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Historical earthquake research in Austria



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Abstract

Austria has a moderate seismicity, and on average the population feels 40 earthquakes per year or approximately three earthquakes per month. A severe earthquake with light building damage is expected roughly every 2 to 3 years in Austria. Severe damage to buildings ($I_0 > 8^\circ$ EMS) occurs significantly less frequently, the average period of recurrence is about 75 years. For this reason the historical earthquake research has been of special importance in Austria. The interest in historical earthquakes in the past in the Austro-Hungarian Empire is outlined, beginning with an initiative of the Austrian Academy of Sciences and the development of historical earthquake research as an independent research field after the 1978 “Zwentendorf plebiscite” on whether the nuclear power plant will start up. The applied methods are introduced briefly along with the most important studies and last but not least as an example of a recently carried out case study, one of the strongest past earthquakes in Austria, the earthquake of 17 July 1670, is presented. The research into historical earthquakes in Austria concentrates on seismic events of the pre-instrumental period. The investigations are not only of historical interest, but also contribute to the completeness and correctness of the Austrian earthquake catalogue, which is the basis for seismic hazard analysis and as such benefits the public, communities, civil engineers, architects, civil protection, and many others.

Keywords: Historical earthquakes, Austria, Earthquake catalogue

Introduction—historical background

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A severe earthquake with light building damage is expected roughly every 2 to 3 years in Austria. Severe damage to buildings ($I_0 > 8^\circ$ EMS) occurs significantly less frequently, and the average period of recurrence is about 75 years.

For this reason the historical earthquake research has been of special importance in Austria.

The interest in historical earthquakes in the past in the Austro-Hungarian Empire is based on an initiative of the Austrian Academy of Sciences and the development of historical earthquake research as an independent research field after the 1978 “Zwentendorf plebiscite” on whether the NPP will start up.

In the following, the applied methods are introduced briefly along with the most important studies and last but not least as an example of a recently carried out case study, one of the strongest past earthquakes in Austria, the earthquake of 17 July 1670, is presented.

The research into historical earthquakes in Austria concentrates on seismic events of the pre-instrumental period. The investigations are not only of historical interest, but also contribute to the completeness and correctness of the Austrian earthquake catalogue, which is the basis for seismic hazard analysis and as such benefits the public, communities, civil engineers, architects, civil protection, and many others.

The Austrian Earthquake Survey was founded in 1904

The interest in historical earthquakes in Austria has a long tradition.

Shortly after the strong Ljubljana earthquake on 14th April 1895 the “Commission for the purpose of promotion of a more intensive study of seismic phenomena in the Austrian countries,” a so-called “Earthquake Commission” was established by the Academy of Sciences in Vienna (Kozák and Plešinger 2003). Laibach, today

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Ljubljana in Slovenia, was the capital of the duchy Carniola in the Austro-Hungarian Empire until 1918.

The goals of the former “Earthquake Commission” were the following:

1. *Compilation of a historical catalogue of earthquakes for the territory of the Austro-Hungarian Empire.* This led to earthquake compilations like Schorn (1902) and Hoernes (1902) which are still important for the study of historical earthquakes today.
2. *Organization of a seismic survey in the Austrian countries.* This was specified as “the most important task” of the project and included two subprojects:
 - the establishment of seismographic stations equipped with autonomously recording seismographs in Trieste, Vienna, Lemberg, Lvov, and Kremsmünster and
 - the establishment of a macroseismic observation network, which was started in 1896. The individual provinces in the Austro-Hungarian Empire each had their own reporter (Erdbebenreferent), who was responsible for the macroseismic survey after an earthquake. Among these earthquake reporters were Franz Noe, Johann Commenda, Josef Schorn, Rudolf Hoernes, Eduard Mazelle, Albin Belar, only to mention a few one.

Since then a comprehensive archive of questionnaires (from 1898 until 2004 at a rough estimate 30,000 and since 2004 more than 50,000 reports) and historical seismograms (all in all the number of seismograms is estimated at about 70,000 for the period 1904–1980) has been built up at the Zentralanstalt für Meteorologie und Geodynamik (ZAMG).

The collected microseismic and macroseismic data were first published by the Austrian Academy of Sciences in the series “Mittheilungen der Erdbeben-Commission der kaiserlichen Akademie der Wissenschaften, in the Sitzungsberichte der kais. Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Classe.”

As a consequence of these initiatives, the Austrian Earthquake Survey was established in 1904 at the Viennese I & R Central Institute of Meteorology and Earth Magnetism. Following this, the institute was renamed to the Central Institute of Meteorology and Geodynamics (ZAMG) in the same year. Victor Conrad (1876–1962) became the first Head of the Austrian Earthquake Survey.

The historical earthquake research became important due to a plebiscite in 1978

The strongest known earthquake in Austria was the 15th September 1590 earthquake with a magnitude of 5.75, and an epicentral intensity of 9° EMS-98 (AEC 2016).

In Zwentendorf, just 15 km from the presumed epicenter of this earthquake the first commercial nuclear plant for electric power generation in Austria was planned. The start-up of the Zwentendorf plant was prevented by a plebiscite on the 5th November 1978. A narrow majority of 50.47% voted against the start-up, and the Zwentendorf NPP never entered service. Following the 1978 referendum, no commercial nuclear power plant ever went into operation in Austria. In 1978 a law was enacted prohibiting the construction and operation of fission reactors for electrical power generation.

The scientists at that time were insufficiently prepared for a debate concerning the seismic safety of the site in the run-up to the plebiscite. Knowledge of the 1590 earthquake in Lower Austria was scarce and inconclusive, leading to conflicting interpretations.

One consequence of this debate was the development of historical earthquake research as an interdisciplinary research field at the University of Vienna by Rolf Gutdeutsch.

In 1986, during the General Assembly of the European Seismological Commission in Kiel, Germany, the “Working Group on Historical Earthquake Data,” later “Historical Seismology” was established and the historical earthquake research is still among the goals of the ESC.

In the following years numerous monographs and papers dealing with historical seismology issued by the Viennese group and by members of the ESC WG were published. (Gutdeutsch et al. 1987, 1992; Stucchi 1993; Albini and Moroni 1994).

Since the beginning one goal of the ESC initiatives was to produce an European earthquake catalogue, revised according to the results of ongoing historical earthquake research.

This goal was partially realized in the SHARE European Earthquake Catalogue, which was assembled and utilized in the SHARE project which was finished in 2013 (<http://www.share-eu.org/node/90>) and in the European Archive of Historical Earthquake Data (AHEAD) (<http://www.emidius.eu/AHEAD/>) which is conceived as a pan-European, common, and open platform to support the research on historical earthquake data and is intended to be a living database.

Historical earthquake research in Austria

What is the historical earthquake research used for?

Earthquake catastrophes have disastrous effects in the densely populated areas as well as at the sites of nuclear power plants, hazardous waste dumping grounds, nuclear waste depositories, large-scale technical constructions, etc. In order to obtain reliable information on the seismic hazard in a specific location, region, or critical technical

facility, the study of as many earthquakes as possible in the area is indispensable.

