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Fault Specific GIS Based Seismic Hazard Maps for the Attica Region, Greece

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Abstract

Traditional seismic hazard assessment methods are based on the historical seismic records for the calculation of an annual probability of exceedance for a particular ground motion level. A new fault specific seismic hazard assessment method is presented, in order to address problems related to the incompleteness and the inhomogeneity of the historical records and to obtain higher spatial resolution of hazard. This method is applied to the region of Attica, which is the most densely populated area in Greece, as nearly half of the country's population lives in Athens and its surrounding suburbs, in Greater Athens Area. The methodology is based on a database of 22 active faults that could cause damage to Attica in case of seismic rupture. This database provides information about the faults slip rates, lengths and expected magnitudes. The final output of this method are four fault specific seismic hazard maps, showing the recurrence of expected intensities that each locality in the map has been shaken at. These maps offer a high spatial resolution, as they consider the surface geology. Despite the fact that almost half of the Attica region lies on the lowest seismic risk zone according to the official seismic hazard zonation of Greece, different localities have repeatedly experienced strong ground motions during the last 15 kyrs. Moreover, the maximum recurrence for each intensity occurs in different localities across Attica. Highest recurrence for intensity VII (151-156 times over 15

29 kyrs, or up to 96 year return period) is observed in the central part of the Athens
30 basin. The maximum intensity VIII recurrence (114 times over 15 kyrs, or up to 131
31 year return period) is observed in the western part of Attica, while the maximum
32 intensity IX (73-77/15kyrs, or 195 year return period) and X (25-29/15kyrs, or 517
33 year return period) recurrences are observed near the South Alkyonides fault system,
34 which dominates the strong ground motions hazard in the western part of the Attica
35 mainland.

36

37 Keywords

38 Athens, active faults, slip rates, earthquakes, intensity, faults database

39 **1. Introduction**

40 ~~Greece is prone to various natural disasters, such as wildfires, floods, landslides and~~
41 ~~earthquakes, due to the special environmental and geological conditions dominating~~
42 ~~in tectonic plate boundaries. Seismic is the predominant risk, in terms of damages and~~
43 ~~casualties in the Greek territory (PreventionWeb, 2011).~~

44 During the last 500 years, more than 170 destructive earthquakes occurred in Greece
45 and the surrounding area, with mean annual casualties of 17 fatalities and 92 wounded
46 (Papazachos and Papazachou, 2003). The historical record of earthquakes in Greece is
47 compiled by various researchers (Galanopoulos, 1961, Makropoulos and Burton,
48 1984, Papazachos and Papazachou, 1997), providing useful data in seismic hazard
49 assessment of Greece.

50 Greece has one of the longest historical catalogues worldwide with the oldest
51 recorded events in 550 B.C. However, there is an incompleteness and inhomogeneity

52 of geographical and temporal coverage in terms of the seismic record, so that this
53 catalogue is considered complete for events $M \geq 7.3$ since 1500 and for $M \geq 6.5$ only
54 since 1845 (Papazachos, et al. 2000). However, the recurrence interval of particular
55 faults ranges from a few hundred years to several thousands of years (Goes 1996,
56 Yeats and Prentice 1996, Machette 2000). Regarding the Attica region, recurrence
57 intervals vary from a few hundred years for the highly active South Alkyonides Fault
58 (Collier, et al. 1998), up to thousands of years, as shown in the Kaparelli fault, which
59 was reactivated in 1981, after being inactive for **several thousands of years**
60 ~~approximately 10 kyrs~~ (Benedetti, et al. 2003; Chatzipetros, et al. 2005; Kokkalas, et
61 al. 2007). Thus, historical earthquake catalogues are generally too short compared to
62 the recurrence intervals of faults. The latter implies that the sample from the historical
63 record is incomplete and that a large number of faults would not have ruptured during
64 the completeness period of the historical record (e.g. Grützner, et al. 2013). Further
65 uncertainties are related to the epicenters location, even for instrumentally recorded
66 earthquakes (Papanikolaou, et al. 2015). The errors can reach up to 20 km for the
67 older events (1965-1980) and up to 10km for the most recent ones (Papazachos, et al.
68 2000). Larger uncertainties result for the older events approximate epicentral
69 locations. For the period 1901-1964 the errors can be up to 30km but they can reach
70 up to 50km for the older events (before 1900) when the number of available
71 macroseismic information is less than 5 (Papazachos, et al. 2000, Stucchi, et al. 2012).
72 Indeed, recorded events in the Attica region are an example, as the uncertainty on the
73 epicentral locations for the most recent Athens 1999 Mw 5.9 earthquake, which are
74 derived from different papers and catalogues, exceed 5km. For the older Oropos 1938
75 Mw 6.0 event, the epicenters in two different catalogues are located 12km away of
76 each other.

77 New Seismic Hazard Assessment methodologies tend to follow fault specific
78 approaches where seismic sources are geologically constrained active faults
79 (WGCEP, 1990, 1999, 2002, 2008; Ganas and Papoulia, 2000; Boncio, et al. 2004;
80 Roberts, et al. 2004; Papanikolaou and Papanikolaou, 2007; Pace, et al. 2010; Stein, et
81 al. 2012; Papanikolaou, et al. 2013). These fault specific approaches are used in order
82 to address problems related to the historical records incompleteness, obtain higher
83 spatial resolution and calculate realistic source locality distances, since seismic
84 sources are very accurately located. Fault specific approaches provide quantitative
85 assessments as they measure fault slip rates from geological data, providing a more
86 reliable estimate of seismic hazard than the historical earthquake record (e.g. Yeats
87 and Prentice, 1996; Papoulia, et al. 2001; Michetti, et al. 2005). Geological data have
88 the potential to extend the history of slip on an active fault back many thousands of
89 years, a time span that generally encompasses a large number of earthquake cycles
90 (Yeats and Prentice 1996), and thus elucidates the long-term pattern of fault-slip. In
91 addition, geologic fault slip-rate data offer complete spatial coverage, providing
92 higher spatial resolution than traditional seismic hazard maps based on
93 historical/instrumental records (Boncio, et al. 2004, Roberts, et al. 2004, Pace, et al.
94 2010, Papanikolaou, et al. 2013). For land-use planning and critical facilities or
95 insurance risk evaluation purposes, a higher spatial resolution is also desirable
96 (Grützner, et al. 2013).

97 As a result, there is an emerging tendency for incorporating fault specific
98 information relating both to the identification and mapping of active faults, as well as
99 extracting information regarding the recurrence interval of associated potential
100 earthquakes (Papanikolaou, et al 2015).

101 ~~1.1 Existing seismic hazard models~~

102 ~~The probabilistic seismic hazard analyses calculate the probability of exceeding~~
103 ~~different levels of ground motion (intensity or acceleration) by considering the~~
104 ~~earthquake location, timing and size. These analyses are based on the likelihood of~~
105 ~~occurrence of various magnitude earthquakes and their contributions to ground~~
106 ~~motion hazards. On the other hand, deterministic analyses only consider ground~~
107 ~~motions or highest intensities due to the maximum credible earthquake (Youngs and~~
108 ~~Coppersmith, 1985).~~

109 ~~The results of probabilistic seismic hazard analysis are usually consisted of maps at~~
110 ~~a given level of probability, based on a combination of the earthquake frequency-~~
111 ~~magnitude distribution, ground motion attenuation data, and local site conditions~~
112 ~~(Main, 1996). The general procedure followed in probabilistic seismic hazard analysis~~
113 ~~includes the individual steps of seismic zoning, estimating the recurrence, and fitting a~~
114 ~~local attenuation law to the ground motion in order to calculate an annual probability~~
115 ~~of exceedance of a particular level of ground motion (Reiter, 1990). The primary~~
116 ~~probabilistic tool for projecting future events is the seismicity record (Yeats, et al.~~
117 ~~1997).~~

118 **2. Methodology**

119 A fault specific seismic hazard assessment approach was used for the seismic hazard
120 assessment of the Attica region. The method of seismic hazard mapping from
121 geological fault throw-rate data was firstly introduced by Papanikolaou (2003) and
122 Roberts, et al. (2004). It consists of the combination of the following four major
123 factors:

- 124 1. compilation of a fault database, that includes the identification of seismic sources,
125 determination of fault lengths and their characteristics regarding their kinematics
126 and slip rates which govern earthquake recurrence.
- 127 2. empirical data which combine fault rupture lengths, earthquake magnitudes and
128 coseismic slip relationships (Wells and Coppersmith, 1994; Pavlides and Caputo,
129 2004).
- 130 3. the radii of VI, VII, VIII, and also IX isoseismals on the Modified Mercalli (MM)
131 intensity scale, within which horizontal ground accelerations exceed 500cm/sec^2
132 in the Greek territory (Theodulidis and Papazachos, 1992) causing damage even
133 to well-constructed buildings (Rieter, 1990).
- 134 4. Attenuation - amplification functions for seismic shaking on bedrock compared to
135 basin filling sediments (Degg 1992).

136 In detail, fault specific Seismic Hazard Mapping methodology can be displayed in
137 the following steps (see also Papanikolaou 2003, Roberts, et al. 2004, Papanikolaou,
138 et al. 2013):

139 **2.1 Active faults identification**

140 When seismic hazard is estimated for a wide region, all the seismic sources must be
141 identified. All active faults that affect the study area must be accurately mapped, as
142 they are going to be analyzed in the next steps. Geological and geomorphological
143 studies are often the primary basis for locating potential seismic sources (Wesnousky,
144 1987). A large set of data are used for understanding the current tectonic regime and
145 rates of activity, including: aerial photographs, remote sensing data (such as those
146 derived from satellite imagery), GPS and interferometry data, strain rate
147 measurements, mapping and analysis of Quaternary formations and/or land - forms

148 (such as terrace analysis and investigation of drainage network evolution), and
149 pedological and sedimentological studies. Usually, it is necessary to perform detailed
150 geomorphological-geological mapping, geophysical prospecting, or subsurface
151 investigation to fully characterize the identified structures (Michetti, et al. 2005). The
152 usual criteria for identifying active faults are the Quaternary deposits disruption,
153 rivers or tributaries delimitation and creation of characteristic and recognizable set of
154 geomorphologic landscapes.

155 The detailed data for faults characteristics were derived from scientific articles,
156 onshore and offshore neotectonic maps and fieldwork observations. In general, two
157 type of sources were used for the active faults determination:

158 a) Already published literature regarding location and fault activity.

159 The published papers of researchers working on the active tectonics of Attica
160 and the surrounding areas were used for the majority of the active faults (19 out
161 of 22) regarding the compilation of the database. For 13 out of the 22 faults
162 (Fault id numbers 1-5, 8-11, 13-15 and 19 of the database, see Figure 3 and
163 Table 3) information regarding fault geometry and slip rates were extracted from
164 the existing literature (see Table 3 for details on corresponding literature)
165 (~~Pantosti, et al. 1996; Collier, et al. 1998; Morewood & Roberts, 2001; Pavlides,~~
166 ~~et al. 2002; Goldsworthy, et al. 2002; Benedetti, et al. 2003; Ganas, et al. 2004;~~
167 ~~Ganas, et al. 2005; Kokkalas, et al. 2007; Papanikolaou & Papanikolaou, 2007;~~
168 ~~Sakellariou, et al. 2007; Rontoyianni & Marinos, 2008; Tsodoulos, et al. 2008;~~
169 ~~Roberts, et al. 2009; Roberts, et al. 2011 and Grutzner, et al. 2016~~). Moreover,
170 onshore and offshore neotectonic maps provided information about the fault
171 geometry and slip rate. The offshore neotectonic maps of the Saronikos and the
172 Southern Evoikos Gulfs (Papanikolaou, et al. 1989a; Papanikolaou, et al. 1989b)

173 were utilized for the depiction of the 6 offshore active faults (Fault id numbers
174 12, 16-18, 21-22) and their characteristics.

175 b) Fieldwork with in situ geomorphological interpretations.

176 Field research was conducted for faults 6-7 and 20, in order to estimate fault
177 lengths, finite throw and slip rate values.

178 2.2 Fault lengths determination

179 ~~The lengths of active faults are usually determined from: a) geological cross-~~
180 ~~sections made from published geological maps; b) fault slip directions, as they vary~~
181 ~~with throw, converging towards the center of the hanging wall (Roberts, 1996;~~
182 ~~Roberts and Ganas, 2000); c) abrupt slope changes; d) deformation rates extracted~~
183 ~~either from trench sites or from geomorphic observations of offset features of known~~
184 ~~age e) profile analysis of catchments crossing the fault.~~ Since fault length was used to
185 determine the expected earthquake magnitude (Figure 4), each one of the active faults
186 that could affect Attica region in case of earthquake rupture was mapped in GIS
187 environment (see Chapter 4 for constraints based on errors and assumptions).

188 Despite the fact that 1:50.000 scale geological maps cover nearly the whole Greek
189 territory, faults depiction is usually restricted to small or inactive structures with no
190 contribution to seismic hazard. Fault lengths for the faults 6-7 and 20 were determined
191 using a combination of geomorphological and geological criteria. In addition to the in
192 situ interpretations, hillshade and slope maps were utilized so that the overall
193 topographic imprint would be observed. In addition to that, geological cross-sections
194 in the tips of these faults were used to identify the sediments offset, which allowed a
195 detailed mapping of the fault lengths.

