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# PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR IRAQ

T. Onur, R. Gok, W. Abdulnapby, A. Shakir, H. Mahdi, N. Numan, H. Al-Shukri, H. Chalib, T. Ameen, N. Abd

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## Disclaimer



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# PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR IRAQ

TUNA ONUR, RENGIN GOK, WATHIQ ABDULNABY, AMMAR M. SHAKIR, HANAN MAHDI, NAZAR M. S. NUMAN, HAYDAR AL-SHUKRI, HUSSEIN K. CHLAIB, TAHER H. AMEEN, NAJAH A. ABD

## INTRODUCTION

Probabilistic Seismic Hazard Assessments (PSHA) form the basis for most contemporary seismic provisions in building codes around the world. The current building code of Iraq was published in 1997. An update to this edition is in the process of being released. However, there are no national PSHA studies in Iraq for the new building code to refer to for seismic loading in terms of spectral accelerations. As an interim solution, the new draft building code was considering to refer to PSHA results produced in the late 1990s as part of the Global Seismic Hazard Assessment Program (GSHAP; Giardini et al., 1999). However these results are: a) more than 15 years outdated, b) PGA-based only, necessitating rough conversion factors to calculate spectral accelerations at 0.3s and 1.0s for seismic design, and c) at a probability level of 10% chance of exceedance in 50 years, not the 2% that the building code requires. Hence there is a pressing need for a new, updated PSHA for Iraq.

Recognizing this need, in 2013 the U.S. Department of Energy through Lawrence Livermore National Laboratory (LLNL) funded a project to engage and train local scientists in Iraq to install new equipment, to improve the quality of seismic monitoring and reporting, and to modernize seismic hazard mapping efforts in Iraq. In 2014, an initial four-day workshop was conducted in Erbil, Iraq to present the planning to various participants from Iraqi universities and other research organizations. This workshop was followed by a smaller hands-on workshop at University of Arkansas at Little Rock, AR in 2015, specifically focusing on and covering all aspects of PSHA. Following the workshop we started a PSHA project that culminated in sharing the preliminary results with the Iraqi government and a consideration of the newly generated hazard maps to form the basis for the new building code of Iraq.

Iraq lies in the northern portion of the Arabian Plate bounded in the east and north by the Bitlis-Zagros Fold and Thrust Belt, where the convergent tectonic boundary between the Eurasian and Arabian plates generates intense earthquake activity. The rest of Iraq is largely located on Arabian Platform, away from major plate boundaries. This study systematically compiles all available data on local seismicity, tectonics, and ground motion attenuation characteristics of the region; and builds a flexible framework to enable a contemporary probabilistic seismic hazard assessment to be carried out with the engagement of local scientists. The PSHA framework developed for this project was used as a blueprint for ongoing training in the form of weekly teleconference meetings, and finally to produce seismic hazard maps to be used in the new building code.

The PSHA framework used in this project has two main components: 1) seismic source characterization, and 2) ground motion characterization. Seismic source characterization requires compilation of all available information on tectonic setting of the region, active faults and a comprehensive earthquake catalogue in terms of moment magnitude, Mw.

## ACTIVE TECTONICS IN IRAQ

Iraq lies in the northern portion of the Arabian Plate (Figure 1) bounded in the north and east by the Bitlis-Zagros Fold and Thrust Belt, where the convergent tectonic boundary between the Eurasian and Arabian plates generates intense earthquake activity. The rest of the country is largely located on the Arabian Platform, away from major plate boundaries. The Dead Sea fault system, a major left-lateral transform fault forms the western boundary of the Arabian Platform, about 250km away from the westernmost part of Iraq. Another significant tectonic feature in the region is the Makran Subduction Zone; however the closest edge of the potential rupture zone is more than 1,000km southeast of Iraq.

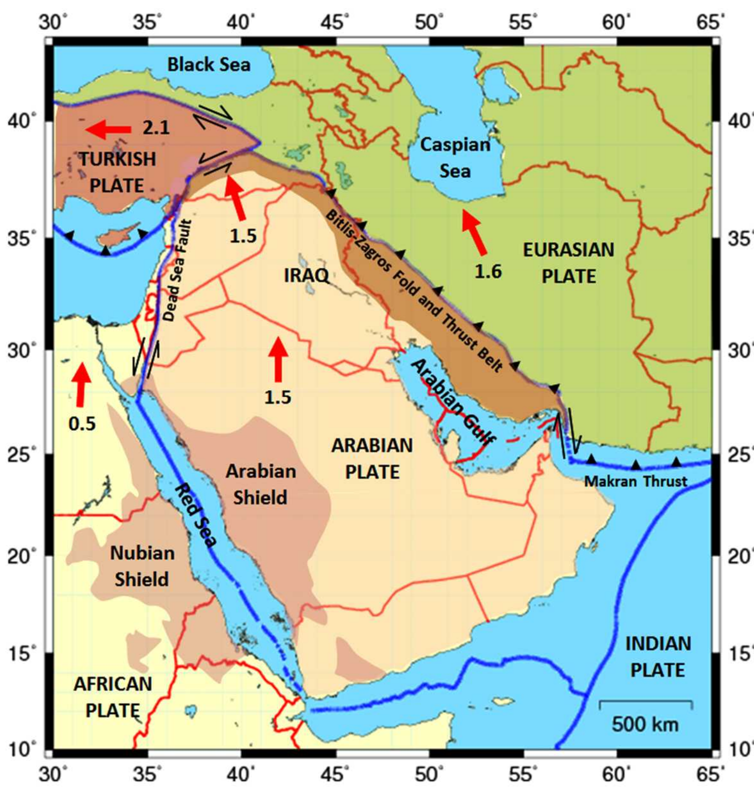



*Figure 1. Tectonic Setting of Iraq and Environs (red arrows indicate plate motions in cm/year)*

Iraq is generally divided into three tectonic zones (see, for example, Numan et al., 1998; Fouad and Sissakian, 2011). These divisions (Figure 2), from northeast to southwest are: 1) the

Fold and Thrust Belt, 2) the Mesopotamian Foredeep, and 3) the Inner (Stable) Arabian Platform.

