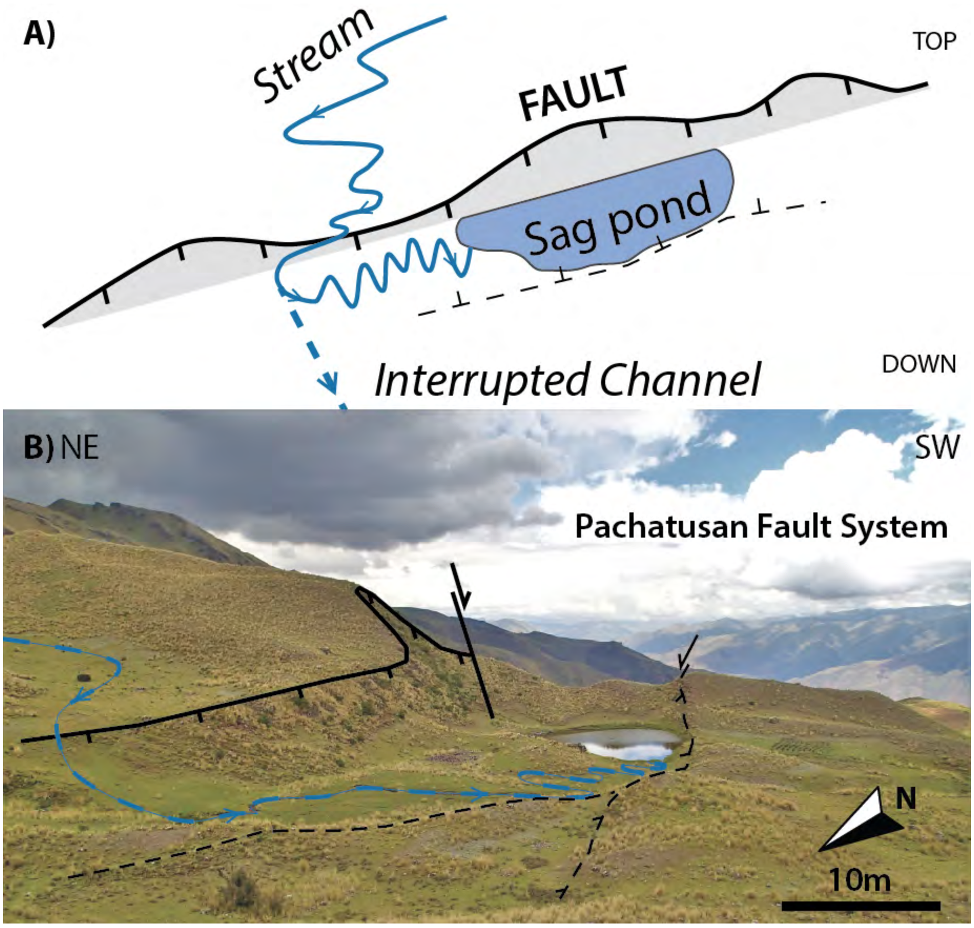

Figure 5.5: A) Sketch of a "sag pond". A depression develops in the shear zone of the fault and interrupts the drainage. The subsequent lakes accommodate along this tectonic landform and highlight the fault trace even in steep landscapes. B) Example of sag pond at the foot of a Pachatusan fault segment.

p.94; Silva Gonzales & Loza García, 2007), but the Picol summit (Pi in fig. 5.3) and the Sinqa waka located on the southern flank of the Sinqa Mountain (Si in fig. 5.3) were also significant places of offerings. We suggest that just as ceremonial sites in the southern part of the Inca Empire are associated with volcanoes (Chávez Chávez, 2001; Reinhard, 1983), the sacred dimension of some Inca shrines of the Cusco Basin are related to this tectonic landform resulting from active faults.

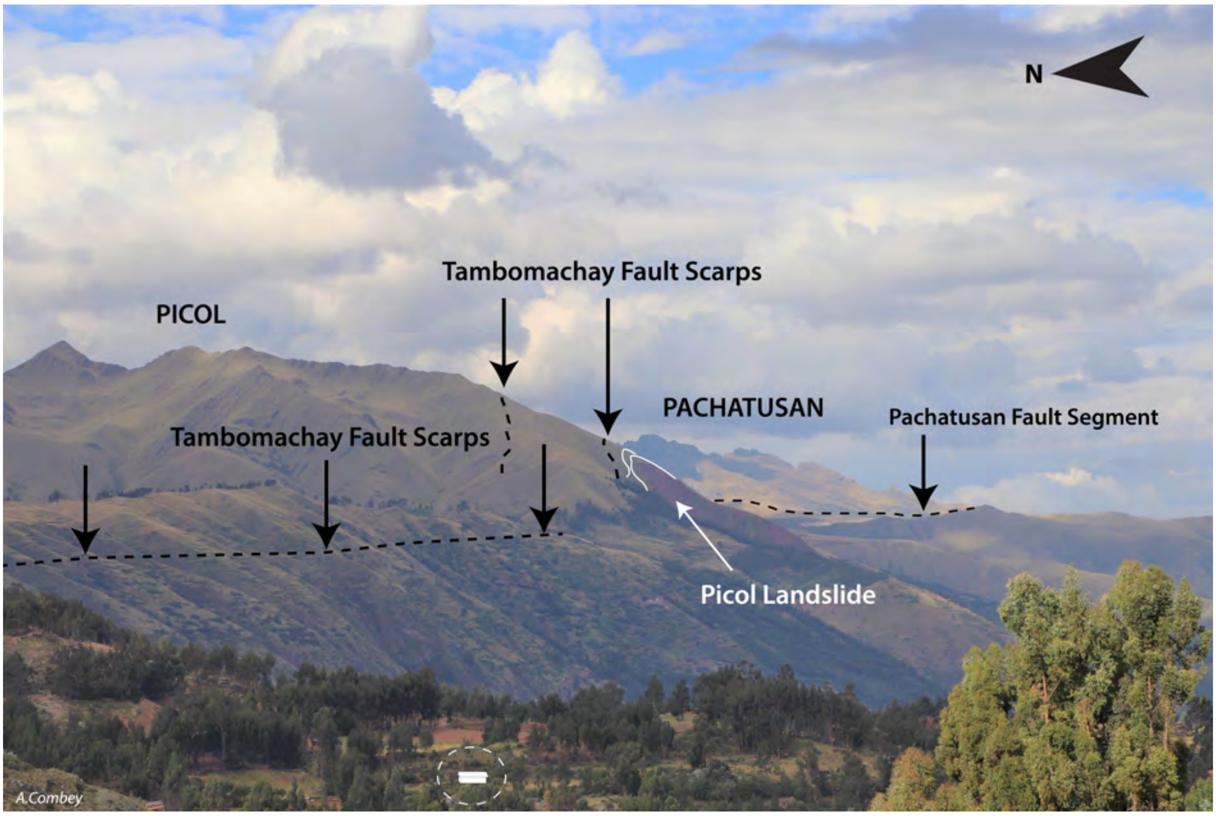

Figure 5.6: Panorama from the Amaru Marca Wasi archaeological site. The Tambomachay Fault Segment and the Picol landslide represent the most salient features in the landscape visible from that location. Note that the Pachatusan Fault segment is also visible in the background, forming a comprehensive panorama of the "snake-like" scarps.

5.5.2 A wavy fault scarp

Based on anthropological studies, Zuidema (1974, p.215) interpreted the snake described in the Pachacuti Yamqui story as a metaphor of a rainbow. Unable to verify the veracity of this association, however, he simply offered a conceptual discussion about Andean mythological representations. Nonetheless, Bandelier (1906) and Gentile (2017) have noticed the geological interest of the passage, and postulated yet, without providing convincing arguments, the hypothesis of a volcanic eruption or seismic event.

In the landscape above Cusco, anywhere fault scarps cut moraines as in Tambomachay, Pachatusan or many other localities, a peculiar feature stands out: a serpent-like form of the scarp (fig. 5.7). Moreover, in some interviews in the Huancavelica province (Zuidema, 1967, p.49) as well as in our conversations in the southern part of the Cusco region

(Sicuani), local people have described openings in the ground or cracks as “amaru”. Cristóbal de Albornoz (Duviols, 1967, p.23) corroborates the frequent association of snakes and geological features in the Andean mythology. The reader may notice that the little quebrada north of Picol summit and driven by one Pachatusan fault segment is currently called Amaro (fig. 5.3). We can easily suppose that pre-Hispanic populations observed the undulating form of the fault trace in the landscape and tried to relate it to something familiar. It is noteworthy that the size of the creature could be consistent with a segment of a surface rupture approximately 2.5 kilometres long and an opening of several meters in width. Relying on rupture of such dimension and considering the seismic disaster of 1950 only associated with small-scale surface rupturing (Cabrera, 1988; Ericksen et al., 1954), we postulate that this “prehistorical” earthquake generated its highest intensities within the Cusco Basin.

Normal faults, which mark the fronts of many of the ridges in the Cusco region (Benavente Escobar et al., 2013) differ from strike-slip faults, like the San Andreas Fault in California, whose traces at the earth’s surface are straight for tens of kilometres. Instead, normal faults, commonly consist of short segments – a few kilometres long – that, when linked together, form an escarpment that undulates across the landscape. Thus, whereas the trace of a strike-slip fault bears little resemblance to a snake, linked normal-fault segments can easily engender such an image, especially during trauma induced by severe ground shaking. Moreover, when an earthquake occurs, slip does not suddenly, and simultaneously, occur on all of the linked fault segments; rather, slip initiates at the epicentre, and the locus of slip propagates away from it at a speed of ∼1-3 km/s. Thus, for a fault that is, say, 30 km long and visible to a single observer, approximately 10 to 30 seconds will elapse as the locus of slip wriggles across the landscape from start to finish. As slip on faults during earthquakes commonly occurs at ∼1 m/s (Bizzarri, 2012; Brune, 1970), and total amounts of slip during earthquakes of the magnitude that have caused damage in the Cusco region are commonly 1-2 m, slip at any point on the fault will last ∼1-2 seconds. Thus, slip within a segment of the rupture will occur concurrently, but segments several kilometres apart will not slip simultaneously, enhancing the undulating and emerging serpent-like aspect of the landform (fig. 5.7).

As explained in 5.2.2, the emergence of a chthonian creature within the world of the living was understood in the Andean worldview as a *pachacuti*, a time and space upheaval, disturbing the entire course of action (Bouysse-Cassagne & Bouysse, 1984, p.57; Huaman Poma de Ayala, 1979, p.68). The *amaru* in Quechua and its rough translation *yauirca* in Aymara (Bertonio, 1879, p.396), correspond to one of these subterranean entities that may surge in the context of destructive events such as landslides and earthquakes. The monstrous creature remains then petrified and turns one landscape feature into the remnant of a geological phenomenon (Hocquenghem, 1989, p.212–213). The landmark is thus the sign and metonymy of the *pachacuti* and the restoration of order. A document from the *quipucamayocs* seems to confirm the occurrence of a *pachacuti* in the region during Inca times and its close relation with the Quibipay place, identified in this work. That document, indeed, quotes the following words of the Atahualpa generals addressed to the ethnic leader in Quibipay after the fratricidal war between Atahualpa and Huáscar: "once again should begin (a new world) of Ticcicapac Inga" (Randall, 1987, p.92). The Atahualpa generals consider their victory over Huáscar as a new upheaval and seem to refer to a previous one that would have taken place in Quibipay. Despite the less devastating impact of a tectonic event, we can easily consider a large fault rupture affecting the capital of the Inca Empire as a tremendous turmoil.

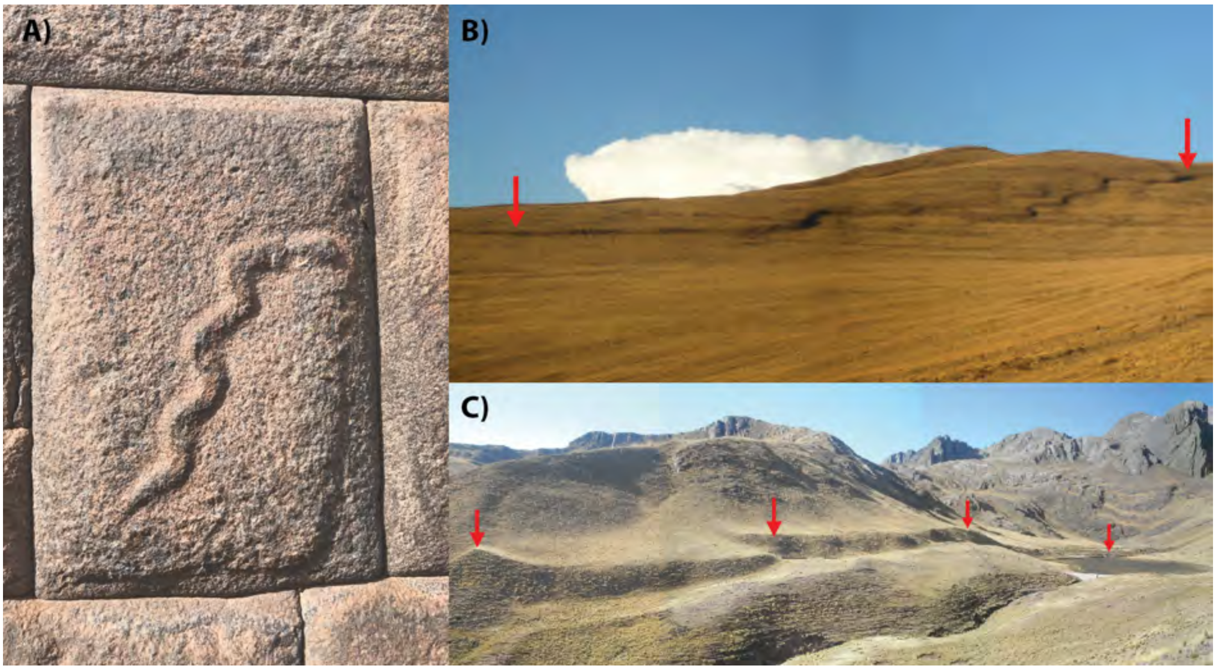

Figure 5.7: A) Apotropaic figure in architectural elements, the serpent carved motif is a common representation in Inca/colonial walls of Cusco (photograph: Beaterio de las Nazarenas – Siete Culebras). B) Qoricocha fault scarp and C) Langui Layo fault segment. In a similar fashion to modern observers, people during pre-Columbian times might have easily perceived these landforms as a serpent making its way underground.

5.5.3 “And so, two sacacas of fire came out…”

The second part of the extract from Pachacuti Yamqui Salcamaygua’s chronicle deals with the simultaneous appearance of two balls of fire (*sacacas*). The meaning of this Aymara word is not entirely clear, but could be defined as a fire emanating visibly in the sky, and different from comets, which are called *wara-wara hali* by Aymara speakers (Bertonio, 1879, p.304). Previous studies did not establish a direct link between this celestial event and the occurrence of the snake. These “fire exhalations” were understood as merely simple falling stars or indirect evidences of the eruption of El Misti (hundreds of kilometres to the west near Arequipa) dated between 1440 and 1470 CE (Bandelier, 1906; Thouret et al., 2001). We suggest two new possible interpretations of this phenomenon.
During colonial times tremors in Cusco were frequently symbolically associated with celestial events (Anónimo, 1819; Esquivel y Navia, 1980). Although we are not able to explain why both phenomena are commonly linked, the appearance of a comet could be mentioned as a divine sign after a catastrophe. The great influence of Christianity in the writings of Juan de Santa Cruz (Duviols, 2017) would support that hypothesis. The second explanation is based on the still poorly explained, but sometimes observed “earthquake lights” (EQL) that have been reported before or during the ground shaking from major earthquakes (Fidani, 2010; Stothers, 2004; Whitehead & Ulusoy, 2015). The *sacacas* could be an expression of fireball-like lights described in various places such as in Lima during the 2007 Pisco earthquake (Heraud & Lira, 2011) as well as in L’Aquila in 2009 (Fidani, 2010). Theriault et al. (2014) noted that reports of earthquake lights seem to be more common in tectonic environments with crustal extension such as the Cusco Basin.

5.6 Conclusion

In ancient and modern Peru, earthquakes frequently shook the ground, modified the landscape, and devastated human settlements. In Cusco, time after time, people built and rebuilt monumental architecture in the vicinity or even along seismically active faults. Ongoing research indeed demonstrates the resilience of Inca buildings affected by past earthquakes (Hinzen & Montabert, 2017; Rodríguez-Pascua et al., 2020).
How much the Incas knew about earthquakes and faults is unclear. Described as a small piece of land where ground motions occurred, *Guaracince* (Ch.2:1 - Cobo, 1979, p.16) constitutes a unique direct reference to an Inca worship site related to earthquakes. Our interpretation of the latter myth suggests nonetheless that the relationship between cer-

emonial Inca sites and regional faults may be much closer and that modern archaeology and anthropology may have underappreciated the cultural significance of earthquakes for the Inca culture. This situation echoes the well-established influence of the tectonic environment on the development of sanctuaries in the Aegean area (De Boer & Hale, 2000; Partida, 2017; Stewart & Piccardi, 2017).

Historical and "prehistoric" seismicity must deal with large earthquakes that predate instrumental seismology. Without an instrumental record, the identification and characterization of ground-shaking episodes require a multi-proxy approach, combining analyses not only of palaeoseismological trenches and sediment cores, archaeological and neotectonic observations but also interpretations of (ethno)historical sources.

Given that first generation accounts from Spanish chroniclers did not mention any major ground-shaking episodes in the Cusco region during pre-Columbian times, the reader may legitimately wonder why we have based our discussion on a later indigenous chronicler. Although descendants of Inca people do not seem to have referred directly to such violent natural phenomena, we argue that earthquake stories may still be "hidden" in mythological episodes told to the first *conquistadores*. We consider thus the Amaru tale extracted from Pachacuti Yamqui's chronicle as a relevant example of a disastrous event preserved indirectly in a legendary story and transmitted over several generations. The "seemingly mythological" content of the *Relación de antiguedades deste reyno del Piru* does not preclude its analysis as a valuable source of information. Moreover, it suggests that an earth science-based approach can offer relevant insights regarding the nature and origin of myths in a given geodynamic and cultural setting.

Thus, despite the metaphorical dimension, various elements make the seismological interpretation of the legend plausible and worthy of consideration. We summarize again the arguments, enounced above, in favour of our hypothesis:

- the similarity of the Amaru's route to the layout of the main Cusco fault complex;
- in the south-eastern part of the Cusco region, indigenous people describe faults scarps as "amaru";
- the lake where the snake vanished might be interpreted as having been a sag pond. Quibipay, known currently as Cruz Verde de Quehuepay, lies at the foot of the Cusco fault scarp; the snake diving into the water would be therefore a metaphor for the rupture ending in the lake;
- bright lights likened to fire described in the same extract by Pachacuti Yamqui might be linked with earthquakes, given the recurrent association of comets with earthquakes in colonial texts or as the occurrence of "earthquake lights".

Following the traditional chronology of the Inca emperors made by John Rowe (1945, p.277), we date the potential earthquake, which occurred apparently around the December solstice (*Qhapaq Raymi*), between approximately 1438 CE (the beginning of Pachacuti's reign) and 1463 CE (when the second son of Pachacuti took command[6]).
Finally, this study highlights the relevant contribution that legends and myths in past risk perception and management may bring. Due to the mythological content, inherent to this type of source, geologic phenomena remain roughly constrained in terms of chronology. However, folk tales and testimonies have yet proved their worth for describing pre-instrumental earthquakes, in particular, in the San Andreas Fault region (MacLean, 1979; Meltzner & Rockwell, 2004). A renewed palaeoseismological and archaeoseismological effort is needed to confirm the occurrence of such large seismic event during Inca times and affecting the Cusco Basin. Improved characterization and mapping of the destructive evidence affecting the LIP and LH settlements would provide useful complementary data. According to the World Bank's Independent Evaluation Group, the number of events considered as natural disasters grew by 200% between 1975 and 2015, which demonstrates the increased threat for our modern societies (CRED, 2015; IEG, 2006). Increasing resilience to future earthquakes in the Cusco area will require fostering innovative approaches to address past human coping strategies. Cross-disciplinary interactions are shown here to be necessary to study such a historic area, ranging from human and social sciences (e.g., archaeology, history, anthropology, sociology...) to physical and natural disciplines (e.g., geology, seismology, hydrology, and geography) and engineering (e.g., architecture), with each, from its own perspective, providing new interpretations for improving hazard assessment.

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5.7 Complementary avenues for research

Apart from the reassessment of the serpent figure in the Andean cosmology[7], this case study demonstrates that the populations of the Cusco Basin had a thorough knowledge of their environment and of its related tectonic processes, even if these processes were not understood and described according to the same thought system. Thereupon, we would like to add complementary information found in the literature that broadens the discussion on the pre-Columbian perception of the earthquakes in the Cusco area.

Among the knowledge about the ground motions, the indigenous populations seem to have elaborated empirical "mental maps" of the seismic hazard. First, the ethnographical work of Howell and Lott (1980) shows that the inhabitants of the Sacred Valley made a clear distinction between their valley and the Cusco Basin regarding the seismic waves' propagation. Secondly, the description made by Cobo (1979) of the huaca *Guaracince* – as the focal point of the ground shaking – suggests an extensive experience of the seismic events and a careful examination of the distribution of the damage in the vicinity of Cusco. It is, indeed, likely that the observation of Howell and Lott (1980) would have been related to the seismotectonic setting of the Urubamba Valley and thus to the lower frequency and intensity of the ground motions there. Regarding the huaca *Guaracince*, its location in the Chuquipampa Square, next to the Sun Temple (Qorikancha) coincide with one of the most affected places during the 1950 and 1650 earthquakes, due to strong sites effects and ground subsidence (Julien, 1995; Kubler, 1951; Ladrón de Guevara, 1967).

Whether they deal with earthquake portents[8] or cultural practices associated with the seismic phenomenon (Calvo, 1994; Cobo, 1979; Gade, 1970; Lavallé, 2011), historical and ethnohistorical sources will need to be reconsidered and reinterpreted in the light of future archaeological and geological evidence. We are convinced that archaeoseismology may complement the traditional historical approaches and improve our poor understanding of the pre-Columbian strategies to cope with the natural hazards (Covey, 2019). This will require, nonetheless, a particular effort to raise awareness on this issue among the archaeological community.

Notes

[1]We are not claiming in any way that the earthquake occurrence may explain all the evidence of destruction registered during the Killke (LIP) and Inca (LH) periods. Bearing in mind the absence of consideration of earthquakes in almost all the investigation interpretations, we may nonetheless wonder to what extent the current lack of awareness of the seismic risk might have affected interpretations of the

archaeological records. We thus stress the need for future investigations to take into account the impact of this natural hazard.

[2]Addendum. Even in Europe, traditional folklore associates earthquakes with large creatures situated at the interface between the surface and the "underworld" (Conrad von Megenberg, *Buch der Natur* in Adams, 1938, p.404): "It often happens in one place or another that the earth shakes so violently that cities are thrown down and that one mountain is hurled against another mountain. The common people do not understand why this happens and so a lot of old women who claim to be very wise, say that the earth rests on a great fish called Celebrant, which grasps its tail in its mouth. When this fish moves or turns the earth trembles."

[3]Juan de Santa Cruz Pachacuti Yamqui Salcamaygua came from an Aymara-speaking area, but in process of "Quechuaisation" during Inca and colonial times (Itier, pers.comm.). This particular situation explains the combined use of those two languages in his chronicle.

[4]"En este tiempo dizen que llegó la nueba como en el Cuzco ubo un milagro que como un yauirca o amaro abía salido del serro de Pachatusan muy fiera bestia, media legua de largo y gruesso de dos bragas y medio de ancho, y con orejas y colmillos <y barbas>[a]. Y viene por Yuncay Pampa y Sinca, y de allí entra a la laguna de Quibipay, y entonges salen de Aosancata dos sacacas de fuego, y passa a Potina <de Ariquipa>, y otro viene para más abaxo de Guamanca, que está y tres o quatro serros muy altos cubierto de niebes, los quales dizen que eran animales con alas y orejas y colas y quatro pies, y ençima de las espaldas muchas espinas como de pescado, y desde lejos dizen que les parecían todo fuego." (Pachacuti Yamqui Salcamaygua, 1993, p.157-f.21–21v)
a Por caussa deste amaro puso por nombre a su hijo Amaro Yupangui (A III).

[5]We consider 1 league = ∼5.5km and 1 fathom = ∼1.6718m (Bauer, 2018, p.47)

[6]We base our chronological interpretation on the traditional Inca's chronology elaborated by John Rowe. He considered that Pachacuti Inca Yupanqui ruled between approximately 1438 CE and 1471 CE, based on colonial texts and calculations of the number of years remaining until the Spanish Conquest. Since he died quite old (∼70-80) according to chronicles, it seems probable that Amaru Tupa was born around 1440 CE. Our assumed dating is, for sure, tentative due to the questions that still surround Inca genealogy and succession (Duviols, 1979; Marsh et al., 2017; Meyers, 2019; Ogburn, 2012), but should be regarded as a baseline for future palaeo-and archaeoseismological investigations. The assumed relation between the Amaru legend and the name of the eldest son of the emperor Pachacuti justifies the dating attempt.

[7]In this regard, the Band of Holes, also called Cerro Viruela and Monte Sierpe in Spanish, located in the Pisco Valley is particularly noteworthy.

[8]"Strong winds or abrupt changes in the weather are said to be earthquake portents, as are changes in the illumination of the moon, or the appearance of rainbows around the rising or setting moon. Dust rising from within a volcano is another earthquake portent. In Cuzco, animal portents of earthquakes include dogs howling, cats conducting a funeral, and roosters crowing in the afternoon or evening (less frequently this can also portend death). In one case tadpoles whistling was reported as a portent of earthquakes" (Howell & Lott, 1980, p.336)

Chapter 6

The Inca architecture: a pre-Columbian seismic culture? Insights from an ambient vibration analysis

"There is no doubt that in Inca architecture aesthetics and dimensions are subjected to the constructive reality, in other words, to the functional reality."

Calderón Peñaylillo (1963, p.19)

Introductory words

When referring to ancient earthquake-proof or earthquake-resistant architecture, the Inca constructions are often held up as an example. Whether it concerns the trapezoidal shape of openings, the slight inclination of walls inwards, the tightly fitted stones, the foundation's design or even the use of clamps, many architectural features have been alleged as proofs of a true Inca engineering expertise regarding the mitigation of the seismic hazard (Calderón Peñaylillo, 1963). However, while most of those features likely contributed to the durability of the finest Inca buildings and protected them from the earthquakes that struck the Cusco region since the colonial period, there is no evidence that the architecture was either the result of a deliberate functional/utilitarian purpose or even aesthetic and symbolic one (Dean, 2010).
Addressing the intentionality of the Inca architecture and its earthquake-proof design led thus to question the existence of a seismic culture at this period. We claim that this requires the implementation of innovative methods and approaches and involves the acquisition of quantitative data on the dynamic behaviour of the pre-Columbian buildings.

In this chapter, we propose to use the ambient vibration-based techniques, namely the Operational Modal Analysis (OMA), on Inca archaeological remains located in the Cusco region. This study aims at characterizing the frequency response of the structures, discuss their behavioural homogeneity at the regional scale and provide relevant inputs to get more robust and accurate predictive models. Unfortunately, due to the sanitary and political issues imposed by COVID-19, we were unable to carry out the initial instrumentation project in Peru. We managed, nonetheless, to learn the necessary skills in signal processing and carry out a survey of a historic masonry tower, the Gate Tower of Viviers (Ardèche, France) in the aftermath of the Le Teil seismic crisis (Nov. 11, 2019). In the first part, we present the main results of this two-month seismic monitoring and show the opportunities of such passive seismic techniques to track the modal parameters of a cultural heritage structure.
Although, no direct parallel can be drawn between this French case study and the specific pre-Columbian dry-stone masonry investigated, we insist, in a second part, on the archaeoseismological potential of a similar ambient vibration-based testing in Peru. We describe, thus, the main objectives of the initial field campaign and update them in the light of our experiment in the Gate Tower of Viviers.

Postseismic survey of a historic masonry tower and monitoring of its dynamic behaviour in the aftermath of Le Teil earthquake (Ardèche, France).

Andy Combey[a], E. Diego Mercerat[b], Philippe Gueguen[a], Mickaël Langlais[a] and Laurence Audin[a]

a Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IGE, ISTerre, 38610 Gières, France.
b CEREMA, Repsody team, Sophia Antipolis, 06360 Valbonne, France.

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Abstract On November 11^{th}, 2019, a M_w 4.9 earthquake struck the middle Rhône valley (South-East France) producing moderate to severe damage in the town of Le Teil and its surroundings. This unexpected event stressed the vulnerability of the French cultural built heritage to a moderate seismic hazard. Commonly applied to modern civil engineering structures, passive seismic methods are still lacking on historic constructions to understand properly the different factors driving their dynamic behaviour. In this paper, the results of a two-month seismic monitoring survey carried out shortly after the Le Teil mainshock in a historic masonry tower are presented and discussed. Located only 5 km south of the epicentre, the Gate Tower of Viviers (eleventh century) was instrumented with four highly sensitive seismic nodes. Ambient vibrations, as well as aftershocks and quarry blasts from the nearby Le Teil quarry, were recorded and used in the analysis. Through vibration-based analysis, the paper addresses three relevant aspects of the dynamic response of ancient masonry structures. We discuss first the differences in the building's response induced by the three reported types of vibrations, focusing on the particular signal characteristics of shallow aftershocks and quarry blasts. Then, we apply the Random Decrement Technique (RDT) to track the dynamic behaviour variations over two months and to discuss the role of the environmental conditions in the slight fluctuations of the structural modal parameters (natural frequencies, damping coefficients) of unreinforced masonry structures. We also show evidence of the non-linear elastic behaviour under both weak seismic and atmospheric loadings. The correlation between the presence of heterogeneities in the construction materials and the non-linear threshold supports the relevance of such types of monitoring surveys as a valuable tool for future modelling works and conservation efforts.

6.1 Introduction

Characterizing the dynamic response of buildings under a wide range of stresses and loadings has turned into a key component of structural health monitoring (SHM) and condition-based maintenance (CBM) studies. Cost-effective and easy to implement, operational modal analysis (OMA) constitutes the starting point to any SHM or damage assessment. These approaches rely on the basic principle that any modification of the building's operational dynamic response indicates a modification of the stiffness or energy dissipation characteristics of the system, since the masses are assumed not to change (Farrar & Worden, 2007). Applied to civil engineering structures (e.g., bridges, towers, buildings, etc.) ambient vibration-based techniques provide an accurate assessment of modal parameters (frequency, damping, mode shapes) for health monitoring.

Regarding cultural heritage buildings, the complexity of their architecture coupled with their successive construction phases makes operational interpretations particularly difficult for the SHM. This limits the implementation of effective preservation strategies, while their vulnerability to dynamic and cumulative loads is amplified by their current structural health status (Cabboi, Gentile, & Saisi, 2017; Korswagen, Longo, & Rots, 2020). Often slender and heavy, tall historic structures are particularly vulnerable to earthquakes. Assessing and modelling their seismic performance has become thus a growing priority of Heritage safeguarding strategies (Clemente, Saitta, Buffarini, & Platania, 2015; Dogangun, Acar, Sezen, & Livaoglu, 2008; Jaishi, Ren, Zong, & Maskey, 2003; Micelli & Cascardi, 2020; Ronald, Menon, Prasad, Menon, & Magenes, 2018). Studying masonry buildings with a cultural heritage value implies nonetheless dealing with additional regulatory and technical constraints. In such cases, the implementation of non-invasive and non-disturbing techniques such as passive seismic methods are particularly suitable and recommended (Ceravolo, Pistone, Fragonara, Massetto, & Abbiati, 2016; C. Gentile & Saisi, 2007). Besides instrumentations of emblematic monuments (Hinzen, Fleischer, Schock-Werner, & Schweppe, 2012; Lacanna, Ripepe, Marchetti, Coli, & Garzonio, 2016; Pau & Vestroni, 2008) and bridges (Azzara, De Falco, Girardi, & Pellegrini, 2017; Roselli et al., 2018), recent works on Italian historic masonry towers (e.g., Azzara et al., 2019; Barsocchi et al., 2020; Cabboi et al., 2017; Saisi, Gentile, & Ruccolo, 2018; Ubertini et al., 2017) demonstrated the relevance of those approaches for conservation purposes.

Material heterogeneities and pre-existing cracks play also a significant role in the dynamic response of structures. Guéguen et al. (2020; 2016) and Astorga et al. (2018; 2019) extrapolated the micro-scale nonlinear elasticity studies applied to rock samples (e.g., Johnson & Sutin, 2005) to large-scale reinforced concrete structures in relation to the damage level. Brossault et al. (2018) estimated the damping fluctuation under small deformation as a proxy of the number of heterogeneities at different scales. Based on both fluctuation-dissipation and nonlinear elasticity theories, the extension of cracks within the masonry may affect notably the variations of modal parameters on quasi-static or moderate dynamic loadings. Despite the uncertainties related to the estimation of the absolute damping value, long-term ambient vibration-based monitoring in historic monuments is, therefore, an efficient way for assessing possible degradation of buildings' elastic properties and structural health.

The M_w 4.9 Le Teil earthquake occurred on November 11, 2019 in the middle Rhône valley (Ardèche, France). The area is well known for its numerous industrial facilities and its rich cultural heritage. The earthquake was particularly shallow (hypocentral depth less than 2 km) and damaging (Causse et al., 2021; Cornou et al., 2020; Ritz et al., 2020). Almost 1,000 houses were severely affected in and around the city of Le Teil. Since the earthquake, monuments with great heritage value such as the church of Mélas and the castle of Saint Thomé (fig. 6.1) have required important retrofitting efforts. Besides the severe lack of knowledge on the local seismic hazard (Mazzotti, Jomard, & Masson, 2020; Naud, 2021), the event highlighted hence the seismic vulnerability issue of the local cultural heritage. Due to this "historically unprecedented earthquake in France" (Ritz et al., 2020), the region has turned into a testing ground for numerous research projects focused on the French seismic hazard assessment and the seismic monitoring of civil engineering structures.
This event provided a rare opportunity to monitor a historic masonry building during a postseismic sequence in France and to use both ambient and transient dynamic vibrations (aftershocks as well as blasts from the open-pit cement quarry of Le Teil). We conducted thus a two-month monitoring of the eleventh-century Gate Tower of Viviers (GTV) located 5 km southeast of the November 11, 2019 epicentre (fig. 6.1). Apart from the characterization and monitoring of the dynamic behaviour of the GTV, the objective of this work is to identify the main factors driving the elastic response of such a complex and heterogeneous masonry structure in the framework of the seismic vulnerability assessment of historical monuments. This paper examines first the response of the GTV to several aftershocks and blasts from the open-pit cement quarry of Le Teil. Then, we analyse the long-term wandering of the modal frequencies and damping ratio using the Random Decrement Technique (RDT), related to the environmental conditions. Finally, based on the damping assessment, the nonlinear elastic behaviour is interpreted and discussed in terms of SHM. It could be a valuable baseline for future SHM studies dedicated to old masonry monuments.

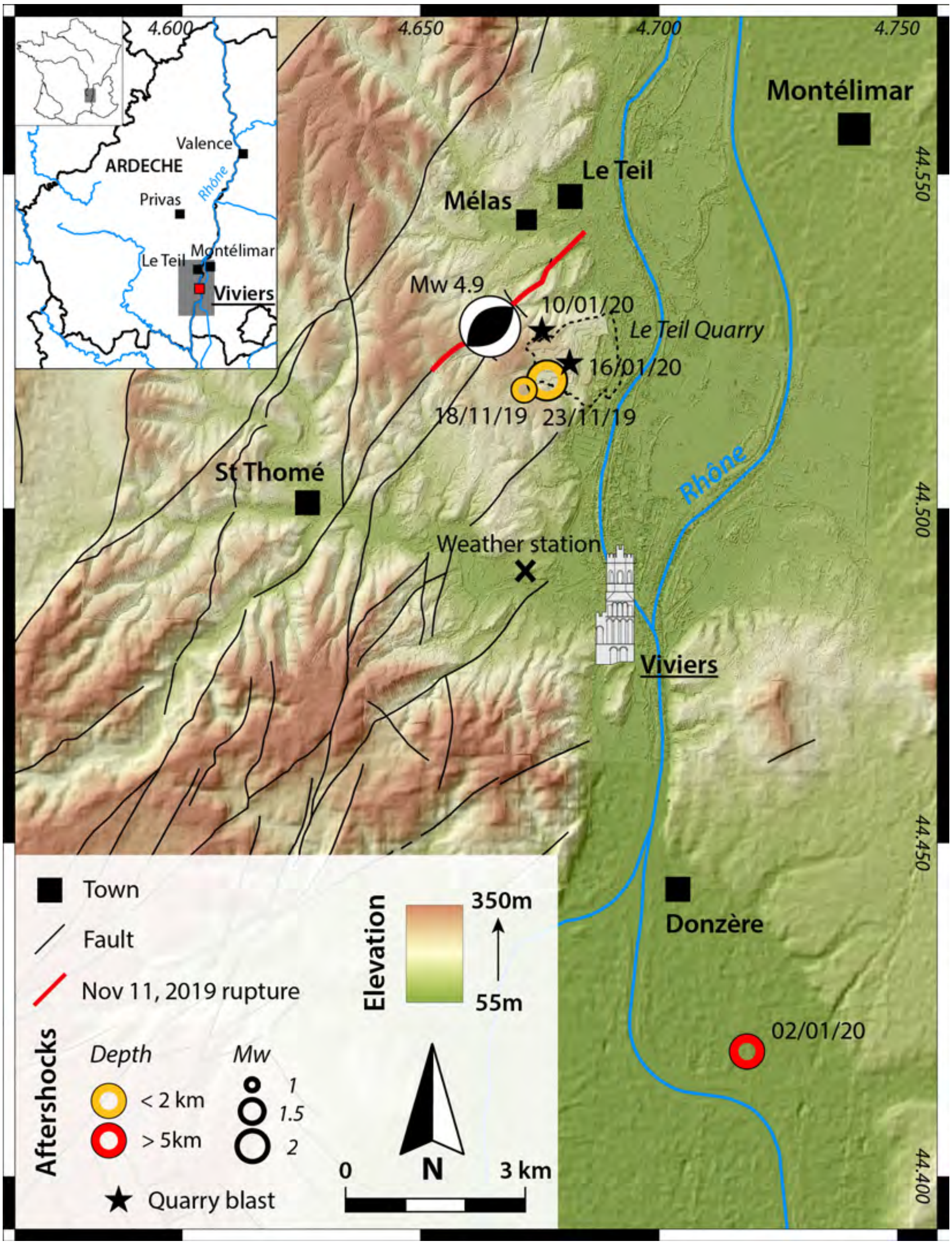

Figure 6.1: The Viviers-Le Teil area lies in the middle Rhône valley, in the department of Ardèche, France (see inset). The Gate Tower of Viviers is located 5 km south of the fault rupture associated with the M_w 4.9 Le Teil earthquake. The location of the main seismic events (coloured circles) and quarry blasts (black stars) discussed in this paper is indicated.