196 **2.3 Registration of fault throw-rate data**

197 Throw-rates are measured values derived from geological data, such as postglacial
198 scarps analysis, palaeoseismological research and geomorphological interpretations.
199 Fault throw-rate values are essential for the Seismic Hazard Assessment, as high
200 values indicate shorter recurrence intervals between earthquake events, implying
201 increased fault activity (Cowie and Roberts 2001, Roberts, et al. 2004). The
202 determination of fault throw rates was based on the published literature findings were
203 applicable. For faults id 1-3, 5, 8-9 and 14-15 throw rates were extracted from the
204 well – described and constrained values already presented in the literature (Benedetti,
205 et al, 2003; Ganas, et al. 2005; **Chatzipetros, et al. 2005**; Papanikolaou &
206 Papanikolaou, 2007; Sakellariou, et al. 2007; Grutzner, et al, 2016). Faults derived
207 from the neotectonic maps did not have an assigned throw rate value. For these faults
208 we used the average thickness of the sediments versus their age, for the extraction of
209 their long term slip rate. Slip rate values extracted from fieldwork were attributed to
210 the maximum scarp heights, assuming that they represent the maximum finite throw
211 since over a fixed time period (i.e. the last glaciation).

212 **2.4 Conversion of throw-rates into earthquake frequencies**

213 ~~Now that fault lengths, throws and throw rates are known, throw-length profiles can~~
214 ~~be constructed for given time periods (e.g. since the last glaciation).~~ Assuming a
215 triangular throw profile for the faults (Cowie and Shipton, 1998) and earthquake
216 surface ruptures, and that the maximum throw is observed at the center of the fault,
217 the number of surface faulting earthquakes of fixed size can be calculated for each
218 one of the faults in a certain time period. Throws in these profiles represent the slip
219 that each fault has accumulated during the last 15 kyrs and most of them have been

220 extracted from geomorphic observations of offset postglacial features. However, for
221 the South Alkyonides Fault, the surface ruptures used (25km) are shorter than the total
222 length of the fault, as the 1981 earthquakes did not rupture the entire length of the
223 South Alkyonides Fault (Roberts, 1996). This results to the assumption that the South
224 Alkyonides fault produces earthquakes of smaller magnitude (e.g. $M_s = 6.7$) more
225 frequently, rather than larger earthquakes that rupture the total fault length but in
226 longer recurrence time. Thus, it is assumed that this fault ruptures in floating
227 earthquakes, which are distributed around a mean magnitude of fixed size (e.g.
228 Papanikolaou, et al. 2013). As a result, by comparing the areas of triangles for faults
229 and ruptures, the number of earthquakes each fault has experienced during the last 15
230 kyrs can be calculated (example shown in Figure 1a,b). ~~The distribution of the~~
231 ~~associated hypothetical epicenters along strike the fault is made using the~~
232 ~~mathematical formula of Papanikolaou (2003).~~

233 **2.5 Earthquake distribution along strike the fault**

234 After calculating how many earthquakes of certain size each fault has experienced
235 during the last 15 kyrs, modeled earthquakes have to be distributed according to the
236 fault throw variation along strike each fault trace. The aim is to extract the earthquake
237 density along strike the fault. ~~The distribution of the associated hypothetical~~
238 ~~epicenters along strike the fault is made using the mathematical formula of~~
239 ~~Papanikolaou (2003), as illustrated in Figure 1c.~~

240 **2.6 Production of isoseismals**

241 Earthquakes are not uniformly distributed throughout the continental crust, but are
242 overwhelmingly concentrated in the upper 10-15 km, close to the base of the
243 seismogenic layer, with the lower continental crust remaining aseismic (Chen and

244 Molnar, 1983; Sibson, 1984). Moreover, large seismogenic faults on the continents
245 appear to be restricted to a dip range between 30° - 60° (Jackson and White, 1989,
246 Chen and Molnar, 1983). ~~The thickness of the seismogenic layer, as well as the dip~~
247 ~~angles of normal faults, constrained the placement of the hypothetical epicenters~~ ~~The~~
248 ~~hypothetical epicenters projected across the active faults.~~ Assuming 50° - 55° dipping
249 faults and hypocenters at the depth of 10 km, they were plotted 7 - 8.5 km away from
250 the fault in the hanging wall. ~~Map plotting of the epicenters was made using the~~
251 ~~Buffer Tool, which was set to expand the buffer zone towards the fault's hanging~~
252 ~~wall.~~

253 The active faults were grouped in two sets, depending on their length, which
254 correlates to the earthquake magnitude they can produce, as shown by Wells &
255 Coppersmith (1994) and Pavlides & Caputo (2004). For faults shorter than 16km we
256 used an average magnitude of 6.25 ± 0.15 , since faults from 9.2 km up to 16 km can
257 produce earthquakes that lie within a range of magnitude 6.1 – 6.4 (Wells &
258 Coppersmith, 1994). Consequently, following the same empirical regressions of
259 surface rupture length and magnitude, faults longer than 16 km produce earthquakes
260 of magnitudes that exceed $M_s=6.5$. However, it is possible that faults around 25 km –
261 40 km length could rupture in sub-events or break parts rather than the entire fault
262 length, thus producing earthquakes around M_s 6.5 – M_s 6.7 (e.g. Roberts, 1996;
263 Roberts et al., 2004). For each group, we used the Theodulidis (1991) attenuation
264 relationships between earthquake magnitude and intensities distribution for the
265 production of the modeled isoseismals (Table 1). It is assumed that the Earth is
266 homogeneous and isotropic so body waves would have spherical wave fronts (Figure
267 1d).

268 Table 1: Radii of the isoseismals for the active faults in Attica, based on the Theodulidis (1991)
 269 attenuation relationships. Intensity IX is not expected in firm sediments affected by faults shorter than
 270 16km.

Faults group by earthquake magnitude	Intensity (MM)			
	IX	VIII	VII	VI
6.65 ± 0.15 (6.5 – 6.8)	11km	25km	44km	74km
6.25 ± 0.15 (6.1 – 6.4)	-	15km	31km	53km

271

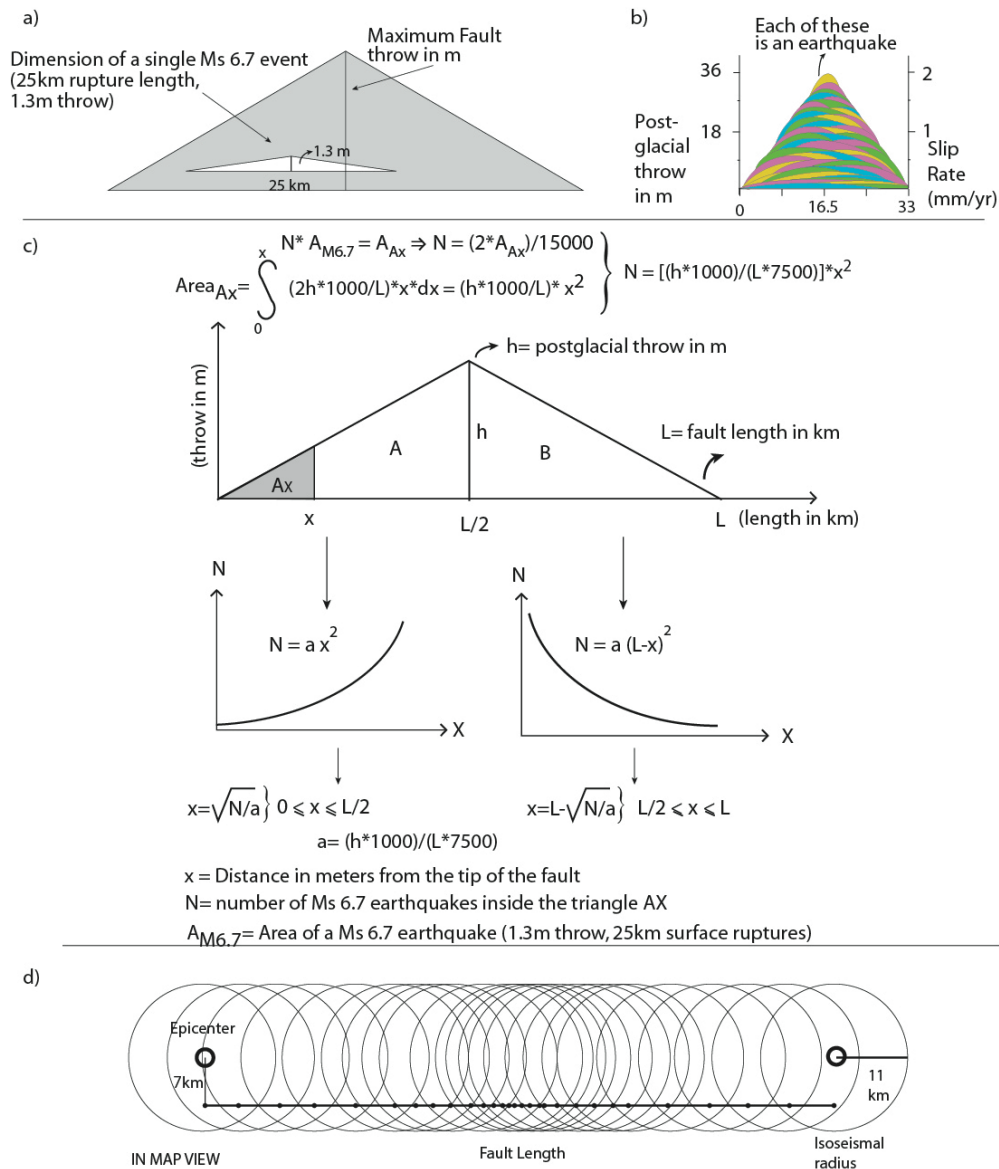


Figure 1: Schematic representation for the construction of the hazard map, modified after Papanikolaou (2003) and Roberts, et al. (2004). a) The concept of the methodology for one of the 22 faults in Attica (South Alkyonides Fault). Assuming a triangular throw profile for the faults and ruptures and that the maximum throw is observed at the centre of the fault, the number of surface faulting earthquakes of Ms=6.7 can be calculated. b) Throw in this profile represents the slip that the fault has accumulated during the post-glacial period (since 15 kyr ago±3 kyr). c) Mathematical formula describing the earthquake distribution along strike each active fault. The distance (x) of each earthquake point from the tip of the fault is calculated. Each fault is divided in two halves (triangles A and B) and the corresponding formula is applied for each one of them. d) Epicentres are plotted 7 km away from the fault in the hanging wall and circles with 11 km radius of intensity IX (representing “isoseismals”) are added. Geology is not yet taken into account.

272 **2.7 Counting and contouring the number of times each locality has been shaken.**

273 Every intensity coverage was represented as a separate raster, so that no overlapping
274 occurred between raster coverages of different intensities around the same modeled
275 epicenter. Buffer zones were created around each hypothetical epicenter for every
276 modeled intensity, using the ranges displayed in Table 1. These buffer zones were
277 converted to raster coverages and attributed by new values. Then, all these coverages,
278 centered to the hypothetical epicenters, were added in separate map views for each
279 intensity scenario, representing areas that receive enough energy to shake at
280 intensities VI – IX.

281 The outcome of this process is four individual maps, showing how many times each
282 locality receives enough energy to shake at intensities VI - IX in 15kyrs, assuming
283 homogenous bedrock geology, **spherical wave fronts for body waves** and isoseismal
284 ranges as shown in Table 1. The hazard distribution varies along strike each fault, so
285 that over long time periods the hangingwall center of a fault receives most of the
286 seismic energy, in contrast to fault tips where the hazard is considerably lower.

287 **2.8 Amplify/Attenuate with the bedrock geology**

288 The modeled intensity coverages are attenuated/amplified according to the **bedrock**
289 **geology surface geologic conditions**, providing the expected intensities for each
290 geological formation. The simple attenuation model decreases the intensity by: i) a
291 single value, if two localities are equidistant from an epicenter, but one lies on
292 Mesozoic or Tertiary limestone and the other lies on flysch/foredeep deposits and ii)
293 two single values if two localities are equidistant from an epicenter, but one lies on
294 Mesozoic limestone and the other lies on Quaternary sediments (Table 2).

295 In the case of the Attica Region, the Quaternary deposits increase the intensity by a
296 single value. The flysch/foredeep deposits will cause no alterations in the intensity
297 value, while the bedrock (mostly Mesozoic or Tertiary limestone) will decrease the
298 intensity by one value (Figure 2). The input data for the surface geology is extracted
299 from: a) the 1:25,000 Earthquake Planning and Protection Organization (EPPO)
300 detailed geotechnical map for the Athens Metropolitan Area (Marinos, et al. 1999a),
301 b) the 12 1:50,000 geological maps of IGME (Tataris, et al. 1966; Gaitanakis, et al.
302 1985; Latsoudas, 1992; Katsikatsos, et al. 1986; Katsikatsos, 2000; Parginos, et al.
303 2007; Katsikatsos, 2002; Katsikatsos, 1991; Dounas, 1971; Mpornovas, et al. 1984;
304 Gaitanakis, et al. 1984; Gaitanakis, 1982) for the rest of the Attica mainland.

