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Earthquake Sources, the Stress Field and Seismic Hazard

A Study in Eritrea and its Surrounding

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Abstract

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Presented in this thesis are some basic concepts and applications of seismic hazard analysis and the elements that influence the amplitude and geometric attenuation of earthquake ground motion. This thesis centers on the identification of the styles of failure, focal mechanisms, and the state of regional stress in the study area. Seismic hazard is a complex problem often involving considerable uncertainties. Therefore it is reasonable to consider different seismic hazard analysis approaches in order to as robustly as possible define zones of different levels of hazard. With the aim of characterizing and quantifying hazard in the east African region of Eritrea and its surroundings, a study is included in the thesis presenting hazard maps constructed using two non-parametric probabilistic seismic hazard analysis (PSHA) approaches. Peak ground acceleration (PGA) values for 10% probability of exceedence in 50 years are computed at given grid points for the whole selected area and results from both methods are compared.

Other aspects addressed in the thesis include the determination of source parameters of selected earthquakes that occur in the Afar region. The styles of faulting, the mechanisms involved during the rupture process and the states of stress along the major tectonic features are also highlighted. Source parameters for selected events in the region were re-evaluated and improved solutions obtained. An aftershock sequence in the Hengill volcanic area in SW Iceland, following the major event that occurred on June 4, 1998, was used to investigate improved methodologies for moment tensor using a relative approach. The sensitive and spatially dense seismic network in this area reveals large sets of clustered events allowing the power of the new methodology to be demonstrated and providing greater insight into the tectonic implications of the activity in the area.

Keywords: Seismic hazard, Focal mechanism, Moment tensor inversion, Stress field, Afar depression, Eritrea

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Dedicated to my mother and sisters

List of Papers

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

I. Hagos, L., Arvidsson, R., and Roberts, R., Application of the Spatially smoothed seismicity and Monte Carlo methods to estimate the seismic hazard of Eritrea and the surrounding region, *Natural Hazards*, 39, 395-418, 2006.

II. Hagos, L., Shomali, H., and Roberts, R., Re-evaluation of focal depths and source mechanisms of selected earthquakes in the Afar depression. *Geophys. J. Int.*, 167, 297-308, 2006.

III. Hagos, L., Shomali, H., Lund, B., Bödvarsson, R., and Roberts, R. An application of relative moment tensor inversion to aftershocks of the June 1998 Hengill earthquake in southwest Iceland. Submitted to *Bull. Seis. Soc. Am.*, 2006.

IV. Hagos, L., Lund, B., and Roberts, R., The state of stress on major tectonic features in the Afar region. To be submitted to *Journal of Seismology*, 2006.

Additional research paper written during my stay as a PhD student but not included in the thesis:

Lijam Hagos, Roland Roberts, Ragnar Slunga, Reynir Bödvarsson and Björn Lund. A preliminary study regarding measures of earthquake risk in Sweden. *Report*, Uppsala, Sweden, 2003.

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Contents

1. Introduction.....	9
2. Methods of non-parametric Probabilistic Seismic Hazard Analysis (PSHA).....	15
2.1 The method of spatially smoothed seismicity	15
2.2. The Monte Carlo approach.....	17
3. Earthquake source assessment	19
3.1. The Seismic Moment Tensor	19
3.2. Decomposition of moment tensor- Styles of failure.....	23
3.3. Relative moment tensor inversion (RMTI)	24
4. Stress field estimation using earthquake focal mechanisms	27
5. Brief tectonics of Eritrea and the surrounding region	29
6. Summary of papers	32
Paper I	32
Paper II	35
Paper III.....	37
Paper IV	41
7. Concluding Remarks.....	44
8. Summary in Swedish	45
Acknowledgments.....	49
References	51

Abbreviations

DSHA	Deterministic Seismic Hazard Analysis
PSHA	Probabilistic Seismic Hazard Analysis
PE	Probability of Exceedence
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PGD	Peak Ground Displacement
SA	Spectral Acceleration
CAV	Cumulative Absolute Velocity
CMT	Centroid Moment Tensor
USGS	United States Geological Survey
ISC	International Seismological Center
NEIC	National Earthquake Information Center
DC	Double Couple
CLVD	Compensated Linear vector Dipole
ISO	Isotropic
RMTI	Relative Moment Tensor Inversion
SIL	South Iceland Lowland
SAG	Spectral Amplitude Grouping

1. Introduction

Learning about earthquakes, understanding their source characteristics and approaches used in predicting their occurrence has been the center of focus for seismologists and earthquake engineers for many decades. The high risk levels associated with earthquake-prone areas are often investigated by integrating all available information gathered from geological, geophysical, seismological and geotechnical data. There are two common terms used in the assessment of earthquake-related damage: *Seismic hazard* and *Seismic risk*. A strict definition of seismic hazard is the probability of occurrence of certain level of ground shaking in a specified period of time. But in its general sense it might also mean the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction. Seismic risk is hazard vulnerability or the probability of occurrence of (vibrational) loading of a given magnitude multiplied by the probability for damage caused by that load. The topics presented in this thesis will illuminate some aspects of seismic hazard analysis and related seismological fields from which some of the input parameters for hazard analysis are extracted.

Seismic hazard analysis involves the characterization of:

- The sources of the seismic hazard (sizes and spatial locations of postulated earthquakes and their causative structures),
- The rate of decay of seismic energy with distance (attenuation of ground motion),
- The effects of these sources at a particular location in terms of earthquake ground motion.

The main aim of conducting seismic hazard analysis is to construct and delineate regions according to the estimated ground shaking expected within a given time period so that useful information can be provided, e.g. to engineers to incorporate the seismic information in their building codes. Depending on the goals of a particular study, seismic hazard assessment can be achieved following either deterministic or probabilistic approaches.

Deterministic Seismic Hazard Analysis (DSHA): The analysis in this approach makes use of discrete, single valued events or models to arrive at scenario-like descriptions of earthquake hazard. It evaluates the maximum expected ground motion at a given site due to a maximum potential earthquake originating from nearby fault. The basic steps in deterministic seismic hazard analysis include 1) defining earthquake source zones, 2) selection of the controlling earthquake which could be the earthquake which is reasonably expected or the maximum credible earthquake, 3) determination of the attenuation relationship which characterizes condition at a particular site, and 4) estimation of hazard at the site. In deterministic seismic hazard analysis it is assessed what the maximum plausible earthquake from each identified potentially dangerous active area or active fault might be. Clearly, the hazard at a given site is dominated by possible activity on a close-lying fault.

Probabilistic Seismic Hazard Analysis (PSHA): The elements of the probabilistic seismic hazard analysis (Fig. 1a) are 1) definition of earthquake sources (delineation of causative structures), 2) estimation of the recurrence characteristics of seismicity for each source (seismic catalogue and recurrence relationships), 3) estimation of the earthquake effect (attenuation relationships), and 4) estimation of the seismic hazard at the site. There are similarities in steps 1 and 3 in both approaches while the other steps may be considered specific to the methods used. Unlike in the deterministic approach, in probabilistic analysis all possibly destructive events (not only the largest) occurring at different locations are considered, with the motivation that even smaller events may have a significant influence on the hazard estimates because they are more frequent in time and (probabilistically) more likely to occur close to any given site. Probabilistic seismic hazard analysis may be viewed as inclusive of all deterministic events with a finite probability of occurrence.

The probabilistic seismic hazard analysis method of Cornell (1968) has been broadly used for regions where sufficient information on the input parameters required by the method is available. Other alternative probabilistic methods used to overcome the lack of detailed knowledge of some of the input parameters needed by source zone approaches, are the smoothing technique of Frankel (1995) and Monte Carlo methods (e.g. Ebel and Kafka, 1999) which will be discussed in detail in chapter 2.

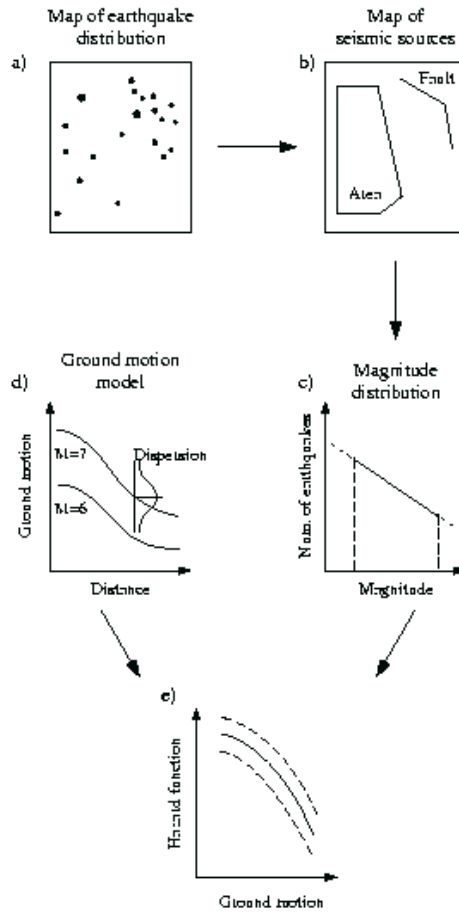


Figure 1a. Steps in probabilistic seismic hazard analysis (Rueggener, 1995).

All these approaches are aimed at providing quantitative measures of seismic hazard in terms of probabilities of exceeding (PE) a certain level of ground motion (e.g., peak ground acceleration, PGA) at a particular site for a specified return period. The results of such analyses are presented mostly as *seismic hazard maps* showing regional differences in estimated ground motion levels. The parameters used to characterize the severity and damage potential of earthquake ground motion may in general be grouped as peak ground motion or spectral values. Peak ground motion may mean peak ground acceleration (PGA), peak ground velocity (PGV), peak horizontal ground displacement (PGD). Other measures are response spectra (SA) and maximal expected intensity (Imax). For more general use, the most commonly adopted measure of the severity of damage potential is the PGA. Unfortu-

nately, no single parameter of ground motion has proved to be an accurate indicator of ground motion damageability. Since PGA has been proven to provide an incomplete measure of the damage potential, other measures such as the cumulative absolute velocity (CAV) have come into use, especially in areas where nuclear power plants are installed and safe power shut-down is deemed necessary.

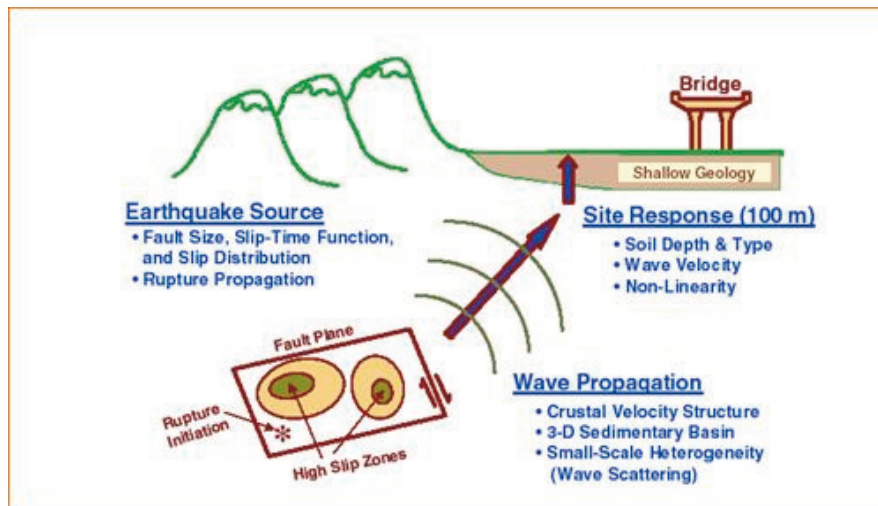


Figure 1b. A cartoon[†] indicating the characteristics of an earthquake source and the influence of earth structure on elastic waves.

