Statistical Seismology Studies in Central America

$b$-value, seismic hazard and seismic quiescence

BY

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ACTA UNIVERSITATIS UPSALIENSIS
UPPSALA 2003
Dissertation presented at Uppsala University to be publicly examined in Axel Hamberg-salen, Geocentrum, Uppsala, Thursday, October 23, 2003 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

The present thesis collects results of research applying theory and methods of statistical seismology to the seismicity of Central America, a region with a complex tectonic setting controlled by the interaction of four major plates, namely the Caribbean, Cocos, Nazca and North American plates.

Three different earthquake catalogues were used for studies focused on stress in a tectonic volume, seismic hazard maps and seismicity patterns (precursors), covering the region 94°W to 81°W and 5°N to 20°N.

Variations in the $b$-value, the parameter in Gutenberg & Richter’s equation $\log N=a-bM$, as a function of depth in the subduction zone were investigated. High $b$-values were identified in the upper part of the slab at depths of 80-110km beneath Guatemala-El Salvador and at depths 130-170km beneath Nicaragua. These anomalies may be related to the generation of volcanism occurring above them. Time dependence of the $b$-value was also studied. Five case studies were selected (events with $M \geq 7.2$) for a detailed analysis. In three out of five cases, it was possible to link $b$-value minima to the time of occurrence of corresponding large events.

Seismic quiescence was mapped as a function of time and space by a gridding technique. The characteristics of the quiescence were calculated using the statistics $Z$ and $\beta$ and for Time Window lengths between 1 and 5 years. Five positive anomalies were found, which can be associated with large earthquakes ($M \geq 7.2$).

Finally, a Monte Carlo approach was utilized to evaluate the ground motion hazard and its uncertainties in northern Central America. A set of new seismic hazard maps exhibiting probabilistic values of peak ground acceleration (PGA) with 50%, 10%, and 5% probabilities of exceedance (PE) in 50 years is presented for a large area of northern Central America, including El Salvador and Guatemala.

Keywords: b-value, seismic hazard, Monte Carlo, seismic quiescence, Central America, stress

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ISSN 1104-232X
ISBN 91-554-5761-4
urn:nbn:se:uu:diva-3613 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-3613)
PAPERS INCLUDED IN THE THESIS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:


II Monterroso, D. A. Seismic Precursory potential of temporal variation of $b$-value: five case studies in Central America. *Journal of Seismology* (Submitted)


IV Monterroso, D. A. Seismic Quiescence in Central America. (Manuscript)

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Additional papers written during my stay at the Department of Earth Sciences but not included in this Thesis:

Cáceres D., Monterroso D. and Tavakoli B. Seismic Active deformation in northern Central America. *Tectonophysics* (Submitted)


This one goes out to the ones I love…

Dedicada a mi familia:
David y Alida (los dos faros que alumbraron mi camino).
Raúl, Carlos, Sandra y Vanesa (en una mano, los cinco dedos importan)
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1. Introduction

Seismology is a multidisciplinary science that studies earthquakes in a broad sense. It is generally accepted to define it as the study of the generation, propagation and recording of elastic waves in the Earth (and other celestial bodies) and of the sources that produce them (Lay & Wallace, 1995). Classical seismology deals with the physics of individual earthquakes or the propagation of seismic waves. However, the study of earthquakes intersects many other disciplines e.g. mathematics, chemistry, engineering. The intersection with the field of statistics is called statistical seismology, which is the study and application of statistical concepts to earthquakes. It focuses on earthquake population (seismicity patterns) and their evolution in space and time. Statistical seismology covers a wide range of modern subjects in current seismology research, such as earthquake self-similarity, seismic hazard analysis, study of precursory phenomena, etc.

One of the most studied subjects in statistical seismology stems from the widely accepted Gutenberg and Richter relationship, \( \log(N) = a - bM \) which explains the distribution of earthquake magnitudes (\( N \) represents the number of events with magnitude greater than or equal to \( M \)). Studies of the parameter \( b \) are plentiful and can be grouped into several categories that include, among others, the use of the \( b \)-value to study a certain physical property (such as stress in a tectonic volume) or considerations of temporal variations of the \( b \)-value as a precursory phenomenon for impending earthquakes.

Another frequent subject of study that falls into the ambit of statistical seismology is probabilistic seismic hazard analysis, which employs probabilistic techniques to estimate seismic hazard.

Statistical seismology also contributes to the elucidation of one of the most topical but rather complex questions: can earthquakes be predicted? This is addressed e.g. by defining statistical variables that help in identifying seismicity patterns, proposing models of earthquake behavior based on statistical distributions, studying the time dependency of parameters from distributions used to describe earthquake populations, etc. Such statistics may be relevant as earthquake precursors. The statistical variables, functions and distributions are the foundation to describe some extensively studied precursors, such as temporal variation in \( b \)-values and seismicity rates.
These and similar kinds of studies are of great importance especially for regions like Central America, where seismic activity is high. This thesis collects results of research applying theory and methods of statistical seismology to Central American seismicity.

