1    **A 3000-year Record of Surface Rupturing Earthquakes at Gunalan;**
2    **Variable Fault Rupture Lengths on the 1939 Erzincan Earthquake**
3    **Rupture Segment of the North Anatolian Fault, Turkey**

4    Short title: Paleoseismology Gunalan Turkey

5    AUTHORS:


6    **Fraser, J. G.***[1], Hubert-Ferrari, A.[1], Verbeeck, K.[1], Garcia-Moreno, D.[1], Avsar, U.[1],
7    Maricq, N.[2], Coudijzer, A.[3], Vlamynck, N.[3] Vanneste, K.[1]


8    *Corresponding author is Dr. Jeff Fraser (jeph4e@gmail.com, Ph: 00447523567585, no fax)

9    1    Royal Observatory of Belgium
10       Seismology Section
11       Avenue Circulaire 3
12       1180 Brussels
13       Belgium

14   2    Université Libre de Bruxelles
15       Départment des Sciences de la Terre et de L'Environnement
16       Avenue F.D. Roosevelt 50
17       B-1050 Brussels
18       Belgium

19   3    University of Gent
20       Department of Geology and Soil Science
21       Krijgslaan 281
22       9000 Gent
23       Belgium

24

| Aurelia.Ferrari@ulg.ac.be | nathaliemaricq@gmail.com |
| koen.verbeeck@oma.be | alexander.coudijzer@gmail.com |
| davidgm08@gmail.com | neel_le@hotmail.com |
| avsarulas@yahoo.com | kris.vanneste@oma.be |

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29

## Abstract

The North Anatolian Fault is a ~1200 km long right-lateral strike-slip fault that forms the northern boundary of the Anatolian plate.  A damaging sequence of earthquakes ruptured almost the entire fault in the twentieth century.  This study adds to the growing number of paleoseismic investigations on the 350 km long 1939 Erzincan earthquake rupture segment, which is toward the eastern end of the North Anatolian Fault in Turkey.  Using three paleoseismic trenches located along about 2km of the principal fault strand, this study determines the timing of five earthquakes prior to the 1939 earthquake.  The first three earthquakes are correlated to historical earthquakes in A.D. 1668, 1254, 499 and two further events were identified at 881 – 673 B.C. and 1406 – 1291 B.C. (2σ age ranges).  By comparing the earthquake timing determined in this study to the results of other paleoseismic investigations on the 1939 rupture segment, it becomes clear that this historical rupture segment does not always rupture in unison.  This analysis indicates that the A.D. 499 earthquake was the last time the 1939 rupture segment ruptured in unison; although partial ruptures of the 1939 rupture segment occur more frequently and also produce large magnitude earthquakes ($> M_w$ 7).

## 1. Introduction

The Anatolian plate is moving toward the west, principally due to the collision of the Arabian plate into Eurasia (Fig. 1a, e.g. *Flerit et al*., 2004; *Sengor et al*., 2005). During the twentieth century a sequence of large magnitude earthquakes ruptured most of the NAF causing catastrophe to local populations and infrastructure (e.g. *Barka,* 1996). This sequence of large earthquakes began with the 1939 Erzincan earthquake and proceeded to migrate in a cascading sequence, first to the west and then to the east and west (*Stein et al*., 1997). The most recent large surface-rupturing earthquakes in the sequence occurred near the eastern end of the Marmara Sea in 1999 (i.e. *Barka et al*., 2002; *Gulen et al*., 2002). Stein *et al.* (1997) modeled the Coulomb failure stress changes caused by the earthquakes of the twentieth-century earthquake sequence on the NAF. They found that earthquake-induced stress changes raised the probability of fault rupture at the sites where subsequent earthquakes occured (*Stein et al.*,1997). Fault rupture causes a stress drop on the slipped fault and an increases in stress at nearby locations, hence bringing nearby faults closer to failure (*Stein et al.*,1997). Where nearby faults have already accumulated near-critical stress levels this can trigger an earthquake. This process suggests a mechanism for the cascading twentieth-century sequence of large earthquake on the NAF. However, it does require that the levels of stress along the sections of the fault that ruptured in the twentieth century sequence were all at a near-critical level. This raises the question; does the NAF always rupture in a cascading sequence like that observed in the twentieth century?

Turkey has a long historical record of earthquakes (e.g. *Ambraseys*, 1970; *Ambraseys and Finkel*, 1995; *Ambraseys and Jackson*, 1998; *Guidoboni and Comastri*, 2005; *Guidoboni et al*., 1994; *Nur and Cline*, 2000; *Sengor et al*., 2005). We have compiled a list of historical earthquakes that may have ruptured all or part of the 1939 Erzincan fault rupture segment from various sources (Table. 1). Historical earthquake records are typically temporally precise and accurate compared to the results of paleoseismic investigations which have relatively low precision in time because of the uncertainties inherent in constraining paleoearthquake ages. However, historical earthquake records are typically spatially imprecise (i.e. it is seldom specified which fault or fault segment(s)

3

77    ruptured to cause an earthquake) whereas paleoseismic investigations can yeild

78    earthquake records for a specific point on a particular fault strand.  A paleoseismic trench

79    investigation can constrain when a particular fault strand ruptured the ground surface; by

80    using radiocarbon dating in conjunction with Bayesian statistical modeling (*Biasi and*

81    *Weldon*, 1994; *Biasi et al*., 2002; *Hilley and Young*, 2008a, 2008b) we can obtain

82    relatively precise paleoearthquake timing that incorporates quantification of uncertainty.

83    By comparing paleoearthquake timing from paleoseismic trenching investigations at

84    multiple sites along adjoining fault segments, we can estimate the ground surface

85    rupturing length for large magnitude earthquakes (generally M >6.5), which is a proxy

86    for paleoearthquake magnitude (e.g. *Wells and Coppersmith,* 1994; *Anderson et al.,*

87    1999).  The completeness of earthquake records from both the historical and paleoseismic

88    investigations is uncertain because the absence of evidence is not evidence of absence

89    (i.e. neither means of investigation provides a definitive complete record of surface

90    rupturing earthquakes).  Therefore combining the historical and paleoseismic data

91    provides the best long-term spatiotemporal earthquake data.

92    To date, more than 50 paleoseismic investigations have been conducted along the NAF.

93    In the present study, we focus on the 1939 Erzincan Earthquake rupture segment.  There

94    have been many paleoseismic investigations along this segment, particularly in the area

95    immediately west of this study area, however these results have not been published (i.e.

96    conference abstracts: *Okumura et al*., 1994; *Zabci et al*., 2008) but investigations at

97    Resadiye (*Fraser,* 2009b), Yaylabeli (*Kozaci et al*., 2011) and Cukurcimen (*Hartleb et*

98    *al*., 2006) are publicly available.

99    This paper presents a paleoseismic study at Gunalan (N:40.024°, E:38.627°), which is

100   located on the 1939 Erzincan earthquake rupture segment (Fig. 1b).  The magnitude $M_w$

101   7.7 *(Anderson et al*., 1996) Erzincan earthquake caused widespread damage and loss of

102   life (*Barka*, 1996).  The paleoseismic investigation at Gunalan focuses on determining a

103   long record of the timing of paleoearthquakes.  The paleoearthquake chronology

104   determined in this study has been used by Fraser *et al.* (2010a), who summarize publicly

105   available paleoearthquake data on the NAF and compare the data from selected studies

106    along the entire NAF.  Gunalan is located between previous paleoseismic investigations

107    on the 1939 Erzincan earthquake rupture segment at Resadiye (*Fraser,* 2009b) to the west

108    and Yaylabeli (*Kozaci et al*., 2011) and Cukurcimen (*Hartleb et al*., 2006) to the east

109    (Fig. 1b).  In this paper the timing of paleoearthquakes determined at Gunalan is

110    compared with the timing of paleoearthquakes determined in the other paleoseismic

111    investigations on the 1939 Erzincan Earthquake fault rupture segment and with the

112    historical earthquake record (Table 1), to investigate the nature of fault rupture along this

113    section of the fault during the preceding cycles of seismicity.

## 114    2. Regional Tectonic Setting

115    Over geological time, as the Arabian plate moves northward relative to the Eurasian

116    plate, the wedge-shaped Anatolian plate is squeezed in an approximately north-south

117    direction causing it to translate toward the west (Fig.1a).  Back-arc extension in the

118    Aegean region, associated with subduction at the Hellenic arc, may provide a pulling

119    force on the Anatolian Plate (*Flerit et al*., 2004; *Pondard et al*., 2007).  The North

120    Anatolian Fault (NAF) formed in a similar tectonic regime as the present and initiated in

121    the east around 13 Ma (*Sengor et al*., 1985).  Utilizing weaknesses in the lithosphere

122    associated with pre-existing suture zones the proto-NAF propagated westwards, reaching

123    the Marmara Sea by about 5 Ma (*Armijo et al*., 1999; *Hubert-Ferrari et al*., 2002)

124    although this is still debated (e.g. *Sengor et al*., 2005).  Offset features such as suture

125    zones, prominent geomorphic features, the Niksar and Tasova-Erbaa pull-apart basins,

126    and other basins that developed during the formation of the NAF, suggest that it has

127    undergone a total of approximately 85 km of right-lateral offset (e.g. *Barka et al*., 2000;

128    *Hubert-Ferrari et al*., 2009; *Sengor et al*., 2005).

129    Offset Holocene geomorphic features along the NAF suggest a slip-rate of 18.5±3.5

130    mm/yr with a right-lateral strike-slip style (*Hubert-Ferrari et al*., 2002).  A GPS based

131    study of the Eastern Mediterranean region (*Reilinger et al*., 2006) indicates that the rate

132    of right-lateral strike-slip offset in the vicinity of the study area is approximately

133    27.7±0.2 mm/yr with a negligible extensional component.  Thus, the Holocene slip rate is

134  ~65% of the GPS-based slip rate. However, because the GPS data have only been
135  collected after the twentieth-century earthquake sequence it may also account for some
136  post-seismic relaxation.  Furthermore, because GPS monitoring stations are mostly
137  located a significant distance from the NAF, GPS rates also account for deformation on
138  subordinate plate boundary structures (faults and folds) and intra-plate deformation.  The
139  comparison of GPS-based and Holocene geomorphic deformation based slip rates
140  suggests that most of the tectonic deformation associated with the northern edge of the
141  Anatolian plate is accommodated by the NAF, with considerably less than 35% of the
142  tectonic deformation accommodated intra-plate.

143  The East Anatolian Fault (EAF) accommodates the left-lateral strike-slip deformation on
144  the Anatolian-Arabian plate boundary, which is the southeastern margin of the Anatolian
145  plate.  Other individual faults near the plate boundary and within the Anatolian plate are
146  likely to be significantly less active (perhaps accommodating an order of magnitude less
147  deformation).  For example, the Ovacik (OF) and Almus Faults (AlF) (Fig. 1b)
148  accommodate some of the Anatolian-Eurasian plate boundary deformation within the
149  Anatolian plate.  Some of the Eurasian-Anatolian plate boundary movement is
150  accommodated by faults to the north of the NAF; for example the North East Anatolian
151  Fault (NEAF) (Fig1b).  Notably, the geological history and activity of many of these
152  faults, particularly those located away from the principal plate boundary faults, are not
153  well constrained.  Therefore, it is only possible to speculate about the relationships
154  concerning crustal stress and strain between these faults and the NAF.

155  *2.1. Neotectonics near the study area*

156  Our study area is located near the western end of the Mihar-Tumekar fault segment
157  (*Barka,* 1996, Fig. 1) on the southern side of the Golova basin.  Kocyigit (1990)
158  described the Golova basin as an active basin along this segment of the NAF and
159  Kocyigit (1989) described the Susehri basin, which is located immediately west of the
160  Golova basin, as an active fault wedge basin. We speculate that the Golova and Susehri
161  basins were originally one pull-apart basin that was abandoned in favor of a new
162  optimally oriented principal deformation zone through the pull-apart basin.  This

163  abandonment of the proto Susehri-Golova pull-apart basin may be coincident with the

164  abandonment of the Tasova-Erbaa pull-apart basin ~125 km to the west (Fig. 1b)

165  documented by Barka *et al*. (2000). However, a detailed neotectonic study is required to

166  support this hypothesis. The presence of these neotectonic structures may have an

167  influence on fault rupture propagation on the Mihar-Tumekar and adjacent fault

168  segments.

169  ## 2.2. Fault Segmentation

170  Active fault traces are generally not continuous, and have discontinuities that appear as

171  steps or bends in the fault geometry. Depending on their scale, such discontinuities may

172  slow or stop fault rupture propagation (*Wesnousky*, 2006). On strike-slip faults, map-

173  view steps in the fault trace cause transpressional or transtensional stress and strain,

174  resulting in structures such as pop-up structures and pull-apart basin, respectively.

175  Wesnousky (2006) studied the importance of the size of discontinuities for fault rupture

176  propagation using historical earthquakes on strike-slip faults and found that

177  discontinuities with step-over distances of up to 4 km could be ruptured across in an

178  individual event, although sometimes smaller discontinuities could inhibit fault rupture

179  propagation.

180  'Fault rupture segments' are sections of a fault that have ruptured during one earthquake.

181  Thus, to define one, the extent of ground surface rupture must be mapped either soon

182  after an earthquake or by detailed observations of relict geological and/or

183  geomorphological features caused by ancient surface rupture (e.g. multiple paleoseismic

184  studies along a fault).

185  'Fault segments' are sections of a fault bounded by discontinuities which may stop or

186  slow fault rupture propagation and a defined based on judgment of fault geometry.

187  The 1939 Erzincan earthquake fault rupture segment was described by Barka (1996) and

188  references therein; it extended from the Erzincan pull-apart basin in the east to near the

189  village of Ezinepazari in the west (Fig. 1b) with a rupture length of ~350 km (*Anderson et*

190   *al.* 1999).  The western end of the rupture included the Ezinepazari fault which splays to

191   the southwest from the main NAF trace at the southern side of the Niksar pull-apart

192   basin.

193   Barka (1996) partitioned the 1939 Erzincan fault rupture segment in to five fault

194   segments as illustrated in Figure 1b and 1c.  He defined the segment boundaries by

195   discontinuities in map view geometry of the active fault trace.  Ezinpazari and Kelkit

196   Valley segments intersect at the south side of the Niksar pull-apart basin, the western and

197   eastern ends of the Ortakoy-Susehri segment are defined by significant bends in the fault

198   trace, and the Mihar-Tumekar to Erzincan fault segment boundary is defined as a 20°

199   restraining bend (see *Barka*, 1996 for further detail).

200   One aspect of this study is to investigate if the fault segments that ruptured in the 1939

201   Erzincan Earthquake always rupture in tandem by comparing the timing of

202   paleoearthquakes identified at Gunalan and three other locations along the fault rupture

203   segment.