The amplitude of ground motion at a particular site is controlled by many factors related to the source, the travel path of elastic waves and the near surface (site) effects (Fig. 1b). In characterizing seismic sources, physical parameters that need to be quantified are the maximum expected magnitude, earthquake recurrence rates and fault geometry. These analyses are greatly enhanced by including detailed information of the site conditions and wave propagation modeling in accordance with the appropriate attenuation relationships. Three parameters that need to be included in seismic hazard analysis are seismic activity rate (λ), the maximum possible magnitude (M_{max}) and the b value. Most of the information regarding seismicity comes from the seismic catalogue and how large an earthquake may occur at a particular region can be estimated either from geological information or using statistical estimates (e.g. Kijko and Sellevol, 1989; Kijko and Graham, 1998).

[†]Kentucky Geological Survey: <http://www.uky.edu/KGS/geologic hazards/risks.htm>

The parameters characterizing the record of a ground motion include the peak amplitude, frequency content, duration and energy. A large part of the uncertainty in seismic hazard estimation comes from incorrect determination of the attenuation functions accounting for the travel path effects. The attenuation of propagating seismic waves is mainly due to geometrical spreading and absorption. Nowadays, there are several empirical relationships derived for many regions which can be adopted elsewhere provided that there are similarities in the geological settings. On the other hand, the site effects, i.e. properties of shallow near surface soils, may also have a large influence on the amplitude, frequency composition and duration of ground shaking.

The ground motion at a particular site is also highly influenced by any variation in maximum magnitude, average depth or focal mechanism of the presumed source. The style (orientation) of faulting affects earthquake ground motions. Fault orientations are indicative of tectonic stresses and can have a strong effect upon earthquake ground motion. The largest ground motions appear to be related to reverse or thrust faulting where the maximum compressional stresses are parallel to the earth's surface (Reiter, 1990). Most hazard estimates assume faults to possess uniform source properties and use ground motion models derived assuming averaged ground motions i.e. the complexity of the source due to the rupture process, and the associated directivity effects, are often neglected. This assumption may result in either overestimation or underestimation of the ground motion level at particular sites. Where sufficient information is available, it may be possible to enhance the accuracy of seismic hazard estimation by including more data regarding the relevant fault features and source properties.

One of the steps (Fig. 1a) in the source zone approaches is the delineation of seismic area zones or identification of single faults where line sources are presumed. It is not always viable to identify earthquake sources (e.g. specific potentially dangerous faults) *in situ*, and therefore, demarcation of seismotectonic provinces may be carried out by including additional information from the results of focal mechanism studies. In addition to such information on faulting parameters, the determination of the present-day stress field is also useful in objectively delineating seismotectonic provinces. A seismotectonic province is in general defined as a geographical region with some geological, geophysical and seismological similarity that is assumed to possess a uniform earthquake potential throughout. In order to understand the evolution of plate boundary faults and the relative motion of the interacting plates, the state of stress field in the region and along the major fault features should be well understood. Source parameters of larger events are available from global monitoring and real-time waveform analysis (e.g. Harvard Centroid Moment Tensor, CMT). Even though, in general, the solutions obtained from the moment tensor inversion approaches used by the CMT and United

States Geological Survey (USGS) provide accurate source orientations, the depth estimates often contain some errors. Where more regional and tele-seismic waveform data is available, more reliable data can be incorporated to re-evaluate and improve the source parameters of events that occur in a region of interest. Recently, a relative approach in the moment tensor inversion of local earthquakes has been in use, (e.g., Dahm 1993; 1996; Dahm *et al.*, 1999) and proven to be efficient when applied to an ensemble of events that occur in a narrow cluster.

This thesis centers on aspects of seismic hazard analysis and related seismological problems in Eritrea and its surrounding region. The studies conducted are presented in four papers. Paper I deals with Seismic hazard assessment in the east African region of Eritrea and its surrounding area. The study area is characterized by complex tectonic setting where large uncertainties are expected in the seismic hazard estimation due to possible errors that may be introduced from the subjectivity in delineating source zones. In order to reduce the subjectivity involved in establishing active source zones, the approach proposed by Frankel (1995) has been employed to estimate the hazard levels from seismicity data alone. The other three papers highlight the different approaches used in determining fault orientations and in the computation of stress tensors from focal mechanism data. Paper II and III are on assessment of focal mechanisms and seismotectonics, with Paper III having an emphasis on a relative approach to moment tensor inversion as applied to large sets of narrowly clustered events in space. We have applied this to events occurring at the Hengill volcanic area, SW Iceland. The South Iceland Lowland (SIL) network monitors the earthquake activity in great detail, providing an enormous amount of data where the method can be efficiently employed. Such methods have limited applicability in areas (such as Eritrea) where the number of recording stations is much lower. However, if it can be demonstrated that methods relying on intense data coverage can significantly enhance the analyses of seismic risk, then this may help to define a long-term strategy for cost-effective improvement of risk assessment everywhere. Paper IV focuses on evaluating the state of stress from focal mechanisms of events that occurred in the region surrounding the Afar depression. It provides insight into the determination of the principal stress directions in relation to the plate interactions and accompanying motion driven by the extensional regional stress.

2. Methods of non-parametric Probabilistic Seismic Hazard Analysis (PSHA)

In contrast to the deterministic analysis of seismic hazard (DSHA), the probabilistic approach (PSHA) allows the use of continuous events and models, which results in an estimate of the likelihood of earthquake ground motion or some other damage measure occurring in an area of interest. Important, and sometimes controversial, components in carrying out probabilistic seismic hazard relate to defining source zones and to determining the maximum magnitude. The former may be handled by using two non-parametric approaches developed to get away from subjective judgments using the spatially smoothed seismicity approach (Frankel, 1995; Lapajne *et al.*, 1997; Lapajne, 2000) and the Monte Carlo methods (e.g. Ebel and Kafka, 1999). The following subsections discuss the underlying concepts of these two non-parametric methods as followed in Paper I.

2.1 The method of spatially smoothed seismicity

The method of spatially smoothed seismicity is different from other parametric methods in that it avoids the use of source zones. Frankel (1995) developed this method for directly using the smoothed historical seismicity in order to get away from the judgments and uncertainties involved in drawing seismic source zones in a region where it is difficult to specify the causative structures of seismicity. The region of interest is divided into a grid and in each grid cell the number, n_i , of earthquakes with magnitude equal to or greater than the lower bound magnitude m_o , are counted, where n_i is the activity rate for each cell i . These values are spatially smoothed to the values \tilde{n}_i using a Gaussian function (Frankel, 1995),

$$\tilde{n}_i = \frac{\sum_j n_j e^{-\Delta_{ij}^2 / c^2}}{\sum_j e^{-\Delta_{ij}^2 / c^2}}, \quad (2.1)$$

Where Δ_{ij} is the distance between the i th and j th cells and c is the correlation distance. The radius of smoothing is $3c$. This is the first stage smoothing to obtain the spatial distribution of past seismicity.

The method was extended by Lapajne (2000) to smooth the activity according to the determined orientations of seismogenic faults in each of the specified tectonic sub-regions. Instead of applying a circular Gaussian smoothing, Lapajne (2000) approximated the fault rupture-oriented elliptical Gaussian smoothing of past seismicity by,

$$\tilde{n}_{ij} = \frac{e^{-\frac{1}{2} \delta_{ij}^T V^T R V^T \delta_{ij}}}{\sum_i e^{-\frac{1}{2} \delta_{ij}^T V^T R V^T \delta_{ij}}} \quad (2.2)$$

Where \tilde{n}_{ij} is the percentage of earthquakes in cells i , added to the number of earthquakes in cell j , T means transpose. The distance from cell i to cell j is defined by vectors δ_{ij} . R is a correlation matrix defined by the first and the second principal half axis of the ellipse of smoothing, V is a matrix which determines the direction of the first principal axis of the ellipse defined by the azimuth α and given by

$$V = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \quad (2.3)$$

The first principal axis (major axis) of the ellipse of smoothing is oriented in the determined direction of the seismogenic fault. It is assumed that the major axis is equivalent to the fault rupture length which in turn can be related to the magnitude of the earthquake (e.g. Wells and Coppersmith, 1994; Vakov, 1996) by,

$$\log L = a_l + b_l m, \quad (2.4)$$

Where L is the subsurface rupture length; m is magnitude of the earthquake; a_l and b_l are constants empirically determined.

For the seismic hazard analysis used in this method, the main input parameters are the activity rate λ , the b -value, and the maximum magnitude, M_{max} . Computed values are the spatially smoothed seismic activity rates at grid points for the region, annual rates of exceeding a given level of ground motion at each grid point, and ground motions for a specified return period. Apart from the three basic input parameters; the activity rate, the b -value and the maximum magnitude, an important parameter in seismic hazard assessment is an appropriate choice of an attenuation relationship. This choice and the uncertainties associated with it, form part of the source of error in the final hazard estimates.

The seismic hazard calculation is performed by computing the annual rates of exceeding specified ground motion levels. Ground motions are then estimated by interpolating the annual rates. For the seismicity models considered, peak ground accelerations are calculated for return period of 475 years, i.e. 10% probability of exceedence in 50 years. The annual rate of exceeding ground motion u_o at a specific site is given by

$$\lambda(u > u_o) = \frac{1}{T} \sum_i \tilde{n}_i \int_{m_{min}}^{m_y} P[u > u_o | d_i, m] P_m(m) dm \quad (2.5)$$

Where T is the number of years for which the activity rate is determined, m_{min} is the minimum magnitude for which $\lambda(u > u_o)$ is calculated, P_m is the probability density function of the magnitude m , and $P[u > u_o | d_i, m]$ stands for the conditional probability that a given ground motion level, u_o , would be exceeded if the distance from the site to the centre of the grid cell, i or the closest distance to the corresponding fault rupture was d_i and the magnitude was m . P depends on the attenuation function.

2.2. The Monte Carlo approach:

Monte Carlo methods are stochastic techniques which are based on the use of random numbers and probability statistics to investigate physical and mathematical problems.