The need for a reliable and as complete as possible dataset for the past (pre-instrumental period) led to the development of, as mentioned before, a new research branch, approximately forty years ago in Europe, the “Historical Seismology,” which is most important in countries where the seismicity is low.

The implementation of the EUROCODE 8—the building code for earthquake-resistant building design—in Austria in 2009 emphasized the need for historical earthquake research. The hazard in terms of the considered average return period was then extended from 100 to 475 years.

Historical earthquake research—methodology

When studying a historical earthquake it is always a good starting point to establish a “family tree” (Fig. 1) to display the dependencies of the literature and sources.

The next step is the search for contemporary sources in the archives, which is very costly in terms of time.

Contemporary sources, which contain records of historical earthquakes, are e.g., annals or chronicles, council records in municipal, provincial, monastery or parish archives, personal diaries or e.g., chimney sweep invoices and many more. After transcribing, translating if necessary and documenting the sources, a critical interpretation of the reports is essential. Not only information about the author of a report, but also the place of origin of the source and the context is important, but in order to interpret reports on historical earthquakes correctly, it is necessary to get acquainted with the then current theories of earthquakes and the zeitgeist. People have come a long way in their understanding of the causes of earthquakes. At first myths, legends, and apocalyptic scenarios were used to explain processes in the Earth’s interior. For

example the founder of the Ionian natural philosophy, Thales of Miletus (625–547 B.C.) was convinced that the earth swims on the water. The induced waves triggered earthquakes, in his opinion.

On the other hand in the sixteenth century earthquakes were used as a tool for social disciplining. The Bishop of Vienna at that time, Caspar Neubeck (1591), held on the occasion of the earthquake of 1590 “Two Catholic sermons [...]” He spoke about God’s punishment and decried the vicious speeches of the citizens as responsible for the natural disaster.

With all the evidence coming mostly from contemporary sources, one gets information on where a certain earthquake caused damage or was felt, the so-called data points. If the quality of information on the earthquake is good enough, it is possible to assign intensities according to the European macroseismic scale EMS-98 (Grünthal 1998) to get the macroseismic (MDP) or intensity data points (IDP). From the intensity data points it is then possible to derive the seismic history of a site. In Austria this was carried out systematically initially for the federal country of Lower Austria. The seismic history of a site is not only of interest for seismologists or geologists but also for architects, civil engineers, for communities, and many others.

Last but not least, the seismologist can assess the earthquake parameters, like depth and magnitude from these IDPs.

Case studies

In the past 30 years, several case studies have been carried out for the Austrian territories. In Table 1 some examples are listed.

Table 1 shows that in some cases the epicentral intensity was slightly overestimated and in two cases out of nine examples, the “earthquakes” were even fake.

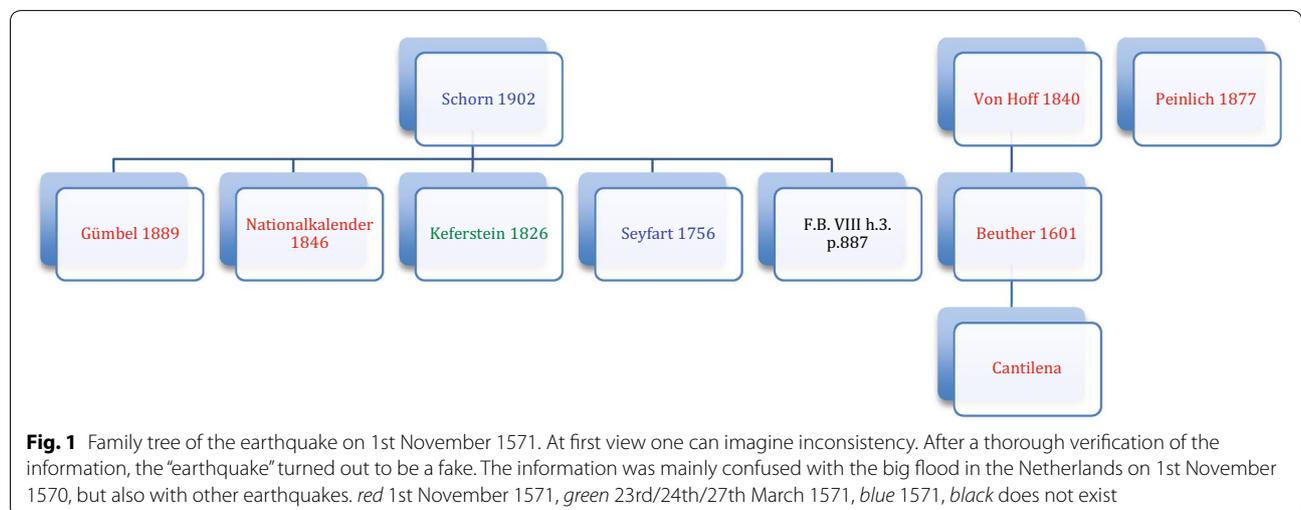


Table 1 Examples of case studies in Austria (AEC)

Year month day	I_0 old	I_0 new	Time UTC	Epicenter old	Epicenter new	Region new	M	z	Study
12010504	9	(9)	10:00	Murau	Katschberg	Carinthia	(6.1)	8	Hammerl (1995)
13480125	10	10	16:00	Villach	Friaul	Italy	6.8	8	Hammerl (1994)
15711101	7	–	–	Innsbruck	Fake	–	–	–	Hammerl et al. (2012)
15900915	9	9	23:50	Neulengbach	Ried am Riederberg	Lower Austria	5.75	6	Hammerl and Lenhardt (2013)
16680827	7	–	–	Wr. Neustadt	Fake	–	–	–	Hammerl and Lenhardt (2013)
16891222	8	7–8	1:00	Innsbruck	Innsbruck	Tyrol	4.8	6	Hammerl et al. (2012)
17680227	8	7	1:45	Brunn am Steinfeld	Wr. Neustadt	Lower Austria	5.0	9	Hammerl and Lenhardt (2013)
17940206	7–8	7	12:18	Leoben	Leoben	Styria	4.7	8	Hammerl (2011)
18410713	7	12:30	12:30	Wr. Neustadt	Wr. Neustadt	Lower Austria	4.0	7	Hammerl and Lenhardt (2013)

I_0 epicentral intensity, M magnitude, z focal depth in km

On November 1st, 1571, no damaging earthquake occurred in Tyrol. The date November 1st correlates with the “Great Flood” in the Netherlands in 1570, which was mentioned in connection with an earthquake by, for example, the geologists Von Hoff (1840) and Keferstein (1826). It’s a question of misinterpretation of the historical sources and is confirmed due to the lack of relevant information in the Innsbruck and Haller Council minutes. This type of occurrence is common in historical earthquake research.

In the case of the 1668 earthquake contemporary sources were missing, no information could be found in connection with an earthquake.

