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Dynamic rupture modeling of the 2017 M6.5 Botswana intraplate earthquake using SeisSol

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Preface

In the eighteenth century, philosophers considered the whole of human knowledge, including science, to be their field and discussed questions such as: did the universe have a beginning? However, in the nineteenth and twentieth centuries, science became too technical and mathematical for the philosophers, or anyone else except a few specialists. Philosophers reduced the scope of their inquiries so much that Wittgenstein, the most famous philosopher of this century, said, "The sole remaining task for philosophy is the analysis of language." What a comedown from the great tradition of philosophy from Aristotle to Kant! [1]

Stephen Hawking

ABSTRACT

In this thesis, we use *SeisSol*[1] to simulate the dynamic

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Chapter 1

Method

The question arises of which numerical scheme is capable of efficiently solving the elastic wave equation on tetrahedron (or generally unstructured) grids. This is the key motivation that led to the transference of the discontinuous Galerkin method to seismology.

- Prof. (Seismology) Heiner Igel, Ludwig-Maximilians-Universität München

1.1 SeisSol

1.1.1 Overview

- Finalist of Gordon Bell Prize in 2014. Its remarkable scaling behaviour as well as the obtained peak performance (1.09 PFlops) was the result of several years of performance optimization(Breuer et al., 2014) [2] [Parallel compututing, p66-67]
- Strong scaling investigate how the run time varies with increasing the number of processors for a fixed size problem.
- *SeisSol* code is a recent example of strong scaling, based on the discontinuous Galerkin method.
- *SeisSol* software reduces the computational error up to 5 order of magnitude, while increase the accuracy order of the numerical scheme from 2 to 7, and this consuming no extra energy.

1.2 Fault model

1.2.1 Overview

The fault model contains two parts, a description of an initial stress field and a nucleation stress field on and off the fault plane.

We first define 3 constant global parameters to constrain the fault model, which are,

$$rs_a = 0.01 \tag{1.1}$$

$$RS_{sl0} = 0.1 \tag{1.2}$$

$$rs_{srW} = 0.1 \tag{1.3}$$

All of these three parameters are related to the Rate-and-State friction law, the values are commonly used by the community. They are either obtain from the lab experiment or from the computational simulations. The most important thing for me is that these value works, they represent the physics and do not need to be changed.

1.2.2 Set up initial stress conditions

We describe the initial stress field via a stress tensor. The stress tensor describes the forces acting on a deformable continuous medium. Because the stress tensor is symmetric [3], we only need 6 parameters ($s_{xx}, s_{yy}, s_{zz}, s_{xy}, s_{yz}, s_{xz}$) to fully describe the state of stress at a given point in the medium. The three diagonal components of the stress tensor (s_{xx}, s_{yy}, s_{zz}), are known as normal stress, while the six off-diagonal components ($s_{xy}, s_{yx}, s_{xz}, s_{zx}, s_{yz}, s_{zy}$) are called shear stress. The former describe body force and the later describe surface force. For a detailed explanation, please check *Stein & Wysession 2009, 2.3.2 stress, p39-41*

In our model, we calculate the initial stress field as following,

$$s_{ij} = \begin{cases} s_{xx} = Omega \cdot b_{xx} + (1 - Omega) \cdot eCS \\ s_{yy} = Omega \cdot b_{yy} + (1 - Omega) \cdot eCS \\ s_{zz} = Omega \cdot b_{zz} + (1 - Omega) \cdot eCS \\ s_{xy} = Omega \cdot b_{xy} \\ s_{yz} = Omega \cdot b_{yz} \\ s_{xz} = Omega \cdot b_{xz} \end{cases} \tag{1.4}$$

Now, you may have been wondering what is *Omega* and *eCS* in the *Equation 2.4*. Well, that is a good question, *Omega* is basically a depth-depended scale or smoothing factor to reduce the calculated stresses on the fault and beneath the fault in a specific mesh. And *eCS* means the effective compressive stress, which is commonly known as effective normal stress.