305

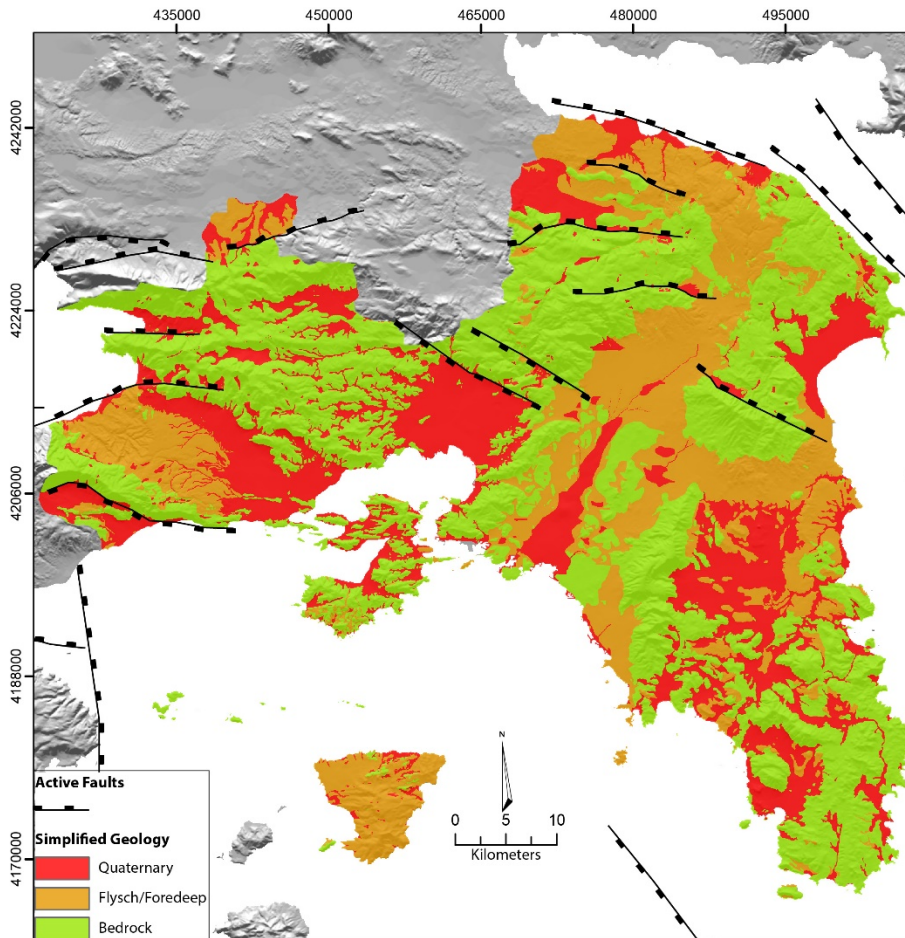


Figure 2: Simplified geological map of the area of Attica, based on 1:50,000 scale geological maps of IGME and the 1:25,000 scale Earthquake Planning and Protection Organization (EPPO) detailed geotechnical map for the Athens Metropolitan Area (Marinos, et al. 1999a).

306

307 Table 2: Average intensity changes depending on different types of surface geology, proposed by
 308 Degg (1992).

Subsoil	Average change in intensity
Rock (e.g. limestone, granite, gneiss, basalt)	-1
Firm sediments	0
Loose sediments (e.g. sand, alluvial deposits)	+1

309 Overall, the produced hazard maps incorporate information on bedrock geology and
 310 its contribution to spatial variations in ground shaking intensity.

311 **3. Results**

312 **3.1 Active Faults Database**

313 The active faults database contains 22 faults that: a) are long enough to produce
314 surface ruptures and b) can sustain damage in the Attica mainland in case of
315 earthquake rupture (Figure 3).

316 Fault lengths and their characteristics regarding their kinematics and slip rates are
317 shown in Table 3.

318 The average expected earthquake magnitude is M_w 6.5, based on empirical
319 relationships between rupture lengths and earthquake magnitudes. However, these
320 faults are located away of the Athens plain, except for the southeastern tip of the Fili
321 fault (id = 15 in Table 3, see Figure 3). As a result, seismic hazard in the Athens Plain
322 is less significant. Moreover, most of the densely inhabited areas in the Greater
323 Athens Area lay on the footwall of the neighboring active faults (id = 3, 4 on Table 3,
324 see Figures 3, 4). Fault lengths vary from 9 up to 35km. Faults that exceed 30km in
325 length were assumed to rupture in floating earthquakes of magnitude $M_s = 6.65 \pm 0.15$.
326 As a result, the expected earthquake magnitude of the South Alkyonides Fault system
327 (id = 8 in Table 3) is not proportional to its length (Roberts, 1986). Instead, we
328 modelled floating earthquakes of magnitude 6.7 along strike the fault, which is in
329 agreement with the 1981 earthquake (Jackson, et al. 1982).

330 The majority of the active faults that affect the region of Attica do not exceed the
331 relatively low slip-rate values of 0.3mm/yr. However, the faults activated during the
332 1981 earthquakes events (South Alkyonides Fault segments) reach or exceed slip-rate
333 values of 2mm/yr, thus the mean slip-rate value of the faults that affect Attica is
334 ~ 0.38 mm/y (Figure 4b).

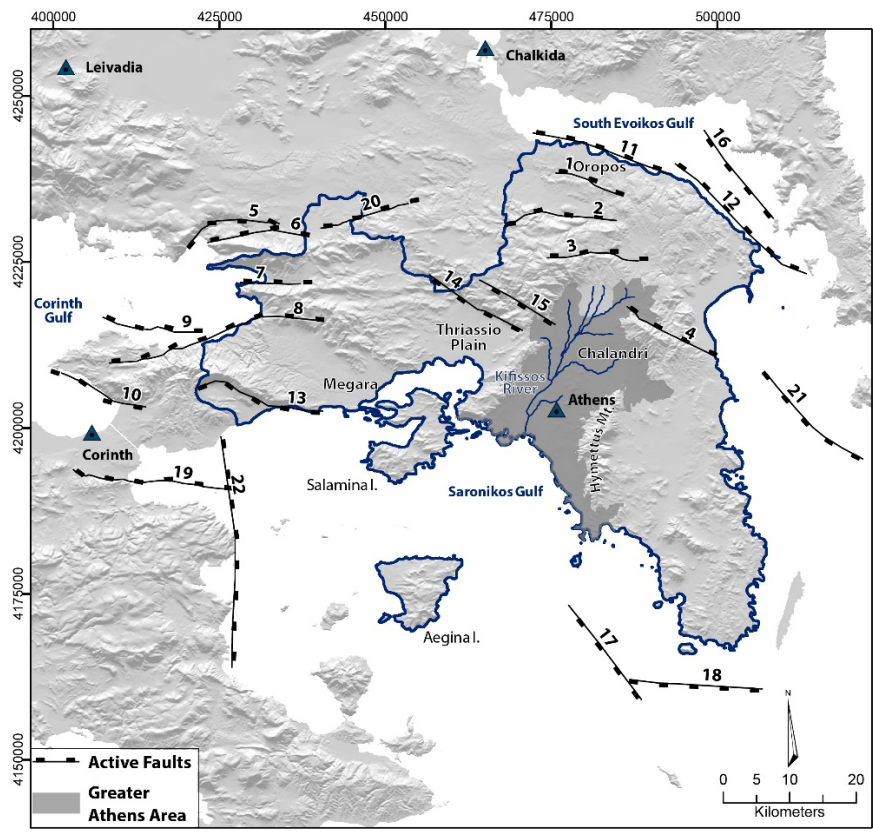


Figure 3: Map of active faults that can sustain damage within the region of Attica. No faults are located in the Athens Plain, except for the southeastern tip of the Fili fault (id = 15 on Table 3), but with low slip rate faults (see Figure 4b). Fault labels refer to the Id numbers on (Table 3).

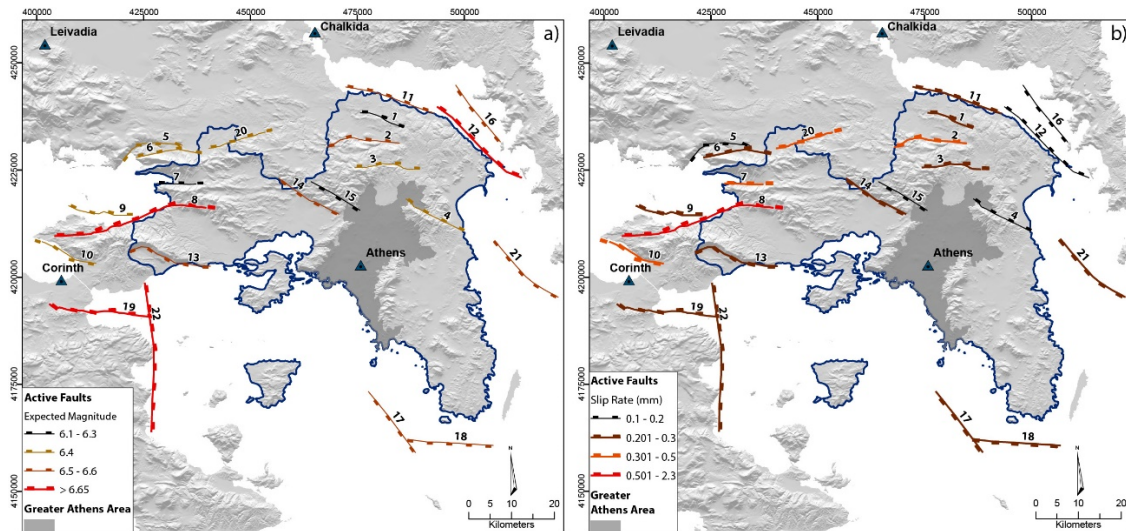


Figure 4: Map of active faults that can sustain damage within the region of Attica. a) Different colors represent the maximum expected magnitude that these faults can generate. b) Different colors represent different slip-rate categories. Slip rates govern earthquake recurrence. As slip rates increase, average earthquake recurrence intervals tend to decrease.

337 Table 3: Fault characteristics used for extracting the earthquake recurrence per site over the last 15
 338 kyrs. Expected Magnitude and Maximum Displacement per Event values are based on Wells and
 339 Coppersmith (1994) equations. Slip rate column refers to short term where available, or long term slip
 340 rate values, induced from published papers and neotectonic maps (see text for details). *Id* numbers refer
 341 to the map displayed in Figure 1. Fault characteristics are based on the following sources (numbers
 342 correspond to the “Source” column): 1) Official Neotectonic map Saronikos Gulf – Papanikolaou, et al.
 343 1989a; 2) Official Neotectonic map South Evoikos Gulf – Papanikolaou, et al. 1989b; 3) Neotectonic
 344 map East Attica – Papanikolaou, et al. 1995; 4) Pantosti, et al. 1996; 5) Collier, et al. 1998; 6) Morewood
 345 & Roberts, 1999; 7) Morewood & Roberts, 2001; 8) Pavlides, et al. 2002; 9) Goldsworthy, et al. 2002;
 346 10) Benedetti, et al. 2003; 11) Ganas, et al. 2004; 12) Chatzipetros, et al. 2005; 13) Ganas, et al. 2005;
 347 14) Kokkalas, et al. 2007; 15) Papanikolaou & Papanikolaou, 2007; 16) Sakellariou, et al. 2007;
 348 17) Rontoyianni & Marinos, 2008; 18) Tsodoulos, et al. 2008; 19) Roberts, et al. 2009; 20) Roberts, et al.
 349 2011 and 21) Grutzner, et al. 2016. *f*: fieldwork findings.

<i>Id</i>	Length (km)	Postglacial Throw (m)	Expected Magnitude	Slip Rate (mm/y)	Maximum Displacement per Event (m)	Source
<i>1</i>	9.7	4.5	6.2	0.30	0.32	<i>9,15,21</i>
<i>2</i>	17.7	6.0	6.5	0.40	0.80	<i>9,11,13,15</i>
<i>3</i>	14.2	4.5	6.4	0.30	0.58	<i>15</i>
<i>4</i>	14.8	1.5	6.4	0.10	0.61	<i>15</i>
<i>5</i>	14.5	3.0	6.4	0.20	0.59	<i>10,14,18,19</i>
<i>6</i>	15.7	4.5	6.4	0.30	0.67	<i>f</i>
<i>7</i>	9.2	7.5	6.1	0.50	0.30	<i>f</i>
<i>8</i>	32.8	34.5	6.7	2.30	2.04	<i>4,5,7,19,20</i>
<i>9</i>	15.1	4.5	6.4	0.30	0.63	<i>16</i>
<i>10</i>	13.9	7.5	6.4	0.50	0.56	<i>20</i>
<i>11</i>	21.8	4.5	6.6	0.30	1.10	<i>15</i>
<i>12</i>	26.2	1.5	6.7	0.10	1.45	<i>2</i>
<i>13</i>	19.6	4.5	6.6	0.30	0.94	<i>13,17</i>
<i>14</i>	16.5	4.1	6.5	0.27	0.72	<i>8,13</i>
<i>15</i>	13.3	2.6	6.3	0.17	0.52	<i>8,13</i>
<i>16</i>	17.0	2.4	6.5	0.16	0.76	<i>2</i>
<i>17</i>	18.1	4.4	6.5	0.29	0.83	<i>1</i>
<i>18</i>	19.3	3.7	6.6	0.25	0.92	<i>1</i>
<i>19</i>	23.7	4.4	6.7	0.29	1.25	<i>20</i>
<i>20</i>	13.9	7.0	6.4	0.47	0.56	<i>f</i>
<i>21</i>	19.6	4.4	6.6	0.29	0.93	<i>2</i>
<i>22</i>	35.0	3.3	6.7	0.22	2.25	<i>1</i>

350

351 3.2 Seismic Hazard Maps

352 Four detailed seismic hazard maps were compiled for the region of Attica, one for
353 each of the intensities VII – X (MM). These maps offer a locality specific shaking

354 recurrence record, which represents the long-term shaking record in a more complete
355 way than the historical/instrumental catalogue, since they incorporate several seismic
356 cycles of the active faults that affect Attica (Figures 5 - 8).