As an example of historical case studies in Austria, the earthquake of July 17th, 1670 in Hall in Tyrol will be discussed. More details, quoting also contemporary sources in the original language, about this earthquake and three other strong Tyrolian quakes can be found in a previous study (Hammerl 2015).

The earthquake of July 17th, 1670 in Hall in Tyrol

The historical seismicity in Tyrol is characterized by a moderate activity and is one of the most seismic active areas of Austria. Hall (see Fig. 2) in the County of Tyrol was first mentioned as a salina (saltern). The current name dates back to 1256 and refers to the Celtic word for salt. From the thirteenth century onwards, the salt mine formed the main industry of the town and its surroundings.

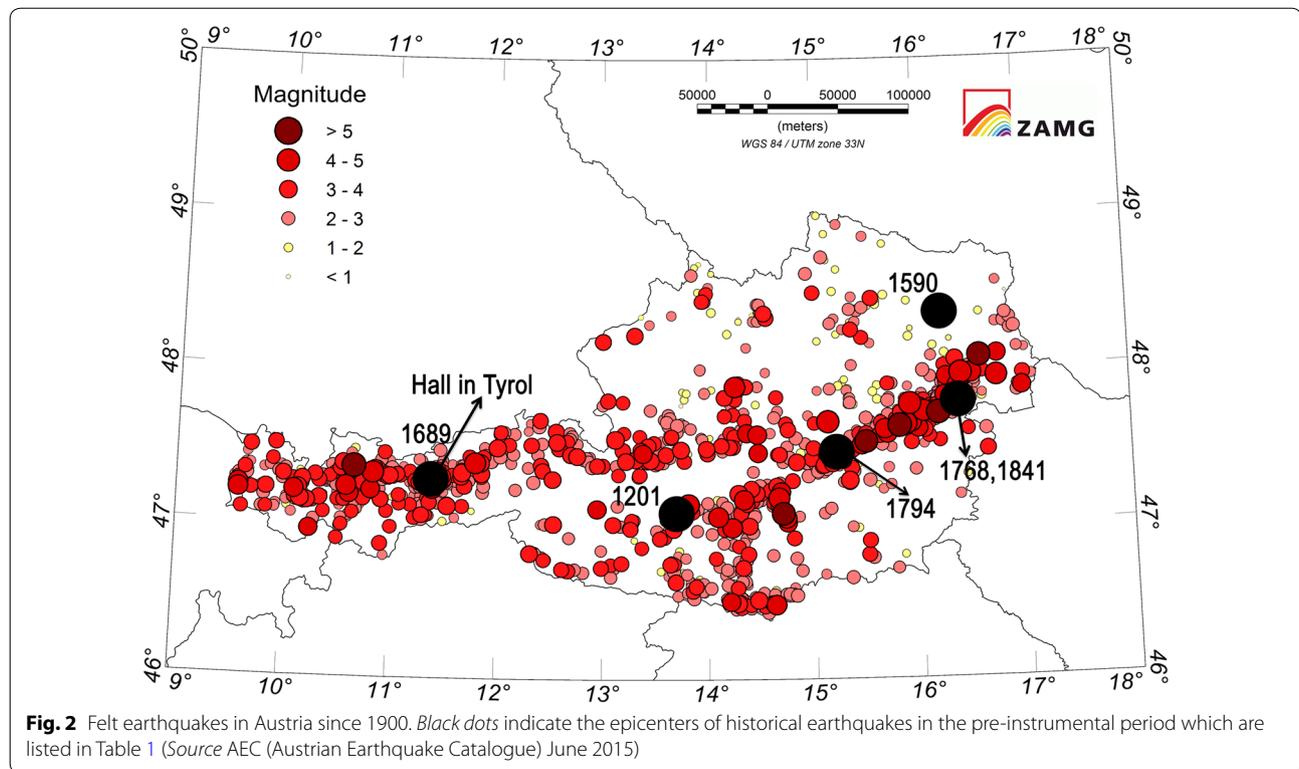
In the fifteenth and sixteenth century, Hall was one of the most important towns in the Habsburg Empire. This period also saw the construction of many of the churches, monasteries, and convents that up until the present day have shaped the appearance of the town. Today Hall has the biggest intact old town in the western part of Austria.

One of the strongest earthquakes that ever afflicted the Tyrolean area was probably that of July 17th, 1670. Many houses in Hall were damaged during the earthquake and some collapsed. Tree trunks were quickly erected to support many of the affected houses. Later, so-called earthquake walls, buttresses made of Höttinger breccia that still dominate the cityscape, reinforced many houses in Hall and Innsbruck.

Many contemporary texts reported on the earthquake of July 17th, 1670, such as the Tyrolean nobleman Johannes Sigmund von Rost zu Kehlburg und Aufhofen (1653–1729), later curator of St. Michael Castle (St. Lorenzen in South Tyrol). He was studying in Innsbruck when the quake occurred and noted in his diary (Humberdrotz 1956), in amazingly clear and precise words, what happened during and after the earthquake in Innsbruck and Hall. He mentioned specific earthquake effects that are important for intensity estimation according to the EMS-98 scale. The end of this earthquake series was half a year later. What a frightful and grim time it was during this period in Innsbruck and Hall, one can imagine from v. Rost’s description.

Three days after the earthquake, v. Rost visited Hall. He saw many houses completely devastated and the tower of the parish church partly collapsed, whereby people had been killed. Many people had to live in tents for some time.

An interesting and mostly unknown aspect is that, due to the earthquake, an additional building northeast of the old castle in Innsbruck was built. Court architect Christoph Gumppl planned an earthquake-resistant residence made of wood for Anna de’ Medici, widow of Archduke Ferdinand Karl, and her daughter Claudia Felicitas. The construction was carried out in 1670 after the earthquake. The new extraordinary residence was actually



earthquake resistant, as can be seen e.g., in the year 1689, when a damaging earthquake struck Innsbruck and the building remained, but it burned down at last in 1728 (Weigl 2007).

The effects of the earthquake in Hall in Tirol On the very day after the catastrophic event, the mayor of Hall in Tirol reported a heavy earthquake in the town that caused damage to the church tower as well as to the houses and the town wall. Again, it was noted that God's "just anger" should be averted by prayers and one sermon and then the town's master builder and master carpenter should evaluate the damage (StAH, Ratsprotokolle, 1670, fol 36v.).

Months after the main quake of July 17th, there were still requests for help addressed to the city council of Hall concerning either repair work or financial support. These concerns were rejected, as the town itself suffered from shortages and therefore the citizens would have to take care of repair works themselves (StAH, Ratsprotokolle 1670, fol 48r.).

For example, Brigitha Zanin asked for her deceased father's salary as the collapsing tower had killed her father. In this special case the city council hesitated with the order and pushed it on the back burner (StAH, Ratsprotokolle 1670, fol 50v.). On the other hand, the

schoolmaster's request from 26th September for money to repair the school and the stoves there was immediately approved (StAH, Ratsprotokolle 1670, fol 54r.).