Omega is a step function and to formulate *Omega*, we need to decide at which depth we want the stress starts to decrease by forcing a smoothing factor and by how much do they decrease. This is of course constrained by the mesh (see later chapter). Normally, we have a fault or multiple faults embedded in a mesh, and the deepest element or the maximum depth of the fault is where the stress starts to decrease (smoothing), and the stress level above this depth is unaffected. The deepest element or the maximum depth of the seismogenic zone is where the stress stops to decrease (smoothing) gradually, and the stress level is set to a very small value beneath this depth to prevent unwanted and unrealistic rupture propagation downwards even below the seismogenic zone.

For instance, in the case of *mesh2* (See mesh section), we want the stress starts to decrease gradually at 33 km (The maximum depth of the fault embedded in *mesh2*), and stop at 37 km (end of seismogenic zone). Based on these constrain, we can write the following equation:

$$Omega = \begin{cases} 1 & z \geq -33000 \\ 1 - Sx & -37000 \leq z \leq -33000 \\ 0.001 & \text{otherwise} \end{cases} \tag{1.5}$$

$$Sx = (3.0 * a * a - 2.0 * a * a * a) \tag{1.6}$$

$$a = 1 - \frac{z + 37000}{37000 - 33000} \tag{1.7}$$

Now, How to calculate *eCS*?

Large compressive stresses occur at depth within the earth due to the weight of the overlying rock [3]. eCS can be constrained from the information about the largest and the smallest principal stresses, σ_1 and σ_3 [4]. We can alternatively constrain eCS by assuming a constant pore pressure gradient [e.g. 27 MPa/km: Rice, 1992; Suppe, 1985][5].

$$eCS = 2670 \cdot (1 - \gamma) \cdot 9.8 \cdot z \tag{1.8}$$

Where γ, fluid pressure ratio, is constant. γ shows the effect of pore pressure in the earth on the eCS. And z is a variable, represents the depth of the fault. The depth of the earthquake's hypocentre is usually denoted as z_{ref}, the characteristic depth.

eCS is mesh-depended. For example, the equation used in the parameter file for our *mesh2* is actually the following:

$$eCS = 2670 \cdot (1 - \gamma) \cdot 9.8 \cdot min(-5000, z) \tag{1.9}$$

min(-5000,z) simply select all the z value above -5 km to be -5km. That is because the fault in *mesh2* is embedded below 5 km depth inside the mesh domain.

The relative fault strength is set by the normal stress and frictional coefficients [6].

we have two constant numbers in *Equation 2.8*, 2670 is the average density (m/s^2) of the overlying crustal rock in the vicinity of the Botswana earthquake [7], 9.8 is the gravitational constant (m/s^2).

γ on the other hand, is a variable, it varies from 0.37 (hydrostatic condition)to 0.95 (lithostatic condition). A small change in γ can influence the rupture result dramatically, fluid pressure ratio is a very sensitive parameter, one has to be very careful when dealing with this parameter. (see result).

Different γ value result in large difference in terms of eCS or σ_{zz} (see Table2.1). Because the product of background rock density, gravitational constant and depth serves as an amplifier. Since we assume the background rock density is 2670 kg/m^3 everywhere, gravitational constant is 9.8 m/s^2 and the maximum depth is 29000 $meters$ (The z component of the hypocenter of the earthquake), then a decrease of 0.1 in γ will gives us an increase of 75.8814 MPa in eCS at depth of 29km. This is considerably large in dynamic rupture model settings, in fact, many dynamic rupture models set the eCS equal to a constant amplitude of around 50 MPa at seismogenic depths of 5km to 20km. [Ramos, section 2.5][6] In the case of lithostatic model, i.e. $\gamma = 0.95$, eCS at 29km is 37.9407 MPa. In the case of hydrostatic model, i.e. $\gamma = 0.37$, eCS at 29km is 478.0528 MPa. Thus, we expect to get a very large earthquake when simulating under the hydrostatic case. As high pore pressure present in mature fault zone is commonly assumed[5]. We use $\gamma = 0.865$ in our perferred model. (see result)

A small variation in background stress may lead to dramatic changes of rupture style and magnitude [8]. In two of our simulations with exactly same setups expect a small variation in fluid pressure ratio, γ, the two models sets the value of γ to 0.865 and 0.864 respectively, the former model gives the final magnitude of Mw 5.9, and the latter gives the final magnitude of Mw 7.4. To see the influence of the variation of the γ value on rupture style and magnitude, please see discussion section for more details.

