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Localización y evaluación de fuentes históricas para el análisis científico de los terremotos y tsunamis chilenos preinstrumentales*

Locating and evaluating historical sources for the scientific analysis of pre-instrumental Chilean earthquakes and tsunamis

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Resumen

Este artículo utiliza la secuencia sísmica chilena para examinar los tipos de fuentes históricas que pueden utilizarse para analizar científicamente los terremotos y tsunamis preinstrumentales (1570-1898). En primer lugar, se aborda el contexto histórico de las fuentes potenciales y su disponibilidad en la actualidad. En segundo lugar, examinamos los tipos de fuentes que nos permiten medir la intensidad de un terremoto en un lugar específico, el tamaño relativo de su tsunami asociado y la presencia de deformación costera cosísmica. Esperamos que esta presentación permita no sólo una mejor comprensión de los procesos históricos relacionados con el estudio de los terremotos y tsunamis preinstrumentales, sino también su reproducción en otras zonas con una actividad sísmica similar.

Abstract

This paper uses the Chilean seismic sequence to look at the types of historical sources that can be used to scientifically analyse pre-instrumental earthquakes and tsunamis (1570-1898). First, we address the historical context of potential sources and their availability today. Second, we examine the types of sources that allow us to measure the intensity of an earthquake at a specific location, the relative size of its associated tsunami, and the presence of co-seismic coastal deformation. We hope that this presentation will allow for not only a better understanding of the historical processes connected to the study of pre-instrumental earthquakes and tsunamis but also its replication in other areas with similar seismic activity.

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1. Introduction

Large earthquakes and destructive tsunamis are an unfortunate part of Chile's history. Since the 16th century, there have been over two dozen large destructive earthquakes and tsunamis in Chile that have laid waste to her cities and coastline. A search for a scientific understanding of the forces associated with their generation and propagation has been a continual and constant focus of the local academic community since the 17th century. Colonial authors, such as the Jesuit Priest Diego de Rosales, included specific sections in their writings explaining the destructive nature of Chile's earthquakes and their connected tsunamis. Rosales could be credited with Chile's first scientific analysis of a seismic event when he tried to explain the origins of the coastal deformation that he saw firsthand after the 1641 Lebu and the 1657 Concepción earthquakes (Rosales, 1877; 2019). Subsequent analysis of Chilean earthquakes in the 19th century by Mary Graham and Charles Darwin advanced our understand of the basic mechanics of Chile's seismic events, known today as subduction earthquakes, and perhaps more importantly the significance of scientifically oriented witness observations (Wesson, 2017).

Today sophisticated mechanical instruments have replaced human observations in some aspects of earthquake science, such as recording the earthquake´s force, duration, and epicenter. However, lessons learned from the 1960, 1985 and 2010 Chilean earthquakes have strengthened our need to further analyze timely post-earthquake observations, related to specific scientific categories (Astroza et al. 2012). In other words, certain visual observations can be used by scientists today to better understand what occurred below ground during a major earthquake. The cumulative results of these observations allow scientists to create computer models of the earthquake, which betters our understanding of the event itself and the geographical areas where future events are most likely to occur. These models show clearly defined rupture zones, which can be described as the areas where accumulated seismic tension was released.

Our understanding today, related to the generation and perpetuation of earthquakes, is a continually evolving science. Since the 20th century, scientists have proposed that the Pacific coastline was the site of the convergence of two massive seismic plaques, whose interactions create subduction earthquakes and large tsunamis. The Nazca plaque which runs underneath the Pacific Ocean is continually moving East, while the South American plaque, located beneath the continent of South American is continually moving West. While the Nazca plaque tries to move beneath the South American plaque, the opposing forces create a locking mechanism that blocks their natural movement and accumulates large quantities of kinetic energy. After a long period of time in this locked position, the pent-up energy is released in the form of a subduction earthquake. Sometimes the earthquake is relatively small and only ruptures and small area such as the 2017 Chiloe earthquake or the 1928 Talca earthquake, which differ from the 1960 Valdivia and the 2010 Maule quakes whose ruptures stretched hundreds of kilometers along the Chilean coastline (Cisternas et al. 2017). When the rupture occurs below the surface of the ocean, the displaced water generates a serious of waves known as a tsunami. The size and destructive nature of these waves corresponds directly with the length and location of the rupture.

Today scientists use human observations and instrumental readings to create computer models that show the rupture zone for each large subduction earthquake. They do this in part because current seismic theory indicates that large subduction earthquakes are cyclical in nature and have the tendency to repeat themselves. However, the reduced number of instrumental earthquakes, does not allow for a clear view of the complete seismic cycle for any given point along the Pacific coastline. In order to resolve this deficiency, it is necessary to include within this equation, Chile's pre-instrumental historic earthquakes. For this investigation, pre-instrumental historic refers to events occurring between the years 1570-1906.[1] We affirm that the rupture zones for these historical earthquakes can be located by using a specific class of available historical documents (observations) to answer the same questions the scientists and government leaders presented to eyewitnesses in the weeks and months that followed Chile's more recent destructive earthquakes and tsunamis (Astroza et al. 2010).

