

Two large earthquakes in western Switzerland in the sixteenth century: 1524 in Ardon (VS) and 1584 in Aigle (VD)

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Abstract The Valais is the most seismically active region of Switzerland. Strong damaging events occurred in 1755, 1855, and 1946. Based on historical documents, we discuss two known damaging events in the sixteenth century: the 1524 Ardon and the 1584 Aigle earthquakes. For the 1524, a document describes damage in Ardon, Plan-Contthey, and Savièse, and a stone tablet at the new bell tower of the Ardon church confirms the reconstruction of the bell tower after the earthquake. Additionally, a significant construction activity in the Upper Valais churches during the second quarter

of the sixteenth century is discussed that however cannot be clearly related to this event. The assessed moment magnitude M_w of the 1524 event is 5.8, with an error of about 0.5 units corresponding to one standard deviation. The epicenter is at 46.27 N, 7.27 E with a high uncertainty of about 50 km corresponding to one standard deviation. The assessed moment magnitude M_w of the 1584 main shock is 5.9, with an error of about 0.25 units corresponding to one standard deviation. The epicenter is at 46.33 N and 6.97 E with an uncertainty of about 25 km corresponding to one standard deviation. Exceptional movements in the Lake Geneva wreaked havoc along the shore of the Rhone delta. The large dimension of the induced damage can be explained by an expanded subaquatic slide with resultant tsunami and seiche in Lake Geneva. The strongest of the aftershocks occurred on March 14 with magnitude 5.4 and triggered a destructive landslide covering the villages Corbeyrier and Yvorne, VD.

Virgilio Masciadri is deceased. This paper is dedicated to his memory.

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1 Survey of historical data for the Valais in the sixteenth century

The Valais is the most active seismic region of Switzerland. Three strong damaging events happened in the last 300 years (1755, [Gisler et al. (2004)], 1855 [Fritsche et al. (2006)], 1946 [Fritsche and Fäh (2009)]). But a complete record of strong events is only available after

the early 1700s. Only a few seismological and historical traces have been found in chronicle sources for earlier times. This paucity of information for certain time periods is due to an insufficient tradition, the complex archival situation, and a limited medieval and early modern literacy (Online Resource 1).

For the sixteenth century, only a few written indices are presently available and cover one third of the time. Two strong events in Western Switzerland during that century can be found in the historical sources: the 1524 Ardon and the 1584 Aigle earthquakes (Schwarz-Zanetti 2008a, b). These events were analyzed within the “Revision of the Earthquake Catalog of Switzerland,” abbreviated “ECOS-02” and “ECOS-09,” a project carried out at the Swiss Seismological Service at ETH Zurich during 1999–2011.

2 Ardon in April (20) 1524

In April 1524, a first document with a contemporary observation of a large Valaisan earthquake turns up, scilicet in the 1490–1525 annals of notary Claude Revilliodi from Monthey. He describes an event in the west of Sion: “In April of this year (1524) occurred an earthquake in the whole world, but most heavily in the Valais, in such a way, that most part of the bell towers in Ardon, Plan-Conthey and Savièse fell on the earth.” (Santschi 1968, 61–65; see Online Resource 2). The only contemporary if indirect written validation of this damage is to be found on a stone tablet at the new bell tower of the medieval Ardon church, but without mentioning explicitly the earthquake of 1524: “Johannes of Platea, capitular of Sion, priest of Ardon, layed the foundation stone of this tower on April 11, 1525.” (Gaillard 1996, p. 29–32, Online Resource 3 and Fig. 1) These two testimonials document clearly heavy damage by the earthquake of April 1524. During the event of January 25, 1946 (Sierre, VS, Mw 5.8), the steepletop was heavily damaged again (Aerni et al. 2005, p. 59).

In the church of Plan-Conthey, any archeological traces of the quake are lost because of several renovations over the last centuries. But in the church of Savièse, archeological findings show uninjured bells for the years 1455 and 1517. Only in the middle of its spire roof are traces of repair which can be linked to earthquake damage (Aerni et al. 2005, p. 189). Therefore, in Savièse, identified damage is smaller than that



Fig. 1 Ardon 1524; stone tablet at the bell tower of Ardon Church (Gaillard 1996)

observed at Ardon. Note that Revilliodi did not mention any destructive impact of the quake in his home, Monthey, located about 20 km west of Ardon.

The expression “in the whole world” in the annals of Revilliodi demands a search for another observation of earthquake damage over a wider area. A promising hint was found in Basel. In a contemporary chronicle attributed to the Basel, councilman Fridolin Ryff (1488–1554; Ryff 1872) occurs the observation of a quake without damage to Basel. This notation can be dated to April 20, 1524, and belongs with high probability to the Ardon event.

Additionally, the review of findings in archeology and the history of art detected significant construction activity in the Upper Valais churches during the second quarter of the sixteenth century. These repairs often concerned church steeples, possible evidence for earthquake damage in 1524 (cp. Table 1). Unfortunately, the volumes of “Kunstdenkmäler der Schweiz” of the Lower Valais are still lacking (Online Resource 4). The observations that can be clearly related to the 1524 event were transformed into macroseismic intensities using the European Macroseismic Scale 1998 (EMS-98; Grünthal ed. (1998)) by a designated working group. Macroseismic intensity was assigned by locality using all sources of information. Depending on the intensity-relevant content of the reports, the project group assigned a most probable intensity (I_w) and a range defined by the minimum (I_{min}) and maximum (I_{max}) probable intensities. The macroseismic field is shown in Fig. 2. The epicentral location and magnitude of the 1524 event was assessed during the revision of the

Table 1 Macroseismic Intensities assessed for 1524 earthquake at Ardon

Place	Longitude/latitude	Imin	I _{max}	I _w	Seismological quality
Ardon, VS	46.21/7.26	7	8	8	Poor
Savièse, VS	46.25/7.35	7	8	7	Very poor
Conthey, VS	46.23/7.31	7	8	7	Very poor
Basel, BS	47.56/7.59	4	5	5	Very poor

Earthquake Catalog of Switzerland in 2002 and 2009 (ECOS-02 and ECOS-09) (Fäh et al. 2003; Fäh et al. 2011). ECOS provides a uniform estimate of the moment magnitudes *M_w* for all historical and instrumental events. The historical events were assessed following a modified version of the method proposed by of Bakun and Wentworth (1997) (Alvarez-Rubio et al. 2011). This uniform earthquake size estimate in terms of magnitude required a magnitude/intensity calibration based on a calibration dataset of earthquakes in the twentieth century for Switzerland and adjacent areas.