Now we know how to calculate eCS and Omega in *Equation 2.4*. In order to set the initial stress condition, we still need to know six $b_{ij,i\subsetneq\{x,y\},j\subsetneq\{x,y\}}$.

So how do we get their values? Of course there are multiple ways to do this task, but the simple answer is through a function called *AndersonianStress* in easi library. (easi is a library for the Easy Initialization of models in three (or less or more) dimensional domains.) It was developed by a former Postdoc in the SeisSol research team, Dr. Carsten Uphoff.

As the name of the function indicates, it computes Andersonian stress. For more details, please click the link below to be redirected to the easi webpage (Carsten Uphoff, 2018)

https://easyinit.readthedocs.io/en/latest/maps.htmlandersonianstress

Table 1.1: Parameter list for easi function *AndersonianStress* Adopted from Uphoff, 2018

variable name $< datatype >$	notation	chosen value	physical meaning
mu_d $< double >$	μ_d	0.1	dynamic friction coefficient
mu_s $< double >$	μ_s	0.6	static friction coefficient
SH_max $< double >$	SH_{max}	132.0	the azimuth of maximum compressive horizontal stress
S_v $< int(1,2,3) >$	S_v	1	define which one is the vertical principal stress
cohesion $< double >$	-	0.0	rock internal property
s2ratio $< double >$	ν	0.5	stress shape ratio
S $< double >$	S	1 / (R-1)	relative fault strength
sig_zz $< double >$	σ_{zz}	$\rho_{eff} \cdot g \cdot h$	the vertical stress

μ_d is the dynamic friction coefficient, it sets the relative fault strength together with μ_s, the static friction coefficient [6]. The product of eCS (Effective normal stress) and μ_d (dynamic friction coefficient) is termed the static fault strength, while the product of eCS and μ_s is termed the dynamic fault strength[6]. The value of μ_d is not possible to measure directly, but it can be inferred [6]. There are at least two approaches up-to-date to infer this parameter, one is to compare shear rock at slip rates to coseismic values from lab experiments [9], the other is to obtain dynamic friction levels from the accessible rocks [10].

We use $\mu_d = 0.1$ in our models as there are no previous studies to provide an accurate value of this specific parameter. (μ_d can vary from 0.01 to 1 derived from experiments of Alice Gabriel's group) On the other hand, μ_s is less tricky, and typically assumed to be 0.6 in order to be consistent with Byerlee's law [11].

SH_{max} is the azimuth of maximum compressive horizontal stress. If SH_{max}, principal stress components, orientation of the intermediate principal stress field, and the seismogenic depth can be constrianed, then the relative prestress ratio (R) can be estimated [Ulrich, Method section] [12].

We use $SH_{max} = 132^o$ in our model. SH_{max} is one of the main result of the static analysis from two former bachelor students, Thomas Obermaier [13] and Sophia Gahr [14]. Basically, They constrain SH_{max} from the World map and vary it from 102^o to 182^o with fluid pressure ratio, γ, stress shape ratio, ν and the initial relative prestress ratio,R_0 being constant, to see the effect of different SH_{max} angle on R value. R describes the spatially distributed fault strength on every point of the fault. [Static Analysis section, Gahr;Static Analysis section, Obermaier] [14][13]

S_v defines which of the principal stress is vertical (Uphoff, easi Documentation, 2018). Under Andersionian theory of faulting and considering a normal faulting of the Botswana earthquake [15], it is clear that $S_v = 1$, i.e. the maximum principal stress, s_1, is vertical.

coheision is a rock internal property. In physics, cohesion means "the sticking together of particles of the same substance". cohesion appears as a term in Mohr-Coulomb failure criterion, namely, it is the intercept of the failure envelope with the τ (shear strength) axis.

$$\tau = \sigma \ \tan(\phi) + c \tag{1.10}$$

where τ is the shear strength, the angle ϕ is called the angle of internal friction, σ is the normal stress, and c is the cohesion.

