The A.D. 1567 $M_w$ 7.2 Ameca, Jalisco, Earthquake (Western Trans-Mexican Volcanic Belt): Surface Rupture Parameters, Seismogeological Effects, and Macroseismic Intensities from Historical Sources

by Max Suter

Abstract The A.D. 1567 Ameca, Jalisco, earthquake (west-central Mexico) is the strongest known historical crustal earthquake in the Trans-Mexican volcanic belt, an active volcanic arc being deformed by an intra-arc extensional fault network. The location of the surface rupture at the base of the Sierra de Ameca mountain range, its length (13–14 leagues, 54–59 km) and the scarp height (1–2 estados, 1.67–3.34 m) are inferred from the description of this earthquake in the Relación de Ameca of 1579, which contains what is probably the earliest documentation of an earthquake surface rupture in the Americas. From scaling relations, the moment magnitude of this earthquake can be estimated as $7.2 \pm 0.3$, based on the rupture length. The A.D. 1567 Ameca earthquake is likely to have ruptured to the surface along two (or all three) major segments of the Ameca–San Marcos normal fault system.

Online Material: Excerpts from five historical documents related to the 1567 Ameca earthquake.

Introduction

The Trans-Mexican volcanic belt, a Miocene to recent volcanic arc, is being deformed by an extensional intra-arc fault network (Suter et al., 2001; Ferrari et al., 2012). The A.D. 1567 Ameca, Jalisco, earthquake (west-central Mexico) is known as the strongest historical crustal earthquake in the Trans-Mexican volcanic belt (Suárez et al., 1994; Zúñiga et al., 1997). Here, I document the location and parameters of the surface rupture of this earthquake (as well as other seismogeological effects and macroseismic intensity observations) from early historical sources, such as the Relación de Ameca of 1579 (Acuña, 1988), a travel diary, and two chronicles. The study of these historical sources and the regional neotectonic and paleoseismic analyses of active faults are relevant for the assessment of the seismic groundshaking hazard of the Guadalajara metropolitan area (Chávez et al., 2011, 2014), which is located only 50–70 km northeast of the epicentral region of the 1567 earthquake. With a reported population greater than four million in 2008, Guadalajara is the second most populous metropolitan area in Mexico (after Mexico City). It has been repeatedly afflicted by earthquakes from nearby crustal sources, as well as from the 200 km distant plate subduction-zone (Iglesias et al., 1877; Ordóñez, 1912; García Acosta and Suárez Reynoso, 1996).

Neotectonic Setting

The westernmost part of the Trans-Mexican volcanic belt (west of Guadalajara) is being deformed by an array of faults with Pliocene–Quaternary activity, which include the Amatlán de Cañas half-graben and the Ameca–San Marcos fault system bounding the Zacoalco and Ameca half-grabens (Fig. 1) (Rosas-Elguera et al., 2003; Ferrari et al., 2012). Active deformation within this array is dominantly extensional, with a north-northeast–south-southwest-oriented least principal stress (Suter, 1991; Ferrari and Rosas-Elguera, 2000). According to Ferrari and Rosas-Elguera (2000), the Pleistocene geologic slip rates are 0.1 mm/yr for the Amatlán de Cañas and San Marcos faults, whereas Global Positioning System geodetic measurements by Selvans et al. (2011) indicate a current maximum extension rate of ≤8 mm/yr across the Ameca–San Marcos fault system. Crustal microseismicity was recorded by local networks in the Zacoalco region (Suárez et al., 1994; Pacheco et al., 1999) and in the region of the Amatlán de Cañas half-graben (Núñez-Cornú et al., 2002). According to the online catalog of the U.S. National Earthquake Information Center (NEIC), recent crustal earthquakes have also originated near the Ameca and San Marcos faults, in the Chapala and Citala grabens, and near the Cotija half-graben (Fig. 1, Table 1). Fault scarps...
displacing colluvium indicate that faulting has continued into the late Pleistocene or Holocene in the Sayula half-graben (Fig. 1) (Allan, 1986). A regional geologic map of the Trans-Mexican volcanic belt west of Guadalajara is provided by Ferrari et al. (2000, plate 2); major additions to that map were made by Ferrari et al. (2003) and Frey et al. (2007).

The Ameca–San Marcos Fault System

The Ameca–San Marcos fault system is formed by three major south to west-southwest-dipping subvertical normal fault segments that bound the Ameca–Zacoalco depression (Figs. 1 and 2; Rosas-Elguera et al., 1997). An extensive paleo-lake existed in this depression during the Pliocene–Quaternary (Bárcena, 1876; Michaud et al., 2000). The western segment of this fault system, the Ameca fault, is ≥24 km long, dips 50°–82° south, and has a minimum throw of 1400 m. Slickenlines measured in the central part of the fault indicate extensional dip slip (Ferrari and Rosas-Elguera, 2000). The fault trace passes at the southern base of the Sierra de Ameca mountain range (Fig. 2) and is likely to coincide with the surface rupture location of the 1567 earthquake reported in the Relación de Ameca (see below).