On November 28th, 1670, six carpenter's servants asked for compensation for their dangerous and exhausting reconstruction work, which had been going on for four months. This request was denied (StAH, Ratsprotokolle 1670, fol 66r.).

The earthquake was also a catalyst for unusual requests: Adelheid Saurwein, wife of Jacob Saurwein, who was the owner of the house in the Salvatorgasse 4 and cutter of the salt bags by trade ("*Pfannhaussalzsackschneider*"), in the letter (TLA, Salinenarchiv, 1670, 183) of September 17th, 1670, requested of the councils and the president of the O. Ö. Hofkammer the assignment of the business "*Salzsackschneiderdienstes*" in the case of her husband's "early passing," after he suffered a stroke due to the earthquake.

A good basis for reconstructing the damages caused by the earthquake of 1670 in Hall is the *Dreifache Chronik der Stadt Hall im Innthale* (Seeböck 1882). In this chronicle there is an accurate description of buildings damaged by the earthquake in a survey which was carried out nine days after the earthquake (Seeböck 1882, 314). Moser (1989) used this chronicle inter alia as a basis for his comprehensive publication on the development of the

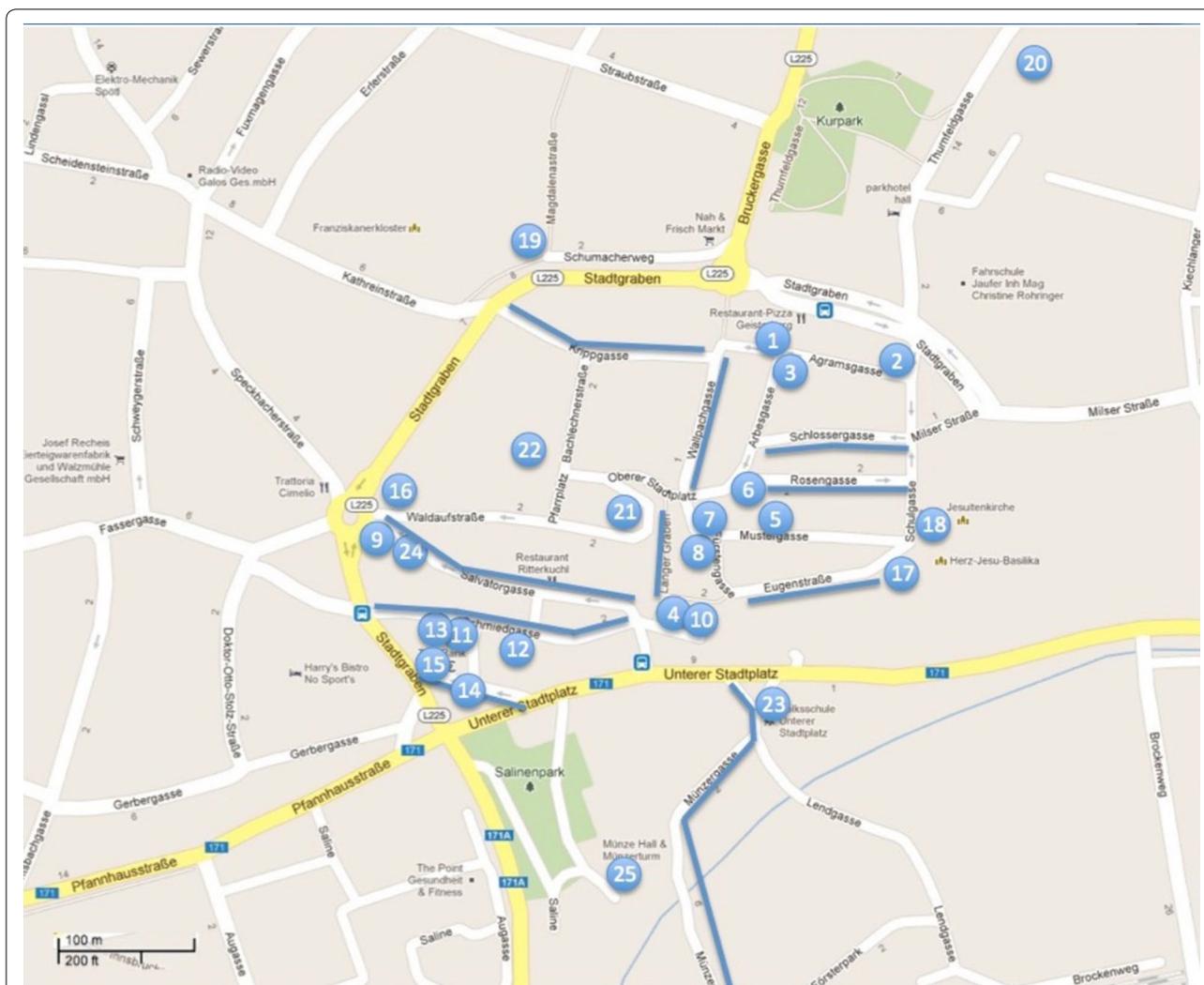


Fig. 3 Damage in Hall in Tirol caused by the earthquake of 17th July 1670. *Blue lines* mean that damage in the respective street was reported, but the damage could not be assigned to an address. 1 Agramsgasse Nr.5, 2 Agramsgasse Nr.23, 3 Arbesgasse Nr.6, 4 Langer Graben Nr.2, 5 Mustergasse Nr. 3, 6 Oberer Stadtplatz Nr. 4, 7 Oberer Stadtplatz Nr. 5, 8 Oberer Stadtplatz Nr. 6, 9 Salvatorgasse Nr.25, 10 Schergentorgasse Nr. 2, 11 Schmiedgasse Nr. 11, 12 Schmiedgasse Nr. 12, 13 Schmiedgasse Nr. 13, 14 Unterer Stadtplatz Nr. 2–6, 15 Unterer Stadtplatz Nr. 2, 16 Waldaufstraße Nr. 16, 17 Damenstift, 18 Jesuitenkolleg und Jesuitenkirche, 19 Franziskanerkirche und Franziskanerkloster, 20 Hl. Sebastian Kirche oder “Gartner Kirchl”, 21 Pfarrkirche St. Nikolaus, 22 St. Veit Kirche, 23 Spital und ehemalige Spitalskirche Heilig Geist Kirche, 24 Salvatorkirche, 25 Münzerturm

old town of Hall, in which he also considered the damages caused by the earthquake.