357 **3.2.1.Intensity X**

358 Intensity X is mostly observed in limited areas in the hanging wall of large faults,
359 covered by loose sediments (Figure 5). Surface geology plays the most important role
360 for the intensity X occurrence, as it increases by a single value the calculated
361 isoseismals of intensity IX that only larger faults can produce in case of seismic
362 rupture. The highest recurrence of intensity X (>20 times in the past 15 kyrs) is
363 observed only in the western part of Attica, close to the Corinth Gulf. This is
364 attributable to the high slip rate value of the fault that was activated during the 1981
365 earthquake (South Alkyonides Fault system), which is capable of producing
366 earthquakes of magnitude $M = 6.7$. A second peak (11 times in the past 15 kyrs) in
367 recurrence is observed in the northern coastal zone (Oropos area). This area is
368 affected by two large faults (faults n.2 and 11 on Table 3) and is also covered by loose
369 alluvial and Plio – Pleistocene sediments. Large areas are expected to have been
370 shaken in such intensities in the Thriassio plain, west of the Greater Athens Area, but
371 their recurrence is relatively low, due to the low slip rates of the neighboring faults. It
372 is important that no intensity X is expected for the Greater Athens Area, as it is
373 located far away, or in the footwall of potentially damaging long faults (id = 2, 8, 11,
374 12, 14 on Table 3).

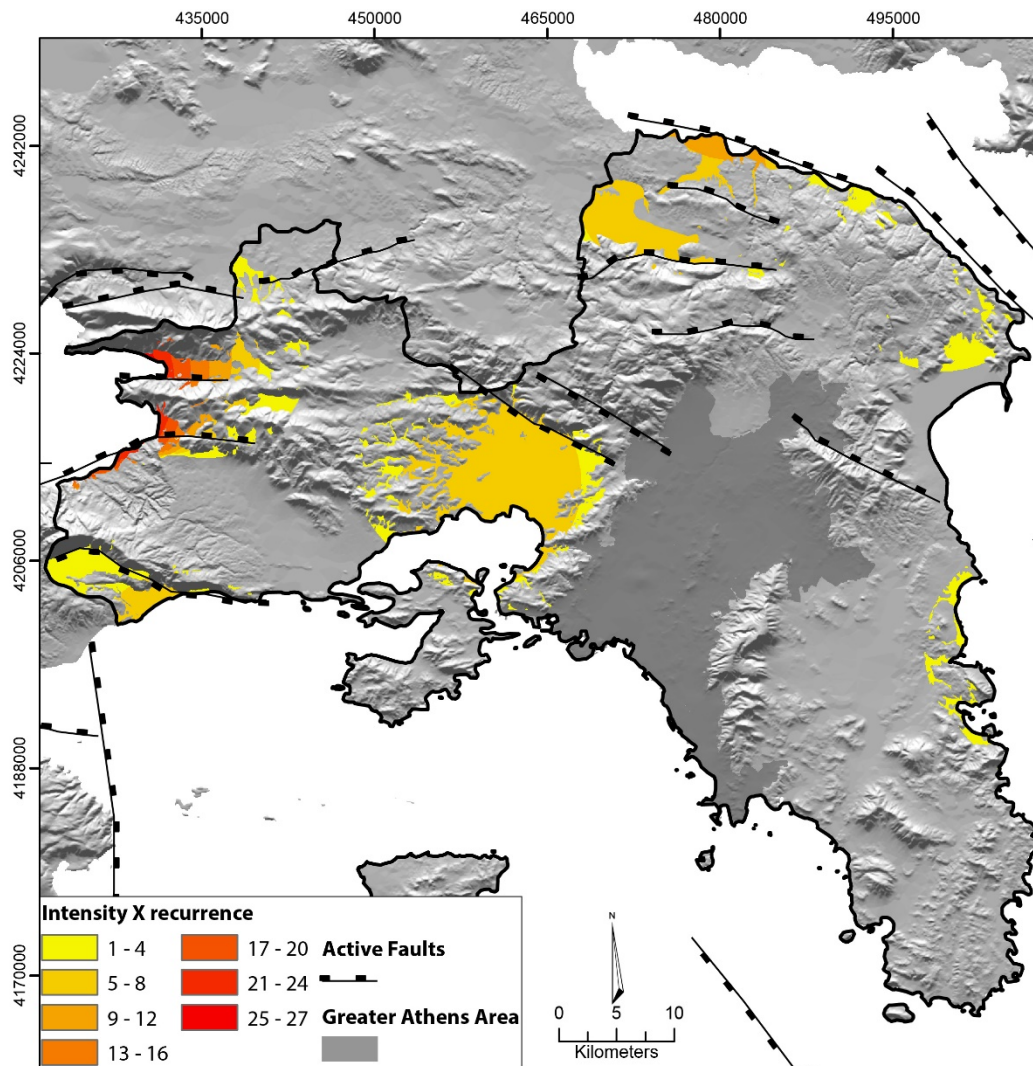


Figure 5: Seismic hazard map of Attica, showing the estimated site specific recurrence for intensities X (MM). The Greater Athens Area is not expected to have experienced such intensities during the last 15 kyrs.

375 **3.2.2.Intensity IX**

376 Intensity IX is expected to have occurred in larger areas of Attica and in higher
 377 recurrence levels, compared to intensity X (Figure 6). This is attributed to the fact that
 378 the calculated isoseismals of the shorter faults (< 16 km) are also taken into account in
 379 the modeling procedure. Intensity VIII isoseismals are amplified by one value when
 380 applied to loose sediments and are then added to the larger faults impact. Even though
 381 recurrence values are relatively low, it is important to note that intensity IX is

382 expected up to 11 times in the western parts of the Greater Athens Area and only 2
383 times in sparse areas in the eastern parts of the Athens plain. The loose alluvial
384 sediments of the Kifissos River which flows near the center of Athens, along with the
385 Upper Pliocene – Lower Pleistocene lake sediments at Chalandri and surrounding
386 areas (Papanikolaou, et al. 2004, localities shown in Figure 3) increase the intensity
387 values. Severe damages were inflicted during the Athens 1999 Mw 5.9 earthquake in
388 such geological formations (Lekkas, 2000). The highest recurrence (77 times, or
389 nearly 195 year return period) is observed in the western part of Attica, due to the
390 highly active South Alkyonides Fault. Moreover, the seismic hazard is also increased
391 close to the Saronic Gulf coastline, which is expected to experience intensity IX with
392 a minimum return period of 288 years. The northern part of Attica is mostly affected
393 by Afidnai, Avlonas – Malakasa, Milessi and Oropos faults (faults no. 3, 2, 1 and 11
394 in Table 3, respectively), which explains the relatively high intensity IX recurrence
395 (up to 37 times, or 405 year return period) that seems to have occurred since the last
396 glaciation.

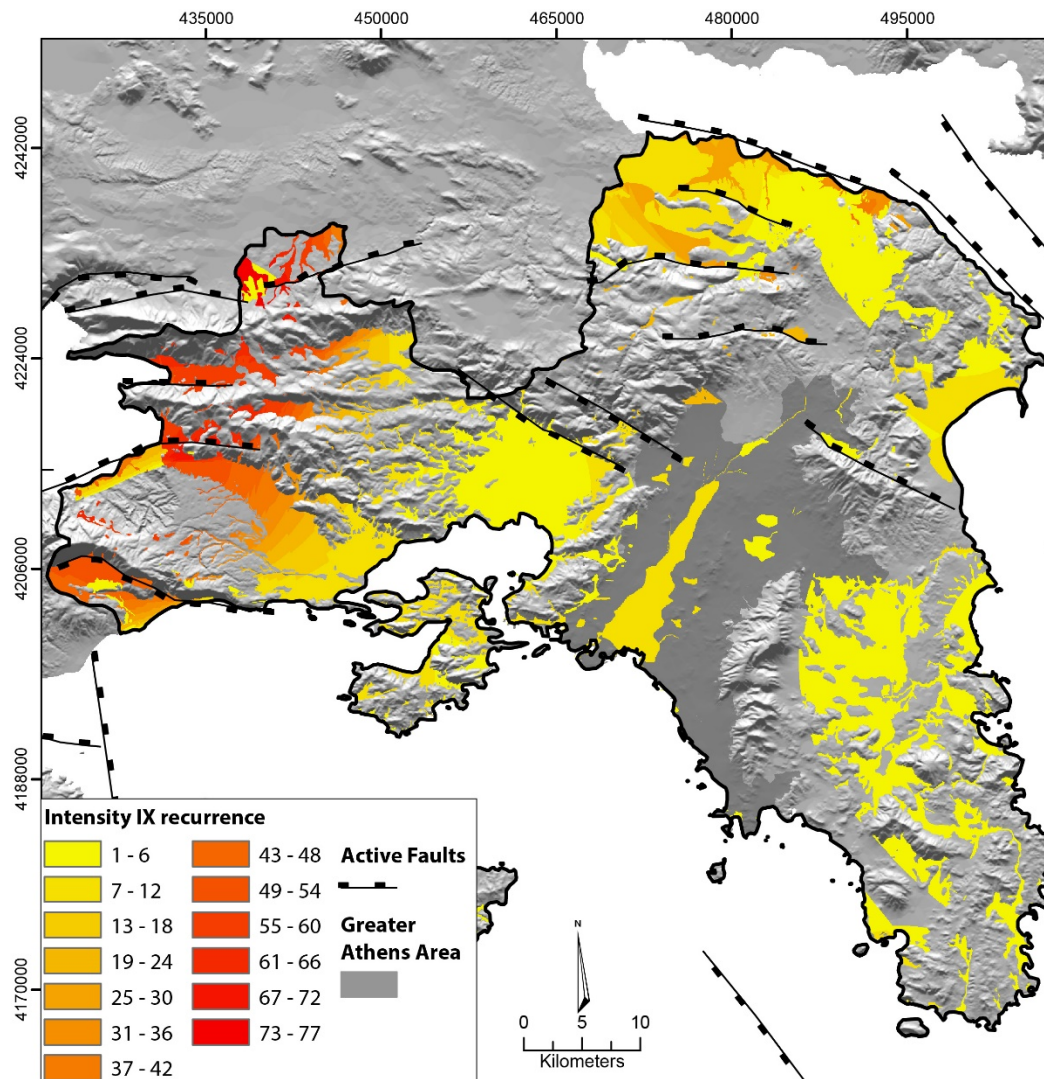


Figure 6: Seismic hazard map of Attica, showing the estimated site specific recurrence for intensities IX (MM).

397 However, as indicated also in the intensity X spatial distribution (Figure 5), it seems
 398 that the central Athens area has not experienced high intensities during the last 15
 399 kyrs, which comes in agreement to Ambraseys and Psycharis (2012) conclusions for
 400 lack of evidence for destructive events in the ancient and historical old part of the
 401 town for the last 2300 years. Nevertheless, the expansion of the city through the last
 402 decades has increased both the vulnerability and the hazard in particular areas with
 403 poor geotechnical conditions.

404 3.2.3. Intensity VIII

405 Intensity VIII covers larger areas in the Attica mainland because of the larger
406 isoseismals for intensity VIII on the larger faults. As a result, there is also an increase
407 in intensity VIII recurrence in the Attica main land, compared to the intensities X and
408 IX (Figure 7). The highest recurrence, outreaching 100 the times over 15 kyrs, seems
409 to have occurred in the Megara basin, NW of Salamina island, mostly because this
410 area is now partly affected by the highly active South Alkyonides fault system, as
411 intensity VIII occurs in a distance between 11 and 25 km from the large faults (see
412 Table 1). Indeed, during the 1981 event, when this fault system ruptured, Megara
413 basin suffered serious damage (Ambraseys and Jackson, 1981; Antonaki,et al. 1988,
414 Papanikolaou, et al. 2009). Moreover, the majority of the central and the western part
415 of the Greater Athens Area seems to have experienced intensity VIII, 20 times during
416 the last 15 kyrs on average, due to the low slip rates of the faults that affect this part of
417 Attica.