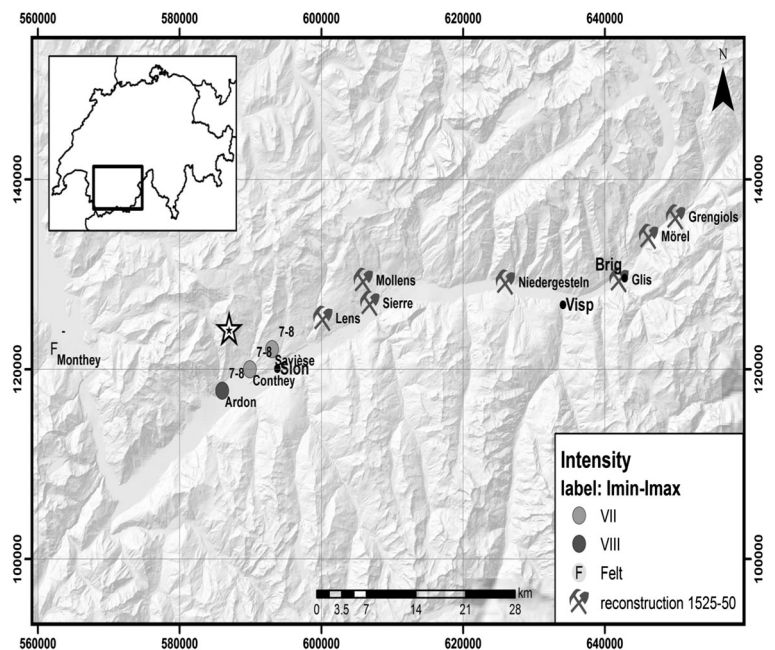
The assessed moment magnitude *M_w* of the 1524 event is 5.8, with an error of about 0.5 units corresponding to one standard deviation (ECOS-09). The epicenter is at 46.27 N, 7.27 E with a high uncertainty of about 50 km corresponding to one standard deviation. The high uncertainty is related to the sparse macroseismic

field with reliable intensity points. An epicenter location more to the east cannot be excluded.

3 Earthquake series, flood wave, and rockslide in the region of Lake Geneva on March 11–14, 1584

On March 11–14, 1584, between seven and 25 seismic shocks affected the regions of Lake Geneva, Saanen (BE), and the adjacent areas, whereof the first and perhaps one from the fourth day caused damage. A rockslide from the mountain Tour d’Aï was triggered and destroyed the villages Corbeyrier and Yvorne (VD). Exceptional movements in the Lake Geneva wreaked havoc along the shore of the Rhone delta and spark interest. The large dimension of this induced damage can be explained by an expanded subaquatic slide with

Fig. 2 Macroseismic field and location of the April (20) 1524 earthquake in Ardon. The shade of gray describes the intensity estimate; numbers depict the possible range from minimum to maximum intensity. It includes also an overview of information for the 1524 earthquake: A contemporary stone tablet, a document of Monthey, and archeological findings prove earthquake damage in Ardon, Savièse and Plan-Conthey. Later repairs to churches in the east can probably be associated with this event: Grengiols, Mörel, Brig-Glis, Niedergesteln, Mollens, Sierre, and Lens (see Online Resource 4)



resultant flood waves (tsunami) and a seiche in Lake Geneva (cp. Lake Lucerne 1601; Schwarz-Zanetti et al. 2003). Such dramatic events awoke fear and interest in contemporaries and left a considerable number of written documents.

The location of the main earthquake of March 11, 1584, has been assumed to be the region of Lake Geneva—Montreux (e.g., Sisfrance, www.sisfrance.net), Aigle (VD) (Fäh et al. (2003) and Montandon (1942–1943)), or Monthey (VS) (Van Gils and Leydecker 1991). It was assessed at intensity VII to VIII. But these assessments had to be revised after our study of contemporary historical sources, and the reassessment is now included in the ECOS-09 catalog (Fäh et al. 2011).

3.1 State of source material

More than 30 contemporary documents of different origin, quantity and quality and some copies of lost sources have been evaluated, and refined by archeological and geological investigation. Compilations as for example Bertrand (1756) and Volger (1857) are incorporated marginal. Together, they form a reliable base for a seismic reconstruction. Never before has the course of an earthquake in Switzerland been so documented in contemporary sources: not even the 1356 event in Basel. Contemporary explanations for the different phenomena were predominantly religious. A dismissive hint of Greek theories about the seismic role of water or fire was also found, indicating rather reading of classical authors (Rohr 2007) and less an early scientific approach. A surprising aspect of several early sources is their high congruence of detail on the number of victims, lost animals, and destroyed houses. This seems to indicate at least a partly common origin; some authors were demonstrably in contact with others. The documentary sources can be separated into two main groups: surveys and local information. Local information can be subdivided geographically into the eastern part including Lake Geneva to St. Maurice, the northern part including Murten and Biel, the western part including Lausanne and Geneva, the southern part with Savoy and Dauphiné, and the German speaking part of Switzerland.