## *3*. Tectonogeomorphology of the study area

205   In this study we use tectonic geomorphology to identify the principal fault across which

206   to undertake paleoseimic trenching studies to investigate the timing of paleoearthquakes.

207   No tectonogeomorphic measurements have been made in this study. The study area is

208   located on the southeast side of the Cobanli River, near the village of Gunalan

209   (N:40.024°, E:38.627°), on the southern side of the Golova basin (Fig. 1b).  There are

210   three clearly active fault strands in the study area (Fig. 2a), which we have labeled Faults

211   A – C, from north to south (Fig. 2).

212   Locally, Kocyigit (1990) documented a broad (~12km fault-normal) damage zone caused

213   by the 1939 earthquake with small vertical displacements on many faults, but the

214   majority of the slip (right-lateral) was accommodated by the principal deformation zone

215   fault (equivalent to Fault A in this study).  This broad damage zone may reflect

216   reactivation of structures associated with the Golova basin.

8

217     Kocyigit (1990) measured four right-laterally offset features near the study area on the

218     principal deformation zone fault (Fault A), although we were unable to identify these

219     features during field work. The three right-lateral offsets were accompanied by 0.3m to

220     3.5m of vertical displacement and comprised: (1) a field boundary offset by 5.5m ~18km

221     west of Gunalan, (2) a field boundary offset by 6.4m ~13km west of Gunalan, (3) a line

222     of Poplar trees offset by 5.7m ~5km west of Gunalan, and (4) an irrigation canal offset by

223     5.6m ~2.5km (Fig. 2a) west of Gunalan (*Kocyigit*, 1990, pg 165). Right-lateral offset (4)

224     was used by Barka (1996) and is shown in Figure 1c. Additionally, Kocyigit (1990, pg

225     165) noted three locations where "…the southern and northern blocks alternately

226     subsided and uplifted up to 3.5m" and these were located: (5) ~300m east of Gunalan

227     (Fig. 2a), (6) ~600m northeast of Gunalan (Fig. 2a), and (7) ~14km east of Gunalan.

228     Kocyigit (1990) described a splay of the principal deformation zone fault that traces

229     along the northern side of a prominent elongate linear ridge shown in the middle of

230     Figures 2c and 2e on which offset (6) was attributed to the 1939 earthquake. We

231     recognized a lateral spread in this area (Fig. 2c and f) but no evidence of faulting. Lateral

232     spreads are a type of shallow translational landslide that occur on gently sloping to flat

233     ground and are relatively abundant during earthquakes due to failure on zones of

234     liquefied soils (*Keefer*, 1984). Discussions with local residents indicate that this lateral

235     spread occurred, or was at least reactivated, during the 1939 Erzincan Earthquake. We

236     interpret that this offset was actually attributable to the lateral spread. Kocyigit (1990, pg

237     165) also notes that the southern strand (fault C) of the bifurcated Coblani fault (faults B

238     and C) were "reactivated by ground ruptures" during the 1939 earthquake (see label 8 in

239     Figure 2a). Based on the geomorphological expression of the three fault strands in the

240     study area we are inclined to agree with Kocyigit's (1990) interpretation of the relative

241     activity of fault strand A, B and C. The very clear tectonogeomorphic features associated

242     with fault A suggest that this is the principal deformation zone. Fault C has clear

243     geomorphic expression suggesting that this strand ruptured in the 1939 earthquake, while

244     Fault B has a less clear geomorphic expression suggesting that this strand did not rupture

245     in the 1939 earthquake.

246 The features of the study area are described from west to east (Fig. 2). The Cobanli River

247 flows towards the north until it crosses the NAF, downstream of which it bends and flows

248 towards the east (Fig. 2a). The geomorphology of the western portion of the study area is

249 an alluvial flood plain across which fault A is evidenced by a subtle fault scarp (i.e. less

250 than ~0.2m) that steps down to the south. The ground is considerably wetter on the south

251 side of the fault, which corresponds to a recognizable change in vegetation color (Fig.

252 2b). Southeast of the alluvial plain the terrain is hilly, dominated by linear ridges that run

253 sub-parallel to the fault. We attribute these linear ridges to low-activity (relative to fault

254 A), possibly reactivated, fault strands. Local ephemeral streams, which generally flow

255 towards the north, have eroded gullies through the linear ridges at some locations. The

256 village of Gunalan is situated near the point where the trace of Fault A leaves the alluvial

257 plain to the west and passes into the hilly terrain (Fig. 2a) where it runs along the

258 southern side of an elongate linear ridge for approximately 3 km east of Gunalan.

259 Alluvial fan and wetland deposits fill a depression formed between the hills to the south

260 and the elongate linear ridge.

261 The elongate linear ridge is composed of Pliocene continental clastics of the Cobanli

262 Group that is part of the Upper Pontus Formation (*Barka*, 1992). There are three possible

263 scenarios that may have formed the elongate linear ridge feature (in order of preference):

264  (1) Strike-slip offset Pliocene deposits making this primarily a shutter ridge. For this

265   scenario there is no need to have a bounding fault on the northern side of the

266   ridge, river erosion alone can explain the concaved slope break along the

267   northern side of the elongate linear ridge. This is consistent with our

268   interpretation that the fault mapped by Kocyigit (1990) on the northern side of

269   the elongate linear ridge is not present.

270  (2) A pop-up-structure or pressure ridge. For such a feature to form, there would

271   need to be a fault on the northern side of the elongate linear ridge, for which we

272   did not recognise any geomorphological evidence.

273  (3) A significant dip-slip component of displacement, down on the south side of the

274   fault, may have caused the topographic step on the south side of the ridge. The

275         topographic step down to the north on the northern side of the ridge may have

276         been caused by river bank erosion. Thus the elongate ridge would be the

277         remains of an elevated area comprising the hanging-wall block, the northern part

278         having been eroded away by the Cobanli River.

279 While we cannot rule out any of these three scenarios, we think that scenario 1 is the

280 most probable as it is the simplest explanation. Regardless of how the elongate ridge

281 formed, it is clearly bounded by a fault on its southern side and the concave slope-break

282 at its base traps small alluvial fans from local northward draining ephemeral streams.

283 The fans have a typical conical geometry with apices at small valleys that drain the hills

284 to the south. Between the alluvial fans, where they abut the fault scarp, reed beds and

285 associated organic-rich wetland deposits have developed.

286 South of the elongate linear ridge faults B and C splay southward. Our interpretation of

287 the local geomorphology is that the depression between faults A and B (which the

288 alluvial fans are filling) reflects long-term incremental subsidence and the linear ridge

289 between faults B and C reflects long-term incremental uplift. Sediments are trapped as a

290 consequence of the linear ridge between faults B and C, and form a flat area on the south

291 side of fault C (Fig. 2d).

292 To the east of the junction of faults A and C, fault A has a relatively simple straight trace

293 across a terrace of the Cobanli River. The ground surface to the north of the fault is

294 slightly folded up, forming a subtle anticline (the eastward continuation of the linear

295 ridge) that traps fine-grained sediments on the south side of the fault. The vegetation is

296 darker on the south side of the fault. Near the eastern end of the field area (Fig. 2a), field

297 observations indicate that saline water ponds are forming a salina on the south side of the

298 fault and travertine is forming on the north side of the fault.

299 **4. Paleoseismic trenching**

300 To investigate the variability of fault rupture lengths along the 1939 Erzincan Earthquake

301 fault rupture segment by comparing the results of paleoseismic investigations we require

302   long records of earthquake timing that incorporate as many seismic cycles as possible.
303   In-light of this objective, this study employs a paleoseismic trenching strategy to attain
304   the longest possible record of earthquake timing rather than focusing on collecting other
305   paleoseismic parameters such as offset per event and slip rate.  In particular, this involves
306   undertaking trenches perpendicular to the fault and in locations with prolonged distinctive
307   and relatively continuous or frequent sedimentation that provide evidence for numerous
308   paleoearthquakes and can be safely exposed in a paleoseismic trench.  These trenching
309   location attributes are traded-off against locations where piercing points might be
310   encountered that could yield rates of horizontal and vertical deformation.

311   We selected a number of potential paleoseismic trenching locations in the study area and
312   evaluated them by opening test-pits.  Apart from test-pits across fault C, where we
313   encountered homogenous strata, all of the other test-pits were across fault A and many
314   were abandoned because of shallow groundwater (0.1 – 1.0 m below the surface).  Four
315   test-pits were expanded into paleoseismic trenches and are labeled T1 to T4, from west to
316   east (Fig. 2a).  Trenches T1 and T2 are located on the alluvial plain between the Cobanli
317   River and Gunalan (Fig. 2b).  Trench T3, by far the largest trench, was situated at the
318   base of the fault-bounded southern side of the elongate linear ridge in the inter-fan fine-
319   grained deposits (Fig. 2c).  Trench T4 was about 2 m deep (to the top of the groundwater
320   table) and revealed evidence of two to four paleoearthquakes, which offset stratified,
321   thinly bedded (~5 cm) organic and inorganic deposits.  Unfortunately, Trench T4 was
322   abandoned because of voluminous (estimated 5 l/s) discharge of unidentified gasses
323   which may have been detrimental to health.  Therefore, trench T4 is not discussed further.

324   Paleoseismic trenches were logged in the field using a 1m x 1m (or smaller) string grid
325   on the trench walls and using a co-ordinate system (with the origin located below the
326   northern base of the trench).  Stratigraphic units were logged, described and given unit
327   symbols.  Photo mosaics of the trenches were made using photos taken during dispersed
328   lighting conditions.  Photos were corrected for spherical divergence and crudely for the
329   geometry of the trench walls, but this is an imperfect process and is the reason for some
330   discrepancies between the trench logs and the photo mosaics.  Further discrepancies may

331  also be due to small-scale erosion and cleaning of the trench walls between trench

332  logging and trench photography.  We describe the results of each paleoseismic trench in

333  the following sections.  We use the term 'event horizon' to describe a horizon that is

334  interpreted to correspond to a former ground surface (i.e. now buried) at the time of a

335  ground surface rupturing earthquake.

336  Paleoseismic trenches T1 and T2 revealed clear evidence of one and three

337  paleoearthquakes respectively.  The more conventional evidence of paleoearthquakes in

338  paleoseismic trenches T1 and T2 are used to validate the less conventional evidence of

339  six paleoearthquakes revealed in paleoseismic trench T3.  Because the number of

340  paleoearthquakes are relatively few in paleoseismic trenches T1 and T2, the age of the

341  event horizons are described along with the evidence of paleoearthquakes in Sections 4.1

342  and 4.2.  Because the record of paleoearthquakes in paleoseismic trench T3 is longer and

343  the timing of earthquakes is validated by the findings of paleoseismic trenches T1 and T2,

344  this paleoearthquake timing record is described in the section 5. Paleoearthquake Timing.

### *4.1. Paleoseismic Trench T1*

345

346  Paleoseismic trench T1 was excavated to the top of the groundwater table on the alluvial

347  plain of the Cobanli River (Fig. 2).  The trench revealed a faulted sequence of

348  interbedded clay (C$n$), silty clay and clayey silt (F$n$), sand (S$n$) and organic soils (Ps$n$)

349  overlying river gravel (Gx$n$).  Figure 3 presents the trench log, Figure 4 presents a photo

350  mosaic of part of the east wall of the trench, and stratigraphic unit descriptions are

351  presented in Table A.A-1 (Annex A).

352  Trench T1 revealed clear evidence for one surface-rupturing earthquake (T1E0) based on

353  clear and multiple fault terminations at or near the  base of sand unit S3.  Based on this

354  interpretation, fault scarps formed following the event remained near vertical while unit

355  S3 was deposited.  Cross bedding in sand unit S3 (above the event horizon) suggests that

356  it is an aeolian deposit, with the sand possibly blown from the bed of Cobanli River or

357  possibly reflecting an abundance of sand produced by liquefaction.  This would explain

358  why the fault scarp or free-face remained intact while unit S3 was deposited, because if

359   the sand deposits were from a fluvial source one would expect the free-face to have been

360   more eroded.

361   Our interpretation is that the one event recorded in this trench is the 1939 Erzincan

362   earthquake.  To confirm our interpretation we radiocarbon-dated a single sample (sample

363   37) from below the event horizon, which yielded a calibrated radiocarbon age of A.D.

364   1494 to present (2σ age range) (Table 2) (note. 'present' is used to reflect 1950 in

365   accordance with *Stuiver and Polach*, 1977).  Therefore, paleoseismic trench T1 provides

366   evidence for one surface-rupturing earthquake that occurred on this segment of the fault

367   after sometime between A.D. 1494 and the present.

368   *4.2. Paleoseismic Trench T2*

369   Paleoseismic trench T2 was excavated down to the top of the groundwater table on the

370   alluvial plain of the Cobanli River, closer to Gunalan than trench T1 (Fig. 2).  The trench

371   revealed a faulted sequence of organic rich soils (Ps$n$), sand (S$n$), silt and clay (F$n$),

372   gravel (G$n$), with fissure infills (I$n$) and liquefaction deposits (L$n$).  Figure 5 is a log of

373   both trench walls, Figure 6 is a photo mosaic overlain with the lines and labels of the

374   trench log, and stratigraphic unit descriptions are shown in Table A.A-2 (Annex A).

375   Trench T2 revealed evidence for three earthquakes, which we label from youngest to

376   oldest T2E0, T2E1 and T2E2.  The youngest event, T2E0, has subtle evidence and

377   therefore evidence for T2E1 is described first.  Event T2E1 is defined by fault

378   terminations that extend to the base of sand unit S6 on the east wall of the trench, (i.e.

379   Fig. 5, at horizontal distances 6.5 m and 8 m on the east wall).  Coincident with these

380   fault terminations is a downward tapering wedge-shaped deposit on the east wall at a

381   horizontal distance of 12 – 13 m (Fig. 5) which we interpret as a fissure-fill deposit (I3).

382   The fissure fill deposit (I3) is interpreted to have formed in a tension crack opened due to

383   the folding of paleosols Ps1a and Ps1b down toward the fault and possibly associated

384   with some horizontal deformation.  Evidence for the youngest event, T2E0, is restricted

385   to the fault zone on the west wall (at ~7 m on the horizontal axis) where there are two

386   fissure fill deposits (I1 and I2) that rest on a block of sand units (sand units S8-4) between

387    two fault strands.  The fault strand on the southern side of these deposits extends to the

388    top of S4 which is a higher stratigraphic level than the faults on the east wall.  Together,

389    these observations suggest that the top of unit S4 is an event horizon, which we label

390    event T2E0, and that the base of sand unit S6 is also an event horizon, which we label

391    event T2E1.    Unfortunatley, T2E0 is only evidenced on the west wall, which

392    considerably weakens the strength of our interpretation.  Event T2E2 is evidenced by

393    increasing deformation with depth.  North of the fault zone on the west wall, paleosol

394    Ps2a is folded down towards the fault, whereas the overlying paleosols are flatter lying.

395    Between the fault strands, at around a horizontal distance of 7 m on the east wall,

396    paleosol Ps2 is also folded down toward the fault and is overlain by fine grained

397    sediments and sand layers that thin to the north indicating onlap on to a folded surface.