6.2 The experiment

6.2.1 The Gate Tower of Viviers

The GTV forms part of the medieval episcopal quarter of Viviers (fig. 6.2) and reaches a height of 37 meters. The building is listed by the French authorities as a historic monument since 1906.

Most likely built in the second half of the 11^{th} century (Esquieu, 1983), preceding thus the construction of the adjoining cathedral, the GTV was initially designed as a monumental and "ostentatious" gate (Esquieu & Guild, 1992) giving access to the episcopal area on the rocky hill of Viviers. Located at the eastern edge of the Urgonian (Early Cretaceous) massif (Elmi et al., 1996), the calcareous outcrop forms a high point segregating naturally the cathedral complex from the rest of the town (fig. 6.2). In the second half of the 12^{th} century, the GTV was raised up, by approximately 10 meters, to serve as the bell tower of the actual cathedral. It is probably during the 14^{th} century and the remodelling works of the Gothic period that a rib vault was constructed on the western porch of the cathedral, connecting tenuously the previous building to the GTV (Esquieu & Guild, 1992 – fig. 6.3). Around 1387, in a context of political tensions and conflicts (Hundred Years' War), the elites of Viviers decided to raise the top of the tower with an important octagonal floor with crenelated walls (Esquieu & Guild, 1992). Since then, the GTV also played a defensive role and became a strategic vantage point of the Rhône valley. Aside from light retrofitting works during the 19^{th} century, the GTV has undergone few changes since the Middle Ages (Esquieu & Guild, 1992).

The building is, therefore, the result of several constructive phases with a great variety of architectural styles that exemplifies its current heritage value. Constructed in Roman style, the quadrangular base of the Tower reaches a height of approximately 27 meters. It is composed of three levels: a lower room (ground floor) surmounted by a vaulted chapel and a second floor, which was designed to host the bells (fig. 6.3b). Almost square in plan (9.3 x 9 m), the Tower is flanked on its western façade by a large buttress wall, 17 meters high, which ends in a terrace accessible from the second floor (fig. 6.3). The Tower is entirely built with limestone rocks and local molasses (Esquieu, 2021, pers.comm.). The stonework is relatively poor, characterized by irregular courses and locally thick mortar joints (Esquieu & Guild, 1992 – fig. 6.3c). Nonetheless, the upper part, octagonal in shape, differs from the base by the common use of ashlars (fig. 6.3d), preferred to the rubbles used in the lower part.

Notable historical events seem to have affected the nine centuries-old building but without jeopardizing its integrity. It survived the ransacking and looting of Viviers by the

Huguenots in 1567 (Esquieu & Guild, 1992) and the fire that affected the cathedral in 1772 (Esquieu, 1988). From the natural hazard point of view, the violent seismic swarm that damaged the Tricastin area in 1873 (MSK intensities VI-VII) and several architectonical features of the cathedral of Viviers (SisFrance database), does not seem to have caused serious damage to the Tower. Regarding the impact of the Le Teil earthquake, a visual inspection three days after the mainshock did not reveal any structural damage in the GTV. However, several pre-existing fractures were re-opened according to the presence of fresh plaster on the chapel's floor.

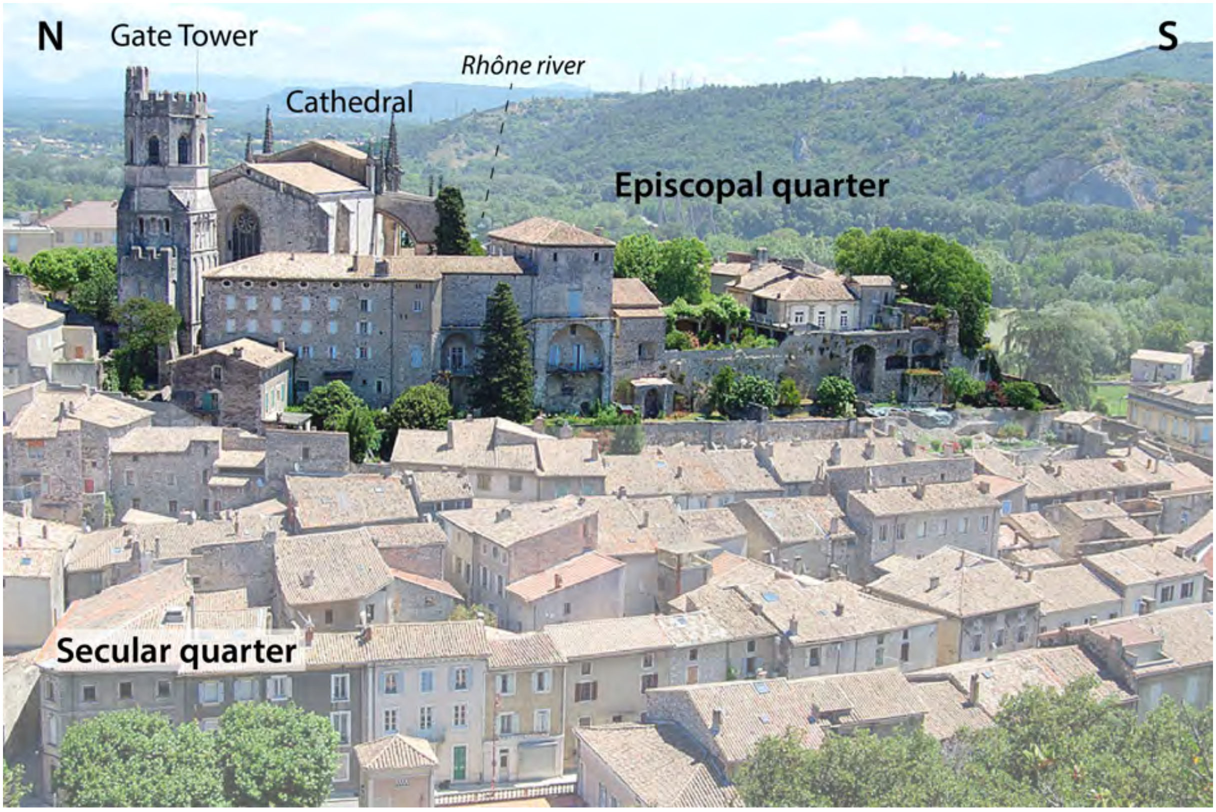

Figure 6.2: View of Viviers historic centre. Note the strategic location of the episcopal quarter that settles on the edge of a calcareous outcrop, overlooking the middle Rhône valley. The Tower was the main access to this sector during the medieval period.

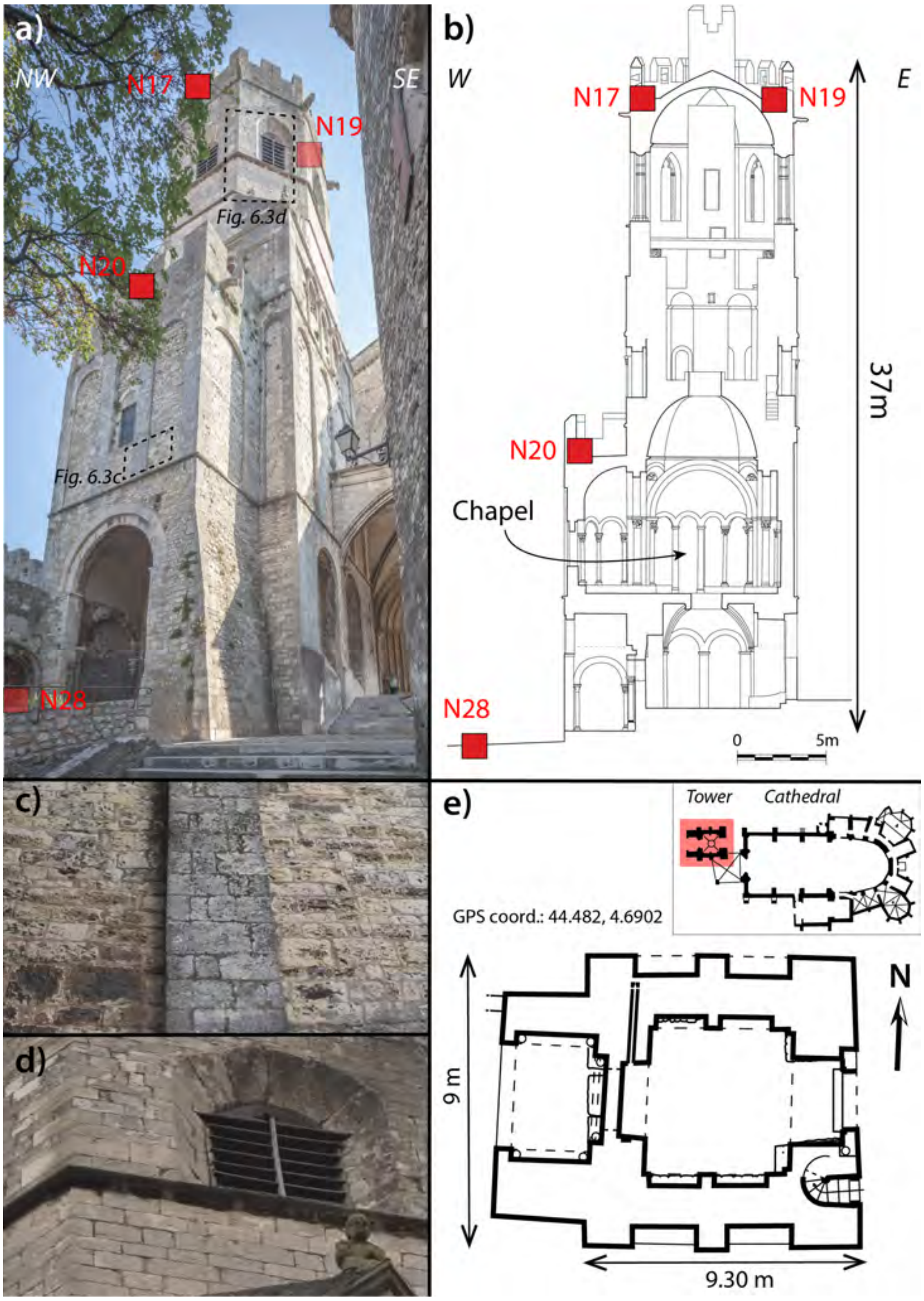

Figure 6.3: The Gate Tower of Viviers. a) Overview of the building from the entry staircase (southwest) leading to the episcopal sector (credits: X. Spertini); b) Sectional drawing of the building (Esquieu & Guild, 1992); c) Stonework at the first floor. Note the poorly cut stones with thick mortar joints on the left and right parts of the photograph; d) Detail of the ashlar masonry characterizing the upper part of the Tower; e) Plan view of the Tower as well as its location with respect to the cathedral. The red squares indicate the location of the sensors.

6.2.2 The postseismic survey

Following the shallow and damaging November 11, 2019 Le Teil earthquake and its disastrous impact on local traditional housing and surrounding historical monuments, we carried out a two-month monitoring of the GTV, through the installation of four Fairfield ZLand nodes. The simple geometry of the Tower facilitated its instrumentation with a reduced number of seismic stations. Compact, the nodes included in the same device three geophones (three component velocimeters), a digitizer (24 bits) and a global positioning system (GPS). The sensors integrated into the nodes have a nominal sensitivity of 76.7 V/m/s and were configured to a sampling rate of 250 Hz. Operating on battery power, the nodes have approximately 35 days of autonomy.
The instrumentation started seven days after the mainshock with the aim of recording the aftershocks sequence. Four nodes were installed between November 18, 2019 and December 11, 2019, and then replaced by four new instruments until January 17, 2020 to avoid the power issue. For GPS synchronization, those sensors require to be settled in open sky to be operational. This requirement conditioned the location of the nodes within the structure (fig. 6.3). N28 was installed at the basement of the tower, half-buried on the western side and was used as a reference ground station. N20 was installed at the western extremity of the terrace located between the first and the second floor of the tower and corresponding to the top of the buttress wall. The vertical position of N20 (relative to N28) is approximately 17 meters. Finally, two stations were installed at the top of the tower (N17 and N19), 37 meters above the ground, respectively at the west and east side of the structure. As shown in Figure 6.3, N28, N20 and N17 were located on the same vertical axis. All the sensors were oriented to the magnetic North. Due to the alignment of the walls of the GTV with the cardinal points (fig. 6.3), we decided to liken the building's mode shapes in the two horizontal components as purely E-W and N-S motions. Following the FDSN nomenclature, we used the acronyms "DPE", "DPN" and "DPZ" to name the three channels of each geophone, corresponding respectively to the E-W, N-S and vertical components.
On November 11, 2019, the M_w 4.9 Le Teil earthquake was associated with the reactivation of a large part of the NE-SW La Rouvière normal fault in reverse motion (Ritz et al., 2020). A small number of aftershocks followed this moderate-sized but very shallow event that induced a 4.5 km long surface rupture (in red on fig. 6.1). The dense temporary network of 52 seismological stations deployed in the field only a few days after the mainshock (Cornou et al., 2020) recorded 84 weak-to-moderate earthquakes, with 17 events with a magnitude > 1. During this sequence, only three events induced a clear

response of the GTV and are considered in this paper (table 6.1). The earthquake that occurred on January 02, 2020 was located to the south of the epicentral region (fig. 6.1) and was not considered as an aftershock. We succeeded in recording on January 10 and January 16, 2020 the two first quarry blasts triggered in the nearby Le Teil quarry after the mainshock (fig. 6.1 - table 6.1).
The recording of seismic events and quarry blasts during the monitoring of the GTV is of great interest for the study of the Tower's dynamic behaviour. Such data allow discussing the impact of moderate transient shakings on the elastic properties of historic masonry buildings.

Time	**Latitude**	**Longitude**	**Depth (km)**	**Magnitude (M_w)**	**Location**	**Type**
2019-11-18 T12:56:16.69831	44.518852	4.674751	1.60	1.63	VIVIERS	Earthquake
2019-11-23 T22:14:54.787128	44.519180	4.676490	1.48	2.78	VIVIERS	Earthquake
2020-01-02 T17:51:05.490607	44.418732	4.718434	5.06	2.26	DONZERE	Earthquake
2020-01-10 T10:08:48.897093	44.526299	4.674372	0.0	1.78	LE TEIL	Quarry Blast
2020-01-16 T10:13:34.975305	44.521587	4.680440	0.0	1.54	LE TEIL	Quarry Blast

Table 6.1: Main information on the five events investigated in the framework of this paper. Their estimated locations are reported in Figure 6.1

6.3 Results and Discussion

6.3.1 Dynamic behaviour analysis

We analysed 1,426 hours of continuous data recorded by the GTV temporary array, except between 9.30 and 10.00 am on December 11, 2019 for maintenance. All the data and metadata from the postseismic survey in Viviers were obtained from the Résif-EPOS portal (see Data and Resources Section).
Using the ObsPy package for seismological signal processing, we deconvolved first the instrument's response from the raw signals. Then the OMA was performed using MACity software developed by Michel et al. (2010) using the Frequency Domain Decomposition (FDD) for modal shape assessment (Brincker, Zhang, & Andersen, 2001) based on the singular value decomposition (SVD) of the cross-spectral power density matrix.

Six clear frequency modes were identified in the range 0-15 Hz (fig. 6.4a-b), associated with six mode shapes of the structure (fig. 6.4c). The first two peaks at 2.332 Hz (f_{N1}) and 2.698 Hz (f_{E1}) correspond to the first bending modes in the N-S and E-W horizontal components, respectively. Similarly, we identified the second N-S and E-W bending modes at 7.104 (f_{N2}) and 7.617 Hz (f_{E2}), respectively. Two other modes were detected, one torsional mode at 5.615 Hz (f_{T1}) and one vertical mode (f_{V1}) at approximately 12.5 Hz. The sixth vibration mode f_{V1} is associated with a dominant motion in the vertical component (fig. 6.4c), which explains its denomination as a "vertical mode." Such modes are only rarely identified with passive seismic techniques (Lacanna et al., 2016; Ronald et al., 2018) due to the small contribution of this mode under ambient vibrations. OMA indicate relatively high modal frequencies for a 37-meter-high structure compared to empirical relations obtained for masonry towers (Zanotti Fragonara et al., 2017) and argue for a relatively stiff behaviour of the monument.

Besides the squared shape of the Tower, structural elements may induce differences in stiffness within the building and consequently distinct frequencies for both orthogonal bending modes. Frequencies of the bending modes in the N-S direction are lower than in the E-W direction (fig. 6.4), arguing for the stiffening contribution of the buttress wall on the western façade as well as the rib vault connecting the Tower to the cathedral to the east. The relation between the two first bending modes in the same components indicates behaviour close to that of a shear beam (f_n=(2n-1)*f_1 – fig. 6.4). For that reason, we considered the potential coupling of the GTV with the adjoining cathedral as not significant.

The GTV and the entire episcopal area are settled on a calcareous outcrop. We carried out H/V measurements (Nakamura, 1989) at the bottom of the Tower and two places located a few hundred meters north of the monument. The H/V spectral ratios are similar and display nearly flat spectra between 0.5 and 12 Hz (fig. 6.4a) that confirms no significant lithological site effects and weak soil-structure interaction.

Transfer functions computed by deconvolution between the top and the bottom of the building have proven to be a useful method to quantify the excitation level of the vibration modes and identify changes in the resonant frequencies resulting from modifications of the building mechanical properties (e.g., Todorovska, 2009). We first calculated the spectral ratio between N17 (full height) and N28 (base) and between N20 (half-height) and N28 (base) on a two-hour window of ambient vibrations. We applied then the same methodology on shorter time windows of 40 seconds using the three seismic events (table 6.1).

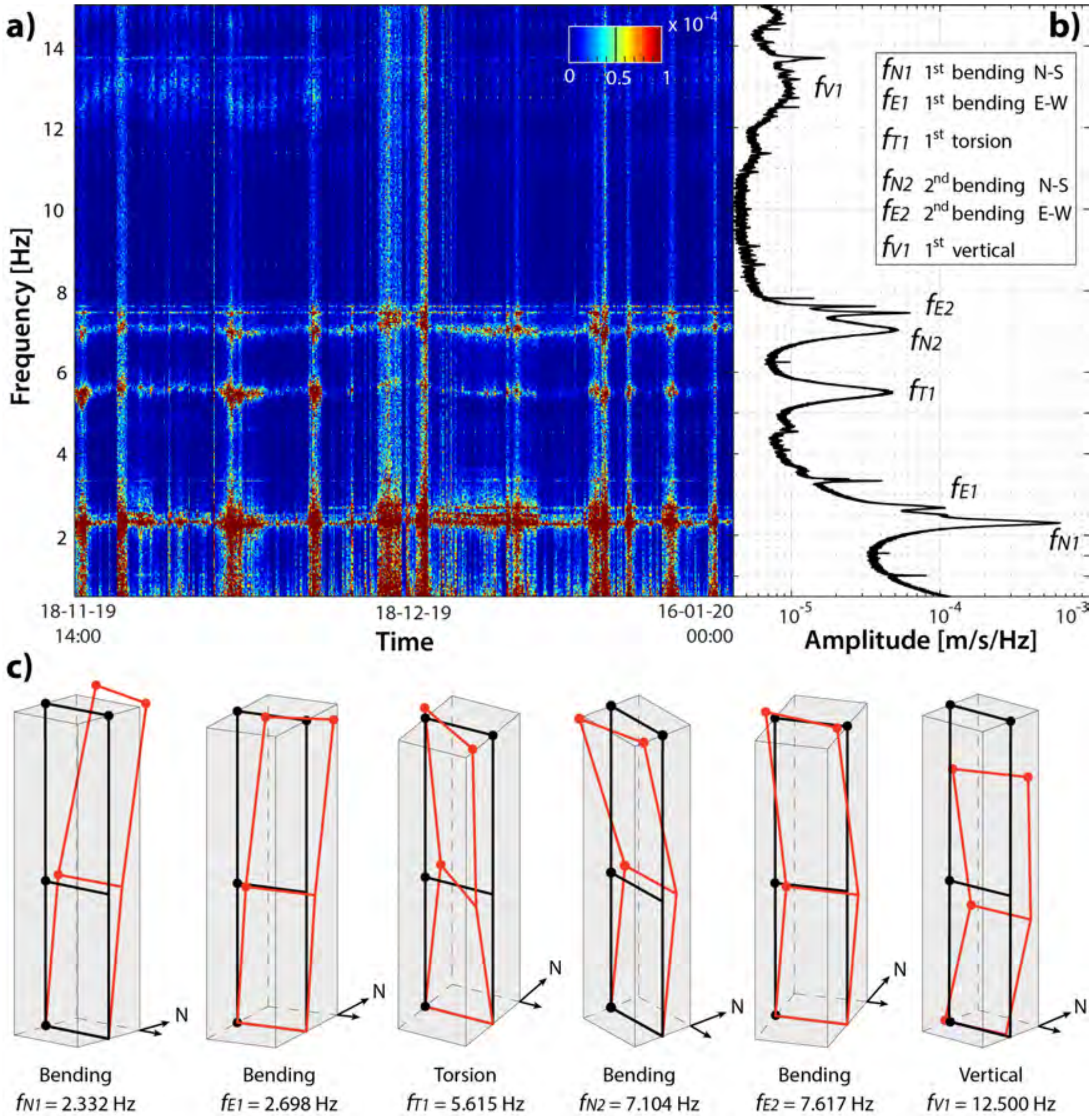

Figure 6.4: a) N19 spectrogram calculated in the bandwidth 0.5-15 Hz for the period ranging from Nov. 18, 2019 to Jan. 16, 2020; b) Resonant frequencies of the GTV derived from the mean amplitude spectrum; c) The six associated mode shapes. The red frames represent the motion of the vibration mode compared to the static position displayed in black. Nexus points indicate the location of the four velocimeters.

The spectral ratios using ambient vibrations and computed between the top and the bottom of the building (fig. 6.5b) highlight several important results. The amplitudes of both bending modes are nearly identical in the N-S direction (f_{N1} and f_{N2}) while the amplitude of the second bending mode in the E-W direction (f_{E2}) is more than two times higher than the amplitude of the first one (f_{E1}). The torsion mode (f_{T1}) is slightly excited under ambient vibrations. Barely visible in the E-W component, the amplitude of the torsion mode only accounts for ∼10% of the first bending mode in the N-S component. It is worth pointing out that the amplitude of the vertical mode can be significant under ambient vibrations. Moreover, the spectral ratio between N20 (half-height) and the base (in red in fig. 6.5b) is significantly different from those obtained between the top and the bottom of the Tower. The amplitude ratio of f_{T1} is larger on the lower part of the building, supporting a non-regular behaviour of the torsional motion throughout the structure. Likewise, the second bending mode in the E-W direction (f_{E2}) mainly occurs at the bottom of the structure that suggest a significant impact of the dissimilar geometry characterizing the base (square) and the top (octagonal) of the GTV (fig. 6.2 - fig. 6.3).

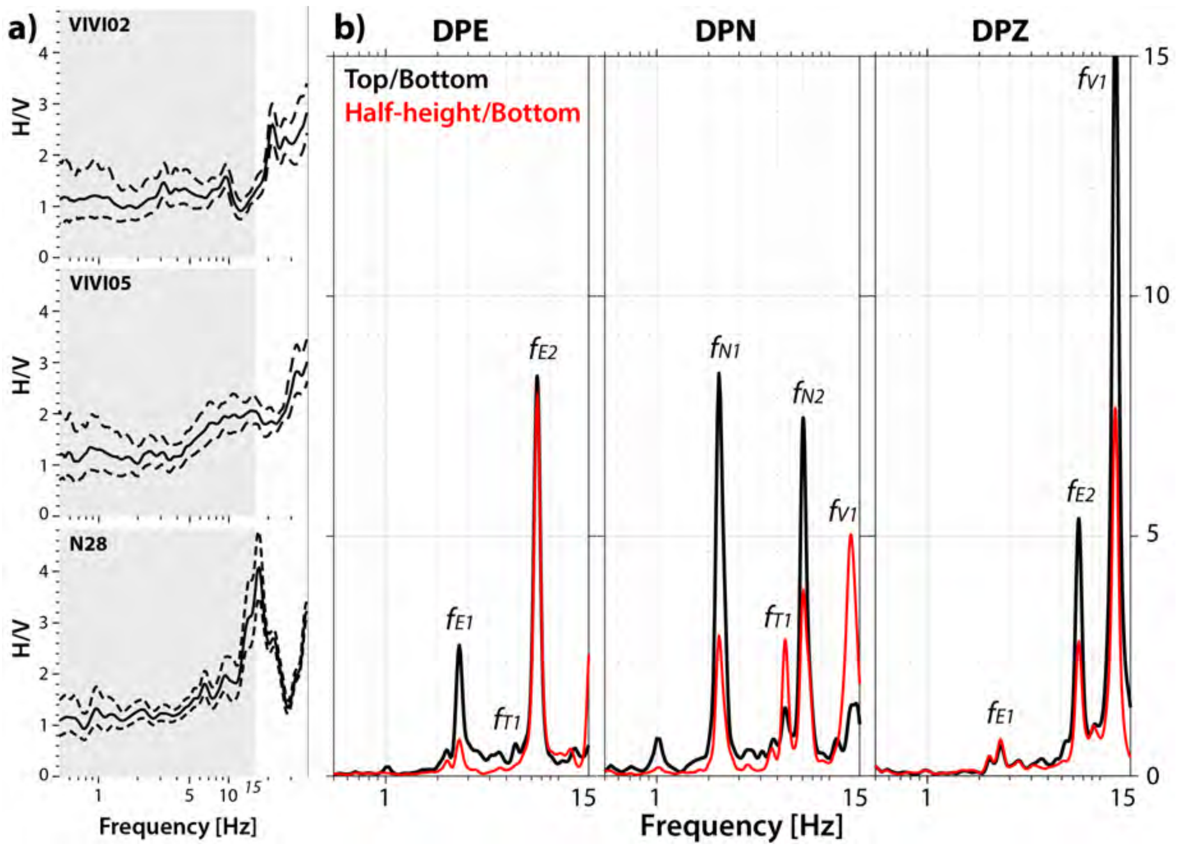

Figure 6.5: a) H/V measurements coming from two places of the episcopal quarter north of the Gate Tower (VIVI02/VIVI05) and from the node at the bottom of the Tower (N28); b) Spectral ratios performed on 2h of ambient noise (Nov. 20, 2019) between N17 and N28 (in black) and between N20 and N28 (in red). Comparison of these spectra evidences dissimilar patterns of solicitation of the two main parts of the Tower, particularly regarding the first torsion mode (f_{T1}).

Notwithstanding their moderate magnitudes, their similar distance from the Tower and the equivalent azimuths between the sources and the building (fig. 6.1 - table 6.1), the five transient events induce different responses of the GTV (fig. 6.6). Regarding first the seismic events, only small differences compared to ambient loading are observed. Figure 6.7 shows the results of the spectral ratios performed between the top and the base of the building for the three events. In all cases, the two bending modes (amplitude ratio >10) have a larger amplitude compared to Figure 6.5b. While in the N-S direction amplitude ratios between f_{N1} and f_{N2} are the same as using ambient vibrations, the first bending mode in the E-W component is more excited, similarly to the second bending mode (fig. 6.7). Surprisingly, the torsion mode appears to be not significantly excited. The response of the GTV during the January 02, 2020 event shows significant differences. Unlike the two other events, the first bending mode is preferentially excited in the E-W direction (fig. 6.6a - fig. 6.7). Moreover, the amplitudes of the second bending modes in the three components are lower, especially in the E-W direction as f_{E2} represents only a third of the amplitude of f_{E1}. The signal recorded on January 02, 2020, was not related to the postseismic sequence of the Le Teil earthquake. The differences are, thus, most probably due to the distinct source parameters and focal mechanisms of the third seismic event (fig. 6.1 - table 6.1 - fig. D.1).

On January 10 and 16, 2020, the nodes recorded the two first quarry blasts triggered in the Le Teil quarry two months after the November 11, 2019 mainshock. Due to the proximity of the GTV to the open pit, the monument was not only sensitive to the ground motions following the explosions but also to the acoustic blasts (fig. 6.6b). Figure 6.8 compares the frequency content of these two types of transient signals for the two quarry blasts. While the seismic signals resulting from the explosions led to a similar excitation of the building modes to that recorded during the seismic events – i.e. almost exclusively the first and second bending modes were excited – the acoustic signals (blasts) were associated with an excitation mainly in the N-S component. Located N350° with respect to the GTV, the explosions generated, therefore, a preferential deformation on the northern façade of the building. The striking presence of a large amplitude peak at f_{N1} in the E-W component is likely due to the complexity of the bending mode shape of f_{N1} and f_{E1} in the upper octagonal part of the GTV.

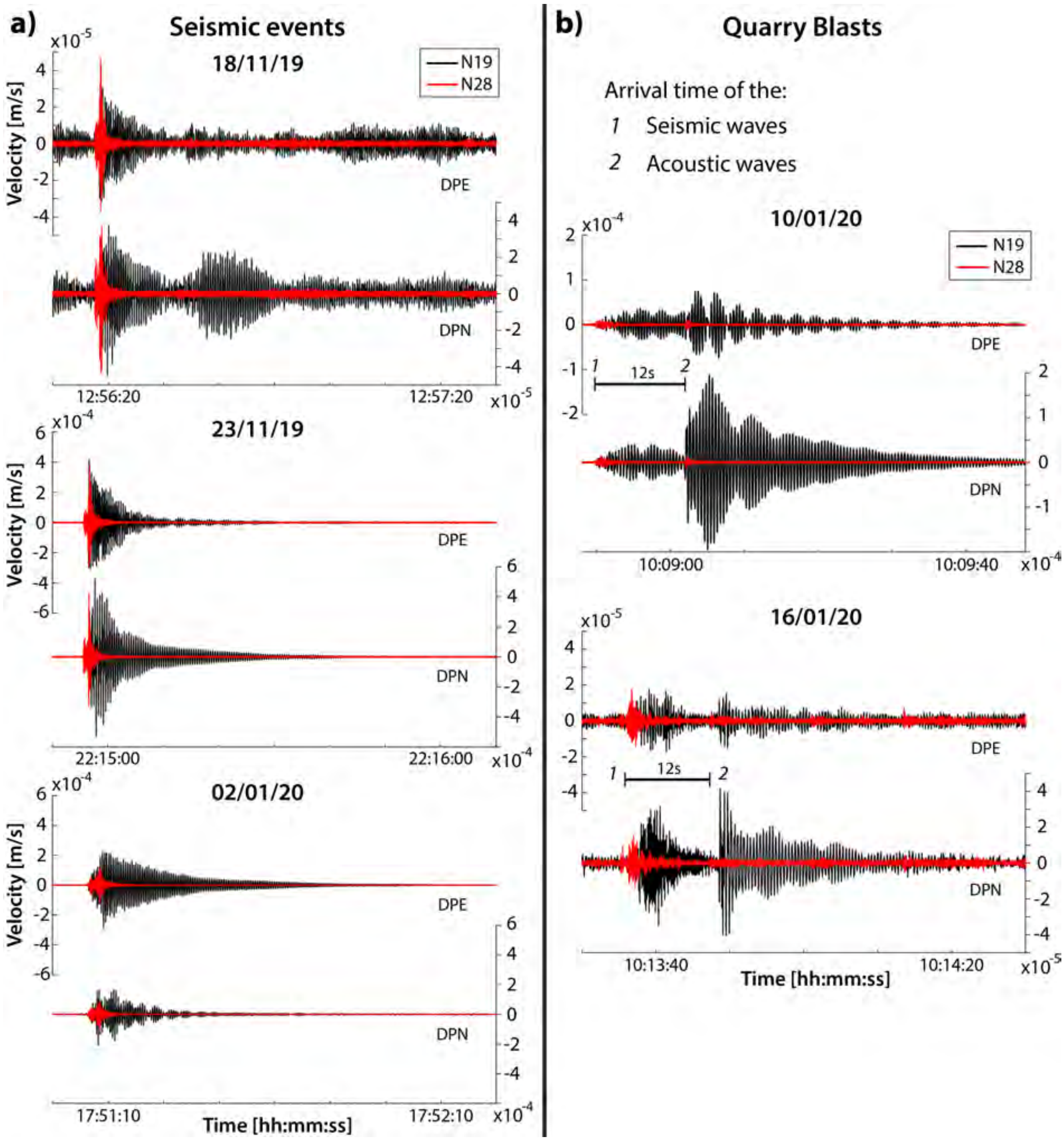

Figure 6.6: Velocities recorded in the two horizontal components during the three investigated seismic events (a) and the two quarry blasts (b) at the foot (in red) and the top (in black) of the structure. Regarding the quarry blasts, the GTV was also sensitive to the acoustic waves resulting from the explosion and following the traditional seismic signal.

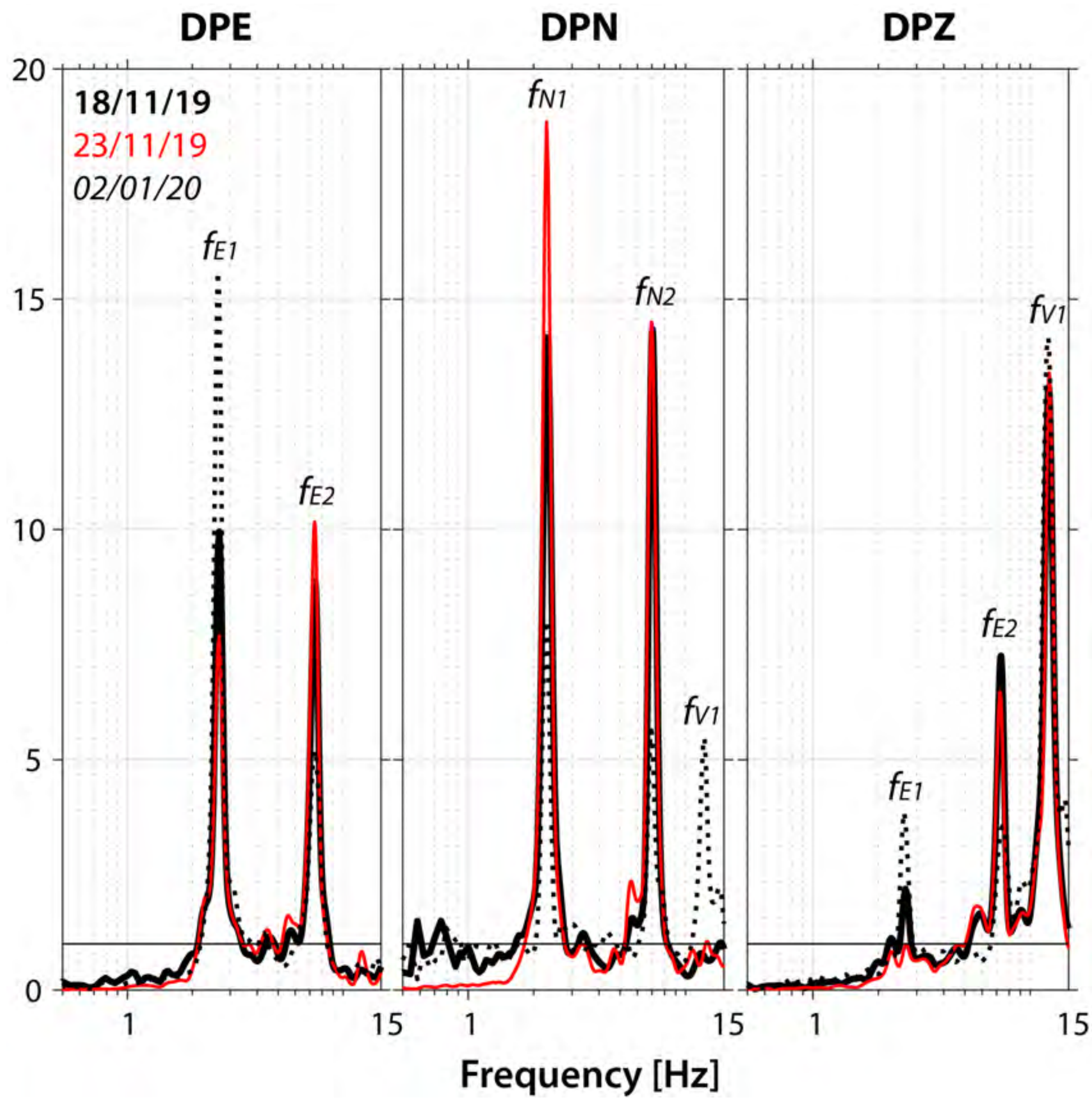

Figure 6.7: Spectral ratios performed between the top (N17) and the bottom (N28) of the GTV during the three seismic events (black, red and dotted).

Due to its proximity with the quarry (∼5 km), the GTV was more sensitive to the blasts. The maximum amplitudes corresponding to the bending modes at f_{N1} and f_{E1} at the top of the Tower is indeed close to the amplitude of these two modes during the magnitude 2.2 and 2.7 seismic events (fig. 6.6). Finally, the amplitudes of the first bending mode in the two horizontal components are more than 8 times higher during the blast on January 10 than during the blast on January 16 and the torsion mode is excited markedly. This result might seem surprising given the similar characteristic and location (table 6.1 - fig. D.2) of both quarry blasts. On January 10, 2020, the quarry blast was nonetheless triggered at the top of the quarry, unlike the one on January 16. That suggests a damped acoustic blast resulting from the second explosion (e.g., due to topography) until the town of Viviers. Interestingly, the dynamic behaviour analysis of the GTV demonstrates the differential response that may have such old masonry buildings to signals generated by similar (shallow and close) explosive sources.