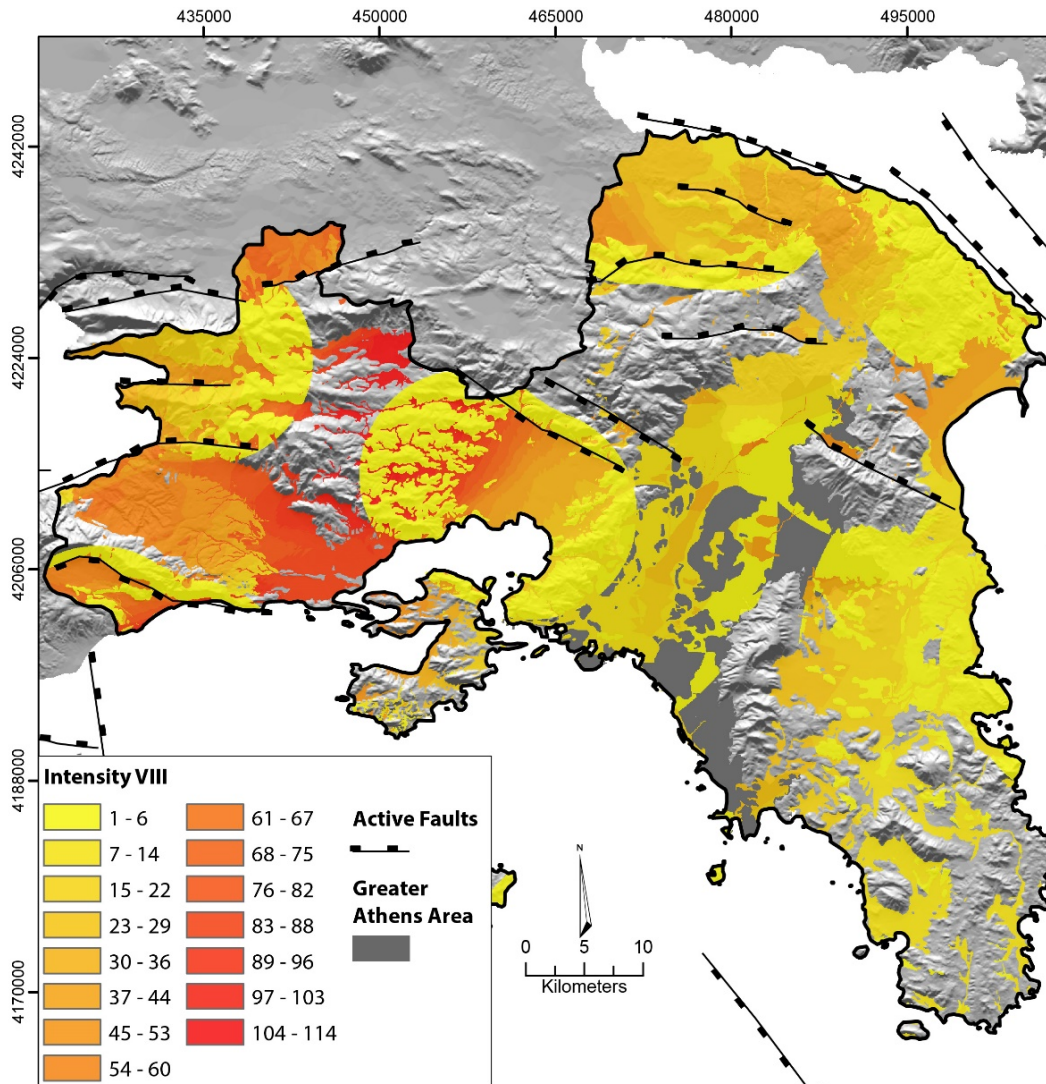


Figure 7: Seismic hazard map of Attica, showing the estimated site specific recurrence for intensities VIII (MM).

418 3.2.4. Intensity VII

419 Almost every part of the Attica mainland seems to have experienced intensity VII at
 420 least once during the last 15 kyrs, except for the Hymettus Mountain which seems to
 421 have not been shaken in intensity VII due to its bedrock geology (mostly marbles and
 422 schists) and its large distance from faults (Figure 8). Recurrence levels in the Attica
 423 mainland reach up to 150 times, mostly observed in the center of the Greater Athens
 424 Area in a NNE – SSW general direction. Even distant faults seem to affect this part of
 425 Attica which lies in the conjunction of the majority of the active faults' lower

426 intensities isoseismals. The seismic risk is increased in this area which is densely
 427 inhabited, although light industries and warehouses are also located mostly near the
 428 Kifissos River. It is noteworthy that during the Athens 1999 Mw 5.9 earthquake,
 429 severe and moderate damages were observed in the northern parts of the Kifissos
 430 riverbed, in a NNE – SSW general direction of the intensity contours (Lekkas, 2000).

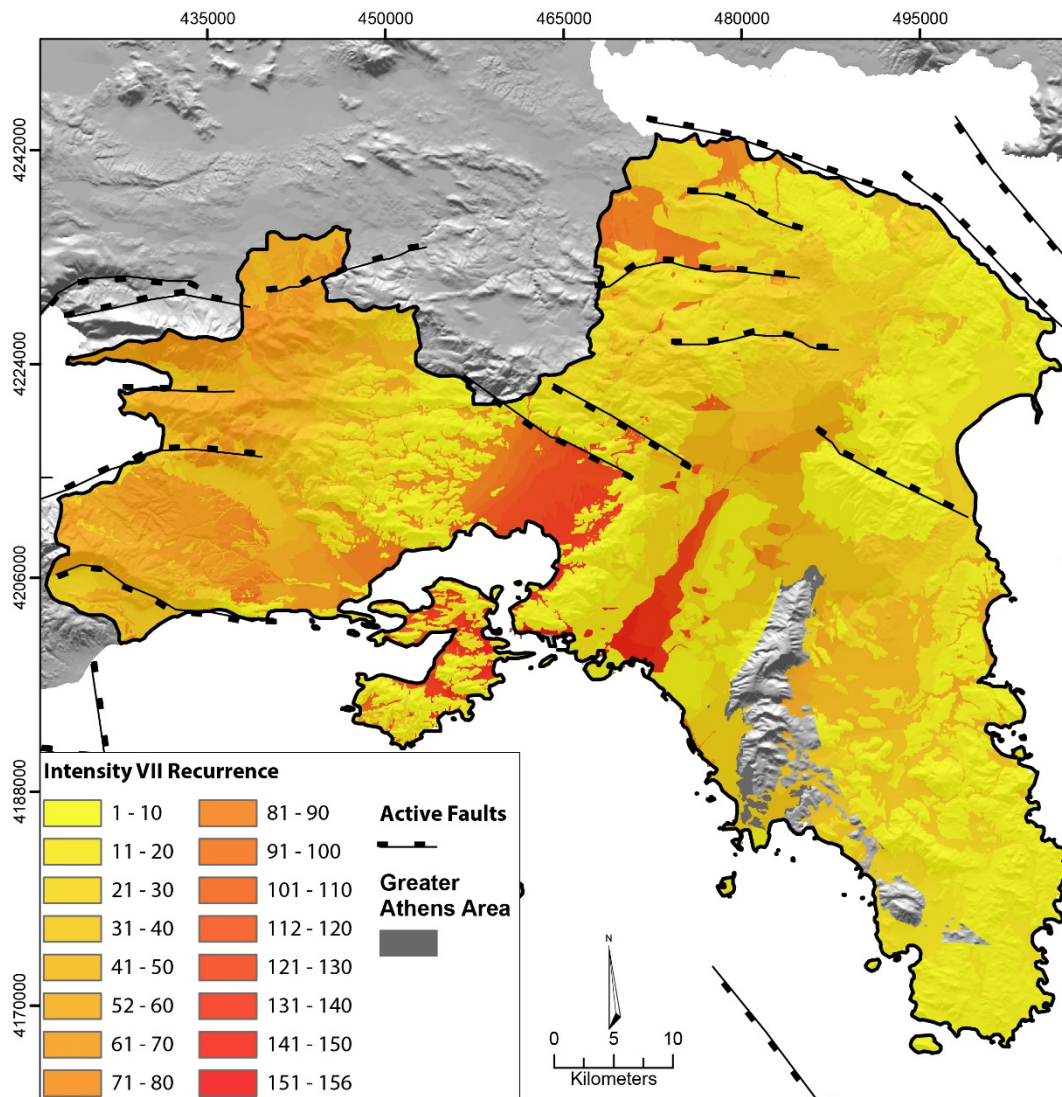


Figure 8: Seismic hazard map of Attica, showing the estimated site specific recurrence for intensities VII (MM). Nearly every suburb of the Greater Athens Area has experienced such intensities in the past 15 kyrs, including the recent 1981 earthquake sequence and the 1999 event.

431

432 **3.2.5. Maximum expected intensity map**

433 **Figure 9a** shows a combination of the intensities layers, providing information for
434 the maximum expected intensities for each locality in Attica mainland. It is important
435 to note that this map contains no information about the intensities recurrences.
436 Instead, it displays the maximum ground motions that any locality seems to have
437 experienced over 15 kyrs, even if they had occurred only once. As a result, this map is
438 valuable for defining the worst case scenario in terms of the maximum ground
439 motions expected.

440 Higher intensities (IX – X) are observed proximal to the large active faults, mostly
441 in the northern and western parts of the Attica mainland. Intensity X seems to occur in
442 areas covered by loose sediments that are close to major faults. Localities that are also
443 covered by loose sediments but lie in a further distance from large faults or close to
444 smaller faults, seem to have at least once been shaken at intensity IX. It is important
445 to note that many localities in the Greater Athens Area seem to have received enough
446 energy to shake at intensity IX over the last 15 kyrs. On the other hand, it seems that
447 the largest part of the Greater Athens has not experienced destructive ground motions
448 and the maximum expected intensities are VIII or VII.

449 **3.2.6. Maximum recurrences distribution**

450 The top quintile of the intensities VII – X recurrences is displayed in **Figure 9b**. This
451 map shows the highest (top 20%) recurrences from each intensity and the
452 corresponding spatial distribution in different colours. Thus, it depicts the locations
453 where the peak recurrences of each intensities are observed, rather than the most
454 hazardous areas in terms of maximum expected intensities. For example, the southern
455 suburbs of the Greater Athens Area seem to have experienced intensity VII more

456 times than the rest of the Athens plain, however, this is not the maximum expected
457 intensity for this area.

458 The peak recurrences for every intensity are observed in the western part of the
459 Attica mainland. The top 20% intensity X recurrence (22-27 times over 15 kyrs) is
460 constrained in a small area, only along the loose sediments of the western Attica
461 coastline, in the Corinth Gulf, close to the highly active South Alkyonides fault
462 system. The highest intensity IX recurrence (62-77 times over 15 kyrs) is observed in
463 a wider area, in the westernmost parts of the Attica mainland. As intensities decrease,
464 their peak recurrences seem to move towards the center of Attica. Intensity VIII
465 seems to occur in its maximum recurrence (91-114 times over 15 kyrs) between the
466 Corinth and the Saronikos Gulfs, while the top 20% of the intensity VII recurrence is
467 observed in the eastern part of the Thriassio plain, the NW part of the Greater Athens
468 Area and Salamina Island in the Saronic Gulf. However, it is possible that the
469 distribution of the top 20% recurrences for intensities VIII and VII in the western part
470 of Attica is underestimated, because active faults located farther offshore in the
471 Corinth Gulf are not included in the model. Furthermore, fault specific seismic hazard
472 maps are able to model events of magnitude $M > 6.0$ and as such they tend to
473 underestimate intensity VIII and predominantly intensity VII recurrence.

474 Apart from the South Alkyonides fault, it is evident that more faults contribute to the
475 total recurrence for intensities lower than X. As the intensities decrease, the
476 isoseismals increase and more faults contribute to seismic hazard. However, as
477 expected, the highest recurrences seem to be highly affected by the high slip rates of
478 the South Alkyonides fault.

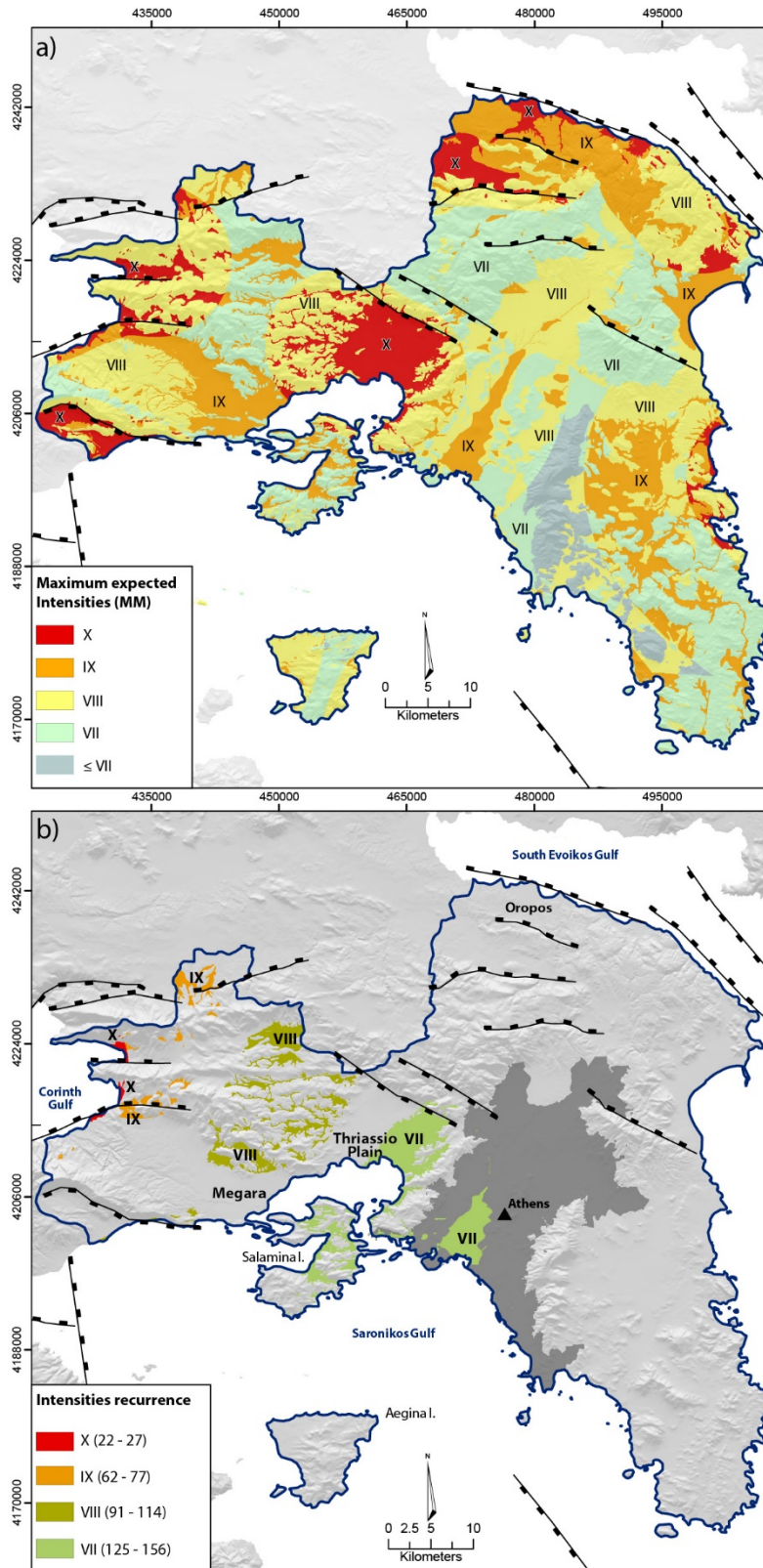


Figure 9: a) Maximum expected intensities distribution for each locality in the Attica mainland. b) the maximum intensity locations are defined by the proximity to the active faults and the surface geology Top quintile (top 20%) for the recurrences of the intensities VII – X.