The $b$-value is used as means to map the stress in the Central American subduction zone, in particular to locate the roots of the regional volcanism (Paper I). The hypothesis that the $b$-value decreases prior to the occurrence of an earthquake is investigated retrospectively by making use of five large earthquakes in the region (Paper II). Similarly, the seismic quiescence hypothesis is also investigated in Central America (Paper IV).

Finally, a Monte Carlo approach was employed to generate seismic hazard maps for El Salvador and Guatemala (Paper III). Seismic hazard maps were updated in the light of the January 13, 2001 earthquake. In this case, the earthquake catalogues are complemented and expanded with a Monte Carlo process.
2. Tectonic setting of Central America

The tectonic pattern of Central America, i.e. the isthmus between Guatemala and Panama and the adjacent areas, is controlled by the interaction of four major plates, namely the Caribbean (CAR), Cocos (COC), Nazca (NAZ) and North American (NOA) plates as shown in Fig. 1. To the south, the tectonic setting is complicated by the interaction of CAR with a smaller tectonic unit, the so-called Panama block and by the subduction of the Cocos Ridge, CR (Fig. 1).

![Figure 1](image-url)

Figure 1: Tectonic setting of Central America: Triangles represent volcanoes, CPFS=Chixoy-Polochioc fault system, MFS=Motagua fault system, SFZ= Swan Fault zone, FG= Fonseca gulf.
South of Costa Rica, where the CAR, COC and NAZ boundaries meet, there is a triple junction close to the area where CR encounters the Middle American Trench (Protti et al., 1994). COC descends beneath CAR and NOA along the trench with a relatively high speed that varies from 72±3 mm/yr off coast of Guatemala to 102±5 mm/yr off the coast of southern Costa Rica (Protti et al. 1994). There is a smooth change of the dip angle from about 33° beneath Guatemala to about 43° beneath Nicaragua. The direction of the volcanic chain axis changes from about N30°E to about N45°E roughly where the Fonseca gulf separates El Salvador and Nicaragua. Close to the Nicaragua-Costa Rica border there is a clear offset of the volcanic chain axis.

The seismicity of the isthmus is concentrated to the Pacific coastal regions (Fig. 2). The arc volcanism in the region constitutes the Central American Volcanic Chain consisting of several tens of active (e.g. Pacaya, Izalco, Cerro Negro, Arenal) and a number of extinct volcanoes. The chain follows the Pacific coast of the isthmus, roughly parallel to the middle American trench (MAT). It extends from the Mexico-Guatemala border, where the chain intersects the CAR-NOA plate boundary (White, 1991), to central Costa Rica. As suggested by Güendel and Protti (1998) the sudden termination of the chain in the south is likely to be due to the subduction of a younger lithosphere.
3. Earthquake data

Three different earthquake catalogues were used for the conducted studies, namely the E-catalogue, the PDE catalogue and the MIDAS catalogue. They all were cut for the region covered by the intervals [-94°, -81°] in longitude and [5°, 20°] in latitude (positive values refer to east and north, respectively. Negative values refer to west and south). Whenever needed, the catalogues were homogenized either to surface wave magnitude, $M_s$, or to moment magnitude, $M_w$.

3.1 The E-catalogue

This catalogue is an updated version of the catalogue by Engdahl et al. (1998). It provides improved locations and spans over the period from 1964 through 1999 (Fig. 2). It was used in papers I, II and III.

Central American seismicity (1964-2000) according to the E-catalogue Stars are earthquakes with $M_s \geq 7.2$. 

Figure 2
3.2 The PDE catalogue

The PDE catalogue (PDE stands for Preliminary Determinations of Epicenters) is provided by the United States Geological Survey (USGS). It starts in 1973 and is regularly updated to date (Fig. 3). Data are available via Internet from the National Earthquake Information Center (NEIC, http://www.neic.cr.usgs.gov/neis/epic/). PDE data were used in Papers II, III and IV. In Paper III only data for the period from 2000 to March 2002 were used.

Figure 3
Seismicity of Central America (1973-2002) according to the PDE-catalogue. Stars are earthquakes with $M_S \geq 7.2$

3.3 The MIDAS catalogue

The MIDAS catalogue was compiled through the sponsorship of the Pan-American Institute of Geography and History as reported by the Middle America Seismograph Consortium (MIDAS) agency. For more details, the reader should consult Tanner and Shepherd (1997). The catalogue, referred to hereafter as the MIDAS catalogue, is an amalgamation of earthquake catalogues of Mexico, South America, Central America and the Caribbean prepared by four different agencies (UNAM, CERESIS, CEPREDENAC and UWI). It lists moment magnitudes and covers the period from 1471 to the middle of 1994. The most reliable section of the catalogue covers only
the more recent period from 1964 to 1994, for which authors of the catalogue claim data completeness for $M_{w} \geq 4$. We consider the MIDAS catalogue to be the best data set currently available for a study of depth distribution of the $b$-value, due to its completeness, magnitude homogeneity and the time-window covered. This catalogue was employed for calculations in paper I.