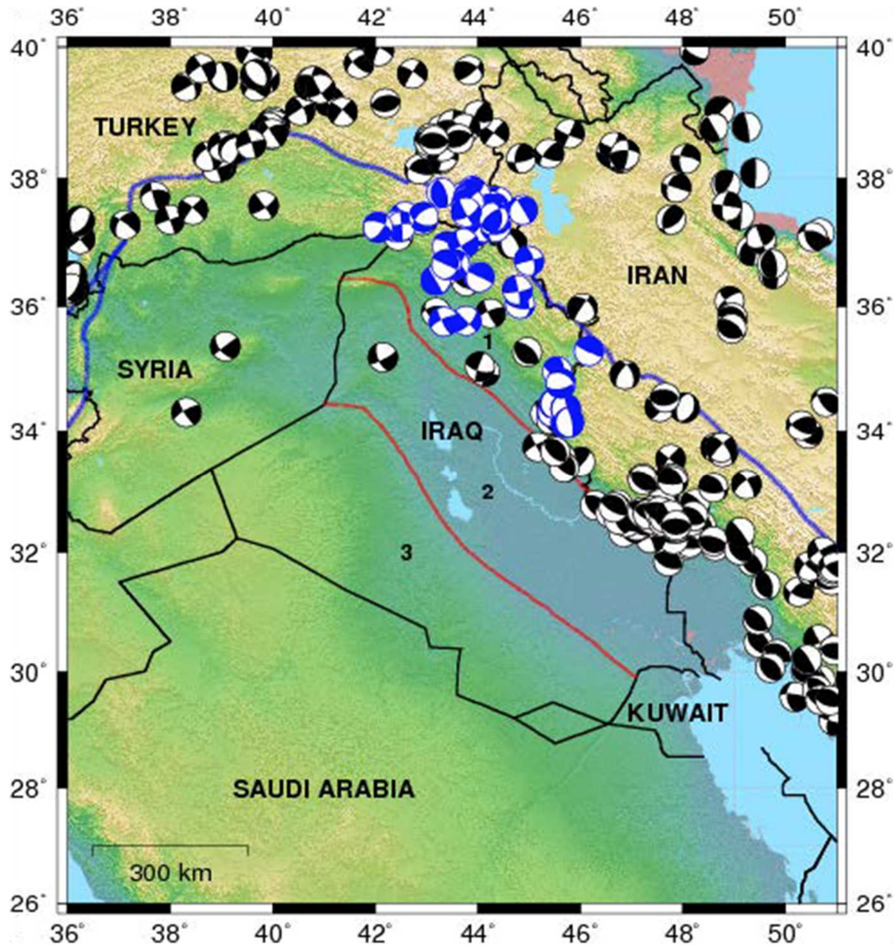



*Figure 2. Focal Mechanisms (after Abdulnaby et al (2014) in blue and GCMT in black) and Tectonic Divisions (after Fouad and Sissakian, 2011) in Iraq: (1) Fold and Thrust Belt, (2) Mesopotamian Foredeep, and (3) Inner (Stable) Arabian Platform.*

The Bitlis-Zagros Fold and Thrust Belt of the Alpine Orogen is a seismically active zone (Jackson et al., 1981; Hessami and Jamali, 2006) with intense earthquake activity. Here, the northward moving Arabian Plate is in oblique collision with the Turkish and Iranian plates along the NW-SE trending suture zone between the colliding plates. The oblique collision results in stress partitioning of the northward stress of the Arabian Plate movement into a NE-SW trending stress perpendicular to the direction of the suture zone, and a NW-SE trending stress parallel to the direction of the suture zone (Numan, 1997). In this region, many of the NE-SW trending (transverse) faults are active, such as the Lower Zab Fault and the Diyala River Fault, as well as the listric (longitudinal) faults that are parallel to the fold axes. According to Abdulnaby et al. (2014) much of the faulting in recent earthquakes is of strike slip, oblique slip, and thrust mechanism.

The Mesopotamian Foredeep forms the northeast edge of the Arabian Platform, however it differs tectonically from the more stable Inner Arabian Platform to the southwest. The

Mesopotamian Plain contains several buried structures that are evident through their effects on the Quaternary stratigraphy and present geomorphological landforms indicating neotectonic activity of the plain (Fouad and Sissakian, 2011). The Quaternary alluvial sediments of the Tigris and Euphrates River systems cover the central and southeastern parts of the Mesopotamian Foredeep completely, forming a thick sedimentary sequence (Sissakian, 2013). The derived seismic models indicate that surface Quaternary sediments thicken southeastwards, from 3km deep in Mosul to 8km deep in Kuwait (Gök et al., 2008). The depth of the basement also changes from 8km (+/- 2km) within the platform in the west of Iraq to 14km (+/- 2km) within the Zagros foreland in the northeast and the Mesopotamian Plain in the southeast (Numan, 1997; Sissakian, 2013). Seismically active faults in the Mesopotamian Foredeep include the Badra-Amarah Fault (along the Iraq-Iran border), Euphrates Fault (represents the tectonic boundary between the Stable Platform and the Mesopotamian Foredeep), Hummar Fault (north of Basra), Al-Refaee Fault, and Kut Fault.

The Inner Arabian Platform constitutes a stable continental region. Although faults do exist in this zone, recent deformation is much less significant and Quaternary activity on the faults is less evident.

Although active faults are identified in the Fold and Thrust Belt and Mesopotamian Foredeep as mentioned above, for most of these faults information that is necessary to characterize the complete geometry and recurrence rate of earthquakes is not available at the required level of detail. Hence, more research is needed before they can be used as fault sources in PSHA.