In the following, damages in Hall (Fig. 3) are given by way of example. The information derives, unless otherwise noted, from the chronicle mentioned above:

Secular buildings: North town gate Absam: heavy damage; Agramsgasse: damage, Nr. 5 heavy damage (complete collapse 13. August) and Nr. 23, the damage here was probably a secondary effect caused by the nearby partially collapsed tower (Frauenturm); Arbesgasse: damage, Nr. 6 heavy damage; well at Oberer Stadtplatz: ruined; Egelhauser gate in the West: damage; Eugenstraße: heavy

damage; Krippgasse: damage; Langer Graben: damage, Nr. 2 collapse of a wall; Münzergasse: damage; Münzer gate in South: heavy damage; Münzer tower and dwelling of mint’s journeymen: heavy damage; Mustergasse: Nr. 3 damage; Oberer Stadtplatz: Nr. 4, 5 damage and Nr. 6 (former Fürstenhaus), partial collapse, earthquake victims were also reported (Pfarrarchiv Hall in Tirol: Totenbuch 1667–1683, 56r.); Rosengasse: damage, collapse of a house, here earthquake victims were also reported (Pfarrarchiv Hall in Tirol: Totenbuch 1667–1683, 56r.); Salvatorgasse: heavy damage, Nr. 25 collapse most probably caused by this earthquake; Salzpfannhaus: damage;

Schergentorgasse: Nr. 2: damage; Schlossergasse: damage; Schmiedgasse: heavy damage, Nr. 11 heavy damage, Nr. 12 collapse (with mortal casualties), Nr. 13 heavy damage; Unterer Stadtplatz: Nr. 2-6, parts of the city wall collapsed in the former fish trench, whereby also house no. 2 was severely damaged; Schmiedtor in the West: damage; Waldaufstraße: damage, Nr. 16 “Ansitz” (estate) Rainegg of the so-called Salzmaier, a sovereign of the country, Freiherr Franz von Wicka: heavy damage; Wallpachgasse: damage, two houses collapsed.

Sacred buildings: Damenstift: damage; Jesuit College and Jesuit church: heavy damage, especially of the monastery; Franciscan church and Franciscan monastery: damage; Saint Sebastian church or “Gartner Kirchl” (Erzdiözese Brixen: Konsistorialakten 1670) (Note: Today’s site of the Hall Psychiatric Hospital, in the Thurnfeldgasse): heavy damage; parish church Saint Nikolaus: damage, tower partially collapsed, whether the Wolfgang Chapel, today’s St. Joseph’s Chapel was damaged on the north side of the parish church by the collapsing tower, cannot be confirmed from the sources. (Seeböck 1882, 317–318). Additionally, one of the two tower guards was killed. (Seeböck 1882, 317–318). The tower guard could not be buried until 12th August because he was trapped under the rubble. (Pfarrarchiv Hall in Tirol: Totenbuch 1667–1683, 57). Saint Veit church (Note: Chapel in the cemetery west of City Hall demolished in 1840): damage; Hospital and former Hospital Church Holy Ghost Church: heavy damage, demolished after the earthquake and rebuilt in the years 1727/28; Salvator Church: heavy damage, the upper part of the tower had to be removed after the quake by a courageous person.

By August 3rd, 1670, 447 wooden struts were counted in the streets of Hall (Seeböck 1882, 321). The fact that such an amount of wood was immediately available for the trunks is related to the Saline, which had stored plentiful wood at the Inn riverbank in Hall for firing the salt pans for salt extraction. From the Saline Official Book of September 8, 1670, it is clear that the wood came from the Saline (TLA, Salinenarchiv, 1670, 213 r.,v.).

The pastor in Hall, Stephan Gifl, was worried about the severe damage to “his” Church of St. Nikolaus and to all other buildings in Hall. At the same time he was concerned about the church service, which was not possible in its usual form due to the damage, and he feared the absence of believers. Therefore, the “holy sacrament” of the parish church of St. Nikolaus was transferred to the Franciscan church on July 18th and kept there until October 17th (Tinkhauser and Rapp 1879).

Nine days after the big quake, Gifl wrote a multi-page letter to the Consistory in Brixen, in which he expressed his deep concern (Erzdiözese Brixen: Konsistorialakten, Ortsmappe Hall, Pfarre 8.).

The effects of the earthquake in Innsbruck Innsbruck, the capital city of Tyrol in western Austria, is located eight km west of Hall in Tirol in the Inn valley. Even today, a largely unknown inscription on the so-called “Goldenes Dachl” (Golden Roof), an Innsbruck landmark, serves as a reminder of the big quake on July 17th, 1670 (Fig. 4a, b). The inscription, attached in 1671, is written in the form of a chronogram and reports on the many earthquakes (foreshocks, main shock, aftershocks) of the last year (1670/71) and of the restoration work after the great earthquake of 1670.

The Mayor and Council in Innsbruck wrote a letter on July 23rd, 1670, to the Upper Austrian Hofkammer. They

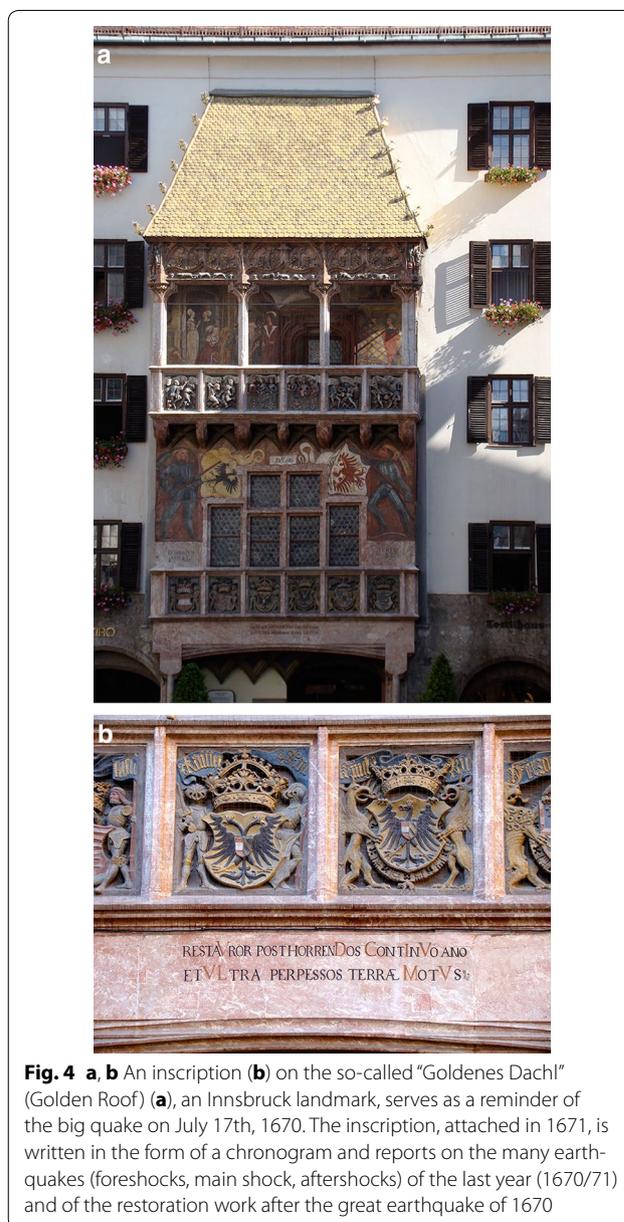


Fig. 4 a, b An inscription (**b**) on the so-called “Goldenes Dachl” (Golden Roof) (**a**), an Innsbruck landmark, serves as a reminder of the big quake on July 17th, 1670. The inscription, attached in 1671, is written in the form of a chronogram and reports on the many earthquakes (foreshocks, main shock, aftershocks) of the last year (1670/71) and of the restoration work after the great earthquake of 1670

reported the great damage to the town wall, and that further repair work would be necessary to prevent its total collapse. (StAI, Ratsprotokoll 1670, 263v.)