Monte Carlo simulations have been used as an alternative approach for estimating seismic hazard. According to the Monte Carlo method of seismic hazard analysis (Ebel and Kafka, 1999), the area surrounding a given site can be constrained by seismic source boundary locations to construct different earthquake catalogues. Each catalogue will list earthquakes of different sizes up to the maximum magnitude at different possible earthquake locations. The method employed uses re-sampling of an observed earthquake catalogue, to construct a long duration synthetic earthquake catalogue and then to find earthquake ground motions from which the hazard values are found (Ebel and Kafka, 1999). This method assumes that magnitudes and locations can be independently selected from the observed catalogue. It further assumes the duration of an observed catalogue to be long enough to represent the mean rate of earthquake occurrence at different magnitudes over the time period of the synthetic catalogue. Assuming events in a catalogue to follow a *Poisson process* and to be *stationary* through the entire period of the catalogue, seismic hazard can be estimated by simply counting the number of occurrences N_T during a time period T and computing annual rates exceeding certain ground motion levels. The temporal and spatial rates of earthquake occurrence in a region of interest are completely determined from the earthquake catalogue used in the analysis. It is neither necessary to compute a - and b -values nor draw source zones. The advantage of using this approach is two-fold, the first being that the uncertainties in the determination of the a - and b -values are not propagated through the analysis into the hazard result. Those magnitudes that occur more frequently in the catalogue contribute more to the seismic hazard. Likewise, those areas that have a higher density of the earthquake epicenters contribute more to the seismic hazard. The second advantage of the method is that the contribution of individual earthquake to the seismic hazards can be calculated explicitly.

3. Earthquake source assessment

There are a number of reasons why we study fault orientation. Identifying the fault plane is important in seismic hazard assessment, prediction of aftershock location, and to infer relative motion between plates. Due to the symmetry of the radiation patterns, when analyzing an individual event it is normally not possible to distinguish the true orientation of the fault plane from the “auxiliary” plane. In many cases, the ambiguity in distinguishing the fault plane from the auxiliary plane can be resolved using additional information on surface faulting, aftershock distribution, bathymetric trends or directivity of rupture deduced from waveform analysis. A focal mechanism is a representation of an earthquake source which includes information on the orientation of the fault plane and the slip direction. Three angles are used to describe the focal mechanism, the strike and dip angle of the fault plane and the rake, which is the angle between the slip direction and the horizontal in the fault plane (see Fig. 2a). A common way of expressing the focal mechanism is in terms of the seismic moment tensor.

3.1. The Seismic Moment Tensor

A simple model for an earthquake may be represented by slip occurring between two blocks of material. The equivalent force system for slip on a fault can be described in terms of two dipoles, the pressure (P) axis and the tension (T) axis. These are constrained by the geometry of the faulting to be orthogonal (Fig. 2a) and at 45° angle to the fault normal. The P and T axes lie in the centers of the dilatational and compressional quadrants of a focal sphere, respectively.

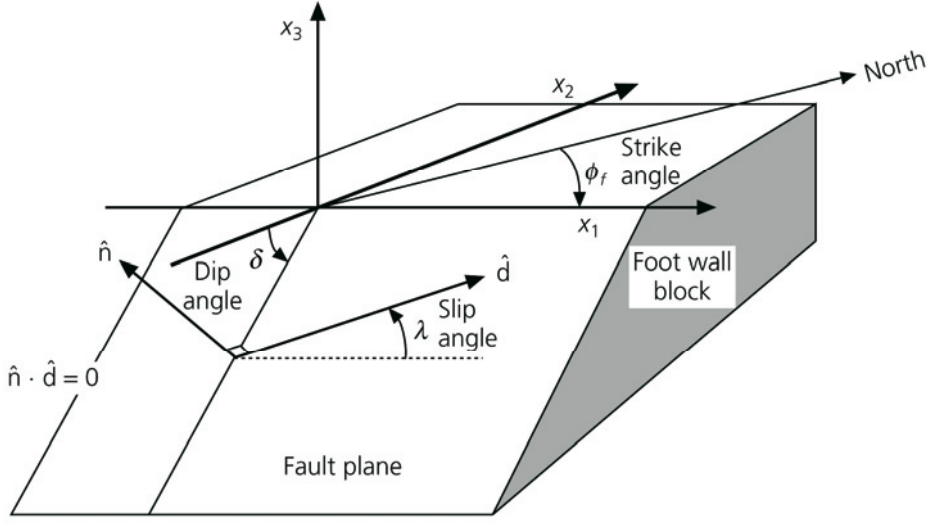


Figure 2a. Configuration of the fault plane defined by the strike angle Φ_f and the dip angle δ , with slip defined by the rake angle λ . The orientations normal to the fault plane \mathbf{n} , and the slip vector \mathbf{d} are shown (After Stein and Wysession, 2003).

Combining force couples of different orientations into a seismic moment tensor, \mathbf{M} , gives a general description that can represent various seismic sources. The moment tensor consists of nine generalized couples representing the movement on a fault during rupture (Fig. 2b).

The equivalent moment tensor is given by,

$$M_{kj} = A\mu s(n_k d_j + d_k n_j). \quad (3.1)$$

Where A is the area of slip, μ is the shear modulus, s is the average slip, and \mathbf{n} and \mathbf{d} are the fault normal and slip direction, respectively. The tensor, M_{kj} in equation (3.1) is symmetric (assuming an isotropic medium) and its trace is zero (for a pure shear), i.e., \mathbf{n} and \mathbf{d} are perpendicular to each other leading to zero isotropic component.

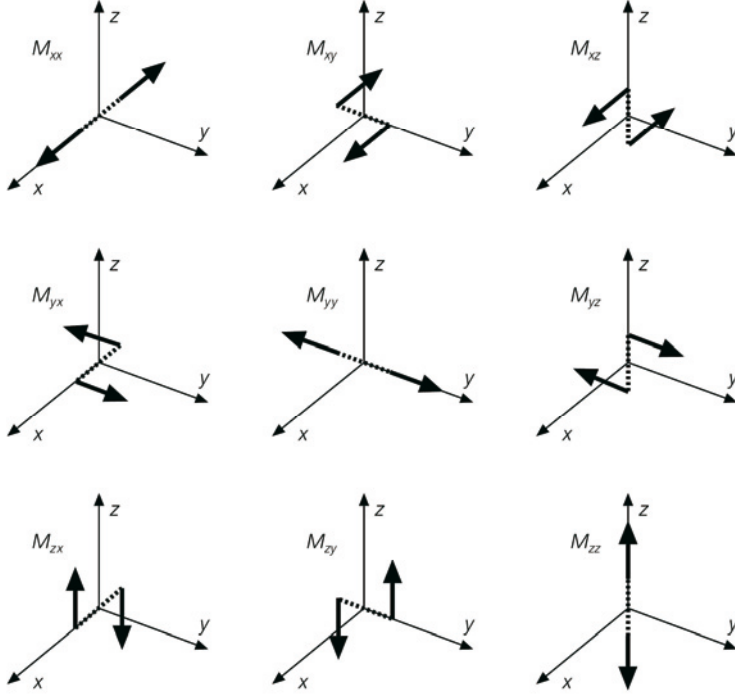


Figure 2b. The nine components of the seismic moment tensor (After Aki and Richards, 1980).

A standard approach in the studies of teleseismic body waveforms is to use a point source approximation. The displacement in the far field is expressed as:

$$u_n(x,t) = M_{kj} [G_{nk,j} * s(t)] \quad (3.2)$$

Where M_{kj} represent the components of the moment tensor \mathbf{M} , and $s(t)$ is the source time function. This is a simplified formulation of the displacement field considering no external forces and time invariant moment tensor. The Green's functions ($G_{nk,j}$) contain information on the propagation effects on elastic waves. They can be computed for a known velocity structure through which elastic waves travel.

The moment tensor formulation has two advantages. First, it allows us to analyze seismograms without assuming that they result from slip on a fault. With such an advantage, it is possible to identify non-double couple sources, i.e. sources other than those attributed to the plane slip on a limited rupture

surface constrained within the solid earth. Second, the moment tensor makes it easier to invert seismograms to find source parameters (linearity) for a known source time function. The predicted seismograms depend on fault geometry factors that are trigonometric functions of the fault strike, dip, and slip angles. Inverting the seismograms to determine the fault angles and the scalar moment, M_0 , is a non-linear problem. The inverse problem is easier if we write the seismograms as linear functions of components of the moment tensor assuming a known source time function. To do this, let the source be represented by vector \mathbf{m} , containing components of the moment tensor. Because of the tensor symmetry only six out of the nine components of the moment tensor are independent. For an event recorded at many stations, the displacement at the i th station is given by,

$$u_i(t) = \sum_{j=1}^6 G_{ij}(t)m_j \quad (3.3)$$

Where G_{ij} is the Green's function at the i th station due to the moment tensor component m_j , which includes the instrument response and the propagation effects along the path from the source to the seismometer (earth structure).

Equation (3.3) can be written in vector-matrix form,

$$\mathbf{u} = \mathbf{G}\mathbf{m}, \quad (3.4)$$

Where \mathbf{u} is a vector composed of the seismograms at n stations and \mathbf{G} is the Green's function matrix. The moment tensor is solved from equation (3.4) in least squares sense as for a generalized matrix \mathbf{G} ,

$$\mathbf{m} = (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T \mathbf{u}, \quad (3.5)$$

Focal mechanisms of earthquakes of magnitudes larger than $M_w > 5.5$ are automatically generated from globally distributed stations. The Harvard CMT provides moment tensor solutions obtained by inverting data from long period body waves ($T > 40$ s) and very long period ($T > 135$ s) surface waves (Dziewonski *et al.*, 1981). Propagation effects have greater influence on regional records than teleseismic signals due the greater influence of crustal heterogeneities which give rise to reflections and conversions. Since no method is perfect, the Harvard CMT method also has its own limitations. Results obtained from this method may be poorly constrained in cases where: a) there are large errors in hypocentral locations, b) there is a complexity in the source (invalidating the point source assumption), and c) events occur at shallow depths. The lack of regional models and the assump-

tion of simple velocity structures may introduce some errors in the solutions obtained from the moment tensor inversion approaches. For large data sets monitored by local to regional network, relative methods may safely be employed to reduce the effect of earth structure on elastic waves when estimating source parameters.

3.2. Decomposition of moment tensor- Styles of failure

Since the non-double components of moment tensor have received much attention during recent years (Kawakatsu 1991, Kuge and Kawakatsu 1992, Foulger and Julian, 1993; Dahm 1996), the decomposition of moment tensor into isotropic and deviatoric components and inferences made from the results about the styles of faulting (Fig. 3) have become popular procedures in earthquake seismology. In general, moment tensor solutions may give indications about the physics of earthquakes including an understanding of rupture process, the local stresses, coefficients of friction on faults, and pore fluid pressures or volume changes. Recently, it has been shown that anisotropy in a material at the source may also significantly contribute to large non-double components of the moment tensor, which are often interpreted as volumetric or tensile sources (e.g., Rössler *et al.*, 2004; Vavrycuk, 2004). It is also possible to obtain apparent non-double couple sources in structurally complex environments due to propagation effects.

The shear failure and faulting or crack orientation are described by the deviatoric components of moment tensors whereas co-seismic volume changes or explosion and implosion are given in the isotropic part (ISO). If all three diagonal terms of the moment tensor are nonzero and equal, the polarity of the focal mechanism is the same in all directions. Such a triple vector dipole of three equal and orthogonal force couples is the equivalent body force system for an explosion or implosion. The physical processes in explosions differ markedly from those for earthquakes. An explosion involves sudden increase in pressure, which causes non-linear deformation close to the source.