398    Units between and including F1 and S9 exposed on the southern side of the northern most

399    fault strand on the east wall appear to have deposited onto a folded Ps2a (i.e. they thin to

400    the north).  Therefore, event horizon T2E2 can be constrained to between units Ps2a and

401    F1.  We interpret the top of Ps2 to be a fault-zone angular unconformity.  Therefore, we

402    consider the top of paleosol Ps2a to be the event horizon that corresponds to event T2E2.


403    Liquefaction deposits were recognized on both walls of the trench.  It is assumed that the

404    source layer(s) for the liquefaction deposits is below the strata exposed in this trench.  L2

405    is a horizontally bedded sand deposit with pebble horizons that rests on top of Ps2a.  L2

406    is only exposed for ~2m on the trench wall and becomes laterally finer and eventually

407    indiscernible from Ps1b.  Near the centre of the horizontal extent of L2, the deposit

408    contains more pebbles, less bedding, and below its center it connects to the upper part of

409    a feeder dike that cross-cuts Ps2a.  We interpret L2 as a surficial sand blow deposit,

410    which provides additional evidence that the top of Ps2a is an event horizon (T2E2).

411    Liquefaction deposit L1 is a sub-vertical dike that terminates upward in Ps1b and cross-

412    cuts L2, which is also faulted (at a horizontal distance of 6.5 m on the east wall).  There is

413    no evidence that this dike reached the surface, so it cannot be tied to a particular event

414    horizon; however, it clearly occurred subsequent to T2E2 because of cross-cutting

415    relations.  We attribute the liquefaction deposit L1 and the faults that offset liquefaction

416    deposit L2 to either of the younger events T2E0 or T2E1.

417      To constrain the age of the three event horizons in trench T2, seven samples were
418      radiocarbon-dated; details of the radiocarbon data and the units from which they were
419      sampled are presented in Table 2. Samples 40 and 47 are clearly reworked as they are
420      substantially older than the other sample ages, which suggests that paleosol Ps1b
421      comprises a significant component of reworked soils. Samples 41 and 42 (both from
422      paleosol PS1a) are the highest in the strata and provide the maximum age of both events
423      T2E0 and T2E1. Both samples 41 and 42 have similar $2\sigma$ calibrated age ranges of ~ A.D.
424      1660 to present, indicating that the two most recent earthquakes (T2E0 and T2E1)
425      occurred after sometime between A.D. ~1660 and the present (i.e. 1950). The minimum
426      age of event T2E2 is constrained by sample 50, and the maximum age by samples 43 and
427      49, which are very similar. Therefore, event T2E2 occurred sometime between A.D. 200
428      and A.D. 1640.

429      *4.3. Paleoseismic Trench 3*

430      Unlike paleoseismic trenches T1 and T2, paleoseismic trench T3 was excavated to about
431      5 m depth and did not encounter groundwater. The trench revealed an interfingering
432      sequence of stratigraphic units comprising of: gravel (G*n,* Rg*,* Rg*n, UG, or Ga,*), gravel
433      wedges (G*n*x), sand layers (S*n*), organic rich soils (Ps*n*) and fine-grained deposits (i.e.
434      various mixtures of silt and clay) (F*n*x). We interpret that these stratigraphic units were
435      deposited in a similar environment as found at the site today which is a small inter-
436      alluvial-fan wet-land at the base of a fault scarp. During the period of deposition the
437      trench location may have evolved subtly; in particular the wetness of the site due to
438      climate, and/or tectonic and anthropogenic influences on drainage paths. Trench 3 was
439      oriented perpendicular to the strike of the fault A (Fig. 2) at the base of a steep (~30°)
440      south-facing slope (the southern side of the elongate linear ridge) composed of Pliocene
441      clastic deposits (*Kocyigit* 1990) that we describe as a poorly sorted gravel with silt to
442      boulder-sized clasts. The strategy for trenching at this location was to find evidence of
443      multiple fault ruptures (reflecting paleoearthquakes) in an area with regular and relatively
444      continuous sedimentation. This location also had the advantage that different sediments
445      are present on either side of the fault, gravels to the north and inter-alluvial-fan wetland

446    sediments (organics and distal fan deposits) on the south side of the fault; this can assist

447    with the interpretation of the origin of strata in the fault zone.


448    Figure 7 is a log of Trench T3, Figure 8 is a photo mosaic overlain by the lines and

449    annotation from the trench log, and Table A.A-3 (Annex A) provides the stratigraphic

450    unit descriptions.  The trench walls were benched with upper and lower walls separated

451    by an ~1 m wide bench (Fig. 7).  The distance between the bases of the lower walls was

452    ~3 m.


453    *Fine-grained deposits*


454    Fine-grained deposits are composed of silt and clay and are interpreted to be distal

455    alluvial fan deposits.  We interpret that these deposits were laid down relatively slowly by

456    deposition of suspended load in flood waters sources from the low hills to the south of the

457    trench site.  This interpretation is consistent with the northward tapering geometry of

458    these units where they interfinger with gravel wedges.  The fine-grained soils may have

459    included organic rich layers but the decomposition of the organic component of such soils

460    has rendered them indistinguishable from the fine-grained deposits below approximately

461    1m below the ground surface.  Organic rich soils in the top one meter of the trench are

462    interpreted to be paleosols formed at the present ground surface (i.e. 'Topsoil' Fig. 7) or

463    at former, now buried, ground surfaces (i.e. 'Ps1' and 'Ps2' Fig. 7).


464    *Sand Deposits*


465    Distinctly continuous and recognizable (in the field) thin beds and laminae of sand (1 to

466    300mm thick) were logged on both walls of the trench and provide very useful marker

467    horizons in the strata.  The sand layers are interbedded with the fine-grained and organic

468    rich strata in the south of the trench and also interfinger with gravel wedges towards the

469    northern end of the trench.  Five sand layers were recognized on the west wall of the

470    trench (S1 – S5), which correlate to sand layers on the east wall with the exceptions of

471    the absence of sand layer S3 and the additional deeper sand layer S6 on the east wall.

472    The origin of the sand layers remains uncertain.  They may have been deposited by flood

473  waters from the alluvial fans, by aeolian processes or perhaps they are associated with

474  liquefaction on the less distal parts of the alluvial fan. It is unlikely that all of the sand

475  layers are caused by liquefaction which we establish below because most of the sand

476  layers do not correspond with other evidence for paleoearthquakes.


477  The sand layers illustrate a clear increase in dip, down to the south, with depth.

478  Regardless of the process of deposition that formed the sand layers, if they had been

479  deposited on a slope with the angle near the base of the trench we would expect to see an

480  increased thickness away from the fault. Therefore, this dip must have formed after

481  burial as a consequence of tectonic deformation. The sand units are steeper near the fault,

482  but south of a horizontal distance of ~10 m the sand layers S1 and S2 are horizontal,

483  whereas S4, S5, and S6 dip at 4° to 7°. Unfortunatley, there are no horizons that we can

484  justifiably measure the angle of between S2 and S4, and therefore we can not use the

485  change in dip to identify event horizons. Nonetheless, the increasing dip of bedding with

486  depth indicates that significant syndepositional tectonic deformation has been occurring

487  while this sedimentary sequence has been deposited. It also indicates that there is a down

488  to the south displacement of the fault and this indicates that the gensis of the elongate

489  ridge described in Section 5 does include some recognizable component of dip-slip

490  displacement over time.


491  *Gravel Deposits*


492  Numerous gravel units have been described in this trench in accordance with their

493  properties and the interpretation of their origin. Stratigraphic descriptions are provided in

494  Table A.A-3 (Annex A). The gravel units have been partitioned into five groups as

495  follows:

496      1. River gravels (Rg and Rg*n*)

497          River gravels are interpreted to be much older than the other gravel units exposed

498          in the trench due to their intense deformation. We correlate this unit to Pliocene

499          continental clastics (Cobanli Group) which form the scarp to the north of the

500        trench (Koccyigit, 1990 pg.157).  This unit may be equivalent to the structureless
501        gravel (Ga).

502      2.  Undifferentiated gravels (UG)
503        This symbol is used for areas where no structure is recognizable due to
504        bioturbation but the material is interpreted to be equivalent to the 'distinctive
505        gravel units (Gn)' and perhaps 'gravel wedges (W$n$ and W$n$x)'.

506      3.  Distinctive gravel units (G$n$)
507        Particular distinctive gravel colluviums deposits sourced from the slope to the
508        north of the fault.  Many of these units are probably equivalent to the 'gravel
509        wedges (W$n$ and W$n$x)' but due to the extensive faulting, which probably includes
510        significant (but unquantified) lateral displacement, and lateral variability in unit
511        thickness and composition, these are seldom correlated across the fault.  Many of
512        the units represent undifferentiated combinations of differentiated units (e.g. unit
513        G2 is undifferentiated units G1 and G3). Gravel unit G13 is interpreted as a
514        fissure-infill based on its structure.

515      4.  Structureless gravel (Ga)
516        This gravel has no coherent internal structure.  It is possible that this unit is a very
517        large 'gravel wedges (W$n$ and W$n$x)' unit; however it is more likely that this is
518        equivalent to the 'River gravels (Rg and Rg$n$)'.

519      5.  Gravel wedges (W$n$ and W$n$x)
520        Gravel wedges are wedge shaped stratigraphic units that interfinger with the fine-
521        grained, organic rich and sand deposits to the south.  These wedges are composed
522        of a range of materials but mostly reworked 'river gravels (Rg and Rg$n$)' and are
523        interpreted to be colluvial wedges.  Each gravel wedge is given a sub number ($n$)
524        which are correlated to the equivalent unit on the opposite wall, where the
525        materials are different a further sub-number (x) is used to provide seperat
526        stratigraphic unit descriptions.

527     *Tectonostratigraphy*

528 Two tectonostratigraphic features are used to identify the location of event horizons; fault
529 terminations and colluvial wedges. Because of the difficulty of distinguishing the extent
530 of faults in gravel deposits (along with evidence of bioturbation) we have a low level of
531 confidence for the stratigraphic location of fault terminations in this trench. We have
532 only logged the location of faults where we were confident of their presence. In response
533 to this low level of confidence fault terminations are only used as corroborating evidence
534 for event horizons and we rely more heavily on colluvial wedges.

535 A colluvial wedge is a deposit formed on the downthrown side of a fault by collapse of a
536 fault scarp (free face) during or soon (i.e. years to tens of years) after an earthquake. The
537 base of a colluvial wedge can be interpreted an earthquake event horizon. We interpret
538 many of the 'gravel wedges (W$n$ and W$n$x)' to be colluvial wedges linked to ground
539 rupturing earthquakes. Arguably, these colluvial wedges could be formed by localized
540 failures of the steep slope to the north of the trench caused by non-seismic processes such
541 as extreme rainfall events. Because the south-facing steep slope comprises a loose gravel
542 deposit that has very little cohesion and negligible tensile strength, localized slope
543 failures are likely to be small (i.e. $<2$ m$^3$) and therefore their associated deposits at the
544 base of the slope would not be laterally continuous. Colluvial wedges caused by surface
545 rupturing earthquakes are expected to be more laterally continuous.

546 Colluvial wedges could be formed by two processes related to fault rupture, fault scarp
547 retrogression (scarp collapse and subsequent erosion up the slope) and widespread slope
548 failures caused by seismic shaking (ground acceleration). Both of these processes could
549 mobilize a significant volume of gravel from the steep slope. We suspect that widespread
550 slope failure as a consequence of high ground accelerations are the cause of the gravel
551 wedges, because we do not see significant evidence of vertical displacement in the fault
552 zone (although this is not quantifiable in a single trench across a strike-slip fault). A
553 similar approach has been used to identify paleoearthquakes at two other locations on the
554 North Anatolian Fault (*Fraser et al.* 2009a & 2010b). To distinguish localized slope
555 failure deposits from colluvial wedges we considered opening two trenches on this
556 section of the scarp so that lateral continuity of gravel wedges could be assessed.

557 However, groundwater was encountered at less than 1 m depth in nearby test-pits so
558 trench T3 was made as wide as practical, with the upper walls ~5 m apart and lower walls
559 ~3 m apart.  South of the fault zone above gravel (Ga) we recognize seven distinct gravel
560 wedges, all of which are present on both walls of the trench.  We interpret that gravel
561 wedge W1 is a consequence of constructing a road along the slope immediately north of
562 the trench (Fig. 2e).  The remaining six gravel wedges are interpreted to be seismogenic
563 colluvial wedges.

564 The amount of horizontal offset cannot be constrained in this trench.  The amount of
565 vertical offset is not discussed as it cannot be used as evidence for displacement rates
566 because of the unknown horizontal displacement and the potential range of orientations
567 of any particular stratum.

568 The evidence for six paleoearthquake events which we label T3E0 – T3E5 youngest to
569 oldest respectively are described below.  The event horizons are shown and labeled in
570 Figures 6 and 7 and stratigraphic unit descriptions are provided in Table A.A-3 (Annex
571 A).

572 Paleoearthquake T3EO
573 Evidence for this event is a small colluvial wedge (gravel wedge W2) which is
574 much more clearly evident on the west wall than the east wall where gravel
575 wedges W1 and W2 were not differentiated.  Corroborating evidence is provided
576 by two fault terminations at the base of gravel wedge W2 at a horizontal distance
577 of ~4m on the west wall.  Supporting evidence for an event horizon at this
578 stratigraphic position is an offset of the base of the preceeding event horizon
579 (T3E1) at a horizontal distance of approximately 5m on the west wall.

580 Paleoearthquake T3E1
581 This event corresponds to the base of the colluvial wedge W3.  A fault
582 termination at the base of of colluvial wedge W3 at a horizontal distance of
583 approximately 4.5 m on the west wall provides corroborating evidence for this
584 event horizon.  On the east wall of the trench there is a lack of distinctive strata

585    immediately south of the fault zone making interpretation difficult.   Because
586    gravel wedge W3 lies between sand S2 and gravel wedge W4a to the south of the
587    fault zone the event horizon is projected into the fault zone on the east wall along
588    the top of the distinctive unit W4a.  This shows an additional fault termination at a
589    horizontal distance of ~5.75 on the east wall.