This paper, within the study of Chile's seismic sequence, will define the types of records that can be used to answer scientific questions regarding the rupture zone of historical pre-instrumental earthquakes. We will take a closer look at the types of available records and the historical questions that need to be answered in order to locate potential records that provide the essential scientific details that computer analysts need to have in order to create their seismic models. While this investigation centers around the Chilean seismic record, the historical processes described here can be replicated in other population centers along any subduction fault line.

[1] Pre-instrumental earthquakes refer to those occurring before the use of modern seismographs at the end of the XIX century.

2. Chile's historical seismic record

A quick review of Chile's seismic record (Table 1) shows nineteen earthquakes whose intensity has been estimated at 8.0Mw or higher. While most large earthquakes were followed by equally destructive tsunamis several earthquakes such as the Santiago 1647 and the Chillán 1939 were not accompanied by a historically documented tsunami. Recent research by Carvajal (2017) has suggested that the 1730 Valparaiso earthquake had an intensity higher that 9.0 Mw and would only be rivaled by the more recent 1960 Valdivia earthquake. Interestingly, while estimated intensities exist for most historical earthquakes in the Chilean seismic sequence, only a fraction of them has a known rupture area.

Table 1 Large Chilean earthquakes 1570-2010

Date	Region	Magnitud	Tsunami
February 8th 1570	Concepción	8.0	Yes
December 16th 1575	Valdivia	8-8.5	Yes
May 13th 1647	Santiago	8.0	Yes
March 15th 1657	Concepción	8.0	Yes
July 8th 1730	Valparaíso	8.5-9.0	Yes
May 25th 1751	Concepción	8.5	Yes
April 3rd 1819	Copiapó	8.5	Yes
November 19th 1822	Valparaíso	8.0-8.5	Yes
February 20th 1835	Concepción	8.0-8.5	Yes
November 7th 1837	Valdivia	8.0	Yes
August 13th 1868	Arica	8.5	Yes
May 9th 1877	Iquique	8.0	Yes
August 16th 1906	Valparaíso	8.6	Yes
November 10th 1922	Huasco	8.4	Yes
December 1st 1928	Talca	8.4	Yes
January 24th 1939	Chillán	8.3	No
May 21st 1960	Concepción	8.3	Yes
May 22nd 1960	Valdivia	9.6	Yes
February 27th 2010	Concepción	8.8	Yes

Source: created from Lomnitz, 2004 and Astroza et al., 2012.

3. Identifying the Rupture Zone for a Historical Earthquake

In order to identify the estimated rupture length or zone for a historical earthquake we will first need to locate and analyze historical sources related to three specific aspects of the earthquake. First, we will locate and analyze sources that describe the quake's intensity, as seen in the damage suffered by manmade structures such as houses, churches, and government buildings. While reports of loss of life or the terror felt by a city's inhabitants are important components in our understanding of an earthquake, they in themselves do not provide useful scientific information (Onetto, 2007). Seismic intensity will be measured using the MSK modified scale (Monge & Astroza, 1989). The use of this particular scale has been the accepted in Chile since the 1985 Valparaiso earthquake and has subsequently been used with slight modifications to study the 2010 Maule (Astroza et al, 2010), 1960 Valdivia (Astroza & Lazo, 2010), 1928 Talca (Astroza et al, 2002) and 1906 Valparaiso (Astroza, 2007) earthquakes from historical sources. This particular intensity scale converts visual damage to houses, churches, and government buildings into numerical values that then can be used to find the associated seismic rupture. The most recent historical studies using the MSK modified scale in Chile allow us to ascertain that the area of seismic rupture best corresponds with an MSK intensity equal to or greater than VII and not an VIII as the study's authors initially hypothesized (Astroza et al. 2002).

The second source of information needed to characterize a historical seismic event is the size and propagation of its associated tsunami. Studies of recent Chilean and international tsunamis have shown that a subduction earthquake generated tsunami is not only larger closer to its source or origin but also reaches shore far quicker (Petit-Breuilh Sepúlveda, 2006). At the same time, the presence of a tsunami does not in itself confirm the occurrence of a seismic event at that location, as shown by the 2011 Japan tsunami or the 2022 Tongan tsunami that flooded parts of the Concepción region (Carvajal et al. 2022). The detailed information about the tsunami´s location, arrival time, size, and runup can be used to create computer generated models which will show the areas of seismic slip or rupture (Carvajal et al. 2017).