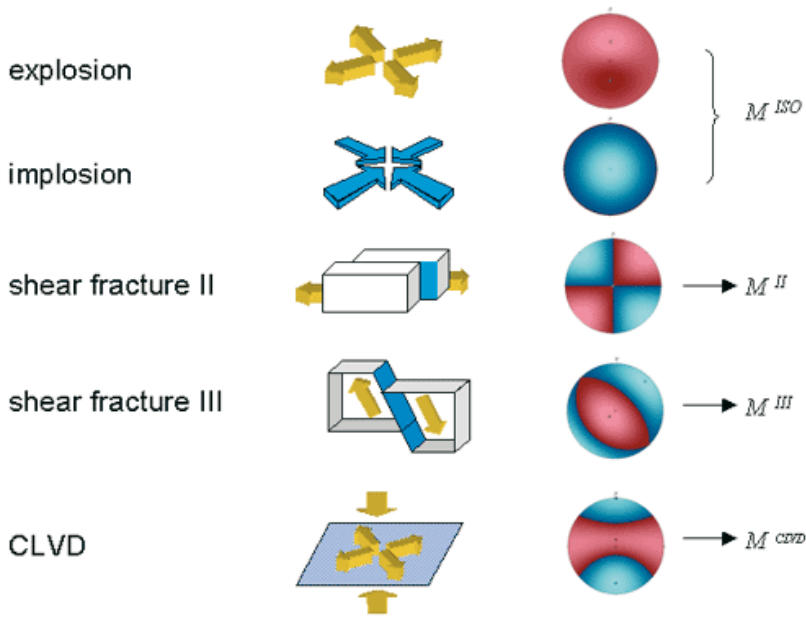


Figure 3. Classification of the modes of rupture and styles of faulting and their corresponding radiation patterns (After Grosse and Flinck, 2006).

The deviatoric component can be further decomposed in the best double couple (DC) and compensated linear vector dipole (CLVD) components. The CLVD component may be considered to be associated with a tensile crack mechanism. In general, since the moment tensor contains all the seismic moments and the forces of rupture, decomposition into its components and careful analysis has the potential to help in understanding even more complex mechanisms of failure.

3.3. Relative moment tensor inversion (RMTI)

Absolute moment tensor inversions require knowledge of velocity structure along the propagation path of elastic waves between the source and the receiver. The Green's function in equation (3.4) as used in many moment tensor algorithms is computed using simple velocity models which may be crude approximations of real earth structure. There is no doubt that the near surface heterogeneities in areas of complex tectonics may significantly influence the amplitudes and waveforms. For well studied areas where a good knowledge of the velocity model is available, absolute moment tensor inver-

sions may result in accurate solutions. However, such detailed information is often not available, which may require a different approach that does not take propagation path effects into account. The procedure followed by the relative moment tensor is one such approach formulated to reduce the propagation path effects and to lessen possible associated errors from propagating into focal mechanism solutions. The relative method of moment tensor inversion is used for ensembles of events that occur in a narrow cluster.

The Green's functions in equation (3.4) can be further separated into parts related to the radiation pattern (\mathbf{h}), and the linear wave propagation effects (\mathbf{I}).

$$u^m = (\mathbf{h}_k^m \mathbf{I}^m) m_k^m \quad (3.6)$$

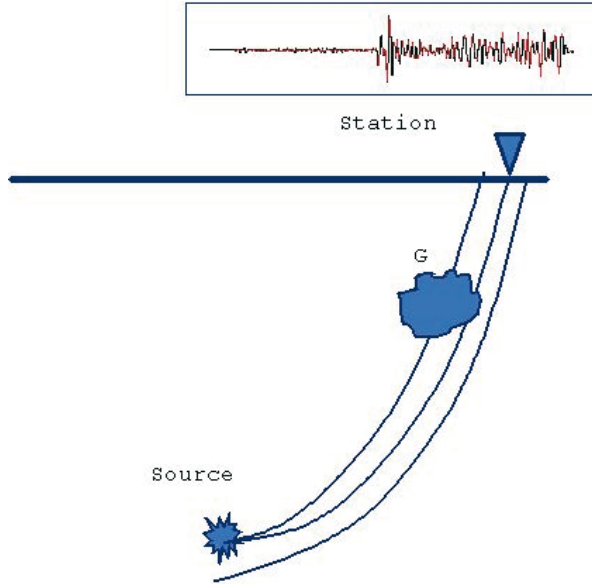


Figure 4. A sketch showing the ray paths and possible propagation effects in a heterogeneous media. Seismic waves generated by close-lying events see the same structure.

h depends on takeoff angles and azimuth to stations. The superscript m in equation (3.6) describes a phase type ($m=1$ for P, $m=2$ for SV and $m=3$ for SH). m_k is a model vector of length 6 such that:

$$\begin{aligned}
m_1 &= 0.5 (M_{yy} - M_{xx}), & m_2 &= M_{xy}, \\
m_3 &= M_{xz}, & m_4 &= M_{yz} \\
m_5 &= -(0.5(M_{xx} + M_{yy}) - M_{zz})/3, & m_6 &= (M_{xx} + M_{yy} + M_{zz})/3
\end{aligned}$$

The ray paths of two earthquakes originating at the same point in space (Fig. 4), experience the same propagation effects (I) leading to the elimination of “ I ” when ratios of their amplitudes are taken. The equations for the RMTI of such two events are related as (Dahm, 1996; Dahm *et al.*, 1999):

$$u^{(2)} h_l^{(1)} m_l^{(1)} = u^{(1)} h_k^{(2)} m_k^{(2)} \quad (3.7)$$

If the moment tensor (m^1) of one of the events is known (reference event) then the mechanism of the other event (m^2) can be estimated. In equation (3.7), u may represent peak amplitude, peak-to-peak amplitude, or polarity weighted plateau value of an amplitude spectrum (Dahm 1996; Dahm *et al.*, 1999).

4. Stress field estimation using earthquake focal mechanisms

The question of how faults interact with each other and whether the activity at one fault delays or triggers the activity on another fault depends on changes in the stress field (e.g. Harris, 1998). The stress field, in general, is a product of the interaction of tectonic forces acting along plate boundaries, tractions at the base of plates, and intraplate rheology (Zoback *et al.*, 1989; Zoback 1992; Sandiford *et al.*, 2004). Small changes in stress may cause a change in spatial distribution of aftershocks (Harris, 1998). Accurate predictions of seismic hazard require knowledge about the regional stress field which reflects the tectonic interactions. An inversion problem can be formulated that uses focal mechanisms or fault slip data (e.g. Angelier, 1979; Gephart and Forsyth, 1984) to determine directions of the principal stress components. Stress inversion from focal mechanism data is carried out with the assumptions that *a*) the whole region of a selected cluster of earthquakes is under a uniform stress field, and *b*) the slip on faults is in the direction of maximum resolved shear stress (Bott, 1959). The assumption of uniform stress field is valid provided that the region for which the stress is computed is small and the time window is small. McKenzie (1969) shows that the approximation of *P* and *T* axes of a focal mechanism as the compressional and tensional stress axis is not correct, instead the principal stress axes *S*₁, *S*₃ may fall anywhere in the quadrant of *P*-axis and *T*-axis, respectively. Using focal mechanism data, only a subset of four of the six independent components of the stress tensor can be determined. These are usually expressed as the directions of the principal stresses and the stress ratio, e.g. $R = (S_1 - S_2)/(S_1 - S_3)$, a relative size of the intermediate principal stress. Neither the shear stress magnitude nor the absolute magnitudes of the principal stresses can be obtained without further assumptions.

Since earthquake focal mechanisms cannot distinguish the fault plane from the auxiliary plane in the mechanism, stress inversion methods have to make a choice, or use both planes. Frequently the two nodal planes are tested by the inversion scheme and the nodal plane with least misfit is chosen as the “correct” fault plane (e.g. Gephart and Forsyth, 1984; Michael, 1987). This is referred to as the slip angle method. Lund and Slunga (1999) suggested

that the nodal plane with least stability in the stress field should be considered as the fault plane candidate. This fault selection criterion is henceforth referred to as the stability method. They showed that stability can be compared between the two nodal planes without explicit assumptions on pore pressure or the coefficient of friction. If an event ruptures to the surface, or has well located aftershocks that define the fault plane, the correct fault plane information can be incorporated into the inversion scheme. The Lund and Slunga (1999) approach also considers uncertainties in the focal mechanisms, as estimated by the Rögnvaldsson and Slunga (1993) method used in the Icelandic SIL system. With this method, the events have an optimum, best fitting focal mechanisms and a range of acceptable solutions which fit the data only slightly less well than the optimum.

5. Brief tectonics of Eritrea and the surrounding region

This section contains a brief discussion on the seismically active zones and the major tectonic regimes where most of the earthquake activity is concentrated. The African Plate is rifting in the eastern interior along the tectonically and volcanically active Afar triangle and Great Rift Valley (Fig. 5). The Afar Depression in Ethiopia, Eritrea and Djibouti in the horn of Africa is a rift-rift-rift triple junction where the NW-trending Red Sea, the EW trending Gulf of Aden and the NE-trending Main Ethiopian Rift systems meet. Earthquakes in the east African region of Eritrea and its surroundings occur mainly along the main tectonic features. The Ethiopian rift system continues to the southern Red Sea with its left margin flanking the main cities of Asmara and Massawa. The opening of the Gulf of Aden propagates WSW towards the Afar depression (e.g. Courtillot *et al.*, 1980; Manighetti *et al.*, 1997). To the west, in the Gulf of Tadjoura, the ridge shows clear evidence of the propagation towards the Afar area (Manighetti *et al.*, 1998; Dauteuil *et al.*, 2001). The Gulf of Aden is the short path from the Carlsberg ridge to the Red Sea and Ethiopian rifts and therefore is interpreted as the locus of stress concentration within the Arabian-Somalian plate boundary (Manighetti, 1993; Manighetti *et al.*, 1997). This rift zone separates the Nubian subplate to the west from the Somalian subplate to the east.

The Red Sea can be divided into three or four distinct zones, each characterized by different morphology and structure which appear to represent different stages in the development of a continental margin and establishment of a mid-ocean ridge spreading system (Cochran, 1983). Several geophysical studies suggest the presence of deep and narrow axial trough formed by sea floor spreading during the last 4 Ma (Pedone *et al.*, 1992). The axial trough is characterized by several normal and oblique NE-SW faults. The strike-slip motion of these faults offset the axial trough. The seismicity of the province is related to the active sea floor spreading which mobilizes wide spread sets of strike slip, transcurrent, normal and inverse faults of the main trough and shelves.