3.2 Dating of the earthquake series

A first step in verifying the reliability of the documents has to compare the dating (date, time), the number of shocks, and the name of the places and villages. The

Gregorian reform of the Julian calendar in October 1582, an astronomical correction of 10 days, was partially introduced in Switzerland in 1584. For more than 200 years, it produced different dates in historical sources and earthquake catalogs, as for example Bertrand (1756) for 1584. In the following, we date in the Gregorian calendar of today but often list double dates for showing the original Julian dating.

The main shock occurred verifiably on March 11, 1584, according to our Gregorian dating (respectively, March 1 according to the old Julian system). It struck between 10 and 11 o'clock (UTC, or between 11 and 12 o'clock local time) in the morning and lasted according to several sources between 10 and 12 min. This duration indicates at least one immediate strong fore- or aftershock. The unusual waves (a tsunami and seiche) in Lake Geneva have to be attributed to this date and time. On March 12 and 13, several smaller aftershocks occurred. The exact date and time for these aftershocks cannot be reliably assessed. On March 14 between 8 and 9 (UTC) in the morning, a landslide covered the villages Corbeyrier and Yvorne above Aigle, in modern Canton Vaud. According to the 1584 leaflet by the printer Samuel Apiarius from Basel, another earthquake had preceded the slide. We corrected also a number of wrong dates (Online Resource 5). Abraham Musculus (or Mues[s]lin), one of the official envoys of the Bernese government to survey damage, mentioned 25 shocks in Saanen (BE) but without defining their time period (BBB: Mss.h.h.l. 130). The high congruence of some descriptions suggests not only copying but a certain reliability of the data.

3.3 Contemporary overviews and local observations

After comparing the collected documents, we see complex connections between these reports.

The first group of documents contains several early surveys, which seem at least partly supported by the same information distributed by the abovementioned leaflet of printer Apiarius (Harms and Schilling 1997, VI, p. 311, Fig. 3 and Online Resource 6) in Basel. On March 10 (March 20), a letter by Andreas Wolf from Lausanne was sent to Rudolf Walter (Gualthero or Gwalther) in Zurich (ZBZ, Hottingeriana, vol. VI, 496; Egli (1901–1904), p. 243). It contains information similar to that of the anonymous letter to Jörg

published with probably copied information. One example is an anonymous report (probably by Rigaud) printed in Troyes in 1584 indicating the shake area. A mostly theoretical paper was published by Aubery/Alberius (1586). The physicist Joseph Du Chesne (1587/1593) from Geneva compiled valuable and detailed information, which is the original of numerous copies by Simon Goulart (1610), Jacob Spon (1680), Benjamin Corbaz (1843, cp. Montandon 1942–1943, p. 50) and an anonymous article in the newspaper “*Messenger des Alpes*” (1927, September 3). In the year 1623, Michael Stettler (1580–1642) wrote a Swiss chronicle (StABE: DQ 11, 1623, vol. H, S. 134–135), containing a description of the 1584 event; a modified version was printed in 1626 /1627. In the following, we summarize the surveys and information contained in specific documents.

3.3.1 Eastern part of Lake Geneva, St. Maurice, and Pays d’Enhaut

As mentioned before in 1584, a summary report was published by an anonymous French author (probably Rigaud; Online Resource 7). It seems to confuse Lyon with the village Glion near Montreux or Leysin. This conclusion is also supported by the letter of Jörg Kindscher from Lausanne (ZBZ, Wickiana, Ms. F 32 f 22). Therefore, the anonymous French publication has to be classified as hyperbole: an early form of sensational press. A similar situation shows the rockslide of Plurs (Piuro) in Italy of 1618, which is documented by numerous prints from Italy through Scotland (Scaramellini, 1988).

More reliable is the survey by the eyewitness Rudolf Bullinger that relies on his own inspection and reports by Bernese Reeves. He describes the damage zone as “from Vevey to Villeneuve and Aigle, all above in Montreux (...)” In the same extent damage occurred in towns, castles, hamlets, villages, and alp cottages until Saanen, Rougement, and Les Ormonts. Buildings were damaged (mostly cracks in walls), chimneys were thrown in, and a not localized church and a rectory collapsed. Damage occurred also in the vineyards on the lakefront caused by waves. In the castle Chillon, most of the rooms showed cracks in walls, towers were split, and supporting walls on the waterside collapsed (Bullinger’s original report cp. Online Resource 8).

Even though Bullinger is a reliable eyewitness, it is necessary to verify his description with crosschecking

from contemporary local reports. They, however, allow only approximate identification of the damaged areas. For the north and south of Aigle, six documents confirm Bullinger’s report. In Aigle 50–60 chimneys, also one of the castle [ACV: Bp 25/4 (comptes baillivaux, 1583–1584), and a large number of tiles have fallen. On the roof of the church, some tiles were lacking. The situation in the village Bex 10 km to the south of Aigle was probably worse. The spiral staircase of the Pfrundhaus, some kind of asylum, was completely destroyed. It had to be reconstructed at high cost (Online Resource 9). According to information from the old director of the public record office of Vaud Canton, the roof and tower of the church in Noville on the southern side of Lake Geneva had to be repaired in 1584 (Schöneich, P. (1.9.2010) personal communication). The mentioned damage in the village Ormont near Leysin, a part of today’s village Ormont-Dessous, can be confirmed by a written request for support for rebuilding and repairs of earthquake damage of the old church Saint Maurice d’Ormont (ACdO: K 62).

For the village of Suchy near Yverdon, a petition for support was sent to the government of Berne in the year 1605. It lists the costs for repairs of the church, stating that the earthquakes of the past years caused cracks in the walls and threatened the vault which had to be taken down (Online Resource 10; not that the French word “escrouler” means in the sixteenth century “shake” and not “collapse” as today (<http://www.cnrtl.fr/etymologie/ébranler>)). If we exclude an attempt to defraud and admit the fact that no other strong earthquake is known between 1584 and 1605, this report can be attributed with a high probability to the 1584 event. A letter by Josua Wyttenbach from Murten (Egli 1901–1904) confirms at least the observation of shocks in Murten. However, the described damage on chimneys, walls, and towers cannot be located. Pastor Josua Winsleu in Biel was preaching at the moment of concussion and feared falling down, but does not mention damage in his place of observation (ZBZ, Wickiana: Ms. F 32 f. 23).