590    Paleoearthquake T3E2
591    Gravel wedge W4 is composed of three distinct units (W4a, W4b and W4c) and
592    collectively this wedge is larger than the younger wedges.  On the west wall of the
593    trench this event horizon is corroborated by fault terminations at a horizontal
594    distance of 7m and if we assume that gravel unit G3 corresponds to gravel wedge
595    W4c there is a fault termination at a horizontal distance of ~2m that offsets the
596    event horizon.  Since gravel unit G2 is undifferentiated gravel units G1 and G3,
597    fault terminations at its base at horizontal distances of ~3.75m and 4.75m on the
598    east wall may also be considered as corroborating evidence for this event horizon.
599    The termination at a horizontal distance of ~4.75m may pass through the event
600    horizon by several cm, this may reflect a small amount of slip associated with a
601    subsequent non surface rupturing event, or a lack of evidence for faulting due to
602    bioturbation above the event horizon, or postseismic slip. The fault termination at
603    a horizontal distance of ~3.75m on the east wall offsets the event horizon which
604    suggests that the offset occurred post deposition of the gravel above the event
605    horizon at this location (i.e. by a subsequent event).   The apparent thrust
606    displacement is attributed to strike-slip displacement as the event horizon T3E3
607    below is not vertically offset.

608    Paleoearthquake T3E3
609    The gravel wedge W5 is interpreted to have formed as a result of this event and its
610    base is interpreted to be the event horizon T3E3.  Gravel wedge W3 is composed
611    of two distinguishable units on the east wall (W5a and W5b) while only the lower
612    unit (W5b) is present on the west wall.  The event horizon is also defined as the
613    contact between gravel units G7 and G9.   At some locations these are

22

| 614 | indistinguishable and are collectively labeled G8.  For example, G8 is present |
| 615 | between horizontal distances ~3.25m and ~5.25m on the west wall of the trench |
| 616 | and in this area we cannot identify the event horizon.  A fault terminates just |
| 617 | below the event horizon at a horizontal distance of ~6.25m on the east wall of the |
| 618 | trench, this may correspond to the event that formed gravel wedge W5 but it is not |
| 619 | definitive.  There is relatively little corroborating evidence for this event horizon. |

| 620 | Paleoearthquake T3E4 |
| 621 | This event horizon is defined as the base of gravel wedge W6 which has a similar |
| 622 | geometry on the trench wall to that of the gravel wedges up-sequence.  No fault |
| 623 | terminations are recognized at this event horizon.  The equivalent gravel units in |
| 624 | and north of the fault zone cannot be correlated to the gravel wedge W6.  This is |
| 625 | attributed to lateral offset which is probably quite significant if there has four |
| 626 | subsequent, predominantly strike-slip, surface-rupturing earthquakes on this |
| 627 | segment. |

| 628 | Paleoearthquake T3E5 |
| 629 | The evidence for this event is a colluvial wedge (gravel wedge W7) which is |
| 630 | notably smaller than many of the wedges in the up-sequence stratigraphy.  There |
| 631 | is also no corroborating tectonostratigrapic evidence for this event horizon, just |
| 632 | the formation of a colluvial wedge. |

| 633 | Further validation of the evidence for the event horizons can be found by comparison of |
| 634 | the ages with the events identified in paleoseismic trenches T1 and T2 and the results |
| 635 | from other paleoseismic studies undertaken on nearby sections of the North Anatolian |
| 636 | Fault. |

| 637 | **5. Paleoearthquake timing** |

| 638 | To constrain the age of the event horizons established using colluvial wedges in trench |
| 639 | T3, we radiocarbon-dated 16 charcoal samples and 14 bulk samples (Table A.B-1, Annex |
| 640 | B).  The bulk samples were processed to extract pollen, but at a late stage in the process |

641 we found that there would not be enough pollen to date.  Therefore, the dated materials

642 comprised 40-63 μm sized organics dominated by micro charcoal and pollen fragments

643 (see Annex B for a description of the processing procedure).  As is common when many

644 samples are dated in a sedimentary sequence, many of the sample ages are inconsistent

645 with their relative stratigraphic positions (e.g. *Hartleb et al.*, 2003; *Fraser et al.*, 2009a;

646 *Fraser et al.*, 2010b).  It is difficult to distinguish between reliable and unreliable sample

647 ages.  However, a parsimonious approach was taken, whereby the least samples were

648 excluded to establish a stratigraphically logical sequence of sample ages.  Eight samples

649 are interpreted as too old relative to adjacent sample ages.  This is attributed to reworking

650 of sample material from the southern face of the elongate linear ridge and alluvial fans

651 and their catchments.  Four of the samples are interpreted as too young relative to the

652 adjacent sample ages, which is attributed to bioturbation although the fine-grained

653 deposits may also be prone to desiccation cracking, which would provide conduits for

654 organic material to be washed into the subsurface (i.e. creating an anomalously young age

655 in the stratigraphic unit in which it is deposited).

656 Using the remaining 18 samples, we made an order-constrained Bayesian model

657 (electronic supplement 1) using the software OxCal (*Bronk Ramsey*, 2007) to derive

658 modeled probability density functions (PDFs) of the sample and earthquake ages (Table 2

659 and Fig. 9).  Where multiple samples from a stratigraphic unit are incorporated in the

660 Bayesian model, they are grouped into "phases" (relative order unspecified), and these

661 phases were grouped into a sequence along with the individual samples from stratigraphic

662 units (i.e. not in a 'phase') according to their stratigraphic order.  The order-constrained

663 Bayesian model has a model index of 91 (*Bronk Ramsey*, 2007), which exceeds the

664 recommended 60 for a conformable model.

665 The order-constrained Bayesian model was also used to determine the PDFs of the inter-

666 event time, the summed inter-event time, and the average recurrence interval (Table 3)

667 (i.e. using the same methodology as Fraser *et al*. 2010b and *Lienkaemper and Bronk*

668 *Ramey* 2009).  The inter-event time is the period between two earthquakes expressed as a

669 PDF that accounts for the uncertainty in the timing of the earthquakes.  The summed

670   inter-event time is the normalized sum of the inter-event times and provides a very good

671   description of the probable time between earthquakes, taking into account both the

672   natural variation in recurrence interval and the uncertainty associated with constraining

673   the age of earthquakes.  The average recurrence interval is simply the period between the

674   youngest (T3E0: 1939 Erzincan earthquake) and the oldest event (as a PDF) divided by

675   the number of inter-event times, in this case 5.

676   The Bayesian model for trench T3 provides by far the best earthquake record of the three

677   trenches, although the data are complimentary to the findings of T1 and T2.  Trench T1

678   informed us that one earthquake (T1E0) occurred after deposition of sample 37 (CRA:

679   A.D. 1494 – A.D. 1951 2$\sigma$), which is consistent with trenches T2 and T3.  Trench T2

680   informed us that two earthquakes happened after ~ A.D. 1660 using only the highest two

681   samples below two event horizons (T2E0 and T2E1).  This is consistent with trench T3

682   where we interpreted the ultimate event as the 1939 Erzincan earthquake (Table 2), and

683   the age of the penultimate event (T3E1) is constrained to between A.D. 1408 and A.D.

684   1804.  The information from trench T2 strongly suggests that the penultimate event

685   (T2E1) occurred between ~ A.D. 1660 and A.D. 1804.  The third event horizon identified

686   in trench T2 (T2E2) was constrained to sometime between A.D. 200 and A.D. 1640,

687   consistent with the event T3E2 (A.D. 1254 – A.D. 1391) from trench T3, but far less

688   precise.  The good correlation between the three trenches provides some significant

689   validation to the link between formation of gravel wedges in trench T3 and other types of

690   evidence of paleoearthquakes revealed in trenches T1 and T2.  Older paleoearthquakes

691   determined in trench T3 are summarized in Table 2.

692   Because event T3E0 corresponds to T2E0 and T1E0, and T3E1 corresponds to T2E1 and

693   so on, hereafter we label the events E0, E1, E2, et cetera.

694   **6. Spatiotemporal Fault Rupture Correlation**

695   This discussion focuses on comparing the earthquake record established in this study

696   (Table 2) to paleoearthquake chronologies from four other paleoseismic investigations on

697    the 1939 Erzincan earthquake rupture segment (*Hartleb et al*., 2006, Fraser, 2009b and

698    *Kozaci et al*., 2011) and with to the record historical earthquakes (Table 1).  Table 4

699    summarizes correlations which are presented graphically in Figure 10.

700    Gunalan is located near the western end of the Mihar-Tumekar fault segment (*Barka,*

701    1996, Fig. 1), Resadiye (*Fraser*, 2009b) is located on the Kelkit Valley fault segment

702    ~130 km west of Gunalan, and Yaylabeli (*Kozaci et al*., 2011) and Cukurcimen (*Hartleb*

703    *et al*., 2006) which are located near the eastern end of the Mihar-Tumekar fault segment

704    are 27 km and 31 km east of Gunalan, respectively.

705    To use paleoearthquake timing data to investigate if previous earthquakes have had the

706    same extent of fault rupture as the 1939 Erzincan Earthquake two assumptions are made:

707    1.  Where paleoearthquakes are dated to around the same time at multiple locations

708        on the fault rupture segment they reflect a single earthquake.  However, this

709        assumption may erroneously group surface rupturing earthquakes that occur

710        closely spaced in time (relative to the age constraint determined in paleoseismic

711        investigations).

712    2.  Where paleoearthquakes are not present in the stratigraphy at one location, but

713        they are at others, then only part of the fault rupture segment ruptured.  This

714        assumption may be erroneous where paleoseismic investigation provides an

715        incomplete paleoearthquake record; this is very difficult to prove or disprove.

716

717    All of the studies on the 1939 rupture segment recognize evidence of the 1939 Erzincan

718    earthquake (*Fraser*, 2009b; *Hartleb et al*., 2006; *Kozaci et al*., 2011) which is consistent

719    with the extent of the fault rupture segment described by Barka (1996).  In this study, the

720    1939 earthquake is interpreted to be E0 but due to the imprecision of radiocarbon dating

721    in the last few hundred years this remains an assumption.

722    In trench T3, event E1 was constrained to A.D. 1408 – .A.D 1804, which corresponds to

723    the timing of 10 possible historical earthquakes (Table 1).  However, Trench T2 indicates

724 that this event occurred after ~A.D. 1660, reducing the possible correlative events to
725 earthquakes in A.D. 1668, 1684, and 1754 (Table 1). This event is interpreted to
726 correlate to one of the three major earthquakes that were reported in A.D. 1668
727 (*Ambraseys and Finkel*, 1995; *Ambraseys and Jackson*, 1998; *Sengor et al.*, 2005). This
728 earthquake was also recognized at Resadiye (*Fraser*, 2009b), but not in the trenches to
729 the east of this study (*Hartleb et al.*, 2006; *Kozaci et al.*, 2011). This suggests that the
730 Mihar-Tumekar fault segment (Fig. 1c) identified by Barka (1996) does not always
731 rupture in unison (i.e. it may comprise of more than one fault segment). Although the
732 evidence of offset associated with the .A.D 1668 event at Gunalan may be interpreted as
733 spillover displacement from the Ortakoy-Susehri segment that terminates about 10 km
734 west of Gunalan (i.e. Gunalan is near a slip patch transition (*Sieh,* 1996)).

735 Event E2 was constrained to the period A.D. 1259 – A.D. 1391 using the data from
736 trench T3 (the results from trench T2 provide a poorer temporal constraint), which may
737 correlate to one of three historical earthquakes that occurred in A.D. 1254, 1287, and
738 1374 (Table 1). Notably, the A.D. 1254 earthquake occurred just outside the $2\sigma$ age
739 range for E2 established in this study. However, because the A.D. 1254 event was also
740 recognized at Yaylabeli (*Kozaci et al.*, 2011) and Cukurcimen (*Hartleb et al.*, 2006) and
741 was reported widely along the 1939 rupture segment in historical records (*Ambraseys and*
742 *Jackson*, 1998; *Guidoboni and Comastri*, 2005), we interpret that E2 corresponds to this
743 earthquake. The A.D. 1254 earthquake was not recognized at Resadiye (*Fraser*, 2009b),
744 which suggests that this earthquake ruptured an eastern portion of the 1939 Erzincan
745 earthquake rupture segment with its western termination located somewhere between
746 Resadiye and Gunalan.

747 Event E3 was constrained to A.D. 241 – A.D. 644 in trench T3, which correlates with
748 timing of three historical earthquake records: (1) vague reports of an earthquake in the
749 3rd, 5th and 7th centurys A.D. from Amasya, Niksar and Nicopolis *(Ambraseys*, 1970); (2)
750 an earthquake was reported in A.D. 499 in Niksar and Nicopolis (*Ambraseys and*
751 *Jackson*, 1998; *Guidoboni and Comastri*, 2005); (3) an earthquake that reportedly
752 destroyed Niksar in A.D. 343 (*Guidoboni et al.*, 2005). Historical earthquake (1) does

753    not necessarily provide evidence for a ground surface rupturing earthquake while

754    historical earthquake (3) is reported only near Niksar which may reflect an earthquake

755    with a rupture similar to the 1942 Niksar Earthquake (Fig.1b shows extent of this rupture)

756    which did not rupture the 1939 rupture segment.  The A.D. 499 earthquake was

757    recognized in all of the paleoseismic studies on the 1939 rupture segment.  We interpret

758    that Event E3 corresponds to the historical A.D. 499 earthquake.  This suggests that the

759    A.D. 499 earthquake was similar in extent to the 1939 earthquake, although further

760    paloesesimic data from the Erzinepazari fault segment is required to validate this

761    interpretation.

762    Notably, there was a long period of time between the A.D. 499 (E3) earthquake and the

763    subsequent earthquake (E2) in A.D. 1254 recognized at Gunalan.  Over that period no

764    earthquakes were recognized at Resadiye (*Fraser*, 2009b), whereas the two studies to the

765    east both recognized an earthquake in A.D. 1045 (*Hartleb et al*., 2006; *Kozaci et al*.,

766    2011) and another event was recognized at Yaylabeli at A.D. 710 – A.D. 850 (*Kozaci et*

767    *al*., 2011).   Again, this suggests that there is a fault rupture segmentation boundary

768    between Gunalan and Yaylabeli.  Alternatively, it is possible that these events were

769    spillover displacements from the Erzincan fault segment (Fig. 1c).

770    Event E4 was constrained to the period 881 B.C. – 673 B.C. which does not correlate to

771    any earthquakes in the historical record.  Event E4 corresponds to an earthquake

772    identified at Resadiye that was constrained to the period 908 B.C. – 702 B.C. (*Fraser,*

773    2009b), but the paleoseismic record from Yaylabeli (*Kozaci et al*., 2011) does not extend

774    beyond the A.D. 499 earthquake.  The Cukurcimen study identified an event at 1450 B.C.