![Figure 4](image-url)

Seismicity of Central America (1964-1994) according to the MIDAS catalogue. Stars are earthquakes with $M_{w} \geq 7.2$. 
4. The earthquake magnitude-frequency distribution

The statistics of earthquakes has been a subject of research for a long time. In the mid 1950s, Gutenberg and Richter (1954) realized that the size distribution of regional earthquakes follows a power law over the entire range of observed events. This type of power law distribution is called the ‘‘Gutenberg-Richter’’ distribution, a widely accepted empirical formula that establishes a relation between earthquake occurrence frequencies and magnitudes with two parameters, $a$ and $b$. It has the following form:

$$\log_{10}(N) = a - bM$$ (1)

where $N$ is the number of events with magnitude equal or larger than $M$.

Relation (1) is frequently used to describe earthquake activity in a particular region. A high $b$-value means that a smaller fraction of the total event count occurs at larger magnitudes, whereas a low $b$-value implies that a larger fraction of seismic events occurs at larger magnitudes. The geometrical interpretation of the $b$-value is the slope of the line that represents eq. 1 (for magnitudes above the so-called threshold magnitude). The $a$-value, also called the seismic activity parameter by many seismologists, is proportional to the seismicity for a given region and is an index of seismicity.

4.1 The $b$-value

The $b$-value can be determined by the least-squares method. The evaluation is also possible by means of other statistical estimators. One such estimator was first proposed by Utsu (1965), for a group of earthquakes and has the following representation:

$$b = \frac{\log_{10}(e)}{\overline{M} - M_{\text{min}}}$$ (2)

where $\overline{M}$ is the average magnitude and $M_{\text{min}}$ is the minimum magnitude in the group of events. Aki (1965) verified that Utsu’s estimator is in fact the
maximum likelihood estimator. This estimator follows the $\chi^2$ statistical
distribution. The statistical significance of the difference in the $b$-value for
two different earthquake groups can be tested by means of the F-distribution.
If the first group has a $b$-value $b_1$, obtained from $n_1$ events and the second
group has a $b$-value $b_2$, obtained from $n_2$ events, then the ratio $F=b_1/b_2$
follows the F-distribution with $2n_1$ and $2n_2$ degrees of freedom (Utsu, 1966).

It has been reported that the $b$-value becomes small prior to a large
earthquake. Imoto (1991) reported that $b$-values calculated based on micro-
earthquakes decrease prior to intermediate-magnitude earthquakes in central
and southwestern Japan. Jaumé and Sykes (1999) suggested that decreases in
the $b$-value preceding large earthquakes could be interpreted in terms of the
accelerating seismic moment/energy release hypothesis (Sykes and Jaumé,
1990; Bufe and Varnes, 1993; Bowman et al., 1998).

4.2 $b$-value and stress in a region

$b$ is a tectonic parameter that provides the possibility of describing the stress
and/or material (structural) conditions in the focal region (Mogi 1962,
Scholz 1968, Gibowicz 1974). High $b$-values are considered to be an
indication of a low-stress level in a seismogenetic zone (Scholz 1968, Wyss
1973). Increased material heterogeneity or an increase in the thermal
gradient also result in high $b$-values (Mogi 1962, Warren and Latham 1970).
Conversely, low $b$ values are correlated with high stress conditions
(Gibowitz, 1974).

Recently, Wiemer and Benoit (1996), Wiemer et al. (1998) and
Gerstenberger et al. (2001), among others, used the depth distribution of $b$-
values to study structural anomalies and stress levels in the crust
(identification of active magma bodies) as well as in the upper mantle
(creation of a volcanic arc).

$b$-values vary as a function of depth in subduction zones, which may
indicate a phase transformation of material in the subducting slab. Figure 5
shows a sketch of this process. An increase in the $b$-value would be
identifiable because the region of transformation is characterized by low
effective stress due to high pore pressure, which results from dehydration of
the subducting slab (Anderson, 1980). The spatial variation of the $b$-value in
the Wadati-Benioff zone (WBZ), beneath Central America along the Mid-
American Trench (MAT) is treated in Paper I, in particular, its possible
correlation with source zones of regional volcanism. $b$-values were mapped
in planes perpendicular to the trend of MAT in two regions. Figure 6 shows
a map of an area covering Guatemala and El Salvador, where high $b$-values
are found below the volcanic chain, different to the surrounding $b$-values with 99% confidence.

Figure 5
Sketch of the process of magma generation. $b$-value are expected to be low in the zone of shallow dehydration.