## EARTHQUAKE CATALOGUE

Since specific faults and their activity rates cannot be included in the PSHA due to scarceness of information, a comprehensive earthquake catalogue becomes a key starting point for a national PSHA for Iraq.

Although global catalogues are available, they are sparse in terms of local earthquakes in this region. For example, the ISC-GEM catalogue has 87 earthquakes for our study region (26N-40N, 36E-51E) between the years 1900 and 2009 (inclusive) with magnitudes between 5.3 and 7.8 (including the supplement provided with the ISC-GEM catalogue). Our compilation includes 237 earthquakes over the same time period and magnitude range.

The most recent regional effort for cataloguing earthquakes in terms of Mw in this area is the Earthquake Model of the Middle East (EMME) project under the auspices of Global Earthquake Model (GEM) (Zare et al., 2014). Although EMME catalogue is rich in terms of earthquakes in the northern portion of our study area (i.e. areas in Eastern Turkey), it is relatively sparse south of the 37.5N latitude.

Consequently, compilation of a comprehensive earthquake catalogue for Iraq was undertaken as part of this project. The Reviewed ISC Bulletin was used as a base and further supplemented by the following sources: a) pre-1964: Fahmi and Al Abbasi (1989), Ambraseys (2001), Zare et al. (2014), Riad and Meyers (1985), and USGS Centennial (Engdahl and Villaseñor, 2002) catalogues, b) post-1976: Global Centroid Moment Tensor (GCMT) solutions,

c) post-1989: Mw calculated by LLNL using coda calibration technique (for nearly 1,000 earthquakes of Mw > 2.5), and European-Mediterranean Seismological Centre (EMSC) data published as the Euro-Med Bulletin, and d) post-2005: Abdulnaby et al. (2014).

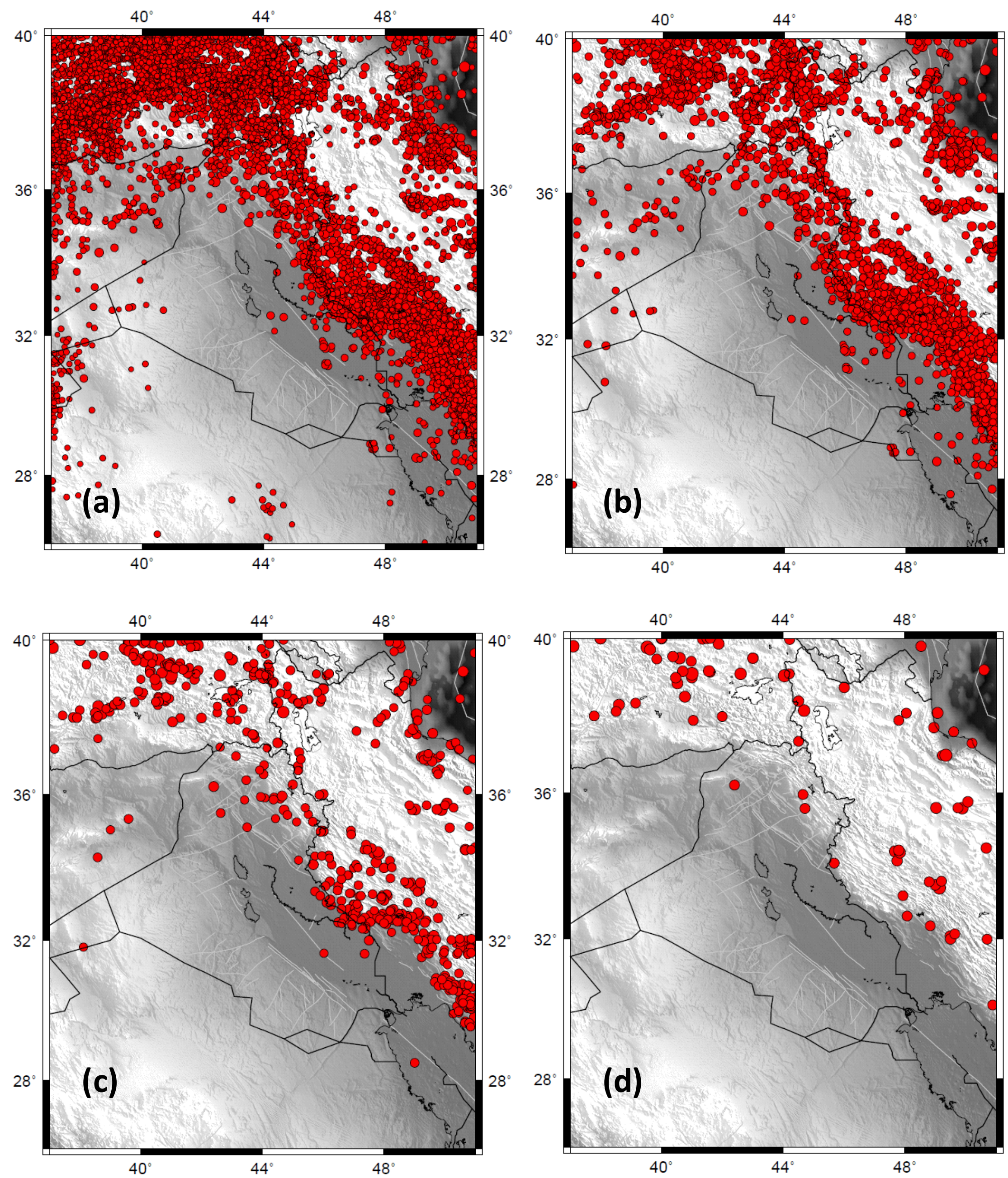



*Figure 3. Catalogue of Instrumental Seismicity in Iraq in terms of Mw. (a) Mw > 3, (b) Mw > 4, (c) Mw > 5, and (d) Mw > 6.*