775    – 800 B.C. which may correspond to this event, but the large age bracket overlaps more

776    with the timing of E5.

777    Between events E3 and E4 an event was identified both west of our trenching site at

778    Resadiye (*Fraser,* 2009b) and to the east at Cukurcimen (*Hartleb et al*., 2006) (Table 1).

779    The absence of this event in trench T3 suggests that either this paleoearthquake did

780    rupture the fault at Gunalan and no evidence was preserved in our trench, or that it

781 corresponds to two separate paleoearthquakes that occurred at around the same period on
782 each end of the 1939 rupture segment.

783 Event E5 (1406 B.C. – 1291 B.C.) is interpreted to correspond with the oldest event
784 identified at Cukurcimen (*Hartleb et al.*, 2006). Although the 2σ range of E5 does not
785 overlap with 1200 B.C., this event may correspond to an earthquake, or series of
786 earthquakes (like that of the 20$^{th}$ Century), that may have occurred around 1200 B.C.
787 (*Nur and Cline*, 2000). The occurrence, timing, and extent of damage associated with
788 this earthquake is relatively speculative and based on archaeological evidence. This
789 event was not identified at Resadiye (*Fraser*, 2009b), which suggests that the earthquake
790 fault rupture stopped somewhere between Gunalan and Resadiye. Notably, the
791 paleoseismic record at Resadiye identified two older earthquakes (Table 4)

792 Figure 9b presents the inter-event times (IET), which are summarized in Table 3. IET0-1
793 corresponds to the interval between events E0 and E1, IET1-2 to the interval between
794 event E1 and E2, et cetera. If our correlation of paleoearthquakes to historical earthquakes
795 are correct, then IET0-1 is 271 years, IET1-2 is 414 years, and IET2-3 is 755 years; the
796 older events were not matched to historical earthquakes. These correlative IETs fall
797 within the IET PDFs determined from our paleoseismic data. The summed inter-event
798 time (SIET), calculated using only paleoseismic data from Gunalan, has a broad 2σ range
799 of 109 – 1385 years, which is very similar to the 0 – 1375 years determined at Resadiye
800 (*Fraser*, 2009b). The summed inter-event time at Resadiye (*Fraser*, 2009b) was found to
801 be bimodal with modes at 100 – 400 years and 900 – 1200 years, which was speculatively
802 attributed to two typical sized earthquakes that rupture the Kelkit valley segment of the
803 NAF. At Gunalan there is a weaker bimodality. The longer SIET mode is due to two
804 long inter-event times between E2 and E3, and between E3 and E4. This suggests a
805 relatively variable period between large earthquakes. Fraser et al. 2010a use these data
806 along with order-constrained Bayesian models for paleoseismic investigations along the
807 entire North Anatolian Fault to investigate spatial temporal patterns of paleoearthquakes.

808 *6.1. Paleoearthquake Magnitude Estimation*

809    Assuming that the paleoseismic investigations identified a continuous (complete) record

810    of earthquakes locally, the fault segments that comprise the 1939 Erzincan earthquake

811    fault rupture segment do not always rupture in tandem.  By roughly estimating the length

812    of fault rupture associated with paleoearthquakes we estimate their magnitude.  Figure 10

813    graphically summarizes the length of rupture associated with paleoearthquakes described

814    in the previous section and summarized in Table 4.


815    Using the length of rupture of the paleoearthquakes based on paleoseismic investigations

816    and the fault segmentation proposed by Barka (1996), we estimate the length of rupture

817    for the paleoearthquakes correlated between investigation sites in Table 4.   Using an

818    empirical equation ($M_w$ = A + B log L) that relates length of rupture (L) and regression

819    coefficients (A – Y intercept and B – regression slope) to moment magnitude ($M_w$) (*Wells*

820    *and   Coppersmith*,  1994)   we   estimate   the   moment   magnitude   ($M_w$)   of   the

821    paleoearthquakes and rupture of the individual fault segments proposed by Barka (1996).

822    The  $1\sigma$  limits  of  the  regression  coefficients  (A=5.16±0.13($1\sigma$),  B=1.12±0.08($1\sigma$))

823    provided by *Wells and Coppersmith*, 1994 are used to estimate the maximum and

824    minimum moment magnitudes.  This estimate assumes that the fault segment boundaries

825    identified by Barka (1996) are valid in most cases.  The magnitudes estimated for the

826    possible fault rupture segment lengths associated with paleoearthquakes (summarized in

827    Table 8) all exceed $M_w$ 7.0, which suggests that shorter ruptures along the 1939 Erzincan

828    earthquake rupture segment also produce large magnitude earthquakes.


829    *6.2. Fault Rupture Cycles*


830    Figure 10 graphically summarizes the rupture lengths and our estimated magnitudes.  An

831    important observation is that we do not recognize a cyclical pattern of earthquakes.  The

832    number of paleoseismic studies along the 1939 fault rupture segment is not great enough

833    to make any definitive conclusions.   Further studies are particularly required on the

834    Ezinepazari, Ortakoy-Susehri and Erzincan fault segments.


835    Sieh (1996) describes fault segments (map-view) as 'patches' in terms of a three-

836    dimensional section of a fault plane.  He documents examples where "adjacent individual

837     patches, 10 km or more in length, failed singly during one event and in tandem during the

838     other" and found that "…large earthquakes commonly result from the failure of one or

839     more patches, each characterized by a slip function that is roughly invariant through

840     consecutive cycles" (*Sieh*, 1996 p. 3764) with the exception of transition zones between

841     slip patches, where slip may deviate from event to event.  With the data available from

842     the paleoseismic studies along the 1939 Erzincan Earthquake rupture segment we are not

843     able to determine if any of the sites are at the transition zones between slip patches.  It

844     would therefore be advantageous to understand the amount of slip during

845     paleoearthquakes along the 1939 rupture segment.


846     Fraser *et al.* (2010a) described the behavior of the eastern sections of the NAF as

847     bimodal, with two apparent typical periods between paleoearthquakes. The variable time

848     between earthquakes, the time-variable fault rupture length and hence the variable

849     earthquake magnitude could be due to the intermittent effect of contagion.  Fault-rupture

850     contagion is where the rupture of one fault or fault segment increases the likelihood of the

851     occurrence of rupture on an adjacent fault or fault segment (*Perkins*, 1987).  "Under

852     certain conditions, the [fault] system can behave as a two-stage process: one stage having

853     a high recurrence rate [i.e. frequent earthquakes] during the contagion processes and a

854     second stage having a long, quiescent inter-contagion time." (Perkins, 1987, p. 429).  In

855     the case of the 1939 fault rupture segment, contagion could be associated with adjacent

856     fault segments of the NAF or from other faults.  By investigating spatiotemporal patterns

857     of seismicity using paleoseismic data from southern California, Dolan *et al*. (2007) found

858     that seismicity on one fault system can suppress seismicity on another fault system that

859     accommodates the same plate boundary motion.  Such a relationship between the NAF

860     and for example, one or a combination of the EAF, NEAF, OF, AlF, (Fig.1a) or other

861     faults, may affect the spatiotemporal distribution of earthquakes on the eastern section of

862     the NAF (*Fraser et al.* 2010a).  This can also be considered in terms of stress transfer.

863     Stein et al. (1997) found that stress changes induced by fault rupture of adjacent fault

864     strands, or other faults, may increase the likelihood of rupture on a particular section of

865     the NAF.

866  Barka (1996) notes that "The 20 November 1939 Tercan earthquake, an M = 5.9 event

867  that occurred 5 weeks before the 1939 Erzincan earthquake on the NE-SW striking

868  Northeast Anatolian fault, is considered to be a preshock of the 1939 Erzincan

869  earthquake" (p. 1240). This suggests that there may be some degree of behavioral

870  coupling between these fault systems in terms of triggering, but does not provide

871  evidence of coupling in terms of long-term behavior. To address this further, studies on

872  adjacent fault systems such as the NEAF, Alf and OF are required to provide long records

873  of paleoearthquakes.

874  **7. Conclusions**

875  A paleoseismic investigation was undertaken on the 1939 Erzincan earthquake rupture

876  segment of the North Anatolian Fault (NAF) near the village of Gunalan between

877  preexisting investigations at Resadiye (*Fraser et al*., 2009b) to the west and Yaylabeli

878  (*Kozaci et al*., 2011) to the east. The investigation comprised three paleoseismic

879  trenches. Trenches T1 and T2 were excavated on the alluvial plain of the Cobanli River.

880  Trench T1 revealed clear evidence for one earthquake after ~ A.D. 1494 which is

881  interpreted to be the 1939 Erzincan earthquake. Trench T2 revealed evidence of two

882  earthquakes near the top of the trench that both occurred sometime after ~A.D. 1660, one

883  of which was interpreted to be the 1939 Erzincan earthquake. A third event in trench T2

884  was constrained to A.D. 200 − A.D. 1640. Trench T3 revealed a record of colluvial

885  wedges that interfinger with fine-grained inter-fan deposits. We interpreted a sequence of

886  six earthquake event horizons including the 1939 Erzincan earthquake. Using 18 of the

887  30 radiocarbon-dated samples, a Bayesian ordering-constrained model was used to

888  constrain the age of the six event horizons. The penultimate earthquake (E1) was

889  constrained to A.D. 1408 − A.D. 1804 in trench T3, while data from trench T2 suggest

890  this earthquake occurred after ~A.D. 1660. We correlate this event to the historical A.D.

891  1668 earthquake. The antepenultimate earthquake (E2) was constrained to A.D. 1259 −

892  A.D. 1391 and is correlated to the historical A.D. 1254 earthquake. The fourth

893  earthquake in the sequence (E3) was constrained to A.D. 241 − A.D. 644, which

894  correlates to the historical earthquake in A.D. 499. Event E4 occurred at 881 B.C. − 673

895  B.C. and cannot be matched to a historical earthquake.  Event E5, the oldest earthquake

896  recognized at Gunalan, occurred at 1406 B.C. − 1291 B.C., which may correlate to a

897  sequence of earthquakes that may have occurred around 1200 B.C.


898  By comparing the earthquake timing data from this study to the results of other

899  paleoseismic studies on the 1939 Erzincan earthquake rupture segment it appears that this

900  section of the NAF does not always rupture in unison.  The A.D. 1668 earthquake seems

901  to have ruptured a western portion of the 1939 rupture segment with the eastern rupture

902  termination being located between Gunalan and the paleoseismic investigation site at

903  Yaylabeli.  The A.D. 1254 earthquake seems to have ruptured an eastern portion of the

904  1939 rupture segment with the western termination of the rupture occurring between

905  Resadiye and Gunalan.  Earthquakes in A.D. 1045, and A.D. 710 to A.D. 1050 were

906  encountered in paleoseismic investigations to the east of Gunalan.  The A.D. 499

907  earthquake was recognized in all of the paleoseismic investigations along the 1939

908  earthquake rupture segment and therefore we tentatively suggest that this earthquake was

909  similar to the 1939 earthquake.  An earthquake between 250 B.C. and A.D. 100 was

910  encountered at Resadiye and Cukurcimen, to the west and east of Gunalan, respectively.

911  This may reflect one earthquake that was not evidenced at Gunalan, or it may reflect two

912  separate earthquakes that occurred within a period of several hundred years.  An

913  earthquake that occurred around 900 B.C. to 700 B.C. appears to have ruptured most if

914  not all of the 1939 Erzincan earthquake fault rupture segment, like the A.D. 499 event.

915  An earthquake around 1200 B.C. may have had a similar rupture pattern as the A.D. 1254

916  earthquake.


917  The pattern of earthquakes revealed by comparing paleoseismic investigation data along

918  the 1939 Erzincan earthquake rupture segment indicates that it does not behave the same

919  during every seismic cycle, which results in earthquakes of different but still large

920  magnitudes.  The time-variable fault rupture lengths are likely to be due to contagion

921  which may come from one or more sources.

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1085　**ANNEX A – Stratigraphic Unit Descriptions**

1086

| Symbol | Unit Descriptions |
|---|---|
| Topsoil | Brown sandy SILT with high organic content. |
| S1 | Grey SAND and silty SAND planar and cross bedded laminated in places. Contains some thin pebbly horizons particularly near the base. |
| S2 | Grey silty SAND finely laminated with cross bedding. |
| S3 | Undifferentiated S2 and S4. |
| S4 | Beige silty SAND, clayey at some points. |
| C1 | Beige silty CLAY. |
| Ps1 | Dark brown SILT. Buried A horizon – Paleosol. |
| C2 | Beige silty CLAY. |
| F1 | Brown clayey SILT. Lower boundary with F2 is gradational. |
| F2 | Grey gravely silty CLAY. Upper boundary with F1 is gradational. |
| Ps2 | Dark brown SILT. Buried A horizon – Paleosol. On the east wall this unit has a lens of unit3 around which it grades laterally into unit C4. |
| C3 | Light brown silty gravelly CLAY. |
| C4 | Brown CLAY. Not present on the west wall. Probably altered Ps2 due to interaction with the water table. |
| C5 | Light brown CLAY with occasional gravel clasts. Grades into blue grey CLAY to the south on the east wall – probably due to interaction with the water table. |
| Ps3 | Dark brown SILT. Buried A horizon – Paleosol. |
| C6 | Light brown CLAY with occasional gravel clasts, contains more gravel near the fault. Only present north of the fault zone on the east wall. |
| C7 | Light brown CLAY. Only present north of the fault zone on the east wall. |
| Gx1 | Beige clayey GRAVEL. |
| Gx2 | Grey GRAVEL with clay coating – no matrix. |
| Gx3 | Grey sandy GRAVEL with some imbrication. |
| Fz | Shear zone mixed materials with a fabric semi parallel to adjacent faut(s). |
| Cx | Light Brown CLAY – This generic label has been generated as we do not know which clay rich unit this correlates to. |

1087　**Table A.A-1.** Paleoseismic trench T1 trench log stratigraphic unit descriptions. Symbols
1088　are used on Figures 3 and 4.