The physicist Joseph Du Chesne from Geneva included in his work “*Le grand miroir du monde*” (1587) an elaborated description of the seismic phenomena of March 1584. He circumscribed the quake area with “Lyonnais, Mâconnais, Dauphiné, Savoy, Piedmont, Valais, Switzerland and Burgundy, (...) all above the region of Lake Geneva, Vaud, Faucigny, Chablais and adjacent regions. For his domicile Geneva, he mentions

“the collapsing of three or four chimneys and of a wall of an old building,” emphasizing the fact of minor damage (“...à Geneue, & n’y eut autre mal”). This declaration is confirmed by the minutes of the council (AEGE: RC 79, 1584) and a letter by Pappenheim (ZBZ: F 37, f. 136). The description by Du Chesne has as precedent a poem that contains again the philological problem of “tours escroulés à Genève,” which only means “shaken towers” and not “destroyed.”

The data situation in Valais is generally scarce. Only two pieces of evidence are available and indicate a small affliction of the western part by the 1584 event. The first is a copy of a letter dated July 20, 1585, from the Monastery St. Maurice to Rome requesting support for urgent repairs due to a rockfall (AASM, DIV, 1.2.24.1, p. 7–10). Allegedly, the church was threatened by collapse. Considering the letter as a petition, the lack of earthquake hints in it, and repeated rockfall on the monastery, the significance of this document is uncertain. Correction: Michelet (1990) connected the earthquake of 1584 with this letter without a historical commenting. The second hint of less affliction by the earthquake informs Bullinger who recorded the assistance for Corbeyrier and Yvorne by people of St. Maurice and Martigny (Egli 1901–1904, p. 244). Therefore, stronger damage in Valais is rather unlikely.

3.3.2 Chillon

The Bullinger report located the main damage on the waterside between Vevey and Villeneuve and in Aigle, where the Castle of Chillon and its closer surroundings seemed most affected. The damage to this castle is documented in a letter from the bailiff (Anonymus, Manuaux Bernoise 1894), the report of Bullinger (Egli 1901–1904, p. 244), and the accounts of the bailiwick (Raemy de et al. 1999, p. 92 ff.). They are supported by the older archeological findings of Naef (1922 and 1929). Those reports describe cracks in the walls and damage to the battlements and chimneys, which were soon repaired. But on the occasion of an inspection with different specialists as archeologists, seismologists, structural engineers, and historians on August 2009 and January 2010, only a few reliable traces were found. The inscription “1585” on a small tower of the battlement and a long crack in the wall of the main tower were identified as possible archeological testimony to the 1584 event (cp. Fig. 5). Other hints were uncertain and many citations seem to be lost over the last centuries.

Nevertheless, the possessor of Chillon, the government of Berne, awarded a contract on March 24 (April 3) to the treasurer Tillier and the architect Salchli to inspect the castle on the premises: if the old disrupted walls could be repaired or if they had to be rebuilt, adequate activities had to be mounted promptly (Anonymus 1894). “In particular in the magnificent castle Chillon, lying on a rock in the water, which was disrupted, the fortification was enfeebled, on the waterside several supporting walls were destroyed, towers were split, only a few rooms exist without cracks. These we have seen with our own eyes together with the envoys of the government and the architect, where we deliberated how the fortification could be cherished/reconstructed (Egli 1901–1904, p. 241).” In the 1584 letter of Josua Vinslevi from Biel (BE) to Rudolf Walter in Zurich, the expense was estimated without citing the source: “(...) that its reconstitution can hardly be done by expending 1000 Kronen” (ZBZ, Wickiana: Ms. F 32 f 23). By comparison, the total loss of the two buried villages Corbeyrier and Yvorne estimated by Bullinger was 75'000 Kronen (Scheuchzer 1716).

Repairs to the castle can also be proved in the accounts of the baillage Chillon 1585–1586 (Raemy de et al. 1999, Fig. 65). Army pinnacles, the gallery, and a roof of a tower had to be renewed. Similarly, the entrance area, where parts of the front of a tower were threatening to collapse, needed repair. The bigger damage on the waterside of the castle and the shore of the environment were an additional factor: cf. the chapter “Flood wave”.

3.3.3 Lausanne and Geneva

In the Wickiana Collection in the Central Library of Zurich (ZBZ), two letters from Lausanne to Zurich describe observations in Lausanne: one by an anonymous writer to Jörg Kindscher, the other by Andreas Wolf to Rudolf Walter. The similarity of specific details suggests one author speaking to two different receptors. The letters mention ruined chimneys and brick walls, and the collapse of an old house in the town, which could not bear up against the earthquake (ZBZ, Wickiana, MS F 32, S. 21 a). Additionally, the letter to Kindscher mentions a broken church vault in “Lyon,” which struck dead a woman and injured several people. With high probability, it is not a question of the French town Lyon, 175 km away from Montreux. Rather, it concerns the village Glion near Montreux or Leysin

Fig. 4 Fictional contemporary picture of the Aigle earthquake of March 11, 1584 (ZBZ, Wickiana, Ms. F 32, folio 19–22)



Fig. 5 Aigle 1584; tower of the battlement with the rebuilding dated 1585 (J.-L. Loizeau, 2010)

(VD) and means the church described in Bullinger's letter and the anonymous print of 1584.

In the Public Record Office of Vaud Canton, two further documents attest to the earthquake and give some uncertain hints of damage in Lausanne. According to them, a tower and the surrounding wall suffered, probably from the earthquake (Stöckli (8.10.2009) personal communication). Additionally, archeological findings of an investigation into the Lausanne Cathedral show some conspicuous not dateable repairs (Stöckli (8.10.2009) personal communication) (Online Resource 11). The chronicle of Jehan Dumur (Reymond 1917, p. 279–280) in Grandvaux on the waterside of Lake Geneva, 12 km east of Lausanne, speaks about old buildings collapsing and a wave in the lake.