Figure 6
Map of $b$-values below Guatemala and El Salvador. Triangles represent volcanoes.
5. Precursory phenomena

Seismicity patterns have attracted the attention of researchers through the years as a means to investigate the tectonic stress behavior of a region. Changes in the rate of earthquake production are believed to be closely related to changes in stress in a particular volume. Precursory phenomena have been proposed to cause changes in seismicity rates, such as localized precursory seismic quiescence, regional activation and accelerated moment release (Zúñiga and Wiemer, 1999).

5.1 Temporal variations of $b$-value

The hypothesis that the $b$-value decreases prior to the occurrence of an earthquake is not new. Fielder (1974) and Smith (1986), among others, have shown that in some cases significant changes in $b$-value precede large earthquakes. Scholz (1968), after testing various rock types, suggested that the $b$-value is inversely related to the accumulation of stress in a given region. Wyss (1973) studied the physical meaning of the $b$-value by relating the stress-drop with the moment, $M_0$, and showed that low $b$-values indicate high stress in the source region. With high-quality data sets from the Parkfield segment of the San Andreas Fault, Wiemer and Wyss (1997) found evidence that supports the inverse dependence of $b$ on stress for crustal earthquakes. From these and other similar studies, one might speculate that a decreasing $b$-value is indicative of increasing stress levels in the crust and upper mantle, i.e. indicative of an impending large earthquake.

Paper II of the present Thesis employs earthquake data associated with six large earthquakes ($M \geq 7.2$) in Central America and examines the precursory potential of changes in $b$-values preceding the selected six events. $b$-value decreases that could be associated with an earthquake were found e.g. for the El Salvador earthquake of January 13, 2001. Figures 7 shows the $b(t)$ plots obtained with the PDE catalogue, for a cylindrical volume with center on the epicenter of the event and a radius of 150km. The plot also shows another minimum, which can be linked with an isolated $M_s=7.0$ event which occurred on June 19, 1982, within the “El Salvador” circle.
Figure 7

$b(t)$ plots for El Salvador using the least-squares (up) and maximum likelihood (down) methods and the PDE catalogue. Arrows indicate the times of the events.

Although the E-catalogue does not contain the El Salvador 2001 event, a plot of $b(t)$ obtained with it confirms low $b$-values prior to the 1982 event, as can be seen in Fig. 8.

Figure 8

$b(t)$ plots for El Salvador using the least-squares (up) and maximum likelihood (down) methods and the E-catalogue. Arrows indicate the times of the events.
5.2 Seismic quiescence

Seismic quiescence is a decrease of the mean seismicity rate as compared to the background rate in the same crustal volume judged as significant by some clearly defined standard. One commonly used test for comparing seismicity rate changes is the $Z$-value test for a difference between two means. The $Z$-value measures the significance of the difference between the mean seismicity rates $\mu_1$ and $\mu_2$ within two groups.

$$Z = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

where $\sigma$ and $n$ are, respectively, the standard deviation of the rate and number of samples in the group.

To determine the time of a single seismicity rate change, the $Z$ test can be applied repeatedly to the data constructing a function, $LTA(t)$ (Long term average). $LTA(t)$ is the $Z$-value resulting from the comparison of the rate within a window, $\mu_{WL}$, and the background rate, $\mu_{All}$, here defined as the overall mean rate in the volume.

![Figure 9](image)

*Sketch to show calculation of $Z$-value with the LTA statistics*
Another test for studying seismicity rates was introduced by Matthews and Reasenberg (1988). This test assumes that the number of events in a subinterval of the data has a binomial distribution with the parameter determined by the duration of the subinterval. The statistic, called $\beta$, is given by:

$$\beta = \frac{No - Ne}{\sqrt{Ne(1 - p)}}$$

where $Ne$ and $No$ are the expected and observed numbers of events in the subinterval, respectively, and $p$ is the ratio of the anomalous period duration to the duration of the entire sample. Similar to the $Z$-test, an LTA(t) function can be constructed by comparing the value of $\beta$ within a window, $\beta_{WL}$, to the background, $\beta_{All}$. This test assumes that the distribution of seismicity is Poissonian.

Regardless of the statistical test chosen, one must remove dependent events from the catalogue prior to application of the test.

The $Z$ and $\beta$ statistics have been used in Paper IV in studies of seismic quiescence linked to four large earthquakes ($M_S \geq 7.2$) in Central America. It was found that all these events show a similar pattern. A significantly high $Z$-value is found at the beginning of a quiescent period preceding the earthquake, followed by a significantly high $\beta$-value (still prior to the earthquake occurrence). Figure 10 illustrates the pattern for an $M_S = 7.2$ earthquake with epicenter off shore Nicaragua that occurred on September 2, 1992.