Further details of the catalogue compilation can be found in Onur et al. (2016). The resulting catalogue encompasses the region between 36E-51E longitudes and 26N-40N latitudes, and includes about 16,000 events of magnitude 3.0 and larger, and about 4,000 events of magnitude 4.0 and larger between the years 1900 and 2009 inclusive (Figure 3). The geographic extent of the catalogue's coverage is intended to include sources of seismicity beyond Iraq's borders, but may be damaging inside the territory of Iraq. The catalogue is harmonized to Mw. The reason why Mw is the preferred magnitude is twofold: 1) almost all contemporary ground motion prediction equations used in PSHA are in terms of Mw, 2) Mw provides a better quantification of the size of earthquakes, particularly large earthquakes, for which other magnitude scales tend to saturate. However conversion from other magnitude scales to Mw is fraught with uncertainties. Hence the compilation effort described in Onur et al. (2106) aimed to include direct Mw calculations to the greatest extent possible, rather than converting from other magnitude scales to Mw, particularly for large earthquakes.

The completeness intervals for the entire catalogue are as follows: Mw6.5 and above are complete since 1900, Mw6.0 and above since 1924, Mw4.2 and above since 1965, Mw3.4 and above since 1995, and Mw3.2 and above since 2006.

Roughly 90% of the earthquakes in the catalogue have a depth of between 0 and 35km. This indicates that majority of earthquakes in the region exhibit shallow crustal seismic activity.

### SEISMIC SOURCE ZONES

Since seismic activity rates and detailed geometry for known active faults in Iraq were not available, area sources were used in the PSHA, within which seismicity rates were assumed to be uniform. When delineating the source zones (Figure 4), tectonics of the region as well as the seismicity patterns were taken into account.

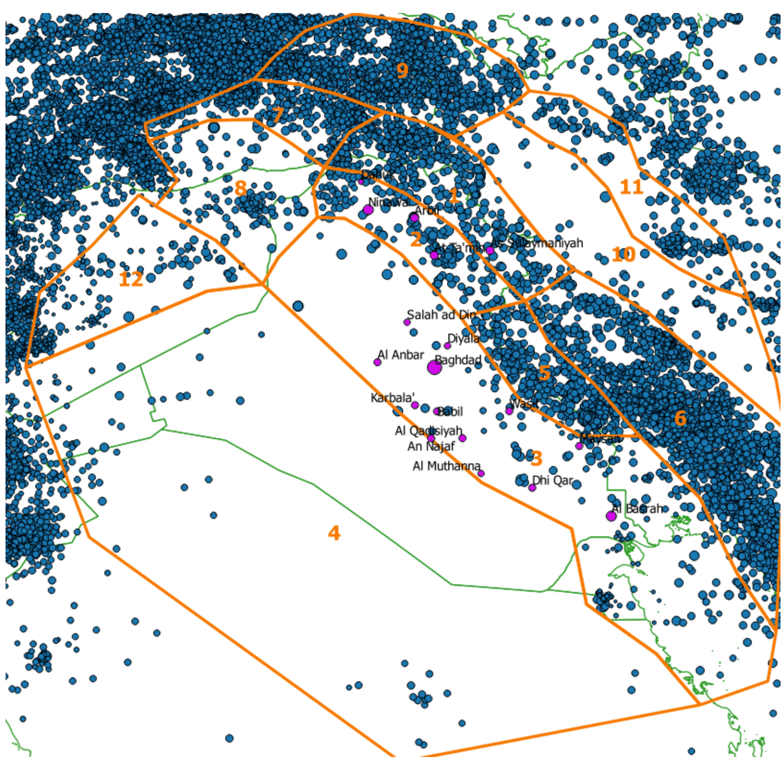


*Figure 4. Delineation of Seismic Source Zones*

Zones 1, 6, and 7 characterize, in three different segments, the main axis of the Bitlis-Zagros Fold and Thrust Belt. Zones 2 and 5 form the southern edge of the Bitlis-Zagros Fold and Thrust Belt. Although they are of similar tectonic origins, Zone 5 to the south has significantly more present day activity than Zone 2 to the north. Zone 3 roughly coincides with the Mesopotamian Foredeep. Zone 4 represents the Stable Platform. Zone 8 characterizes the seismicity in and around Sinjar Uplift and Zone 12 along the Palmyrides and the northernmost section of the Euphrates Fault System. Zone 9 captures the intense seismic activity in Eastern Turkey. Zones 10 and 11 represent relatively low seismic activity to the northeast of Zagros Fold and Thrust Belt. The detail level of geographic characterization of the zones generally gets lower for zones that are relatively distant from Iraq (e.g. Zones 9, 10, 11 and 12).

Maximum magnitudes were assigned to each source zone based on various considerations such as maximum historical earthquake inside the zone and geometry of known faults within each zone. For the sources characterizing the multiple segments of the Bitlis-Zagros Fold and Thrust Belt, the lengths of the segments were used as a guiding consideration as well. The geometry and length of the faults were taken into account using Wells and Coppersmith (1994) relations between rupture length/area and magnitude.

The uncertainty in the maximum magnitudes was captured by assigning the central maximum magnitude estimate a weight of 50%, and the lower and higher maximum magnitude estimates 25% weight each. Generally, no zone was assigned a central maximum magnitude lower than Mw7.4. This is in light of recent events around the world where Mw > 7 earthquakes can happen even in relatively low seismic activity parts of the world (there are at least eight events in USGS's instrumental earthquake catalogue for stable continental regions globally, including the Mw7.6 Bhuj earthquake in India).

For each of the sources, Gutenberg-Richter recurrence parameters (a- and b-values) were calculated for each source zone using the catalogue developed for this project (Table 1; Figure 5). Truncated Gutenberg-Richter relations were used for the hazard analyses with a minimum magnitude of 4.4 for all sources, and maximum magnitudes varying by source (Table 1).