A third source of information needed to characterize the rupture zone of a historical earthquake is the existence of coastal deformation, referred to in the scientific literature as vertical changes. In simple terms, since the 1822 Valparaiso earthquake scientists have observed that after a large earthquake and tsunami that some parts of the coast remain higher or lower in relation to the level of the ocean than before the event. Today, scientists know that these changes are a clear sign of underground seismic activity. Vertical changes for recent earthquakes are recorded by sophisticated GPS systems which allow us to recognize patterns and analogs for historical events. GPS recordings from the 2010 Maule earthquake and visual observations from the 1960 Valdivia quake show that vertical changes (subsistence or uplift), can range from a few centimeters to several meters (Astroza et al, 2012). While smaller changes, resulting from a historical earthquake, would have gone unnoticed without the help of precise GPS measurements, larger changes would have been noticed even by the most unobservant officials. The existence of vertical changes in historical texts allow us to show seismic rupture in specific locations in the absence of tsunami records or seismic intensities. This is especially true for sparsely populated areas such as around the town of Pichilemu and along the Arauco Peninsula.

3.1. Understanding Chilean historical Records and their Context

The easiest way to learn about pre-instrumental earthquakes and tsunamis is through surviving the historical documentation. Letters, reports, journals, newspapers, and court cases are just some of the vast arrays of possible source material for historical earthquakes and tsunamis. Each type of document includes specific information and an inferred level of reliability. Since the XIX century, scientists using historical texts have created descriptive catalogs of seismic events. However, most in the scientific community today use these catalogs without first checking the authenticity of or questioning the use of the historical texts. For example, Soloviev included the following in his catalog of Chilean earthquakes the following statement about the May 25th, 1751, Concepción earthquake, "There are some reports to the effect that the bottom of Concepción Bay had risen 7m (24 feet) during the earthquake; the resulting shoal consisted of hard sandstone rather than sand" (Soloviev, 1975). A recent analysis of his unnamed sources revealed that the quote he used to insinuate major vertical changes was not a firsthand account, but the musings of a local sea captain over one hundred years after the earthquake.

In order to better understand and position our vast collection of historical documents, it is necessary to explain in part how and why they were produced and more importantly what records, that have been lost, would have been useful in our analysis of historical earthquakes and tsunamis had they survived. This renewed analysis is needed in itself since many texts used in recent historical earthquake investigations were not included in the original seismic catalogs or in any of their more recent adaptions (Lomnitz, 2004).

Up until recently most Chilean seismic catalogs have focused on retrieving documents stored in Spanish archives (Montessus de Ballore, 1911). Letters, reports, and petitions from local civilian, military and religious leaders were often sent to Spain requesting funds for rebuilding public and religious buildings. Some reports, like those from the governor or the army's commanding officer, explained how the earthquake or tsunami negatively affected the colony's ability to defend itself from hostile Indian groups and European marauders and that weapons and munitions were in short supply (Palacios, 2016; Stewart, 2023).

Large earthquakes, such as the 1730 Valparaiso and 1751 Concepción earthquakes, generated hundreds of pages of documents that were filed together in the *Archivo General de Indias* at Sevilla which has facilitated their use in investigations (Onetto y Palacios, 2019). For the more recent 1835 Concepción earthquake earlier catalogs relied heavily on the writings of Darwin (1837; 1839) and Fitz-Roy (1839), while including some locally generated official damage reports. Recent investigations by the author have located dozens of new letters, reports, and court documents from the Chilean National Archive that refer to specific earthquakes and tsunamis (Stewart, 2019; 2020; 2021; 2024a). Most of these sources have not been previously used since they form part of unrelated court proceedings or are part of uncatalogued letters and reports. For the 1835 Concepción earthquake we have added to our source list whaling ship logbooks and firsthand reports from local newspapers and international papers from the East Coast of the United States, where many firsthand accounts were published in the months after the earthquake as well as an expanded set of local reports from the Chilean National Archive (Cisternas et al. 2017). That being said, it is necessary to understand some basic historical details related to the archive sources that we use in analyzing each earthquake.

3.1.1. Source Records-Letters

One of the clearest sources that we have for historical earthquakes and tsunamis are letters sent from a local authority to his superiors. City Councils and Corregidores sent letters to the Governor or Viceroy, many of which were forwarded to the Spanish King. Priests and Bishops sent letters to authorities in Rome, Lima or Madrid. While the Governor sent letters to the King in Spain or to the Viceroy in Peru.

Letters served to inform their reader or audience that serious damage occurred and that additional funds would be needed to either solve the individual needs of the letter´s author or the needs of the community that the author represented. Limited or reduced earthquake damage did not justify a written request and thus did not generate letters or damage reports.