The southeastern segment of this fault system, the San Marcos fault, separates the Zacoalco half-graben from the Sierra de San Marcos mountain range (Figs. 1 and 2). It measures 22 km in length and dips 60°–82° west-southwest (Ferrari and Rosas-Elguera, 2000). Slickenlines measured on the fault indicate extensional dip slip (Quintero Legorreta, 1995). The existence of several playa lakes in the Zacoalco half-graben (Fig. 1) may be the result of ongoing tectonic subsidence. With a topographic relief up to 750 m, the compound fault scarp bounding the Sierra de San Marcos is morphologically by far the most prominent feature of the

Figure 1. Locations of the traces of normal faults (bold lines with tick marks on down side) with Plio-Quaternary activity in the western part of the Trans-Mexican volcanic belt. The fault scarp was traced on orthorectified pan-sharpened Landsat ETM+ imagery (pixel size 14 m). They include the Ameca–San Marcos normal fault system, which is likely to have ruptured in the 1567 Ameca earthquake. Recent crustal earthquakes in the Chapala and Citala grabens and near the Cotija half-graben (marked by closed circles; references and source parameters in Table 1) indicate that these structures are tectonically active. The gray rectangle indicates the region shown in Figure 2. The location map (inset) provides the plate tectonic setting of the study area; the black rectangle indicates the region shown in Figures 1 and 3. (TMVB, Trans-Mexican volcanic belt). The color version of this figure is available only in the electronic edition.
likely to be sackung scarps resulting from deep-seated gravitational slip. These scarps yield a potassium–argon (K–Ar) whole rock age of 1.44 ± 0.03 Ma (Allan, 1986). Based on a 68° average dip of the fault plane, an assumed 1500 m throw, and 1.4 Ma age of the displaced bedrock surface, I obtain a 1.2 mm/yr Pleistocene slip rate for the San Marcos fault, which is an order of magnitude higher than the estimate by Ferrari and Rosas-Elguera (2000). Numerous short, parallel, southwest-dipping, high-angle normal faults, distributed over a 15 km wide zone southwest of Zacoalco, on the slope of the Sierra de Tapalpa mountain range (Fig. 2), were interpreted as synthetic secondary structures of the San Marcos fault by Rosas-Elguera et al. (1997), Pacheco et al. (1999), and Ferrari and Rosas-Elguera (2000). However, the traces of these faults and the related uphill-facing scarps are not parallel to the San Marcos fault, but instead are orthogonal to the steepest descent of this major mountain slope with a relief >1400 m. These are likely to be sackung scarps resulting from deep-seated gravitational slope deformation.

The central segment of the Ameca–San Marcos fault system links the Ameca and San Marcos faults. This major relay zone, 20 km long, is itself composed of two segments, the Ahuisculco and Villa Corona faults, which may be linked by a breached relay ramp (Figs. 1 and 2; Rosas-Elguera et al., 1997). Slickenlines measured on the Villa Corona fault indicate extensional dip slip (Quintero Legorreta, 1995, his fig. 5.1). These faults displace volcanic rocks of Pleistocene age (Allan, 1986; Ferrari et al., 2000).

### Historical Sources

The early historical sources about the 1567 Ameca earthquake include the 1579 Relación de Ameca (Acuña, 1988); earthquake-related observations in 1587, reported in the travel diary by Antonio de Ciudad Real (de Ciudad Real, 1976); the 1615 chronicle by Juan de Torquemada (de Torquemada, 1979); and the 1653 chronicle by Antonio Tello (Tello, 1891, 1942). Excerpts from these sources, as well as numerous secondary sources, can be found in the catalog of the historical seismicity of Mexico by García Acosta and Suárez Reynoso (1996). On the other hand, several other preserved sixteenth-century Relaciones Geográficas of towns and provinces near Ameca (Acuña, 1988), such as the Relación de la Provincia de Amula (located southeast of Ameca), the Relación de Poncitlan y Cuiseo del Río (located north of Lake Chapala), the Relación de la Provincia de Tenamaztlan (located south of Ameca), and the Relación de las Minas de Xocotlan (located north of Ameca), do not contain any additional information, either about this earthquake or about earthquakes in general. Neither could I find information about this earthquake in the reports of the royally sponsored 1571–1577 scientific expedition to New Spain by Francisco Hernández (Hernández, 1959). The treatise by the natural history writer Juan de Cárdenas, published in Mexico City in 1591, provides theoretical–philosophical Aristotelian explanations about the frequent earthquakes in Mexico but no specific information about the earthquake under study (de Cárdenas, 1591, 1580). Similarly, de Acosta