479 The recurrence values in each locality of the fault specific hazard maps (Figures 5 -
480 8) can be used as input for calculating probabilities of strong ground shaking in high
481 spatial resolution, over a certain time period. Since the historic seismic record is
482 incomplete for the majority of the active faults, the stationary Poisson model can be
483 utilized for the calculation of locality specific probabilities (see also Papanikolaou, et
484 al. 2013) for each locality of the Attica mainland, based on the average recurrence
485 intervals of the intensities VII - X. If λ is the rate of occurrence of certain seismic
486 events within a time t , the probability that n events take place within such interval
487 is: $Poisson = \frac{\lambda^n e^{-\lambda}}{n}$. If the occurrence of events follows a Poisson distribution, then
488 the intervals of time t between consecutive events have an exponential distribution
489 (Udias, 1999). In this case the equation for the probability density function is:
490 $P(n) = \lambda e^{-\lambda \delta t}$, whereas the cumulative distribution function is $P = 1 - e^{-\lambda t}$
491 (Papoulis, 1991; Udias, 1999). This model is usually applied when no information
492 other than the mean rate of earthquake production is known (WGCEP, 1999).

493 The high spatial resolution of the maps allows an assignment of the λ value in
494 different scales, varying from building blocks, to Postal Code or Municipality level
495 (e.g. in Figure 10). Using the Poisson model and the λ values derived from the
496 intensities recurrence, a time-independent probability of shaking at intensities VII - X
497 can be calculated for every desired area in the map, for a given time period.

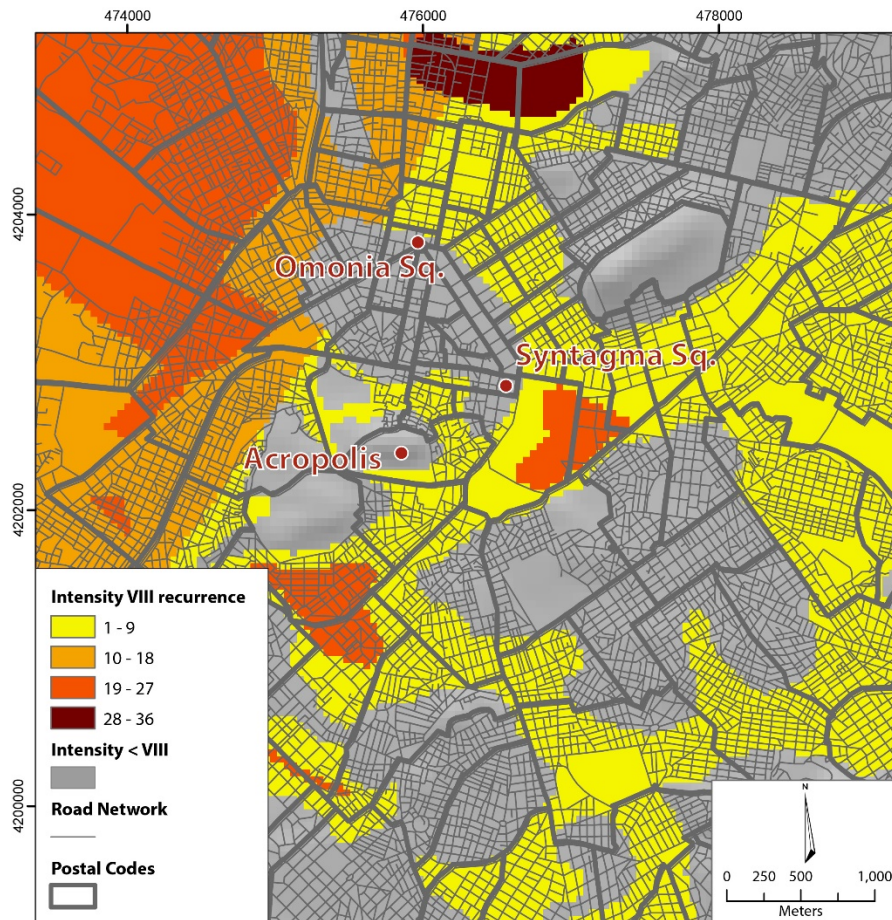


Figure 10: Fault Specific Seismic hazard map of the Athens center. Color variations show how many times these localities have received enough energy to shake at intensity VIII over the past 15kyrs. This map offers a high spatial resolution of the intensities' distribution and recurrence, therefore it allows a detailed calculation of λ values in Postal Code or even building block level.

498 **4. Errors and major assumptions**

499 Seismic hazard maps incorporate uncertainties as their predictions vary significantly,
 500 depending on the choice of many poorly known parameters (Stein, et al. 2012). The
 501 analysis of the active faults and the geologic conditions in the Attica mainland aims
 502 on reducing the major uncertainties attributed to the historic earthquake catalogues.
 503 However, assumptions made in key methodology aspects are connected to: a) faults

504 determination and fault geometry, b) fault slip rates, c) surface geology and d)
505 intensity attenuation relationships.

506 a) Both qualitative and quantitative assumptions were made for the delineation of
507 the fault database. The presented active faults are constrained in a way that
508 literature findings and personal fieldwork are in agreement to the tectonic activity
509 regime in Attica. Regarding fault lengths, the error parameters are well
510 communicated in the corresponding literature, where applicable (see Benedetti, et
511 al, 2003; Ganas, et al. 2005; Papanikolaou & Papanikolaou, 2007; Sakellariou, et
512 al. 2007; Roberts, et al. 2009; Grutzner, et al, 2016;). Faults lengths are estimated
513 around $\pm 10\%$, whereas faults derived from neotectonic maps may also include a
514 spatial error of the order of $\pm 300 - 400\text{m}$ that can reach 500m (Ganas and
515 Athanassiou, 2000). Fieldwork findings were based on 1:50,000 geological maps
516 and crosschecked using slope maps, based on the 20m contours of topographic
517 maps with a nominal accuracy of 25m in the XY axes (Ganas and Athanassiou,
518 2000).

519 One of the major questions is whether all active faults have been traced and
520 included in the database. Considering that Attica is a well-studied area with major
521 infrastructure, all major active faults have been identified. However, four potential
522 active fault structures are not taken into account in the modeling procedure (see
523 faults P1 – P4 in Figure 11 for approximate locations). It is not clear whether these
524 are active structures, due to considerably unclear indications about their existence
525 and level of activity. Indications in neotectonic maps of East Attica (Papanikolaou,
526 et al. 1995) and the South Evoikos submarine neotectonic map (Papanikolaou, et
527 al. 1989b) are not clear about the existence and throw rate regarding the P1
528 probable fault. In fact, the neotectonic map of East Attica suggests that P1 is a

529 probably inactive structure, with an overall small amount of finite throw. It seems
530 that P1 is a WNW – ESE trending structure, parallel to the Oropos fault, dipping
531 towards the center of the South Evoikos Gulf. In addition, geomorphic and
532 geologic signs about P2 and P3 faults suggest that these structures need further
533 analysis. Antoniou (2010) argues that small faults like P2 (Figure 11) may act as
534 active boundaries on the existing basins in east Attica. However, these structures
535 were characterized by Papanikolaou, et al. (1995) as “mostly inactive”. Regarding
536 P3, there is some evidence for neotectonic activity, according to Mariolakos, et al.
537 2001 and Theocharis & Fountoulis, 2002. Moreover, this structure seems to be
538 related to an offshore WNW – ESE trending fault zone with a noticeably small
539 total throw, rupturing Mesozoic sedimentary rocks and Plio-Quaternary sediments
540 (Papanikolaou, et al. 1989). Similarly, Papanikolaou, et al. (1998) describe the P4
541 fault in Aegina Island as a SW-NE trending structure. This fault seems to have an
542 offshore prolongation with a small amount of throw in the northeastern submarine
543 area (Papanikolaou et al. 1989) and forms small scarps throughout the sedimentary
544 and volcanic formations in the surface of Aegina.

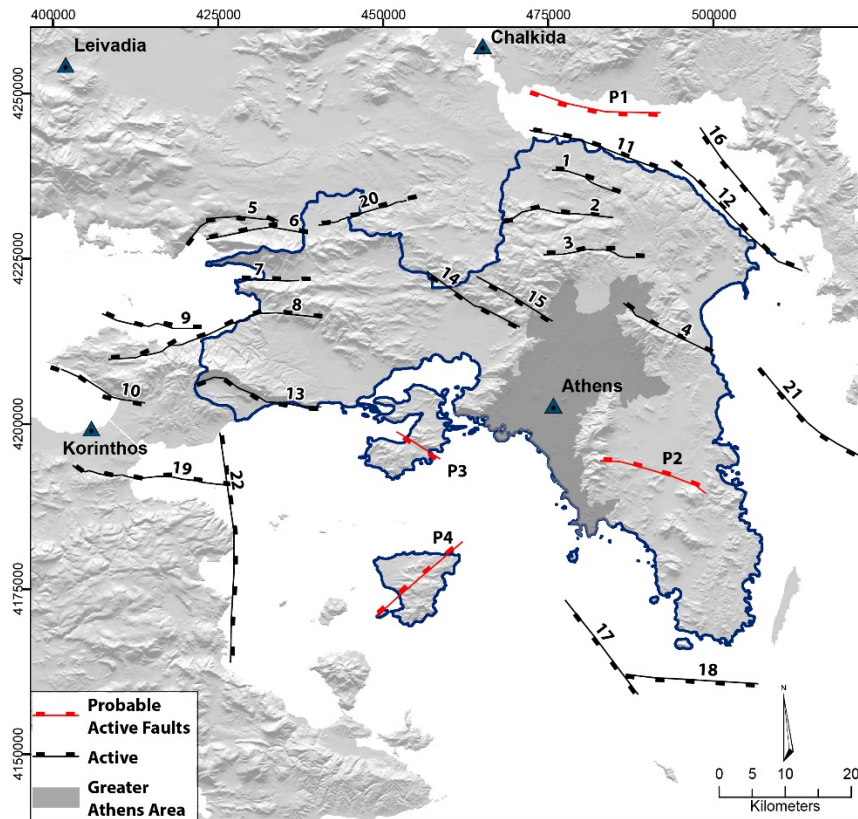


Figure 11: Probable active fault structures (red colour) in Attica region. These faults are not taken into account in seismic hazard mapping as they are either antithetic structures of major fault zones (northern part of Attica), or it is unclear whether they are active or not. In any case, their contribution to seismic hazard modeling is considerably lower than the already analyzed active structures.

545 Consequently, no significant changes would occur in the hazard maps if these
 546 faults had been included in the seismic hazard mapping of the Attica region, as
 547 their slip rate values would be less than 0.1mm/y, judging from their finite throw.
 548 This implies an earthquake recurrence of less than 3-4 times over 15 kyrs, making
 549 no considerable difference to the total recurrence values. However, since this is a
 550 GIS based methodology, new data or updated data on the already analyzed faults
 551 can be incorporated in seismic hazard scenarios, should any more information for
 552 these faults occur in the future.

553 It is also important to note that we chose to model only active faults that were
 554 capable of producing earthquakes of magnitude $M_s > 6.0$, with clear surface

555 ruptures. Indeed, earthquakes with magnitude $M_s < 5.5$ are unlikely to break the
556 surface (Michetti et al., 2000) and earthquakes of magnitude $< M_s 6.0$ are usually
557 poorly expressed at the surface, as discontinuous traces or fractures (e.g. Bonilla, et
558 al. 1984; Darragh & Bolt, 1987).