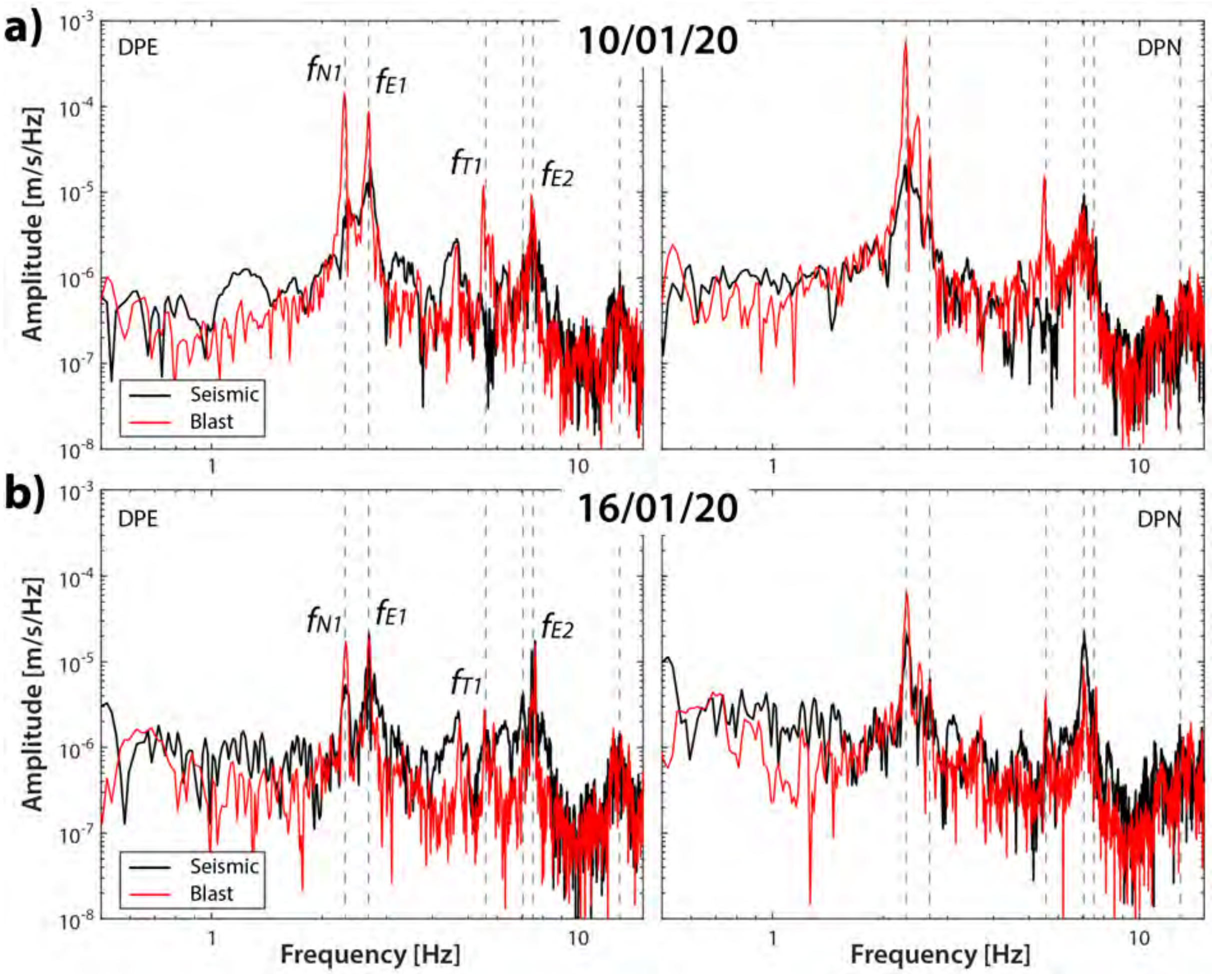

Figure 6.8: Comparison of the Tower's responses to the seismic (black) and acoustic (red) signals generated by the January 10 (a) and January 16 (b) quarry blasts at the top of the GTV (N19) in the two horizontal components. The acoustic "blast" on Jan. 10, 2020 (a) induces a strong excitation of the first vibrations modes of the building (f_{N1}, f_{E1}, f_{T1}).

6.3.2 Influence of environmental factors

As already highlighted by previous works on reinforced concrete buildings (e.g., Clinton, Bradford, Heaton, & Favela, 2006; Guéguen et al., 2016; Herak & Herak, 2010; Mikael, Gueguen, Bard, Roux, & Langlais, 2013; Wu, Wang, Chen, & Lai, 2017), and masonry constructions (e.g., Azzara et al., 2018; Cantieni, 2015; Saisi et al., 2018; Ubertini et al., 2017) the wandering of structural parameters depends strongly on external factors and particularly on environmental conditions. Assessing the role of these environmental factors in the short and long-term variability of the modal parameters is thus a key issue towards a suitable condition assessment, especially for complex historic structures. Recent works (Guéguen et al., 2016; Mikael et al., 2013) have demonstrated the relevancy of the Random Decrement Technique, first proposed by Cole (1973), in reinforced concrete buildings to follow very slight variations of the resonant frequencies and damping ratios. In this study, we apply and check the relevance of the RDT to a more heterogeneous medium.

Continuous data were first converted into one-hour files. No overlap was set up between these time windows. The RDT was implemented by filtering around the resonant frequencies presented in Section 6.3.1. We adapted the band-pass filter to each target frequency mode (± 10% for f_{N1}, f_{E1}, ± 8% for f_{T1}, f_{V1} and ± 5% for f_{N2}, f_{E2}). We compared then the wandering of the natural frequencies and damping ratios with the variation of several weather parameters (temperature, humidity, wind speed and rainfalls) provided by a weather station (see Data and Resources Section) located less than 2 km northwest of the GTV (fig. 6.1).

Table 6.2 presents the mean values of the modal frequencies (μf) and associated damping coefficients ($\mu\ \zeta$) computed over the monitoring period. It also contains the standard deviation (σ) and coefficient of variation for both modal parameters (COV). Note that the mean value of the coefficients of variation of the natural frequencies is less than 1%, i.e. more than thirty times smaller than the mean of the coefficients of variation of the damping coefficients. This simultaneously illustrates the intrinsic variability of damping values under weak motion (Brossault et al., 2018) and the greater calculation uncertainties related to the complex nature of damping mechanisms (Kareem & Gurley, 1996; Koruk & Sanliturk, 2011; Magalhães, Cunha, Caetano, & Brincker, 2010; Mikael et al., 2013). The first five vibration modes are characterized by very low damping coefficients (table 6.2), inferior to 1% (from f_{N1} to f_{E2}). Only the vertical mode (f_{V1}) is presenting values around 1.5-2%. Such low values of damping are rather unusual for tall masonry structures (Azzara et al., 2018; Cantieni, 2015; C. Gentile & Saisi, 2007; Lacanna et al., 2016).

	Mode	f_{N1}	f_{E1}	f_{T1}	f_{N2}	f_{E2}	f_{V1}
DPE	μf [Hz]		2.6807	5.5871		7.518	
	σf [Hz]		0.0217	0.0606		0.0489	
	COVf		0.0081	0.0108		0.0065	
	$\mu\ \zeta$ [%]		0.4986	0.6899		0.2993	
	$\sigma\ \zeta$ [%]		0.0921	0.1835		0.1428	
	COV ζ		0.1847	0.266		0.4771	
DPN	μf [Hz]	2.3109		5.5682	7.059		12.952
	σf [Hz]	0.0237		0.0702	0.0527		0.127
	COVf	0.0103		0.0126	0.0075		0.0098
	$\mu\ \zeta$ [%]	0.563		0.8102	0.3583		1.4488
	$\sigma\ \zeta$ [%]	0.1022		0.3746	0.0665		0.5621
	COV ζ	0.1815		0.4624	0.1856		0.388
DPZ	μf [Hz]		2.6806			7.5149	12.186
	σf [Hz]		0.0219			0.0459	0.0935
	COVf		0.0082			0.0061	0.0077
	$\mu\ \zeta$ [%]		0.6244			0.3304	1.9218
	$\sigma\ \zeta$ [%]		0.2243			0.1509	0.9765
	COV ζ		0.3592			0.4567	0,5081
Temp.	μ [°C]	7.9550					
	σ [°C]	4.1962					
	COV	0.5275					
Wind	μ [kph]	5.4023					
	σ [kph]	5.0088					
	COV	0.9272					

Table 6.2: Table summarizing the mean frequency and damping values (μf, $\mu\ \zeta$), their associated uncertainties (σf, $\sigma\ \zeta$) and the coefficient of variation (COV) for each mode of vibration in the three components computed with the RDT. Mean value (μ), standard deviation (σ) and coefficient of variation (COV) of the temperature and wind speed datasets are also indicated.

We observe (table 6.2 and fig. 6.9) a strong dependence of the frequency and damping values to weather conditions and according to different timescales: monthly-seasonal variations, day-night cycles as well as short events of a few hours. The GTV demonstrates, first, a strong sensitivity to temperature variations. A clear positive correlation is observed between the temperature and the frequency variations. Temperature variations of almost 125% (-2.2 to 18.6°C) compared to the mean value result thus in frequency variations around 3% for the first bending mode in the N-S component (fig. 6.9a-c). Although no global conclusions can be drawn on the nature of this correlation since the structural behaviour related to temperature variations may vary greatly from one building to another (Mikael et al., 2013), the current trend has also been reported for other historic masonry buildings (Azzara et al., 2018; Casciati, Tento, Marcellini, & Daminelli, 2014; Ubertini et al., 2017). Thermal dilatation due to the increase in temperature leads to an apparent stiffening of the GTV by the closure of pores and cracks. This phenomenon is illustrated in Figure 6.10a by a phase shift in time between temperature and frequency variations due to thermal inertia. The positive correlation deviates from the linearity over 13-14°C (black arrow in fig. 6.10b) and natural frequencies tend to increase more significantly above this threshold. This result coincides with observations reported in Cabboi et al. (2017). Our results suggest the decisive role of structural elements and pre-existing weaknesses of the masonry in the expansion-contraction cycles related to daily variations of temperature.

Located in the middle Rhône valley, the GTV is frequently exposed to moderate to strong wind events. The effect of wind may represent an important source of loading for tall buildings (Mendis et al., 2007) and may alter noticeably their response (Azzara et al., 2019; Li, Li, Ou, & Li, 2010; Wu et al., 2017). The time histories of the GTV do not support a correlation ($R^2<0.05$) between frequency variations and wind speed (fig. 6.9a-e, fig. D.3), contrary to the findings from Li et al. (2010) and Wu et al. (2017) for reinforced concrete buildings. We can observe, nonetheless, significant frequency drops corresponding to a softening of the structure during the windiest periods (wind velocities >15 km/h).
Notwithstanding the large uncertainties in the estimation of the absolute coefficients of damping – illustrated by the large scatter among the data –, the variations of the damping ratios evidence a positive correlation with the wind velocity. Figure 6.9b and fig. 6.9e show the coincidence of the windiest periods, for instance on December 10, December 20, 2019 and January 05, 2020, and the damping maxima. More generally the wind dataset exhibits a satisfactory coefficient of determination ($R^2 \sim 0.10$-0.15) when plotted with damping values (fig. 6.10c). Despite the reduced sample size of windy hours, the covariance tends to increase as wind speed increases. This observation is in agreement with conclusions from Wu et al. (2017) and Azzara et al. (2017). In the case of strong wind velocities, wind speed turns out to be the dominant contributor in terms of ambient excitation, driving thus the Tower's response. The wind has, nevertheless, a lesser influence on the torsion mode (fig. 6.10c). In addition, damping variations seem to correlate simultaneously with the humidity level (fig. 6.9b-d). Although this finding is not surprising due to the strong impact of wind velocities on the degree of moisture, it raises the strong interdependency of many meteorological factors.

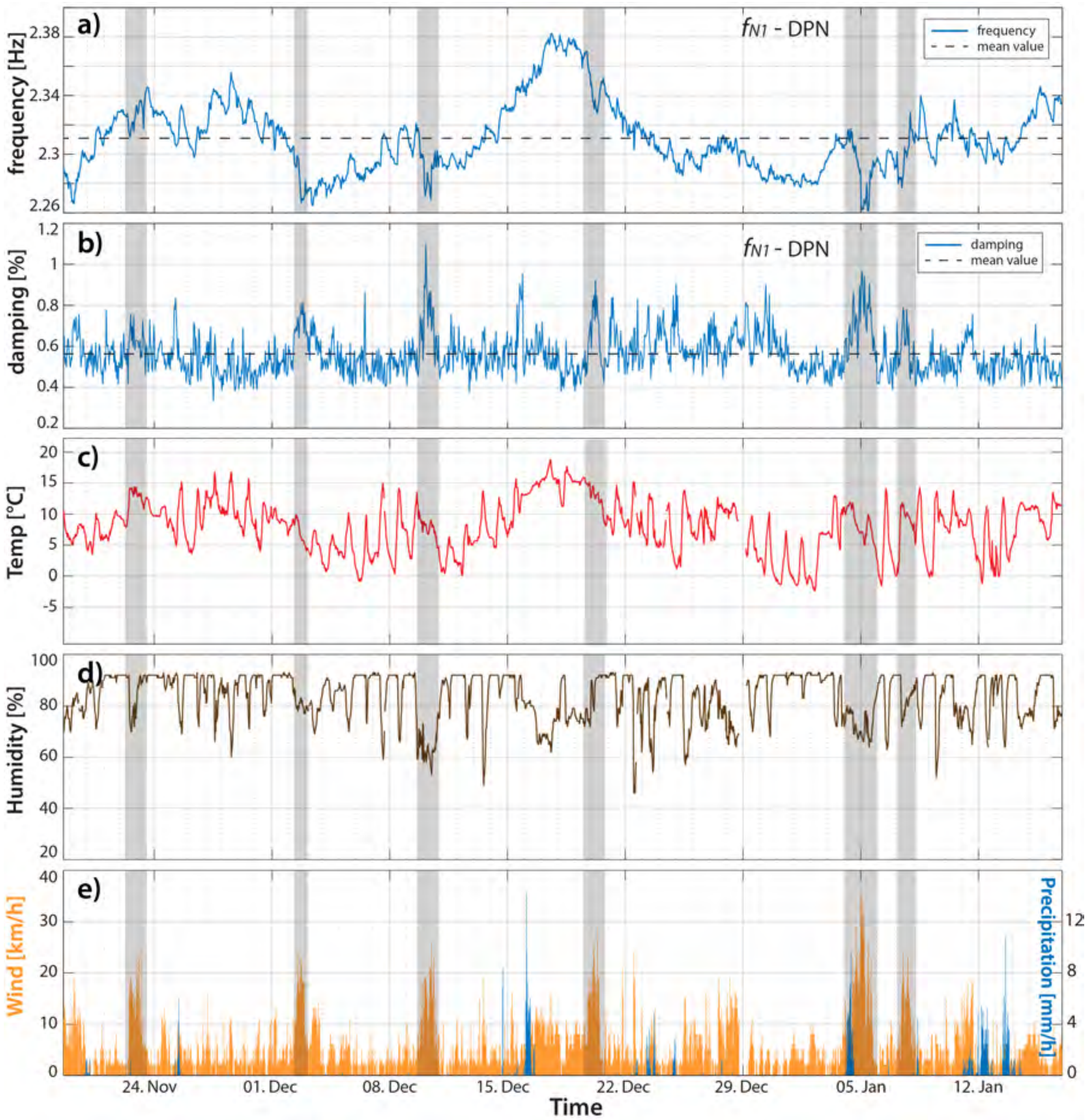

Figure 6.9: Frequency and damping fluctuations (a and b) of the first bending mode in the N-S component (f_{N1}) compared to the variations of weather parameters: temperature (c), moisture (d), wind and precipitation (e). Shaded areas indicate the windiest periods.

In addition, we were not able to see any clear correlation between the temperature and the damping variations (fig. D.3). The effect of the stiffening observed on frequency during the hottest periods has no impact on damping or is completely blurred by the wind gusts. Finally, rainfalls do not show any appreciable effect on frequency and damping variations. However, a correlation cannot be ruled out due to the scanty amount of precipitation recorded during the monitoring period.

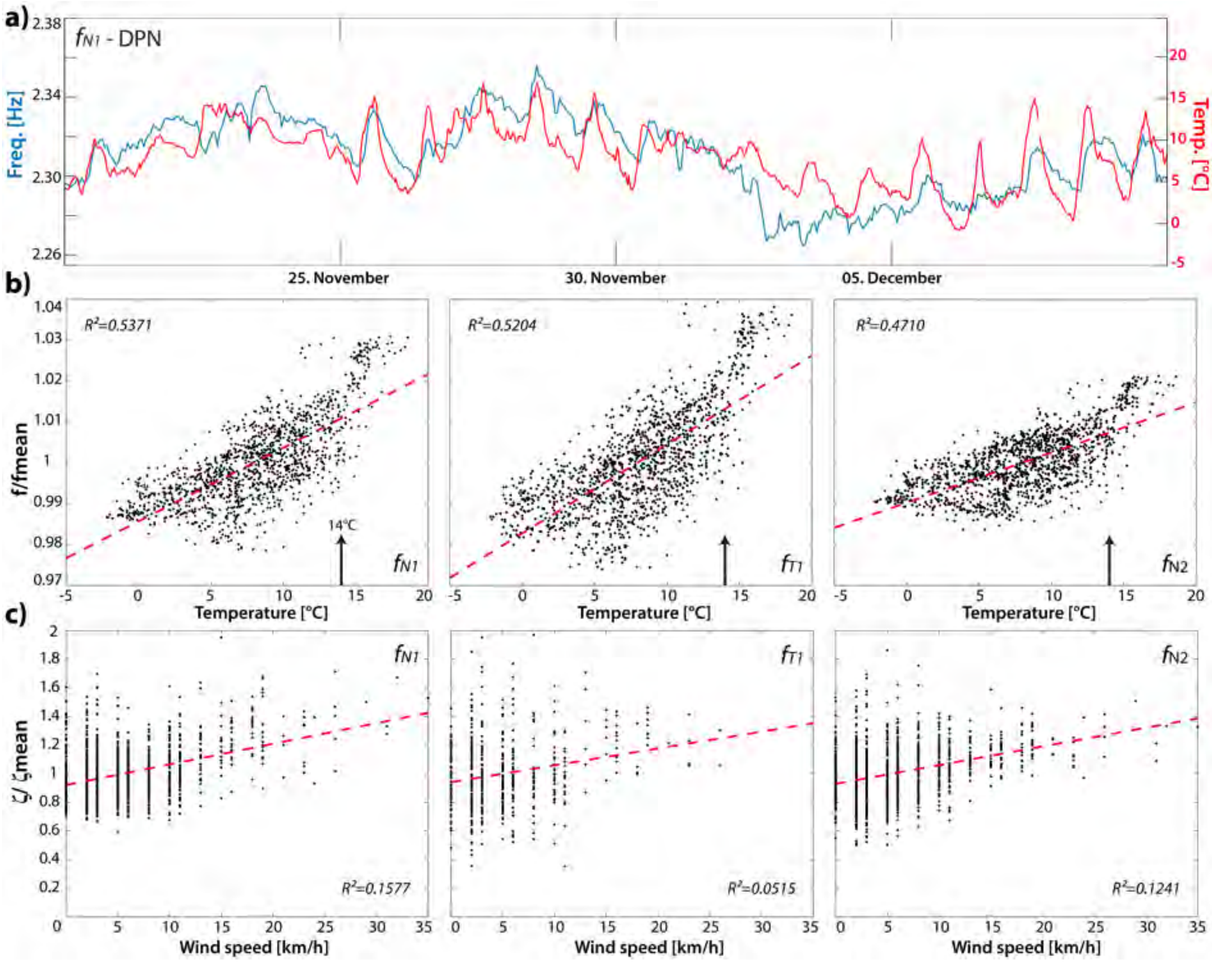

Figure 6.10: a) Fluctuations of the frequency of the first bending mode in the N-S component (in blue) and the temperature values (in red) measured between Nov. 20 and Dec. 10, 2019; b) Correlation between temperature and normalized frequency for the first bending mode, the torsion mode and the second bending mode (left to right) in the N-S component; c) Correlation between wind speed and normalized damping for the same modes as b). Despite the large scatter of point clouds, the data seem to follow linear relations. Plots are based on the recordings of N19.

Summarizing the main observations:

- The rise of temperature induces an apparent stiffening of the building. Unlike reinforced concrete buildings, historic masonry structures are highly heterogeneous media. Pores and cracks that characterize the eleventh-century construction make it particularly sensitive to thermal effects;

- Strong wind gusts that periodically affect the middle Rhône valley represent a major source of atmospheric loading, influencing therefore strongly the damping variations. However, the wide dispersion of the results displayed in Figure 6.10c highlights both the uncertainties related to the estimation of the damping (Kareem & Gurley, 1996) and the complex nature of its wandering in structures (Guéguen et al., 2016; Mikael et al., 2013). This modal parameter seems to be "loading dependent" and is therefore mainly driven in our case by the wind forcing;

- Accordingly, our results support rather uncorrelated variations of the frequency and damping values. The results presented in this section demonstrate that both structural parameters are conditioned mainly by distinct external factors. Whereas frequency appears to be exclusively temperature dependant, the damping ratio seems to be influenced particularly by the wind velocity. In other words, notwithstanding the wide spectrum of environmental factors that may have an impact on the dynamic response of buildings, temperature controls predominantly the stiffness of the building, while wind blow has a higher impact on damping fluctuations. In both cases, weather conditions lead to significant variations of modal parameters regarding the first vibration modes ($f \sim 3\%$ and $\zeta \sim 60\%$).

6.3.3 Nonlinear elasticity

Several works at different scales have yet observed significant alterations of the elastic properties of materials and structures under moderate loadings and not associated though to apparent damage (Brossault et al., 2018; Johnson & Sutin, 2005). The causes behind this phenomenon remain unclear but seem to be related to the rearrangement of the internal components of the material and/or structure, entailing variations in their physical properties (Brossault et al., 2018; Guyer & Johnson, 2009). Highly heterogeneous and fractured media, the historic masonry buildings might be particularly sensitive to nonlinearity. The variations of modal parameters are then studied as a function of the deformation of the GTV, computed as the structural drift between the top and the bottom (D).
We calculated the mean drift for the 1,426 one-hour time windows of ambient vibrations and compared it with the associated frequencies and damping values (fig. 6.11). We, first, filtered around the resonant frequencies in order to assess the deformation related to each vibration mode of the Tower. Then, the displacement was obtained by integrating the velocities following the recommendation of Boore (2005). The drift value for each 1h-window

was then calculated as the difference of the root mean square (RMS) displacements at the top (N19) and at the base (N28) of the structure divided by its height (37 m). Moreover, the dataset was divided based on temperature intervals (ΔT=2°C) to reduce as much as possible the influence of this weather parameter detailed in 6.3.2.

Figure 6.11a-b displays frequency and damping variations of the first bending mode in the N-S component (f_{N1}), as a function of drift, for the temperature interval 8-10°C. Frequency and damping coefficients were normalized by the first 10% of the dataset corresponding to the lowest drift values, i.e. representing the frequency and damping values of the linear domain (f_0 and ζ_0 respectively). Three transient events fall within the temperature interval: the November 23, 2019 aftershock as well as the two quarry blasts. According to Guéguen et al. (2016) who demonstrated the applicability of the RDT on short time windows to track sudden variations of modal parameters associated with ground shakings, we calculated the frequency and damping coefficients on 40 sec. and 15 min. windows, respectively (stars and diamonds in fig. 6.11a-b).

In a similar manner to previous studies on reinforced concrete structures (Guéguen et al., 2016) and modern brick masonry buildings (Michel, Zapico, Lestuzzi, Molina, & Weber, 2011), the results highlight a clear nonlinear behaviour independently from temperature fluctuations. Regarding f_{N1}, we note a first trend (fig. 6.11a) with stable frequency and damping values (<1% fluctuations for frequency and <20% for damping). Over a certain threshold D_0 ($\sim 10^{-8}$), the stiffness of the structure appears to decrease significantly (2-3%) and the damping increases (40-80%).

Regarding the effect of transient events recorded during this specific temperature interval, the results fit well with the global trend discussed above. The drift values associated with the one-hour windows including the considered ground shakings (coloured dots on fig. 6.11a-b) do not attest properly from the deformation following the events. The magnitude and duration of the events are indeed too small to induce noticeable changes on one-hour windows. More surprising, drift values calculated on 40 sec. (f-variations – stars on fig. 6.11a) and 15 min. (ζ-variations – diamonds on fig. 6.11b) windows do not exceed much the range of values from ambient vibration recordings.

Drift results from the GTV are in agreement with the observations of Michel et al. (2011) and Guéguen et al. (2016) who identified, within the elastic domain, a threshold in the dynamic behaviour of masonry structures beyond which internal micro-cracks start to open progressively, modifying the overall response of the structure to dynamic strains. In our case, the onset of the nonlinear elastic response (D_0) appears at much lower drift values (fig. 6.11a-b) than documented by the previous authors for reinforced concrete and modern brick masonry structures. This finding is not surprising owing to the high heterogeneity level of the building that is indeed controlling the nonlinear response (Astorga et al., 2018; Brossault et al., 2018).

As noted in Section 6.3.2, the damping values are more scattered than natural frequencies and part of this dispersion cannot be explained by the sole calculation uncertainties (Guéguen et al., 2016). Figure 6.11a-b shows the linear fits of the frequency (f(D)=a*log(D)+c) and damping variations (ζ(D)=b*log(D)+d) and their associated slope values under and over D_0 (a_1-b_1 and a_2-b_2 respectively). The slope values over D_0 are more than ten times higher for damping coefficient (b_2 in fig. 6.11b) than for natural frequencies (a_2 in fig. 6.11a) that highlights the stronger sensitivity of the damping to the level of strain and loading. As demonstrated on Plexiglas and limestone beams by Brossault et al. (2018), the level of damping variation under weak loading is directly correlated to the heterogeneity of the material according to the fluctuation-dissipation theorem. In our case, the sharp rupture of the slope over D_0 confirms, therefore, the highly heterogeneous nature of the Tower and suggests a significant role of those heterogeneities in the damping values under low levels of strain.

Figure 6.11c presents the values of the slope b_2 of the linear fit (ζ(D)=0.8585*log(D)+6.7570) applied to the damping values over D_0 for each ΔT. b_2 values increase gradually with the increase of the temperature until reaching a maximum at around 13-14°C.

Brossault et al. (2018) have shown the relation between the inner heterogeneities of beam-like structures and the slope of the damping values variation under weak loading. Applied to the GTV, this reflects the variation of the inner structure of the tower with temperature (e.g., the number of opened cracks), which influences the wandering of the damping values observed under weak loading. This wandering reflects the activation of the number of cracks with the amplitude of the loading (in our case the wind speed). At a certain value of temperature (13-14°C), the slope of the linear damping – and loading – relationship is not changing anymore, explained by the stable inner structure above this temperature and the constant number of activated cracks. Thus, the apparent stiffening of the GTV with the increase of temperature (fig. 6.10b) below 14°C would be due to the closure of the structural defaults (Cabboi et al., 2017), associated with the increase of b_2. The reduction of the b_2 slope above 14°C coincides with the faster increase of natural frequencies mentioned earlier (black arrows in fig. 6.10b). The underlying processes that explain this observation are not yet identified but the role of the structural heterogeneities (e.g., cracks) is assumed, in relation to the expansion-contraction cycles related to thermal effects and the influence of the multiphasic structure of the masonry (particularly the

mortar interface). Further research is needed to assess a possible correlation and address the complex contribution of the factors driving the damping variation.
However, we support that the very strong structural heterogeneity, which characterizes historic masonry buildings, constitutes one of the main contributors of this nonlinearity (Brossault et al., 2018; Guyer & Johnson, 2009) and might be responsible for the very low threshold D_0 observed herein. The complex building fabric of the Tower, composed of limestone blocks of different sizes connected with a heterogeneously distributed soft mortar echoes well, although at a different scale, with the “bond system” described by Johnson and Sutin (2005). The block-mortar interface as well as the numerous pre-existing fractures and vulnerabilities that characterize old masonries may act as the “bond system”, increasing the energy dissipation through friction and dilatation.
This discussion raises the further issue: is an ambient vibration-based instrumentation of a historic masonry building sufficient to monitor slight and progressive degradations of its structural state? The results confirm the interest in tracking and quantifying the nonlinear behaviour of the damping coefficient, and this despite the difficulties to estimate it precisely in complex systems like buildings. More sensitive to the level and distribution of heterogeneities, this parameter might become a relevant proxy for SHM and a relevant warner of damage, at an early stage (Brossault et al., 2018; Guéguen et al., 2016; Modena, Sonda, & Zonta, 1999).

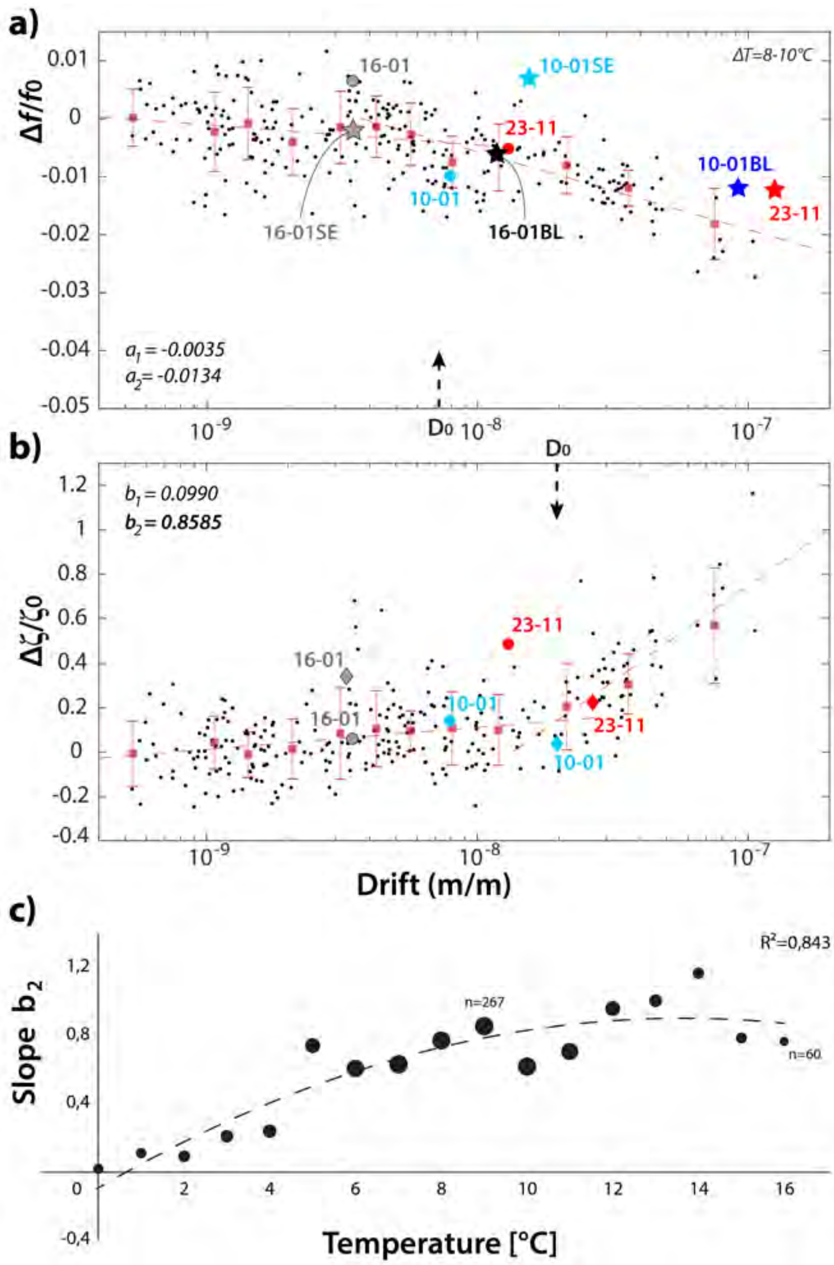

Figure 6.11: Variation of the normalized frequency (a) and the associated damping (b) of the first bending mode as a function of the drift of the structure for the temperature interval 8-10°C. Error bars indicate the average (red square) and standard deviation values (vertical red lines) computed by bins of 23 consecutive values. Large coloured dots correspond to the one-hour windows including the Nov. 23 aftershock and the two quarry blasts. Coloured stars and diamonds correspond to values calculated respectively on 40 sec. and 15 min. windows containing those transient signals. On 40 sec. windows, we distinguished between the GTV's response to the seismic (SE) and acoustic (BL) signals of the quarry blasts; c) Evolution of the damping variations according to thermal conditions. Dots are scattered by the size of the sample.

6.4 Conclusions

As Ahmad and Ali (2017, p.4) noticed, "the behaviour of masonry material is dramatically different from the counterpart concrete and steel material due to high non-homogeneity and composite nature of masonry components." This strong heterogeneity "makes the masonry behaviour difficult to predict." The concern is thus even more acute for cultural heritage buildings. Conducting ambient vibration measurements has proved to be a valuable tool to deepen the knowledge on their global dynamic behaviour, develop more realistic numerical models (Sivori, Lepidi, & Cattari, 2020), improve the seismic response predictions and support the decision-making (Ercan, 2018; Reuland, Lestuzzi, & Smith, 2019) while limiting our imprint on those vulnerable structures. The M_w 4.9 Le Teil earthquake, i.e. the strongest seismic sequence in mainland France since the 1967 Arette and 1996 Epagny earthquakes, stresses the necessity to foster research even in areas affected by a low to a moderate seismic hazard. The instrumental survey implemented in the GTV immediately after the mainshock contributes to improving our understanding of a complex and emblematic monument of the middle Rhône valley. More generally, our work acts as a baseline and demonstrates the relevance of several methods for the analysis of the elastic response of ancient masonry buildings to both quasi-static (atmospheric) and dynamic (aftershocks and blasts) loadings.

In a first step, the OMA allows the identification of the first six structural modes of the GTV. The moderate transient signals recorded during its monitoring confirm the empirical structural model obtained from the ambient vibration data but reveal a different response of the monument to very near ground shakings. An interesting additional finding: historic masonry structures may show a remarkably strong sensitivity to acoustic blasts generated by nearby triggered explosions.

Secondly, the application of the RDT to the GTV monitoring demonstrates the robustness of this signal processing method to track slight variations of the modal parameters in function of time and the strong influence of environmental factors on their wandering. Our results support a major contribution of temperature fluctuations on the apparent stiffness of the structure while damping variations appear more strongly influenced by the local wind gusts, the primary source of atmospheric loading. The effects of weather conditions are of the same order of magnitude or even stronger than those of the aftershocks and quarry blasts.

Last but not least, we highlight the non-linear elastic response of the unreinforced masonry constructions under particularly low levels of strain and stress the major role of the heterogeneities and pre-existing fragilities in dissipating the energy. While previous studies have yet demonstrated the interest in tracking frequency shift for damage identification (Cavalagli et al., 2017; Michel & Gueguen, 2010), our results show the greater sensitivity of the damping ratio to the level of heterogeneity of the structure and the complex interactions existing between the mobilization of those structural weaknesses and the environmental conditions. While further research is required to remove the influence of environmental effects on the fluctuation of the damping coefficient, the present work argues for considering it as a promising tool for SHM and conservation efforts dedicated to the built heritage.

6.5 Data and Resources

Information on the historical seismicity and its impact on the GTV is available on the database of historical earthquakes SisFrance (`https://www.sisfrance.net/`; last accessed December 18, 2021).

The Résif-EPOS (French permanent seismological network) data centre gathers the whole regional seismological dataset into a homogeneous archive and provides access to the data through FDSN web services (Péquegnat et al., 2021). The seismological data and metadata from this survey are therefore freely available through the Résif-EPOS portal (`https://ws.resif.fr/` - last accessed December 18, 2021; network 3C - `http://dx.doi.org/10.15778/RESIF.3C2019`).

Weather parameters were downloaded from an open-access weather station using `https://www.infoclimat.fr/observations-meteo/archives/15/septembre/2019/viviers/000U8.ht-ml#!` (last accessed December 18, 2021 - StatIC network).

Supplemental Material for this article includes the spectral densities of the aftershocks (Nov 18, 2019, Nov 23, 2019 and Jan 02, 2020) and the quarry blasts (Jan 10 and Jan 16, 2020) computed at two free-field stations (VIVI and CLAU - network 3C). Inconclusive correlations between weather and structural parameters are included also.

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6.6 Outlook on the Cusco region

The use of non-destructive testing to monitor and assess the structural integrity of cultural heritage buildings is still relatively uncommon in the Andean region, and notably if we look at the pre-Columbian remains. Aside from the pioneer ambient vibration survey and the modelling attempts of large pre-Columbian adobe and stone masonry (with mortar) monuments conducted by R. Aguilar et al. (2015, 2018), very few works have addressed the dynamic behaviour of the Inca fine dry-stone constructions. The implementation of such kind of earthquake engineering techniques on this type of architecture does not present, though, major difficulties. The simple building geometry, the low complexity of the building fabric (reduced number of constructive phases and architectural features) and the absence of mortar facilitates both the instrumentation and modelling steps, by avoiding numerous approximations regarding the behaviour of specific structural components (e.g., stone-mortar interactions).
To the best of our knowledge, two studies have intended to model Inca masonry (Hinzen & Montabert, 2017; Ogawa, Cuadra, Karkee, & Rojas, 2004). Their objective was to assess the role of the geometry and structural parameters, such as the friction coefficient, in the wall's resistance to ground shaking. While Ogawa et al. (2004) conclude that the Inca megalithic walls tend to behave as single rigid body in case of a stable and homogeneous friction coefficient, Hinzen and Montabert (2017) demonstrate that the polygonal walls are more resistant than rectangular block walls to ground motions. Showing more contrasted

results for test with real earthquake records than for cycloidal pulses, the latter study insists, nonetheless, on the complex response of the walls submitted to transient loadings. More broadly, these works emphasize the significant role played by the structure's shape and dimensions (height/width ratio) in the earthquake resistance. Unfortunately, the scope of both studies remained limited to freestanding walls, making the comparison with field data even more difficult. Finally, although the work of Hinzen and Montabert (2017) did not address the impact of sites effects and processes of amplifications of the seismic signal in narrow frequency bands, the prediction of wall collapse for frequencies of pulses inferior to 2 Hz argues for considering those phenomena in further experiments. In addition, Cuadra et al. (2008) conducted an exploratory ambient vibration survey on Inca buildings of Machu Picchu. Performed on two typical types of residential structures of the Inca architecture – called *Colca* and *Huayrana* – the OMA aimed at calibrating a Finite Element Model, whose objective was to identify the main mode of failure of those structures and adapt, ultimately, the protection measures. Among the main achievements, we may highlight the identification of the dominant frequency of the investigated buildings at around 5.5 Hz. Acquired on strongly restored buildings with more traditional masonry style, these data seem, though, difficult to apply to the finest Inca stonework.