### Table 1

Earthquake Source Parameters of Recent Crustal Earthquakes in the Region Covered by Figure 1

| Reference† | Date (yyyy/mm/dd) | Origin Time (hh:mm:ss) | Latitude (° N)* | Longitude (° W)* | Focal Depth (km)† | Magnitude‡ |
|------------|-------------------|------------------------|-----------------|-----------------|------------------|------------|
| 1          | 1987/10/26        | 08:15:55               | 20.084          | 104.27          | 33               | 4.2        |
| 2          | 1994/01/28        | 04:29:25               | 19.537          | 102.61          | 33               | 3.5        |
| 3          | 1998/03/05        | 20:04:20               | 20.529          | 104.277         | 4.6              | 4.6        |
| 4          | 2003/04/02        | 02:53:41               | 19.721          | 102.555         | 1.7              | 3.9        |
| 5          | 2003/04/07        | 07:07:16               | 19.67           | 102.589         | 20               | 4.0        |
| 6          | 2003/04/07        | 07:42:04               | 19.602          | 102.521         | 15.6             | 3.9        |
| 7          | 2003/10/13        | 09:06:31               | 20.221          | 102.927         | 61.8             | 4.2        |
| 8          | 2004/03/14        | 18:16:21               | 20.282          | 104.363         | 59.6             | 3.9        |
| 9          | 2004/06/17        | 15:46:00               | 20.434          | 103.577         | 29.1             | 3.9        |
| 10         | 2004/07/06        | 10:16:13               | 20.444          | 102.761         | 7                | 3.8        |
| 11         | 2004/07/08        | 12:05:41               | 20.42           | 102.767         | 15               | 4.1        |
| 12         | 2005/05/13        | 04:19:35               | 19.48           | 102.583         | 3.7              | 3.7        |
| 13         | 2008/10/09        | 12:10:17               | 20.081          | 103.379         | 37.2             | 3.9        |
| 14         | 2012/05/18        | 03:07:59               | 20.241          | 103.375         | 5                | 4.2        |

Source: Preliminary Determination of Epicenters (PDE) Bulletin of the U.S. Geological Survey through the online catalog of the National Earthquake Information Center (NEIC).

*The epicenters and reference numbers are graphed in Figure 1.

†The focal depths indicated for events 1 and 2 are likely to be default values for shallow sources of unspecified depth. The focal depths indicated for events 7 and 8 are likely to be too large, because no subduction zone epicenters are known from this region.

‡The magnitudes are duration magnitudes, except the ones of events 1, 2, and 14, which are body-wave magnitudes.
Ahuisculco fault; VC, Villa Corona fault; SM, San Marcos fault.

in the 1567 Ameca earthquake (white lines). A, Ameca fault; AH, showing the traces of the faults that are interpreted to have slipped verso and 419 recto of the letter).

felt or heard about in the Guadalajara region (folios 418 verso) in Seville, Spain, makes reference to a report to the Audiencia de Guadalajara, Legajo 51, folios 417 to 422 (document 1). However, the referenced report is neither attached to the letter nor lo-
mountains are located one league north and two leagues south of the village.

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(1590, 2002) puts forward a hypothesis about the cause of the earthquakes affecting Mexico City but does not provide information about specific Mexican earthquakes.

A letter by the Bishop of Guadalajara, Fray Pedro de Ayala, to the Spanish crown, dated 9 March 1568 and preserved in the Archivo General de Indias (Sección Gobierno, Audiencia de Guadalajara, Legajo 51, folios 417 to 422 verso) in Seville, Spain, makes reference to a report to the Spanish crown about an earthquake of a size not previously felt or heard about in the Guadalajara region (folios 418 verso and 419 recto of the letter). A partial facsimile (Fig. S1) of the letter and its transcription are provided in the electronic supplement to this article (document 1). However, the referenced report is neither attached to the letter nor located elsewhere within Legajo 51 (Guillermo Pastor Núñez, written comm., 2006). It is likely that this letter refers to the 1567 earthquake.

The Relación de Ameca

The Relación de Ameca, which was written between 2 October 1579 and 15 December 1579 by Antonio de Leyva, provides the response by the colonial government to a 50 chapter geographic questionnaire commissioned by the Spanish crown. This report, which is preserved in the Benson Latin American Collection of the University of Texas at Austin, contains what is probably the earliest documentation of an earthquake surface rupture in the Americas. The earthquake-related sections are included in the electronic supplement (document 2) from the transcription and edition of the Relación de Ameca by Acuña (1988).