![Figure 10](image_url)

LTA(t) functions for a cylindrical volume containing the Nicaragua 1992 event. a) $Z$-values, thick line, two significant high value anomalies are found. b) $\beta$-values, thick line, only one significant high value anomaly is found. In both cases, a 3-year window length was used and the location in time of the high value anomaly, which is linked to the event, is displayed. The cumulative number of events is shown in a thin line and the star indicates the 1992 event.
6. Probabilistic seismic hazard

The probabilistic seismic hazard approach (PSHA) includes one or more random variables that are characterized by a probability distribution from which values are drawn. Probabilistic concepts allow spatial and temporal uncertainties to be explicitly considered in the evaluation of seismic hazard. Results can be presented as frequency or cumulative distributions, each of which corresponds clearly to the range and likelihood of possible values. It also illustrates the contributions of different magnitude-distance pairs to the exceedance of the probabilistic ground motion, which is useful to define design earthquake(s) for the dominant contributor(s). Monte Carlo simulation is a technique to estimate such ranges of values. The Monte Carlo method can be used to investigate the properties of any proposed estimation parameter in the seismic hazard analysis.

The essence of the Monte Carlo method is straightforward, to select earthquakes that would actually generate the ground motion parameters (e.g. PGA) at a specified site.

In Paper III, we have chosen the Monte Carlo approach developed by Ebel and Kafka (1999), which eliminates the need to define source zones and hazard parameters to compute ground motion at the site. Using Monte Carlo simulation to convert a deterministic model to a probabilistic model involves three steps: first, replace uncertain input values with generation of random numbers; second, run a simulation that evaluates the model many times and saves the outcome of each evaluation as one observation; third, analyze the result of all observations.

According to the Monte Carlo method, the area surrounding a given site can be constrained by seismic source boundary locations to construct different earthquake catalogs. The catalogs will represent earthquakes of different sizes up to the maximum magnitude earthquake at the site due to the different possible earthquake locations. The earthquakes are usually assumed to have a uniform spatial distribution over the time of the catalogs, and a Poisson temporal distribution with an activity rate \( \lambda \) describing their occurrence. The activity rate is determined empirically from the past seismicity data. In general, \( \lambda(t,x,y,z) \) depends not only on a particular location of an event in time-space \((t, x, y, z)\) but also on the times and locations of preceding events. When events in the catalog follow a Poisson
process, $\lambda(t,x,y,z)$ depends only on time-space coordinates. We subdivide the spatial region into a finite number of sub regions and fit the Poisson process models to the data within each sub region. Then the conditional rate may be written as

$$\dot{\lambda}(t,x,y,z) = \sum \dot{\lambda}_i(t) \times \ell_i(x,y,z),$$  \hspace{1cm} (5)$$

where $\ell_i$ is an indicator function denoting the relevant region.

For each catalog, the seismic recurrence relationship shows that possible ranges of magnitude and distance will be $M_0 < M < M_u$ and $R_0 < R < R_u$, respectively. Using a Monte Carlo approach to generate a synthetic earthquake catalog, we can divide the ranges of $M$ and $R$ into a convenient number of intervals and a grid superimposed over the region of interest. As a result, the region is divided into bins or segments of width $\Delta M$ and $\Delta R$, respectively. For each bin, $ij$, in the grid of a catalog $k$, the number of occurrences in the interval $\Delta M$ around $M_i$ per year and unit area is determined by the portion of earthquakes in the catalog $k$ that is located at a distance $R_j$. We enter this value at the location $ij$ of the $[M-R]$ matrix for catalog $k$ and repeat the procedure for all $i$’s and $j$’s in $[M-R]_k$ and all earthquakes in the synthetic catalogs. The information contained in a row, $i$, of a matrix can be physically interpreted as the contribution of all earthquakes in catalog $k$ located at a distance $R_j$ from the site. The above procedure can be repeated for all catalogs.

The probability $q_{ij}(y)$ that the spectral acceleration, $Y_{ij}$, of a structure with period $T$ and damping factor 5% on a certain ground condition, $GC$, at the site under consideration exceeds $y$ as a consequence of the occurrence of an earthquake, $E_{ij}$, in bin $ij$ could be evaluated by

$$q_{ij}(y) = P[Y_{ij} > y \mid T, GC, E_{ij}]$$  \hspace{1cm} (6)$$

This earthquake $(E_{ij})$ is usually identified by magnitude, $M$, distance, $R$, and standard deviation, $\varepsilon$, away from the median with respect to level $y$. At this stage, to obtain the rate of occurrence of various levels of ground motion at the site of interest, any attenuation relationship can be used. Taking a target level $y_t$, we can scan the $[M-R]$ matrix and identify all pairs $M_i$ and $R_j$ for which $Y_{ij} = f(5\%, M_i, R_j, \varepsilon, GC, T) > y_t$. Then, the probability of $Y_{ij}$ exceeding $y$ in $t$ years may be expressed as

$$P[Y_{ij} > y \mid t] = 1 - \exp(-t\dot{\lambda}_{(y)})$$  \hspace{1cm} (7)$$

where

$$\dot{\lambda}_{(y)} = \sum_{i=1}^{N_M} \sum_{j=1}^{N_R} \dot{\lambda}_{ij} q_{ij}(y)$$  \hspace{1cm} (8)$$

where $N_M$ and $N_R$ are numbers of possible ranges of magnitude and distance, respectively. Comparison of equations (5) and (8) illustrates that the

indicator function can be replaced by the probability \( q_{ij}(y) \) in a given region. Equation (8) counts the number of times that ground motion exceeds the target level and equation (7) is then used to calculate the probability that ground motion will exceed that level.