In order to neglect normal stresses on the surface and to introduce the linear relationship of depth and stress, we set *cohesion* to a very small value [14], here we use $cohesion = 0$, i.e. our model is cohesionless. In Sophia's model setup, she uses $cohesion = 0.1$, but end up with getting a too small earthquake, which means the rupture propagation stopped earlier than expected. Decreasing cohesion would favour the rupture to propagate further, i.e. the fracture energy needed to overcome the static friction decreases and the fault became easier to break.

$s2ratio$ is stress shape ratio, this concept has put forward by another member of Alice Gabriel's group, Thomas Ulrich, together with Alice and others. Considering extensional stress regime of the 2017 Botswana event, we use $s2ratio = 0.5$ [In other section, the stress shape ratio also denoted as ν], in the case of $S_v = 1$, $s2ratio = 0.5$ means pure extension, $s2ratio < 0.5$ means transpression and $s2ratio > 0.5$ means transtension.[16]

S is the relative fault strength. As can be seen in table 2.1, its value is depended on R, we use $R = 0.7$ here (can vary form 0.7 to 0.9, [14]). The value of R comes from static analyses that performed by Thomas Obermaier [13]and Sophia Gahr [14] independently. In easi documentation, section 4.10 *AndersonianStress*, the author states: static and dynamic friction coefficient and cohesion are required to prescribe S. [Uphoff, 2018] As discussed before, the aforementioned parameters have a certain given value, namely, $\mu_s = 0.6, \mu_d = 0.1 \; and \; cohesion = 0$.

σ_{zz} is one of the diagonal element in the stress tensor, it can be understood as the z-component of the traction across x-y plane in 3D Cartesian coordinate system. When x- and y- component equal to zero, the traction is perpendicular to x-y plane, i.e. no shear stress. σ_{zz} is as the same as aforementioned parameter, eCS. The variable h in *Table 2.1* and z in the *Equation 2.8* are equivalent.

1.2.3 Nucleation - make the rupture start

Assuming static and dynamic friction coefficients,

$$\mu_d = 0.1 \tag{1.11}$$

$$\mu_s = 0.6 \tag{1.12}$$

and some other necessary parameters.

Rupture nucleation is caused by smoothly over stressing an area centred at the hypocenter in space and time. This can be accomplished by increasing the initial relative prestress ratio R_0 as:

$$R_{0nuc} = R_0 + F(r) \tag{1.13}$$

$$r = \sqrt{(x - x_c)^2 + (x - y_c)^2 + (x - z_c)^2} \tag{1.14}$$

where r is the nucleation radius, defined as the euclidean distance to the hypocenter (x_c, y_c, z_c), we use $(34.404734, -18.497915, -29004.1863)$ in our simulation, that is the closest point from the fault at the depth of 29km.

$F(r)$ is a bell-shaped function:

$$F(r) = \begin{cases} exp(\frac{r^2}{r^2 - r_c^2}), & \text{if } r < r_c. \\ 0, & \text{otherwise.} \end{cases} \tag{1.15}$$

where r_c is 1 km, represent the nucleation radius.

$$r = \sqrt{(x - x_c)^2 + (x - y_c)^2 + (x - z_c)^2} \tag{1.16}$$

1.3 Material Perperties

RhoMuLambda.nc attached Material properties (rho, mu and lambda) translated from a regional velocity model,

$$\rho = -0.0000045 \cdot V_s^2 + 0.432 \cdot V_s + 1711 \tag{1.17}$$

1.4 Friction law

1.4.1 Overview

Other friction law can also be invoked in SeisSol...