The Travel Diary by Antonio de Ciudad Real

The Franciscan friar Antonio de Ciudad Real visited most convents and churches of the Jalisco region in 1585–1587. In his travel diary Tratado curioso y docto de las grandezas de la Nueva España, which includes many observations related to the natural sciences and anthropology, he writes about a large, distinct, and long earthquake surface rupture he observed 5 March 1587 near Zacualco (Fig. 2), along the slope of a high mountain range (de Ciudad Real, 1976, p. 153; document 4).

The Chronicle by Juan de Torquemada

Juan de Torquemada, a Franciscan friar like Antonio de Ciudad Real, includes in his chronicle Monarquía Indiana (published 1615 in Seville, Spain), a section (libro 14) about earthquakes. De Torquemada was on an assignment in Nueva Galicia (west-central Mexico) in ~1585 and wrote his chronicle between 1605 and 1612 (León-Portilla, 1983). He reports a major earthquake in the province of Ávalos and related surface rupture and/or fissures (document 5; Orozco y Berra, 1888, p. 309; de Torquemada, 1979). The province of Ávalos reached from just east of Ameca in the west to the western part of Lake Chapala in the east and Sayula in the south (Fig. 3; Acuña, 1988; Gerhard, 1993). It included the towns of Chapala, Cocolu, Zacualco, Amaceuca, and Sayula (Fig. 3). De Torquemada does not indicate the origin of the event but mentions that no other major earthquake had occurred in Ávalos up to the time of his writings (between 1605 and 1612), when many of these earthquake-related morphological features were still visible and some major ones filled located in the plain of a major river (now known as the Ameca River), flowing from east to west. The map also shows two east–west-trending mountain ranges on either side of the river plain. According to this map and the response to chapter 18 of the questionnaire, the two mountain ranges are located one league north and two leagues south of the village.

According to the Relación de Ameca (response to chapter 21 of the questionnaire), a rupture formed during the earthquake along the mountain range located one league from the village (now known as the Sierra de Ameca; Fig. S2). The rupture is continuous over a distance of more than 13 or 14 leagues and has a height of 1–2 estados (the metric equivalents of these colonial time length units are given below). The rupture is clearly distinguished in the text from large and deep fissures that developed in the plains. The ground shook so violently that people were thrown off their feet. Many buildings were destroyed and their inhabitants died below the debris (based on the response to chapters 5 and 31 of the question-naire, these were mostly one-story adobe dwellings). The intensity of the earthquake was so terrifying that the world was thought to have come to an end. The Ameca River was damned by an earthquake-induced landslide. The dam was breached after 20 days, which caused a muddy flash flood with a sulfurous smell. The river water remained so turbid that it could not be consumed for more than three months.

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and 1653. This supports the hypothesis that the surface rupture observed by de Ciudad Real in 1587 near Zacoalco and the earthquake-related morphological features mentioned by de Torquemada formed in the 1567 Ameca earthquake.

Interpretation

Origin Time of the Earthquake

Based on the response to chapter 21 of the questionnaire (see above and © document 2), the Ameca earthquake occurred nearly 12 years before the writing of the Relación de Ameca between 2 October 1579 and 15 December 1579 (Acuña, 1988), therefore most likely in late 1567 or early 1568. The letter by the Bishop of Guadalajara to the Spanish crown (mentioned above and © in document 1) referring to a report to the Spanish crown about an earthquake of a size not previously felt or heard about in the Guadalajara region, is dated 9 March 1568. It is likely that the letter refers to the Ameca earthquake, which would support the late 1567 to early 1568 origin of the earthquake stated in the Relación de Ameca. According to the 1653 chronicle by Antonio Tello, this earthquake occurred either 30 December 1567 or 27 December 1568 (Tello, 1891). Only the first date is within the time window inferred for this earthquake from the Relación de Ameca and the letter by the Bishop of Guadalajara. The 27 December 1568 origin, which was preferred by Suárez et al. (1994) and Zúñiga et al. (1997), is not compatible with these two independent historical sources. In summary, the Ameca earthquake must have originated in late 1567 or early 1568, most likely 30 December 1567 in the Julian calendar.

Magnitudes Inferred from the Surface-Rupture Scarp Length and Height

According to the Relación de Ameca, the surface rupture measures more than 13 or 14 leguas (leagues) in length. However, the Mexican league at the beginning of the colonial period was equal to 3000 old Toledo varas or 4179 m. In A.D. 1589, the Burgos vara was established as the standard of length, and a Mexican league was defined as 5000 Burgos varas, or 4190 m (Carrera Stampa, 1949). Based on these conversions 13–14 leagues correspond to 54–59 km.