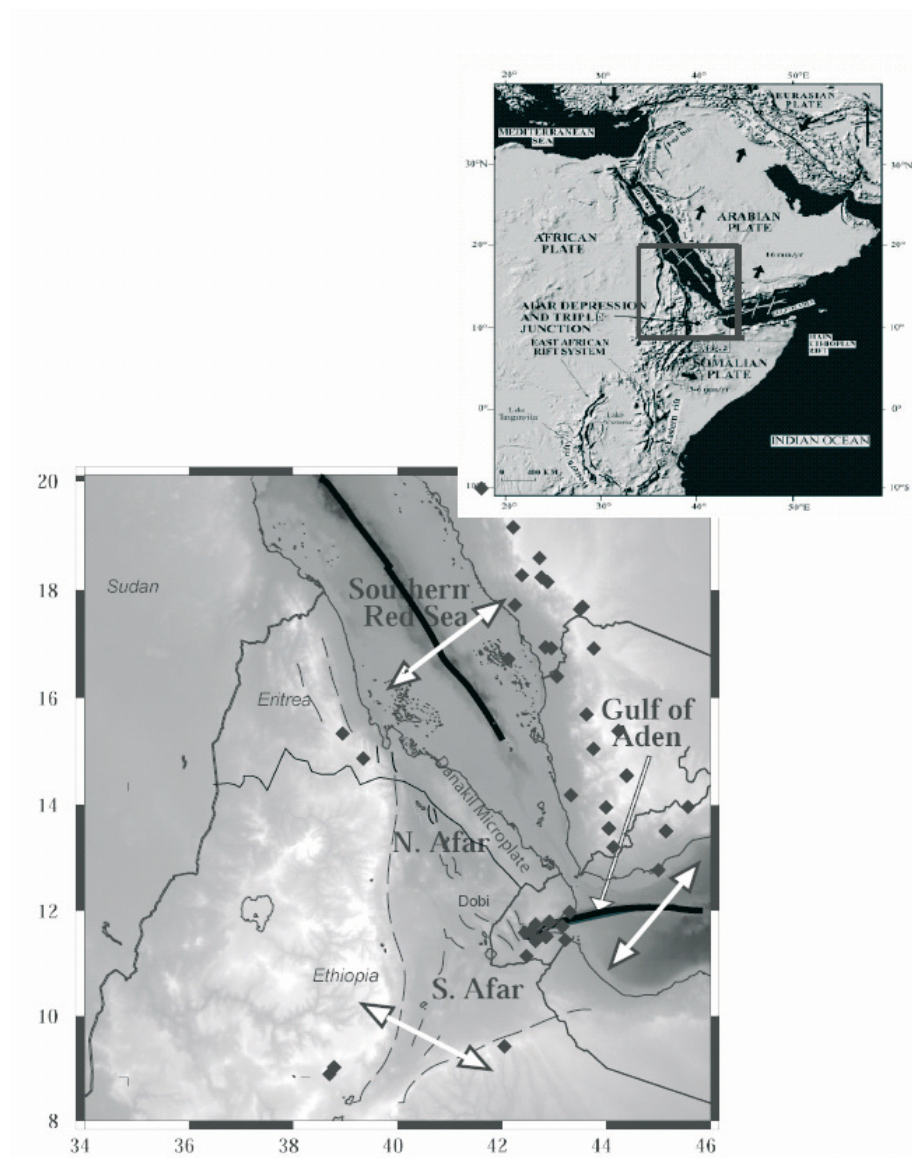


Figure 5. A simplified tectonic map showing the major faults and structural elements in the study region. Heavy lines indicate the axial trough along the Red Sea and Gulf of Aden. **Arrows** show the directions of relative plate motion between African-Somalian, Somalian-Arabian and African-Arabian plates. **Squares** are the seismic station distribution in the region. Inset map: A digital topographic map showing the regions surrounding the study area (After Tesfaye *et al.*, 2003)

In Central Afar, a broad zone of active extensional deformation exists where the tectonically active Gulf of Aden and the two arms of the rift system in the region meet (Manighetti *et al.*, 1998). Central Afar is characterized by predominantly normal faulting but with numerous NW-oriented sinistral shears striking parallel to the rifting axes (Abbate *et al.*, 1995). The rifting process in the region was accompanied by dike intrusions, faulting, and thinning of the lithosphere that led to a stable spreading centre (Acton and Stein, 1991) by a process known as rift localization. As a result, motion is transferred from a broad zone of faults and fissures to a single dominant rift. Most previous focal mechanism studies (Sykes, 1967; Fairhead and Girdler, 1971; Fairhead and Stuart, 1982; Hofstetter and Beyth, 2003) indicate that the rift system is dominated by extension. Focal mechanism studies (e.g. Hofstetter and Beyth, 2003) show that most of the larger (at least three $M_w > 6$) earthquakes that occurred in the Eastern and Central Afar show predominantly normal faulting. To the east, the Danakil microcontinent, bound between Nubian, Arabian and Somalian plates is deforming under regional extension in front of the westward propagating Gulf of Aden spreading centre. Recent studies of the evolution of Danakil (e.g. Chu and Gordon, 1998; Eagles *et al.*, 2002) suggest that the Red Sea and Aden rifts link through Afar, isolating the Danakil horst as microcontinent on the Arabian margin.

Seismicity in the region is generally of tectonic origin occurring mainly along the main tectonic features. Owing to the complicated tectonics of the region, a variety of focal mechanisms are observed within a given small area (Hofstetter and Beyth, 2003; Paper IV) occurring at shallow depths (e.g. Paper II). Even though it is not easy to associate every event that occurred in the region to a specific corresponding fault, the presumed dominance of the normal type of faulting is shown from the focal mechanism studies and stress tensor analysis conducted in Papers II and IV, respectively. The suggested continental break-up and formation of a sea floor in the Afar depression is exhibited in the recent magmatic episode that took place on September 26, 2005 and the following rupture on the surface. After the event a horizontal component of the deformation field at the surface shows a maximum opening of 6m perpendicular to the Dabbahu rift segment (Wright, *et al.*, 2006).

6. Summary of papers

This thesis work covers some aspects of seismological problems that deal with the assessment of the seismotectonics and seismic hazard of the region under study. Paper I discusses a preliminary hazard estimate of Eritrea and the surrounding region estimated using non-parametric approaches of seismic hazard analysis. Paper II and IV also provide information about the source and the state of stress along the main tectonic regimes, aimed at obtaining constrained focal mechanisms and estimation of the principal stress directions. Paper III is a study carried out on Icelandic data where an efficient method of waveform analysis is applied. Possible seismotectonic inferences are also made from the studied clusters of aftershocks that occurred following a major event of June 4, 1998.

Paper I

Prompted by the need to investigate the potentially hazardous region, and delineate area of potential risk, seismic hazard analysis for the region was conducted with the limited information available, i.e. the seismic catalogue. Previous studies seismic hazard estimation in the region were carried out on a larger scale and using methods that require the delineation of seismic source zones. Given the complex nature of deformation in the region, detailed information of active faults in the area and consequently the demarcation of source zones becomes a non-trivial procedure which might possibly result in significant uncertainties in the derived ground motion estimates. Thus, we employ two non-parametric methodologies for estimating seismic hazard in order to elucidate the robustness of the results: the method of spatially smoothed seismicity introduced by Frankel (1995) and its extension (Lapajne *et al.* (1997); Lapajne (2000) and a Monte Carlo approach presented by Ebel and Kafka (1999). In the first method, fault-rupture oriented elliptical Gaussian smoothing was performed to estimate future activity rates along the causative structures. Here in this method, we used four seismicity models to characterize seismic hazard; three models as used by Frankel

(1995) and a fourth one by Lapajne *et al.* (1997) which takes into account the total energy release to estimate the seismic activity. These models are based on historical and instrumental seismicity that has been spatially smoothed to different length scales. This differs from the traditional approach where area source zones are drawn around seismicity or tectonic provinces for the estimation of seismic hazard (Cornell, 1968). The first model considers the whole region as one source zone, and takes into account only instrumental data. Alternative seismicity models 2 and 3 have been used to constrain results from model 1 as done by Frankel (1995) for the central and eastern US.

The earthquake catalogue for this region consists of both historical and instrumental data, compiled from the National Earthquake information centre (NEIC), the international seismological centre (ISC), and from Turyomuryendo (1996). The horizontal Peak ground acceleration (PGA) attenuation relation of Joyner and Boore (1988) was adopted as representative for the ground conditions for previous studies (Kebede and Van Eck, 1997). Comparison between the attenuation curves of Boore *et al.* (1994) and Ambraseys *et al.* (1996) indicate higher values at shorter distances in the latter and vice versa at larger distances. In the absence of a ground motion data, an average of several attenuation relationships could be taken for hazard estimation. Comparison between plots of different attenuation curves (Paper I) indicates that the Ambraseys *et al.* (1996) relationship is an average of the other relationships for shorter distances. At large distances, however, this relationship tends to overestimate the ground motion level.

The maximum possible magnitude of an earthquake, M_{max} , that may occur in the study region is estimated using the method of Kijko and Graham (1998). An average deviation of about 0.3 has been observed in reported magnitudes of the same event from different agencies, thus we assumed a uniform standard deviation of 0.3 for each magnitude in the catalogue. An upper bound magnitude is therefore estimated to be 7.3 with a standard error of 0.5. Thus, we chose to use the maximum magnitude in the catalogue $M_s = 6.8$ to be our upper bound magnitude, as the standard deviation is higher which would reduce it back to 6.8.

PGA values for 10% probability of exceedence in 50 years (return period of 475 years) were computed for each model and a combined seismic hazard map was produced by subjectively assigning weights to each of these models. A worst-case map is also obtained by picking the highest value at each grid point from values of the four hazard maps. The combined seismic hazard map indicates high hazard values along the Gulf of Aden and low values on the western part of the study region where seismicity is low (Fig. 6).

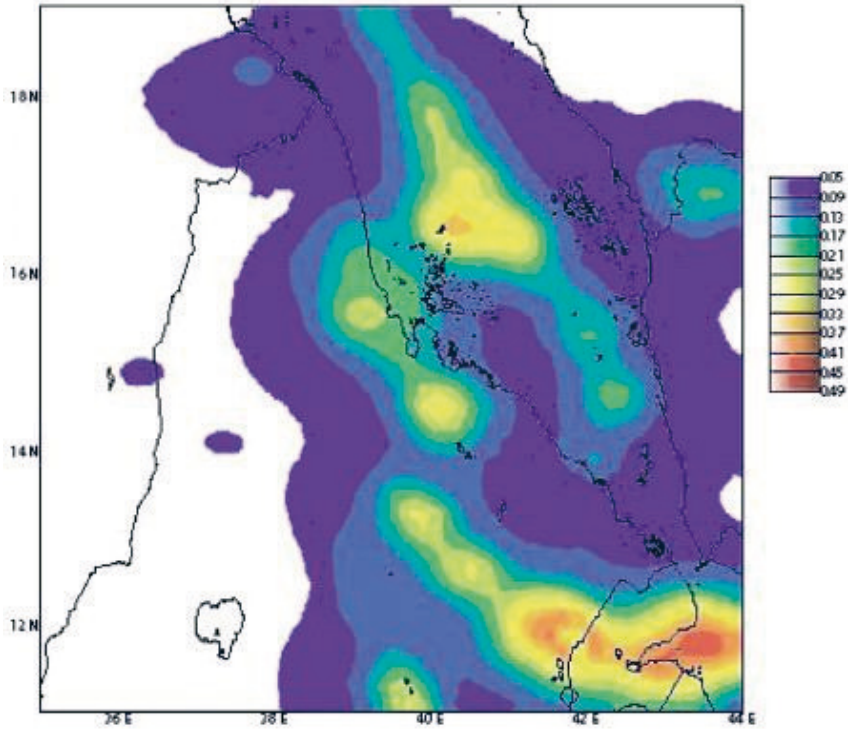


Figure 6. A combined seismic hazard map showing PGA values (in % of g) estimated using the spatially smoothed seismicity approach.