Pappenheim reports in his letter of June 1 (June 11) from Geneva to Walter in Zurich a collapse of a house in April, which was traced back to the quake (ZBZ, Wickiana: F 37, f. 136). Spon in his chronicle of 1682 speaks about the Gate Cornevin or Cornavin, which was thrown in the fosse by an earthquake dated May 3, 1574. Since no other documents prove such an earthquake,

this notation could be due to a confusion or a misprint of years and the months. The minutes of the Council of Geneva (AEGE: RC 79, 1584) confirm the letter by Pappenheim (ZBZ: F 37, f. 136). In Jakob Spon's chronicle of Geneva (1680), the description of the water wave is further elaborated, unfortunately from unknown sources and with dubious dating.

3.3.4 Savoy and Dauphiné, F

A group of contemporary French documents contains information about the earthquake in the adjacent regions Savoy and Dauphiné. Several solicitors wrote about observations in Annecy (Mangé 1888, p. 280; ADHS, Charrier), Duingt, Talloires, and Saint-Jorioz (Bovard, ADHS, E 719), Marboz (Dupasquier 2004, p. 15), and from St. Antoine in the Dauphiné (Brun-Durand 1885, p. 148–149). Only the observed motions in the place of observation are authentic. Some hints of damage in the reports cannot be located, although they probably speak about Geneva. For example in the *Minutaire* of Annecy: “An earthquake was noted in the whole town (Annecy), at some other places old buildings and chimneys collapsed (Mangé, 1888, p. 280).” A manuscript of the “Archives du prieuré” from Chamonix shows not established details: allegedly a pasture near Parsaz was covered by a rockslide from the Aiguille Pourrie around 1584 (Payot 1950, p. 51). At present, it cannot be determined if it is a question of confusing the places or dates, or if it is a trace of a simultaneous rockslide at the same time.

Further hints on French departments based on uncritical earthquake compilations cannot be considered because of the leading principle of historico-critical seismology, scilicet the eyewitness observations.

3.3.5 German-speaking Switzerland

Observations from the more distant German-speaking part of Switzerland include two contemporary letters in the Wickiana Collection (ZBZ) that note observations in Zurich, Kilchberg (ZH; StAZH, E III 062), Ottenbach (ZH), Glarus and Entlebuch (LU) (both ZBZ, Wickiana: Ms. F 32 f 19a and 20a). In Aarberg (BE; ZBZ: Ms. F 32 f 22), Stein am Rhein (SH; Steinemann, 1939), and Kilchberg (ZH; StAZH: E III 062.1) observations of small movements were noted down. The famous town clerk Renward Cysat (1969, p. 882) recorded his observations in Lucerne and mentioned hints from the

cantons of Uri, Schwyz, Unterwalden, and Zug; for all of these, no further proof is available. This information speaks only of fear, i.e., intensities V or smaller. Candreia's earthquake compilation (1905) contains no hints in Grisons Canton of a 1584 event.

Apart from sources basing on the Bernese governmental reports and the leaflet by Apiarius from Basle, there is a noticeable deficiency on further eyewitness observations in the region between Bern and Basle. That can be the result of a scarce literacy or it is a hint on lacking observations.

3.4 Flood wave and Seiche in Lake Geneva

After the first shock, a flood wave was observed in Lake Geneva around half past 11 local time. Several historical sources mention these “unnatural” movements in the water of the lake and the destruction of its shore, similar to the observations for Lake Lucerne during the 1601 earthquake (Schwarz-Zanetti 2003). The damage reports clearly indicate the effects of sub-aquatic slides triggered by the earthquake ground motion and the formation of a tsunami. The reported subsequent changes of flow direction indicate a standing wave of the lake known as “seiche.”

Bullinger located the shore damage in the northern delta of the Rhone, without mentioning the south: “It is such a pity to see the damage in the beautiful and fruitful vineyards on the lakefront between Vevey and Aigle and, as reliable witnesses told, a lot of them were sunk in the water (Bullinger in Egli, 1901-1904, 244; Online Resource 12). A similar location of the bank erosion is given by Wytttenbach (Egli, 1901-1904, 241) with “near the Castle Chillon.” Near Villeneuve, the floods extended to the next village.

According to two contemporary letters from Lausanne, the body of water was divided like the description in the bible: “Against his own nature the Lake Geneva flowed back and opened itself so that you could have passed through the lake by dry feet, but it did not last a long time” (ZBZ-Wickiana: Ms. F 32, 21a; Online Resource 13). and “Additionally the Lake Geneva moved in such a way as you could believe you could pass through by dry foot.” (ZBZ-Wickiana: Ms. F 32, 22; Online Resource 14). As mentioned before, these letters are probably from the same writer. Josua Wytttenbach in Murten gives a more reliable and important observation from an unknown source: “The lake was agitated and stormy in the ports of many places, but

a stone's throw away from the ports the lake was quiet. In some places it drew back, in others it expanded, at the end it rolled back in the old bed" (Egli 1901–1904, 241).

Only Bullinger speaks about three waves, probably only according to metaphors in antique Grecian writers (trikymia): "The earthquake presented itself in the lake three times as the waves drove back with great power and carried up the water the length of three spears (...) (Egli 1901–1904, 244, Online Resource 15)]." The winegrower Jehan Dumur in Grandvaux, 12 km east of Lausanne, heard a rush, and after it, he saw a swelling and flooding of the water of 12–18 m (Reymond 1917, 279). After this, he described the shores of several places as ruined and grooved and gave the example of Trex in Montreux (probably Territet, a part of the present-day Montreux), where deep holes were created along the riverside areas.