1.4.2 Parameters related to Rate-and-State friction law with strong velocity weaking

Adopted from Palgunadi et al. [17]

Table 1.2: SeisSol Dynamic Rupture Parameters

	Parameter	Symbol	Value
1	Direct effect parameter	a	$0.01z$
2	Evolution effect parameter	b	0.014
3	Reference slip velocity	V_0	$10^{-6}m/s$
4	Steady-state friction coefficient at V_0	f_0	0.6
5	State-evolution distance	L	$0.2m$
6	Weakening slip velocity	V_W	$0.1z$
7	Fully weakened friction coefficient	f_W	0.1
8	Initial slip rate	V_{ini}	$10^-16m/s$

"Rapid weakening friction law parameters used for dynamic rupture simulations. Note, the direct effect parameter and the weakening slip velocity are depth dependent. The steady state friction coefficient f0 needs to be similar to the static friction coefficient μ_s used in the static analysis."(Obermaier, 2020)

1.5 Mesh

1.5.1 Overview

Our mesh use unstructured tetrahedron grids. Contain two faults, implement DR boundary conditions on fault, side absorbing, and free surface boundary conditions.

The mesh domain is determined by the fastest speed of the P wave and total simulation time. Even implemented with absorbing boundary conditions, we still do not want to risk getting wave reflection from the sides, therefore, we can make the domain large enough.

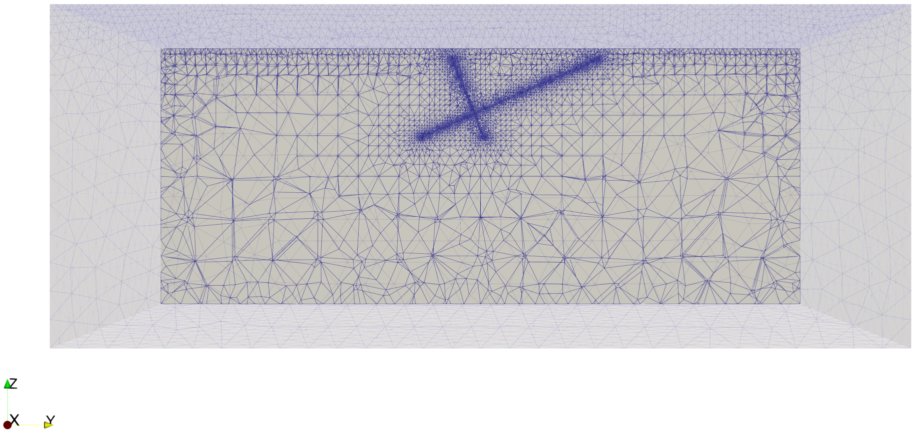


Figure 1.1: Mesh visualization - faults implementation

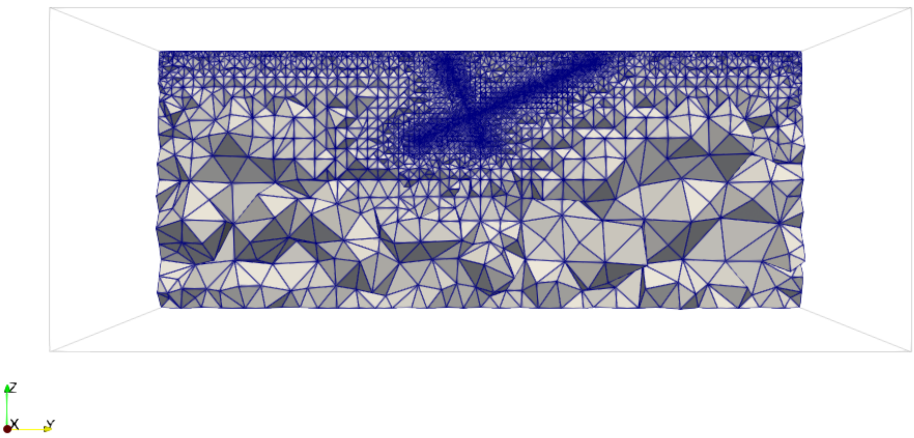


Figure 1.2: Mesh visualization - unstructured grid

1.5.2 Fault geometry

- Fault location obtained from a fault trace that was estimated from the resistivity model in shallow depth, i.e. 5 km See **B.0.1**

  The length of the fault trace is 108.46 km, use a smoothing parameter 10^7 leads to a characteristic length of 92 m.

  the horizontal cell length of MT model is 2 km

- Modelled fault is assumed at 5 km beneath the surface because the fault has no surface expression.