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| Symbol | Unit Descriptions |
|--------|-------------------|
| Topsoil | Brown sandy SILT with high organic content. |
| S1 | Brownish grey, silty SAND |
| S2 | Pale brown silty fine SAND. In and north of the fault zone contains some gravel layers. |
| S3 | Undifferentiated S2 and S4 |
| S4 | Greyish brown silty fine SAND |
| S5 | Undifferentiated S2, S4, and S6 |
| S6 | Pale brown silty fine SAND |
| S7 | Greyish brown silty fine SAND |
| S8 | Pale yellowish brown, silty fine SAND. Near horizontal 13 contains some lenses of coarse sand. In and north of the fault zone contains some gravel layers. |
| I1 | Pale brown laminated SAND. Not present on the east wall. |
| I2 | Pale brown silty CLAY. Not present on the east wall. |
| I3 (g) | This unit is comprised of material similar to unit s8 in the upper half and a mixture of unit Ps1, Ps2 and S8 in the bottom half. 2 of the subunits in this infil, denoted with a "g" contain abundant gastropod fragments. Not present on the west wall. |
| G1 | Grey brown, silty sandy GRAVEL. In some places this unit is bedded with gravel rich beds in others it is well mixed. |
| Ps1a | Purple brown SILT. A buried A horizon – Paleosol. |
| G2 | Grey brown, silty sandy GRAVEL. Very localized and only present on the east wall. |
| Ps1b | Grayish brown silty SAND with some oxide nodules. A buried B horizon – Paleosol. On Both walls, in the fault zone and north of the fault zone the lower part of this unit has obvious liquefaction features and much of this unit may owe its origin to this source. It is unlikely that there was co-seismic sedimentation that was not associated to the earthquake. |
| Ps2a | Red brown gravelly sandy clayey SILT with some gravel.PS2# denotes 3 interesting features. The top area is disturbed and slightly darker. The middle area is rich in oxide nodules. The bottom area is silty sand. These 3 features seem to be related to bioturbation. |
| Ps2b | Brown silty sand GRAVEL. |
| S9 | Greenish Brown Silty SAND. |
| S10 | Brown silty fine SAND. |
| S11 | Grayish brown, clayey medium SAND. |
| S12 | Brown clayey silty fine SAND. |
| F1 | Brown silty CLAY. More greenish brown on the east wall. F1# denotes 3 lenses within unit F1. The northern lens is comprised of coarse SAND, and the middle and southern lens are fine sand. |
| F2 | Blue grey CLAY. |
| F3 | Light reddish brown Sand SILT. More light brown on the east wall. |
| G3 | Grey brown silty GRAVEL. Not present of the west wall. |
| L1 | Graying brown pebbly silty SAND. (liquefaction deposit) |
| L2 | Grayish brown silty pebbly SAND. (liquefaction deposit) |

1092  **Table A.A-2.** Paleoseismic trench T2 trench log stratigraphic unit descriptions. Symbols
1093  are used on Figures 5 and 6.
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| Symbol | Description |
|---|---|
| *South of the fault* | |
| Topsoil | Dark brown SILT with some pebbles – gravels. |
| W1 | Brown gravelly pebbly SILT grading upwards into sitly pebbly GRAVEL, grain sizes vary N-S within unit. |
| S1 | Orange brown fine SAND, thin and discontinuous on the east wall. |
| W2 | Dark brown silty GRAVEL, not recognized on the east wall. Becomes less gravelly away from the fault. |
| Ps1 | Dark grey SILT, columnar soil structure, Paleosol. |
| F1 | Dark red brown, silty CLAY, columnar soil structure, not recognized on the west wall. Buried C horizon. |
| S2 | Pale brown silty SAND with some laminations and a blocky soil structure. Becomes more silty and has a columnar structure near the fault. Upper limit is generally gradational on the west wall and sharp on the east wall. |
| Ps2 | Pale brown gravelly (mainly at base of unit) SILT. |
| W3 | Grey silty GRAVEL, becomes less gravelly towards the fault zone and becomes more red brown and less gravelly south of a horizontal distance of 9m. Upper contacts with unit Ps2 and lower contacts with unit F2 are gradational. On the east wall the contacts with overlying unit Ps2 and underlying F2 are gradational and subtle. On the west wall these units can only be clearly distinguished north of a horizontal distance of 10m, to the south there is only a subtle and vertically streaked color change – pale brown at the top and the bottom with a band of red brown (W3?). |
| | Pale brown SILT. |
| W4a | Brown sandy PEBBLES, not recognized on the west wall. |
| W4b | Brown silty PEBBLES, not recognized on the west wall. |
| W4c | Brown Cobbly SILT/ silty COBBLES with some sand. There is less coarse materials south of a horizontal distance of 9m. South of a horizontal distance of 10m on the east wall, the unit becomes red brown pebbly clayey SILT. South of a horizontal distance of 10m on the west wall and a horizontal distance of 12m on the east wall this unit is indistinguishable from the underlying unit F3a and is described as F3b. |
| F3a | Brown silty PEBBLES grading horizontally to SILT with some pebbles. |
| F3b | Brown clayey silty PEBBLES with some cobbles. |
| F3/4u | This unit is used to describe an area of strata where we could not recognize continuous units. Generally there is some colour variation between pale brown and red brown but it is vertically streaked in "flame like" structures which we attribute to dense plant roots probably associated with a phase of wet-land vegetation e.g. reeds. |
| W5a | Brown pebbly silty COBBLES, not recognized on the west wall. |
| W5b | Red brown silty GRAVEL. |
| F4a | Brown (pale brown grading upwards to red brown at the southern end of the trench) clayey SILT with some gravel, south of a horizontal distance of 9m this unit is vertically streaked with red brown. |
| F4b | Greenish grey (pale brown towards base at the southern end of the trench) silty CLAY. The upper contact of this unit with F4a and the lower contact of unit F4b, with unit F5 is vertically streaked. |
| S3 | Pale brown silty SAND. This unit is mostly very thin and is not present south of a horizontal distance of 9.5m this unit was not recognized on the east wall. |
| W6 | Brown sandy pebbly silty GRAVEL with some cobbles. Between the horizontal distances of 9m and 10m the percentage of coarse clasts decreases from the dominant fraction to nearly absent, therefore unit W6 grades horizontally into unit F5. |

| | |
|---|---|
| F5 | Grey brown SILT with some pebbles. |
| F6a | Pale brown silty CLAY. Grades to the south into unit F6c. Not recognized on the east wall. |
| F6b | Light pale brown silty CLAY with some sand. Grades to the south into unit F6c. Not recognized on the east wall. |
| F6c | Red brown near the top of the unit grading down to pale brown clayey SILT, abundant vertical color streaking. |
| S4 | Grey brown fine-medium SAND. |
| W7a | Grey Brown Sandy PEBBLES/Pebbly SAND. |
| W7b | Grey Brown Sandy PEBBLES/Pebbly SAND. |
| F7 | Red brown CLAY, grading down into pale brown SILT, grading down into pale brown sandy SILT with some cobbles distributed along the base of the unit. |
| S5 | Grey brown fine-medium SAND. |
| F8 | Brown and grey brown CLAY. |
| Ga/F8 | Gradational transition between units Ga and F8. |
| S6 | Grey brown fine SAND, this unit is seldom thicker than 5mm. Not exposed on the west wall. |
| F9 | Brown and grey brown CLAY. Not exposed on the west wall. |
| Ga/F9 | Gradational transition between units Ga and F9. Not exposed on the west wall. |
| Ga | Brown silty GRAVEL and gravelly SILT (varies chaotically) with increased cobble content along the top of this unit. |
| *North of the southernmost fault* | |
| UG | Undifferentiated gravel – Brown silty GRAVEL/ Gravelly SILT.  Structure, including package boundaries, destroyed by burrowing animals and to a lesser degree vegetation. Equivalent to units G1 – 13 which are generally hard to trace. |
| G1 | Grey silty GRAVEL. |
| G2 | Undifferentiated G1 and G3. |
| G3 | Grey brown gravely silty PEBBLES. |
| G4 | Grey brown PEBBLES clast supported (no matrix) with some cobbles in the southern half of the unit. |
| G5 | Undifferentiated G4 and G6. |
| G6 | Grey brown PEBBLES clast supported with some silt matrix. |
| G7 | Brown silty GRAVEL clast supported. |
| G8 | Undifferentiated G7 and G9. |
| G9 | Brown silty gravelly COBBLES clast suported |
| G10 | Grey brown silty pebbly GRAVEL |
| G11 | Brown silty GRAVEL |
| G12 | Grey brown (grey mottled brown in some places) silty sandy GRAVEL. Not present on the east wall. |
| G13 | Brown silty PEBBLES, horizontally imbricated. This is interpreted as an fissure-infill deposit. Not present on the east wall. |
| Rg1 | Illuviated river gravel (see the unit description for Rg). Grey brown (grey mottled brown in some places) silty sandy GRAVEL. |
| Rg | River Gravel, grey sandy GRAVEL, weakly defined bedding strongly deformed (generally tilting down to the South), many clasts have carbonate coatings on their bottom half, near faults clasts are aligned (near vertical) with their coatings also rotated.  We correlate this unit to ”Pliocene continental clastics (Cobanli group)” which form the scarp to the north of the trench (Koccyigit, 1990 pg.157). |

1097   **Table A.A-3.** Paleoseismic trench T3 trench log stratigraphic unit descriptions.  Symbols
1098   are used on Figures 7 and 8.

## ANNEX B – Detailed Radiocarbon Dating Information

**Bulk Sample Processing**

A 60 g sub-sample was selected from the bulk sample. The samples were split into two 30g samples and the following procedures were applied.  Samples were submerged in hydrochloric acid (40% HCl) for 24 hours to remove carbonates. Then the samples were placed in hydrofluoric acid (40% HF) for 12 hours and continuously agitated, and then they rested in stronger hydrofluoric acid (70% HF) for 7 days to remove silicates.  The samples were then treated with potassium hydroxide (10% KOH) for 15 minutes and with hot hydrochloric acid (10% HCl) for 5 minutes to remove humic acid as well as additional unwanted organic and inorganic residues. The samples were then sieved and the 10 – 63 micrometer fraction of the samples were treated with hot hydrochloric acid (10% HCl) for 5 minutes. They were then washed, dried, the samples were recombined (i.e. the two portions of the sample) and were submitted to the radiocarbon dating laboratory where no further chemical pretreatments were administered.

| Trench | Event Horizon | Sample # | Soil unit | Trench wall | Lab Number (Aeon:) | Material | Yield (%) | Mass (mg) (3 d.p.) | d13C (vpdp) (3d.p.) | FMC (4.d.p.) | FMC uncertainty | Unrounded CRA (yrsBP) (2.d.p) | ± | Rounded CRA (yrsBP) | ± | Calibrated age | Order constrained calibrated age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trench 1 | *T1E1* | | | | | | | | | | | | | | | | |
| | | 37 | C4 | E | 139 | C | 49.2 | 1.198 | -26.360 | 0.9671 | 0.0041 | 268.55 | 33.57 | 270 | 35 | A.D. 1494–1951 | not modelled |
| Trench 2 | *T2E0 and T2E1* | | | | | | | | | | | | | | | | |
| | | 42 | Ps1a | W | 215 | C | 51.8 | 1.184 | -27.579 | 0.9801 | 0.0041 | 161.70 | 33.73 | 160 | 35 | A.D. 1663–1953 | not modelled |
| | | 41 | Ps1a | W | 141 | C | 56.9 | 1.034 | -24.485 | 0.9790 | 0.0039 | 170.39 | 32.11 | 170 | 35 | A.D. 1657–1953 | not modelled |
| | | 40 | Ps1b | W | 140 | C | 28.6 | 1.289 | -27.896 | 0.0193 | 0.0003 | 31723.31 | 109.12 | 31700 | 150 | 29995–29559 B.C. | not modelled |
| | | 47 | Ps1b | E | 217 | C | 3.3 | 1.286 | -27.871 | 0.8434 | 0.0033 | 1367.94 | 31.44 | 1370 | 40 | A.D. 608–761 | not modelled |
| | | 50 | S9 | E | 218 | C | 59.6 | 1.304 | -27.205 | 0.9586 | 0.0040 | 339.23 | 33.50 | 340 | 35 | A.D. 1468–1641 | not modelled |
| | *T2E2* | | | | | | | | | | | | | | | | |
| | | 43 | Ps2 | W | 216 | C | 59.7 | 1.257 | -26.490 | 0.8044 | 0.0049 | 1748.66 | 49.02 | 1750 | 50 | A.D. 137–402 | not modelled |
| | | 49 | Ps3 | W | 142 | C | 44.3 | 1.099 | -24.395 | 0.8069 | 0.0033 | 1723.06 | 32.69 | 1720 | 40 | A.D. 242–399 | not modelled |
| Trench 3 | | 26 | W2 | W | 134 | C | 5.3 | 1.055 | -22.295 | 0.9158 | 0.0040 | 706.84 | 35.04 | 710 | 40 | A.D. 1227–1388 | reworked |
| | *T3E0* | | | | | | | | | | | | | | | | |
| | | 2 | F1 | E | 130 | C | 57.2 | 1.138 | -23.322 | 0.9930 | 0.0040 | 56.58 | 32.34 | 60 | 35 | A.D. 1693–modern | A.D. 1706–1926 |
| | | B51 | Ps2 | E | 266 | B | 26.6 | 1.109 | -26.466 | 0.9816 | 0.0047 | 149.38 | 38.42 | 150 | 40 | A.D. 1666–1953 | A.D. 1666–1888 |
| | | B53 | F2 | E | 262 | B | 36.5 | 1.102 | -24.209 | 0.9286 | 0.0036 | 595.31 | 31.13 | 600 | 35 | A.D. 1297–1411 | reworked |
| | *T3E1* | | | | | | | | | | | | | | | | |
| | | 27 | F3b | W | 136 | C | 18.2 | 1.140 | -24.099 | 0.9338 | 0.0037 | 549.92 | 31.39 | 550 | 35 | A.D. 1311–1434 | A.D. 1337–1440 |
| | | B54 | W4c | E | 263 | B | 25.0 | 1.319 | -24.525 | 0.9357 | 0.0038 | 534.20 | 32.96 | 530 | 35 | A.D. 1317–1440 | A.D. 1324–1428 |
| | | 6 | W4c | E | 132 | C | 50.6 | 1.056 | -22.888 | 0.9318 | 0.0036 | 567.37 | 31.36 | 570 | 35 | A.D. 1304–1425 | A.D. 1305–1413 |