*Table 1. Recurrence Parameters for Source Zones*

| SOURCE ZONE NO. | SOURCE ZONE NAME | $M_{MAX}$ | G-R B-VALUE | G-R A-VALUE |
|---|---|---|---|---|
| 1 | Bitlis Zagros Thrust A | 7.8 | 1.1316 | 5.4698 |
| 2 | Unstable Shelf A | 7.6 | 1.1996 | 5.3674 |
| 3 | Unstable Shelf B | 7.6 | 1.2236 | 5.4069 |
| 4 | Stable Shelf | 7.4 | 1.5743 | 5.9980 |
| 5 | Zagros A | 7.8 | 1.0439 | 5.0625 |
| 6 | Southern Zagros | 8.0 | 1.0719 | 5.7632 |
| 7 | Bitlis Zagros Thrust B | 7.8 | 1.0779 | 4.9800 |
| 8 | Sinjar Uplift | 7.6 | 1.2143 | 5.4451 |
| 9 | Eastern Turkey | 7.9 | 0.9696 | 4.9833 |
| 10 | Northeast of Zagros | 7.6 | 0.7987 | 3.1741 |

| | | | | |
|---|---|---|---|---|
| 11 | Iran Intermediate | 7.8 | 0.8324 | 3.6274 |
| 12 | Palmyrides | 7.8 | 1.5743 | 5.9980 |

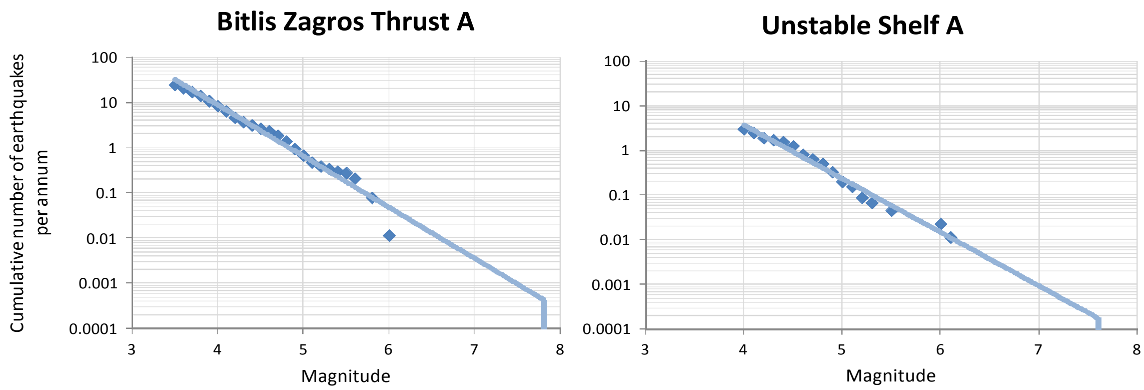



*Figure 5. Cumulative number of earthquakes per annum plotted against magnitude for two example source zones*

Uncertainties in source parameters listed in Table 1 are accounted for in a logic tree framework (Figure 6). In addition, uncertainty in depth of the shallow crustal seismicity is accounted for by assigning 50% weight to 10km source depth, 25% to 15km source depth and 25% to 5km source weight (Figure 6).

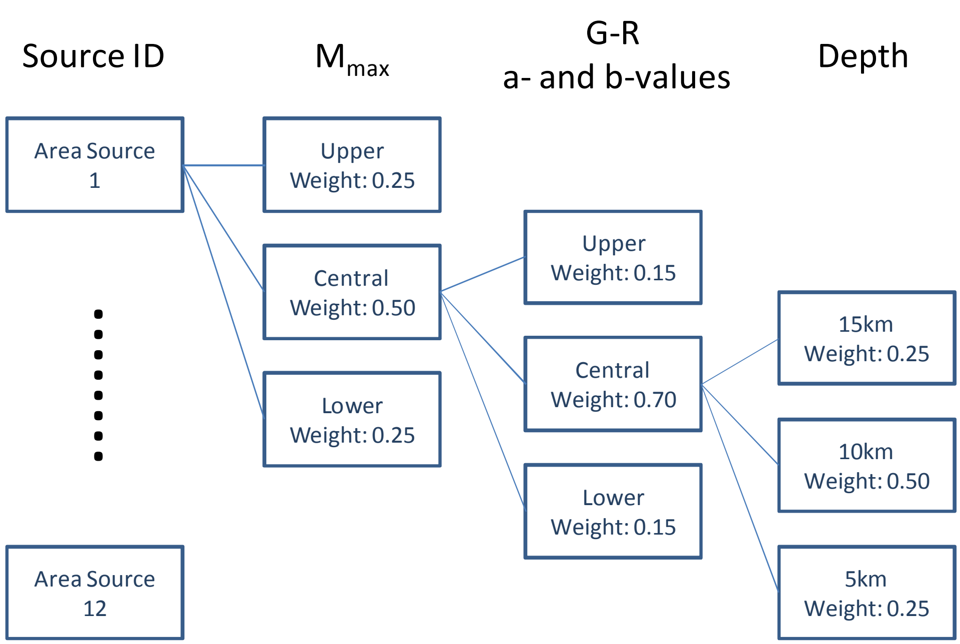



*Figure 6. Logic Tree Used for Source Characterization*

## GROUND MOTION CHARACTERIZATION

Iraq lies in the northern portion of the Arabian Plate, bounded in the east and north by the Bitlis-Zagros Fold and Thrust Belt, where the convergent tectonic boundary between the Eurasian and Arabian plates generates intense earthquake activity. South of this narrow belt of activity that falls within the territory of Iraq, the rest of the country is largely located on Arabian Platform, away from major plate boundaries.

The choice of ground motion prediction equations (GMPEs) used in PSHA to characterize strong ground motion is dependent on the tectonic setting of the study area and availability of strong motion data. In order of decreasing amount of data, options are to: 1) empirically derive region-specific GMPEs, 2) choose regionally or globally derived GMPEs based on comparisons and/or calibrations against locally recorded strong motion data, and 3) choose regionally or globally derived GMPEs based on judgement taking into account the local attenuation characteristics.