Unfortunately for us today, during the 16th century earthquakes and other extreme phenomena were looked on as a punishment from God for the collective sins of a city, country, or local leader (Ciruela, 2024; Petit-Breuilh-Sepúlveda, 2006). A letter to the King reporting a large earthquake or volcanic eruption was the same as voluntarily admitting to serious crimes and sins in a court of law. Taken into context with the Spanish Inquisition that was in full force, it should be no surprise that there are few letters or damage reports from the 16th century

and those that we have located are written in such a way as to show the author as an outsider viewing the destruction of a specific city or region and not part of the problem that brought upon them God´s "punitive wrath". One such instance can be seen when the civilian and religious leaders of the city of Concepción recognized their collective guilt as a
cause for the February 8 th , 1570, earthquake and tsunami and attempted to make amends by founding a hermitage on the hill above the city in July of the same year (Carvallo Goyeneche, 1770).

3.1.2. Source Record-Written Reports

This category can be divided into three groups, the first of which corresponds to town council minutes. Colonial town councils met weekly and recorded the subject of each meeting and their resolutions in yearly logbooks, a few of which have survived to this day. The cities of Santiago and La Serena provide us with detailed examples of post-earthquake town council minutes and record several earthquakes not included in letters due to their reduced damage and intensity (Palacios, 2016).

The second group of reports includes narratives, usually written by Jesuit Priests that combined many first and secondhand account to create a detailed account of a specific earthquake for a European audience. Many Jesuit reports include specific detailed stories whose original sources are now lost or unknown. Some expanded reports include a small number of temporal or spatial errors by the author who was writing the text weeks or months after the events occurred. Most of these reports form part of the yearly history that the Jesuits convents and missions in Chile sent to their superiors in Rome.

The last group of reports that we use to recreate earthquake and tsunami damage are chronicles, written histories, produced by monks or military leaders, while some rely solely on known letters or reports most cite unknown documents, or the authors own firsthand experiences. They permit a more global view of the event by not focusing entirely on either the city of Santiago or Concepción. Some authors like the Jesuit Priest Diego de Rosales (Rosales, 1877; 2019) provide detailed firsthand accounts of earthquakes and tsunamis, while others like Alonso de Ovalle rely almost entirely on reports from local leaders or institutions (Ovalle, 1646).

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3.1.3. Source Records-Court Cases

Civil and criminal court cases represent a new and unique vantage point from which to analyze the destructive nature of historical earthquakes and tsunamis. In Stewart (2019), surviving judicial records were analyzed from the town of Concepción which permitted the creation of detailed tsunami runups and specific earthquake damage reports for that city.

While only a small portion of the colonial judicial records exist today, specific references to seismic events abound therein and allow us to not only confirm local reports but to pinpoint specific damage zones. Court cases from the regions of Colchagua and Maule have included seismic references from rural haciendas or coastal installations, not included in general regional damage reports given by Corregidores or Town Councils. Furthermore, court cases and notary books also show the condition that specific buildings were in, when they were sold in the months or years after a seismic event. Lastly, court cases in Colchagua entered into evidence that the 1751 earthquake drastically changed the elevation of the coastline in ways that the residents could see and describe, but not explain scientifically at that time.

3.2. Identify Available Historical Records

In order to focus an investigation on a specific earthquake or tsunami it is necessary to understand which types of historical records are most likely to exist and which records would not have existed at that time. The existence and availability of records varies by region and period which makes this step essential in the timely completion of the investigative process.

3.2.1. Rural vs. Urban

In the 16th century in Chile there were fourteen villas or colonial towns. Each had a town council that administered justice and attempted to maintain contact with the capital city of Santiago and the judicial center of Concepción. The number of Spanish officials who knew how to read and write was very limited, with several towns sharing notaries in the absence of other capable scribes. During this period the Chilean countryside was dotted with Indian villages, controlled by Spanish *encomenderos* who lived in one of the towns. However, very little documentation was produced outside of the towns themselves, limiting our records to letters written by a specific town council to the Spanish Governor or King.

In 1598 a major Indian uprising reduced the number of towns in Chile from fourteen to five, La Serena, Santiago, Chillán, Concepción, Castro, and a sixth Valdivia that was rebuilt in 1646. While these cities retained their administrative power, we no longer see letters from their town councils, which were expected to resolve most issues locally. Furthermore, today we only have partial city council records from Santiago and La Serena, the rest of their records and those from the remaining cities were either destroyed by earthquakes or military activity (Palacios, 2016).

During the first half of the 17th century several thousand Spanish soldiers arrived in Chile from Spain and Peru, some of which knew how to read and write, and hundreds of haciendas and ranches were built in the Chilean countryside filling many of Chile's rural valleys with herds of cattle and vineyards and the occasional adobe or wooden structure. Property disputes and labor disagreements were resolved by local courts and in some cases were appealed to the Spanish courts in Santiago. The surviving documentation from these courts permit us to fill in parts of the geographical void that were left with the destruction of Chile's southern cities and the large empty area between Santiago and Concepción. However, limitations still exist, such as the Indian uprising in 1655 that forced the abandonment of the haciendas South of the Maule River for a period of ten years or the destruction of regional judicial archives during the Chilean war of independence (Stewart, 2021).

