Summary of Ph.D Thesis of Mohamed Reda SBEINATI
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Title : Historical Seismology, Paleo-Archeoseismology and seismic hazard along the Dead Sea Fault in Syria

The aim of this work is the study of major earthquakes along the Dead Sea Fault (DSF) in Syria. The Middle East region is among the few seismically active regions that have a rich and long historical seismicity catalogue with major events that date several centuries BC. Several previous works report the occurrence of large and destructive earthquakes (with M > 7) along the fault. Although a considerable work on their seismic characteristics has been achieved, the analysis of historical documents and field observations were, however, still needed in order to prepare a parametric catalogue of historical and instrumental earthquakes necessary for a realistic seismic hazard evaluation.

The seismicity of Syria can be qualified as moderate if we restrict the period of study to the last 2 centuries. The instrumental and historical seismicity during this period indicate magnitudes M 5.5 but with a clear clustering of events along the Dead Sea Fault (DSF) and at the intersection with the East Anatolian Fault. However, a seismic gap appears clearly between the Ghab pull-apart basin and the Lebanese restraining bend.

A compilation of focal machanisms (from Harvard CMT, Mednet and Salomon) indicates a NNW-SSE trending P axes alonf the DSF strike-slip fault. These mechanisms illustrate the stress distribution along the main active zones of western Syria with transpressive deformation and normal faulting in pull-apart basins. Slip rates range between 5.6 to 7.5 mm/yr. are estimated from geological, paleoseismological studies and in good agreement with results of GPS campaigns. In parallel, the return period of large earthquakes, related seismic cycle, fault segmentation and its long term behavior are the main issues to be addressed throughout our work.

The episodic seismicity of Syria (with the Missyaf seismic gap and quiescence period since the Middle Age) have increased my interest in the historical seismicity, paleoseismology and archeoseismology, and the seismic hazard assessment. In this work, the problem of long term seismic activity along the DSF is addressed from field investigations in archeoseismology, paleoseismology and the analysis of historical documents. This work benefited from the support of the EC funded APAME Project [« *Archéo-PAleoseismology for the protection of cultural heritage in the Middle East »* (EC contract ICA-CT-2002-10024), from March 2003 to September 2006]. In parallel, I also benefited from support of the project "*Seismic Data for Siting and Site-Revalidation of Nuclear Facility*" under the coordination of the International Atomic Energy Agency (IAEA, Vienne) for the study of 181 historical seismic events (see Chapter IV).

This thesis is organized into 5 main chapters accompanied by an introductory chapter I and a chapter VII of general conclusions with 2 appendixes for published articles in international journals and professional reports prepared in the frame of my scientific research programme.

The introduction in **chapter I** shows the general tectonic and seismological context of the work, the main issues, motivations and structure of the work. **Chapter II** titled « *Active faults and their relationships to earthquakes* » presents the fundamental aspects in active tectonic studies and the main concepts and theory of earthquake ruptures and surface faulting and deformation. The methods and approaches used to document the analysis of historical documents and its parametric component, and field investigations in archeoseismology and paleoseismology are presented with the integration of seismic parameters in the seismic hazard evaluation.

The active tectonics and seismotectonic context is presented in **chapter III** where the plate tectonics between Arabia, Africa-Sinai and Anatolia shows the regional geodynamics.

The detailed fault mapping, geological and volcanic setting since the Miocene and the focal mechanism solutions provide some constraints on the lithospheric deformation along the plate boundary in western Syria.

The historical seismicity between 1365 BC and 1900 is documented in **chapter IV** through the extensive description of seismic events and their sources; this work is published in Annals of Geophysics :

Sbeinati M. R., R. Darawcheh and M. Mouty, (2005), The historical earthquakes of Syria: an analysis of large and moderate earthquakes from 1365 B.C. to 1900 A.D. *ANNALS OF GEOPHYSICS* 48, N. 3, June 2005, pp. 347-435.

The original sources have been studied in order to prepare a unified and homogeneous catalogue of 181 past events, with an estimate of macroseismic intensity using standard macroseismic scaling (EMS-92 and EMS-98) as already tested in Italy, Russia, United Kingdom and Iran. In a collaborative work with some colleagues, numerous historical documents in Arabic, Latin, Byzantine and Assyrian were studied for the identification of past earthquakes with some of them not mentioned in previous works. In particular, I have studied in detail the effects of major earthquakes in Arabic manuscripts. The study includes foreshocks and aftershocks, surface ruptures, soil liquefaction, landslides, tsunami, fires and building collapses. A parametric catalogue of 36 major earthquakes is prepared with their epicentral location, maximum and minimum intensities (V $\leq I_o \leq$ IX) and estimated magnitudes. Our calculation shows a completed parametric catalogue for $M_s > 6.5$ and contributes to a better estimate of the seismic hazard and risk in Syria.

Chapter V documents the field investigations in archeoseismology and paleoseismology along the DSF with a particular attention to some specific archeological sites that allow the study of seismic ruptures and their long term behaviour.