| | Lab | | | Mat | Mass | Yield | d13C | FMC | FMC err | CRA | CRA err | CRA | err | Max | Min |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *T3E2* | | | | | | | | | | | | | | | |
| | B55 | F3a | E | 281 | B | 12.8 | 1.163 | -28.100 | 0.9069 | 0.0035 | 785.03 | 30.59 | 790 | 35 | A.D. 1190–1281 | A.D. 1189–1280 |
| | 5 | F3a | E | 131 | C | 28.7 | 0.648 | -25.900 | 0.9128 | 0.0035 | 733.25 | 31.06 | 730 | 35 | A.D. 1222–1296 | A.D. 1224–1291 |
| | B57 | F3a | E | 282 | B | 12.0 | 1.114 | -28.700 | 0.8842 | 0.0033 | 988.21 | 30.35 | 990 | 35 | A.D. 989–1154 | A.D. 989–1153 |
| | 28 | F3/4u | W | 227 | C | 3.2 | 1.272 | -26.176 | 0.6778 | 0.0025 | 3123.95 | 29.00 | 3120 | 30 | 1490–1314 B.C. | reworked |
| | B60 | W5b | E | 283 | B | 6.9 | 0.867 | -27.900 | 0.8391 | 0.0038 | 1409.51 | 35.84 | 1410 | 40 | A.D. 576–667 | A.D. 578–669 |
| *T3E3* | | | | | | | | | | | | | | | |
| | B61 | F4a | E | 284 | B | 11.6 | 1.032 | -29.300 | 0.8027 | 0.0039 | 1765.76 | 39.00 | 1770 | 40 | A.D. 136–381 | A.D. 133–379 |
| | B64 | F4b | E | 285 | B | 7.0 | 1.185 | -29.500 | 0.7458 | 0.0030 | 2356.06 | 32.05 | 2360 | 40 | 536–380 B.C. | reworked |
| | 25 | F4b | W | 226 | C | 2.3 | 0.808 | -26.841 | 0.6207 | 0.0026 | 3830.38 | 33.80 | 3830 | 40 | 2458–2150 B.C. | reworked |
| | 24 | F4b | W | 225 | C | 7.0 | 0.672 | -27.627 | 0.7662 | 0.0029 | 2139.63 | 30.27 | 2140 | 40 | 353–55 B.C. | 338–52 B.C. |
| | 23 | F5 | W | 224 | C | 10.0 | 0.699 | (-25) | 0.7653 | 0.0041 | 2148.84 | 43.23 | 2150 | 50 | 359–54 B.C. | 363–122 B.C. |
| | B68 | F5 | E | 287 | B | 11.3 | 0.984 | -29.500 | 0.7238 | 0.0026 | 2596.71 | 28.34 | 2600 | 30 | 815–672 B.C. | 811–568 B.C. |
| | 33 | W6 | W | 137 | C | 33.5 | 1.248 | -25.119 | 0.7892 | 0.0029 | 1901.40 | 29.09 | 1900 | 30 | A.D. 27–213 | too young |
| *T3E4* | | | | | | | | | | | | | | | |
| | 12 | F6c | E | 220 | C | 4.0 | 1.064 | -28.047 | 0.5882 | 0.0021 | 4262.80 | 27.99 | 4260 | 30 | 2919–2779 B.C. | reworked |
| | 16 | F6c | W | 221 | C | 23.1 | 1.351 | -27.085 | 0.7975 | 0.0035 | 1817.79 | 35.59 | 1820 | 40 | A.D. 86–323 | too young |
| | B70 | F6c | E | 264 | B | 26.6 | 1.330 | -24.450 | 0.7203 | 0.0028 | 2635.86 | 31.49 | 2640 | 40 | 890–774 B.C. | 897–789 B.C. |
| | 10 | F6c | E | 236 | C | 2.4 | 1.002 | -25.729 | 0.5935 | 0.0022 | 4190.86 | 29.37 | 4190 | 30 | 2889–2676 B.C. | reworked |
| | B71 | F6c | E | 261 | B | 17.9 | 1.115 | -24.186 | 0.6854 | 0.0023 | 3033.88 | 27.11 | 3030 | 30 | 1394–1213 B.C. | 1359–1134 B.C. |
| | 17 | F6c | W | 222 | C | 9.6 | 0.981 | -26.671 | 0.6870 | 0.0032 | 3015.41 | 37.18 | 3020 | 40 | 1390–1130 B.C. | 1347–1127 B.C. |
| | 34 | F6b | W | 138 | C | 22.7 | 1.154 | -22.9292 | 0.8120 | 0.0031 | 1672.71 | 30.98 | 1670 | 40 | A.D. 258–429 | too young |
| | B72 | S4 | E | 267 | B | 3.9 | 0.401 | (-25) | 0.6829 | 0.0029 | 3064.06 | 33.86 | 3060 | 40 | 1417–1220 B.C. | 1381–1266 B.C. |
| *T3E5* | | | | | | | | | | | | | | | |
| | B73 | F7 | E | 265 | B | 15.0 | 1.083 | -23.746 | 0.6640 | 0.0022 | 3289.49 | 26.95 | 3290 | 30 | 1628–1500 B.C. | reworked |
| | 9 | F8 | E | 133 | C | 48.3 | 0.628 | -31.200 | 0.8193 | 0.0039 | 1601.24 | 37.81 | 1600 | 40 | A.D. 385–553 | too young |
| | B81 | F9 | E | 286 | B | 37.7 | 0.887 | -29.200 | 0.6822 | 0.0023 | 3071.52 | 27.22 | 3070 | 30 | 1413–1268 B.C. | 1420–1321 B.C. |

**Table A.B-1.** Radiocarbon dating data from paleoseismic investigations at Gunalan. See text and figures for description of event horizons. 'Lab-number' is the unique identifier for each radiocarbon analysis performed by Aeon. In the 'Material' column 'C' stands for charcoal and 'B' stands for bulk sample. 'Yield' is the percentage of carbon in the subsample analyzed. 'Mass' is the mass of the carbon subjected to AMS measurement and does not include the portion used for stable isotope measurement. 'd13C' is the difference between the 13C/12C ratio of the sample and that of the VPDB standard, expressed in per mille, values in brackets are estimated. 'FMC' is the 14C activity ratio, which is corrected for isotopic fractionation and background activity. 'CRA' is the conventional radiocarbon age, normalized to -25 based on a 5568-year half-life. All ages are given at the maximum (Max) or minimum (Min) of the 2σ age range.

## Figure Captions

**Figure 1.  a.)** Map of the Anatolian plate region.  Heavy black arrows show the direction of plate motion based on GPS studies (relative to a fixed Eurasia), with the velocity in mm/yr shown in brackets (Reilinger et al., 2006). Red lines depict present plate boundary faults, and black lines are important faults.  DSF, Dead Sea fault; NAF, North Anatolian Fault; EAF, East Anatolian fault; NEAF, Northeast Anatolian fault; MCT, Main Caucasus thrust; AR, Alborz Range; CB, Caucasus Block; CF, Chalderan Fault; TF, Tabriz Fault; AsF, Ashgabat Fault; PSSF, Pembak-Sevan-Sunik Fault; and OF, Ovacik fault. (modified from *Fraser et al. 2010a*).  **b.)** Map of 20th century earthquake ruptures near Gunalan (location of map shown by rectangle labelled 'box b' in Fig. 1a). Paleoseismic trench locations are shown with stars (this study white, other studies black), and filled circles show selected major settlements.  Significant pull-apart basins are numbered: 1) Tasova-Erbaa pull-apart basin, 2) Niksar pull-apart basin and 3) Erzincan pull-apart basin.  Significant fault splays are labelled: EF, Ezinepazari fault; AlF, Almus fault; and OF, Ovacik fault.  **c.)** Fault segments and right-lateral displacements associated with the 1939 Erzincan earthquake (modified from *Barka*, 1996 see references therein). The irrigation canal offset by 5.6m ~2.5km west of Gunalan (Fig. 2a) (*Kocyigit*, 1990, pg 165) is included in Barka's (1996) plot and indicated with an arrow.

**Figure 2.  a.)** Fault map of the study area draped over a satellite image with key features highlighted.  **b. and c.)** Geomorphic maps of areas near paleoseismic trenches.  **d.)** A photo showing faults C and A,  **e.)** A photo showing faults A and B and the depression in between.  **f.)** A photo showing the lateral spread the structure of which is depicted in box c.  The location and orientation of the photos in Fig. 2 d, e, and f is shown in Fig2a.

**Figure 3.  a)** Trench log of paleosesimic trench T1.  The horizontal and vertical axes are labeled in meters.  **b)** Legend for box a.  Unit symbols correlate to stratigraphic descriptions that are presented in Table A.A-1 (Annex A).  See Figure 4 for a photo mosaic of a section of the east wall.

1147   **Figure 4.** Photo mosaic of a section of the east wall of paleoseismic trench T1. The

1148   horizontal and vertical axes are labeled in meters. Unit symbols correlate to stratigraphic

1149   descriptions that are presented in Table A.A-1 (Annex A). See Fig. 3 for legend.


1150   **Figure 5. a)** Trench log of paleoseismic trench T2. The horizontal and vertical axes are

1151   labeled in meters. **b)** Legend for box a. Unit symbols correlate to stratigraphic

1152   descriptions that are presented in Table A.A-2 (Annex A).


1153   **Figure 6.** Photo mosaic of paleoseismic trench T2 overlain by the lines and unit labels of

1154   the trench log for comparison with the trench log (Fig. 5). The horizontal and vertical

1155   axes are labeled in meters. Unit symbols correlate to stratigraphic descriptions that are

1156   presented in Table A.A-2 (Annex A). See Fig. 5 for legend.


1157   **Figure 7. a)** Trench log of paleoseismic trench T3. The horizontal and vertical axes are

1158   labeled in meters. Note that (1) a gap has been plotted between the upper and lower walls

1159   so that the whole logs can be seen, (2) the yellow outline of the sand layers lightly

1160   exaggerates the real thickness of these layers. **b)** Legend for box a. Unit symbols

1161   correlate to stratigraphic descriptions that are presented in Table A.A-3 (Annex A).


1162   **Figure 8.** Photo mosaic of paleoseismic trench T3 overlain by the lines and unit labels of

1163   the trench log for comparison with the trench log (Fig. 7). The horizontal and vertical

1164   axes are labeled in meters. Unit symbols correlate to stratigraphic descriptions that are

1165   presented in Table A.A-3 (Annex A). Note that a gap has been plotted between the upper

1166   and lower walls so that the whole logs can be seen. See Figure 7 for legend.


1167   **Figure 9. a)** Plot of the order-constrained Bayesian model (using OxCal software, Bronk

1168   Ramsey, 2007) constructed for trench T3, showing the calibrated sample age probability

1169   density functions (PDFs) (blue fill, no boundary), modeled sample age PDFs (no fill, red

1170   boundary), and earthquake age PDFs (black filled). Samples grouped into phases in the

1171   order-constrained Bayesian model (electronic supplement 1) are indicated with brackets.

1172   Samples were calibrated using the IntCal04 curve (*Reimer et al.*, 2004). T3E0 was

1173   entered into the model as a fixed date corresponding to the Erzincan rupture in A.D.

1174   1939. **b)** Plot of the PDFs of the inter-event times calculated using OxCal (*Bronk*

1175   *Ramsey*, 2007). PDFs labeled IET*n-m* correspond to individual inter-event times (i.e.

1176   IET0-1 is the inter-event time between event E0 and event E1), SIET is the summed

1177   inter-event time, and RIavg is the average recurrence interval. Black stars show the inter-

1178   event times inferred from the correlated historical earthquakes.


1179   **Figure 10.** Summary plot of along-strike paleoearthquake fault rupture segments

1180   estimated using the timing of earthquakes determined in the different paleoseismic

1181   investigations along the 1939 Erzincan earthquake fault rupture segment. Data for each

1182   of the sites come from: Resadiye, Fraser (2009b); Gunalan, this study; Yaylabeli, Kozaci

1183   et al. (2011); and Cukurcimen, *Hartleb et al.* (2006);


1184

1185

| Year | Ref. | X | Comment |
|---|---|---|---|
| A.D. 1919 | a | A | Reported ~50km north of Resadiye. |
| A.D. 1754 | b | B | Reported in Sivas. |
| A.D. 1684 | b | A | Reported from Amasaya – refers to Niksar. |
| A.D. 1668 | a,b,c | D | Reported widely in northern Turkey. Probably reflects more than one earthquake closely spaced in this year. |
| A.D. 1583 | a | D | Extensive destruction in Erzincan. |
| A.D. 1579 | b,c | B | Damage reported in Corum, Amasaya, and Erzincan Regions – may have been 2 separate events. |
| A.D. 1575 | b | A | Reported 5 November in Erzincan. Probably a localized earthquake. |
| A.D. 1543 | b | B/C | Reported 4 April Corum, Tokat, and Erzincan. |
| A.D. 1535 | b | A/B | Reported near Erzincan. |
| A.D. 1481/82 | d | B | Extensive destruction in Erzincan. |
| A.D. 1457 | d | B | Reported 23 April. Extensive destruction in Erzincan. |
| A.D. 1374 | d | B | Reported 8 December. The Erzincan city walls collapsed. |
| A.D. 1287 | d | B | Reported 16 May. Extensive destruction in Erzincan. |
| A.D. 1254 | a, d | E | Reported epicenter near Susehri, with damage also reported in Niksar and Erzincan. |
| A.D. 1236/37 | d | A | Possibly doublet of 1206/7 AD earthquake. Caused collapse of a church in Erzincan. |
| A.D. 1206/7 | d | A | Reported in Erzincan. |
| A.D. 1166 | d | B | A strong earthquake reported in Erzincan. Possibly causing ~18k deaths. |
| A.D. 1050 | a, d | A | Reported at Cankiri (~30km south of Ilgaz). |
| A.D. 1045 | a, d | B | Erzincan was destroyed along with many churches in the region. |
| A.D. 1043 | e | A/B | A rupture from Nicopolis (ancient city near modern Susehri) in a line to Erzerum is reported. |
| A.D. 1011 | a, d | A | Reported earthquake in Erzincan. There was also a major flood in this year – the damage may be compounded reflecting a smaller earthquake. |
| 3rd, 5th, 7th Centuries A.D. | e | ? | Vague reports of seismicity in Amasya, Niksar, and Nicopolis. Exact dates are not available. |
| A.D. 499 | a, d | E/D | Reported in Niksar and Nicopolis. |
| A.D. 343 | f | A/B | Almost total destruction of Niksar. The localized location of reports suggest this event may have been similar to the 1942 Earthquake on the northern side of the Niksar basin. |
| c.1200 B.C. | g | D? | A sequence of earthquakes along the NAF may be attributable to the destruction of a collection of major cities at the transition of the Bronze Age to the Iron Age. |

References:
a: (*Ambraseys and Jackson*, 1998)
b: (*Ambraseys and Finkel*, 1995)
c: (*Sengor et al.*, 2005)
d: (*Guidoboni and Comastri*, 2005)
e: (*Ambraseys*, 1970)
f: (*Guidoboni et al.*, 1994)'
g: (*Nur and Cline*, 2000)

X – this column denotes our interpreted likelihood of rupture of the 1939 rupture segment of the NAF:
    A: Probably did not rupture this segment
    B: Possibly ruptured part of the segment
    C: Possibly ruptured the whole segment
    D: Probably ruptured part of the segment
    E: Probably ruptured the whole segment