In the 18th century the Spanish crown introduced a new political and administrative system which entailed the creation of new towns with the hope of congregating the rural population in urbans settings (Lorenzo, 1985). Dozens of towns were founded around existing parish churches (Talca, San Fernando, San Carlos, Cauquenes), frontier forts that no longer needed an exclusive military zone (Nacimiento, Santa Barbara, Los Angeles, Tucapel, Yumbel, Rere), or in abandoned Indian villages (Coelemu, San Carlos, Haulqui, Quirihue). The addition of these towns returned the creation of relevant historical documents back to the town councils. During the 19th century additional towns were formed. For this reason, rural towns play a large role in our understanding of the 1835 earthquake.

3.2.2. Specific vs. General

One of the trickiest aspects in analyzing historical documents is understanding the nature of the information relayed by its author to its intended audience. Since we are not that intended audience, it is imperative that we understand the conditions not only of the text's author but its intended reader. For example, local Spanish leaders such as Governors, Corregidors, Alcaldes, Bishops, and military commanders generally wrote on behalf of their respective jurisdictions. For that reason, the Corregidor of Maule would write in 1751 that every building in his district had been destroyed (Palacios, 2016). Did he personally confirm the destruction of each building before sending the report? Of course not. His affirmation cannot be used to ascertain the level of destruction in any particular building but can be used to assign a minimum level of destruction for the region or town. Over half of the compiled damage reports can be described as general, even though some of them include information about specific buildings within their jurisdictions. The opposite is seen in judicial records where witnesses and plaintiffs provide detailed information about specific locations and then general regional information to put their testimony into context. For example, after the 1657 earthquake and tsunami in Concepción, witnesses were called upon to explain the death of Doña Maria Gatica (Stewart, 2021). They made it clear that she died when a wall of her house, whose location was identified as part of a larger investigation, fell on top of her during the earthquake and that they had not been able to rescue her before the tsunami reach her. Their testimonies first allow us to chart the earthquake's damage and the presence of the tsunami at Doña Maria Gatica's house and then general information about the state of the city of Concepción itself.

3.3. Locating Records of Historical Tsunami

Since most tsunami references come from coastal locations, it is necessary to understand the historical occupation of Chile's coastal communities. During the sixteenth century, the Chilean coast was explored, and secure anchorages were recorded on nautical charts. However, ports and military defenses were built around only a fraction of these potential anchorages.

Table 1 Chilean anchorages with tsunami reports 1570-1837

Name	Location		Port Facilities	Local Officials	Port Usage	Tsunami Reports
Coquimbo	-29,960	-71,338	Yes	After 1750	High	1730
Concon	-32,922	-71,508	No	No	Low	1647?
Valparaiso	-33,047	-71,603	Yes	After 1750	High	1730,1751
Juan Fernandez	-33,636	-78,833	No	After 1750	Low	1751, 1835
Talcahuano	-36,720	-73,111	After 1760	After 1750	High	1657, 1730, 1751, 1835, 1837
Tome	-36,614	-72,958	No	After 1850	Low	1751, 1835
Penco	-36,739	-72,995	Yes	Until 1750	High	1570, 1575, 1657, 1730, 1733, 1751, 1835
Arauco	-37,248	-73,316	No	Yes	Low	1657, 1751, 1835
Santa Maria	-37,022	-73,525	No	No	Low	1657, 1835
Mocha	-38,397	-73,908	No	No	Low	1835
Imperial	-38,765	-73,403	No	Until 1600	Low	1575, 1737
Valdivia	-39,827	-73,236	Yes	Yes	Low	1575, 1737, 1751, 1835, 1837
Ancud	-41,870	-73,821	Yes	After 1800	Low	1835, 1837
Castro	-42,474	-73,774	Yes	Yes	Low	1575, 1835, 1837

Source: created from original sources by the author.

Table 2 shows fourteen coastal locations used as anchorages during colonial times between Coquimbo and Chiloe, where references of historical tsunamis have been located. Most ports were appendages to existing cities and only became separate jurisdictions in the late 18th century. While in some cases, such as Castro, Concepción and Valdiva, a portion of the port facilities were located within the town´s urban tracts, in most instances there was a large geographical separation between the port and its associated town. For example, the port of Valparaiso formed part of the city of Santiago, government officials would travel to the port during the summer to supervise the activities of the merchant and military vessels (Stewart, 2024b). However, during the remainder of the year all port operations were handled by written messages sent overland to Santiago.

Any earthquake or tsunami that occurred at a port during the months when government officials were not present would simply go unreported in official documents and any physical damage caused by such an event would be included within the general report for the city´s jurisdiction, without a need to separate or even mention the port by name. In part this explains the near absence of tsunami reports from the port of Valparaiso. The same relation exists between the port of Coquimbo and the city of La Serena.