How reliably can a sixteenth-century Mexican map-scale length estimate be converted to the metric system? Surveying prior to A.D. ~1630 did not employ instruments, but instead relied on textual surveys, which required an ability to read the landscape, estimate distance and direction, and write the survey report (Hunter and Sluyter, 2011). A league was therefore not necessarily a uniform unit of measure corresponding exactly to the nominal 3000 old Toledo or 5000 Burgos varas. The length of a league in the Relación de Ameca can be evaluated, because the two east–west-trending mountain ranges on either side of the village (Fig. 2) are said to be at a distance of one and two leagues, respectively, from the

Figure 3. Map showing the compiled macroseismic intensity observations and seismogeological effects (Table 2) of the 1567 Ameca earthquake. The color version of this figure is available only in the electronic edition.

with water. The observations by de Torquemada, like the ones by Antonio de Ciudad Real, therefore most likely refer to the 1567 Ameca earthquake.

The Chronicle by Antonio Tello

Another valuable source is the extensive, 1001folio chronicle Crónica Miscelánea de la Sancta Provincia de Xalisco by the Franciscan friar Antonio Tello, which is dated 20 April 1653 at its end. The chronicle is composed of six volumes. The first one is lost, but a table of its chapters is annexed to the sixth volume. The manuscripts of the second and third volumes are preserved at the John Carter Brown Library, Providence, Rhode Island. Volume 2, which includes information about numerous earthquakes in the Jalisco region, was transcribed by Victoriano Salado Álvarez, edited by José López Portillo y Rojas, and published in 1891 in Guadalajara (Tello, 1891). The third volume (folios 668–693) was transcribed by José Cornejo Franco and published in 1942 in Guadalajara (Tello, 1942). The manuscripts of volumes 4–6 (folios 695 to 1001) are preserved at the Biblioteca Pública de Guadalajara.

Tello was Guardian of monasteries in Zacoalco and Cocula (Fig. 3), in the epicentral region of the 1567 Ameca earthquake. He must have been about 86 years of age in 1653, when he put the final touches to his chronicle (van Horne, 1936). Tello (1891, 1942) provides damage observations for several Franciscan churches and convents, which are summarized in Table 2. He repeatedly refers to the 1567 Ameca earthquake as “el temblor grande” (the big one). It can therefore be assumed that no other earthquake of a comparable size occurred in the Ameca–Zacoalco region between 1567

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Table 2

Macroseismic Intensity Observations and Seismogeological Effects for the 1567 Ameca Earthquake Obtained from Historical Sources

| Township* | Longitude (° W) | Latitude (° N) | Description | Intensity† | Source‡ |
|-----------|----------------|----------------|-------------|------------|---------|
| Amacueca  | 103.60         | 20.01          | The church and convent, made of good quality masonry (*cal y canto*), were destroyed. Some of the major walls of the church and convent sank into the ground. | IX         | 1/531   |
| Ameca     | 104.05         | 20.55          | Extensional surface rupture along the mountain range north of Ameca. Large and deep fissures in the Ameca River plain. Massive landslide dammed the Ameca River. Destruction of many adobe dwellings. People were thrown off their feet. Alarm approached panic. | 3         |         |
| Atoyac    | 103.52         | 20.01          | The convent was destroyed. The major chapel of this village was partly destroyed. The parish priest, Fray Hernando Pobre de Segura, perished in the collapsing convent. | IX         | 1/609   |
| Chapala   | 103.19         | 20.30          | The major chapel of this village was partly destroyed. The parish priest, Fray Esteban de Fuente Ovejuna perished in the collapsing convent. | VIII      | 4/77    |
| Cocula    | 103.82         | 20.36          | The convent and church were destroyed. The parish priest, Fray Esteban de Fuente Ovejuna perished in the collapsing convent. | IX         | 1/609   |
| San Juan Cosalá | 103.34 | 20.29 | Two hot springs burst forth. Very distinct and extended surface rupture along the flank of a high mountain range could still be observed near this village in 1587. The water level of the nearby lake dropped drastically. The convent was destroyed. The parish priest, Fray Antonio de Gordejana, perished in the collapsing convent. Sixty native people perished (from which it can be inferred that many dwellings collapsed). Many irrigation canals were damaged greatly. | VIII      | 1/609   |
| Zacoalco  | 103.57         | 20.23          |                                            | 2/153      |         |

*All location names have been changed to reflect modern Mexican usage.
†The intensity assessments are based on the 12-degree European Macroseismic Scale 1998 (EMS-98) (Grünthal et al., 1998; Musson et al., 2010).
‡Source/page: 1, Tello (1891); 2, de Ciudad Real (1976); 3, Relación de Ameca (Acuña, 1988); 4, Tello (1942).