The pioneer investigations carried out on the dynamic behaviour of Inca buildings are still exploratory and are not sufficient to contribute to our scientific issue. Besides, some of the previous results turn to be inconsistent. While Hinzen and Montabert (2017) conclude that the differential block sliding (internal deformation) increases with increasing frequency content, the multiple rigid body model of Ogawa et al. (2004) supports the occurrence of larger displacements with low frequency signals. Hence, further research on the frequency response and variations of the modal parameters are needed to question the development of an intentional earthquake resistant design within the Cusco area during Inca times.

Based on the fruitful experience of Viviers and the archaeoseismological data presented in the previous chapters, we propose four lines of investigation and detail the analysis that should be done:

- The Inca architecture is characterized by a simplicity in terms of shape and a great importance of proportions that makes it highly standardized. The diversity of buildings' styles results, therefore, in the combination and association of a limited number of architectural features, including the types of rock and stonework, the masonry style and the building size. Aside from the benefits that it provides regarding the instrumentation and characterization of the dynamic behaviour (i.e., quicker and

with a reduced number of sensors), this enables to compare easily the results of the OMA between different structures located in the same place or even in distinct sites. Hence, assessing the dynamic response of Inca buildings may contribute to address the following assumption: despite its earthquake-proof design, does Inca stonework consist of a standardized architecture that does not take into account the local geological setting?
By coupling ambient vibration-based measurements in the sites of Machu Picchu, Pisaq and Cusco on well-preserved and similar structures (fig. 6.12) with H/V measurements (horizontal-to-vertical spectral ratio), we aim to identify potential discrepancies of the frequency response between those remains. Considering the distinct site effects and amplification phenomena within the three sites due to their distinct geological settings (fig. 6.13), the collected data may cast a new light on the Inca constructive culture. Are they any significant response discrepancy between similar buildings? And if so, is it due to architectural adaptations?

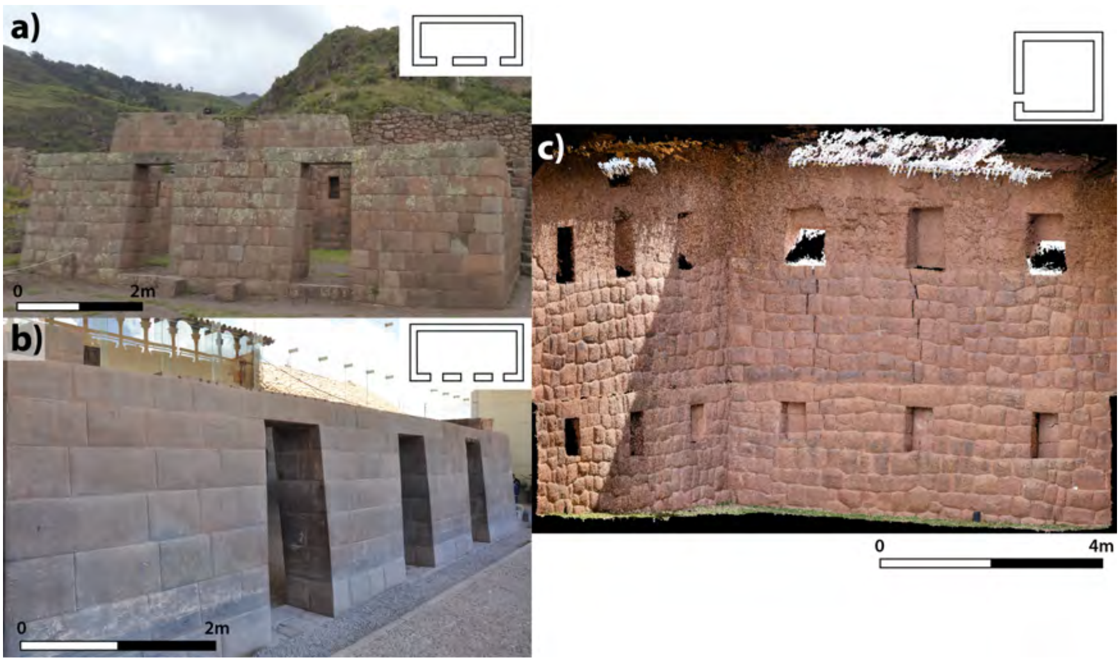

Figure 6.12: Rectangular buildings with a) two doorways in the *Intiwatana* sector of Pisaq (personal picture), b) with three doorways in the Qorikancha in Cusco (CC license) or, even, c) with two stories in Huchuy Qosqo (point cloud; credit: the author) are very similar structures that constitute variations of the Type 1 defined by Nair and Protzen (2015)

- Among the architectonical features assumed as earthquake-resistant, two might be discussed thanks to our instrumentation: the foundations allegedly shallow and composed of poorly cut stones that act as a shock absorber (Calderón Peñaylillo, 1963) and clamping devices documented in the Qorikancha in Cusco (fig. 6.14), which prevent the sliding of blocks. By analysing the dynamic response of rectangular structures in the Qorikancha in Cusco and in the *Intiwatana* sector of Pisaq we will be able to quantify the soil-structure interactions in both contexts and assess the contribution of clamps, given that such device seem to be reported only in Cusco and Ollantaytambo (Protzen, 1993). This information will constitute relevant inputs for future modelling efforts.

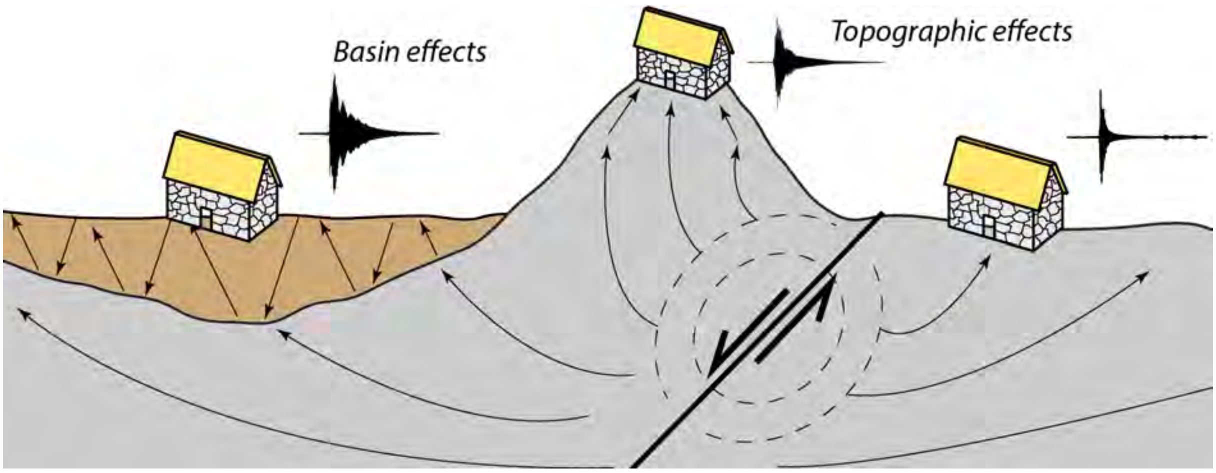

Figure 6.13: While the archaeological remains of Machu Picchu and Pisaq lies on bedrock, on artificially flattened crests, the city of Cusco is built at the edge of a large sedimentary basin. Those distinct geological setting may induce clear distinct local responses to ground motions, as highlighted in this scheme.

- How dry-stone masonry buildings composed of perfectly-fitted stone blocks behave in response to different types of loadings (environmental, anthropic and seismic)? Considering the lack of detailed studies on this topic, our instrumentation will be particularly useful to constrain numerical models, and ultimately compare the damage observed in the field with those predicted. Regarding the seismic engineering field, the results of the Gate Tower of Viviers have shown that ambient vibration-based testing can allow monitoring the modal parameters of the structure and their variations. It will be thus possible to compare the dynamic behaviour of dry-stone masonry with traditional historic masonry constructions involving mortar.

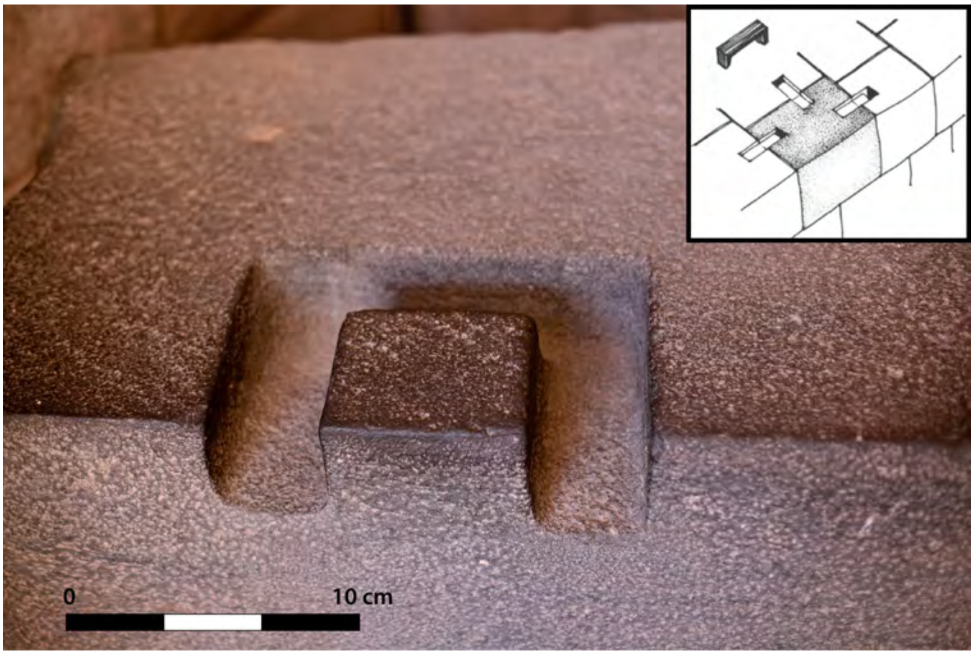

Figure 6.14: Example of a clamp socket on a stone block in the Qorikancha (CC BY-NC-SA license). Inset: Agurto Calvo (1987)

- Finally, apart from the archaeoseismological issues, the instrumentation and the use of passive seismic techniques on the archaeological remains of the Cusco region may serve as a complementary tool for managing the cultural heritage. As an illustration, the Main Temple in Machu Picchu suffers from a severe differential settlement process (fig. 6.15). The punctual instrumentation will provide information on the contribution of the structural damage to its current seismic vulnerability. Moreover, as we shown in the framework of the French survey, a short-term monitoring campaign enables discussing the sensitivity of the modal parameters (the damping particularly) to the structural heterogeneity and the degradation of the building's state. Is it similar in dry-stone masonry? In any case, based on the ambient vibration data we will be able to quantify the amplitude of the anthropic noise, such as the influx of tourists, in vulnerable sites like Machu Picchu and assess its impact on the behaviour of Inca remains.

Figure 6.15: Main Temple affected by a strong differential settlement. Taken a) in 1911-1912 during the Bingham's expeditions (National Geographic) and b) in 2002 (CC BY-NC license). We may note that this process has worsened since then (Carlotto et al., 2007).

This project has three main limitations that need to be considered. First, the investigated pre-Columbian remains are only partially preserved and have no roof yet. Hence, we cannot extrapolate the dynamic behaviour inferred from the current structures to the buildings occupied 500 years ago. On a more marginal scale, the plaster that covers the Inca constructions at that time may has modified slightly the building's response. The results should be treated with caution and turn out to be relevant only for comparative purposes and the improvement of numerical models. Second, due to power issues and maintenance of instruments (even on battery power) on restricted archaeological areas (e.g., Machu Picchu), it is not realistic to plan on keeping material on-site for several weeks or even days. The long-term monitoring of the buildings will require agreements between French and Peruvian institutions. Thirdly, we must keep in mind that they are

still many unknowns on how Inca walls are internally structured. To overtake this limitation and avoid necessary approximations, further architectural and archaeological data is needed to complement the ambient vibration-based analysis.
In this second section we presented the different research axes that should have been pursued during the field campaign planned in 2020-2021 in Peru. This project could not be completed due to the health restrictions related to the COVID-19 crisis.

6.7 Overall summary

Within approximately 50 years, the scope of the OMA has been progressively broadened and such method constitutes now a key step in the conception and monitoring of civil engineering structures, notably in order to address the seismic vulnerability. Regarding historic buildings and archaeological remains, the technique is though slow to be implemented. Given the current heritage value of these monuments but also the past constructive knowledge they represent, improving our understanding on their dynamic behaviour is all the more crucial. Such approach allows identifying both the factors of seismic vulnerability and resistance.
As we demonstrated through the case study of Viviers, a reduced number of sensors enables to reach a sufficient resolution to perform the OMA on large historic structures and assess the existing interactions between the structural components and the external sources of loading. As the quantitative approach is now becoming an integral part of the archaeoseismological field, there is an increasing need to get more robust and precise predictions. In this regard, the ambient vibration-based testing turns out to be particularly suited to characterize the dynamic behaviour of the Inca structures and contribute, quickly and at little cost, to modelling efforts.
We also support that the implementation of such experiment on several similar structures and the comparison of the results will contribute significantly to the discussion about the Inca earthquake-proof knowledge. Hence, we believe the OMA constitutes a promising archaeoseismological technique to bridge the gap between the quantitative approach of the earthquake engineering and the qualitative perspective on the seismic culture and past risk perception. Finally, as we demonstrated through the example in Viviers, tracking the variations of the building's response might be a relevant proxy of the degradation of its structural state. This non-destructive and non-invasive technique opens up thus interesting avenues for the seismic hazard mitigation and monitoring of the pre-Columbian heritage to any kind of degradation process.

Part IV

General conclusion

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Chapter 7

Conclusion and Perspectives

"The public holds the impression that the mechanism of earthquakes is difficult to understand. However, by looking at the earthquakes traces at the archaeological sites, they can easily understand that in the past, a great earthquake struck the area they reside and left markings."

Sangawa (2009, p.91)

Summary

We opened this work with four questions:

1. Do Inca stone architecture show evidence of ground motions?
2. Did the Inca stone buildings record the impact of "pre-historical" earthquakes?
3. What role did tectonic processes play in the lives of pre-Columbian populations?
4. What is the dynamic behaviour of the archaeological remains?

The aim of these questions was to contribute to a better knowledge of the seismicity and to (re)define the relation between past populations and the telluric hazard in the region of Cusco. We answer the questions by presenting successively three key results of our project, from the lowest to the highest interpretative level. We conclude this section by summarizing the main opportunities and limitations of our approach to the assessment of the seismic hazard and past earthquake perception.

A revised and updated methodology

The development of an unambiguous and robust methodology is a prerequisite for the identification of seismic markers in the archaeological record. Over the past 20 years, several works have led to major methodological advances in archaeoseismology (e.g., Noller & Lightfoot, 1997; Rapp, 1986; Sintubin & Stewart, 2008; Stiros, 1996). Among them, the concept of Earthquake Archaeological Effects (EAE - Rodríguez-Pascua et al., 2011) has enabled a harmonization and standardization of the terminology around seismic damage. However, there was no simple and effective protocol to record in a detailed and orderly way the EAE identified in the field.

Based on what has been developed for repairs in the Roman world (Dessales et al., in press; Dessales & Tricoche, 2018), we designed a relational database entitled RISC (Risque sismique, Incas et Société à Cusco) for the systematic recording of earthquake-induced damage in Inca buildings. This data acquisition and storage system greatly facilitated and accelerated the fieldwork. It also allowed the acquisition of a uniform dataset, regardless of the operator in charge of the recording and the archaeological context considered. The architecture of the database is now freely available (see Chapter 3) and may constitute a template for other types of studies of the built heritage in South America.

Thanks to a straightforward and user-friendly interface, RISC enables the capture of a large amount of data not only on seismic pathologies but also on the geographical and architectural context in which they occur. Key information includes the level of confidence of the seismic origin of the damage and the orientation of the structures affected by EAE. These metadata are particularly useful during the data processing and analysis phases. The numerical simulations of Hinzen and Montabert (2017) point towards distinct deformation patterns of structures, and not damage, according to the direction of highest acceleration. In Chapter 4, we demonstrate that the analysis of the orientation of the EAE is not sufficient to support the directivity of the seismic deformation (Giner-Robles, Pérez-López, Barroso, Rodríguez-Pascua, & Martín-González, 2012; Rodríguez-Pascua et al., 2012). Our results for the Cusco region reveal a strong constraint of the orientation of structures in the orientation of damage. This is obviously the case for block slides (DMB) but also for dipping broken corners (DBC). Nevertheless, we show that it is possible to address the anisotropy of the deformation by sorting and weighting the orientation of the EAE according to the orientation and length of the structures. The objective is to identify an over-representation of damage along a given orientation.

Given the influence of the geometry and orientation of the structures, the identification of distinct orientations among the EAE do not prove, therefore, the impact of multiple

destructive earthquakes. The methodology developed in this project thus contradicts the conclusions of Rodríguez-Pascua et al. (2020) for the site of Machu Picchu and highlights the need for carrying out further experimentation on the influence of seismic signal properties on the damage distribution within archaeological remains.
The approach developed in the framework of this project also included a quantitative component. This component aimed at complementing and improving the methodology detailed above. The ambient vibration based analysis conducted in France, and planned in the region of Cusco (see Chapter 6), should constitute a baseline for the calibration of more complex and consistent numerical models of the Cusquenian stone architecture.

Tracking a major Inca earthquake

The survey carried out in the Cusco region led to the identification of more than 3,400 earthquake-induced damage (medium and high level of confidence) in 14 archaeological sites, thus confirming the impact of past earthquakes on the monumental stone architecture of the Inca period. In the Cusco Basin, the earthquake features seem, moreover, to have been generated by local seismic intensities greater than VII (M.M.). The analysis of the historical data rules out the responsibility of the post-1650 CE seismicity.
In the city of Cusco, the analysis of the EAE affecting the Inca (∼1400-1533 CE) and neo-Inca (∼1533-1650 CE) constructions highlights two distinct patterns of deformation, suggesting the occurrence of, at least, two violent earthquakes, one of which would have occurred before the construction of the neo-Inca buildings, i.e. before the Spanish Conquest (see Chapter 4).
Furthermore, the account of the indigenous chronicler Pachacuti Yamqui also seems to refer to a major earthquake that would have occurred in Inca times. The emergence and route of the serpent-like creature, the Amaru, described in this legendary episode are indeed similar to the propagation of a surface rupture associated with the Tambomachay-Pachatusan fault segment (∼20-30 km in length) located north of the Cusco Basin. Several elements, such as the locations of the snake's route, its size and shape, are in strong agreement with the normal faults layout and their behaviour during a rupture. Although the chronicle originates from the oral tradition and has a fantastic dimension, the event is precisely dated. It would have occurred at the same time as the birth of the first child of the Inca ruler Pachacuti, that is to say around 1440 CE (Rowe, 1945).
It is too early to conclude that the earthquake referred to in the legend corresponds to the one that caused damage to the Inca buildings of Cusco before the colonial period. However, several elements are worth to be mentioned. Based on the empirical relations

of Wells and Coppersmith (1994), the alleged surface rupture could result from an earthquake of $M_w \geq 6.5$, sufficient to generate a seismic intensity equal to or greater than VIII in the Cusco Basin and cause accordingly damage to the Inca constructions. It should be noted that the cluster of sites showing consistent orientations of deformation and described in Chapter 4 is located in the immediate vicinity of the Amaru's route (fig. 7.1). Finally, the date of the emergence of the creature suggests the occurrence of an earthquake during the Imperial period, i.e. at a time when the prospected sites were probably already built, or under construction.

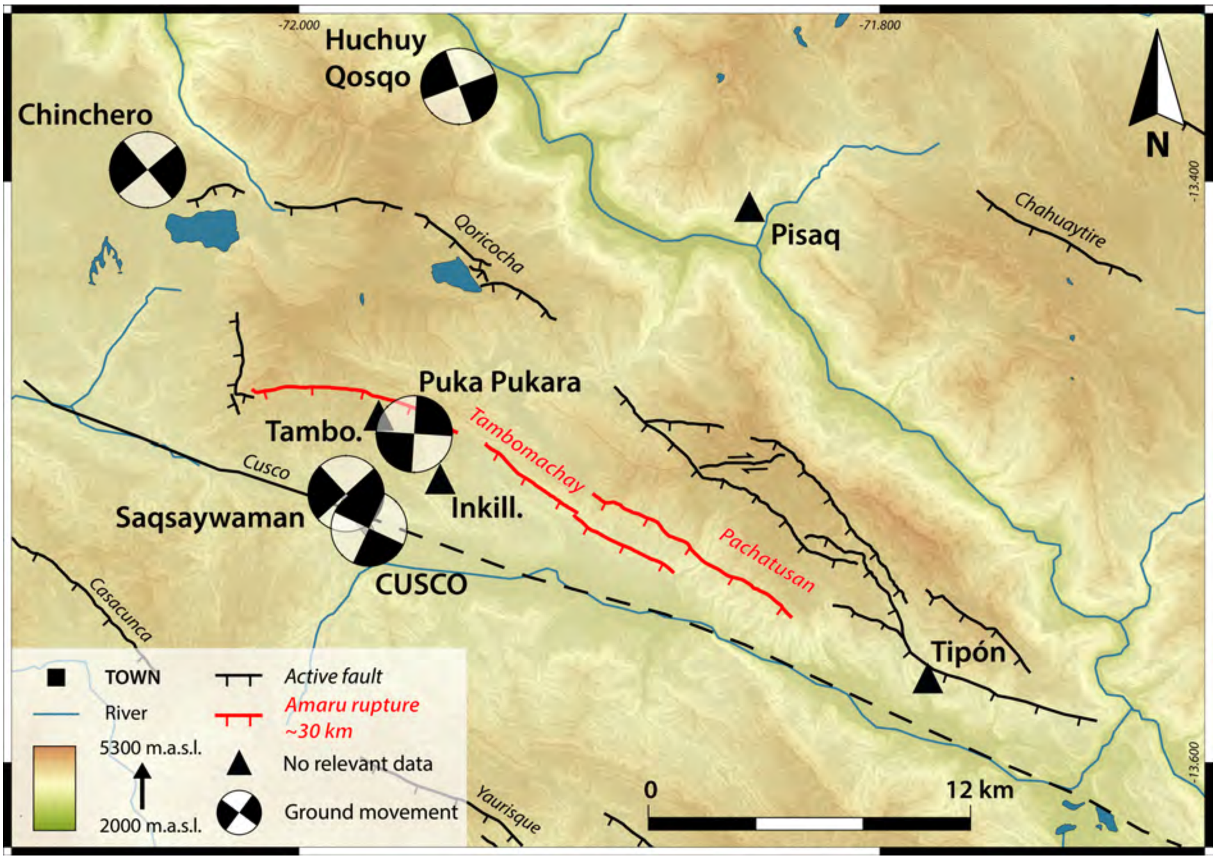

Figure 7.1: Map summarizing the data coming from the archaeological site survey and the reinterpretation of ethnohistorical sources. Archaeological sites with consistent orientations of ground movement lies near (< 10 km) the surface fault rupture inferred from the Pachacuti Yamqui narrative (in red).

The Incas, a seismic culture?

As we have just pointed out, the Inca monuments bear the traces of the seismic activity of the last 600 years. Nevertheless, several pieces of evidence points towards a high degree of resistance of the high-status stone architecture to earthquakes. These include the massive nature of the constructions (Hinzen & Montabert, 2017), the complex nature of the masonry (Calderón Peñaylillo, 1963), and the damage threshold estimated around M.M. ~VIII in this work. What about its design, however? Did the Incas intentionally develop a seismic culture?

A local seismic culture results from the entrenchment of specific knowledge, cultural and architectural practices within society in order to cope with the seismic hazard (Ferrigni, 1990; Ferrigni et al., 1993; Ortega et al., 2017). This comes with the development and persistence of an empirical knowledge about the local seismic activity. This culture is not based on economic principles but aims at "minimizing the disadvantages and maximizing the advantages of a given natural and social environment" (Helly, 1995, p.794). Several results of this work are worth discussing in the light of this concept.

The tectonic context of the Cusco region does not correspond to the conditions conducive to the establishment of a seismic culture (Ferrigni et al., 1993). The long recurrence periods that characterize the crustal seismicity (~2000 years), i.e. violent earthquakes (M_w>6) not occurring every generation, suppose a progressive disappearance of specific skills and collective memory. The relationship maintained by the populations with the seismic hazard/risk is nevertheless complex and sometimes even counter-intuitive. Although the link between perception and risk preparedness remains controversial, the contribution of public/collective actions and beliefs is now considered to be decisive (Becker, Paton, Johnston, & Ronan, 2013; Marincioni et al., 2012; Wachinger et al., 2013).

Although few violent and damaging earthquakes have been documented in the Cusco area, our work pointed out the regular occurrence of a moderate seismicity, which punctuates the life of the local inhabitants (unlike other places in Peru or Chile far from the subduction). Moreover, by demonstrating the occurrence of one, or more, major earthquakes before the Spanish conquest (see Chapter 4), our work shows that the late pre-Columbian populations experienced just as much of the ground motions and had probably suffered severely from their consequences.

Furthermore, while evidence of constructive strategies for coping with earthquakes remains tenuous, evidence of a strong collective memory of earthquakes is established. Except from the tradition of the *Señor de los Temblores*, which emerged in the 17^{th} century and originated probably from the pre-Hispanic culture (Altez, 2017), our study

has demonstrated that there was a true pre-Columbian oral tradition attached to telluric phenomena. The legend of Pachacuti Yamqui (see Chapter 5) suggests that the Incas had an acute knowledge of their landscape and the tectonic processes that may take place there. Bouysse-Cassagne (1988, 2006) stresses the key role that the environment played in the social existence of Andean populations and in their memorization processes. The narrative suggests a form of rationalization of the inexplicable, i.e. the ground motion, through myths rooted in the sacred landscape of Cusco. The legend thus becomes a means of fixing the event in the memory and belief system, perhaps contributing to a collective awareness of the seismic risk (Ibrion, 2018).
Finally, the use of methods from civil engineering such as ambient vibration measurements is particularly promising to improve our understanding of the Inca constructive culture. Although we were not able to implement the instrumentation planned in Peru, the French case study (see Chapter 6) demonstrates the relevance of such an approach to characterize the dynamic behaviour of a massive historical stone structure. The modal analysis emphasizes the contribution of certain architectural elements in the dynamic response of the whole building and highlights the potential soil-structure interactions. Pending a better dating and understanding of the origins of the Inca stone architecture, the comparison of OMA results on several similar buildings represents an unprecedented opportunity to characterize Inca construction strategies and decipher their motivations.
At this stage, it turns out to be difficult to decide whether the Incas were a seismic culture or not. Nevertheless, our results shed new light on this issue and demonstrate the relevance of archaeoseismology in fostering archaeological and anthropological discussions.

Opportunities and challenges of the approach

Opportunities:

- **A-** The archaeoseismological survey provided the opportunity to develop, for the first time, a simple tool adapted to the identification of earthquake-induced damage. This data collection, storage and management system not only facilitated the fieldwork, but also provided an interface model for the registration of deformation features on the historical and archaeological heritage;

- **B-** The analysis of architectural and historical data has provided empirical insights on the seismic resistance of the Inca fine stone architecture. The collected data support a low vulnerability of the building to seismic intensities equal to or less than VII (M.M.);

- **C-** Studying the Inca remains has extended the time window of the regional seismic catalogue by about 150 years and has revealed the occurrence of at least one violent earthquake in the vicinity of the Cusco Basin;

- **D-** Through a geomorphological analysis and the reinterpretation of an indigenous legend, it was possible to open a new field of investigation addressing the relationship between pre-Columbian populations and their tectonic environment. The ethnohistorical study suggests indeed a completely new dimension of the figure of the snake in the Andean cosmology, probably intimately associated with tectonic processes;

- **E-** Carrying out ambient vibration measurements on archaeological buildings allows assessing the impact of geometry and architectural components on the dynamic response of a structure. In addition, the monitoring of modal parameters offers the opportunity to quantify the impact of environmental and anthropogenic parameters on its behaviour;

- **F-** In a similar manner to Machu Picchu, where the seismic risk was until then underestimated or even ignored (Carlotto et al., 2007), our approach has allowed to break down some postulates and received ideas, which are particularly detrimental from the viewpoint of the archaeological heritage preservation.

Challenges:

- **A'-** The assessment of the seismic origin in the RISC database is based on well-established criteria but remains qualitative due to fieldwork requirements. This type of assessment introduces an additional subjective dimension to the data collection phase;

- **B'-** The impossibility of carrying out an instrumentation of Inca buildings (prohibited access to the field in 2020-2021 due to the health crisis) significantly limits the quantitative dimension of this work. The characterization of the dynamic behaviour of the structures through an ambient vibration based survey would have provided complementary information on the resistance/vulnerability factors;

- **C'-** Without repairs, damage to buildings accumulates and even worsens. The semi-quantitative analysis of the deformation features on archaeological remains does not make it possible to differentiate the potentially repeated effects of several seismic events. It is therefore impossible, at this stage, to make any assumptions about the exact number of episodes that affected the Inca architecture, except in Cusco;

- **C"-** It is very difficult to date the damage precisely because of the numerous dating issues of the Inca architectural phenomenon and the lack of identifiable constructive sequences in the buildings. In most cases we can only propose a *terminus post-quem*;
- **D'-** Due to a lack of awareness among archaeologists, there is still very little evidence of seismic activity in the archaeological record in Cusco and the interpretation of destructive contexts is often lacking. It is thus very difficult to get a comprehensive regional picture and a real discussion of the interactions between past societies and telluric hazards. This gap represents one of the major challenges to be taken up in the future;
- **E'-** The scope of passive seismic techniques corresponds to the analysis of the behaviour of structures under low levels of loading. It is most often restricted, therefore, to the elastic response domain (Michel et al., 2011). Drawing general lessons in terms of vulnerability to transient strong loadings is still a matter of debate;
- **F'-** As McCalpin and Nelson (2009) and Bilham and Hough (2006) noted, pointing out the potential dangers and vulnerability of facilities is not enough to increase public awareness. This should be coupled with a long-term work to make the archaeoseismological approach credible and visible.

Research prospects

The archaeoseismological approach that we have carried out in the Cusco region, which is unprecedented in South America in terms of its scope, has made it possible both to provide new data on the regional seismicity since the 14^{th} century and to question the relationship that pre-Columbian populations had with this hazard (fig. 7.2). Nevertheless, most of the research we have conducted has been hampered by the sparseness, or even absence, of preliminary data and studies, as well as by the deficiencies of the current seismic risk perception. We hope that this exploratory work will pave the way for future projects in the Andes. For Cusco, we detail below several promising lines of research in order to confirm and complete the acquired data. To do so, we propose methods that could be implemented in the more or less long term.

Testing out the hypothesis of the Inca earthquake

Whether it is the data collected during the archaeoseismological survey (see Chapter 4) or inferred from the reinterpretation of the ethnohistorical sources (see Chapter 5), several elements presented in this manuscript tend to support the hypothesis of a major earthquake in the Cusco Basin during the Inca period. Several works can help to corroborate this hypothesis.

<u>In the short to medium term</u>:

- We surveyed 17 archaeological sites in the framework of this project. First of all, it seems necessary to complete the dataset and to increase/densify the archaeoseismological coverage. In particular, the sites of Machu Picchu and Huchuy Qosqo have only been partially studied. We claim that a more systematic identification of damage is needed. Other sites with high-status stone architecture might be visited, such as Mawkallaqta (Pacariqtambo), Moray and satellite sites of Machu Picchu. The acquisition of additional data would allow increasing the regional resolution, identifying potential common deformation patterns at the scale of sub-regions (see Chapter 4) and discussing the geographical distribution of seismic damage.

- In order to meet the time and logistical constraints inherent in a thesis project, this work aimed to identify earthquake-induced damage only in the Inca preserved architecture. Nevertheless, collaborations could be initiated with site curators (e.g., Machu Picchu, Raqchi) and archaeologists to integrate the results of recent excavations into the archaeoseismological analysis. One of the many examples is the currently excavated site of Qotakalli, located 5 km south-east of Cusco that shows strong Inca occupation (Dirección Desconcentrada de Cultura - Cusco, 2015). In case of a major earthquake in Inca times, it is likely that evidence was reported but not interpreted, or even misunderstood.

- Like the OPUR database (repairs in the Roman world - Dessales et al., in press; Dessales & Tricoche, 2018), which is intended to become accessible to all, RISC could be hosted on a remote server to allow free access to the collected information. The database could thus constitute a first step towards the centralization of the archaeoseismological data on Inca architecture.
- Given the likely association between the emergence of a mythological snake and the propagation of a surface rupture on the fault complex overlooking Cusco, it could be interesting to simulate several fault rupture scenarios and predict the maximum ground acceleration (PGA) at various points in the region (P. Silva et al., 2017). These shaking maps could then be compared with field data to discuss the possible link between the mythological event and the seismic damage recorded around Cusco.
- The ambient vibration based survey planned and discussed in Chapter 6 will provide support for future modelling efforts. Simulations will be crucial to identify the properties of the ground shakings required to generate the EAE. In addition, these models will provide explanations for the directivity of the deformation observed in the field.

In the longer term:

- Putting dates on the damage is all the more complex as the Inca fine masonry is poorly constrained in terms of chronology and few repair/remodelling stages seem to be traceable. Among the avenues to be explored is that of the dating by cosmogenic isotopes (Gosse & Phillips, 2001) and in particular the use of beryllium (^{10}Be). Beryllium can be used to date the surface exposure of a rock or soil. In the case of block fractures associated with a seismic event (e.g., Dipping Broken Corners), it would be possible to date the exposure of the fracture planes and therefore the associated seismic event. However, this method faces several important problems, including the relatively large associated dating uncertainties and the authorization for collecting archaeological material on protected sites.

- The analysis of the Amaru legend (see Chapter 5) has brought to light the lagoon of Quibipay, the place where the mythological snake is said to have disappeared. For the first time, we have proposed a precise and well-founded location of this ancient pond, near the present-day locality of Cruz Verde de Quehuepay. Although the lagoon is now dry, two methods would allow us to confirm its location and obtain additional information on its possible tectonic origin. The calculation of the NDVI (Normalized Difference Vegetation Index - Rouse, Haas, Schell, & Deering, 1974) could be carried out using high-resolution satellite images and would highlight the presence of live green vegetation, and therefore water in this area. Besides, a core sample in the area would allow reaching a conclusion on the existence of an ancient lagoon. The study of the stratigraphic sequence, close to the Cusco fault, might also prove to be useful in understanding the formation of this potential sagpond and identifying earthquake markers.

Improving the seismic catalogue of the last 2000 years

In this project, we have focused on the Inca period and the associated massive stone architecture. Thanks to the tools and methods developed, we can consider, though, extending the approach to all types of archaeological and historical remains in the region.

<u>In the short to medium term</u>:

- In contrast to Inca megalithic architecture, which has little or no observable evidence of repair, other architectural styles could be the subject of an in-depth analysis of their constructive history. Usually built on the remains of Inca constructions and reworked several times, colonial walls built in neo-Inca style show numerous deformations features and potential earthquake-induced damage. A stratigraphic approach of buildings (building archaeology - Arrighetti, 2019; Forlin et al., 2018; Poursoulis et al., 2006) would be thus particularly relevant to enhance our understanding of the deformation events and their chronology. This method can also be effectively supported by the use of photogrammetry, as demonstrated by the Master's internship of Sarah Perrinel (2021) on a colonial wall in Cusco. Several colonial constructions in Cusco, probably affected by the 1650 earthquake, could thus be studied using numerical models. By combining historical and architectural analysis, it would be possible to associate deformation features to recent seismic activity and to quantify its impact on neo-Inca buildings.

- Similarly, the 1950 earthquake had a strong impact on many colonial and republican buildings in Cusco. The spatial distribution of damage and the calibration of predictive models could be greatly improved by carrying out a comprehensive survey of the EAE. The data compilation could be fed by the collection of photographs or even periodicals, probably archived in the Municipality of Cusco, which could contain unpublished/salient information (Camassi & Castelli, 2004). Combined with shaking maps, the results would allow drawing up hypotheses regarding the source of the earthquake.

In the longer term:

- The Cusco region has many pre-Incan monumental sites that can be archaeologically prospected (e.g., Pikillaqta, Chokepukio, Pukara Pantillijilla). These consist of adobe and/or rustic stone masonry walls. The architecture of the RISC database, designed to record earthquake damage affecting Inca dry stone architecture, is modular and could be easily adapted to other needs.

- A detailed inventory of the destructive contexts found in the archaeological record as well as the assessment of their origin would be particularly useful. Although this task requires a clear protocol for establishing the cause of these levels (e.g., by means of a confidence index), it would provide a geographical and chronological inventory of disruptions experienced by past societies. Regarding the assessment of the seismic origin of destructive contexts, the protocol could be based notably on the results of experimental archaeology (DezhamKhooy & Yazdi, 2010).

- Finally, archaeoseismology should be coupled with lake coring to identify potential earthquake-induced deposits (e.g., Gastineau et al., 2021). Such a palaeoseismological approach has only be conducted in Lake Huacarpay up until now. Unfortunately, the nature of the lake system has not allowed the identification of event deposits (Babo, 2018; Dumont, 2018).

Understanding better the perception and management of the seismic hazard

The strategies developed by pre-Columbian populations to cope with tectonic processes remain too often neglected, due in particular to the lack of awareness of the seismic hazard among archaeologists. We suggest two avenues of research for a deeper study of the topic:

In the short to medium term:

- As previously developed in the research perspectives in Chapter 6, we urge to instrument several Inca high-status buildings using ambient vibration techniques. This passive seismic method would allow characterizing the dynamic behaviour of the archaeological remains, while the comparison of results between different structures would offer new insights into construction strategies and potential vulnerabilities/adaptations to the geological context.