The Monte Carlo method can be used to investigate the properties of any proposed estimation parameter in the seismic hazard analysis. The essence of the Monte Carlo method is straightforward, to select earthquakes that would actually generate the ground motion parameters (e.g. PGA) at a specified site. Figure 11 shows the resulting PGA maps.
Seismic hazard map of northern Central America and western Caribbean by using a Monte Carlo approach. Peak ground acceleration (%g) is depicted having a) 50%, b) 10% and c) 5% probability of being exceeded in 50 years. GC=Guatemala City, SS=San Salvador.
7. Summary of papers

7.1 Paper I

Spatial variations of $b$-value in the subduction zone of Central America.

Frequency-magnitude distribution along the Mid-American Trench (MAT) has been studied by means of 2345 earthquakes during the period 1964-1994. We used the regional MIDAS catalogue with a magnitude of completeness of 4.2. To resolve the $b$-value as a function of depth (one dimensional approach), we applied vertically sliding windows containing a constant number of events. To obtain more details in the $b$ distribution, we projected catalogue hypocenters in three selected regions (approximately Guatemala and El Salvador, Nicaragua, Costa Rica) onto planes perpendicular to the trench. $b$-values were calculated in sliding cylindrical volumes (two-dimensional approach) containing a constant number of earthquakes and centered at nodes of a 5km x 5km grid. $b$-value varies significantly along a large part of MAT. High $b$-values were identified in the upper part of the slab at depths of 80-110km beneath Guatemala-El Salvador and at depths 130-170km beneath Nicaragua. Anomalous (high) $b$-values in the lower part of the slab were located at depths of 50-90km and 50-160km beneath Guatemala-El Salvador and Nicaragua, respectively. Anomalies observed at the upper part of the slab may be related to dehydration and successive increase in pore pressure in the downgoing lithosphere, which in turn will generate volcanism occurring above the anomalies in the upper part of the slab. Anomalies on the lower surface of the Wadati-Benioff zone are likely to be associated with the high thermal gradients between the slab and mantle.
7.2 Paper II


The time dependence of the $b$-value, the parameter in Gutenberg & Richter’s equation, $\log N = a - bM$, was studied for the Central American region. Events with $M_S \geq 7.2$ were selected for a detailed analysis. A circular area with radius of 150km with the center in the epicenter of each studied event was used to calculate $b$-values and to obtain $b(t)$ curves. In three out of five cases, it was possible to link $b$-value minima to the time of occurrence of corresponding events. These drops in $b$-value were found to be significant (using both maximum likelihood and least-squares methods) to 99% confidence level, for the El Salvador, 2001, $M_S=7.8$ earthquake; and to 90% or higher confidence levels for the 1993, $M_S=7.3$ event near the Mexico-Guatemala border. A significance level 80% or more was found in the drop of $b$-value linked to the Nicaragua, 1992, $M_S=7.2$ event.

The results presented support the hypothesis that $b$-value decreases significantly prior to the occurrence of a large earthquake.

7.3 Paper III


A Monte Carlo approach is utilized to evaluate the ground motion hazard and its uncertainties in northern Central America. In this approach, the seismic source boundary location is only considered to construct different earthquake catalogs. For each catalog, a Monte Carlo simulation is then used to generate numerous synthetic catalogs that have the same properties as the observed catalog but with random occurrences of earthquakes following the Poisson model and with epicentral locations randomly determined from the observed catalog. Selecting models to describe seismic source zones and earthquake recurrence is not required since such considerations are implicit in the synthetic earthquake catalogs. Thus, uncertainties related to gathering and manipulating the appropriate data for seismic hazard parameters and source zone boundaries are not propagated through the analysis into the
hazard result. The characteristic earthquake recurrence model is used to describe the occurrence of large magnitude events from the geological data. A set of new seismic hazard maps, exhibiting probabilistic values of peak ground acceleration (PGA) with 50%, 10%, and 5% probabilities of exceedance (PE) in 50 years, is presented for a large area of northern Central America, including El Salvador and Guatemala. The hazard is highest in the coastal regions adjacent to the megathrust and the transcurrent fault zones. As a case history, disaggregation of seismic hazard is carried out for cities of San Salvador and Guatemala by using a spatial distribution of epicenters around these sites to select design ground motion for seismic risk decisions.