3.3.1. Informants and Eyewitnesses of Historical Tsunamis

Identifying geographical sources of historical tsunami records is the first step in locating and understanding historical references. The second step is understanding who would be producing the historical record and what its purpose would be. For example, damage reports or witnesses accounts from the coastal military installations of Arauco, Colcura, Talcahuano, Valdivia and Valparaiso would be limited exclusively to the location´s commanding officer or the parish priest, since most military officials did not know how to read or write. Their written communications would have been sent to the governor and would be stored today in either the Real Audiencia copy books or as part of the overall earthquake documentation sent to Spain.

In the coastal cities of Concepción or La Serena the town council joined religious and military leaders in writing letters and reports describing the tsunami and its effect upon the city or its port facilities. Those reports would have been sent directly the Spanish Governor, who would then send copies to the Viceroy in Peru and the King in Spain, if he deemed it appropriate. Today copies can be found in the surviving town council minutes and disaster reports submitted to the Spanish king for the 1730 and 1751 earthquakes (Onetto y Palacios, 2019).

Apart from the specific government authorized reports, individual reports exist from port cities and other rural coastal locations. In general, these reports were not sent to government officials and form part of secondary proceedings. In civil and criminal court cases, the tsunami was referenced as a geographical and logistical placement for the events pertaining to the case, some of which revolved directly around the tsunami itself. Colonial histories known as chronicles and Jesuit annual reports known as *cartas anuas* also are exceptional secondary tsunami sources. They use a combination of personal experiences and assembled texts to create a general work whose complete accuracy cannot be ascertained.

Letters, damage reports and funding requests, sent to the Chilean government, became common occurrences in the aftermath of the 1822, 1835 and 1837 tsunamis (Palacios, 2016). Copies of official communications between the central government and local officials were also generally preserved in the Chilean National Archive and published in local newspapers. Apart from government sources, many 19th century tsunamis were described in detail by American and British military and whaling ship captains who wrote down their experiences in their logbooks, some of which were later published in American newspapers or scientific journals. For example, the June 5th, 1835, edition of the New Bedford Mercury contains a detailed account of the February 20th, 1835, Concepción earthquake from Capitan Whaton of the whaling ship Coral (Stewart, 2019).

4. Forms of Measuring Historical Earthquakes and Tsunamis

The scientific and historical study of earthquakes and tsunamis requires the use of specific forms of measurement that allow for comparisons between events that occurred in different locations, times, and surrounding characteristics. For that reason, it is essential that we identify what measurements or characteristics are needed to compare a past event with a more recent one. This is even more important today where most post-earthquake or tsunami surveys follow strict methodological procedures in order to better standardize their results. Since those standards were not in place even a few years ago, historical documents need to be analyzed in search of these key measurements.

4.1. Forms of Measuring Historical Earthquakes

The majority of the historical records analyzed in this investigation make reference to one or more earthquakes. Depending on the author's intended audience, specific details were included or omitted, which allow us to not only better understand the specific seismic sequence for each major earthquake, also its intensity in specific geographical locations.

4.1.1. Seismic Sequence

Many letters and reports give specific times and durations for the foreshocks, mainshock and prominent aftershocks pertaining to a large earthquake. Some sources also give an estimated number of aftershocks over a specific period of time directly following the earthquake. These details allow us to ascertain the size and overall complexity of the earthquake and the general location of the main aftershocks.

4.1.2. Sounds and Direction of Seismic Waves

Several authors refer to the loud sounds that accompanied the arrival of an earthquake. Others mentioned subterranean rumblings and strange lights in the sky. Lastly many texts refer to the direction the earthquake was traveling as seen by the seismic waves rolling along the ground or the direction which buildings or walls collapsed. This information allows us to better understand the earthquake and pinpoint its epicenter.

4.1.3. Ability to Remain Standing

Many individual earthquake reports include firsthand accounts of people being violently thrown to the ground by the quake or barely being able to remain standing. These details align with current intensities scales used to describe earthquakes today and allow for comparisons between earthquakes.

4.1.4. Structural Damage to Buildings

Formal damage reports describe generalized and specific damages that occurred as a result of the earthquake. These damages, which are used to assign a MSK intensity, include but are not limited to collapsed roofs, cracked or fallen walls, damaged finishings, upended foundation stones, smashed wine jars, and fallen shingles.

4.1.5. Ground Deformation

Many texts describe specific geomorphological changes that occurred to non-coastal ground surfaces as a direct result of the seismic shaking. Examples found in historical texts include, liquification, deep cracks along the ground, water spewing out of cracks, sulfur geysers, and fires caused by toxic gasses. Today we know that these events are triggered by exact geological features combined with a specific level of seismic intensity. Thus, this information allows us to assign an intensity in the absence of other sources.

4.2. Forms of Measuring Historical Tsunamis

Historical records that include references to tsunamis are analyzed or broken down into specific components that allow for size comparisons and computer-generated tsunami models. While, we have identified five specific components to a historical tsunami, generally, only two or three are present within the historical texts for each location and event.