We also used the Monte Carlo approach (Ebel and Kafka, 1999) as an alternative for seismic hazard estimation in order to compare to results obtained from the spatially smoothed seismicity approach. Several tests were conducted to investigate the effects of the duration of the synthetic catalogue on the computed seismic hazard values for a site in Asmara. The duration in the synthetic catalogue seemed to change the hazard values at a grid points. It was suggested in previous studies that the longer the duration, the more reliable the hazard estimate will be. A duration of synthetic catalogue of 10000 years for a 10% probability of exceedence is found to give reliable estimates of the seismic hazard.

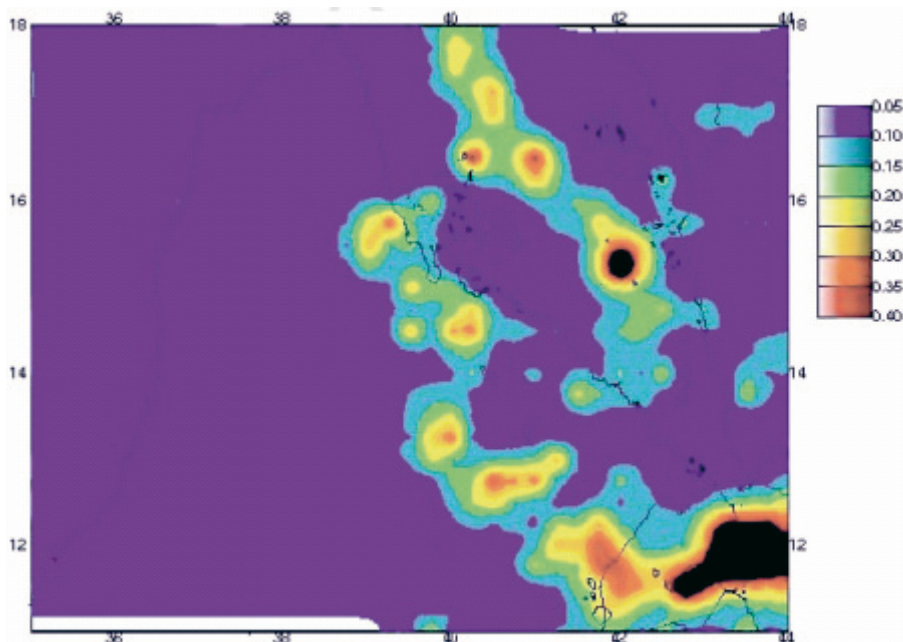


Figure 7. Seismic hazard map estimated using Monte Carlo approach. Values are in % of g.

Results obtained from both methods (Figs 6 and 7) are comparable except for some differences in hazard values at grid points. Both maps indicate a higher hazard along the main tectonic features of the east African, the Gulf of Aden and the Red Sea rift systems. Within Eritrea, the highest PGA exceeded a value 25% of g, located north of Red Sea port of Massawa (Fig. 6). In areas around the capital, Asmara, PGA values exceed 10 % of g. In general, this paper presents a preliminary seismic hazard map, delineating the whole region under study according to the expected ground motion levels (PGA).

Paper II

The aim of this project is to assess the reliability of previously determined focal mechanisms of selected events using a moment tensor inversion procedure applied to teleseismic body waves. The underlying motivations to conduct this study were 1) the assessment of focal depths and the mechanisms involved during earthquake rupture process, and b) the inherent limitations that exist in some methodologies to resolve certain earthquake source pa-

rameters may mean that previous results were sub-optimal. We present a stepwise inversion procedure to resolve the focal depth and model earthquake source complexity of seven moderate sized earthquakes ($6.2 > M_w > 5.1$) that occurred in the Afar depression and the surrounding region. The Afar depression is a region of highly extended and intruded lithosphere, and zones of incipient seafloor spreading. Earthquakes in this region occur at relatively shallow depths, where the seismogenic layer beneath is subject to continental break-up, thinning of the lithosphere resulting from plume activity (e.g., Manighetti *et al.*, 1998; Ebinger and Sleep, 1998), magmatism and fault block rotation. Refraction seismic experiments (Berckhemer *et al.*, 1975; Ruegg, 1975; Makris and Ginzburg, 1987) show that the crustal layer beneath the Afar depression has thinned to thicknesses ranging from 14 - 26 km. Different approaches of earthquake source parameter determination have limitations in resolving certain parameters of an earthquake, in particular the focal depth. In studying areas like Afar, where up-welling of mantle and thinning of crust takes place, precision in the determination of these parameters is essential and avoids possible misinterpretation. A full moment tensor inversion scheme is used to resolve the source characteristics of the studied events using teleseismic body waves and a ray theory approach for the computation of synthetic seismograms. In this study, attempts have been made to obtain more reliable solutions especially to estimate the focal depth using similar approaches to those followed by Maggi *et al.* (2000) and Piliidou *et al.* (2004). A better understanding of the tectonic activities in the region can be gathered by obtaining a well-constrained focal depth and a relatively improved solution. Waveform inversion of the selected events estimated focal depths in the range of 17-22 km, deeper than previously published results. This suggests that the brittle-ductile transition zone beneath parts of the Afar depression extends more than 22 km. The effect of near-source velocity structure on the moment tensor elements was also investigated and was found to respond little to the models considered. Synthetic tests indicate that the size of the estimated, non-physical, non-isotropic source component is rather sensitive to incorrect depth estimation. The dominant double couple part of the moment tensor solutions for most of the events indicates that their occurrence is mainly due to shearing. Parameters associated with source directivity (rupture velocity and azimuth) were also investigated. Re-evaluation of the analyzed events shows predominantly normal faulting consistent with the relative plate motions in the region. We decompose the moment tensor into DC, CLVD, and ISO for the studied events in order to investigate the mechanisms involved during rupture processes and obtain information of the styles of faulting and identify possible aseismic sources (e.g. magma related activity). We used a graphical display of Riedesel and Jordan (1989) to show the 95% confidence regions associated with the components of the moment tensor (Fig. 8).

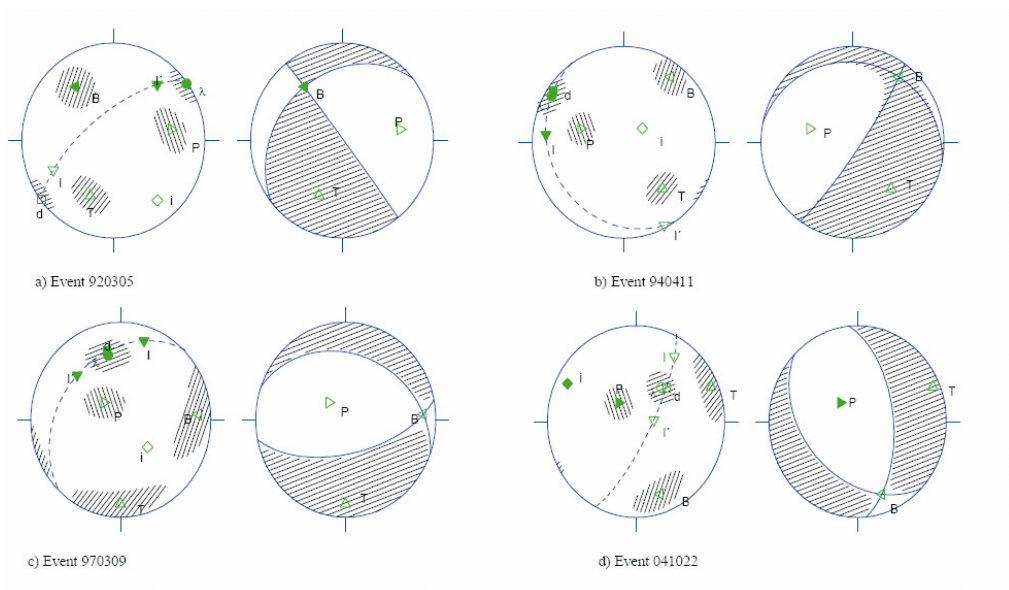


Figure 8. Graphical display of the source mechanism of some of the events analyzed in this study. Shaded region show the 95% confidence ellipses computed from the variance matrix of the moment tensor. λ =the solution; d=DC; l and l' are CLVD (with P and T axis); i=isotropic; P, T and B are the principal axes.

Paper III

For the large sets of data recorded by monitored by the Icelandic SIL network, an efficient approach to waveform analyses and evaluation of their source parameters is required. The quality of data obtained from the dense station distribution in the SIL network provides constrained solutions of the mechanisms. The highly automated SIL system detects transients at the stations, associates these to events centrally, locates and performs an automatic analysis of all located events to determine source characteristics and focal mechanisms. The available database includes onset time, duration, phase type (P or S), maximum amplitude, signal and noise averages, spectral parameters such as DC-level and corner frequency etc. The spectral amplitude focal mechanism method that runs in the system often provides accurate solutions, but since the effect of structure might introduce some errors in the solutions, an alternative method that reduces these effects is needed for bet-

ter focal mechanism estimation. Here, we apply the relative moment tensor inversion method that requires a well studied master event among spatially narrow clustered events, nominally not more than about one wavelength apart. The objectives of this research work are: a) to compute focal mechanisms using a relative moment tensor inversion for 25 events (aftershocks of the main event) and compare these to mechanisms previously computed using a single event spectral amplitude method (Rögnvaldsson and Slunga, 1993), and b) to study their source characteristics (possible non-double mechanisms).

First, we tested the method with synthetic data generated for real event-station distribution. Then, using spectral amplitudes from the SIL seismic network, it was applied on aftershocks of the June 1998 $M_w=5.4$ event that occurred at the Hengill triple junction, SW Iceland. Three distinct groups of spatially clustered events are observed in the region for 25 selected events that occurred during the period of June 4-5, 1998. These clusters have previously been relocated with very high accuracy using cross-correlation techniques. The focal mechanisms determined using the RMTI method, were then compared with those obtained by the spectral amplitude method used in the SIL system. Most focal mechanisms obtained in this study show a predominantly right lateral strike-slip motion, similar to those obtained by the SIL network, but the relative results are more consistently in agreement with the orientations of the surface faults in the area.

At this point similarity tests between the studied events was necessary to check the reliability of the results, for which we used the spectral amplitude grouping method to investigate discrepancies between some of the focal mechanisms obtained using both methods. Lund and Bödvarsson (2002) devised a method to compare focal mechanisms based on the recorded spectral amplitude distribution for each event. This spectral amplitude grouping (SAG) method cross-correlates the distributions of spectral amplitudes recorded at stations in common for two events. Each event's distribution is cross-correlated with all other events' distributions to form a matrix of correlation coefficients. Clustering of the events is then performed to form groups of highly similar spectral amplitude distributions, i.e. highly similar focal mechanisms. The SAG method has been applied to composite focal mechanism calculations, data reduction for stress tensor inversion and temporal pattern analysis (Lund and Bödvarsson, 2002). The similarity test could resolve apparent differences in the focal mechanism solutions for some of the studied events.