In the longer term:

- The reinterpretation of the Pachacuti Yamqui legend (see Chapter 5) has led us to question the relationship between the sacredness of the Inca landscape and the regional ongoing tectonic processes. Are some Inca shrines dedicated to the seismic hazard? We believe that specific archaeological surveys near fault zones, combined with targeted test pits and an analysis of the evolution of the settlement pattern in those areas would shed new light on this topic. Amongst others, we could mention (1) the Pachatusan summit, a sacred mountain for the Incas (Silva Gonzales & Loza García, 2007), (2) the Tambomachay valley characterised by a dense archaeological occupation at the foot of the fault and (3) the Raqchi area where the link between the pilgrimage site, monogenic volcanism (Global Volcanism Program) and the faults bordering the basin (Sillar et al., 2013) deserve a thorough examination.

Increasing the protection of the archaeological heritage to earthquakes

Several tools used in this project might contribute to a better monitoring and management of the archaeological heritage.

In the short to medium term:

- A major modelling effort of Inca buildings is now required to go beyond the simple simulations performed by Kamai and Hatzor (2008); Ogawa et al. (2004) and Hinzen and Montabert (2017). The use of finite element method-based models calibrated using ambient vibration data will enable identifying/quantifying the main damage mechanisms of the archaeological heritage (R. Aguilar et al., 2015; Montabert, 2021) and developing more appropriate protection strategies.

In the longer term:

- The implementation of warning and prevention systems is now a priority in heritage management policies in the face of natural risks (ICCROM, 2004; UNESCO, 2007). The RISC database, designed to facilitate *ad hoc* surveys, could easily be converted into a periodic monitoring tool of the degradation of structures (see Chapter 3) in order to address conservation issues. This could be achieved by adding a temporal dimension into the records. A new table could be created to act as a registration sheet, indicating the date of the observation and the severity of the damage. It would then be possible to link this table to the table of architectural damage so that several records might be associated with the same EAE. Such a modification of the database would also make it possible to compare the vulnerability of construction techniques and/or buildings to past ground shaking events and pervasive environmental pressures (Dessales et al., in press).

- The instrumentation of pre-Columbian buildings over several months/years with seismic sensors would be the opportunity to follow the wandering of the damping values and thus to monitor the evolution of the structural health (see Chapter 6).

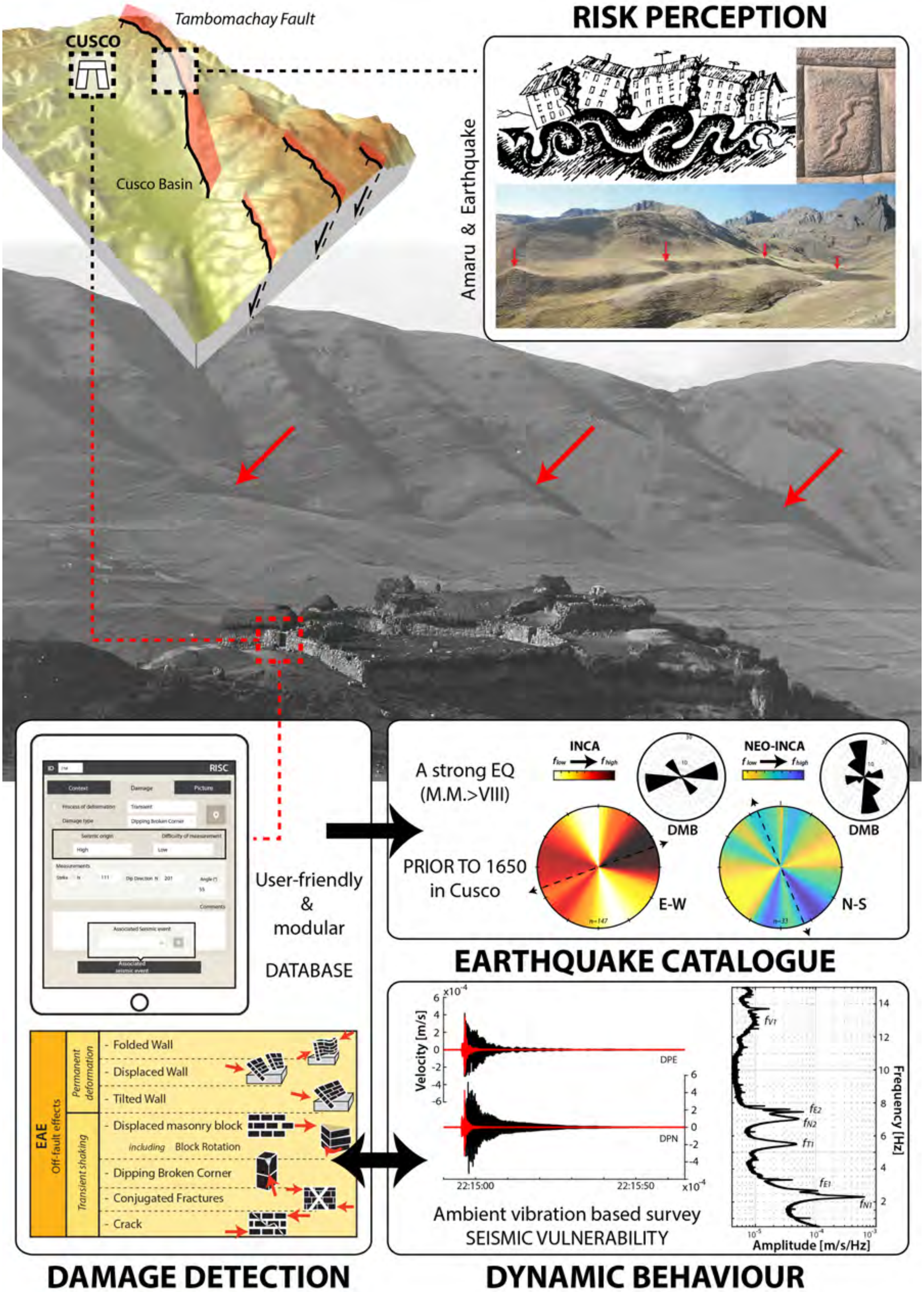

Figure 7.2: Conceptual diagram summarizing the holistic archaeoseismological approach carried out in this thesis. Our work contributed both to the seismic hazard assessment and the past seismic risk perception.

Conclusion et Perspectives

Synthèse

Quatre questions ont amorcé ce travail:

1. L'architecture en pierre taillée inca a-t-elle souffert de l'activité sismique ?

2. Les édifices inca présentent-t-ils des traces de séismes "pré-historiques" ?

3. Quelle place occupaient les processus tectoniques dans la vie des populations pré-colombiennes ?

4. Quel est le comportement dynamique des vestiges archéologiques ?

Ces questionnements avaient pour objectifs de contribuer à une meilleure connaissance de la sismicité et de (re)définir la relation entre les populations passées et l'aléa tellurique dans la région de Cusco. Pour y répondre, nous résumerons successivement trois résultats clefs de notre projet, allant du niveau interprétatif le plus faible au plus élevé. Nous conclurons cette partie en synthétisant les principales opportunités et limites de notre approche pour l'évaluation de l'aléa sismique et la perception passée des tremblements de terre.

Une méthodologie réévaluée et renouvelée

Le développement d'une méthodologie claire et robuste est un préalable à l'identification de marqueurs sismiques dans le bâti archéologique. Depuis environ 20 ans, plusieurs travaux ont permis des avancées méthodologiques majeures en archéosismologie (Noller & Lightfoot, 1997; Rapp, 1986; Sintubin & Stewart, 2008; Stiros, 1996). Parmi elles, le concept des *Earthquake Archaeological Effects* (EAE - Rodríguez-Pascua et al., 2011) a permis une standardisation et uniformisation de la terminologie autour des dommages sismiques. Il n'existait cependant pas de protocole simple et efficace permettant d'enregistrer de manière détaillée et ordonnée les EAE recensés sur le terrain.

À l'image de ce qui a pu être développé pour les réparations dans le monde romain (Dessales et al., in press; Dessales & Tricoche, 2018), nous avons conçu une base de données relationnelle intitulée RISC (Risque sismique, Incas et Société à Cusco) permettant l'enregistrement systématique des dommages sismiques dans le bâti inca. Ce système de saisie et de stockage de données a grandement facilité et accéléré le travail de terrain. Il a également permis d'acquérir un jeu de données uniforme, quel que soit l'opérateur responsable de l'enregistrement et quel que soit le contexte archéologique considéré. L'architecture de la base de données est désormais disponible librement (cf. Chapitre 3) et pourra constituer un modèle déclinable à d'autres types d'études du patrimoine bâti en Amérique du Sud.

Dotée d'une interface simple et intuitive, RISC permet de renseigner un grand nombre d'informations, non seulement sur les pathologies sismiques mais également sur le contexte géographique et architectural dans lequel elles s'inscrivent. Parmi les principaux renseignements, figurent l'indice de confiance sur l'origine sismique des dommages et l'orientation des structures présentant des EAE. Ces métadonnées s'avèrent particulièrement utiles durant la phase de traitement et d'analyse des données. Les simulations numériques de Hinzen and Montabert (2017) indiquent des motifs de déformation distincts des structures, et non des dommages, selon la direction de plus forte accélération. Dans le chapitre 4, nous démontrons que l'analyse de l'orientation des EAE est insuffisante pour conclure à une directivité de la déformation sismique (Giner-Robles et al., 2012; Rodríguez-Pascua et al., 2012). Nos résultats pour la région de Cusco révèlent une forte contrainte de l'orientation des structures dans l'orientation des dommages. C'est le cas, évidemment, pour les déplacements de blocs (DMB) mais également pour les angles de blocs brisés (DBC). Néanmoins, nous attestons qu'il est possible d'examiner le caractère anisotrope de la déformation en catégorisant et pondérant l'orientation des EAE selon l'orientation et la longueur des structures. L'objectif est alors d'identifier une surreprésentation des dommages le long d'une orientation donnée.

Compte tenu de l'influence de la géométrie et de l'orientation des structures, l'identification d'orientations distinctes parmi les dommages n'est donc pas la preuve de plusieurs séismes destructeurs. À ce titre, la méthodologie développée dans le cadre de ce projet contredit les conclusions de Rodríguez-Pascua et al. (2020) sur le site de Machu Picchu et souligne le besoin d'expérimentations plus poussées sur le lien entre propriétés du signal sismique

et distribution des dommages archéologiques.
L'approche développée dans ce projet comportait également un volet quantitatif visant à compléter et enrichir la méthodologie détaillée précédemment. L'analyse vibratoire conduite en France, et prévue dans la région de Cusco (cf. Chapitre 6), doit constituer une base de référence pour la calibration de modèles numériques plus complexes et plus fiables de l'architecture en pierre cusquénienne.

Sur les traces d'un séisme à l'époque Inca

La prospection conduite dans la région de Cusco a mis en évidence plus de 3400 pathologies d'origine sismique (indices de confiance moyen et haut) dans 14 sites archéologiques, confirmant ainsi l'impact de séismes passés sur l'architecture en pierre monumentale de la période inca. Dans le bassin de Cusco, les dommages semblent d'ailleurs avoir été provoqués par des intensités sismiques locales supérieures à VII (M.M.). L'analyse des données historiques écarte, de plus, la responsabilité de la sismicité post-1650 CE.
Dans la ville de Cusco, l'analyse des déformations affectant le bâti inca (∼1400-1533 CE) et néo-inca (∼1533-1650 CE) nous a permis de mettre en évidence deux schémas de déformation distincts, suggérant l'occurrence d'au moins deux secousses violentes, dont l'une serait survenue avant la construction du bâti néo-inca, soit avant la Conquête espagnole (cf. Chapitre 4).
En parallèle, le récit du chroniqueur indigène Pachacuti Yamqui semble également faire mention d'un tremblement de terre majeur à l'époque inca. L'émergence et le parcours d'une créature serpentiforme, l'Amaru, décrits dans ce récit légendaire s'apparentent en effet à la propagation d'une rupture de surface associée au segment de faille Tambomachay-Pachatusan (∼20-30 km de longueur) situé au nord du bassin de Cusco. Plusieurs éléments présents dans le récit, tels que les lieux de passage du serpent, sa taille et sa forme présentent une forte concordance avec le tracé des failles normales et leur comportement en cas de rupture. Bien que le récit provienne de la tradition orale et comporte une dimension fantastique, l'événement relaté est daté précisément. Il serait survenu lors de la naissance du premier enfant du souverain inca Pachacuti, soit aux environs de 1440 CE (Rowe, 1945).
Il est encore trop tôt pour affirmer que le séisme évoqué dans la légende corresponde à celui ayant généré des dommages dans le bâti inca de Cusco avant l'époque coloniale. Plusieurs éléments méritent cependant d'être soulignés. En se basant sur les relations empiriques de Wells and Coppersmith (1994), la prétendue rupture de surface pourrait résulter d'un séisme de $M_w \geq 6.5$, suffisant pour générer une intensité sismique égale ou

supérieure à VIII dans le bassin de Cusco et provoquer des dommages sismiques dans le bâti inca. On notera d'ailleurs que le groupe de sites présentant des orientations de déformation cohérentes, décrit au Chapitre 4, est situé à proximité immédiate du tracé de l'Amaru (fig. 7.3). De plus, la date évoquée pour l'émergence de la créature suggère l'occurrence d'un séisme durant la période impériale, c'est à dire à une période où les sites prospectés étaient probablement déjà construits, ou en pleine construction.

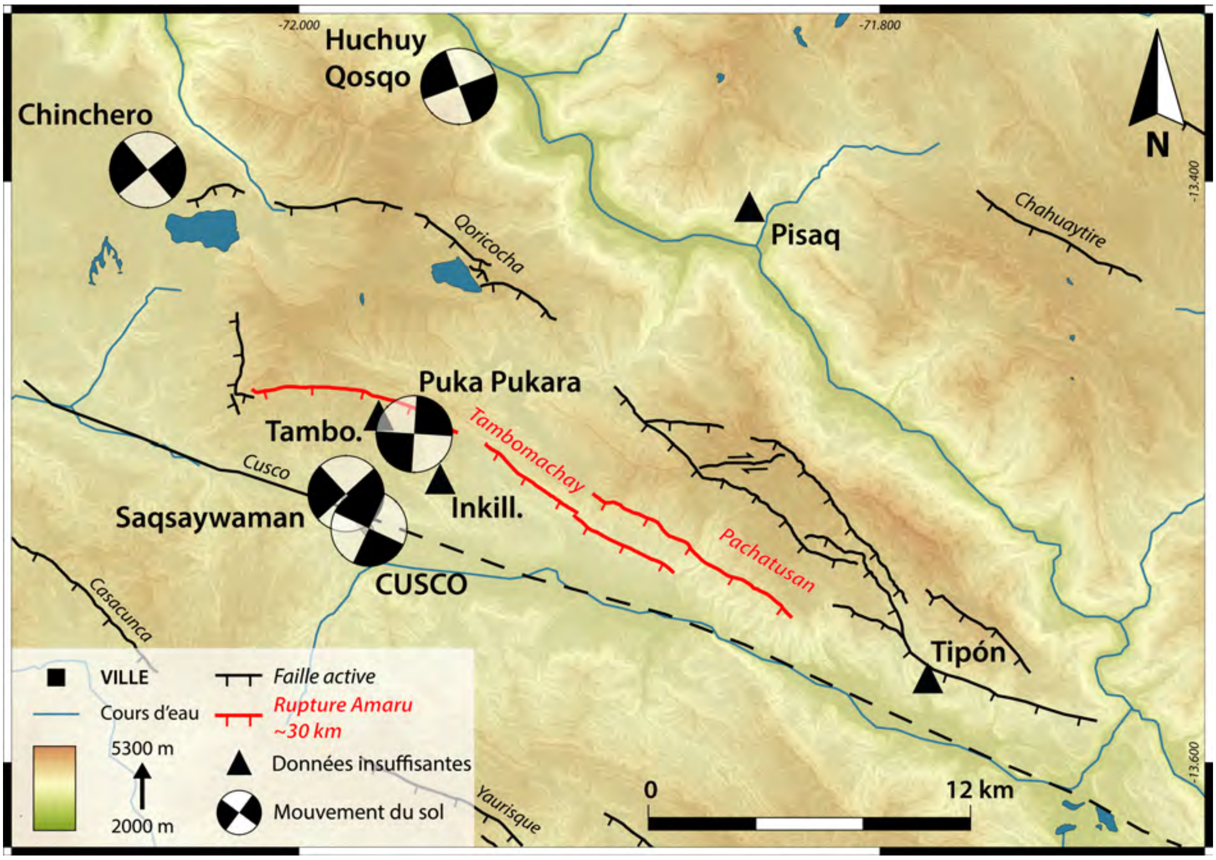

Figure 7.3: Carte synthétisant les données issues de la prospection des sites archéologiques et de la réinterprétation des sources ethnohistoriques. Les sites archéologiques présentant des orientations de déformation cohérentes se situent à proximité immédiate (< 10 km) de la rupture en surface déduite du récit de Pachacuti Yamqui (en rouge).

Les Incas, une culture sismique ?

Comme nous venons de le souligner, les monuments incas ne sont pas épargnés par l'activité sismique des 600 dernières années. Malgré tout, plusieurs éléments indiquent un haut degré de résistance de l'architecture monumentale face aux tremblements de terre. C'est le cas notamment de la nature massive des constructions (Hinzen & Montabert, 2017), du haut degré de complexité des maçonneries (Calderón Peñaylillo, 1963) et du seuil d'endommagement évalué autour de M.M. ∼VIII dans le cadre de ce travail. Qu'en est-il, en revanche, de sa conception ? Les Incas ont-ils développé sciemment/intentionnellement une culture sismique ?

Une culture sismique locale se définit par un enracinement de connaissances, de pratiques culturelles et architecturales spécifiques au sein de la société afin de faire face à l'aléa sismique (Ferrigni, 1990; Ferrigni et al., 1993; Ortega et al., 2017). Elle se traduit donc par le développement, la transmission et la persistance d'un savoir-faire empirique vis à vis de l'activité sismique locale. Cette culture n'est pas fondée sur des principes économiques mais vise à "minimiser les désavantages et maximiser les avantages d'un environnement naturel et social donné" (Helly, 1995, p.794). Plusieurs résultats de ce travail méritent d'être abordés à l'aune de ce concept.

Le contexte tectonique dans la région de Cusco ne correspond pas aux conditions favorables à l'instauration d'une culture sismique (Ferrigni et al., 1993). Les longues périodes de récurrence qui caractérisent la sismicité crustale (∼2000 ans), i.e. des séismes violents (M_w>6) ne survenant pas à toutes les générations, supposent une disparition progressive des savoirs-faire et de la mémoire collective. La relation entretenue par les populations avec l'aléa/risque sismique s'avère néanmoins complexe et parfois même contre-intuitive. Bien que le lien entre perception et préparation face au risque demeure controversé, la contribution des actions collectives et des croyances est aujourd'hui considérée comme déterminante (Becker et al., 2013; Marincioni et al., 2012; Wachinger et al., 2013).

Bien que peu de séismes violents et destructeurs aient été documentés dans la région de Cusco, notre travail a rappelé le caractère fréquent et commun d'une sismicité modérée qui rythme la vie des populations locales (contrairement à d'autres sites éloignés de la subduction au Pérou ou au Chili). En mettant d'ailleurs en évidence l'occurrence d'un ou plusieurs séismes majeurs avant la conquête espagnole (cf. Chapitre 4), notre travail démontre que les populations précolombiennes tardives étaient tout autant sujettes aux caprices de la terre et avaient probablement souffert durement de ses conséquences.

En outre, si les preuves de stratégies constructives pour faire face aux séismes demeurent ténues, les évidences d'une mémoire collective forte et solide des séismes sont établies.

Au-delà de la tradition du *Señor de los Temblores* qui émerge au XVIIe s et puise probablement ses racines dans la culture préhispanique (Altez, 2017), notre étude a permis de démontrer qu'il existait bel et bien une tradition orale précolombienne attachée aux phénomènes telluriques. La légende de Pachacuti Yamqui (cf. Chapitre 5) suggère que les Incas avaient une connaissance aigüe du paysage et des processus tectoniques qui pouvaient s'y dérouler. Bouysse-Cassagne (1988, 2006) rappellent d'ailleurs que l'environnement jouait un rôle crucial dans l'existence sociale des populations andines et dans leurs processus de mémorisation. Le récit étudié laisse envisager une forme de rationalisation d'un phénomène en apparence inexplicable, le tremblement de terre, au travers de mythes ancrés dans le paysage sacré de Cusco. La légende devient donc un moyen de fixer l'événement dans la mémoire et le système de croyances, contribuant peut-être à une conscience collective du risque sismique (Ibrion, 2018).

Enfin, le recours à des méthodes issues de l'ingénierie civile tels que les mesures de vibrations ambiantes s'avère particulièrement prometteur pour mieux comprendre la culture constructive inca. Si nous n'avons pas été en mesure de mettre en œuvre l'instrumentation prévue au Pérou, le cas d'étude français (cf. Chapitre 6) démontre la pertinence d'une telle approche pour caractériser le comportement dynamique d'une structure massive en pierre historique. L'analyse modale souligne la contribution de certains éléments architecturaux dans la réponse dynamique du bâtiment et met en lumière les potentielles interactions sol-structure. En attendant une meilleure datation et compréhension des origines de l'architecture en pierre inca, la comparaison d'analyses vibratoires sur plusieurs édifices similaires représente une opportunité inédite de mieux caractériser les stratégies constructives inca et de déchiffrer leurs motivations.

Il est trop tôt pour trancher la question de l'existence d'une culture sismique inca. Néanmoins, les résultats que nous avons présentés éclairent sous un nouveau jour cette problématique et démontrent l'intérêt de l'archéosismologie à alimenter des discussions archéologiques et anthropologiques.

Opportunités et limites de l'approche

Opportunités:

- **A-** La prospection archéosismologique a été l'occasion de développer pour la première fois un outil simple d'utilisation et adapté au recensement de dommages sismiques. Ce système de collecte, de stockage et de gestion des données n'a pas seulement facilité le travail de terrain, il a constitué, plus largement, un modèle d'interface pour le recensement de pathologies architecturales sur le patrimoine historique et archéologique;

- **B-** L'analyse des données architecturales et historiques a permis de fournir un éclairage empirique sur la vulnérabilité du bâti inca en pierre taillée. Les données collectées supportent une faible vulnérabilité du bâti à des intensités sismiques inférieures ou égales à VII (M.M.);
- **C-** Etudier les vestiges inca a permis d'étendre d'environ 150 ans la fenêtre temporelle du catalogue sismique régionale et a mis en lumière l'existence d'au moins un séisme violent aux abords du bassin de Cusco;
- **D-** Au travers d'une analyse géomorphologique et d'une réinterprétation d'une légende indigène, il a été possible d'ouvrir un nouveau champ d'investigation abordant la relation entretenue par les populations précolombiennes avec leur environnement tectonique. L'étude ethnohistorique suggère en effet une toute nouvelle dimension de la figure du serpent dans la cosmologie andine, probablement intimement associée aux processus tectoniques;
- **E-** Entreprendre des mesures de bruit sismique sur le bâti archéologique permet d'évaluer l'impact de la géométrie et des composants architecturaux sur la réponse dynamique d'une structure. En outre, le suivi des paramètres modaux offre l'opportunité de quantifier l'impact des facteurs environnementaux et anthropiques sur son comportement;
- **F-** A l'image de Machu Picchu, où le risque sismique était jusqu'alors sous-estimé, voire ignoré (Carlotto et al., 2007), notre approche a permis de battre en brèche certains postulats et idées reçues, particulièrement néfastes dans une optique de préservation du patrimoine archéologique.

Limites:

- **A'-** L'évaluation de l'origine sismique intégrée à la base de données RISC est fondée sur des critères précis mais demeure qualitative pour les besoins du travail de terrain. Ce type d'appréciation introduit une dimension subjective supplémentaire à la phase de collecte des données;
- **B'-** L'impossibilité de mener à bien une instrumentation sur des édifices incas (accès au terrain interdit en 2020-2021 en raison de la crise sanitaire) limite consid-

érablement la dimension quantitative de ce travail. La caractérisation du comportement dynamique des structures au moyen d'une campagne de mesure du bruit sismique aurait fourni des informations complémentaires sur les facteurs de résistance/vulnérabilité;

- **C'-** En cas de non réparation, les dommages sismiques sur le bâti s'agrègent, voire s'aggravent. L'analyse semi-quantitative des dommages sur le bâti en élévation ne permet pas de distinguer les effets potentiellement répétés de plusieurs événements. Il est donc impossible, à ce stade, d'émettre la moindre hypothèse sur le nombre exact d'épisodes ayant affecté l'architecture inca, mis à part à Cusco;

- **C"-** Il est aujourd'hui très difficile de dater précisément les dommages en raison des nombreux problèmes de datation du phénomène architectural inca et du manque de séquences constructives identifiables dans le bâti. Le plus souvent, seul un *terminus post quem* peut donc être avancé;

- **D'-** En raison d'un manque de sensibilisation des archéologues, les évidences d'activité sismique dans le registre archéologique à Cusco sont encore très peu nombreuses et l'interprétation des contextes destructifs trop souvent absente. Il est donc très compliqué d'obtenir une vision régionale et d'aboutir à une véritable discussion des interactions entre sociétés passées et aléas telluriques. Cette lacune représente un des défis majeurs à relever dans le futur;

- **E'-** Le champ d'étude des méthodes de sismique passive correspond à l'analyse du comportement des structures à faibles niveaux de chargement. Il est donc le plus souvent restreint au domaine de réponse élastique (Michel et al., 2011). Tirer des leçons générales en terme de vulnérabilité à de fortes sollicitations transitoires reste débattu;

- **F'-** Comme le soulignent très bien McCalpin and Nelson (2009) et Bilham and Hough (2006), pointer les dangers potentiels et la vulnérabilité des installations ne suffit pas à susciter une prise de conscience à l'échelle de la société toute entière. Ceci doit s'accompagner d'un travail de longue haleine pour rendre crédible et visible l'approche archéosismologique.

Perspectives

Inédite en Amérique du Sud par son ampleur, l'approche archéosismologique que nous avons conduite dans la région de Cusco a permis à la fois, de fournir de nouvelles données sur la sismicité régionale depuis le XIVe s. et d'interroger la relation qu'entretenaient les populations précolombiennes avec cet aléa (fig. 7.2). Néanmoins, la plupart des travaux que nous avons engagés se sont heurtés à la faiblesse, voire l'absence d'antécédents et de données préliminaires ainsi qu'aux déficiences de la perception actuelle du risque sismique. Ce travail exploratoire ouvre, nous l'espérons, la voie à de futurs projets dans les Andes. Concernant Cusco, nous détaillons, ci-après, plusieurs axes de travail prometteurs afin de conforter et compléter les données acquises. Pour ce faire, nous proposons les méthodes susceptibles d'être mises en œuvre pour y répondre à plus ou moins long-terme.

Conforter l'hypothèse d'un séisme à l'époque inca

Qu'il s'agisse des données collectées lors de la prospection archéosismologique (cf. Chapitre 4) ou de la réinterprétation des données ethnohistoriques (cf. Chapitre 5), plusieurs éléments présentés dans ce manuscrit tendent à conforter l'hypothèse d'un séisme majeur à l'époque inca dans le bassin de Cusco. Plusieurs travaux permettraient de corroborer cette hypothèse.

<u>A court/moyen terme</u>:

- Nous avons étudié 17 sites dans le cadre de ce projet. Il semble tout d'abord nécessaire de compléter les données acquises et d'augmenter/densifier la couverture archéosismologique. Les sites de Machu Picchu et Huchuy Qosqo, notamment, n'ont été que partiellement étudiés. Une identification plus systématique des dommages est nécessaire. D'autres sites présentant une architecture en pierre taillée pourraient être visités, tels que Mawkallaqta (Pacariqtambo), Moray et des sites satellites de Machu Picchu. L'acquisition de données supplémentaires permettrait d'obtenir une meilleure résolution régionale, d'identifier de potentiels schémas de déformation communs à l'échelle de sous-régions (cf. Chapitre 4) et d'émettre des hypothèses quant à la distribution géographique des dommages sismiques.

- Pour répondre aux contraintes de temps et de logistique inhérentes à un projet de thèse, ce travail visait à recenser uniquement les EAE dans l'architecture inca en élévation. Des collaborations pourraient néanmoins être engagées avec des conservateurs de sites (e.g., Machu Picchu, Raqchi) et des archéologues pour intégrer les résultats de fouilles récentes dans l'analyse archéosismologique. Nous pensons au site actuellement fouillé de Qotakalli, situé à 5 km au sud-est de Cusco et présentant une forte occupation inca (Dirección Desconcentrada de Cultura - Cusco, 2015). En cas de séisme majeur à l'époque inca, il est probable que des évidences aient été identifiées mais non, ou mal, interprétées.

- A l'image de la base données OPUR (réparations dans le monde romain Dessales et al., in press; Dessales & Tricoche, 2018) qui a vocation à devenir accessible à tous, RISC pourrait être hébergée sur un serveur distant afin de permettre un accès libre aux informations collectées. La base de données pourrait donc constituer un premier pas vers une centralisation des données archéosismologiques portant sur le bâti inca.

- Compte tenu de l'association probable entre l'apparition d'un serpent mythologique et la propagation d'une rupture de surface sur le complexe de faille dominant Cusco, il pourrait être intéressant de simuler plusieurs scénarii de rupture de faille et de prédire l'accélération maximale du sol (PGA) en divers points de la région (P. Silva et al., 2017). Ces *shaking maps* pourraient ensuite être comparées aux données collectées sur le terrain afin de discuter le lien possible entre l'événement mythologique et les dommages sismiques recensés aux alentours de Cusco.

- Les mesures de bruit ambiant planifiées et discutées au Chapitre 6 représenteront un support pour de futurs efforts de modélisation. La réalisation de simulations s'avérera cruciale pour identifier les propriétés des secousses nécessaires à la génération des EAE. De plus, ces modélisations permettront de proposer des explications à la directivité de la déformation observée sur le terrain.

<u>A plus long-terme</u>:

- Dater les dommages s'avère d'autant plus complexe que la maçonnerie fine inca est mal contrainte en terme chronologique et que peu d'étapes de réparations/reprises semblent pouvoir être décelées. Parmi les pistes à explorer figure celle de la datation par isotopes cosmogéniques (Gosse & Phillips, 2001) et notamment l'emploi du béryllium (^{10}Be). Celui-ci permet en effet de dater l'exposition à la surface d'une roche ou d'un sol. Dans le cas de fractures de blocs associées à une secousse sismique (e.g., *Dipping Broken Corners*), il serait possible de dater l'exposition des plans de fracture et donc l'événement sismique associé. Cette méthode se heurte cependant à plusieurs problèmes majeurs dont ceux des incertitudes relativement larges associées aux datations et des autorisations de prélèvement de matériel archéologique sur des sites protégés.

- L'analyse de la légende de l'Amaru (cf. Chapitre 5) avait mis en exergue le site de Quibipay, lagune où aurait disparu le serpent mythologique. Nous avons proposé pour la première fois, une localisation précise et argumentée de cet ancien point d'eau, à proximité de la localité actuelle de Cruz Verde de Quehuepay. Bien que la lagune soit aujourd'hui asséchée, deux méthodes permettraient de confirmer sa localisation et obtenir des informations complémentaires sur sa possible origine tectonique. Le calcul du NDVI (Normalized Difference Vegetation Index - Rouse et al., 1974) pourrait être effectué à l'aide d'images satellite haute résolution et permettrait de souligner la présence d'une forte végétation et donc d'eau à cet endroit. Un carottage dans la zone permettrait, quant à lui, de conclure sur l'existence d'une lagune. L'étude de la séquence stratigraphique, à proximité de la faille de Cusco pourrait également s'avérer utile pour comprendre la formation de ce potentiel *sagpond* et identifier des marqueurs de séismes.

Enrichir le catalogue sismique des 2000 dernières années

Dans le cadre de ce projet, nous nous sommes focalisés sur la période inca et l'architecture massive en pierre associée. Les outils et méthodes développées permettent cependant d'envisager un élargissement de l'approche à tout type de vestiges archéologiques et historiques de la région.

A court/moyen terme:

- A la différence de l'architecture inca mégalithique qui n'offre pas, ou peu, de traces de réparations observables, d'autres styles architecturaux pourraient faire l'objet d'une analyse approfondie de leur histoire constructive. Souvent édifiés sur les restes de constructions incas et plusieurs fois remaniés, les murs coloniaux en style néo-inca présentent de nombreuses déformations et de potentiels dommages sismiques qu'une analyse fondée sur la stratigraphie du bâti permettrait de mieux appréhender (archéologie du bâti - Arrighetti, 2019; Forlin et al., 2018; Poursoulis et al., 2006).

Cette méthode peut d'ailleurs être efficacement secondée par l'usage de la photogrammétrie, comme l'a démontré le stage de M1 de Sarah Perrinel (2021) sur un mur colonial à Cusco. Plusieurs édifices coloniaux de Cusco, probablement affectés par le séisme de 1650, pourraient ainsi être étudiés à l'aide de modèles numériques. En combinant analyses historique et architecturale il serait possible d'associer certains dommages à l'activité sismique récente et de quantifier son impact sur le bâti néo-inca.

- De la même manière, le séisme de 1950 a eu un impact certain sur de nombreux édifices coloniaux et républicains de la ville de Cusco. La distribution géographique des dommages et la calibration de modèles prédictifs pourraient être grandement améliorées en effectuant un recensement exhaustif des EAE. La compilation pourra être nourrie par l'analyse des photographies mais également des périodiques d'époque, probablement archivés à la Municipalité de Cusco, et qui pourraient contenir des informations inédites (Camassi & Castelli, 2004). Combinés à des scénarii de ruptures *(shaking maps)*, les résultats permettraient d'émettre des hypothèses sur la source du séisme.

A plus long-terme:

- La région de Cusco comporte de nombreux sites monumentaux pré-incas qui peuvent faire l'objet d'une prospection archéosismologique (e.g., Pikillaqta, Chokepukio, Pukara Pantillijilla). Ces derniers se composent de murs en adobe et/ou en pierre liées avec du mortier. L'architecture de la base de données RISC, conçue pour enregistrer les dommages sismiques associés à l'architecture en pierre sèche inca, est modulable et pourrait très facilement être adaptée à d'autres besoins.

- Un inventaire détaillé des évidences destructives recensées en contexte archéologique et de leur origine s'avérerait particulièrement utile. Bien que cette tâche requiert de mettre en place un protocole clair pour évaluer la cause de ces niveaux (au moyen par exemple d'un indice de confiance), elle permettrait d'obtenir un inventaire géographique et chronologique des perturbations vécues par les sociétés passées. Concernant l'évaluation de l'origine sismique des perturbations, un protocole pourrait être basé en partie sur les résultats de l'archéologie expérimentale (DezhamKhooy & Yazdi, 2010).

- Enfin, l'approche archéosismologique doit être couplée à des carottages lacustres afin d'identifier de potentiels dépôts induits de séismes (e.g., Gastineau et al., 2021). A ce jour, seul le lac de Huacarpay a fait l'objet d'une étude de ce type mais la nature du système lacustre n'a pas permis de mettre en évidence ce type de dépôts (Babo, 2018; Dumont, 2018).

Mieux appréhender la perception et la gestion dans le passé de l'aléa sismique

Les stratégies élaborées par les populations précolombiennes pour faire face aux processus tectoniques demeurent trop souvent négligées en raison, notamment du manque de sensibilité des archéologues à l'aléa sismique. Nous suggérons deux pistes de recherche pour approfondir les éléments développés dans ce manuscrit:

A court/moyen terme:

- Conformément aux perspectives de recherches développées dans le Chapitre 6, nous suggérons d'instrumenter plusieurs édifices inca finement construits afin d'enregistrer le bruit sismique. Ces mesures de sismique passive permettraient de caractériser le comportement dynamique des vestiges archéologiques tandis que la comparaison des résultats entre les différentes structures offrirait un nouveau regard sur les stratégies constructives et les potentielles vulnérabilités et adaptations au contexte géologique.

A plus long-terme:

- La réinterprétation du récit de Pachacuti Yamqui (cf. Chapitre 5) nous a conduit à nous interroger sur la relation existant entre la sacralité du paysage inca et les processus tectoniques à l'œuvre dans la région. Certains lieux de vénération sont-ils dédiés à l'aléa sismique ? Des prospections archéologiques circonscrites aux zones de failles, associées à des sondages ciblés et à une analyse de l'évolution du schéma d'occupation dans ces régions permettraient probablement d'apporter un nouvel éclairage. On pourra mentionner entre autres (1) la zone de Pachatusan, sommet sacré pour les Incas (Silva Gonzales & Loza García, 2007), (2) le vallon de Tambomachay caractérisé par une occupation archéologique dense au pied de la faille du même nom et (3) la région de Raqchi où le lien entre le lieu de pèlerinage, le volcanisme monogénique (Global Volcanism Program) et les failles bordant le bassin (Sillar et al., 2013) mérite d'être approfondi.

Mieux protéger le patrimoine archéologique face à l'aléa sismique

Plusieurs outils employés dans le cadre de ce projet pourraient contribuer à la surveillance et gestion du patrimoine archéologique.

A court/moyen terme:

- Un important effort de modélisation des édifices incas est aujourd'hui requis pour dépasser les simulations simples réalisées par Kamai and Hatzor (2008); Ogawa et al. (2004) et Hinzen and Montabert (2017). Le recours à des modèles basés sur la méthode des éléments finis, et calibrés à l'aide de mesures de bruit ambiant, permettra d'identifier et de quantifier les principaux mécanismes d'endommagement de ces vestiges (R. Aguilar et al., 2015; Montabert, 2021) et d'établir des stratégies de protection plus adaptées.