Village. On modern maps, these mountain ranges are at distances of 4–5 km and 10–11 km, respectively, from the central plaza of Ameca. Similarly, a major spring of the Ameca River (indicated in the northeastern part of the map accompanying the Relación de Ameca, near the junction of three river branches ([Fig. S2] and now known as Los Hervores thermal spring) is said to be at a distance of five leagues from the village. On modern maps, Los Hervores (latitude 20.605° N, longitude 103.887° W) is at a distance of ~20 km from the center of Ameca. The indicated surface rupture length of 13–14 leagues is therefore likely to be very close to its stipulated size of 54–59 km. Furthermore, this length is compatible with the length of the Ameca–San Marcos fault system (Figs. 1 and 2). Based on a length of 54–59 km and the scaling relation between surface rupture length and magnitude for normal faults by Wells and Coppersmith (1994, their table 2A), the moment magnitude of the Ameca earthquake can be estimated as 7.2 ± 0.3.

According to the Relación de Ameca, the surface rupture height measures 1–2 *estados*. An *estado* is a unit of vertical distance corresponding to two *varas*, the average height of adult men or approximately 1.67 m (Carrera Stampia, 1949, his table 1). Therefore, a rupture height of 1–2 *estados* corresponds to 1.67–3.34 m. Based on a maximum slip of 3.60 m (maximum rupture height of 2 *estados* or 3.34 m divided by the sine of a 68° average normal fault dip) and the scaling relations between maximum slip and magnitude for normal faults by Wells and Coppersmith (1994, their table 2B), the moment magnitude of the Ameca earthquake can be estimated as 7.0 ± 0.4. Similarly, based on an average slip of 2.71 m (average rupture height of 1.5 *estados* or 2.51 m divided by the sine of a 68° average normal fault dip) and the scaling relations between average slip and magnitude for normal faults by Wells and Coppersmith (1994, their table 2B), the moment magnitude of the Ameca earthquake can be estimated as 7.1 ± 0.3.

These three magnitude estimates fall into a very narrow range between 7.0 and 7.2, which supports their significance. In a segmented normal fault rupture, the rupture segments are self-similar; for each individual segment, slip scales linearly with the segment length (e.g., Scholz, 2002). The average and maximum displacements therefore depend on the size...
of the largest segment rather than the size of the entire rupture, which would explain the lower magnitudes obtained from the scaling relations for the maximum and mean displacements. For that reason, I consider the magnitude resulting from the rupture length-versus-magnitude scaling relation or $M_w \ 7.2 \pm 0.3$ to be the most reliable estimate for this earthquake.

Location of the Surface Rupture Trace

According to the compelling description in the *Relación de Ameca*, the surface rupture passes along the base of the Sierra de Ameca mountain range, located north of the village (❼ Fig. S2). The rupture is likely to have originated on the Ameca fault (Figs. 1 and 2). Suárez *et al.* (1994), on the other hand, assume the rupture to be located between Ameca and Ahuacatlán, Nayarit, which is located 75 km northwest of Ameca (Fig. 3). Their assumption is based on the partly fictitious narrative about the *Relación de Ameca* by Pérez Verdía (1910, p. 232).

Furthermore, Suárez *et al.* (1994) caution that the observations in the *Relación de Ameca* may not refer to an earthquake surface rupture but to landslides. In a strict sense, the *Relación de Ameca* reports a fissure, continuous over a length of 54–59 km, and a vertical 1.67–3.34 m displacement of the ground surface across the fissure (❼ document 2). This description is very similar to the observations after the 1887 $M_w \ 7.5$ Sonora earthquake (southern Basin and Range Province), where a continuous fissure formed along the base of the entire surface rupture scarp (Suter, 2006, 2008a,b, 2015). Fault scarp-bounding fissures have also been observed in other earthquake surface rupture studies (for example, Kurushin *et al.*, 1997; Fenton and Bommer, 2006). It is therefore very likely that the observations in the *Relación de Ameca* refer to a tectonic surface rupture.

The long and distinct earthquake surface rupture observed by Antonio de Ciudad Real in 1587 near Zacualco (Fig. 2) at the base of a major mountain range (de Ciudad Real, 1976, and ⩉ document 4) is likely to pass at the base of the Sierra de San Marcos and to have originated on the San Marcos fault (Figs. 1 and 2) during the 1567 event (Quintero Legorreta and Barrier, 1996). The 1567 rupture of yet another structure, the relay zone between the Ameca and San Marcos faults (Figs. 1 and 2), postulated by Quintero Legorreta and Barrier (1996), would be compatible with the overall surface rupture length of 54–59 km indicated in the *Relación de Ameca* for this earthquake.

Dam Caused by the Earthquake

According to the Relación de Ameca, the Ameca River was dammed by an earthquake-induced landslide, and the dam was breached after 20 days, which caused a muddy flash flood with a sulfurous smell. The river water remained so turbid that it could not be consumed for more than three months. This description indicates that the slide blocked the river upstream, east of the village of Ameca, for example, where the river crosses the scarp of the Ameca fault (Fig. 1). On the other hand, Suárez *et al.* (1994) assume the landslide to have occurred between Ameca and Ahuacatlán, Nayarit, downstream of Ameca, which seems unlikely.