The earthquake damaged not only the ring wall in Innsbruck, but also numerous sacred and secular buildings. Among other contemporary sources, a very precise description of damages in Innsbruck was written by an anonymous author on behalf of Anna de' Medici von Toscana. This source serves as a good basis for damage estimation in Innsbruck. Originally he describes the loud noise that could be heard during the earthquake (TLME, Dipauliana 1080/2, 1670, 2v.-2r.). The noise was almost as loud as the yelling of 30 cats bound together, he said.

It was also reported that the rooms were shaking, the wooden beams began to crack, the windows rattled, and plaster and pictures fell from the walls. Furthermore, ornaments fell from the cornices and arches suffered damage. In some churches bells rang on their own accord and several dozen chimneys collapsed. The author of the report mentioned at the same time that it was difficult to find one house without a crack, but he realized that many of the cracks had existed before the earthquake occurred, which is a very important consideration in order to assess damage (TLME, Dipauliana 1080/2, 1670, 3r.). Also interesting is the following remark: "nobody in Tyrol, although earthquakes are not seldom, has suffered ever such a misery..." (TLME, Dipauliana 1080/2, 1670, 3r.). 340 years later, in modern disaster research, Tiedemann (1992) formulated this line of thought similarly: "*Human memory is, fortunately and unfortunately, shorter than the return period of most disasters.*"

Among the damaged buildings, the anonymous author mentions the parish church St. Jakob, where a statue of the apostle Jacob fell from the church rooftop, the Court church, where the tower was damaged (TLME, Dipauliana 1080/2, 1670, 3v.) and the Jesuit's church, where the cupola suffered damage. The other churches showed cracks, but most of them did not suffer any serious damage.

On September 7th, 1670, the dean and pastor Caspar Schwarz reported on the earthquake of July 17th, 1670, to the Episcopal consistory in Brixen. He estimated that the damage to the parish church St. Jakob was indeed small, but respected people's fear of aftershocks. He also mentioned the risk of a panic while celebrating Mass (Felmayr 1981, 509). To repair the damage to the parish church, 700 florins were needed, of which 400 florins were procured solely from funds of the St. Barbara Brotherhood. The approval of the Ordinariate in Brixen was therefore necessary (Felmayr 1981, 510).

Even the Franciscan monastery suffered damage from the earthquake; three chimneys collapsed and many vaults were destroyed. (Ruggenthaler 2005).

Other effects caused by the earthquake in the damage area The church of the Franciscan monastery in Schwaz was damaged. The chronicler of the monastery reported stones falling out of the ceiling of the church and the bells ringing on their own accord (Ruggenthaler 2005).

According to the *S. Georgenberger Chronicle* Kolsass and Vomp also suffered from the earthquake (Schorn 1902). The *Dreifache Chronik der Stadt Hall* (Seeböck 1882) reported another three earthquake victims (DAL, Pfarrarchiv Thaur, Totenbuch III 1661–1729)/(DAL, Pfarrarchiv Mils bei Hall, Tauf-, Trau- und Sterbebuch 1668–1703).

In the register of baptisms, weddings and deaths in the Parish of Mils, an earthquake on July 17th, 1670 is listed, but there is no evidence of any earthquake victims.

Ferdinand Lechleitner, pastor of Absam, describes the impact of the quake in March 1837 on the Church of St. Magdalena in Halltal. Due to the shaking it was necessary to hold the walls of the church tower together with iron cramps. (Erzdiözese Brixen, Konsistorialakten, Absam).

The "Würtenbergersche Wochen-Protokolle" (1660–1689) reported that in Hall and Absam, churches and towers were damaged and eight people were killed.

In a letter (Erzdiözese Brixen: Konsistorialakten, Ortsmappe Thaur, 1670) from August 16th, 1670, to the President of the Consistory and to the councils in Brixen, the pastor of Thaur, Matheus Obrist, writes among other things of the severe damage to the chapel of the residence Fritzenheim in Fritzens.

The effects of the earthquake in the far field Information on effects in the far field of the earthquake can be found in the *Theatrum Europaeum* (1677), founded by Matthäus Merian and published from 1633 to 1738 as a German historical work, for the following places:

Regensburg: heavily felt;
 Donauwörth: heavily felt, bed: swinging motion;
 Wildungen: the mortar clinks in the pharmacy;
 Nürnberg: dishes fell off the table, bed: swinging motion;
 Augsburg: heavily felt;
 Lindau: felt;
 Memmingen: felt;
 Kempten: felt;
 Leutkirch: felt;
 Venedig: felt;
 Salzburg (Mezger 1692): moderately felt.

The chronicler Weng in Nördlingen reported: On July 7th, (probably old style = July 17, new style) an earthquake was felt there, but not in all places of the city (von Gümbel 1889).

The Swiss physician and naturalist Scheuchzer (1718) reported that the quake was felt in St. Gallen, Switzerland, too. He refers to a paper (Haltmeyer 1683) from 1683. Such messages are to be used with restrictions.

The effects of the earthquake on the natural environment The effects on the natural environment, which can be assigned to the 12-part ESI scale (Environmental Seismic Intensity Scale, also ESI 2007), an intensity scale that was developed by the INQUA (International Union for Quaternary Research), are important for the correct and full assessment of an earthquake.

The estimate for the following descriptions corresponds to the intensity between 7° and 8° on the ESI scale, which matches the intensity estimate of 8° for the epicenter according to the EMS-98.

The impact of the quake on “the natural environment” is described in the *Dreifachen Chronik der Stadt Hall* (Seeböck 1882) for the surroundings of Volders, Baumkirchen, and the Zillertal and mentions mostly rockfalls and the appearance of fissures of different length between 90 and 570 m (Seeböck 1882, 313).

After the earthquake, the springs of the spa in Baumkirchen ran dry and St. Anna Chapel suffered severe damage (Seeböck 1882, 323). Significant temporary variations of the water level in wells and/or of the flow rate of springs are locally recorded from degree VI upwards on the ESI scale.

Seldom, small springs that may temporarily have run dry would appear from degree VII upward.

In the surroundings of Innsbruck, e.g., in Mühlau, water turbidity was observed and the flow rate changed. (TLMF, Dipauliana 1080/2, 1670, fol 2v-3r).

In a later copy of the *Haller Erdbeben-Chronik* (TLMF, Dipauliana 931 I), additional locations affected by the quake were reported, e.g., surface fault ruptures and water turbidity.

The effects of the earthquake in the *Haller Salzberg* are also interesting. It was reported that the miners underground heard a terrible roar, and the ground shook so strongly that they were not able to stand. The earthquake did not cause damage underground, but again rockfalls were reported (Seeböck 1882, 306). This description is consistent with the experience that earthquake effects underground are more minor than at the surface.