A plus long-terme:

- La mise en place de systèmes d'alerte et de prévention constitue aujourd'hui une priorité de la gestion du patrimoine face aux risques naturels (ICCROM, 2004; UNESCO, 2007). La base de données RISC, développée pour faciliter des prospections *ad hoc*, pourrait être convertie aisément en un outil de surveillance périodique de la dégradation des structures (cf. Chapitre 3) afin de répondre à des problématiques de conservation. Il suffirait, pour cela, d'intégrer une dimension temporelle aux enregistrements. On pourrait ainsi envisager de créer une nouvelle table jouant le rôle de fiche d'observation, indiquant la date de la visite et la gravité des dommages. Il serait ensuite possible de lier cette table à la table des désordres architecturaux afin que plusieurs fiches d'observation soient associées à un même dommage sismique. Une telle modification de la base de données permettrait également de comparer la vulnérabilité de certaines techniques constructives et/ou édifices aux secousses passées et aux pressions constantes de l'environnement (Dessales et al., in press).
- L'instrumentation sur plusieurs mois/années d'édifices précolombiens à l'aide de capteurs sismiques permettrait de suivre les fluctuations des valeurs d'amortissement et ainsi de surveiller l'évolution de leur santé structurale (cf. Chapitre 6).

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Appendix A

Supplementary data Chapter 1

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Appendix B

Supplementary data Chapter 3

B.1 Crustal seismicity in the Cusco area

B.1.0.1 General comments

The instrumental regional seismic activity that characterizes the Cusco area is rather rare, diffuse, and unexpectedly low in magnitude (M_w<5), contrasting with the various destructive events of the historical period (Seiner Lizárraga, 2009, 2016; Silgado Ferro, 1978). The main objective of Figure 3.1 was to present the seismic energy released in the Cusco region in a reliable way for our study. However, no major earthquakes have been recorded in more than 40 years (fig. B.1). We relied on the IGP (Instituto Geofísico del Perú) catalog (shared by IGP, personal comment H. Tavera), which reports instrumental earthquakes since 1960. It appears relevant to illustrate and enhance the seismicity representation based on two criteria rather than the classical source location or sources parameters (magnitude, focal mechanism – fig. B.1): we here chose to represent the source location and the "size" of the event. We decided thus to plot crustal earthquakes on a GIS (Geographic Information System) and scale each point depending on the amount of energy released along an equivalent seismic segment. Note that IGP catalog does not consider seismicity of M_w<4.0.

B.1.0.2 Crustal seismicity

The IGP catalog contains all the seismic events recorded in Peru between March 11, 1960 and January 23, 2019. To highlight the regional seismicity that may impact the population and buildings in the Cusco region, we had to remove megathrust earthquakes generated by the distant or deep subduction process. Although crustal earthquakes should only nucleate in the upper fragile crust (∽15-20km), wave velocities are still poorly constrained in the southern Peruvian Andes due to the flat-slab subduction (Bishop et al., 2017). This process may lead, locally, to a thickening of the brittle and seismogenic part of the crust. Hence, we considered, conservatively, all the events whose hypocentre was located above the Wadati-Benioff zone. Regarding the crustal thickness, we used the liberal estimate of 70 km (McGlashan, Brown, & Kay, 2008).

IF Focal Depth$\leqslant$70 (in km)
THEN Crustal earthquakes
ELSE Subduction earthquakes

B.1.0.3 Seismic buffer zones

Method Once the subduction earthquakes were removed, we needed to select a relevant criterion to scale the size of the buffer zones around each seismic episode plotted on the GIS. We discarded the option to generate those buffer zones based on the moment magnitude to avoid a linear relation between buffer radius and magnitude. We here propose to take into account the length of the fault rupture rather than its magnitude. Scaling the buffer zones on this parameter present the benefit of preserving the logarithmic relation and being a direct indicator of the energy released during the earthquake. We detailed below the different steps and assumptions we take to estimate the fault rupture's length based on the moment magnitude available in the IGP catalog.
Considering the basic definition of the moment magnitude:

$$M_w = \frac{\log(M_0)}{1.5} - 6.06$$

Where M_0 is the seismic moment commonly defined as follows:

$$M_0 = \mu \; A \; D$$

- A = area of the fault that ruptured during an earthquake (m^2)
- D = average displacement on the fault (m)
- μ = shear modulus for an elastic solid (Pa)

And considering in parallel the stress drop observed during an earthquake and estimated thanks to the following relations:

$$\Delta\sigma \approx \mu\varepsilon \approx \mu\frac{D}{A^{0.5}}$$

And

$$c\ \mu\frac{D}{A^{0.5}} \approx c\ \mu\frac{D}{L}$$

If we approximate here the area of the fault plane that rupture as a perfect square area (L^2=A).

- σ = shear stress (Pa)
- ε = shear strain (dimensionless quantity)
- c = a constant of the order of 1 (dimensionless quantity)
- L = length of the fault rupture (m)

The seismic moment can be expressed according to this new relation:

$$M_0 = \mu\ L^2\frac{\Delta\sigma}{\mu}\ L = \Delta\sigma\ L^3$$

Therefore:

$$\log(L) = \frac{1.5(M_w + 6.06) - \log(\Delta\sigma)}{3}$$

And:

$$L = 10^{\frac{1.5(M_w+6.06)-\log(\Delta\sigma)}{3}}$$

In the framework of this study, we consider $\Delta\sigma$ = 3MPa (estimated value for most earthquakes in continental interiors; Allmann & Shearer, 2009). For a M_w = 4 earthquake, we obtained 0.743 km and 2.349 km for a M_w = 5 earthquake. Those values are consistent with empirical data (Wells & Coppersmith, 1994).

Data representation To improve the clarity and readability of the map, we multiplied the length of the fault rupture by a factor 2 (the size of the buffer zones remains directly correlated to the rupture length). Moreover, we decided not to merge overlapping zones to make visible all the seismic events.

B.1.0.4 Figure

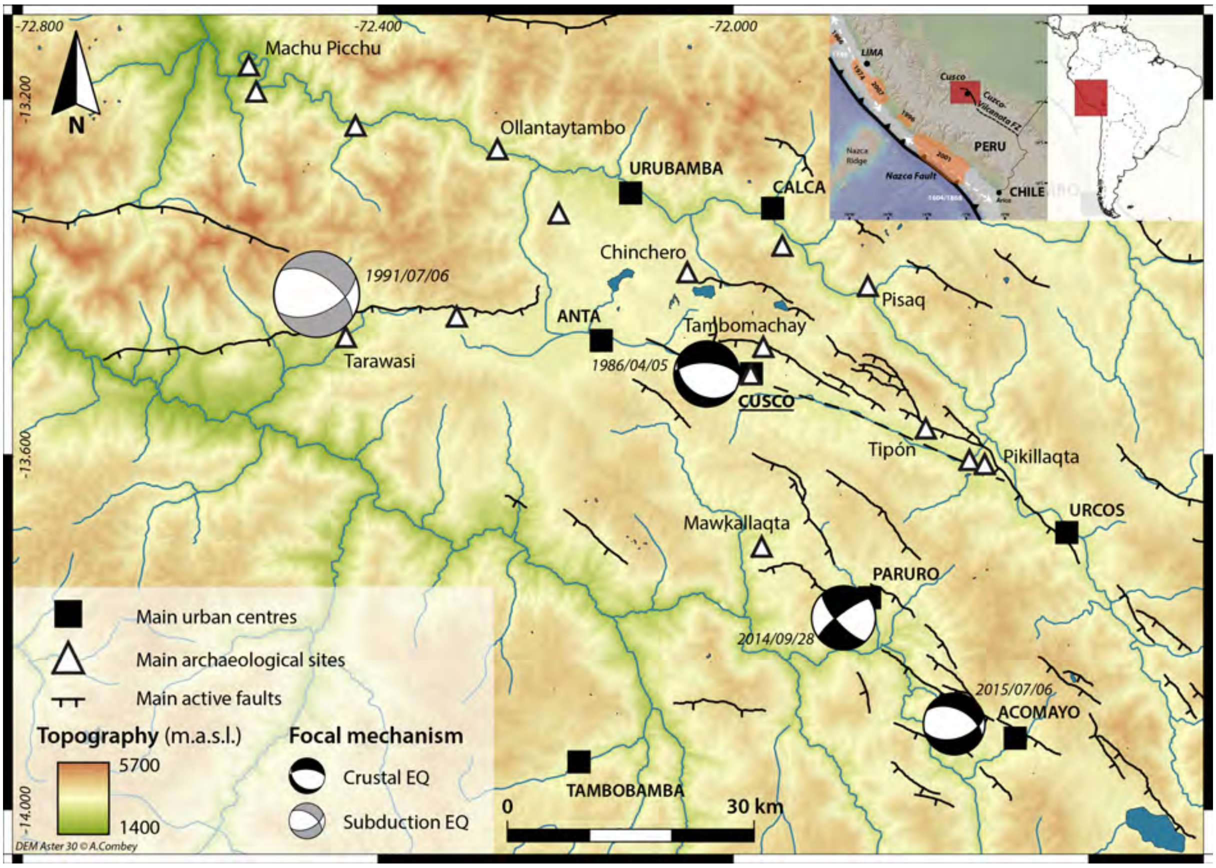

Figure B.1: Focal mechanisms of $M_w \geq 5$ earthquakes within the Cusco region between 1976 and 2017. The size of "beach balls diagrams" depends on the magnitude of the event. We extracted earthquakes and their focal mechanisms from the Global CMT catalog (Dziewonski et al., 1981; Ekström et al., 2012). Due to large uncertainties on source location, we preferred to consider the geographical coordinates reported in the IGP catalog. Note the limit of this kind of representation for Cusquenan seismicity: very little information on source parameters is available for the area.

B.2 RISC database content and structure

B.2.0.1 Introductory words

We conceived and designed RISC as a methodological tool and data container capable of archiving the greatest possible amount of archaeoseismological data collected during our fieldwork in an intelligible and structured way. Thanks to their particular "table-link" organization, relational databases prevent redundant information and facilitate specific queries. We designed the RISC database around ten entities (fig. B.2), forming the tables:

- Architectural damage (table **"Desordre"**, main table)
- Seismic hazard (table **"Alea"**, add-on)
- Site (table **"Site"**)
- Archaeological building (table **"Edif_archeo"**)
- Modern building (table **"Edif_moderne"**)
- Architectural feature (table **"Element_architectural"**)
- Deformation process (table **"Typ_deform"**)
- Damage type (table **"Nature_desordre"**)
- Image (table **"Image"**)
- Bibliography (table **"Biblio"**)

We decided to classify the table into four groups:

1. Main tables (architectural damage and seismic hazard)
2. Context tables (site, archaeological and modern buildings, and architectural feature)
3. List of values (deformation process and damage type)
4. Related tables (image and bibliography)

To make the database structure clearer and for ease of understanding, we use distinct graphic types for Tables and Fields, emphasizing the difference between those two database components (**"Bold"**: Table – *Italic*: Field). We will present the properties of each table (fig. B.3), following the categories previously established.

B.2.0.2 Tables overview

Main tables

"Desordre" (entity: the architectural damage)
RISC database aims to record seismic damage affecting megalithic Inca architecture. The database is thus organized around the table that registers and characterizes the Earthquake Archaeological Effects (EAE), the **"desordre"** table. This latter includes 21 fields and provides information about the main EAE attributes and relevant metadata on damage recording.
The semi-quantitative archaeoseismological approach relies on the damage directionality principle, meaning that EAE appears to be statistically oriented with respect to seismic wave propagation. **"Desordre"** contains measurement fields that allow describing the orientation and severity of the architectural features effectively. Calculation scripts facilitate some of the field entries. That is the case for *sens* indicating the dip direction value of the fracture plane (Dipping Broken Corners). Orthogonal to the Plane Strike obtain with the compass, the Dip Direction may be calculated automatically based on the following relationship:

$$\text{If } (\ azimuth{<}270\ ;\ azimuth{+}90\ ;\ azimuth{+}90{-}360\ )$$

"Desordre" articulates the whole database and is directly linked to five other tables through foreign keys. Four of them contribute to contextualize the EAE: *ref_site*, *ref_moderne*, *ref_archeo* and *ref_element_archi*. Moreover, x and y fields of the main table refine the spatial and geographical data by providing GPS coordinates. The mobile function "Location" available on the FileMaker Go app returns the current latitude and longitude on the iOS tablet, running the application, automatizing the field entry. We use the following script to get and record the GPS location:

```
Set Variable [$latlong ; Value : Location ( 100 ; 20 )]
Set Variable [$lat; Value: GetValue ( Substitute ( $latlong ; "," ; ¶ ) ; 1)
Set Variable [$long; Value: GetValue ( Substitute ( $latlong ; "," ; ¶ ) ; 2)
Set Field [desordre::x; $long]
Set Field [desordre::y; $lat]
```

Field type	Name	Function
ID Number (auto.)	*id_desordre*	Primary key
ID Number	*ref_site* *ref_moderne* *ref_archeo* *ref_element_archi* *ref_alea*	Foreign key for **“site”** table Foreign key for **“edif_moderne”** table Foreign key for **“edif_archeo”** table Foreign key for **“element_architectural”** table Foreign key for **“alea”** table
Text	*deformation*	Type of deformation that generates the EAE (Rodríguez-Pascua et al., 2011) – dynamic list of values (cf. **“typ_deform”**)
Text	*nature_desor*	EAE types (Rodríguez-Pascua et al., 2011) – dynamic list of values (cf. **“nature_desordre”**)
Number	*azimuth*	Plane strike (in deg. from magnetic north)
Number	*sens*	Plane dip direction (in deg. from magnetic north) – automatized
Number	*depla*	Amount of displacement (in cm)
Number	*hauteur*	Height variation (in cm); in case of inclined wall especially
Number	*angle*	Rotation angle (in deg. and about the initial/previous position)
Text	*commentaire*	Any additional comment
Text	*proba*	Qualitative estimation of the seismic origin of the damage (confidence) – closed list of values
Text	*diff*	Difficulty of measurement (accessibility or vegetation) – closed list of values
Number	*x*	Longitude (in decimal degrees) - automatized
Number	*y*	Latitude (in decimal degrees) - automatized
Text	*auteur*	Record creator – open list of values
Date/Time	*creation*	Date of creation of the record – automatized
Date/Time	*modification*	Latest date of modification of the record – automatized

Table B.1: **“Desordre”** composition

List of values:
proba: “Low”, “Medium”, “High” and “Certain”.
diff: “Low”, “Medium” and “High”.

Add-on – **“Alea”** (entity: the seismic hazard)

The observation and registration of an EAE imply the occurrence of a violent seismic event. If a set of pieces of evidence demonstrates the causal relationship between one EAE and a particular ground-shaking episode, we consider necessarily mentioning it. We conceived **“alea”** as a short synthesis of the main characteristics of past earthquakes that occurred in the investigated area (fig. B.3). This table may appear particularly useful during the implementation of a large condition assessment survey, consequently to the occurrence of a new devastating earthquake in the area. The table will make possible queries based on past seismic event criteria. Rather than creating only one field providing the precise date of the event, we prefer establishing two fields: a lower and upper chronological boundary (*post_quem* and *ante_quem*). A time range seems better suited to prehistorical or pre-instrumental events whose dating involves necessarily uncertainties. Similarly, we prefer providing intensity data (maximal estimated intensity) to magnitude information due to the difficulty to estimate precisely such indicators in the case of prehistorical earthquakes.

Field type	**Name**	**Function**
ID Number (auto.)	*id_alea*	Primary key
Text	*ville*	Closest large city of the epicentre
Number	*post_quem*	Lower chronological limit for seismic event occurrence
Number	*ante_quem*	Upper chronological limit for seismic event occurrence
Number	*intensite*	Maximum estimated intensity – closed list of values (MMI scale)
Number	*x_epicen*	Longitude of the estimated epicentre (in decimal deg.)
Number	*y_epicen*	Latitude of the estimated epicentre (in decimal deg.)
Text	*commentaire*	Any additional comment
Text	*concat*	Concatenation of ville - *post_quem* - *ante_quem* - *intensite*

Table B.2: **“Alea”** composition

<u>List of values</u>:
intensite: “<V”, “V”, “VI”, “VII”, “VIII”, “IX” and “X+”.

Context tables

"Site" (entity: the archaeological site)
This table provides a short description of archaeological sites surveyed and affected by seismic damage. It gathers five fields, which places the EAE record in a broader/regional context.
Any additional fields useful to the archaeoseismological data analysis might be added without affecting the global structure.

Field type	Name	Function
ID Number (auto.)	*id_site*	Primary key
Text	*nom*	Name of the archaeological site
Number	*altitude*	Mean elevation (m.a.s.l.)
Text	*provincia*	Administrative province in which the site is located
Text	*type_sol*	Ground type (soft sediment, basement...)

Table B.3: **"Site"** composition

"Edif_archeo" (entity: the archaeological building)
This section describes the second main level of EAE contextualization: the archaeological building. By means of nine fields, the table defines precisely the ancient Inca buildings affected by an earthquake. Each construction is associated with a unique archaeological site recorded in **"site"** (*ref_site*). If available, information relative to the period of occupation (*post_quem* and *ante_quem* limits) and to subsequent restorations can be reported. We decided to create a the concatenation field (*concat*) to identify archaeological structures easier during the use of database layouts.*Concat* replaces thus the primary key as an intelligible identifier in the dynamic list of values.

Field type	Name	Function
ID Number (auto.)	*id_archeo*	Primary key
ID Number	*ref_site*	Foreign key for **“site”** table
Text	*nom*	Name of the archaeological building, if it exists (could be a code name find in the archaeological literature)
Text	*secteur*	Archaeological sector/compound where the construction is situated
Number	*post_quem*	Lower chronological limit of occupation
Number	*ante_quem*	Upper chronological limit of occupation
Yes/No	*restaur*	Existence of potential restoration works
Text	*commentaire*	Any additional comment
Text	*concat*	Concatenation of *nom-secteur*

Table B.4: **“Edif_archeo”** composition

“Edif_moderne” (entity: the modern building)
Identifying the archaeological building that displays seismic damage is not always easy, in particular where current urban areas are covering archaeological remains. To overcome this difficulty, we designed an additional table **“edif_archeo”** that supplements the geographical and architectural characterization of the EAE in a specific context. Where archaeological remains are incomplete and fragmented due to modern constructions, it has proved necessary to by-pass the simple archaeological building description and based EAE location on the current city cadastre. The present table allows associating **“desordre”** records with the modern buildings that exhibit the archaeological remains of interest. Beyond even the benefits it can bring in terms of mapping, this supplementary table furnishes valuable data to analyze the potential impact of restructuration on EAE occurrence. In a similar manner to **“edif_archeo”** table, we created a concatenation field, a more suitable identifier for users (dynamic lists of the layouts) than the primary key *id_moderne*.

Field type	Name	Function
ID Number (auto.)	*id_moderne*	Primary key
ID Number	*ref_site*	Foreign key for **"site"** table
Text	*rue*	Street name
Number	*numero*	House number
Text	*nom*	Common name of the building, if exists/known
Text	*cote_rue*	Side of the street – closed list of values
Text	*commentaire*	Any additional comment
Text	*concat*	Concatenation of *rue-numero-nom*

Table B.5: **"Edif_moderne"** composition

List of values:
cote_rue: "east", "west", "south" and "north".

"Element_architectural" (entity: the architectural feature)
This fourth and final contextual table focuses on the smallest architectural feature exhibiting EAE. Those features are architectonical elements that compose the archaeological buildings described in **"edif_archeo"**. Several fields contain the main attributes of the architectural entity: masonry type, internal/external position, orientation... Lastly, a concatenation field was developed in order to identify each architectural feature easily in a dynamic list of values. The table is linked with both **"site"** (*ref_site*) and **"edif_archeo"** (*ref_archeo*), representing the two superior architectural levels.

Field type	Name	Function
ID Number (auto.)	*id_element_archi*	Primary key
ID Number	*ref_site* *ref_archeo*	Foreign key for **"site"** table Foreign key for **"edif_archeo"** table
Text	*type*	Type of architectural feature – open list of values
Text	*archi*	Masonry type – open list of values
Text	*position*	Internal or External wall – closed list of values
Text	*cote*	Direction in which is looking the architectural feature – closed list of values.
Text	*orientation*	Orientation of the architectural feature (main cardinal orientation) – closed list of values
Text	*commentaire*	Any additional comment
Text	*concat*	Concatenation of *type-archi-position-cote-orientation*

Table B.6: **"Element_architectural"** composition

List of values:
type: "foundation", "wall", "buttress", "door", "window", "niche", "stairway", "hydraulic structure", "terrace/Retaining wall" and "platform".
archi: "rustic", "pirqa", "cellular", "sedimentary", "polygonal" and "cyclopean".
position: "Internal wall" and "External wall".
cote: "north", "south", "east" and "west".
cote: "N-S", "E-W", "NE-SW" and "NW-SE".

Dependent drop-down list values

"Typ_deform" (entity: the deformation process)
This table is a values list for the **"desordre"** *deformation* field

Field type	Name	Function
ID Number (auto.)	*id_deform*	Primary key
Text	*deform*	Deformation process based on EAE classification (Rodríguez-Pascua et al., 2011) – closed list of values

Table B.7: **“Typ_deform”** composition

List of values:
deform: “permanent ground deformation” and “transient shaking”.

“Nature_desordre” (entity: the damage type)
This table is a values list for the **“desordre”** *nature_desor* field. It is linked to the previous table to create a dynamic list adapted to the type of deformation recorded.

Field type	Name	Function
ID Number (auto.)	*id_desor*	Primary key
ID Number	*ref_deform*	Foreign key of **“type_deform”**
Text	*natur_desor*	Damage type based on EAE classification (Rodríguez-Pascua et al., 2011) – open list of values

Table B.8: **“Nature_desordre”** composition

List of values:
natur_desor: “tilted walls”, “folded walls”, “displaced walls”, “conjugated fractures”, “dipping broken corner”, “displaced masonry blocks”, “block rotation”, “collapsed structures” and “cracks”.

Related tables

“Image” (entity: the image)
The present table consists in storing all the pictures associated with **“desordre”**. **“Image”** is organized around the container field *image* but also keeps a record of the provenience of each picture. Linked indirectly with the bibliographical table **“biblio”**, any database user may thus find quickly the references for which illustrations contained in **“image”** are coming from. Moreover, we

use the mobile function "Insert From Device" available on iOS devices to transform *image* as a target container field for the tablet camera. A photo taken with the camera may therefore be directly inserted in the container. We write the function as follows:

Insert From Device ["image"::image; Type: Camera; Camera: Front/Back; Resolution: Full/Small/Medium/Large]

Field type	**Name**	**Function**
ID Number (auto.)	*id_image*	Primary key
ID Number	*ref_desordre*	Foreign key for **"desordre"** table
	ref_biblio	Foreign key of **"biblio"**
Container	*image*	Container that hosts the picture. A SQL script enables the direct record of the picture taken with the tablet camera
Text	*commentaire*	Any additional comment

Table B.9: **"Image"** composition

"Biblio" (entity: the bibliographical resources)
The bibliographical table aims to gather all the necessary bibliographical references related to **"edif_archeo"**, **"alea"** and **"image"**. We find it more appropriate to segregate bibliographical resources in a specific table. It keeps the door open to any future database evolution that would require the creation of new bibliographical fields in other tables.

Field type	**Name**	**Function**
ID Number (auto.)	*id_biblio*	Primary key
Text	*abreg_ref*	Bibliographical reference abbreviated
Text	*complet_ref*	Complete bibliographical reference

Table B.10: **"Biblio"** composition

Additionally, three-link tables were created and were associated with **"biblio"** to create a bidirectional [0:N] cardinality with **"edif_archeo"**, **"image"** and **"alea"** (fig. B.2). Those three intermediary tables were called **"r_biblio_archeo"**, **"r_biblio_image"** and **"r_biblio_alea"**. The page field is conceived each time as the link field, resolving the [N:N] relationship.

B.2.0.3 Dynamic list of values

We also automatized part of the database filling to facilitate its use and reduce the entry time. Hence, we created conditional values lists for the "Context Tables" referred to as **"L_table"** (in grey – fig. B.3). Thanks to those lists, the database user can fill the Context Tab according to a hierarchical tree. Depending on the site he selected, only modern and archaeological buildings belonging to this site will be proposed. Likewise, only the architectural features belonging to the archaeological building picked will be available to select. At any moment, the user can also create a new entry in those tables (in case of a new context). The peculiar behavior of the interdependent lists has the advantage of considerably narrowing down the size of the large value list that represent **"edif_archeo"**, **"edif_moderne"** and **"element_architectural"**. **"L_site"**, **"L_edif_archeo"**, **"L_edif_moderne"** and **"L_element_archi"** are linked to **"desordre"** through *ref_site* (fig. B.3).

B.2.0.4 Figures

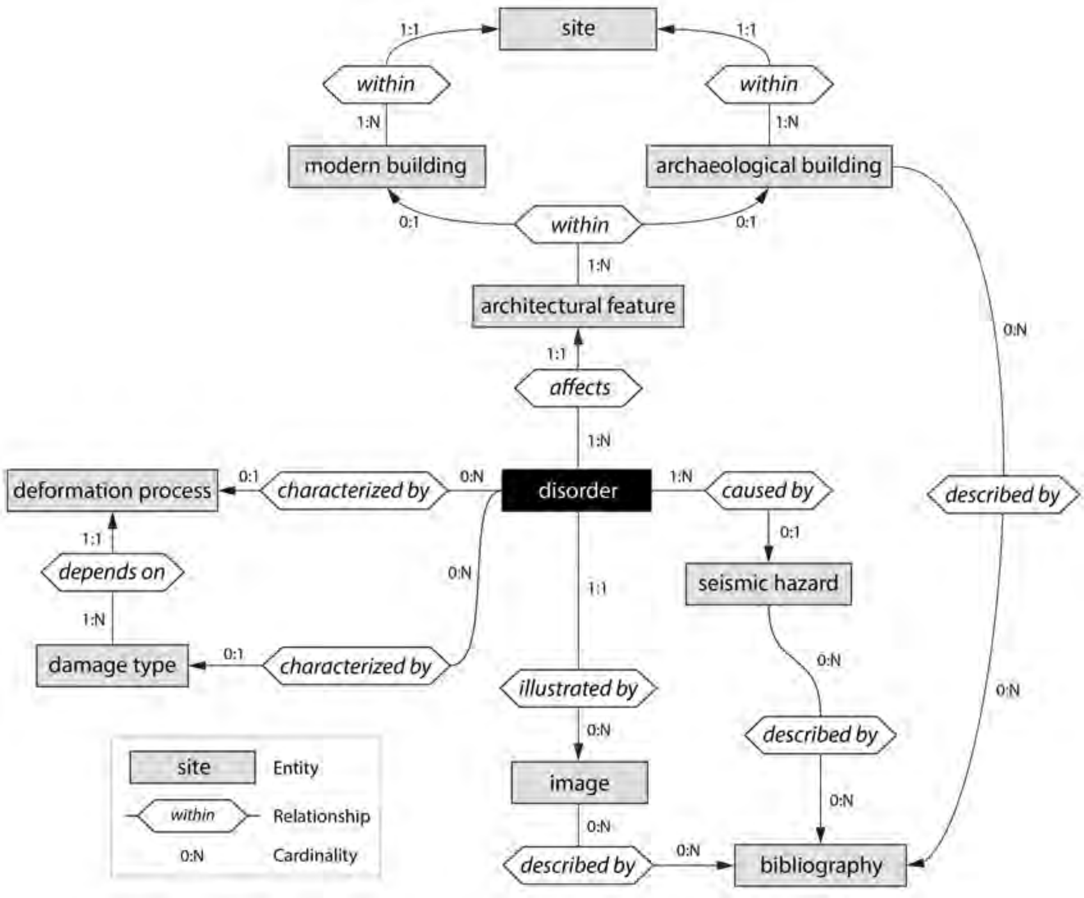

Figure B.2: Conceptual data model (CDM) that conveys the fundamental principles and logical construction of RISC.

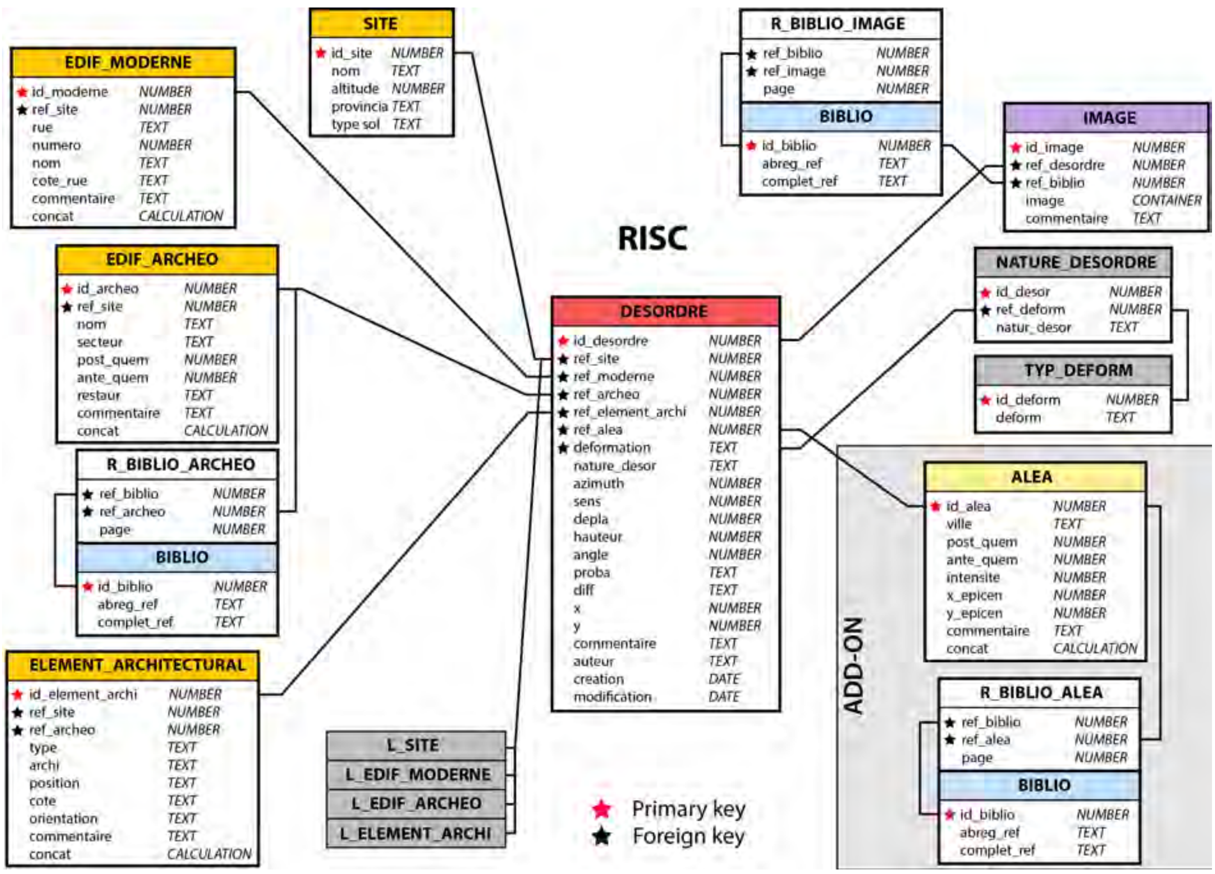

Figure B.3: Physical RISC database model (PDM) displays the data design (tables, field types and relations) implemented in the RDBMS.

Appendix C

Supplementary data Chapter 4

C.1 The archaeoseismological survey

C.1.1 Site description

- **Chinchero**: The Inca site is located at approximately 3,750 m.a.s.l. in the Urubamba province. According to Spanish chronicles, the place was chosen by the sovereign Tupac Yupanqui (1471-1493 CE) to build a royal estate. An extensive complex of finely built terraces and large rectangular structures characterizes this estate. Dedicated mainly to ceremonial functions, the monumental sector was completely abandoned some years after the Spanish Conquest, when the site was partly fired by the troops of Manco II in 1540 (Alcina Franch, 1970).

- **Cusco**: Former capital of the Inca polity, the city lies at 3,400 m.a.s.l. Occupied at least from the Killke period (11-14th c.), the city is allegedly rebuilt by the emperor Pachacuti Inca Yupanqui (1438-1471 CE). The massive dry-stone construction seem to date from this period. The occupation within the city does not cease up to the present day.

- **Huchuy Qosqo**: Located in the Sacred Valley, in the Calca province, the site of Huchuy Qosqo is known as the royal estate of the Inca ruler Viracocha (∼1400-1438 CE). The site was called “Caquia Xaquixaguana” in the early Colonial period (Covey, 2006).

- **Inkilltambo**: Situated on the calcareous outcrop, north of Cusco, no historical / archaeological data on the Inca occupation are available.

- **Machu Picchu**: Machu Picchu is located in the lower Urubamba Valley, at 2,400 m.a.s.l., on a narrow N-S granitic crest dominating the river. Difficult to access and surrounded by rainforest, the site was discovered scientifically only in 1911 by Hiram Bingham. The place was artificially flattened during the Inca period and stabilized thanks to numerous terraces (Carlotto et al., 2007) and hydraulic engineering systems (Wright & Zegarra, 2000). Based on the documents presented by John Rowe (1990), Machu Picchu was designed as a royal estate, sometime after the conquest of the region by the emperor Pachacuti Inca Yupanqui (1438-1471 CE). However, new radiocarbon dating suggests that the site was built and occupied as soon as the first half of the 15^{th} century (Burger et al., 2021; Ziólkowski et al., 2020).

- **Ollantaytambo**: Unlike the current town of Ollantaytambo, the former Inca settlement occupied both banks of the Patakancha River, constituting two main sectors: the Temple Hill and the residential sector (Protzen, 1993). Characterized by its megalithic constructions, monumental terraces and numerous fountains (Wright, 2017) that cover the rocky hill west of the river, the Temple Hill assumed most probably a ceremonial function. The residential sector lies on the left bank of the river (Gasparini & Margolies, 1980). The well-preserved remains of the Inca walled-in habitation compounds forms the regular grid of the modern town. Occupied during pre-Inca times, the site was strongly redesigned under Pachacuti's reign (1438-1471 CE) and continuously occupied until the retreat of the troops of Manco II in ∼1540 CE (Protzen, 1993).

- **Pisaq**: The site lies above the current city of Pisaq in the Sacred Valley. According to chronicles, the ruler Pachacuti Inca Yupanqui (1438-1471 CE) established it as a royal estate (Kaulicke et al., 2003). Nowadays, Pisaq site is constituted of four main sectors: P'isaqa, Intiwatana, Qallaq'asa and Kinchiraqay.

- **Puka Pukara**: The site is located less than 5 km north of Cusco, near the Tambomachay Fault. The settlement might have functioned as a defensive site, protecting the main road to the *Antisuyu* (western province of the Empire).

- **Raqchi**: The site is located 100 km southeast of Cusco in the upper part of the Vilcanota Valley, between the colonial *reducciones* of Tinta and San Pedro. Settled at the base of the Kinsach'ata volcano, Raqchi was an important ceremonial site for pre-Columbian populations. The site evidences an important occupation from, at least, the Middle Horizon (600-1000 CE) and acquires a regional dimension under

Inca dominion. The site turned into an important centre of pilgrimage (Sillar et al., 2013) with the construction of the Viracocha Temple (mid-15th c.).

- **Saqsaywaman**: Overlooking the city of Cusco, Saqsqaywaman was a significant ceremonial site during Inca times and perhaps as early as the Killke period (Mar & Beltrán-Caballero, 2015). The site is well known for its cyclopean terraces constructed during the 15th century. However, the site was probably still under construction at the time of the Spanish conquest (Protzen, 1987). Abandoned immediately after, the site served as a stone quarry for the inhabitants of Cusco during several centuries (Dean, 1998).

- **Tambomachay**: Tambomachay is a ceremonial site settled on a spring 6 km north of Cusco (Bauer, 1998), near the Tambomachay Fault. No clear chronological data are available.

- **Tarawasi**: Located close to the town of Limatambo, in the upper catchment of the Apurimac River, Tarawasi is a small Inca site lying at approximately 2,700 m.a.s.l. The current Inca remains are composed of a succession of five preserved levels terraces, surmounted by a fine monumental platform called *ushnu*. This platform, built in the cellular masonry style, was included to a Spanish encomienda during colonial times and suffered fire damage in its northeastern part. The archaeological remains were probably part of an Inca complex assuming administrative and military purposes (*tambo*) along the *Chinchaysuyu* road (Heffernan, 1989).

- **Tipón**: This is an extensive site composed of various agricultural sectors with monumental terraces (*andenes*). The place might have been occupied from the Killke or Wari period. According to the chroniclers, Pachacuti Inca Yupanqui (1438-1471 CE) decided to establish there a royal estate (Wright, 2006).

- **Wiñaywayna**: Situated 7 km walk from Machu Picchu, along the Inca trail, Wiñaywayna constitutes a satellite site of the royal estate. The site consists in two sectors of houses and terraces connected by a staircase and located halfway up a steep hillside overlooking the Urubamba River. Following the assumption of Ziólkowski et al. (2020), the site might have been built around the same period of Machu Picchu, between 1400 and 1450 CE.

C.1.2 General statistics

The archaeoseismological survey carried out in the fourteen investigated sites led to the identification of 4,967 EAEs, including 3,473 with a high or medium level of confidence (seismic origin). Three types of EAEs were mainly registered: the DBC, DMB and Cracks (fig. C.1). Due to the reduced number of cracks registered (n=72 – 2%) with a high or medium level of confidence and their presence mostly in Cusco and Ollantaytambo, we did not consider them in the framework of this work.

The EAEs were not distributed homogeneously at the regional scale. Considering a robust level of confidence, the sites of Cusco and Pisaq present the majority of the EAEs identified (48%), while Wiñaywayna, Huchuy Qosqo, Puka Pukara, Tipón, Inkilltambo and Tambomachay together represent only 7% of the dataset (fig. C.2). This heterogeneous distribution is not only dependent on the "sensibility" of the archaeological remains to past ground motions but depends also on the availability of Inca fine stonework – not fully restored – in the sites and the area that we achieved to survey during the field campaign.

We may highlight, notably, the reduced number of EAEs identified in the sites of Tambomachay, Inkilltambo and Tipón (fig. C.1). In those three sites, the number of EAEs is inferior to 40 and turns out to be insufficient to implement further statistical analyses.

Finally, regarding Pisaq, we should mention that several parts of the site were surveyed during the field campaign. Nonetheless, we registered an overwhelming majority of EAEs in the Intiwatana sector (91%). Hence, we considered only the results from this sector in our work.

C.1.3 Implementing a semi-quantitative approach

In order to assess the anisotropy of the seismic deformation, we divided the wall's orientations into four main classes, approximated as cardinal directions (table C.1). We classified, then, each type of EAE with a High or Medium level of confidence according to the orientation of the wall affected by the EAE (table C.2). Regarding the cumulated amount of DMB, we considered both in-plane and out-of-plane gap openings that took place in each wall trend.