Also, the contemporary chronicler Joseph du Chesne (1587) emphasized the damage to the riverside of Montreux and described an inundation from Villeneuve to the next village. In 1680, his copyist Spon added some unsecured, but probably important information that seems to fit into the overall picture. He describes a wave movement in the Rhone in Geneva with the date September 16, 1600, which seems confused with the earthquake of September 18, 1601, in central Switzerland. But after comparing the description with other sources, we deduce that it concerns 1584 with high probability. According to Spon's description, the waves mounted to a height of 5 ft (at least 1.5 m), appeared three or four times at intervals of 15 min, and uncovered the bed of the Rhone. This allowed the children to catch fish, and the knife maker who lived on the bridge collected metallic waste. But these observations are not listed in the two contemporary sources from Geneva: the Council minutes (AEGE, RC 79, 1584) and the letter of Pappenheim (ZBZ, Wickiana: F 37, f. 136).

Three centuries later, the partial collapse of the Montreux quay "Trait de Baye" on May 19, 1891, pointed to the earthquake in 1584 and its flood wave. The engineer responsible for rebuilding examined the shore and found between Corsier and Chillon most embankments and little natural beach. He cites a copy of a source that speaks of 3000–7000 m² of lost vineyard at Grand Trait de Bayes below Montreux in 1584 (Schardt 1892).

Such data permit us to assume sub-aquatic slump in the area of the Rhone delta at the eastern extremity of Lake Geneva. Seismic investigation in this region

revealed the presence of disorganized sediments that could be attributed to a large slump of 2.5 km long and 900 m wide, and 15 m of thickness (Loizeau 1991; Zingg et al. 2003). It is up to now the only large sediment mass observed in that part of the lake, with a sediment volume of approximately 30 million m³. A major seismic reflector has also been observed by these authors over a larger area of the lake and corresponds mainly to a change in the grain size of the sediments deposited in the delta. Radiocarbon dating suggests that this important change in sedimentation occurred around 1400 (Loizeau (in prep.)). The possible slump lies over this major seismic reflector, indicating a younger age, compatible with the date of the 1584 earthquake.

However, the limnogeological setting is not favorable for ascertaining the slump's origin. Sedimentation rates in the deltaic region are relatively high (from 0.5 to 2.5 cm per year (Loizeau et al. 1997) compared to other settings where seismoturbidites and slumps triggered by quakes have been reported (about 1 mm per year, e.g., Schnellmann et al. 2002 and 2004; Schwarz-Zanetti et al. 2003). Here, the authors have specifically ignored deltaic settings because slides and slumps may also be triggered by other processes such as rapid sediment accumulation, flood, etc. A recent example of such an event in Lake Brienz, induced by sediment instability in 1996, has been reported (Girardclos et al. 2007). Moreover, elevated sediment accumulation rate can "rapidly" obliterate in the lake bottom morphology traces of slope failure where the slump originated. Finally, sand and gravel exploitation of the lake shore over many decades has deeply modified the natural morphology of the shallow delta slope, wiping out any evidence of scar in the lake bed.

To detect synchronous density flow deposits that could relate to the 1584 earthquake, high-resolution seismic profiles, sediment coring, and radiocarbon dating would be needed.

3.5 Landslide on Corbeyrier and Yvorne on March 14, 1584

Probably during the first day, a landslide from the mountain Tour d'Aï was triggered that over about 3 days came to rest on a plateau. Although contemporary observers focused on the disastrous landslide, the sequence of events cannot be clearly reconstructed from documents. For example, 4 days after the catastrophic slide, the letter by Bailiff Marquart Zehender (BBB: Mss.h.h.l.

Table 2 Macroseismic Intensities assessed for March 11, 1584, main shock at Aigle (SisFrance intensities are not included), including castle of Chillon, in the sources cited as “Lyon,” probably confusion with Glion (or Leysin)

Place	Lat.	Long.	Imin	Imax	Iw	Seismological quality
Montreux, VD	46.43	6.91	7	8	8	Poor
Bex, VD	46.25	7.01	7	8	8	Very poor
Aigle, VD	46.32	6.97	6	7	7	Good
Lausanne, VD	46.52	6.63	6	7	7	Poor
Glion, VD	46.43	6.93	6	7	7	Very poor
Les Ormonts, VD	46.35	7.11	6	7	7	Very poor
Corbeyrier, VD	46.35	6.9	6	–	7	Poor
Vevey, VD	46.46	6.84	6	7	7	Poor
Murten, FR	46.93	7.13	6	7	6	Poor
Genève, GE	46.21	6.14	6	7	6	Poor
Villeneuve, VD	46.4	6.96	6	7	6	Poor
Saint-Maurice, VS	46.22	7	6	7	6	Very poor
Noville, VD	46.38	6.90	5	7	6	Very poor
Suchy, VD	46.72	6.6	5	6	6	Very poor
Luzern, LU	47.05	8.29	5	6	6	Poor
Yvorne, VD	46.33	6.9	6	–	–	Very poor
Kanton Glarus, GL	46.98	9.06	5	6	5	Very poor
Stein am Rhein, SH	47.66	8.86	4	6	5	Very poor
Grandvaux, VD	46.5	6.73	4	6	5	Very poor
Marboz, F	46.35	5.25	4	6	5	Very poor
Aarberg, BE	47.04	7.28	4	5	5	Very poor
Kilchberg, ZH	47.32	8.54	4	5	5	Very poor
Rougemont, VD	46.49	7.2	4	–	5	Very poor
Saanen, BE	46.49	7.2	4	–	5	Very poor
Biel, BE	47.14	7.25	4	5	5	Very poor
Entlebuch, LU	46.99	8.06	4	5	5	Very poor
Annecy, F	45.91	6.1	–	–	5	Poor
Zürich, ZH	47.37	8.54	4	5	4	Poor
Monthey, VS	46.25	6.94	–	–	Felt	Poor
Duingt, F	45.83	6.20	–	–	Felt	Very poor
Talloires, F	45.83	6.22	–	–	Felt	Very poor
Saint-Jorioz, F	45.83	6.16	–	–	Felt	Very poor
Kanton Uri, UR	46.76	8.68	–	–	Felt	Very poor
Ottenbach, ZH	47.28	8.41	–	–	Felt	Very poor
Kanton Wallis, VS	46.26	7.62	–	–	Felt	Very poor
Piedmont, I	45.25	7.67	–	–	Felt	Very poor
Saint Antoine, F	45.17	5.22	–	–	Felt	Very poor
Lake Constance, CH/D/A	47.57	9.43	–	–	Felt	Very poor
Kanton Schwyz, SZ	47.06	8.69	–	–	Felt	Very poor
Kanton Zug, ZG	47.16	8.55	–	–	Felt	Very poor
Kanton Nidwalden, NW	46.9	8.4	–	–	Felt	Very poor
Boswil, AG	47.3	8.31	–	–	Felt	Very poor
Maienfeld, GR	47.01	9.53	1	2	1	Very poor