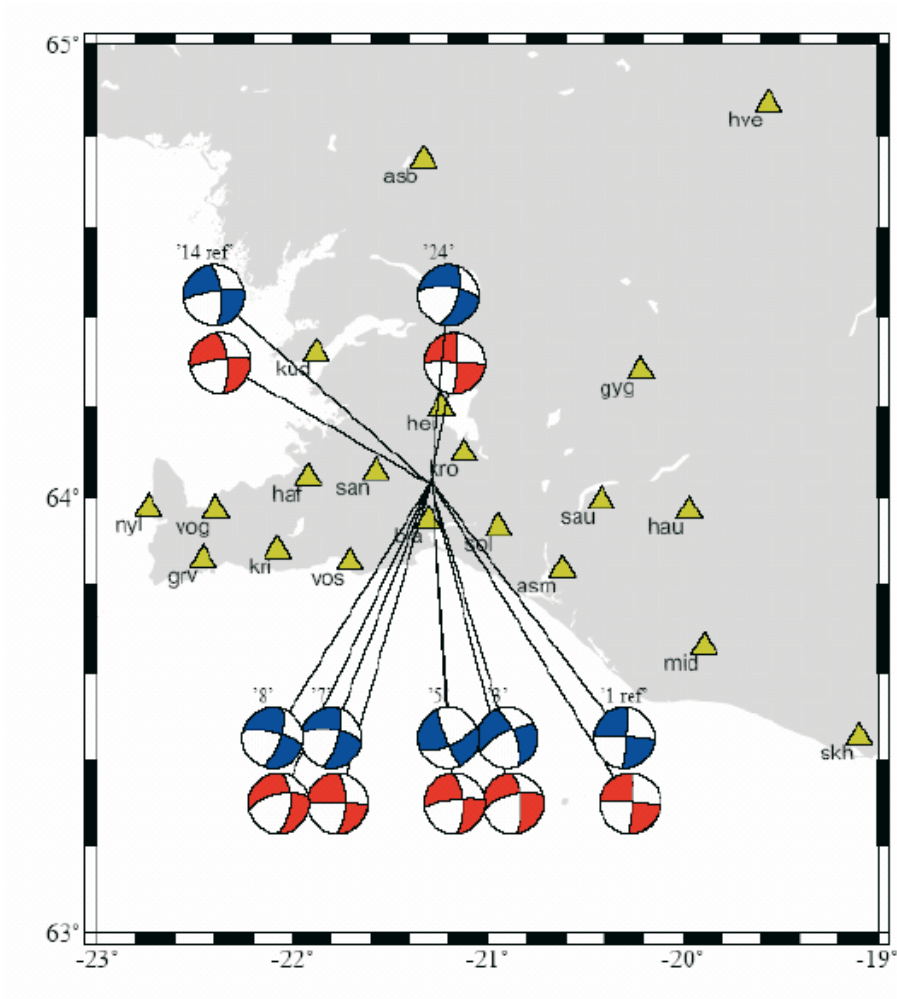


Figure 9. Focal mechanism solutions for seven events in cluster 2. Events 1 and 14 are the reference events. Blue/white beach balls=SIL solutions; Red/white=RMTI results with reference event having a DC constrained solution.

We also decompose the moment tensor into DC and non-DC (NDC) components in order to assess the mechanisms involved during the rupture processes. For the synthetic tests, the RMTI algorithm introduces 10-15% isotropic component, and various degrees of NDC (CLVD) components into the pure DC mechanisms. While the size of the spurious NDC components is significant, the DC parameters are well estimated. Decomposition of the moment tensors into double couple and isotropic components shows that the isotropic components are small, suggesting that the styles of failure for the events analyzed was mainly due to shearing, as we would expect.

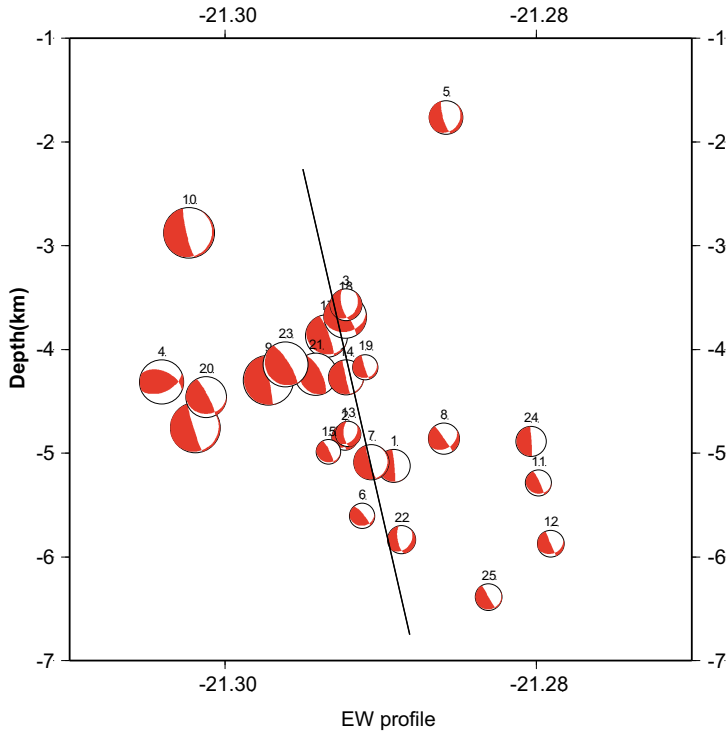


Figure 10. Focal mechanisms on a depth section along EW profile and across N-S trending fault. Larger focal mechanism symbols indicate location of events closer to the southern part and vice versa. North is perpendicular to the figure inwards. Solid line shows the average dip angle deduced from cluster alignment of the events. Individual focal mechanisms viewed from a cross section also show similar direction to the cluster alignment.

The seismotectonic implications of the events were also studied (Fig. 10). Cluster alignment across the presumed fault and the individual event mechanisms agree well, suggesting the occurrence of the events along a fault plane dipping steeply towards the east. Consistency in the pressure and tension axes of the focal mechanisms suggests that the region was under NE-SW oriented compression during the activity.

Paper IV

The aim of the study presented in this paper was to investigate the stress field in the Afar region using earthquake focal mechanism data. Despite the general agreement between the focal mechanisms of the events that occurred in this region and the causative structures or opening directions of the rift systems in the study area, the pressure and tension axes from individual focal mechanisms may not sufficiently describe the direction of principal stresses (McKenzie *et al.*, 1969), and hence an appropriate stress tensor inversion is required from a number of focal mechanism data. For a region like the Afar depression in East Africa, which is characterized by different fault orientations owing to the complex nature of the tectonics, approximations of possible directions of principal stresses from the pressure and tension axes of focal mechanisms may result in inaccurate conclusion. Based on earlier studies in the region, we compiled a catalogue of 93 earthquakes ($M > 4$) with known focal mechanisms, spanning the time period from 1969 to present. From this data set, we select three clusters suitable for inversion from areas along the EW trending Gulf of Aden and Tadjoura rift, the central Afar, and the western margin of the Afar depression. The stress tensor inversion method (Lund and Slunga, 1999) was developed for SIL data to evaluate the stress field from focal mechanisms of earthquakes occurring in a relatively smaller spatial and temporal window where high concentration of events are observed. The Lund and Slunga (1999) method is modified to be used for stress inversion with focal mechanisms that do not have explicit estimates of the uncertainty, or which have been determined by different techniques and therefore have different definitions of their uncertainties. In the modified method, the focal mechanisms are slightly perturbed during the inversion. For each stress field tested in the inversion grid search, each focal mechanism is systematically perturbed in a number of directions and the perturbed focal mechanism with the smallest misfit is chosen as the preferred mechanism. The mechanisms are perturbed using a spherical cap grid of predefined density for one of the nodal plane normals. A new normal direction is calculated and then the rake direction is perturbed while keeping the normal and slip vector orthogonal. Using the modified grid-search based inversion of Lund and Slunga (1999) we assess how the choice of fault plane from the nodal planes affects the results and how the chosen nodal planes agree with the tectonic lineations.

Stress tensor inversion was conducted on the three selected sub-regions using both the stability and slip-angle fault selection criteria. The two methods give similar results which indicate that the estimated stresses are not biased by the fault plane selection criterion. The broad zone of active extensional deformation at the Afar Depression, a triple junction where the Red Sea, the

Gulf of Aden and the Main Ethiopian rift systems meet, constitutes a complicated tectonic region. Our results are compared with the existing plate motion vectors between the interacting plates in the region. The resulting stress states show an overall normal faulting stress regime. This is especially pronounced in the cluster on the western margin of the Afar depression, whereas the southern two clusters have more oblique stress states with significant strike-slip components (e.g. for cluster 1 see Fig. 11). The estimated directions of the minimum principal stress vary from NE on the Danakil-Somalia plate boundary to an approximate EW direction at the western margin of the Afar depression.

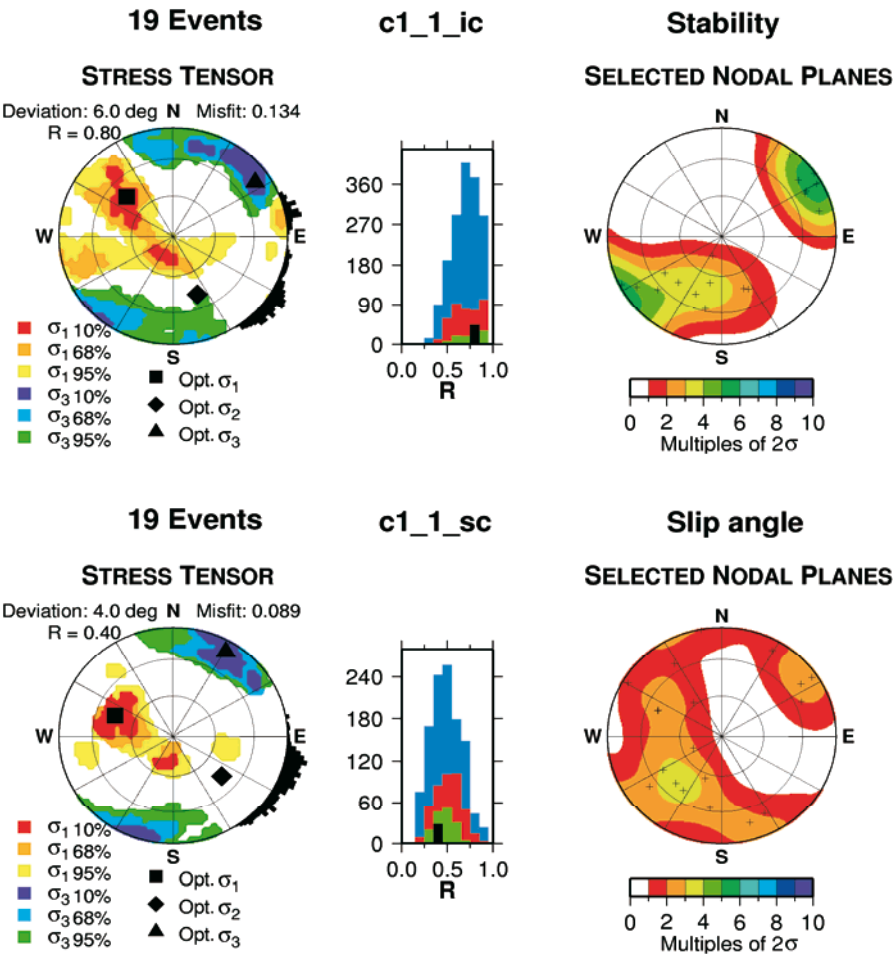


Figure 11. Stress inversion results for cluster 1 using: top) a 5° spherical cap for the perturbations and the stability criterion, bottom) a 5° spherical cap for the perturbations and the slip angle criterion. Grids are equal area projections of the lower hemisphere. Figures on the *Left column*: shows resulting optimal stress tensors (S1, S2 and S3) for 10%, 68% and 95% confidence limits, ***Deviation*** is the average angle between the directions of estimated shear stress and observed slip on the planes, and ***misfit*** is deviation weighted with amplitude errors. Black histogram on the perimeter shows the 95% confidence level of the maximum horizontal stress. *Middle column*: shows the R value with histograms in color indicating the 10%, 68% and 95% confidence limits in R, and the optimum value in black. *Right column*: shows Kamb contours of the fault plane normals chosen by the inversion.