The representativeness of the sample (EAE number per walls' orientation) depends obviously on the architectural area surveyed for each of the given orientations. To facilitate the calculation, we decided to estimate the length of the surveyed "wall segments" affected by at least one EAE, rather than the area. Due to the height limit of measurement that

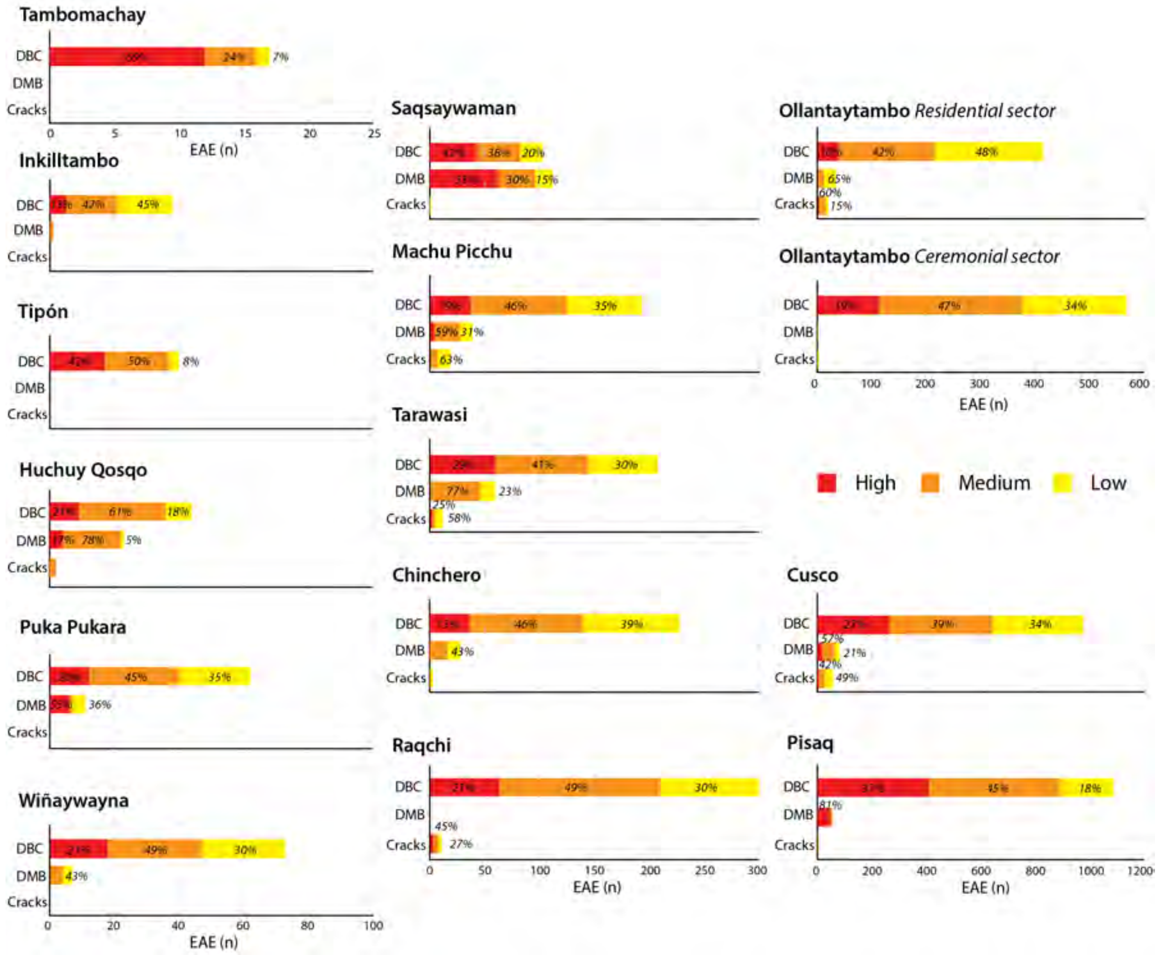

Figure C.1: Number of DBC, DMB and Cracks for each archaeological site investigated. The diagrams display the proportion of EAEs with a High (red), Medium (orange) and Low (yellow) levels of confidence.

we considered as constant (constrained by man's height with arms raised, i.e. ∼2m), we assumed the surveyed area as directly proportional to the wall length. Regarding the delimitation of the "wall segment", we defined it as a distinctive architectural element[1]. We normalized the number of DBC (DBC_{norm}) and the cumulated amount of DMB (DMB_{norm}) for each class of wall trend by the wall length. The results for each site and each orientation is contained in Table C.3. The same table presents the values of σ_{50}, which is regarded as a good indicator of the data dispersion.

[1]In case of a well-preserved structure, the wall segment is therefore the entire wall façade of the building. In case of an isolated/free-standing wall, the wall segment only consists of the architectural unit (e.g., distinctive type of masonry) presenting the EAEs.

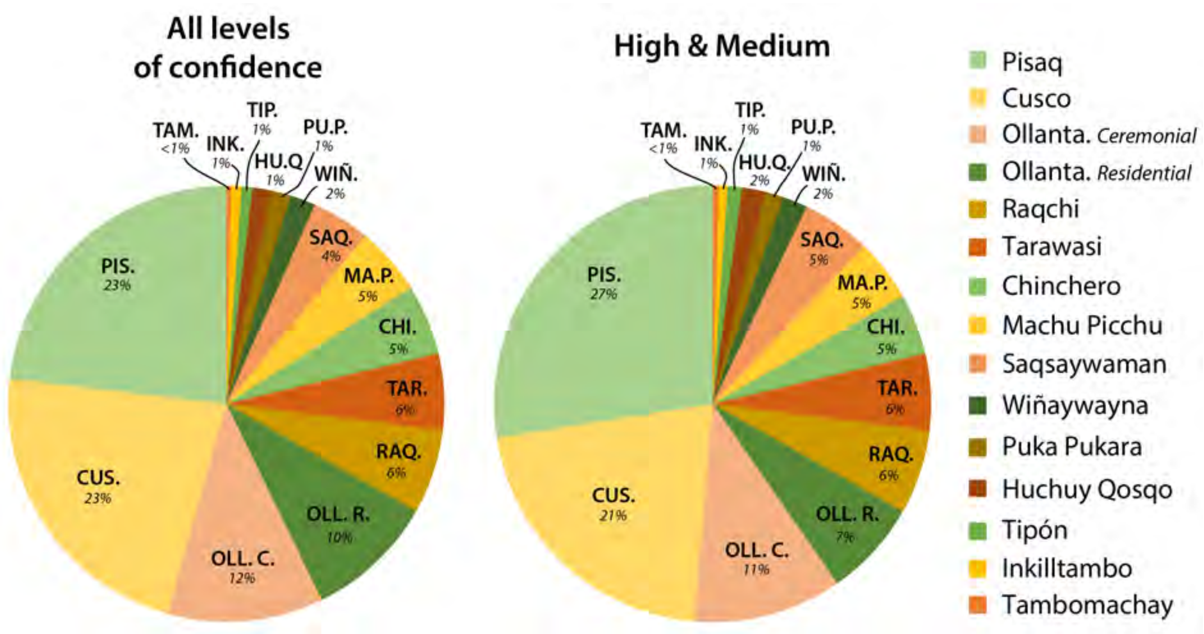

Figure C.2: Pie charts indicating the proportion of EAEs according to the sites, considering all the levels of confidence (left) and only the High and Medium levels (right).

Sites	Angular Interval			
	N-S	NE-SW	E-W	NW-SE
Cusco				
Inca walls	*N150-160* *N330-340*	*N045-065* *N225-245*	*N065-085* *N245-265*	*N130-150* *N310-330*
neo-Inca walls	*N150-160* *N330-340*	*N045-065* *N225-245*	*N065-085* *N245-265*	*N130-150* *N310-330*
Saqsaywaman	N340-010 N160-190	N040-065 N220-245	N065-095 N245-275	N130-160 N310-340
Chinchero	N350-020 N170-200		N080-110 N260-290	
Pisaq (Intiwatana)	N350-020 N170-200		N085-115 N265-295	
Puka Pukara	N350-010 N170-190	N035-055 N215-235	N080-110 N260-290	N130-150 N310-330
Huchuy Qosqo	N020-030 N200-210		N110-120 N290-300	
Inkilltambo	N000-030 N180-210		N090-120 N270-300	
Tambomachay	N005-025 N185-205	N030-050 N210-230	N095-115 N275-295	N120-150 N300-330
Tipón	N335-005 N155-185		N070-100 N250-280	
Raqchi	N020-030 N200-210		N110-120 N290-300	
Machu Picchu	N140-155 N320-335		N050-070 N230-250	
Wiñaywayna	N160-170 N340-350		N060-070 N240-250	N110-120 N290-300
Ollantaytambo				
Residential sect.	*N020-030* *N200-210*		*N100-110* *N290-300*	
Temple Hill	*N170-200* *N350-020*	*N040-070* *N220-250*	*N080-110* *N260-290*	*N120-150* *N300-330*
Tarawasi		N050-060 N230-240		N135-145 N315-325

Table C.1: Angular interval for each class of walls' orientation and each investigated site.

Sites	Wall length (m)				DBC (n)					DMB (n)				
	N-S	NE-SW	E-W	NW-SE	N-S	NE-SW	E-W	NW-SE	**Tot.**	N-S	NE-SW	E-W	NW-SE	**Tot.**
Cusco	362	**1278**	443	756	114	**186**	168	175	643	10	10	**28**	16	64
Inca	*335*	***1209***	*374*	*640*	*81*	*129*	***147***	*94*	*451*	*6*	*7*	***23***	*14*	*50*
neo-Inca	*27*	*69*	*69*	***116***	*33*	*57*	*21*	***81***	*192*	*4*	*3*	***5***	*2*	*14*
Saqsaywaman	367	283	**692**	177	26	16	**40**	0	82	33	26	**34**	3	96
Chinchero	245		**390**		55		**85**		140	**13**		3		16
Pisaq	308		**310**		419		**474**		893	**33**		24		57
Puka Pukara	8	**86**	49	30	5	10	**15**	10	40	0	0	0	7	7
Huchuy Qosqo	24		**33**		**21**		15		36	**14**		8		22
Inkilltambo	20		**54**		5		**16**		21	**1**		0		1
Tambomachay	3	6	**10**	3	**6**	2	3	5	16	0	0	0	0	0
Tipón					**28**	0	8	1	37	0	0	0	0	0
Raqchi - Wiracocha	**91**		23		**102**		29		131	0		0		0
Machu Picchu	**97**		60		**73**		52		125	13		**14**		27
Wiñaywayna	**25**		5	6	**46**		10	4	60	**3**		1	0	4
Ollantaytambo														
Residential sect.	*426*		***615***		***114***		*101*		*215*	***8***		*4*		*12*
Temple Hill	*66*	*56*	*109*	***201***	*27*	*24*	*71*	***256***	*378*	*0*	*1*	*0*	*1*	*2*
Tarawasi		**131**		99	**82**		63		145		16		**30**	46
Total									2962					354

Table C.2: The table summarizes the length of surveyed walls according to their orientation as well as the number of DBC and DMB (High and Medium levels of confidence) for each of these classes and each archaeological site. Highest values are highlighted in bold.

Sites	$\mathbf{DBC}_{norm}$ **(n)**				σ_{50}				$\mathbf{DMB}_{norm}$ **(cm)**			
	N-S	NE-SW	E-W	NW-SE	N-S	NE-SW	E-W	NW-SE	N-S	NE-SW	E-W	NW-SE
Cusco	31	15	**38**	23	0.55	0.69	**0.71**	0.39	2.9	2.0	**22.4**	13.5
Inca	*24*	*11*	***39***	*15*	*0.44*	*0.70*	***0.72***	*0.40*	*1.1*	*1.8*	***24.2***	*13.5*
neo-Inca	***122***	***83***	*30*	*70*	***0.82***	***0.67***	*0.62*	*0.48*	***25.2***	*5.2*	*12.8*	*13.9*
Saqsaywaman	7	6	6	0	**0.63**	**0.63**	0.55		**51.9**	42.7	37.3	7.7
Chinchero	22		22		**0.82**		0.80		**24.9**		5.1	
Pisaq	136		**153**		**0.55**		0.52		**23.9**		14.0	
Puka Pukara	**63**	12	31	33	0.40	0.50	0.40	**0.60**	0	0	0	**79.7**
Huchuy Qosqo	**88**		45		**0.84**		0.40		**656.3**		93.9	
Inkilltambo	25		**30**		**0.60**		0.44		**92.0**		0	
Tambomachay												
Tipón					**0.43**		0.25		0		0	
Raqchi - Wiracocha	113		**126**		**0.45**		0.31		0		0	
Machu Picchu	75		**87**		0.73		**0.77**		67.5		**480.7**	
Wiñaywayna	181		**208**	67	**0.78**		0.60	0.50	18.0		**44.0**	0
Ollantaytambo												
Residential sect.	***27***		*16*		***0.52***		*0.46*		***3.0***		*1.7*	
Temple Hill	*41*	*43*	*65*	***127***	*0.33*	***0.63***	*0.55*	*0.49*	*0*	*1.3*	*0*	*0.4*
Tarawasi		63		**64**		0.54		**0.65**		48.3		**165.3**

Table C.3: Normalized number of DBC, proportion of DBC's dip directions within the range Wall's orientation ±45° (σ_{50}-value) and normalized amount of DMB for each class of wall's orientation and each archaeological site. Highest values are highlighted in bold.

In order to identify patterns of deformation, we also plotted the angular distribution of the DBC's dip directions and the normalized amount of DMB. Regarding the rose diagrams representing the cumulative gap openings sorted by wall's orientations, we fixed the maximum bin size to 30°. This value corresponds, indeed, to the largest angular interval for the classes of walls' orientation (table C.1).
The polar plots from Cusco, Saqsaywaman, Huchuy Qosqo, Machu Picchu, Ollantaytambo and Raqchi are presented and discussed in detail in Chapter 4. Below, we present the outputs from Chinchero, Pisaq, Puka Pukara, Wiñaywayna and Tarawasi.

Chinchero

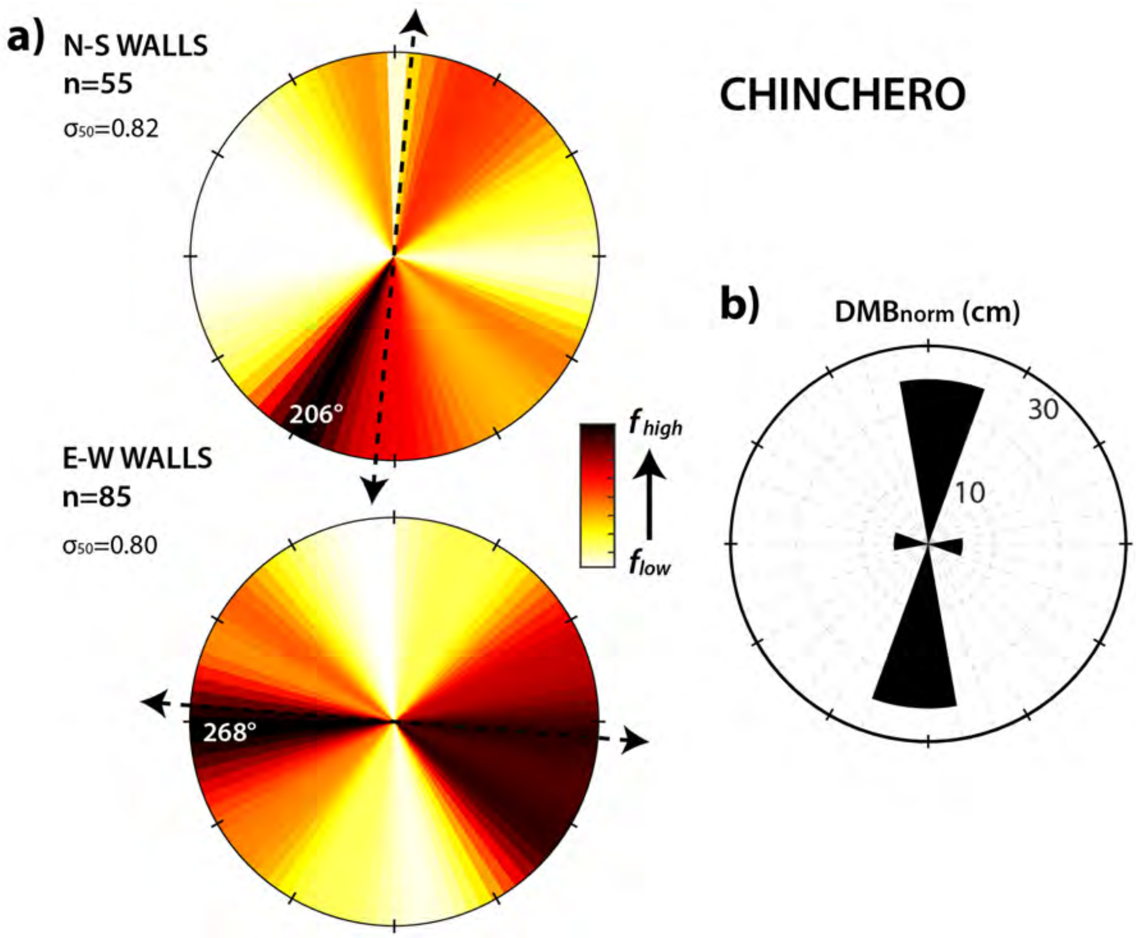

Figure C.3: a) Polar plots displaying the kernel density function of the DBC's dip direction in Chinchero. The size of the plots is function of the normalized number of DBC. The dotted arrows indicate the wall trends; b) Normalized cumulated amount of displacement taking place along the different wall's orientations.

Pisaq

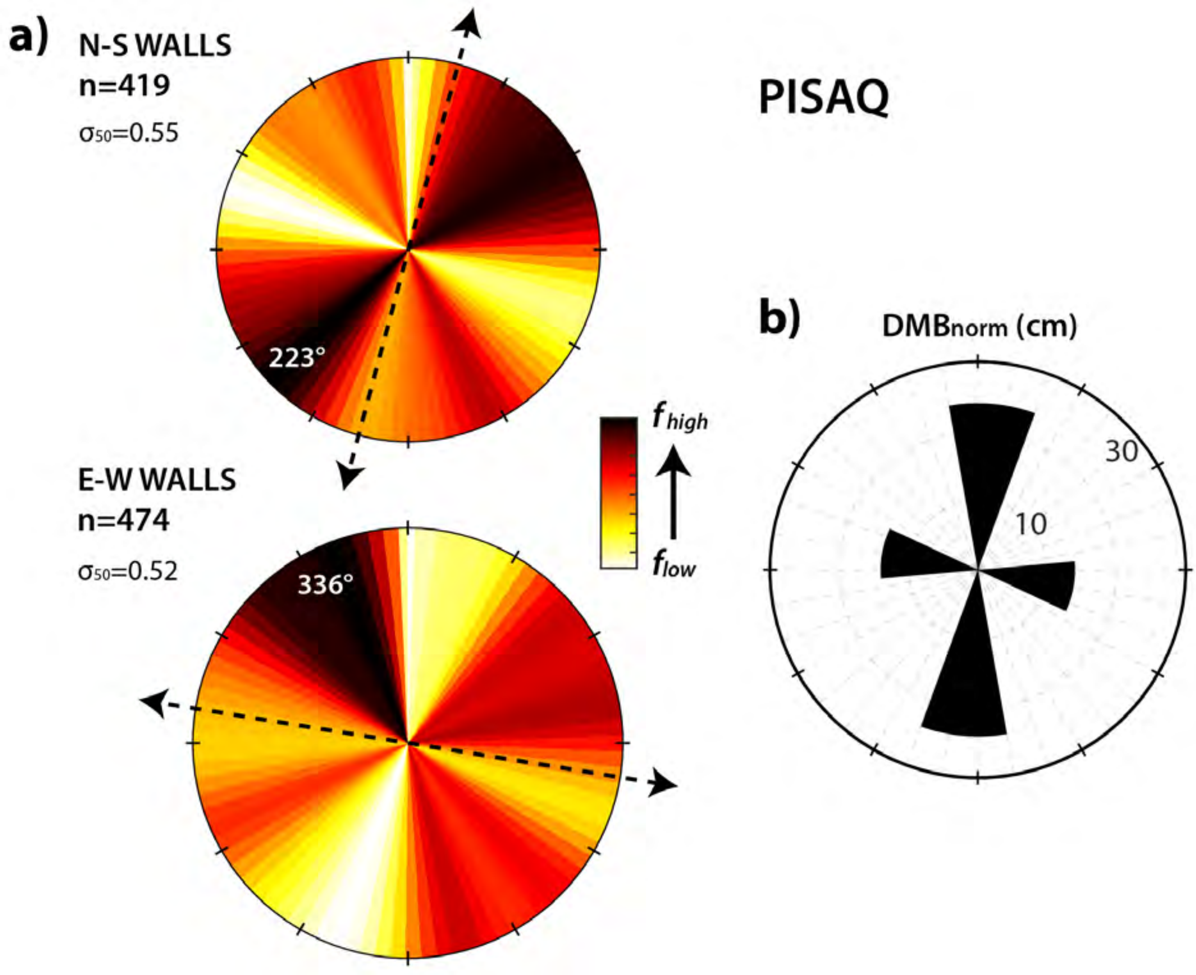

Figure C.4: a) Polar plots displaying the kernel density function of the DBC's dip direction in Pisaq. The size of the plots is function of the DBC$_{norm}$-value. The dotted arrows indicate the wall trends; b) Normalized cumulated amount of DMB according to the wall's orientations.

Puka Pukara

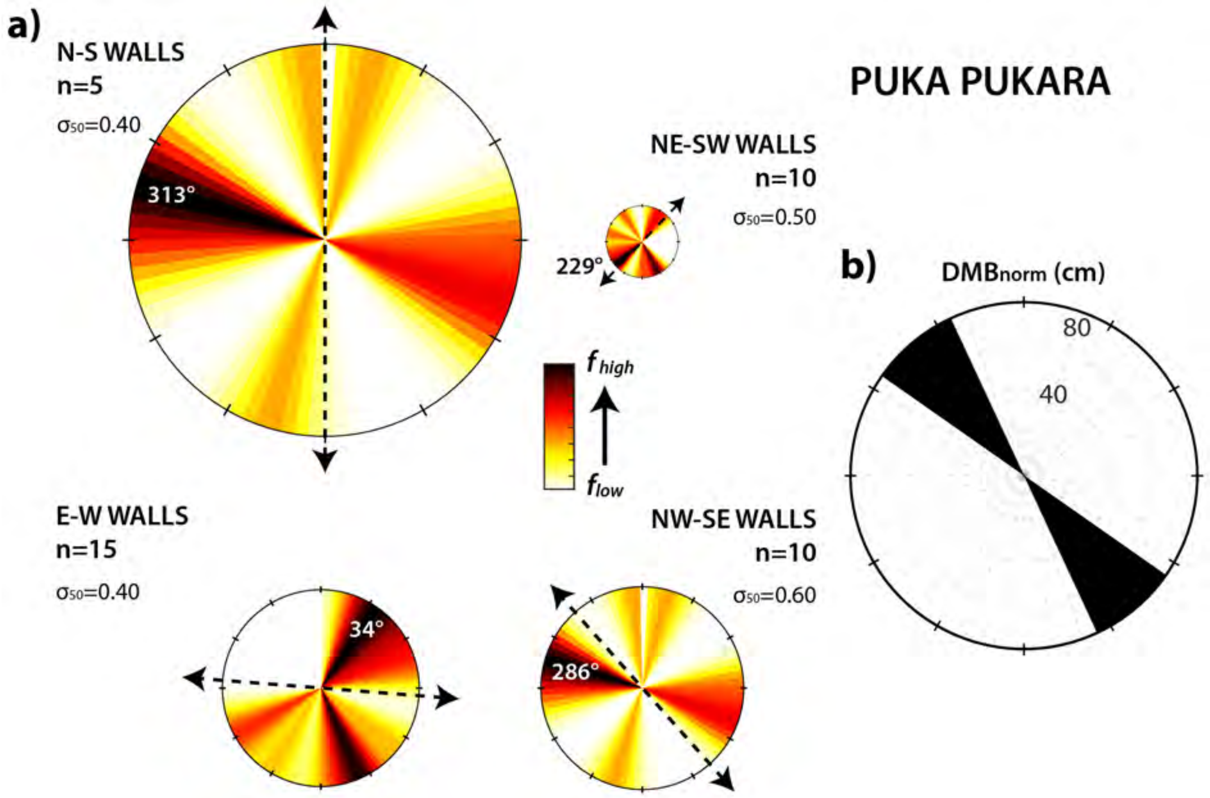

Figure C.5: a) Polar plots displaying the kernel density function of the DBC's dip direction in the site of Puka Pukara. The size of the plots is function of the DBC_{norm}-value. The dotted arrows indicate the wall trends; b) Normalized cumulated amount of DMB according to the wall's orientations.

Wiñaywayna

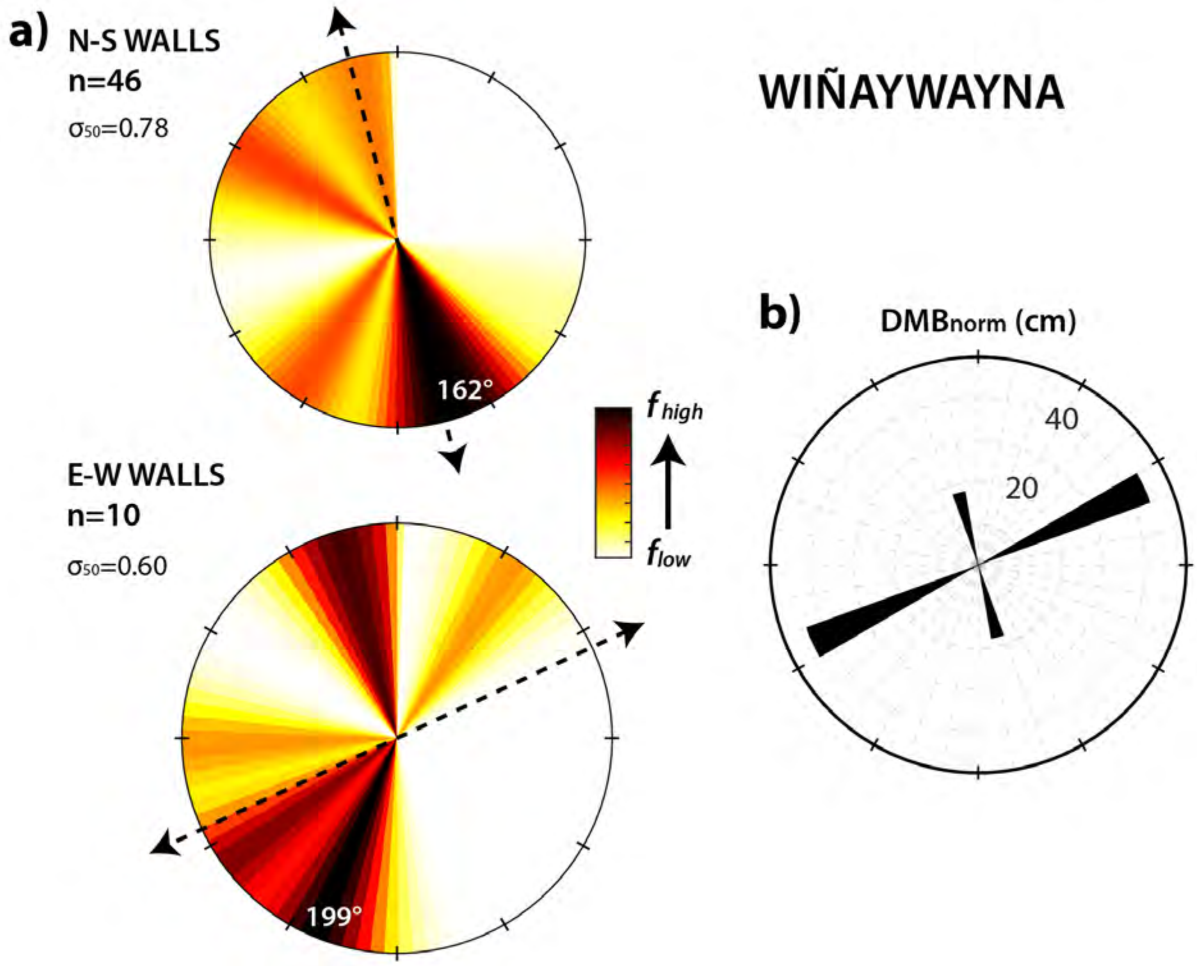

Figure C.6: a) Polar plots displaying the kernel density function of the DBC's dip direction in the site of Wiñaywayna. The size of the plots is function of the DBC_{norm}-value. The dotted arrows indicate the wall trends; b) Normalized cumulated amount of DMB according to the wall's orientations.

Tarawasi

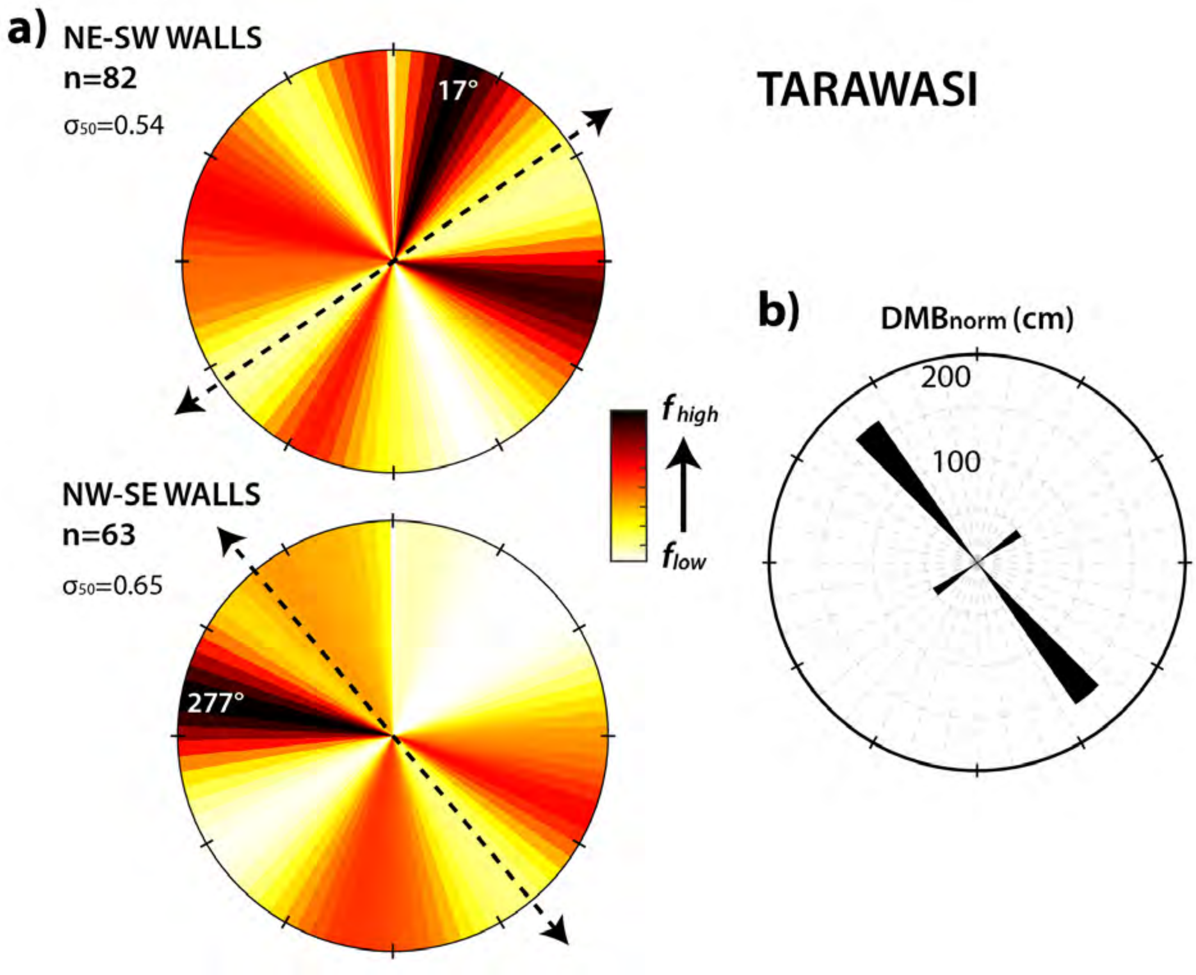

Figure C.7: a) Polar plots displaying the kernel density function of the DBC's dip direction in the site of Tarawasi. The size of the plots is function of the DBC_{norm}-value. The dotted arrows indicate the wall trends; b) Normalized cumulated amount of DMB according to the wall's orientations.

C.2 Photographs comparison

C.2.1 General comments

We performed a photograph comparison on six Inca/neo-Inca remains of the city of Cusco (fig. C.8) and on one Inca structure of Tambomachay (fig. C.15). Considering the aim of this analysis, which was the assessment of the impact of the 1950 earthquake on the fine stonework, the main criterion for selecting the places was the availability of relevant historical photographs taken prior to 1950.
Beyond the sharp contrast that any observer may notice between the state of conservation of the Inca and colonial architecture in the aftermath of the 1950 event (fig. C.12 - LIFE pictures), the comparison of photographs before and after the event supports a very limited impact of the 1950 earthquake.
The Inca street corners of Waynapata (fig. C.9), Hatunrumiyoq (fig. C.10) and Tullumayo (fig. C.11) show, nowadays, almost no new strain structures compared to the end of the 19^{th} century. Although, the analysis of the modern pictures do not preclude potential restorations after the ground motion, it should be emphasised that the strain structures observed on the historical photos still exist today.
Similarly, Figure C.12, Figure C.13 and Figure C.14 showing the Qorikancha curved wall and *La Casa de las Sierpes* (Nazarenas square) complement the detailed comparison carried out in the manuscript. Their analysis is in accordance with the observations made in Figure 4.11 and Figure 4.12 of the paper. A large majority of the strain structures observed today on those two buildings cannot be associated with the seismic event of 1950, and neither 1941 (fig. C.14).
Last but not least, very few historical documents are available regarding the archaeological sites located near Cusco. We could only find one relevant historical photo in Tambomachay and dated 1934 (fig. C.15). While several pieces of evidence point towards substantial restoration works and the use of the *anastylosis* technique[2], the similar state of conservation of the structure nowadays and in the first half of the 20^{th} century suggests a limited impact of the 1950 earthquake. However, further research is needed to confirm this assumption.

[2] Potential DMB were removed between 1934 and today. One potential DBC, which cannot be restored, is still present (fig. C.15).

C.2.2 Resources

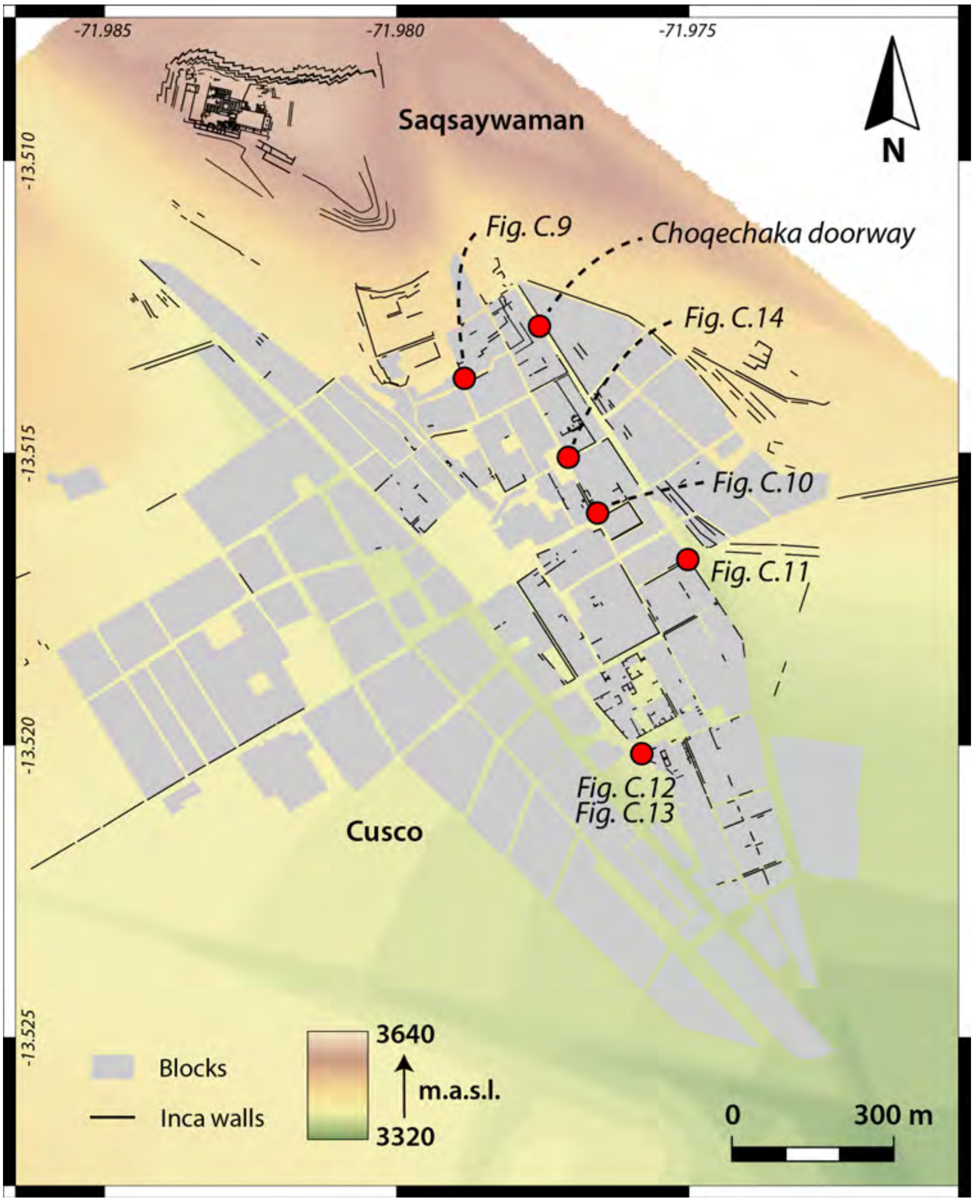

Figure C.8: Map of the historic city centre of Cusco showing the location of the different architectural remains investigated thanks to historical photographs.