4.2.1. Presence of a Tsunami

Many historical records are limited to providing information about the presence of a tsunami in a specific geographical location. This occurs generally in locations where there were no prominent or notable landmarks that the writer´s audience would recognize. On the other hand, the author of many generic tsunami reports did not actually see the tsunami and only based his observations on a post-tsunami survey. A clear example of this can be seen after the 1751 tsunami, where civil court cases clearly demonstrated the presence of the tsunami in the coastal lagoons of Bucalemu and Cahuil, without ever giving a clear description of the event itself. Another example are the descriptions of debris littering the beaches and hills of the Quiriquina Island after the 1657 and 1751 tsunamis, which shows their occurrence but gives no further measurable information as to size (Stewart, 2019).

4.2.2. Runup

The second category is the runup or the area flooded by the tsunami. A study of historical tsunamis in the Bay of Concepción used colonial records to locate the runup or physical extension of each tsunami in the locality of Penco (Concepción) (Stewart, 2019). Individual court cases and public records allowed us to differentiate between specific buildings reached by the tsunami and those that only suffered earthquake related damage. Similar studies, to a lesser extent, have been done for the port of Valparaiso and the coastal forts of Arauco and Colcura (Stewart, 2023). Recreating the flood zone for a specific tsunami allows for the calculation of its runup for computer modeling which is then used to determine the size of the wave.

4.2.3. Flooding Depth

Reports of tsunamis in the populated port cities of Concepción and Valparaiso include detailed descriptions of what occurred at specific locations. Many times, these locations included churches, government buildings, or military installations, whose present-day location is known. These locations were not only well known to the local reader but also could be imagined by those unfamiliar with the general layout of the city. For this reason, many of the more detailed reports include the depth of the flood waters at specific iconic locations. The level of detail shown in many of the measurements and the differences in the recorded depths between one location and another suggest that some were measured after the water receded, just as occurs today in a post-tsunami survey. In Penco (Concepción), we have specific locations where the water depth was measured after multiple tsunamis, which also allows for size comparisons (Stewart, 2019, 2020, 2021).

4.2.4. Changes in Water Depth

Some witnesses of historical tsunamis were not on land when the events took place. Sailors described tsunamis from their unique vantage point. In most cases they were on board their respective ships, that were anchored at known locations whose water depth was recorded on nautical maps. Some recorded that their boats were beached as the water receded from the bay while others measured the variations in the water depth between the top and bottom of each wave or as the water receded from the bay. These measurements allow us to recreate the height of the tsunami waves before they reached the shore and can be used to project the wave’s inland movement. For smaller tsunami’s, such as those recorded in Valparaiso in 1751, the variations in the water depth are the only source we have that allows us to recreate the tsunami´s size.

4.2.5. Wave Height

Many of the historical records include the initial height of the wave as it reached the beach. In most cases it is unclear how this measurement was made, but in 1838 French explorers used the high-water marks made by the 1835 and 1751 tsunamis on the hills next to Penco to calculate the height of the wave based on the traditional spring high tide markers (Stewart, 2019). In the cases of Penco, Valparaiso, and Valdivia the walls of the beachfront military installations provided a convenient form of measuring or estimating the height of the incoming waves.

4.3. Forms of Recognizing and Measuring Coastal Deformation

Locating references of coastal deformation in the historical record, previous to Mary Graham's 1822 observations, is not without controversy. After the 1835 Concepción earthquake, Charles Darwin and others interviewed many ship´s captains who informed them that it was common knowledge that after large earthquakes that there were notable changes in the depth of the water near the shoreline and in the anchorages. One indicated that the depths recorded on nautical maps for the Concepción Bay prior to the 1751 earthquake were very different from those observed afterward. However, these seemingly obvious and important observations were not included in the historical record and were only recognized as being important after Mary Graham's and Charles Darwin's initial findings (Wesson, 2017).

4.3.1. Examples of Coastal Subsidence

In the days following the 1575 Valdivia earthquake we have located two references of coastal subsidence or sinking. First a letter from the Imperial Town Council to Melchor de Calderon, Chile's Provisional Governor, stated that the Cautin River was now navigable, which was inferred by Cisternas (Cisternas et al. 2005) as a sign of coastal subsidence. Second in Valdivia, anonymous reports describe the river in front of the city remaining salty months after the tsunami, Cisternas indicated that the increased presence of salt water in what originally had been a freshwater estuary was a sign of coastal subsidence.

As mentioned by Carvajal (2017), examples of coastal subsidence were recorded in civil court proceedings after the 1751 Concepción earthquake. Several landowners whose lands adjoined the Bucalemu and Cahuil coastal lagoons, filed civil complaints over the proliferation of new salt works as a direct result of the earthquake and tsunami. Joseph Gomez sued his extended family to regain operation control over his expansion of the family's Bucalemu saltworks and a second lawsuit between the Gomez family and Antonio Penrose, focused around a freshwater lagoon on the Gomez ranch that Penrose had converted into a new saltwork. Penrose explained that after the 1751 earthquake that the lagoon had been flood during the tsunami and the subsequent spring high tides had continued to reach it. Both accounts confirmed that fields above the high tide marks before the earthquake were now under over a meter of water.