Unfortunately, Iraq currently lacks a national strong motion network. Sparse strong motion instrumentation is reportedly in place in some dams and possibly other facilities; however exact status of instrumentation is unknown and data from these installations is not publicly available. Recently, as part of the broader instrumentation effort in collaboration with LLNL, two strong motion instruments were installed in Iraq; one in Suleymaniyah, and one in Basra. As data becomes available from these instruments and others that are in planning phases, a more robust strong motion characterization in Iraq will emerge.

Since there are no strong motion data to utilize for options (1) and (2) described above, ground motion characterization for this PSHA study uses globally derived GMPEs. Global GMPEs broadly fall into one of the following tectonic groupings: a) active tectonic regions with shallow crustal seismicity, b) stable continental regions, and c) subduction zones. Iraq lies largely in a stable continental region, but most of its earthquake activity happens in active tectonic regions bordering with Turkey and Iran. Ground motion attenuation is generally faster and has lower high-frequency content in active tectonic regions compared to stable continental regions.

As guidance for selection of the GMPEs in the absence of locally recorded strong motion recordings to compare to, we examine the attenuation characteristics of the region. Al-Damegh et al. (2004) and Pasyanos et al. (2009) studied Sn and Lg attenuation in the Middle East. Their analyses show that even the "active" parts of Iraq have slower attenuation compared to areas such as California and parts of Turkey, where much of the data for global GMPEs for active tectonic regions come from. On the other hand, the "stable" parts of Iraq have faster attenuation than stable craton regions. Therefore, we weigh attenuation relations from active tectonic regions against stable continental regions, in a logic tree approach, for this project.

Four GMPEs from Next Generation Attenuation (NGA) West-2 project (active tectonic regions) and two GMPEs from NGA East project (stable continental regions), one of which with four variations, were used in this project (Figures 7 and 8). NGA West-2 GMPEs that were used are: Abrahamson et al. (2014) – referred to as ASK14 in the rest of the document, Boore et al.

(2014) – BSSA14, Campbell and Bozorgnia (2014) – CB14, and Chiou and Youngs (2014) – CY14. The NGA East GMPEs that was used are: Pezeshk et al. (2015) – PZCT15 and Darragh et al. (2015) – DASG15 with the following variations: single-corner variable stress parameter (1CVSP), single-corner constant stress parameter (1CCSP), double-corner variable stress parameter (2CVSP), and double-corner constant stress parameter (2CCSP).

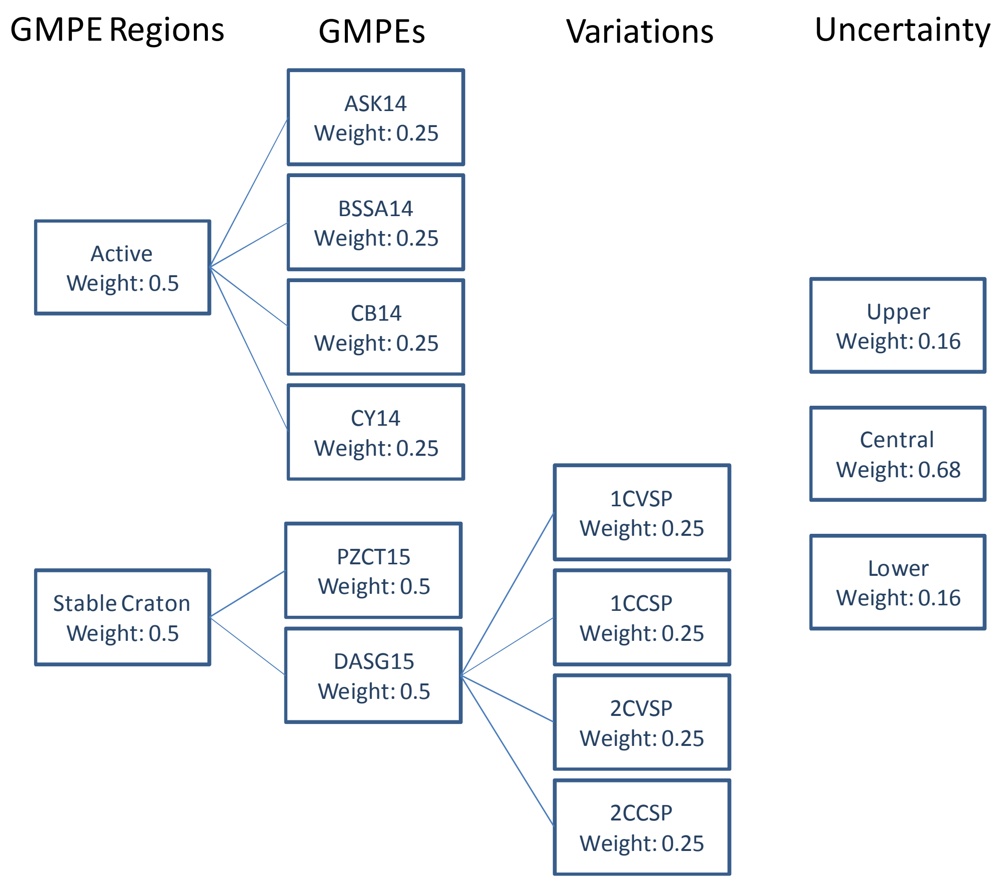



*Figure 7. Logic Tree Used for Ground Motion Characterization*

Ground motions from all GMPEs were computed for Site Class B site condition, since the draft update of the building code of Iraq uses Site Class B as the reference site. Site classification is based on National Earthquake Hazard Reduction Program (NEHRP) site classes (BSSC, 2001) that are widely used in recent building codes. It is based on the average shear-wave velocity of the top 30 m of the site.