559 b) Fault slip rate values dominate the intensity recurrences of the fault specific
560 seismic hazard maps. It is of decisive importance that errors in slip rate
561 measurements are reduced in way that they do not affect the final earthquake
562 recurrence values. Already published slip rate values for active faults included
563 information about the error or minimum and maximum values (e.g. Ganas, et al.
564 2005). Both in this case, and in case of neotectonic maps, we used the average slip
565 rate values or the average finite throws and sediments thickness. **The latter was**
566 **applied on faults derived from the official neotectonic maps. Since there is no**
567 **detailed information about the sediments thickness or the active faults total throw,**
568 **long term slip rate values were extracted by combining both values. Value ranges**
569 **for both sediments thickness and faults total throw have a maximum variation of**
570 **$\pm 100\text{m}$, which results to ± 0.04 on long term fault slip rate values.** Slip rate
571 characteristics for faults derived from fieldwork depended on errors in scarp height
572 measurements. A scarp height variation of $\pm 20\%$ (see also Roberts, et al. 2004) is
573 assumed, which results to $\pm 0.2\text{mm/y}$ for a fault with a slip rate of 1mm/y .

574 c) Geological maps at 1:50,000 scale often include a standard error of ± 200 m.
575 1:100.000 scale neotectonic maps exceed ± 400 m spatial error (Ganas and
576 Athanassiou, 2000). Except for the exact fault location and length, these
577 uncertainties affect the accuracy of the spatial distribution of the strong ground
578 motions, since surface geology amplifies or attenuates the calculated intensities.
579 For the spatial distribution of the modeled intensities we used the official 1:50,000

580 Geological Maps of IGME and the 1:25,000 map of E.P.P.O. (Marinos, et al.
581 1999). These maps provide an adequate spatial analysis regarding surface geology
582 and the corresponding attenuation or amplification of the strong ground motion.
583 Furthermore, they can offer critical information about earthquake-induced
584 secondary effects, such as landslides and liquefactions.

585 d) Expected intensity at certain localities is highly sensitive to the relationships that
586 calculate the attenuation of strong ground motion with distance from the epicenter.
587 Final results can be drastically affected by the uncertainties incorporated in the
588 fault geometry (and thus in the epicenters location) and in the attenuation
589 relationships that are based in the traditional intensity scales. For example,
590 Papanikolaou (2011) quantified errors in both spatial distribution and recurrence
591 intervals of the expected intensities in the Apennines and showed that they can
592 outreach the aforementioned 20% error of the fault slip rates, modifying the
593 estimated recurrence intervals by as low as 10-25% and as high as 1000%.
594 Therefore, the attenuation relationships used, form a major source of uncertainty
595 and in several cases they overshadow all the other factors of uncertainty, even fault
596 slip-rates, which directly affect the calculated earthquake recurrences.

597 **5. Discussion**

598 **5.1 Uncertainties in intensity distribution**

599 The largest uncertainty in seismic hazard mapping lies on the attenuation
600 relationships, based on the traditional intensity scales. From a point of view, this is an
601 inevitable assumption that has to be made when intending to examine damages in the
602 built environment. On the other hand, Earthquake Environmental Effects (EEE) are

603 objective criteria indicating the severity or ground shaking in the non-built
604 environment. Since they are not influenced by human parameters, they overstep
605 problems that are inherited in traditional intensity scales, which tend to reflect mainly
606 the economic development and the cultural setting of the area that experienced the
607 earthquake, instead of its “strength” (Serva, 1994). The Environmental Intensity Scale
608 - ESI 2007 (Michetti, et al. 2007) incorporates the advantages of Earthquake Geology
609 and uses EEE for the determination of seismic intensity (Michetti, et al. 2007;
610 Reicherter, et al. 2008; Silva, et al. 2009). Moreover, it can define the intensities
611 above VII degree with a high level of accuracy as also shown in several recent and
612 historic earthquakes worldwide (e.g. Serva, et al. 2007; Tatevosian, 2007;
613 Papanikolaou, et al. 2009). New attenuation relationships for the ESI 2007 intensity
614 scale, would remarkably reduce the error incorporated in the existing seismic hazard
615 maps. Papanikolaou, et al. 2009 implemented the ESI 2007 intensity scale for the
616 1981 Alkyonides earthquake sequence in the Corinth Gulf ($M_s = 6.7$, $M_s = 6.4$, M_s
617 $=6.3$) and showed that it allows accurate assessment on sparsely populated areas. This
618 implies that ESI 2007 could be used outside of the Greater Athens Area for modeling
619 the ground shaking distribution in a higher accuracy than the traditional intensity
620 scales.

621 The implementation of the topographic amplification factor in the modeling
622 procedure, as described in Eurocode 8 for the European Union (Bisch, et al. 2011),
623 could potentially increase the accuracy on the intensity distribution in the final
624 seismic hazard maps. This factor incorporates slope instability effects, usually
625 observed on isolated cliffs and ridges with crests and can be applied on Seismic
626 Hazard Analysis based on Peak Ground Acceleration (PGA) values (values are
627 multiplied by 1.2 to 1.4). However, according to Wald, et al. (1999) and Paolucci

628 (2002), an increase of PGA by a factor ranging from 1.2 to 1.4, implies an increase of
629 MMI ranging from 0.29 to 0.53, which is less than the increase (or decrease) derived
630 from the incorporation of geological conditions. Furthermore, we performed a test
631 regarding the impact of the topographic gradient in the Greater Athens Area. The test
632 showed that less than 0.4km² of inhabited areas (or ~ 0.1% of the Greater Athens
633 Area) meet the anaglyph parameters for the application of the topographic
634 amplification factor, thus the final maps would have imperceptible changes. This
635 parameter can be incorporated in more detailed microzonation studies.

636 **5.2 Historical seismic record compared to geological fault slip data**

637 The analysis of the active faults that can sustain damage (intensities \geq VII on the
638 Modified Mercalli intensity scale) in the Attica region in case of seismic rupture, aims
639 on addressing the problems related to the incompleteness of the historical records,
640 since geological data sample much greater periods of time. The historical seismic
641 record can be used for the seismic hazard analysis where smaller or blind faults can
642 cause moderate earthquakes up to magnitude 6, with potentially damaging effects in
643 older buildings. It is clear though, that the official seismic zonation in Greece
644 (E.P.P.O.) is based only on the historical earthquake catalogue and does not consider
645 a fault specific approach.

646 Despite the inconsistencies and inhomogeneity in historic earthquake catalogues, the
647 majority of the recorded events lie in the hanging wall of the hereby modelled active
648 faults. Among them, there are few recorded strong events that could cause
649 considerable damage, especially in the eastern part of the Attica Region (Figure 12).
650 However, large uncertainties regarding the position of the instrumentally recorded
651 epicenters are evident even for recent earthquake events. For example, the most

652 recent 1999 Mw 5.9 is recorded in both NOA-UOA (National Observatory of Athens
653 – University of Athens) and AUTH (Aristotle University of Thessaloniki) catalogues,
654 but the epicentral localities lay more than 5km apart. This uncertainty is magnified
655 more than two times for the 1938 Mw 6.0 Oropos event, where the distance between
656 the epicenters from these two catalogues is 12km. suggest that the errors on the
657 location of the instrumentally recorded epicenters can reach up to 20 km for the older
658 events (1965-1980) and up to 10km for the most recent ones. Larger uncertainties
659 result for the older events approximate epicentral locations. For the period 1901-1964
660 the errors can be up to 30km but they can reach up to 50km for the older events
661 (before 1900) when the number of available macroseismic information is less than 5.
662 Stucchi, et al. (2012) also observe uncertainties larger than 50km for regional
663 catalogues that cover the time window 1000 – 1899 in the Broad Aegean area.
664 Regarding the errors in magnitude, Papazachos, et al. (2000) suggest a ± 0.25 interval
665 for the instrumental period (1911-1999).They also attribute an ± 0.35 error for the
666 historical data, when the number of available macroseismic observations (number of
667 places where the intensity is known) is ≥ 10 , otherwise the magnitude errors reach up
668 to a half of the magnitude unit. Furthermore, focal depths are not available for many
669 events recorded in the historic earthquake catalogues, thus there is a strong possibility
670 that many of the epicenters displayed in Figure 12 are actually attributed to the
671 subduction zone. Regarding the total number of historic earthquake events, there
672 seems to be no consistency, as there are events that don't exist in both catalogues.

673 In total, 9 events affecting the Attica region could be related to the analyzed faults.
674 Large uncertainties occur for 5 of them, as there are large variabilities regarding their
675 location and depth. On the contrary, 4 major events can be related to specific faults
676 with lower uncertainties. The 1981 Alkyonides earthquake sequence in the Corinth

677 Gulf ($M_s = 6.7$, $M_s = 6.4$, $M_s = 6.3$) can be attributed to South Alkyonides and
678 Kapareli faults (id No 5 and 8 in Table 3) (Jackson, et al. 1982). Moreover, the 1938
679 Oropos event ($M_s = 6.0$) could have probably ruptured the Oropos offshore fault (id
680 No 11 in Table 3, see also Papanikolaou and Papanikolaou (2007)), causing
681 considerable damage in the north part of Attika (Ambraseys and Jackson, 1990).
682 Other events, like 1705 (Figure 12b) have large uncertainties in their location, or even
683 are not included in both catalogues. For example, Papadopoulos, et al. (2002) argue
684 that the 1705 event could be located at a distance of about 30 km from the center of
685 Athens; however, the little macroseismic information available makes their epicentral
686 locations very uncertain. Ambraseys and Jackson (1997) fitted significant damage in
687 Athens and to the north of the town to the 1705 event, while for other events there
688 were no clear reports for serious damage in Athens or in other areas in Attica.

689 Eventually, 4 major events can be attributed to the fault database, suggesting that:

690 a) Due to low slip rates, the majority of the active faults may have not ruptured
691 during the last 200 or 500 years, which is the time period when historic seismic
692 catalogues are considered to be complete for earthquakes of $M \geq 6.5$ and $M \geq 7.3$
693 respectively.

694 b) There is a lack of resolution in the historic earthquake catalogues, as the number
695 of significant earthquake events is limited.

696 As a result, there is an overall spatial concurrence between the fault database and the
697 existing earthquake catalogues, for recent earthquake events. On the other hand, the
698 historic earthquake catalogues are inadequate for displaying the full extent of seismic
699 hazard, due to the lack of temporal and spatial resolution.

700 The large differences between the two catalogues shown in Figure 12 also indicate
701 that the information for recorded earthquakes, even for the most recent events like the
702 Athens 1999 earthquake, is not consistent. Thus, the association of the recorded
703 events to the known active faults need verification through further
704 palaeoseismological research.

705 **5.3 The role of the Miocene detachment in fault activity and intensities** 706 **distribution**

707 A major, now inactive, NNE-SSW striking fault system characterizes the geological
708 structure of Attica. It trends northeast and separates metamorphic rocks to the south
709 (Cycladic and Attica units) from non-metamorphosed units of the internal Hellenides
710 to the north (Papanikolaou and Royden, 2007). Although this zone acted during the
711 early and late Miocene time (Papanikolaou and Royden, 2007), it causes significant
712 local variations of strain rates. The southeastern part of Athens plain seems to be
713 under minor deformation rates, in contrast to the northwestern part, where higher
714 strain rates are observed, indicating the control of the inactive detachment on the
715 current deformation field of the region (Foumelis, et al. 2013). Moreover, this
716 detachment separates the E-W trending faults towards the western part of Attica, from
717 the NW-SE trending less active faults towards the eastern part (Papanikolaou and
718 Papanikolaou, 2007). The seismicity pattern is also influenced by the detachment, as
719 it coincides with the line that separates zone I (lowest category of seismic risk) from
720 zone II (intermediate zone) of the national seismic building code (EAK-2003, see
721 Figure 11), which has been compiled based on the seismicity level (Papanikolaou and
722 Papanikolaou, 2007).

723 Eastern Attica (the area east of the zone) lies mostly on metamorphic rocks, such as
724 marbles and schists that compose a massive, westward-dipping body. The area west of
725 the detachment (Western Attica) is mainly comprised of sedimentary rocks, such as
726 limestones and clastic formations. Recent post-alpine sediments, such as talus cones
727 and scree, that cover areas of lower altitude or even the slopes of the mountain fronts,
728 are often being used as the commonest foundation soils for urban structure (Lekkas,
729 2000).

730 Apart from the significant effect of the Miocene detachment on the neotectonic
731 structure of Attica, influencing the geometry, style and intensity of deformation
732 (Papanikolaou and Papanikolaou, 2007), it seems to have played a fundamental role in
733 the intensities distribution in case of earthquake events. During the Athens 1999
734 Mw=5.9 earthquake, the distribution of the strong ground motions and the heavy
735 building damages were concentrated in NNE-SSW oriented zones. These zones
736 coincide with or are parallel to the Miocene detachment, which seems to have
737 performed passively from the coastline of the Greater Athens Area, up to its
738 northernmost borders. High intensities, that were restricted in the areas west of the
739 detachment, were abruptly blocked and didn't enter the eastern suburbs
740 (Papanikolaou, et al. 1999; Marinou, et al. 1999b; Lekkas, 2000).

741 In this study, two parameters attributed to the effects of the detachment influenced
742 the intensities distribution. The first has to do with the different fault orientation and
743 activity on either sides of the detachment. Higher intensities and recurrence values are
744 observed in the western parts of the Attica mainland (see also Figures 5 and 6), due to
745 higher fault slip rate values. On the contrary, they lower intensities seem to affect the
746 eastern part of the Greater Athens Area or even the easternmost parts of Attica. The
747 second has to do with the loose sediments along the Kifissos riverbed, that flows

748 parallel and near to the detachment. This part of Attica seems to have been shaken
749 several times at intensities from VII to IX (see also Figures 6-8) while the intensities
750 distribution are in agreement with the observed values during the Athens 1999
751 earthquake event.