To the North of Bucalemu, in the Cahuil Lagoon, a similar court case played out between Nicolas Pavez and his cousins over the ownership of the saltworks that he had constructed after the 1751 earthquake. Pavez claimed that the saltworks, constructed on a small lagoon nearly five kilometers inland from the coast belonged to him since he had made improvements that facilitated the production of sea salt. On the other hand, his cousins claimed that after the 1751 earthquake that the water level had risen over a meter which made any improvements made by Pavez unnecessary, since the Spring high tides would naturally reach the site making it legally part of the coastline. Today we can ascertain that co-seismic subsidence was clearly the source of the changes referred to in both court cases.

4.3.2. Examples of Coastal Uplift

Reports of coastal uplift can first be seen in the writings of the Jesuit Priest Diego de Rosales. His two written histories, described as a mixture of scientific and religious knowledge, include reports from 16th and 17th century earthquakes and his own experiences relating to the 1641 Lebu and 1657 Concepción earthquakes (Rosales, 2019; Rosales, 1877). The first earthquake that he described in his History of Chile, occurred on an unknown date during the first half of the year 1641. He stated that the Spanish Governor ordered the army´s commanding officer to relocate the fort of Lebu from its inland location along the Lebu River to a new location at the mouth of the river due to the fact that the earthquake “must have” caused many rocks to fall into the river since it was now unnavigable. The larger version of his text includes the observation that large sandbars had also formed in the river which prevented its navigation. Both texts, allow up to ascertain that the earthquake, caused coastal uplift in the area of Lebu, as seen in the recent 1960 earthquake.

The second earthquake described by Diego de Rosales was the 1657 Concepción earthquake (Rosales, 2019; Rosales, 1877). While the text mainly focuses on his observations from within the city of Concepción, in another section of his book, where he was describing the Chilean coastline, several firsthand observations were including that pertain directly to the aftermath of the 1657 earthquake. The first observation refers to the entrance of the Carampangue River which was used for nearly fifty years by the Spanish soldiers in Arauco as an anchorage and naval resupply point. Rosales observed that the river´s natural entrance and anchorage had been filled with sand bars which made it unusable for the supply frigates that used to anchor there.

Next, Rosales mentions that as they approached Lavapie on horseback he noticed that the recent earthquake had caused many large rocks to fall from the hills surrounding the entrance of the Tubul River. Before the earthquake, the entrance of the river was capable of anchoring frigates. They did not enter the river itself but were anchored offshore in the river's deep channel. Most of the Spanish naval vessels used this anchorage while resupplying at the nearby Santa Maria Island. After the earthquake, the channel was no longer deep enough for the navy´s midsized vessels. The author assumed that this occurred because many of the fallen rocks had eroded into the bay. However, a closer look at the region´s topography shows that this idea is not possible since the majority of the fallen rocks would not have reached the river´s channel.

Lastly, he explained that before the earthquake, that the entrance of the Tubul River reached the edge of the surrounding hills and filled the valley floor with water, creating a formidable marsh that protected the inland island of Lavapie. Furthermore, he reiterated that it could only be reached and crossed on horseback at low tide, since the Peñas Hills provided a natural barrier that could only be avoided by crossing the beach at low tide. He described that in 1658 when they reached the Peñas Hills some 500 meters before the mouth of the Tubul River they were surprised to see that a wide beach had formed along the base of the hill that allowed them to reach the river crossing while the tide was still high. The very same sequence of events at the Tubul River occurred after the1835 earthquake (Darwin, 1835) and then again in 2010 (Astroza et al, 2012), which allows us to assume that what Diego de Rosales was describing was co-seismic coastal uplift.

Conclusions

This article, although not exhaustive, defines the types of sources that can be used to answer scientific questions regarding the rupture zone of historical pre-instrumental earthquakes and tsunamis within the framework of the Chilean seismic sequence. Understanding the availability and importance of specific types of historical records will allow not only for a better more focused evaluation of pre-instrumental seismic events but will permit the continued discovery of new sources within Chile's vast national and regional Archives. Furthermore, recognizing the differences in format and content that exist between the scientifically oriented sources from the 19th century and the more rudimentary colonial sources will allow for a cognitive differentiation between the two and the reduction of lost hours in the search for the nonexistent perfect historical record. At the same time, the methods, source types and scientific observations described in this paper are not specific to the Chilean seismic sequence and can be used as guide in other similar zones prone to subduction earthquakes. Lastly, we while the recurrence of large destructive earthquakes is inevitable in Chile's near future, we hope that the study of her pre-instrumental earthquakes will allow researchers to better understand Chile's seismic cycles.

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