¹ Montreux, VD² Glion, VD

130) of the Castle of Aigle does not mention the earthquake series. The anonymous writer of the letter to Jörg Kindscher (ZBZ, Wickiana: Ms. F 32 f 22) speaks about a large crack in an unnamed mountain caused by the earthquake on March 11, followed by the landslide on March 14. In turn, Johann Rudolf Bullinger describes a three-phase process, starting with the earthquake on March 11 triggering the rockslide. This rock mass movement stopped on a plain, identified at least by Ebel and Heim as the rockfall from the Tour d'Äi to the plain of En-Luan (Ebel 1843, and Heim 1932, 155; Eisbacher and Clague, 1984, 110–111).

According to the leaflet by Apiarius, on March 14 at 9 o'clock local time, this mass was triggered by another earthquake and covered the two villages Corbeyrier and Yvorne. A water impact on the mass is not recognizable because in Switzerland, the winter 1583/84 belongs to a series of cold and rather dry winters (Pfister 1984a, b), while a source of the Dauphiné (F) speaks about a mild and dry time until March 14 (Brun-Durand 1885). Corresponding to unnamed sources in the printed chronicle by the Bernese Michael Stettler (1626/27), inhabitants of the village Monthey on the other side of the valley saw a large crack in a high mountain above Corbeyrier and Yvorne and warned the inhabitants. This warning met little success. Heim suggests the detection of this crack in the time before March 1, similar to the misinterpretation by Stettler.

The sources pursuant Marquart Zehender's letter, such as the leaflet by Apiarius and reports by Haller and Musculus (BBB, Mss.h.h.l. 130) and his copyists, often report partly similar figures of victims. According to Bullinger, the rockfall probably killed 122 inhabitants and 206 farm laborers outside the two villages.

The observations for the main shock and stronger aftershock were transformed into macroseismic fields.

Table 2 and 3 list the information; Fig. 6 shows the macroseismic field of the main shock in the epicentral area. The assessed moment magnitude M_w of the 1584 main shock is 5.9, with an error of about 0.25 units corresponding to one standard deviation (ECOS-09). The epicenter is at 46.33 N, 6.97 E with an uncertainty of about 25 km corresponding to one standard deviation. Probably around 25 aftershocks followed, four of which are identified precisely from historical sources on March 11, 12, 13, and 14. The strongest of the aftershocks occurred on March 14 with magnitude 5.4 and triggered the second, destructive landslide.

3.6 Contemporary interpretations

Even though the theologian Josua Wytenbach from Murten mentioned considerations by antique philosophers, he probably spoke about seismological theories transmitted by Anaxagoras, Aristoteles, Albertus Magnus, Thomas of Aquin, and Konrad of Megenberg (Rohr 2007). The summary of his report is an impressive religious metaphor about the cause of the earthquake and the landslide: "God (...) is quasi plucking us the ear (...) for opening the eyes of our spirit (Egli 1901–1904, p. 241–242)." And Andreas Wolf concluded in his letter on "highly equitable anger of God" (ZBZ, Wickiana: 6.3. [21a]; cp. also Fig. 4) and Du Chesne called the landslide an "Earth-Deluge" (Du Chesne 1587, p. 349–350). The eyewitnesses describe the ruin of the two villages as a destruction of a paradise garden allegedly containing almond and pomegranate trees. Lost silver plate and money are also mentioned. In Lucerne, two processions were organized in April (Cysat 1969, 882). Despite the allegedly obvious anger of God, the Bernese government organized on April 6 (April 16) the

Table 3 Macroseismic Intensities assessed for the largest aftershock, March 14, 1584, at Aigle

Place	Lat.	Long.	Imin	Imax	Iw	Seismological quality
Genève	46.21	6.14	–	–	Felt	Very poor
Montreux	46.43	6.91	6	–	Felt	Very poor
Yvorne	46.33	6.96	5	–	Felt	Very poor
Corbeyrier	46.35	6.96	7	–	Felt	Very poor
Neuchâtel	46.99	6.93	3	5	Felt	Very poor
Aigle	46.32	6.97	7	7	7	Very poor
Vevey	46.46	6.84	6	7	6	Very poor
Villeneuve, VD	46.4	6.96	5	6	6	Very poor