1186 **Table 1.** Summary of historical earthquakes in the region of the 1939 Erzincan
1187 earthquake rupture segment.
1188

| Sample # | Soil unit | Trench wall | CRA (years B.P.) | Calibrated Age years (A.D./B.C.) 2σ | |
|---|---|---|---|---|---|
| | | | | unmodeled | modeled |
| *Trench T1* | | | | | |
| T1E1: younger than A.D. 1494 | | | | | |
| 37 | C4 | E | 270 ± 35 | A.D. 1494 – A.D. 1951 | not modeled |
| *Trench T2* | | | | | |
| T2E0 and T2E1: younger than ~1660 A.D. | | | | | |
| 42 | Ps1a | W | 160 ± 35 | A.D. 1663 – A.D. 1953 | not modeled |
| 41 | Ps1a | W | 170 ± 35 | A.D. 1657 – A.D. 1953 | not modeled |
| 40 | Ps1b | W | 31700 ± 150 | 29995 B.C. – 29559 B.C. | reworked |
| 47 | Ps1b | E | 1370 ± 40 | A.D. 608 – A.D. 761 | reworked |
| 50 | S9 | E | 340 ± 35 | A.D. 1468 – A.D. 1641 | not modeled |
| T2E2: A.D. 200 - A.D. 1640 | | | | | |
| 43 | Ps2a | W | 1750 ± 50 | A.D. 137 – A.D. 402 | not modeled |
| 49 | Ps2b | W | 1720 ± 40 | A.D. 242 – A.D. 399 | not modeled |
| *Trench T3* | | | | | |
| 26 | W2 | W | 710 ± 40 | A.D. 1227 – A.D. 1388 | reworked |
| T3E0 - base of W2 - interpreted to be the 1939 earthquake | | | | | |
| 2 | F1 | E | 60 ± 35 | A.D. 1693 – modern | A.D. 1706 – A.D. 1926 |
| B51 | Ps2 | E | 150 ± 40 | A.D. 1666 – A.D. 1953 | A.D. 1666 – A.D. 1888 |
| B53 | F2 | E | 600 ± 35 | A.D. 1297 – A.D. 1411 | reworked |
| T3E1 - base of W3 | | | | | A.D. 1408 – A.D. 1804 |
| 27 | F3b | W | 550 ± 35 | A.D. 1311 – A.D. 1434 | A.D. 1337 – A.D. 1440 |
| B54 | W4c | E | 530 ± 35 | A.D. 1317 – A.D. 1440 | A.D. 1324 – A.D. 1428 |
| 6 | W4c | E | 570 ± 35 | A.D. 1304 – A.D. 1425 | A.D. 1305 – A.D. 1413 |
| T3E2 - base of W4 | | | | | A.D. 1259 – A.D. 1391 |
| B55 | F3a | E | 790 ± 35 | A.D. 1190 – A.D. 1281 | A.D. 1189 – A.D. 1280 |
| 5 | F3a | E | 730 ± 35 | A.D. 1222 – A.D. 1296 | A.D. 1224 – A.D. 1291 |
| B57 | F3a | E | 990 ± 35 | A.D. 989 – A.D. 1154 | A.D. 989 – A.D. 1153 |
| 28 | F3/4u | W | 3120 ± 30 | 1490 B.C. – 1314 B.C. | reworked |
| B60 | W5b | E | 1410 ± 40 | A.D. 576 – A.D. 667 | A.D. 578 – A.D. 669 |
| T3E3 - base of W5 | | | | | A.D. 241 – A.D. 644 |
| B61 | F4a | E | 1770 ± 40 | A.D. 136 – A.D. 381 | A.D. 133 – A.D. 379 |
| B64 | F4b | E | 2360 ± 40 | A.D. 536 – 380 B.C. | reworked |
| 25 | F4b | W | 3830 ± 40 | 2458 B.C. – 150 B.C. | reworked |
| 24 | F4b | W | 2140 ± 40 | 353 B.C. – 55 B.C. | 338 B.C. – 52 B.C. |
| 23 | F5 | W | 2150 ± 50 | 359 B.C. – 54 B.C. | 363 B.C. – 122 B.C. |
| B68 | F5 | E | 2600 ± 30 | 815 B.C. – 672 B.C. | 811 B.C. – 568 B.C. |
| 33 | W6 | W | 1900 ± 30 | A.D. 27 – A.D. 213 | too young |
| T3E4 - base of W6 | | | | | 881 B.C. – 673 B.C. |
| 12 | F6c | E | 4260 ± 30 | 2919 B.C. – 2779 B.C. | reworked |
| 16 | F6c | W | 1820 ± 40 | A.D. 86 – A.D. 323 | too young |
| B70 | F6c | E | 2640 ± 40 | 890 B.C. – 774 B.C. | 897 B.C. – 789 B.C. |
| 10 | F6c | E | 4190 ± 30 | 2889 B.C. – 2676 B.C. | reworked |
| B71 | F6c | E | 3030 ± 30 | 1394 B.C. – 1213 B.C. | 1359 B.C. – 1134 B.C. |
| 17 | F6c | W | 3020 ± 40 | 1390 B.C. – 1130 B.C. | 1347 B.C. – 1127 B.C. |
| 34 | F6b | W | 1670 ± 40 | A.D. 258 – A.D. 429 | too young |
| B72 | S4 | E | 3060 ± 40 | 1417 B.C. – 1220 B.C. | 1381 B.C. – 1266 B.C. |
| T3E5 - base of W7 | | | | | 1406 B.C. – 1291 B.C. |
| B73 | F7 | E | 3290 ± 30 | 1628 B.C. – 1500 B.C. | reworked |
| 9 | F8 | E | 1600 ± 40 | A.D. 385 – A.D. 553 | too young |
| B81 | F9 | E | 3070 ± 30 | 1413 B.C. – 1268 B.C. | 1420 B.C. – 1321 B.C. |

**Table 2.** Summary of sample radiocarbon ages from this study. CRA is Conventional Radiocarbon Age (*Stuiver and Polach,* 1977). A table with more extensive data is presented in Table A.B-1 (Annex B). Figure 9 is a graphical presentation of the order-constrained Bayesian model (electronic supplement 1) compiled using selected samples from trench T3.

1195

| Variable | 2σ Age Range (years) |
|----------|----------------------|
| IET0-1   | 135–530              |
| IET1-2   | 75–504               |
| IET2-3   | 654–1086             |
| IET3-4   | 993–1450             |
| IET4-5   | 460–701              |
| SIET     | 109–1385 (bimodal)   |
| RIavg    | 646–669              |

1196 **Table 3.** Duration between earthquakes derived from the OxCal model (see Fig. 9 and

1197 electronic supplement 1). Note: IET0-1 is the inter-event time between event 0 and event

1198 1. SIET is summed inter-event time, RIavg is the average recurrence interval.

1199

1200

| Resadiye (*Fraser,* 2009b) | Gunalan (this study) | Yaylabeli (*Kozaci et al.,* 2011) | Cukurcimen (*Hartleb et al.,* 2006) | Historical Earthquakes (See Table 4) | |
|---|---|---|---|---|---|
| Event 0 unconstrained | E0 unconstrained | E1 A.D. 1150–A.D. 1939 | Event A unconstrained | A.D. 1939 Erzincan earthquake | |
| Event 1 A.D. 1570–A.D. 1939 | E1 A.D. 1408–A.D. 1804 | — | — | A.D. 1668 ? | |
| — | E2 A.D. 1259–A.D. 1391 | E2 A.D. 1150–A.D. 1939 | Event B A.D. 980–A.D. 1420 | A.D. 1254 | |
| — | — | E3 A.D. 910– A.D. 1110 | Event C A.D. 930–A.D. 1070 | A.D. 1045 | |
| — | — | E4 A.D. 710–A.D. 850 | — | — | |
| Event 2 A.D. 262– A.D. 642 | E3 A.D. 241– A.D. 644 | E5 A.D. 320– A.D. 690 | Event D A.D. 360–A.D. 540 | A.D. 499 | |
| Event 3 258 B.C.– A.D. 206 | — | X | Event E 230 B.C.–A.D. 50 | — | |
| Event 4 908 B.C.–702 B.C. | E4 881 B.C.–673 B.C. | X | Possibly Event F 1450 B.C.–800 B.C. | — | |
| — | E5 1406 B.C.–1291 B.C. | X | Possibly Event F 1450 B.C.–800 B.C. | 1200 B.C. | |
| Event 5 2020 B.C.–1804 B.C. | X | X | X | — | |
| Event 6 2280 B.C.–2066 B.C. | X | X | X | — | |

— Earthquake not recognized
X Older than exposed earthquake record

1201 **Table 4.** Earthquake timing comparison with nearby paleoseismic studies on the North
1202 Anatolian Fault and correlated historical earthquakes (historical-earthquake records are
1203 summarized in Table 1), summarized graphically in Figure 10.  Note: '—' corresponds to
1204 'earthquake not recognised' and  'X' corresponds to 'older than exposed in earthquake
1205 record'.

1206

| Event | Event Number (in this study) | Segments ruptured [a] | Total length of rupture (km) | Magnitude estimate (Mw) [b] | |
|---|---|---|---|---|---|
| | | | | Maximum | Minimum |
| *Individual fault segments* | | | | | |
| schematic | - | A | 90 | 7.1 | 7.6 |
| schematic | - | B | 100 | 7.1 | 7.7 |
| schematic | - | C | 45 | 6.7 | 7.3 |
| schematic | - | D | 65 | 6.9 | 7.5 |
| schematic | - | E | 60 | 6.9 | 7.4 |
| *Scenarios* | | | | | |
| A.D. 1939 | E0 | A, B, C, D, E | 350 | 7.7 | 8.3 |
| A.D. 1668 | E1 | A, B, C, D, | 250 | 7.6 | 8.3 |
| A.D. 1254 | E2 | D, E | 170 | 7.2 | 7.8 |
| A.D. 1045 | Not observed | D (partial) , E | 100 | 7.1 | 7.7 |
| A.D. 499 | E3 | A, B, C, D, E | 360 | 7.7 | 8.4 |
| 250 B.C. - A.D. 100 | Not observed | unsure | | | |
| 900 B.C. - 700 B.C. | E4 | A, B, C, D, E | 360 | 7.7 | 8.4 |
| ~1200 B.C. | E5 | D, E (?) | 170 | 7.2 | 7.8 |

1208    **Table 5.** Earthquake magnitude estimates for a range of rupture lengths. Note[a] letters
1209    correspond to fault segments shown on Figure 1: A- Ezinepazari, B- Kelkit Valley, C-
1210    Ortakoy - Susehri, D- Mihar - Tumekar, E- Erzincan. Note[b], magnitude estimated
1211    using formula and regression coefficients from *Wells and Coppersmith et al.* (1994),
1212    see text for description.

**a)**

Eurasian Plate

Black Sea

Marmara Sea

NAF

Greater Caucasus

Lesser Caucasus

MCT

Eurasian Plate

Box b

NEAF

CB PSSF

Caspian Sea

[21]

Anatolian Plate

OF

CF

AsF

Aegean Sea

H H H

[13]

TF

Hellenic Trench

EAF

AR

Iranian Plate

Mediterranean Sea

Cyprus Arc

Bitlis-Zagros fold and thrust belt

[16]

Hellenic active margin

DSF

Sinai

Arabian Plate

African Plate

[15]

[5]

Red Sea

Arabian Gulf

**b)**

37°        Black Sea        38°        39°        40°

Samsun

Destek

Ordu

41°

| | NAF - Principal strand no historical surface rupture |
| | Significant splays with no historical surface rupture |
| | 1943-Tosya earthquake rupture (eastern end) |
| | 1942-Niksar-Erbaa earthquake rupture |
| | 1939-Erzincan earthquake rupture |

1

2

EF

Pontus Mountains

Eurasian Plate

Gunalan

Yaylabeli Cukurcimen

Resadiye

AIF

Tokat

Elevation a.s.l.

3km

2km

1km

0m

N

Susehri

Anatolian Plateau

Anatolian Plate

NEAF

40°

Erzincan

3

0km    50km

X fault segment boundary

OF

**c)**

8

6

4

2

Right lateral displacement (m)

8

6

4

2

Ezinepazari Segment

Kelkit Valley Segment

Ortakoy-Susehri segment

Mihar-Tumekar segment

Erzincan segment

**a.**

Cobanli R.

Box B

Lateral Spread

Box C

Cobanli R.

Fault A

6

Box F

Fault A

4

Fault A

T1

T2

Gunalan

5

T3

Box E

N

Fault B

Box D

8

Fault C

500m

T4

**b.**

T1

T2

Gunalan

No fault trace

500m

**c.**

Lateral spread

Elongate ridge

RAMP

T3

500m

## Legend

Inter-fan wetland

Alluvial flood plain - dry

Alluvial flood plain - damp

Hilly terrain. Ridges are shown with black lines and crude shading of ~northwest facing slopes is shown with grey.

→ Stream

⇢ Canal

━ Master fault

─ Fault

╌ Fault (did not rupture in 1939)

⌢ Scarp (teeth show ~height)

Alluvial fan

T1 Trench location

Photo taken from apex looking toward the fading direction.

5 Approximate location of dispacements associated with the 1939 earthquake according to Kocyigit 1990. Number refers to that used in text.

**d.**

South

North

Fault C

Fault B

Fault A

Gunalan

**e.**

South

North

Gunalan

Elongate ridge

Faults C and B

Fault A

**f.**

West

East

Cobanli R.

Lateral spread

Failure direction

a.

**West Wall** (horizontally inverted)

N ←→ S

Surface

Topsoil

Topsoil

B horizon

S1

S1

S1

C2

C1

Ps1

T1E0

S2

Ps1

S2

S2

C3

Ps2

S4

C1

C2

C2

S2

S4

C5

Ps2

Ps2

C1

C2

S2

Ps3

Gx2

Gx3

Gx3

Ps2

Ps1

C2

Gx3

Gx3

Gx3

Gx1

F1

F2

Meters 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21

**East Wall**

N ←→ S

Surface

See Photo Mosaic

Topsoil

B horizon

S1

S1

S1

S2

G1

Ps1

C1

Ps1

T1E0

S2

C2

C2

S3

C3

C6

Ps2

Cx

C1

Ps3

Ps2

C5

C2

Gx3

C6

Gx3

Fz

Ps2

C3

C5

Ps2

C2

C2

Ps1

C5

C4

C3

C4

C3

C4

Ps2

▲037

C5

C4

C5

Gx3

Gx3

Gx3

Meters 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22

b.

| | | |
|---|---|---|
| Organic rich soil | Clay | Fault zone |
| Sand | Gravel | Fault trace |

Form lines

Ps3  Soil unit label

▲037  Radiocarbon sample

T1E0  Event horizon