Previously, an inventory of archeological sites with earthquake damage is presented in the **Annexe 2** after an introduction on the nomenclature and typology of seismic effects on ancient buildings. In this report, I have described more than 10 archeological sites with clear earthquake-induced damage with field evidence of displaced key stones in Roman buildings, cracks, ruptures, waving and rotation in walls and stones, and collapse of constructions. I have attributed to each site a degree of destruction following the classification given by EMS-92 and EMS-98 scales.

The detailed archeoseismic work that I conducted for the study of the Al Harif aqueduct is presented throughout the excavations, trenching and analysis of Tufa deposits and collected cores. An article has been submitted for publication :

Sbeinati et al., (2010), Timing of Earthquake Ruptures at the Al Harif Roman Aqueduct (Dead Sea fault, Syria) from Archeoseismology, Paleoseismology and Tufa Cores, submitted to Geological Society of America Bulletin, Special Issue on "Ancient Earthquake" (in revision).

These studies and related analyses describe the faulting behavior and seismic cycle during the last 3000 years along the Missyaf segment of the DSF.

In parallel, I also conducted detailed works in 3 other different sites: The seismic ruptures discovered in the fortress « Krak des Chevaliers » (classified historical monument) immediately west of the DSF illustrate the seismic deformation associated with a moderate earthquake taking place between 1285 AD and 1295 AD. The collapse of main colonnades in the city of Apamea (II – III century BC) and a building collapse with deposited fire ashes indicate the occurrence of two major events in 420 – 570 AD and during the XII century. Archeological investigations at Deir Dahess show clear building collapses at different locations which can be dated around 526 AD and may be correlated to the 29 May 526 large earthquake that affected Saint Simon. The archeoseismic and paleoseismic investigations benefited from more than 70 radiocarbon dating that help in the determination of past earthquakes of the pre-Islamic period.

The integration of data and results from the historical seismicity, archeoseismology and paleoseismology are prepared for the seismic hazard evaluation in **chapter VI**. A statistical analysis of seismicity catalogue (both instrumental and historical) following the Gutenberg-

Richter relation provides the frequency of past events as a function of their magnitude. The analysis is coupled with the determination of recurrence time of large seismic events for different fault segments. The use of both deterministic and probabilistic approaches for the seismic hazard calculation allowed us to estimate peak ground acceleration and prepare maps for different scenarios of earthquake faulting. These maps and estimated return period of large earthquakes in zones of seismic gaps along the DSF constitute an important element for the seismic hazard and risk in Syria and surrounding regions.

The conclusion in **chapter VII** indicates the importance of multidisciplinary approaches in the study of past earthquakes. The combined studies of historical documents with field investigations in archeoseismology and paleoseismology provide with some insights on the physics of seismic ruptures and seismic damage to ancient buildings. The spatial and temporal distribution of large earthquakes observed from the historical catalogue is now constrained with physical observation of faulting episodes in excavations and trenching. Several past earthquakes described only in historical archives are now documented using archeoseismic and paleoseismic investigations and their seismic parameters listed in the parametric catalogue. The integration of different dataset with the seismic parameters of fault segments allows a better evaluation of the seismic hazard and risk in Syria.

I present in the appendixes the published articles and reports prepared in the framework of my research during the thesis preparation.

Appendix 1: Publications

Sbeinati M. R., R. Darawcheh, and M. Mouty (1994). Field archeological evidences of seismic effects in Syria, in Materials of the CEC Project "*Review of Historical Seismicity in Europe*" – vol. 2., Albini P. and A. (edit.), CNR – Consiglio Nazionale delle Ricerche, Milano, Italy.

Darawcheh, R., **Sbeinati, M.R.,** Margottini, C., and Paolini, S., (2000), The 9 July 551 A.D. Beirut earthquake, eastern Mediterranean region: *Journal of Earthquake Engineering*, v. 4, p. 403–414, doi: 10.1142/S1363246900000229.

Meghraoui, M., Gomez, F., **Sbeinati, R.,** Van der Woerd, J., Mouty, M., Darkal, A., Radwan, Y., Layyous, I., Najjar, H., M., Darawcheh, R., Hijazi, F., Al-Ghazzi, R., & Barazangi, M., (2003), Evidence for 830 years of seismic quiescence from paleoseismology, archeoseismology and historical seismicity along the Dead Sea fault in Syria, *Earth. Planet. Sci. Letters* 210, 35-52.

Gomez, F., Meghraoui, M., Darkal, A., **Sbeinati, R.,** Darawcheh, R., Tabet, C., Khawlie, M., Charabe, M., Khair, K., and Barazangi, M., (2001), Coseismic displacements along the Serghaya Fault: an active branch of the Dead Sea Fault System in Syria and Lebanon, *J. Geol. Soc. London* 158, 405 – 408.

Appendix 2: Report

Sbeinati, M. R., R. Darawcheh (1997). Archaeological evidences of earthquake damage in Syria", Atomic Energy Commission of Syria, (A report presented to the International Atomic Energy Agency under the research project entitled Seismic data foe siting and site revalidation of nuclear facilities, No. 6247/R3/RB), 1997.