752 **5.4 Comparison with existing macroseismic intensity data from historic** 753 **earthquake events**

754 The difficulties and constraints on the comparison of the results with the available
755 macroseismic data lie on two major factors. Firstly, the deficiencies in spatial
756 resolution of the macroseismic intensity, especially for past events, affect the
757 comparison regarding the intensities distribution. Secondly, the incompleteness of the
758 existing earthquake catalogues makes it difficult to compare the recurrence values
759 over large periods of time, even for lower intensities (VIII or VII). Moreover, fault
760 specific seismic hazard maps are able to model events of magnitude $M > 6.0$ and as
761 such they tend to underestimate intensity VIII and predominantly intensity VII
762 recurrence. Indeed, events of lower magnitude are associated to the background
763 seismicity and can sustain moderate damage in a limited area. However, they can't
764 produce intensities as high as IX on the Modified Mercalli Scale. Also it is possible
765 that the fault specific based recurrences for intensities VIII and VII in the western part
766 of Attica are underestimated, because active faults located farther offshore in the
767 Corinth Gulf are not included in the model. In any case, there could be a comparison
768 of the fault specific seismic hazard maps with the existing descriptions of the damages
769 distributions for recent earthquake events.

770 Four earthquake events affecting parts of the Attica region are recent enough to
771 provide data for macroseismic intensity distributions. The 1938 Mw 6.0 Oropos is

772 reported as an intensity VIII (MM) event in areas close to the epicentre, at Northern
773 Attica (Ambraseys and Jackson, 1990). The central and southern parts, including
774 Athens, experienced lower intensities (VI) during the same event. During the
775 February Alkyonides earthquake sequence in the Corinth Gulf ($M_s = 6.7$, $M_s = 6.4$),
776 intensity VIII occurred in the town of Megara at the western parts of Attica, while the
777 Greater Athens Area experienced similar or lower intensities (VIII – VII). During the
778 March 1981 event ($M_s = 6.3$), intensity VII occurred near the Greater Athens Area
779 (Antonaki, et al. 1988). A more detailed picture of the intensities distribution during
780 the Athens 1999 Mw 5.9 earthquake is available by Lekkas (2000). He shows that the
781 highest intensity values (VIII – IX) are observed in a limited zone over the northern
782 parts of the Kifissos River sediments, mostly in NNE-SSW orientation. These areas fit
783 well to the ones that are shown to have experienced maximum intensities of VIII – IX
784 in [Figure 9a](#). Although the observed intensities were recorded using the E.M.S.-1998
785 scale, they were directly converted to the MM Intensity scale for comparison
786 purposes, according to Musson, et al. (2010).

787 Regarding the recurrence values, the historic earthquake catalogues are considered
788 complete for less than 200 years for such events. However, based on these historic
789 events, a minimum return period of 100 years is observed for intensity VII in the
790 Greater Athens Area and for intensity VIII in the western parts of Attica. A minimum
791 200 years return period is observed for intensity VIII in the northern Attica and in
792 limited zones in the Greater Athens Area. Intensity IX is also observed in sparse
793 locations in the Greater Athens Area and in the westernmost parts of Attica mainland.
794 The findings for intensity VII in Athens agree with Papaioannou and Papazachos
795 (2000), who suggest that this area shakes at such intensities every 110 years.

796 However, there is a large difference for intensity VIII, as they suggest that the return
797 period outreaches 1000 years.

798 Based on the fault specific seismic hazard maps, the same localities that experienced
799 intensity VII during the 1981 series of 3 earthquakes (February - March) and the 1999
800 event show a return period from 200 years (western Attica) and 170 years (Megara),
801 to 106 years (central part of the Attica plain, see also Figure 8). For the areas that
802 have experienced intensity VIII during the February – March events, the return
803 periods vary from 240 years in the western part of Attica, to more than 280 years in
804 the central part and 440 years for the northern part of Attica (Figure 9a). Intensity IX
805 seems to have a return period that varies from 714 to 1360 years in the same areas that
806 were shaken in such intensities during the 1999 earthquake event and as low as 230
807 years for the westernmost part of Attica. Despite the fact that intensities VII and VIII
808 are underestimated in the fault specific seismic hazard maps (see also Chapter 3.2.6),
809 there is an agreement with the findings of Papaioannou and Papazachos (2000) for the
810 recurrence of intensity VII in Athens. However, there is a large difference on higher
811 intensities, as they suggest a 1000 year return period of intensity VIII in Athens,
812 which is more than double comparing to the results of the fault specific hazard maps
813 in most localities of the Greater Athens Area.

814 The differences between the historic catalogues and the seismic hazard maps based
815 on geologic data indicate the need for longer observation time periods and higher
816 spatial resolution in seismic hazard assessment.

817 **5.5 Technical constraints on GIS processes**

818 Seismic hazard mapping is primarily based on the perception of the spatial
819 distribution of hazard. Final products, such as high spatial resolution seismic hazard

820 maps, are developed under complex GIS techniques. In this study we developed a GIS
821 database for the active faults characteristics, which also allowed us to apply various
822 GIS tools and techniques for the creation of the seismic hazard maps. We used
823 relative positions along the linear fault objects to store the geographic locations of the
824 earthquake distribution along strike each active fault line and from that point, we
825 automated the whole procedure in order to simplify the whole mapping process.
826 Existing tools were combined in order to develop a new powerful tool that
827 significantly reduces the time and inherent complexity in spatial analysis techniques,
828 allowing a consistent reproduction of the desired map outcomes. Moreover,
829 modifications regarding faults' activity, attenuation relationships and surface geology
830 can be easily implemented, while a full overview of the errors and assumptions
831 incorporated in seismic hazard mapping is possible. In any case, the accuracy of the
832 final maps depends on the main errors and assumptions already mentioned.

833

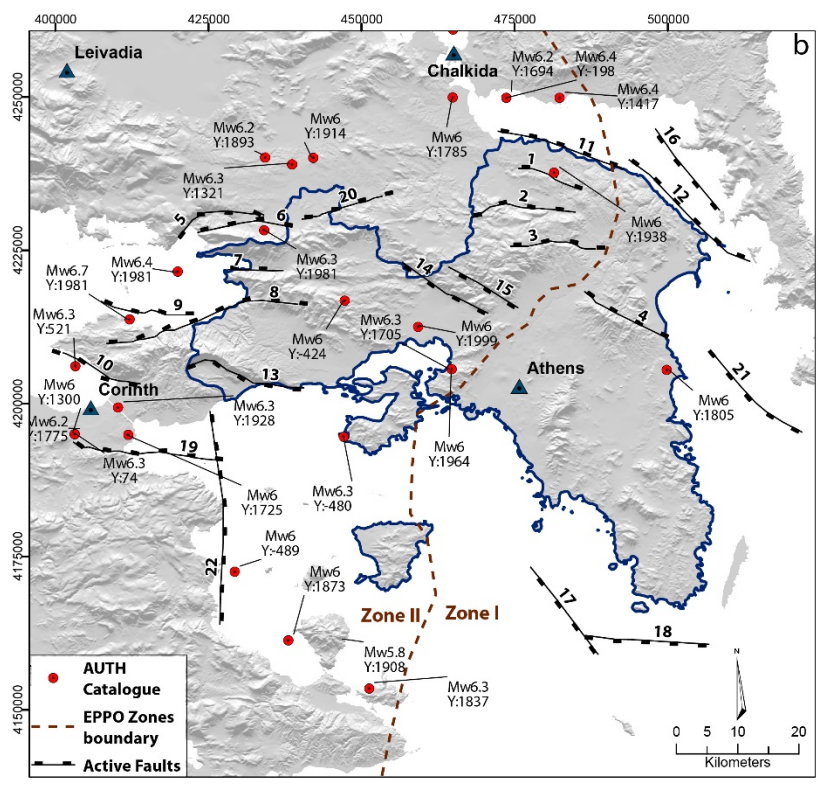
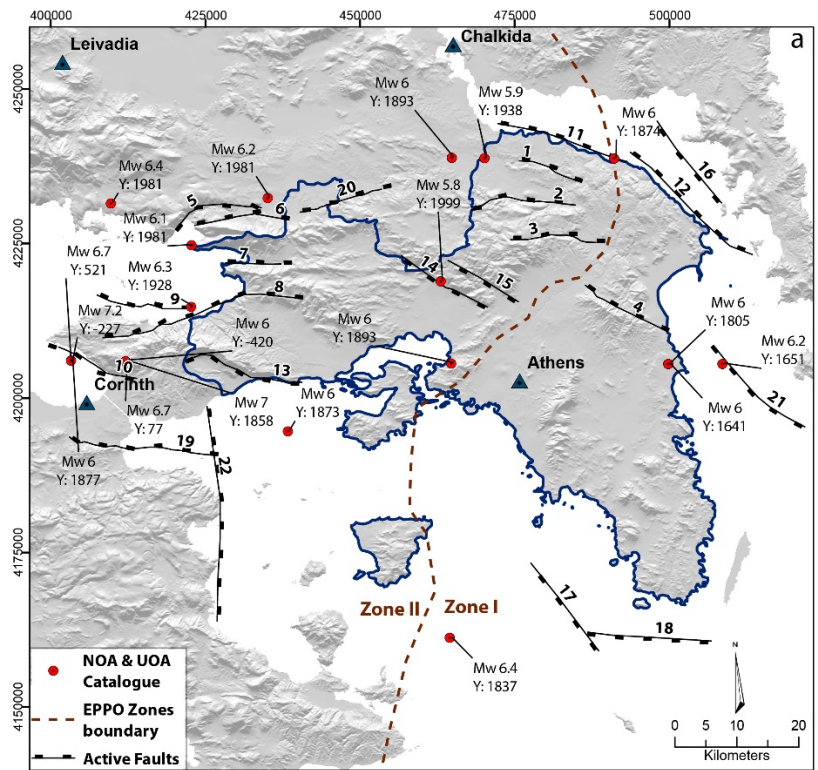


Figure 12: Historical earthquake record from a) the National Observatory and University of Athens (NOA&UOA) and b) the Aristotle University of Thessaloniki, for shallow earthquakes of magnitudes $M_w > 6$ in comparison to active faulting in the Attica Region. The Athens 1999 and Oropos 1938 events are displayed in the NOA& UOA catalogue, although they are recorded as $M_w 5.8$ and $M_w 5.9$ events respectively. Focal depths are not available for the majority of the events in both catalogues, thus events with focal depth > 20 km might be also displayed. Both catalogues are complete for $M_w \geq 7.2$ since 1500 and for $M_w \geq 6.5$ since 1845. Active faulting is taken from

834 **6. Conclusions**

835 Four high spatial resolution seismic hazard maps have been developed for the region
836 of Attica. These maps display both the spatial distribution and the recurrence, over 15
837 kyrs, of the intensities VII – X (MM intensity scale). They are based on a database of
838 22 active faults that could affect Attica region in case of seismic rupture. The majority
839 of these faults have relatively low slip rates and the Greater Athens Area lies mostly
840 on the active faults footwall. The spatial distribution of hazard depends on soil
841 conditions for intensities X and IX and is governed by the distance from faults for
842 intensities VIII and VII.

843 The Attica mainland seems to have been exposed to intensity X for more than 20
844 times in the last 15 kyrs, along the west coastline, in Corinth Gulf. Intensity IX is
845 expected to have occurred up to 77 times over 15 kyrs in the westernmost parts of the
846 Attica mainland. The highest recurrences for intensity VIII (114 times over 15 kyrs)
847 are expected between the Corinth and the Saronikos Gulfs. The eastern part of the
848 Thriassio plain, the NW part of the Greater Athens Area and Salamina Island in the
849 Saronikos Gulf seem to have experienced intensity VII for up to 156 times over 15
850 kyrs. Large residential districts, even in the Greater Athens Area, have been shaken in
851 high intensities (VIII – IX) for at least 10 times in the last 15 kyrs. In particular,
852 intensity IX distribution is significant in the western parts of the Greater Athens Area
853 and in sparse places in the eastern parts of the Athens plain. This is attributed to the
854 loose alluvial sediments of Kifissos River, along with Upper Pliocene lake sediments
855 at Chalandri and surrounding areas. Intensity VIII distribution depends both on large
856 and small faults, so an increase of recurrence values (over 100 times in the last 15
857 kyrs in the western parts) is observed in Attica main land, compared to intensities X
858 and IX. Almost every part of the Attica mainland seems to have experienced intensity

859 VII at least once during the last 15 kyrs. Recurrence levels reach up to 150 times, and
860 are mostly observed in the center of the Greater Athens Area in a NNE – SSW general
861 direction. Overall, the maximum expected intensities appear in the northern and
862 western parts of Attica in high recurrences. On the other hand, the eastern part of
863 Attica is possessed mostly by lower intensities, in low recurrences.

864 Regarding the seismicity record, there is an overall spatial concurrence between the
865 fault database and the existing earthquake catalogues, for recent earthquake events.
866 On the other hand, the historic earthquake catalogues are inadequate for displaying
867 the full extent of seismic hazard, due to the lack of temporal resolution, highlighting
868 the necessity for fault specific seismic hazard assessment.

869

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874 **7. References**

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