7. Concluding Remarks

This thesis studies aspects of seismic hazard and the factors influencing the magnitudes of ground shaking levels at a particular site and thereby affecting the seismic hazard maps. The reliability of seismic hazard maps depends on the input parameters used in hazard assessment procedures. The characterization of earthquake sources, and the information obtained from geological, geophysical, seismological data are often updated when new techniques and improved measurements are used. For seismological data with the advent of new methodologies and the improved azimuthal coverage of seismic stations the accuracy in the determination of sizes, locations and source parameters of earthquakes may be improved. Re-definition of seismic source zones, estimation of the maximum magnitude in a specific source area, and relocation of events are done very often. The results obtained from such analysis are incorporated to PSHA to enhance the accuracy of seismic hazard estimation. In this light, re-assessments of the previously obtained parameters that characterize the earthquakes are carried out so as to reduce any possible bias in the estimates of seismic hazard. The preliminary seismic hazard map presented in this thesis (Paper I) provides information on the estimates of ground motion level based on past seismicity. The results, however, can be improved as adequate information regarding other source characteristics and detailed knowledge of the structural units become available. Discussed in Papers II to IV are some seismological aspects related to earthquake sources and the approaches used in estimating, e.g. the slip type, focal depths, and stress field. The topics highlighted in this thesis by no means provide the complete picture of seismic hazard but are aimed at reflecting certain contributing factors to seismic hazard estimates. Moreover, future modifications and revision of seismic hazard maps are expected to be made when other factors influencing the hazard estimation such as site effects rupture directivity and shaking duration are taken into account. Results obtained from seismic hazard analysis are important in alleviating the possible earthquake damage inflicted upon people, buildings and facilities.

8. Summary in Swedish

Jordbävningar är ett av de mest katastrofala fenomen som orsakar stor förlust av människoliv och stora skador på egendomar och anläggningar. Åtgärder för att mildra jordbävningsrelaterade faror och risker involverar många vetenskapsmän och policyskapare. Att förutspå förekomsten av potentiellt farliga jordbävningar med precision är en inte enkel uppgift. Vi ska kunna svara på frågor såsom: hur jordbävningar inträffar, hur ofta de förekommit tidigare, var finns de potentiellt farliga jordbävningskällorna lokaliserade i rummet, och vad är sannolikheten för att jordbävningar som äger rum i dessa källpunkter överstiger bestämda nivåer för markskakningar. Ofta presenteras sådana studier i form av kartor som visar ett mått på den seismiska faran (eng: seismic hazard). Sådana kartor indikerar skillnader mellan olika regioner för uppskattade sannolikheter att markrörelser relaterade till jordbävningar ska överstiga bestämda nivåer på en given plats för en given tidsperiod. Medan en strikt definition av seismisk fara innebär studier av den förväntade markrörelsen på grund av jordbävningar var som helst på jordklotet kan en generell betydelse vara potentialen för farliga, jordbävningsrelaterade, naturfenomen såsom markskakningar, rörelser på förkastningar eller förvätskning av jord. De mått på seismisk fara som används i kartor och andra kurvor inkluderar maximal markacceleration (PGA), maximal markhastighet (PGV), maximal horisontal förskjutning (PGD), responsspektrum (SA) och maximal förväntad intensitet (Imax). För allmän användning så är det oftast använda måttet på storleken av skadopotentialen PGA. De värden som erhålls från sådana analyser används av ingenjörer vid konstruktion och design av byggnader i seismiskt aktiva områden och inkorporeras i byggnadsstandarder.

Analys av seismiskt relaterade faror involverar många människor från olika ämnesområden. Informationen som krävs för att konstruera kartor för seismisk fara kommer exempelvis från ett flertal geologiska, geofysiska och seismologiska data. Den här informationen ska beskriva beteendet hos seismiska vågor vid deras källa, längs deras utbredningsväg och nära ytan. Energin hos seismiska vågor registrerad på en given plats (mottagarposition) beror på flera faktorer: spänningsfältet, typen av förkastningsrörelse, effekter

av utbredningsväg och lokala effekter är de som påverkar styrkan och frekvensinnehållet hos seismiska vågor. Under det att det är detta flertal faktorer som styr de centrala ingångsparametrarna i analys av seismisk fara, så fokuserar vi här på information relaterad till identifiering av typ av förkastningsrörelse, fokal mekanism och det regionala spänningstillståndet som kontrollerar den tektoniska växelverkan som finns i det studerade området. I detta avhandlingsarbete presenteras några grundläggande element i och tillämpningar av analys av seismisk fara samt företeelser som påverkar amplitud och geometrisk dämpning av markrörelser orsakade av jordbävningar. Avhandlingen betonar några aspekter av seismologi som rör bestämningen av viktiga parametrar vilka, i sin tur, påverkar uppskattningen av markskakningsnivåer vid bestämda platser.

Den här avhandlingen fokuserar på aspekter av analys av seismisk fara och relaterade seismologiska problem i Eritrea med omgivning. De genomförda studierna presenteras i fyra artiklar. Seismisk fara är ett komplext problem som ofta innebär betydande osäkerheter. Därför är det rimligt att överväga olika tillvägagångssätt för analys för att på ett så robust sätt som möjligt definiera zoner med olika nivåer av fara.

I artikel I, med målet att karakterisera och kvantifiera seismisk fara i den östafrikanska regionen kring Eritrea inkluderas en studie i denna avhandling som presenterar kartor konstruerade med två tillvägagångssätt för icke-parametrisk probabilistisk seismisk faroanalys (PSHA). Det studerade området kännetecknas av en komplex tektonisk miljö där stora osäkerhetet förväntas i uppskattningen av den seismiska faran på grund av de möjliga fel som kan introduceras genom subjektiviteten i indelningen av källzoner. Metoderna som används i artikel I antas reducera subjektiviteten i definitionen av aktiva källzoner. Eftersom de använda metoderna i denna studie enbart baserar sig på den seismiska katalogen är det inte nödvändigt att definiera seismiska källzoner. De enda parametrar som behövs för analysen är storleken på den största möjliga jordbävningen, aktivitetsgraden samt b-värdet, alla erhållna enbart från den seismiska informationen. Värden på maximal markacceleration (PGA) beräknas för 10 % sannolikhet av överskridande på givna punkter i hela det utvalda området och resultatet från de båda metoderna jämförs med varann.

Andra aspekter som tas upp i denna avhandling innefattar bestämningen av källparametrar för utvalda jordbävningar och beräkning av momenttensorer från data för fokalmekanismer. Artikel II och III behandlar analys och utvärdering av fokalmekanismer och seismotektonik, med tonvikten i artikel III på ett relativt tillvägagångssätt för momenttensorinversion tillämpad på stora mängder av, i rummet, tätt grupperade jordbävningar. I artikel II, valde vi 7

jordbävningar, och genomförde en teleseismisk vågformsanalys för att erhålla förbättrade lösningar, i synnerhet med målet att förbättra djupbestämningen för fokalmekanismen. De djupbestämningarna som vi erhöll i vår analys av de utvalda jordbävningarna visar att de ägde rum mellan 17-22 km djup, på ett större djup än de tidigare uppskattningarna anger. Jordbävningar som äger rum på lägre djup är farligare än de som äger rum på större djup. Att omvärdera djupuppskattningar för jordbävningar bidrar därför till förbättringar i härledning av lämpliga relationer för dämpning av seismiska vågor samt riktiga uppskattningar av den seismiska faran.

Den tredje artikeln fokuserar på tätt grupperade jordbävningar som äger rum i Hengills vulkaniska område, sydvästra Island. Den metodik som tillämpas här är lämplig för de stora mängder data som registreras av det seismiska nätverket (SIL) på södra Island. SIL-nätverket registrerar jordbävningsaktiviteten med stor detaljrikedom och tillhandahåller en enorm mängd data där metoden kan användas effektivt. De fokalmekanismer som bestämts med relativ momenttensorinversion jämfördes med de som bestämts med den spektralamplitudsmetodik som används i SIL-systemet. De flesta fokalmekanismer som erhöles i den här studien visar att högerlaterala strykningssrörelser dominerar, liknande de som SIL-nätverket ger, medan de relativa resultaten uppvisar mer konsistent överensstämmelse med orienteringen av de förkastningar som kan ses i området. En relativ metodik har begränsade möjligheter för användning i Eritrea där antalet registrerande seismiska stationer är mycket lägre. Dock, om det kan visas att metoder som bygger på en hög grad av datatäckning kan ge en signifikant förbättring av analyser av exempelvis seismisk fara så kan det, överallt, hjälpa till att definiera långsiktiga strategier för kostnadseffektiv riskbedömning.

Artikel IV behandlar uppskattningen av spänningstillståndet utifrån fokalmekanismer för jordbävningar som ägt rum i området kring Afar-sänkan, mestadels längs plattgränserna för de afrikanska, somaliska och arabiska plattorna. Spänningstensorinversion genomfördes för tre utvalda områden i den östafrikanska regionen med både stabilitets- (modifierad version av Lund och Slunga, 1999) samt slip-riktnings- (Gephart och Forsyth, 1984) metodiken. De två metoderna ger liknande resultat, vilket indikerar att de uppskattade spänningarna inte påverkas av villkoret för val av förkastningsplan. Resultaten ger insikt i bestämningen av huvudspänningsriktningar i relation till interaktionen mellan plattorna och den tillhörande rörelsen som drivs av det regionala spridningsorienterade spänningstillståndet.

De ämnen som behandlas i denna avhandling ger inte en komplett bild av analys av seismisk fara men är ämnade att spegla vissa bidragande faktorer i uppskattningar av seismisk fara. Utöver detta förväntas framtida ändringar och revisioner av kartor för seismisk fara ske när hänsyn tas till andra påver-

kande faktorer såsom lokala effekter, brottriktning och hur lång tid markskakningar pågår. Resultat från analys av seismiska faror är viktiga för att lindra de möjliga skador som jordbävningar kan medföra för människor, byggnader och anläggningar.

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“I would like to do seismic hazard” was my reply when asked what my research interests were the first time I joined the Geophysics program at Uppsala University. Later on, as suggestions from my supervisors and other colleagues started to flow my way, and motivated by the research areas they were involved in, my research interests broadened to include other aspects of seismology. During all these years, I received a lot of help from many people at the Geophysics department while defining my projects and while actually working on them, which all wholeheartedly deserve a due appreciation and acknowledgment.

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