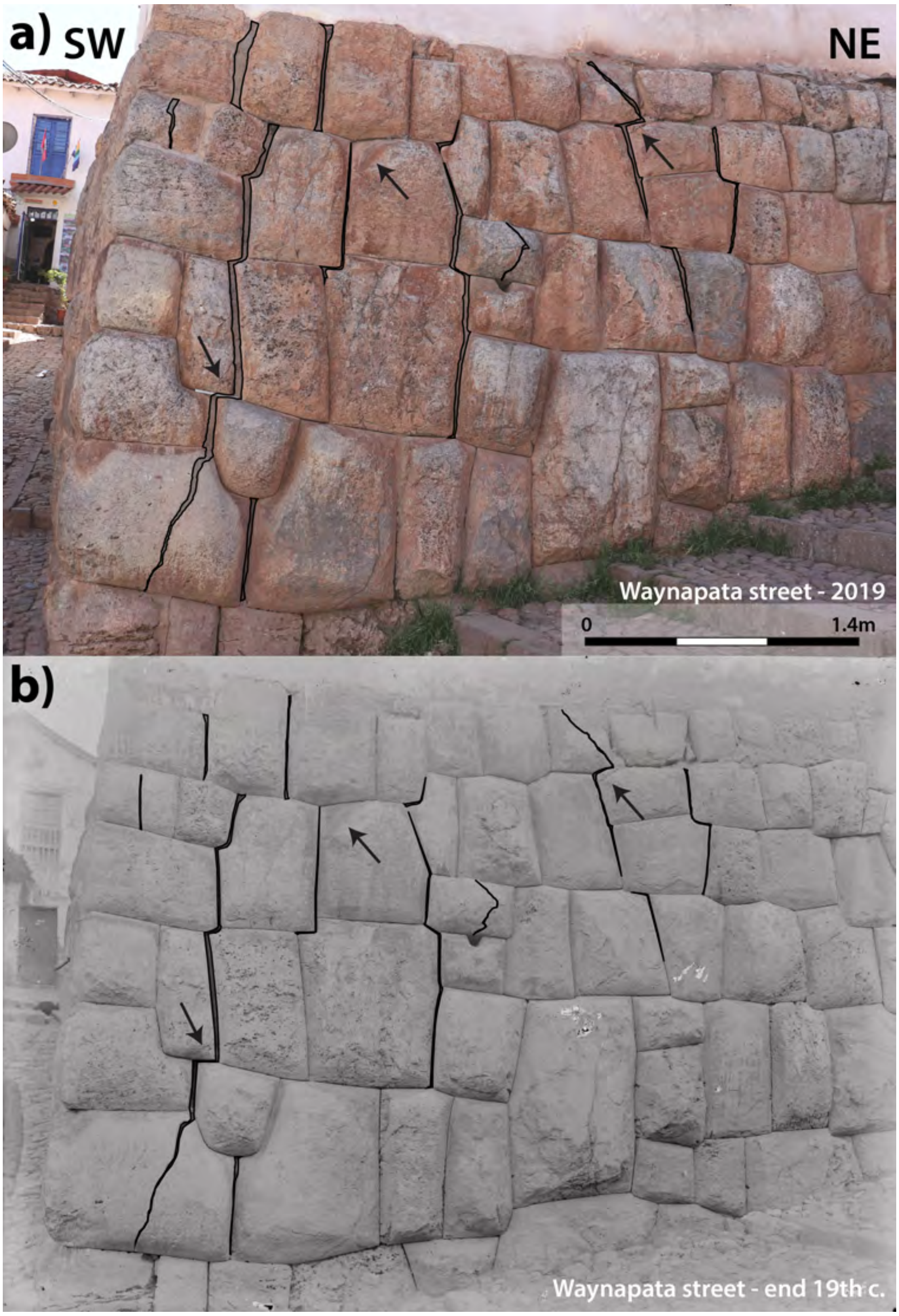

Figure C.9: Pictures of the eastern corner of Waynapata street with Arco Iris street in a) 2019 (credits: the authors) and b) at the end of the 19^{th} c. (credits: Max Uhle). Black lines point out the main cracks/DMB. Black arrows indicate potential DBC.

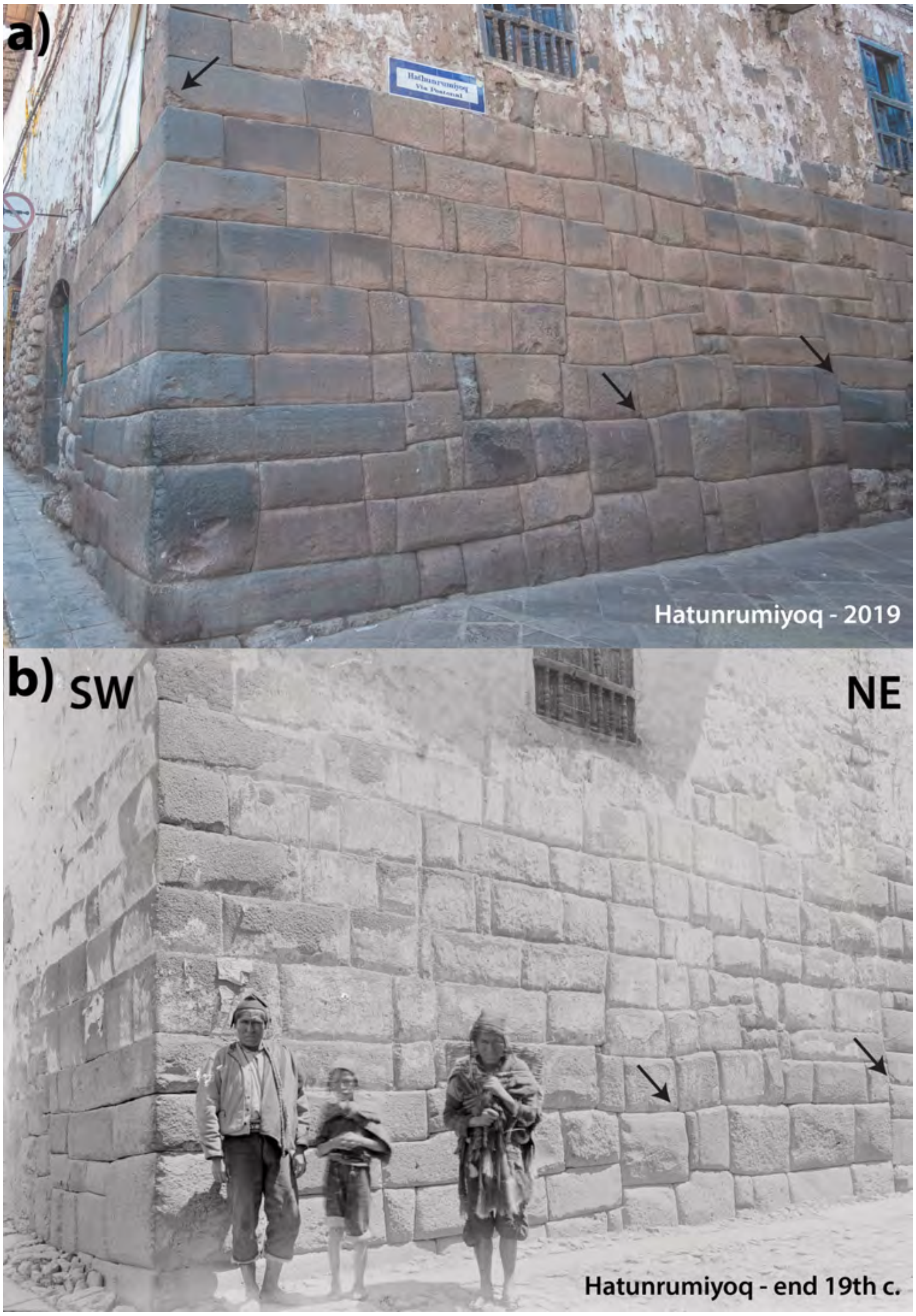

Figure C.10: Pictures of the northern corner of Hatunrumiyoq street with Herrajes street in a) 2019 (credits: the authors) and b) at the end of the 19^{th} c. (credits: Max Uhle). Black arrows indicate potential DBC.

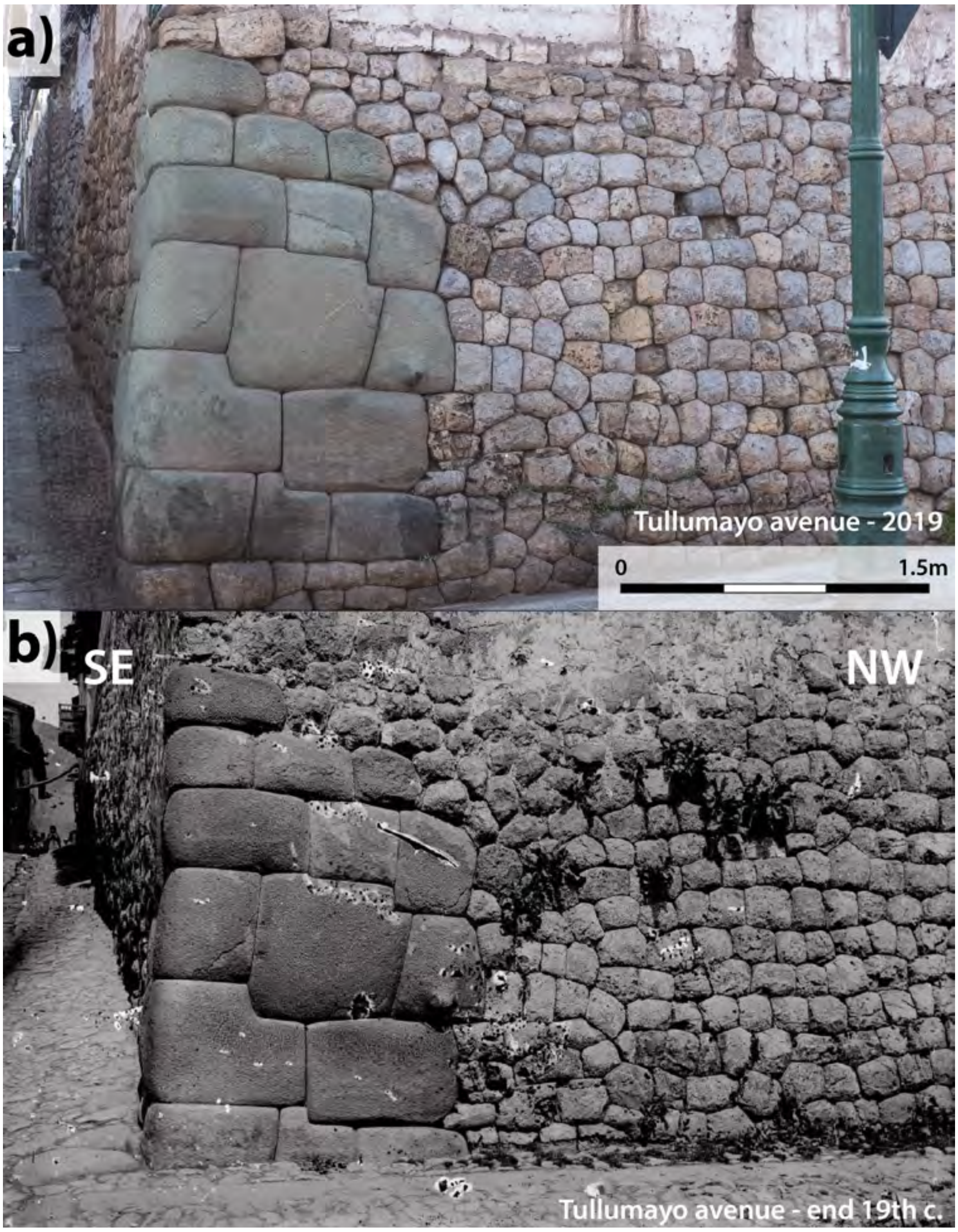

Figure C.11: Pictures of the northern corner of Cabracancha street with Tullumayo avenue in a) 2019 (credits: the authors) and b) at the end of the 19^{th} c. (credits: Max Uhle). No clear strain structure can be noticed.

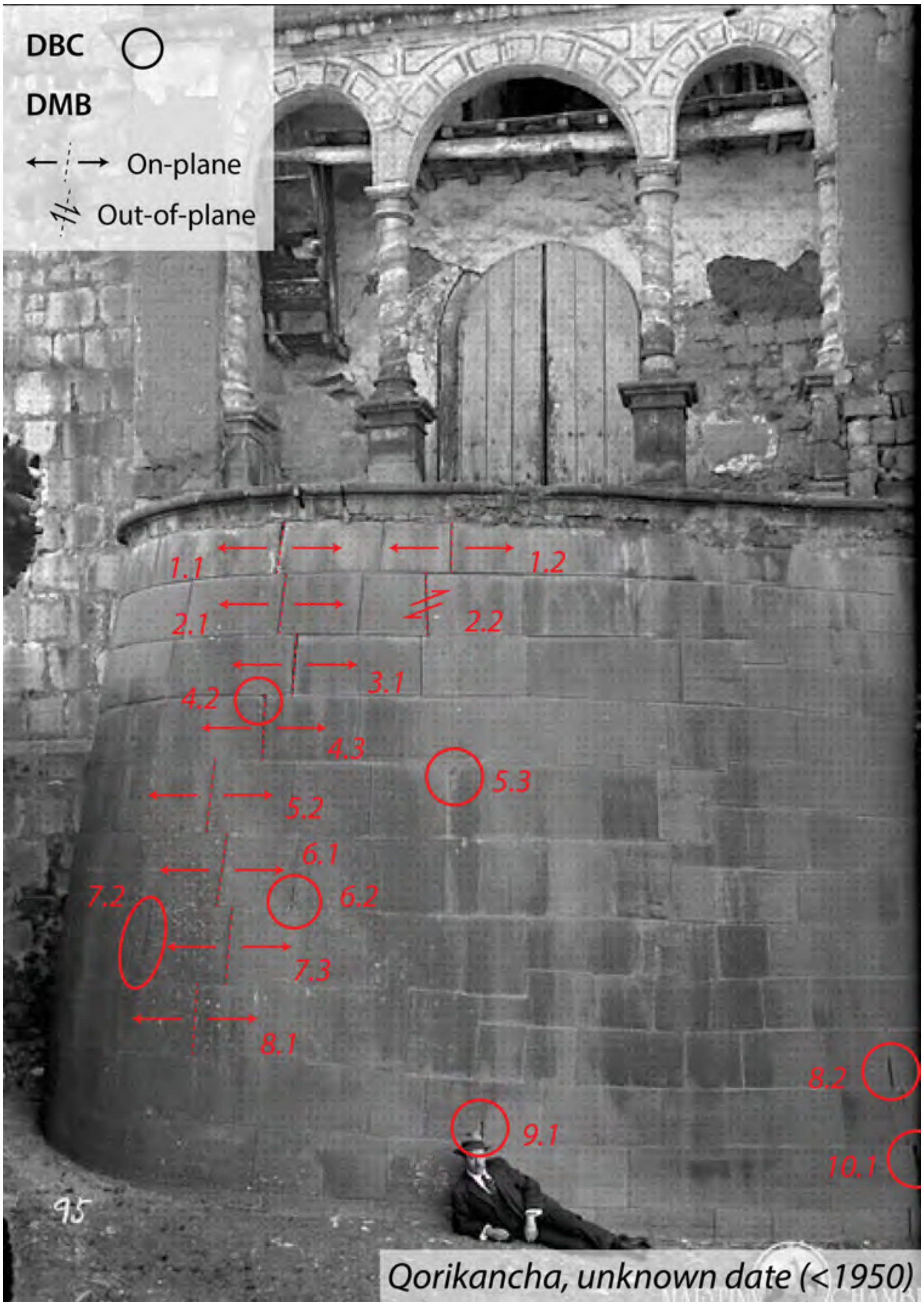

Figure C.12: Martín Chambí's photograph of the curved wall of the Qorikancha (dated before 1950), highlighting the EAEs.

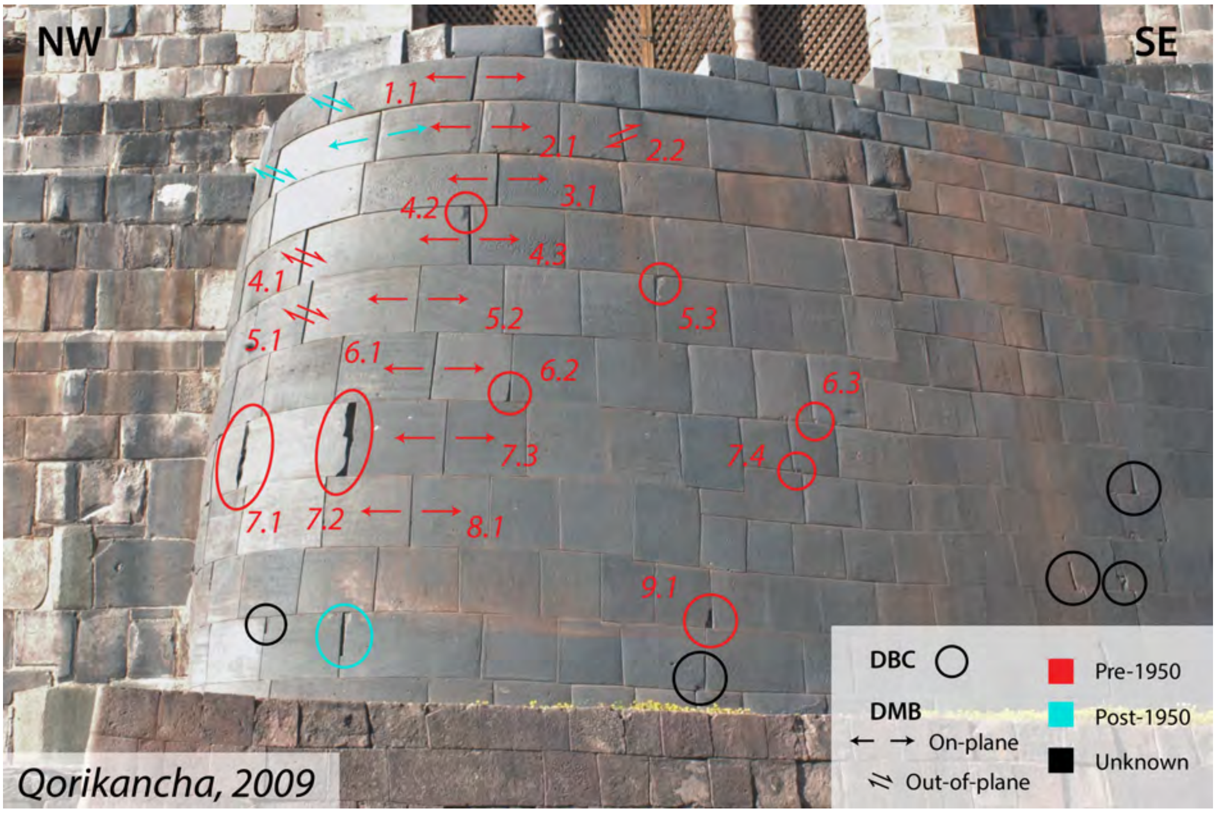

Figure C.13: Picture of the curved wall of the Qorikancha in 2009 (credits: Instit. Nacional de Cultura, Center for Advanced Spatial Technologies - University of Arkansas - and Cotsen Institute for Archaeology - UCLA), highlighting the EAEs. The dating of the strain structures (colors) is based on the analysis of the photographs in Figure 4.11.

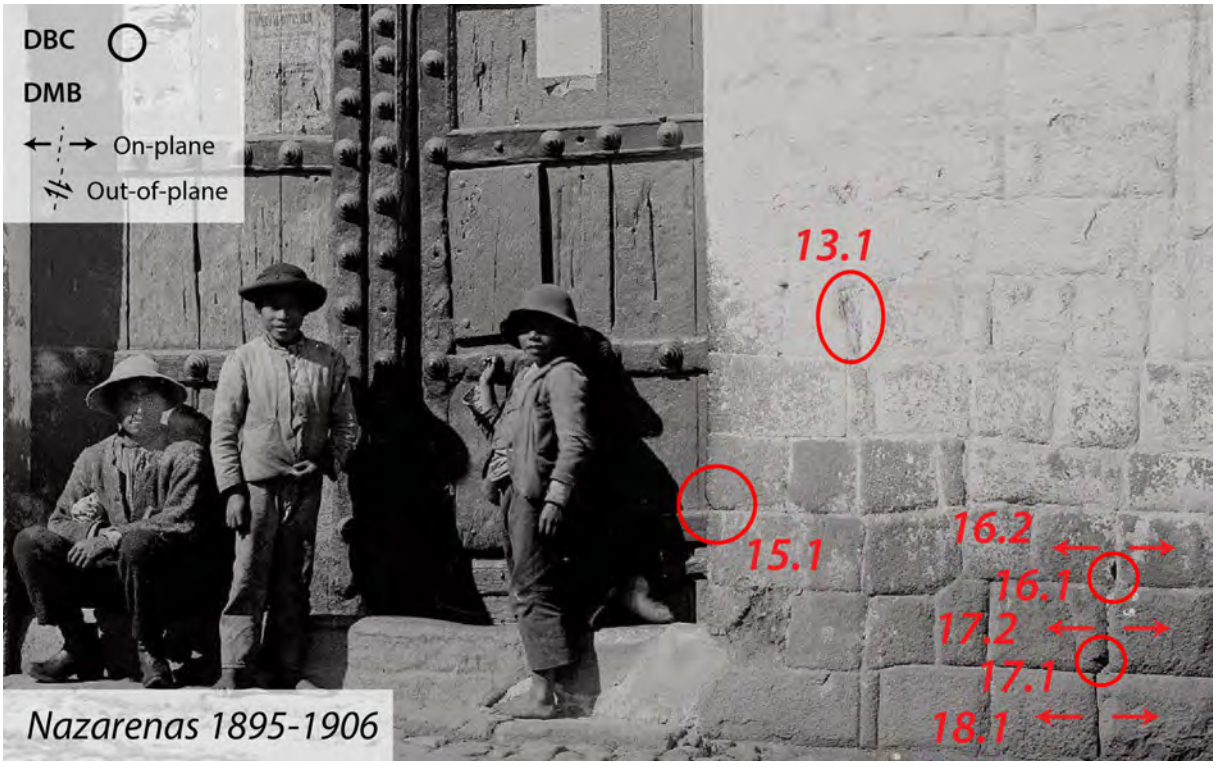

Figure C.14: Max Uhle's photograph of *La Casa de los Sierpes* gateway (probably at the end of the 19^{th} c.), highlighting the EAEs.

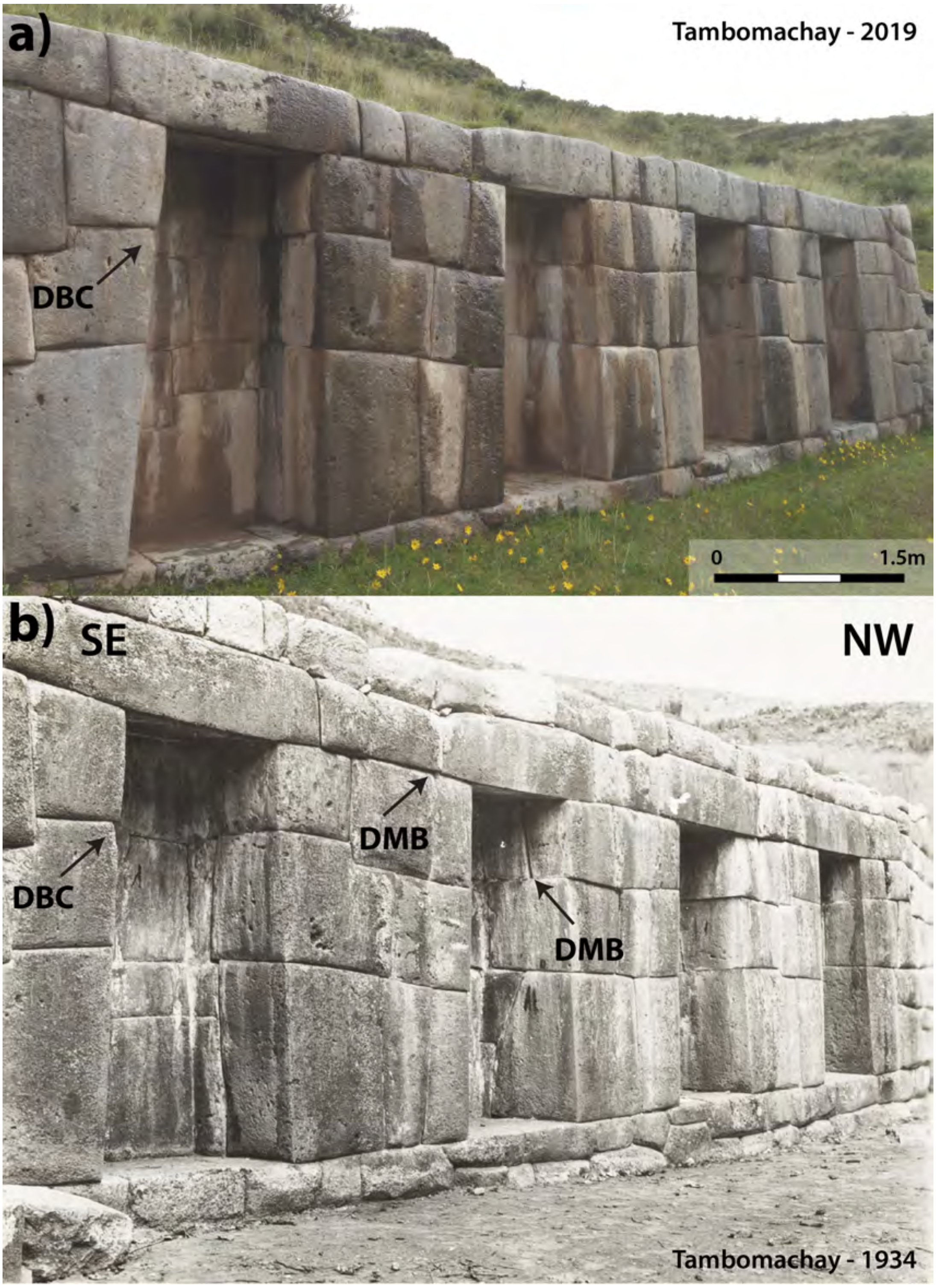

Figure C.15: Pictures of the monumental niches at the top the Tambomachay site taken in a) 2019 (credits: the authors) and b) in 1934 (credits: A.Giesecke). Black arrows indicate potential DBC and DMB.

Appendix D

Supplementary data Chapter 6

Supplemental Material for this article includes the spectral densities of the aftershocks (Nov 18, 2019, Nov 23, 2019 and Jan 02, 2020) and the quarry blasts (Jan 10 and Jan 16, 2020) computed at two free-field stations, VIVI and CLAU respectively (network 3C). Inconclusive correlations between weather and structural parameters are included also.

D.1 Spectral densities

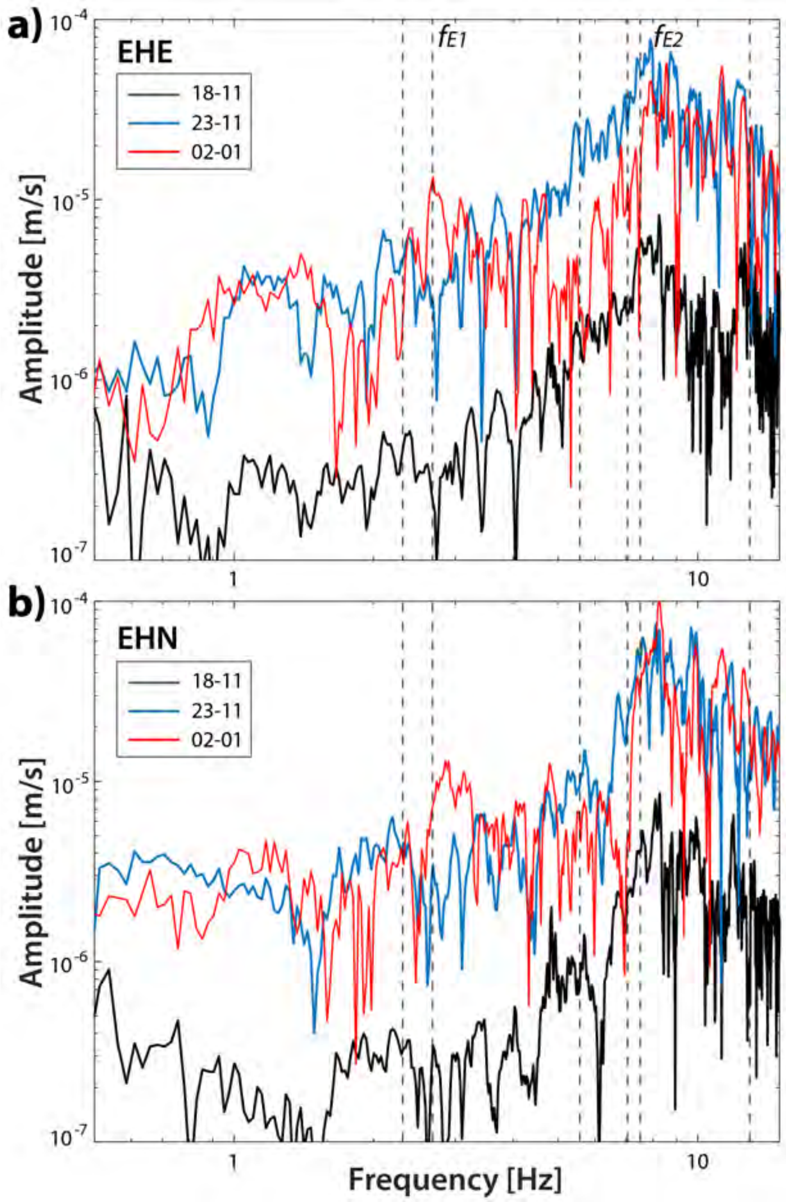

Figure D.1: Comparison of the frequency content of the three seismic events (Nov 18, 2019, Nov 23, 2019 and Jan 02, 2020) in both horizontal components (a-b) recorded at a free-field station 300 meters south of Viviers (VIVI-network 3C). We may note the highest amplitudes of the Jan 02, 2020 ground motion around the first E-W bending mode (f_{E1}) and, on the contrary, the lowest amplitudes around the second E-W bending mode (f_{E2}) in the E-W component. "EHN" and "EHE": two horizontal components of Extremely Short Period Seismometers.

Information on VIVI station is available here.

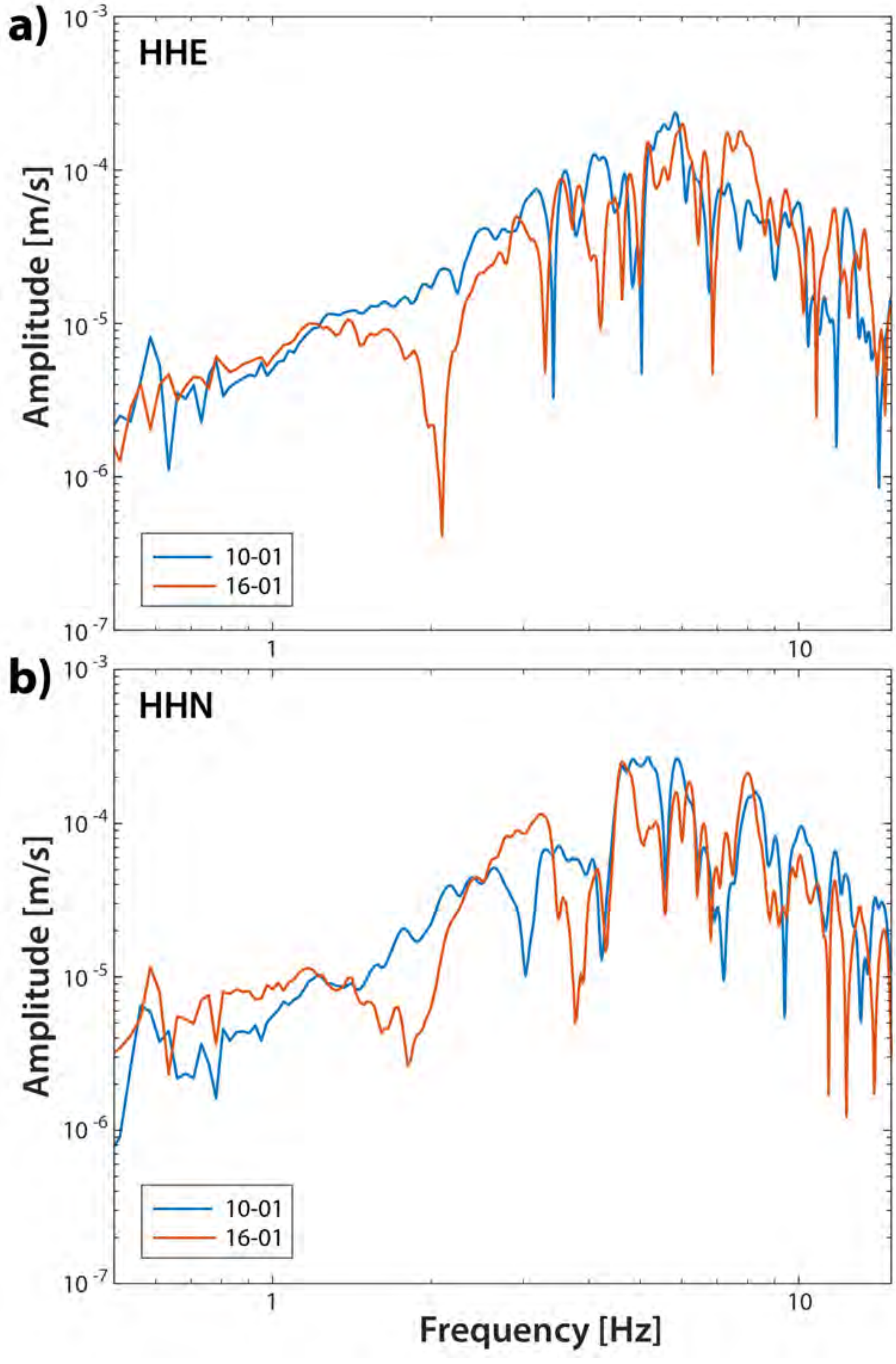

Figure D.2: Comparison of the frequency content of both quarry blasts (Jan 10 and Jan 16, 2020) in both horizontal components (a-b) recorded at a free-field station located less than 1 km west of the cement quarry (CLAU-network 3C). The spectra of both explosions are very similar. “HHN” and “HHE”: two horizontal components of High Broad Band Seismometers.

Information on CLAU station is available here.

D.2 Inconclusive correlations

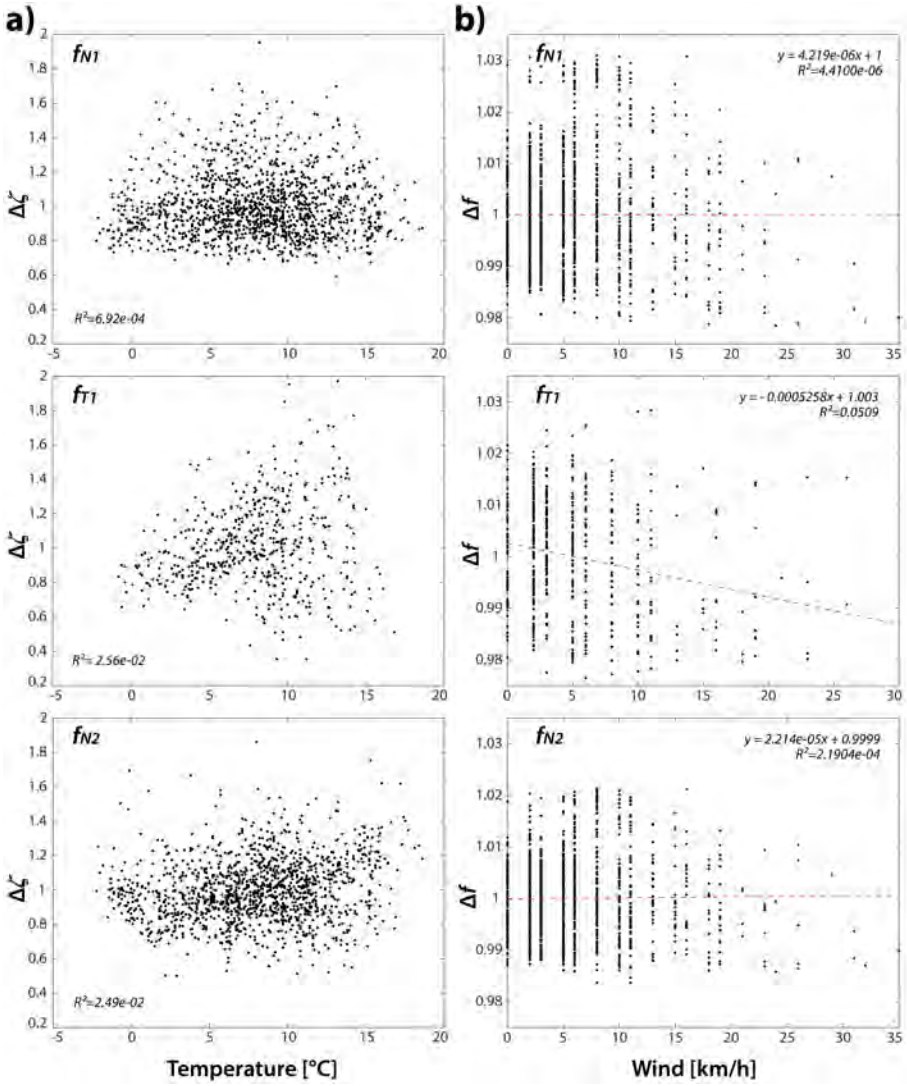

Figure D.3: a) Correlation between temperature and normalized damping for the first bending mode, the torsion mode and the second bending mode (top to bottom) in the N-S component; b) Correlation between wind speed and normalized frequency for the same vibration modes as a) in the N-S component. In both cases, parameters were not found linearly dependant. Plots are based on recordings extracted from N19.

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