7.4 Paper IV

**Seismic Quiescence in Central America.** David A. Monterroso. (Manuscript).

Seismic quiescence in Central America was mapped as a function of time and space by applying a gridding technique using the ZMAP computer code. The characteristics of the quiescence were calculated using the statistics $Z$ and $\beta$ and for time window lengths between 1 and 5 years. Between 1973 and 2003, five positive $Z$ anomalies were found that can be associated with large earthquakes ($Ms\geq7.2$). Although other significant $Z$-value anomalies were found, the $\beta$ statistic was also used to single out these ones by identifying $\beta$ anomalies coupled with the $Z$ anomalies. A pattern in the seismicity was recognized for all of the 5 large earthquakes. The $Z$-value anomalies are followed by significant high $\beta$-value anomalies, which end with the occurrence of the earthquake. Values of $Z$ reach 5.2, 3.2, 3.1, 6.3, and 3.9 for the anomalies related to the 1993, $M_S=7.3$ event near the Mexico-Guatemala border; the El Salvador, 2001, $M_S=7.8$ earthquake; the Nicaragua, 1992, $M_S=7.2$ event; the Costa Rica, 1983, $M_S=7.2$ event and the Costa Rica, 1991, $M_S=7.5$ event, respectively. Likewise, $\beta$ values are 5.6, 6.9, 6.8, 5.5, and 6.5. All these values have corresponding statistical significance levels of more than 99%. The hypothesis of precursory seismic quiescence seems to contribute positively to the prediction of mayor earthquakes in Central America.
Acknowledgements

I would like to express my gratitude to everyone who has contributed to the development of this thesis, one way or the other. First, I would like to thank my supervisor Ota Kulhánek for the guidance and support through all these years, as well as giving me freedom to point my research in the direction I chose (although, it seems like prediction should be left for retirement, as you said!).

In addition, I thank F. Guendel, S. Wiemer and A.J. Anderson for useful discussions comments and suggestions at different stages. Ing. Franklin Matzdorf for believing in me from the beginning of this journey (looks like I made it!). Dr. Raúl Gonzalez for encouraging me to take the “seismology courses with the Swedish people”.

While in Sweden, the Swedish International Development Agency (SIDA-SAREC) supported me and my work through the projects Seismotectonic Regionalization of Central America (SERCA) and Natural Disaster Mitigation in Central America (NADIMCA). I also acknowledge the fellowship received from the Department of Earth Sciences, Uppsala University.

This would not have been possible without the tremendous support from my father (Puedo seguir hasta el final a mi manera) and my mother (y tenés que dejar a la gente que amás y a ella que te mira con tristeza y alegría y te dice “que ta vaya bien mi amor, yo te espero…”). My brothers, Raúl (Winter, spring, summer or fall, all you have to do is call and I’ll be there…) and Carlos (We were so in phase in our dance hall days…). My sisters, Sandra (monta en una estrella pero enganchate de ella) and Vanesa (porque siempre estarán en mi, esos bellos momentos que pasamos…). ¡Gracias por el apoyo incondicional! Regreso a casa, me lo reclama el corazón…

Much support came also from friends and colleagues in both Guatemala and Sweden while following the sandwich model of studies from SAREC.

In Guatemala, I wish to thank:

Antonio Hernández, Julio Gallegos and Víctor Morales, who have been my partners in crime (physics) from those days when we were studying at Universidad del Valle until now. We have shared many things, including the distance from home. Look at us now… Spain, USA and Sweden… (so far away, doesn’t anybody stay in one place anymore?).
La mara de Guate: Héctor Homero Juárez (vendrá silvando un tango simplemente…) for the friendship and a very active contact and even in the long distance. Luis Fernando Barrera (Estoy clavado, estoy herido, estoy ahogado en un bar), for always being there for me, supporting me in different ways and now, with Edel, making me feel so welcome everytime I was in Guate. Leonardo Morales (I have stood here before inside the pouring rain), for the confidence you pour on me regarding my capacity and now with Claudia, for the relaxing movie nights at your place. Giovanna and Eunice for taking care of my brothers and receiving me with happiness. Luis Miguel, for making my sister happy and taking it easy with me. José Luis Alvarado (few words but a lot of shared experiences), Sergio Dávila, Roberto Bonilla, Flor Mencos, Jeffrey Rivera, Ottoniel Monterroso, Carmen Monterroso, Bidkar Monterroso, Ramiro Morales (QK), Guillermo Chacón (Willy), all of the respective significant others and all of those who helped while I was there. Specially the long distance cheering while I was here in Uppsala. I recharged my batteries with our “meetings” that normally ended with “pinche police” and/or Mugrabi. ¿Quién dijo salud?