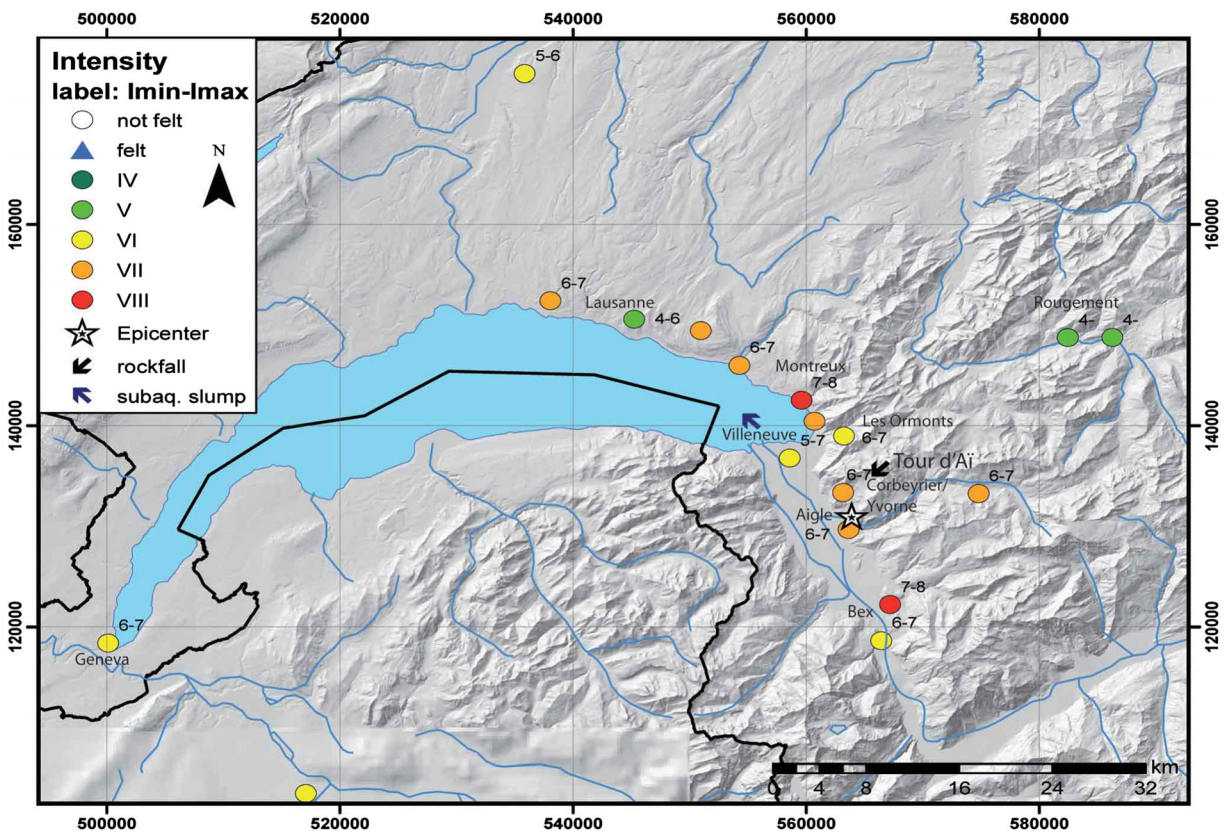


Fig. 6 Macroseismic fields and assessed locations of the earthquakes on March 11, 1584. The color of the point describes the intensity estimate; numbers depict the possible range from minimum to maximum probable intensity

collection of an extraordinary sympathy tax for supporting the victims (StABE: A III 38, vol. LL, 214 f).

4 Conclusion

For the whole sixteenth century, only a few written sources related to earthquakes are presently available for southwestern Switzerland and the Valais. These sources cover only one third of the time. Two strong events in the sixteenth century can, however, be assessed from the presently available historical information. These are the April 1524 Ardon Mw 5.8 event and the March 11, 1584, Aigle Mw 5.9 earthquake. For the Aigle event, a number of aftershocks can be identified from historical documents. The strongest aftershock on March 14, 1584, reached a magnitude of Mw 5.4. The Aigle event caused wide-spread damage, triggered a landslide that came at rest on a plateau, and caused a tsunami and seiche in Lake Geneva. The aftershock on March 14 reactivated the landslide which then destroyed

two villages. For the 1524 Ardon event, only a small number of reports is available and the quality of the database cannot be compared with 1584. An existing stone tablet at the bell tower of the Ardon Church confirms a document about destruction of this tower and archeological findings in Savièse support them. Increased building activity in the Upper Valais area during the second quarter of the sixteenth century assists the cited sources. But exceptionally, the cracks in a church of Brig-Glis could not be clearly related to the 1524 event due to the lack of written testimonials. Reported building damage in Brig of unknown cause is not sufficient to consolidate the earthquake hypothesis.

Over March 11–14, 1584, about 25 seismic shocks affected the regions between Lake Geneva and Saanen (BE): two events, on March 11 and 14, caused damage. During the first day, a landslide from the mountain Tour d’Ai was triggered that over about 3 days came to rest on a plateau. The debris was then triggered by the largest aftershock on March 14 and destroyed the villages

Corbeyrier and Yvorne (VD). Exceptional water movements in Lake Geneva induced by the main shock caused damage to the Rhone delta and the shore of Lake Geneva. The large dimension of this induced damage can be explained by an expanded sub-aquatic slide, resultant tsunami, and a seiche in Lake Geneva. The destruction of two villages and the effects in Lake Geneva awoke fear in contemporaries and left a considerable number of written documents that we assessed. In this context, the new building law of Solothurn established in 1585 is interesting, which requested improved counterforts (Studer 1987, p. 500–502), however without mentioning the 1584 earthquake.

To fill gaps in our historical knowledge of the sixteenth century, a future project should revise both the promising but laborious Church Register Section from the first half of the seventeenth century (Walliser Kirchenmatrikeln), the Family Section (Familienfonds) in the Public Record Office of the Valais (Staatsarchiv Wallis), and the archives of the villages.

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StABE: Staatsarchiv Bern - StAB A III 38: Deutsches Missivenbuch der Stadt Bern, Band LL, S. 214 f. – StAB DQ 11: Berner Chronik von Michael Stettler, 1623, Band H, S. 134 f

StAZH: Staatsarchiv Zürich E III 062.1: Kilchberg, Pfarrbuch 1536–1617: 1584

StoA: Stockalperarchiv, Brig: Dokument Nr. 161

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