Macroseismic Intensity Observations and Seismogeological Effects

The macroseismic intensity observations (12-degree European Macroseismic Scale 1998 (EMS-98); Grünthal *et al.*, 1998; Musson *et al.*, 2010) and effects on the natural environment compiled from the *Relación de Ameca* (Acuña, 1988), the travel account by Antonio de Ciudad Real (de Ciudad Real, 1976), and the chronicle by Antonio Tello (Tello, 1891, 1942) are summarized and sorted alphabetically by location in Table 2 and graphed in Figure 3, whereas the observations by Juan de Torquemada (de Torquemada, 1979) were not specific enough to be included.

The damage area (area with intensities of degree VII and higher) of the 1567 Ameca earthquake (Fig. 3) results to be significantly smaller than indicated by Suárez *et al.* (1994); it is unlikely to have reached as far northwest and south as assumed by these authors. I have not found any specific damage descriptions in the above-mentioned historical sources for Ahuacatlán, Zapotitlán, Tuxpan, Zapotlán (now Ciudad Guzmán), Tamazula, or Colima (Fig. 3) that explicitly would be related to the 1567 Ameca earthquake. The intensity degree of VII for Ahuacatlán in Suárez *et al.* (1994) seems to be based on the partly fictitious narrative about the *Relación de Ameca* by Pérez Verdía (1910, p. 232). The earthquake damage reported by Tello (1891, p. 695–696) in Zapotitlán occurred only in ~1591, whereas the earthquake damage Tello (1942, p. 21–22) describes from Tuxpan, Jalisco occurred according to him in 1577. As for Zapotlán and Tamazula, the damage description by Tello (1942, p. 21–22) is so general (“all the churches and houses in all the villages of Zapotlán and in the provinces of Tamazula, Zapotitlán, Ávalos and elsewhere were ruined”) that it should not be taken at face value. Based on the context, the earthquake mentioned by Tello (1891, p. 688) as having destroyed the church of Colima must have occurred already in ~1561, before the 1567 Ameca earthquake. Consequently, an origin of the 1567 rupture on the major fault bounding the Sayula half-graben (Fig. 1), postulated by Suárez *et al.* (1994) based on the high macroseismic intensities they assume for that region, is questionable. The size of the damage area is also implicitly constrained by the fact that the sixteenth-century Relaciones Geográficas of the towns and provinces surrounding Ameca (see above) do not contain any information about the 1567 earthquake.

The known damage is concentrated along the flat-bottomed valleys that are associated with the faults of the Ameca–San Marcos system, the Sayula half-graben, and the Chapala graben (Fig. 1), but so are the settlements and consequently the damage to man-made structures as well as the damage reports. In addition to these biases, the concentration of damage has several possible physical explanations: given
The A.D. 1567 Mw 7.2 Ameca, Jalisco, Earthquake (Western Trans-Mexican Volcanic Belt)

The A.D. 1567 et al. circle with a radius of 48 km. The earthquake caused moderate damage in Mexico City (Suter, 2014), which can be explained by site effects. By comparison, it is not unlikely that the damage area of a repeat of the 1567 Ameca earthquake would include the Guadalajara metropolitan area (Fig. 3), given the large seismic vulnerability of its construction stock (Chávez, 1995, 2000). The macroseismic intensity data are limited to seven places and a very narrow intensity range between degrees VIII and IX, with most being IX (Table 2). As a result, it is impractical to contour the intensity distribution (Fig. 3). For the same reason, the intensity attenuation cannot be defined. The damage area is likely to be somewhat larger in size than that of the M ~ 7.0 Acambay earthquake of 1912, which is the strongest historical earthquake in the central part of the Trans-Mexican volcanic belt. Like the 1567 Ameca event, the Acambay earthquake ruptured to the surface along several normal faults of a major intra-arc lake basin (Urbina and Camacho, 1913; Suter et al., 1991, 1992, 1995, 2001; Langridge et al., 2000). Based on an isoseismal map for the 1912 Acambay earthquake, constrained by intensity data for 86 places, its damage area measures 7228 km² (Suter et al., 1996), which corresponds to a circle with a radius of 48 km. The earthquake caused moderate damage (macroseismic intensity of degrees VII–VIII) up to a distance of 100 km from its source, in the colonial center of Mexico City (Suter, 2014), which can be explained by site effects. By comparison, it is not unlikely that the damage area of a repeat of the 1567 Ameca earthquake would include the Guadalajara metropolitan area (Fig. 3), given the large seismic vulnerability of its construction stock (Chávez, 1995, 2000).