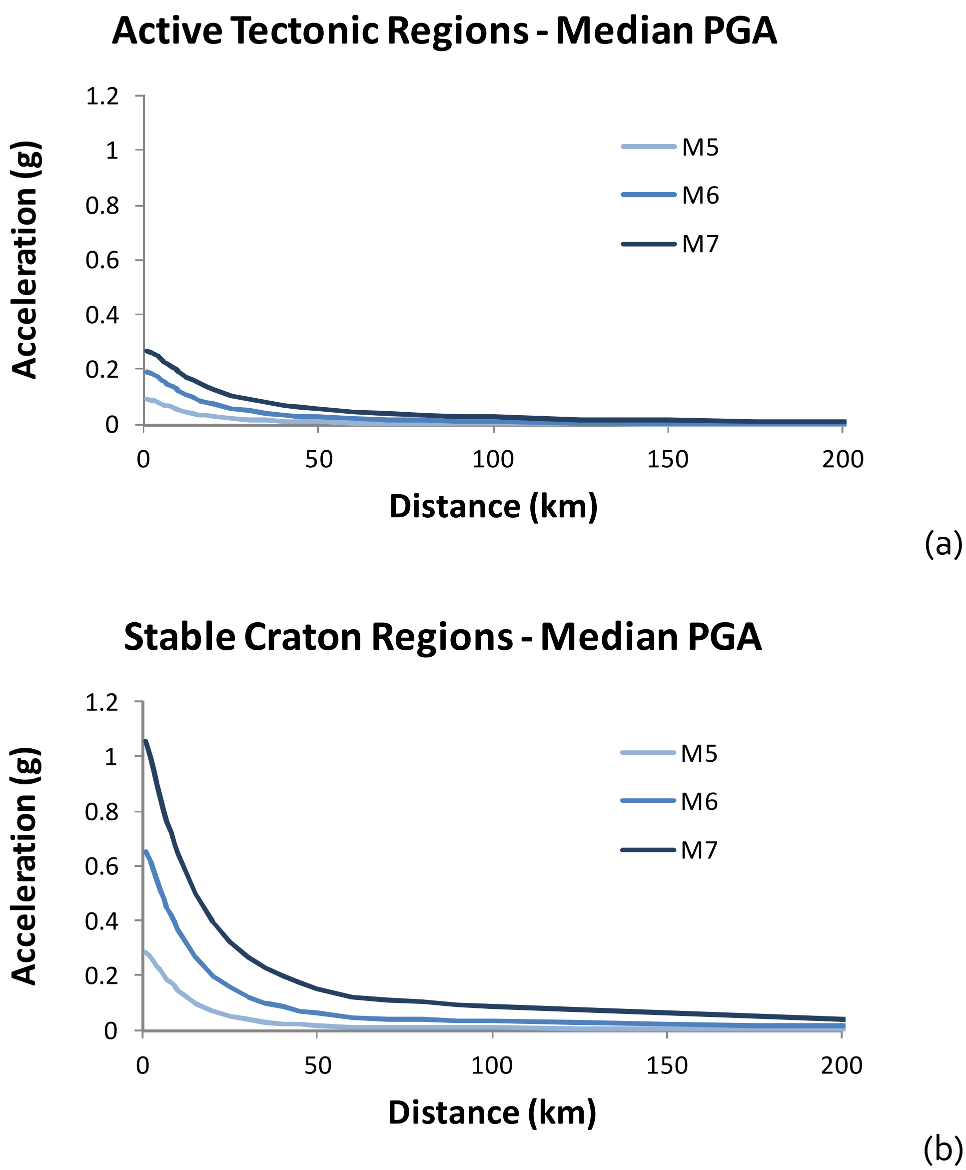
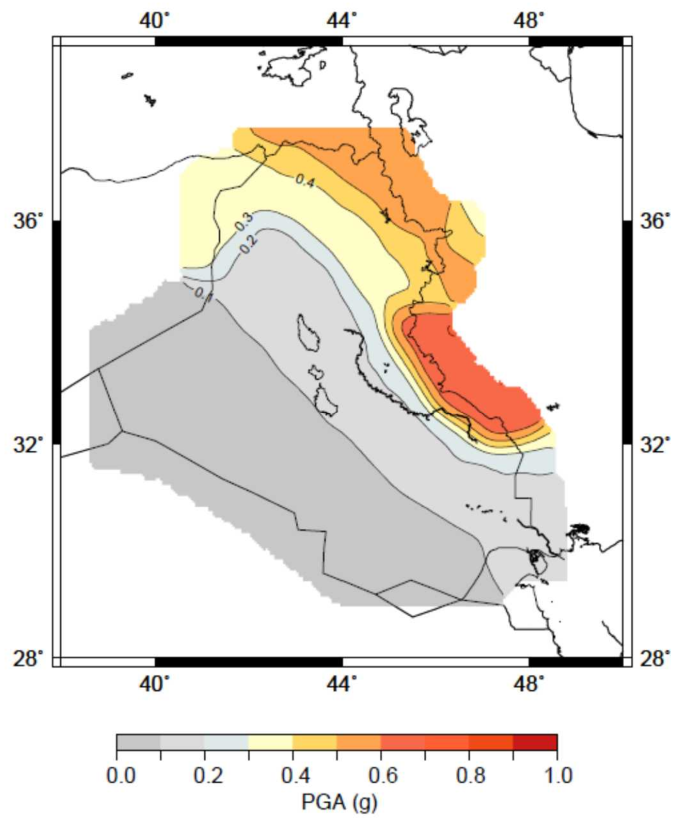



*Figure 8. Median GMPE for PGA on Site Class B in (a) active tectonic regions, (b) stable craton*