In Sweden, I would like to thank:

Sonia for always being willing to help, and for moral support in going to the stress therapy called Gympa. Thomas for support and for showing me those good things in the German catalogue (I wonder why, I wonder how). Sonia & Thomas as couple, for all those times we had in the company of a good beer (or maybe more) mostly at Norrlands nation or enjoying asados (I will miss them, but not as much as I will miss you!). Johiris for the most needed female touch and balance in the geophysics corridor and for her ability to listen. Diego, with whom I shared the most (all the god and the bad) while we were pursuing our seismology studies. Ronnie, who also shared part of the seismology way with me, and his wife Maria for their hospitality. Hossein, my ever worried friend, for all the things we have survived, the help with the studies and all the going out to nations and the likes even if that meant having to listen to some techno (Everything has a solution, man… Relaaax!). Jaime, Leif and others who helped while in the Observatory Park, as well as, Puy, Björn L., Lena, Vincent and other colleagues that welcomed us at the solid earth physics. Andrzej, because in more ways than you know you helped me to keep my feet on the ground here in Sweden (and I am not talking about Modern Talking…) and Aneta for welcoming my friendship and making it necessary for Andrzej to come back, only now as the half of a great couple. My fellow vodqueteers, Tomasz and Dmitri, with whom I shared many things and release much pressure by just being ourselves listening to music while drinking some Vodka in the company of Lisa S., Diana K., Kim A., Suzanne V., etc. Tomasz, thanks for helping me moving from Flogsta to Djäknegatan, the music we share (Sade,
the blues traveler, all that jazz, etc.). Dmitri, for the language control in many of my articles, for remembering the 80’s as good as I do (wouldn’t it be good if we could wish ourselves away…). Sverker, CJ, Lijam and the rest of the unconditional Orvars krog gang, we had many great moments, I also remember and appreciate those mid summer afternoons that Sverker and Ingrid invited us to their house to celebrate. The Flogsta family and the rest of the bunch, in particular Marta, Vittorio, Daniela, Martina, Silke, Ariane and Claudia for enhancing my stay in Uppsala with their company and the many get-togethers we had. Raimund, for the important reminder that a part of the thesis that is in manuscript is still a work in progress, which made me realized I have all I needed for the thesis, and of course also for the gympa. Taher and Ana for all the help in the printing of the thesis and for letting the deadline slide for me. The colleagues at the department, past and present, for the cordiality, in particular, Artem, Abbas, Vassili, Heikki, Staszek, Achim, Björn (a mac exhaust valve in a PC world and an 80’s music lover too), Cédric, Kristin, Palmi, Maxim.

Finally, I would like to thank to everyone who has helped surviving the long cold winters, during the development of the thesis.

David Aníbal Monterroso Juárez, autumn 2003.
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Resumen

El presente trabajo de investigación recopila resultados de aplicar la teoría y los métodos de la sismología estadística a la sismicidad de Centroamérica, una región con un marco tectónico complejo controlado por la interacción de cuatro placas tectónicas: la placa del Caribe, la placa de Cocos, la placa de Nazca y la placa de Norteamérica.

Tres catálogos de eventos sísmicos fueron usados para estudios enfocados a temas relacionados con el esfuerzo en un volumen tectónico, mapas de amenaza sísmica y patrones de sismicidad (precursors), cubriendo la región entre 94°O a 81°O y 5°N a 20°N.

Se investigaron las variaciones en el valor $b$, el parámetro de la ecuación de Gutenberg & Richter, $\log N = a - bM$, como función de la profundidad. Se identificaron valores altos de $b$ en la parte superior de la litosfera subducida por debajo de Guatemala-El Salvador, a profundidades entre 80-110km; y por debajo de Nicaragua, a profundidades entre 130-170km. Estas anomalías podrían estar relacionadas con la generación del volcanismo que ocurre por encima de ellas. Además, se estudio la dependencia temporal del valor $b$. Se seleccionaron cinco estudios de caso (eventos con $M_S \geq 7.2$) para un análisis detallado. En tres de los cinco casos, fue posible vincular los mínimos del valor $b$ con el tiempo de ocurrencia de grandes eventos correspondientes.

Se mapeo la quietud sísmica como función del tiempo y el espacio por medio de una técnica de enrejillado. Las características de quietud sísmica fueron calculadas utilizando las variables estadísticas $Z$ y $\beta$ para ventanas temporales de duración entre 1 y 5 años. Se encontraron cinco anomalías que pudieron ser asociadas con terremotos (eventos $M_S \geq 7.2$).

Finalmente, se utilizó el enfoque de Monte Carlo para evaluar el movimiento del suelo y sus incertidumbres en el área norte de Centroamérica, incluyendo El Salvador y Guatemala. Se introduce una colección nueva de mapas de amenaza sísmica, que exhibe valores probabilísticos de aceleración “Pico de Terreno” ó “Peak Ground Acceleration” (PGA) para sitios con probabilidad de excedencia de 50%, 10% y 5% correspondiendo a períodos de retorno de 50 años.
A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to October, 1993, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science”.)