Side effects at intensity 8 on the ESI scale are “anomalous waves,” which were observed at the river Inn (Seeböck 1882, 306).

Results of the 17th July 1670 earthquake study Table 2 and Figs. 5 and 6 show all localities which were damaged by the earthquake of 17th July 1670 or where the earthquake was felt. In summarizing the reports on the earth-

Table 2 Localities affected by the earthquake in 1670

Locality	Long.	Lat.	Intensity EMS-98
Absam	11.500	47.300	D $\hat{=}$ 7–8
Augsburg	10.883	48.367	F $\hat{=}$ 5
Baumkirchen	11.567	47.300	7
Donauwörth	10.800	48.700	F $\hat{=}$ 4
Frankfurt	10.798	45.160	F $\hat{=}$ 5
Fritzens	11.590	47.306	D
Hall in Tirol	11.517	47.283	D $\hat{=}$ 8
Innsbruck	11.400	47.267	D $\hat{=}$ 7–8
Kolsass	11.633	47.283	F $\hat{=}$ 3–4
Kempten	10.317	47.717	F $\hat{=}$ 3–4
Leutkirch im Allgäu	10.022	47.826	F $\hat{=}$ 3–4
Lindau	9.683	47.550	F $\hat{=}$ 3–4
Mantova	10.798	45.160	F
Memmingen	10.167	47.983	F $\hat{=}$ 3–4
Mils	11.529	47.294	D $\hat{=}$ 7–8
Nördlingen	10.498	48.850	F
Nürnberg	11.083	49.450	F $\hat{=}$ 5
Regensburg	12.100	49.017	F $\hat{=}$ 3–4
Salzburg	13.033	47.800	F $\hat{=}$ 3
Schwaz	11.700	47.333	D $\hat{=}$ 6
St. Gallen	9.400	47.467	F $\hat{=}$ 3–4
St. Magdalena im Halltal	11.493	47.327	D
Thaur	11.472	47.295	D $\hat{=}$ 7–8
Vellenberg (Götzens)	11.313	47.242	D
Venezia	12.327	45.439	F $\hat{=}$ 3–4
Volders	11.567	47.283	F $\hat{=}$ 7
Volderwildbad	11.561	47.251	F-D
Vomp	11.683	47.333	F $\hat{=}$ 3–4
Wattenberg	11.600	47.283	D $\hat{=}$ 6

If the description of the damage is not precise enough, no intensity was assessed

F felt, D damage

quake that occurred at 1:00 UTC, one can say that it was well documented by contemporary sources. The epicenter was in Hall in Tirol and the epicentral intensity was 8 degrees on the 12-part EMS-98.

This means, according to this scale, that many people found it difficult to stand. Many houses showed large cracks in walls. A few well-built ordinary buildings showed serious failure of walls, while weak older structures may have collapsed. The quake killed at least nine people in Hall in Tirol and Thaur.

Aftershocks were still being reported over 50 days after the quake.

Austrian earthquake catalogue

The Earthquake Survey of the ZAMG maintains the Austrian earthquake catalogue.