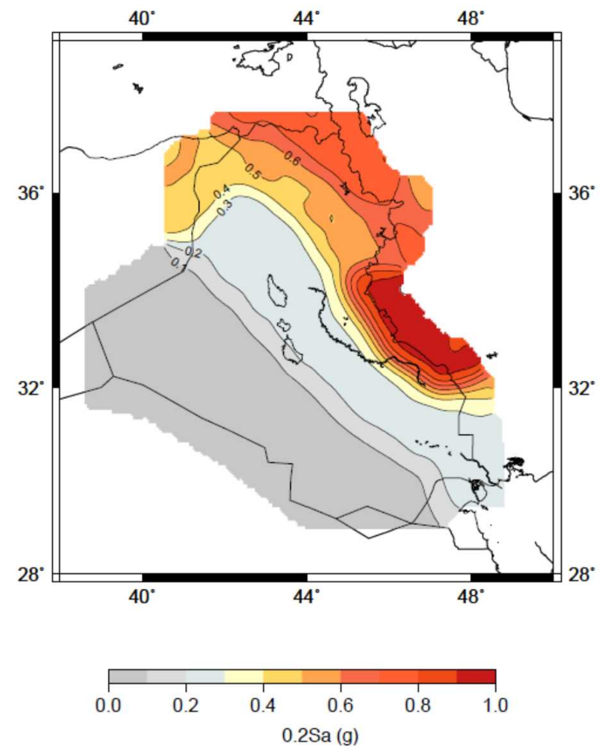
Once strong motion data becomes available from recently installed instruments, a more informed update can be made to the ground motion characterization. Recorded strong motion data may also reveal the need for new GMPEs for regions like Iraq, where the attenuation is not as fast as California and not as slow as stable craton. A region-specific ground motion modeling study, also accounting for the thick sedimentary deposits in the Mesopotamian Plain, would also be valuable for future PSHA studies in Iraq.

Various free and open-source PSHA software are available to implement the source and ground motion characterizations and run probabilistic analyses, such as OpenQuake (Pagani et al., 2014), OpenSHA (Field et al., 2003), and EqHaz (Assatourians and Atkinson, 2013). EqHaz was used for this study.

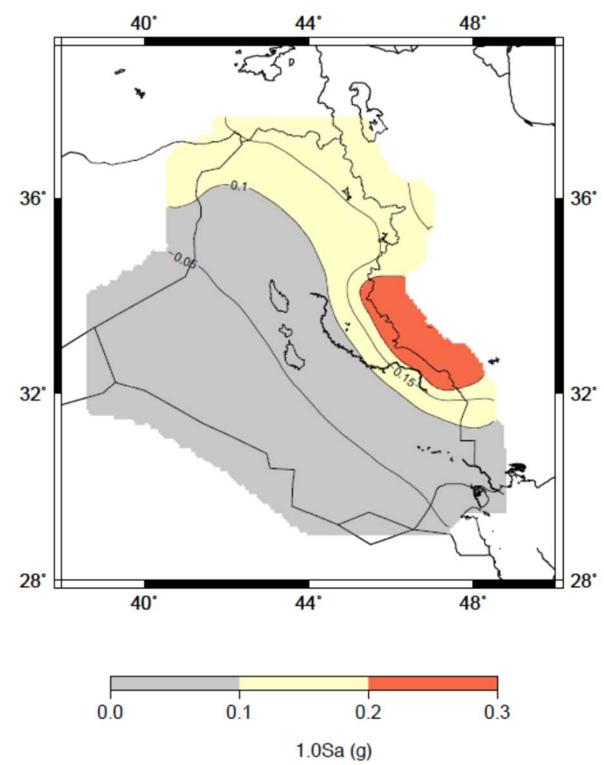
The ground motions were calculated for 2% chance of being exceeded in 50 years, or a return period of 2,475. Results are presented in hazard maps of PGA, and spectral accelerations at periods of 0.2 sec and 1.0 sec (Figure 9).




(a)




(b)




(c)

*Figure 9. Probabilistic seismic hazard in Iraq with a 2% chance of exceedance in 50 years on Site Class B in terms of (a) PGA, (b) Spectral Acceleration at 0.2 sec, (c) Spectral Acceleration at 1.0 sec*

Design spectra for selected cities, as constructed according to the provisions in the draft building code of Iraq, are plotted in Figure 10.

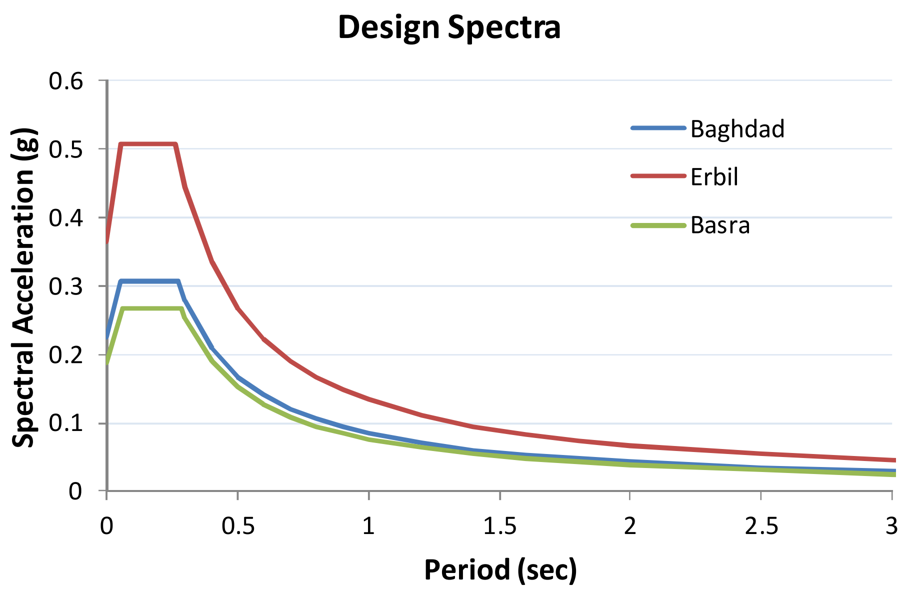



*Figure 10. Design spectra for selected cities*

**DISCLAIMER**

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