By another comparison, the 11 February 1875 San Cristóbal de la Barranca, Jalisco, crustal earthquake (source: ~45 km north-northwest of Guadalajara, Fig. 3), which was devastating in its epicentral region (macroseismic intensity of degrees IX–X), caused moderate damage in Guadalajara (Bárcena, 1875; Iglesias et al., 1877).

Conclusions

1. The 1567 Ameca, Jalisco, earthquake is the strongest known historical crustal earthquake in the Trans-Mexican volcanic belt. The location and parameters of the surface rupture of this earthquake are documented in the Relación de Ameca of 1579, which is likely to be the earliest concise historical record of an earthquake surface rupture in the Americas. According to the Relación de Ameca, the surface rupture passes at the base of the Sierra de Ameca and has a length of 54–59 km (13–14 leguas) and a scarp height of 1.67–3.34 m (1–2 estados).
2. Based on independent historical sources, such as a 1568 letter by the Bishop of Guadalajara to the Spanish crown, the 1579 Relación de Ameca, and the 1653 chronicle by Antonio Tello, the Ameca earthquake must have occurred in late 1567 or early 1568, most likely 30 December 1567 in the Julian calendar.
3. From scaling relations, the moment magnitude of the 1567 Ameca earthquake can be estimated as 7.2 ± 0.3 based on the surface rupture length, 7.1 ± 0.3 based on the average slip, and 7.0 ± 0.4 based on the maximum slip. The magnitude resulting from the rupture length-versus-magnitude scaling relation, Mw 7.2 ± 0.3, is considered to be the most reliable estimate, because in a segmented normal fault rupture, the average and maximum displacements depend on the size of the largest segment rather than the size of the entire rupture.
4. From the writings by Antonio Tello, it can be inferred that no other earthquake of a comparable size occurred in the Ameca–Zacoalco region between 1567 and 1653, when he finished his chronicle. This supports the hypothesis that the surface rupture observed by Antonio de Ciudad Real in 1587 near Zacoalco, as well as the earthquake-related morphological features in that region mentioned by Juan de Torquemada in his 1615 chronicle, formed in the 1567 Ameca earthquake.
5. The surface rupture described in the Relación de Ameca is likely to have originated on the Ameca fault, whereas the long and pronounced earthquake surface rupture observed in 1587 by Antonio de Ciudad Real near Zacoalco, along the slope of a high mountain range, is likely to have originated on the San Marcos fault.
6. The rupture length indicated in the Relación de Ameca is compatible with the mapped length of the segmented Ameca–San Marcos normal fault system. An A.D. 1567 rupture of the entire Ameca–San Marcos fault system is also supported by the damage field of this earthquake. However, the faults of the Ameca–San Marcos fault system are not the only ones with known Pleistocene tectonic activity in the epicentral region of this earthquake; fault scarps displacing colluvium have been reported from the Sayula half-graben (Allan, 1986), and recent crustal earthquakes have also originated in the Chapala and Citala grabens (Fig. 1, Table 1). The hypothesis of an A.D. 1567 rupture of the Ameca–San Marcos fault system will have to be further corroborated by paleoseismic work, such as trenching of the fault segments.
7. A repeat of the 1567 Ameca or the 1875 San Cristóbal de la Barranca earthquake (crustal sources at a distance of 45–70 km, epicentral intensity of degrees IX–X) is likely to cause moderate damage in the Guadalajara metropolitan region.

Data and Resources

All data necessary to understand, evaluate, replicate, and build upon the reported research are contained within the article and in the electronic supplement. For the recent seismic activity in the epicentral region of the 1567 Ameca earthquake, I consulted the online catalog of the National Earthquake Information Center (NEIC) at http://earthquake.usgs.gov/earthquakes/search/ (last accessed January 2015). The 12-degree European Macroseismic Scale 1998 (EMS-98) used
for the macroseismic intensity assessments can be downloaded from http://media.gfz-potsdam.de/gfz/sec26/resources/documents/PDF/EMS-98_Original_english.pdf (last accessed May 2014). The Landsat orthorectified pan-sharpened ETM+ imagery used to trace the faults marked in Figure 1 was obtained from the U.S. Geological Survey. The digital elevation model underlying Figures 1 (inset), 2, and 3 is from the Global Multi-Resolution Topography (GMRT) compilation (Ryan et al., 2009; www.geomapapp.org, last accessed September 2014). The partial facsimile of the A.D. 1568 letter by Fray Pedro de Ayala to the Spanish crown (Fig. S1) was obtained from the Archivo General de Indias in Seville, Spain, and is reproduced with their permission. Similarly, the facsimile of the map accompanying the A.D. 1579 Relación de Ameca (Fig. S2) was obtained from the Benson Latin American Collection of the University of Texas at Austin and is reproduced with their permission.

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