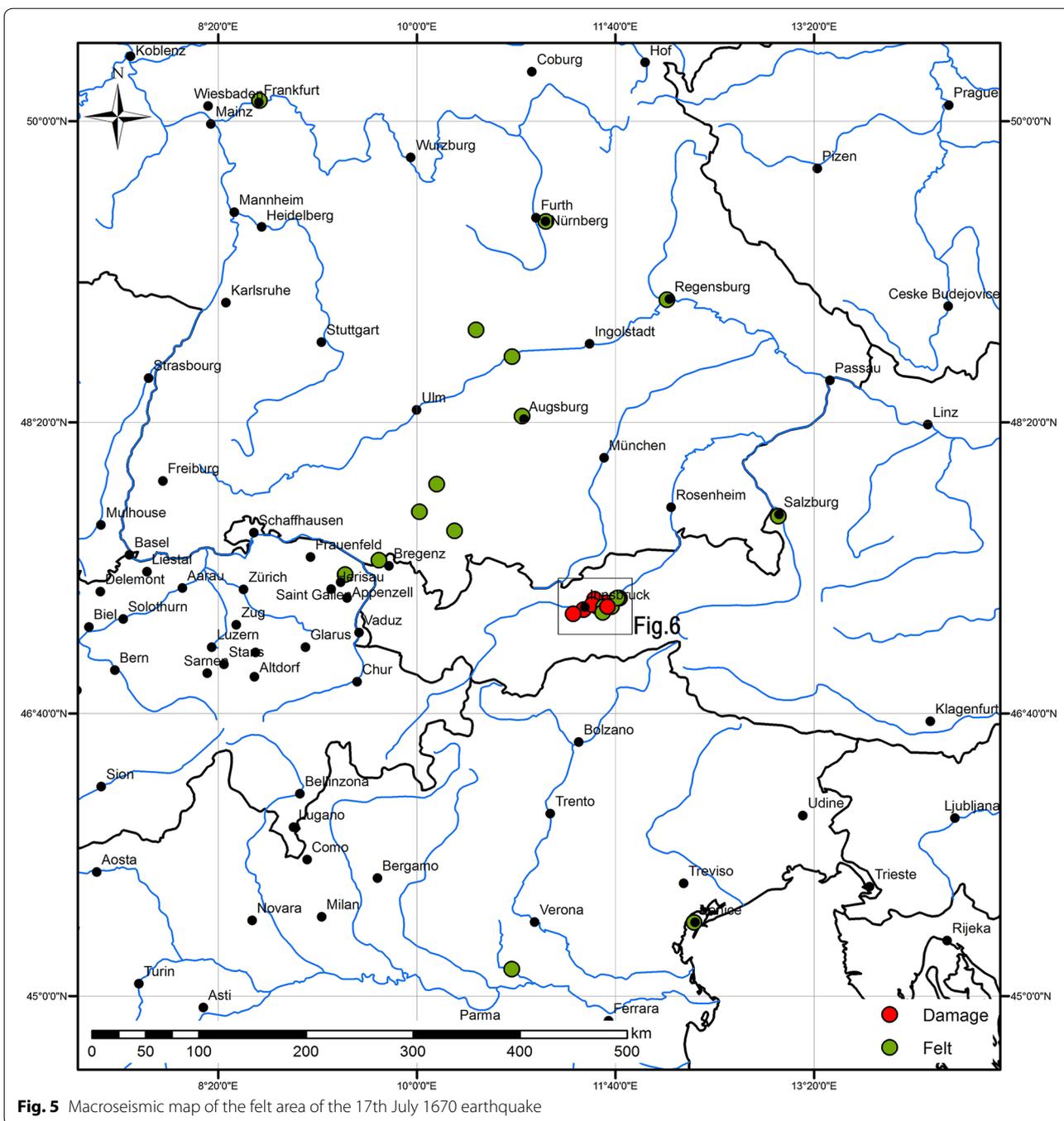


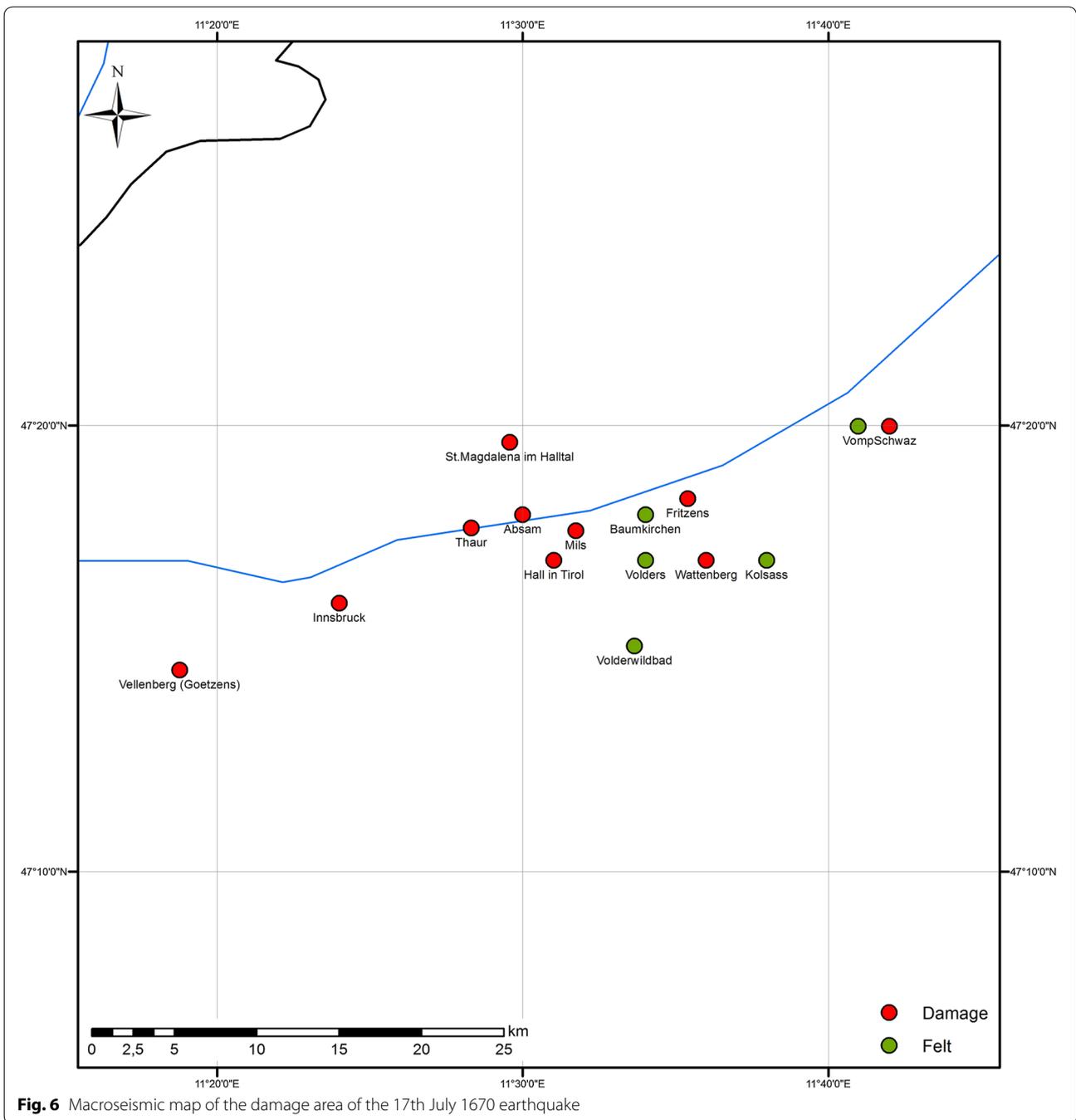
Fig. 5 Macroseismic map of the felt area of the 17th July 1670 earthquake

The department monitors recent earthquakes on a regular basis, both locally and worldwide. More than 7000 tremors are investigated per year, 500 of which are caused by local earthquakes in Austria. For that purpose, the department maintains several seismic stations across Austria.

In 2013, the new earthquake catalogue for the federal country of Lower Austria was published (Hammerl and Lenhardt 2013). In the catalogue, which contains data on earthquakes from 1000 to 2009, original reports for the

pre-instrumental period are quoted. For the first time, IDPs and consequently the seismic history for all localities in Lower Austria are listed. Altogether the catalogue contains approximately 6900 IDPs, of which 823 are from the time period 1000–1899. One IDP has the local intensity $I_{loc} = 9$, 19 have $I_{loc} = 8$, 38 have $I_{loc} = 7$, 218 have $I_{loc} = 6$, and 872 IDPs have an $I_{loc} = 5$.

In total 972 earthquakes are recorded in the new catalogue, 200 from the years 1000 to 1899. For the period



1000–1899, the catalogue contains one earthquake with $I_0 = 9$, three with $I_0 = 8$, two with $I_0 = 7$, 10 with $I_0 = 6$, and 14 with $I_0 = 5$. However for the period 1900–2009 it contains one earthquake with $I_0 = 8$, two with $I_0 = 7$, six with $I_0 = 6$, and 57 with $I_0 = 5$.

It is planned to realize new earthquake catalogues on the basis of the Lower Austria study (Hammerl and

Lenhardt 2013) for the other federal countries in Austria too.

Conclusion

The implementation of the EUROCODE 8—the building code for earthquake-resistant building design—in Austria in 2009, emphasized the need for historical earthquake

research. The hazard in terms of the considered average return period was then extended from 100 to 475 years.

Historical earthquake research concentrates on seismic events in the pre-instrumental period. The investigations contribute to the completeness and correctness of the earthquake catalogue, which is the basis for seismic hazard analysis and as such benefits the public, communities, civil engineers, architects, civil protection, etc.

In areas such as Austria where the seismicity is low to moderate, it is especially important to study historical earthquakes. Although damaging events occur only rarely, earthquakes of such intensity can cause much personal suffering and huge economic losses. It is therefore important to investigate the effects of historical earthquakes according to the state of the art to improve knowledge of past damaging earthquakes.

An important outcome in Austria's historical earthquake research, among other things, is that recently for the first time intensity and macroseismic data points have become available for a part of the country, which allows transparency in the assessment of the new parameters and contributes to the seismic history of single locations.

Abbreviations

DAI: Diözesanarchiv Innsbruck; OA: Ordensarchiv; O.Ö.: oberösterreichisch/upper Austria (not identical with the present-day province of Upper Austria); StAH: Stadtarchiv Hall in Tirol; StAI: Stadtarchiv Innsbruck; TLA: Tiroler Landesarchiv; TLMF: Tiroler Landesmuseum Ferdinandeum.

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Competing interests

The author declares that she has no competing interests.

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