  The depth of the modelled fault is set to 37 km, supported by the kinematic model of Materna et al. [18] and aftershocks distributions.

  In general, the depth of a fault is bounded by the end of the seismogenic zone, where ductile deformation takes over (becomes dominant).

- Rapid weakening Friction Law (FL=103), because I simulate dynamic scenarios.

- hydrostatic conditions, produces too large earthquake; The lithostatic case shows good consistence in observed results from other authors [13]

- SH_{max} values from 132^o to 142^o to be most realistic.[13]

- Translate 3D velocity model into 3D material properties.

- Possible fault plane is obtained by analyze different datasets, including 1. Focal mechanism (Two solutions from the *Global Centroid Moment Tensor*, indicating two fault planes are equally fit the source parameters and can explain the physics); 2. Aftershock distribution (our two fault planes intersection model fits aftershock location best among only 1st fault plane model, only 2nd fault plane model and the two fault planes model); 3. magnetotelluric data (make use of Moorkamp's resistivity model to determine the possible trace of the first fault **on the surface or in the shallow depth**)

- We also compared our fault model to the published literature. (My thesis advisor, Dr. Max Moorkamp has regular meetings with those authors (From Table 1.1) to discuss the fault location and geometry. After gathering different aspects of information towards the fault plane, they had agreed on a more precise description on the first fault plane, but the second fault plane remains large uncertainties. Since the discussion about the fault model is still on going, it very likely that by the time I submit this thesis, a more accurate fault model becomes available).

- In our current fault model. The two fault planes intersect. The first fault plane has a dip angle of 28 degree to southwest, strike angle of 126 degree NW-SE. The second

1.5.3 Two faults model

- First fault, non-planar, strike 126, dip 74
- second fault, plane, strike 126, dip -28

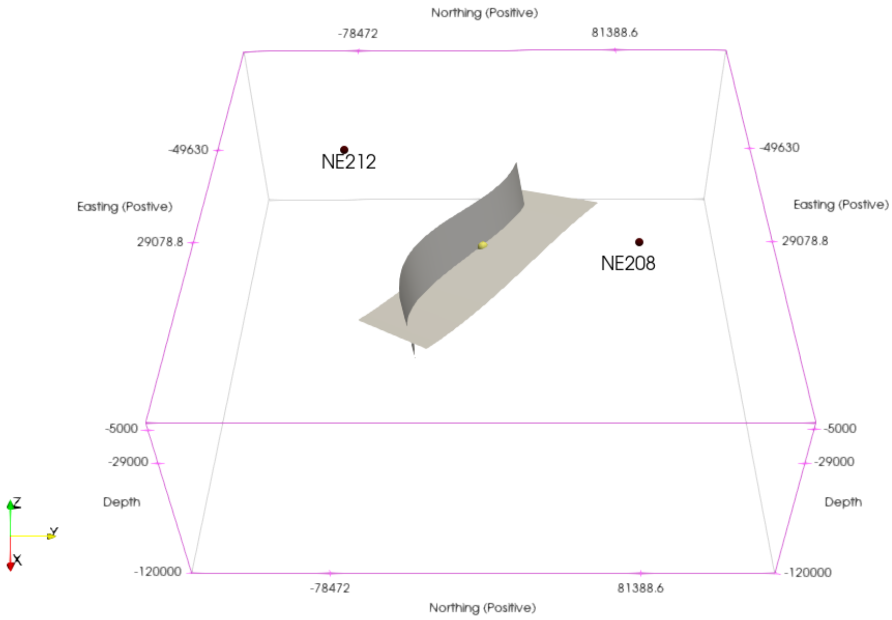


Figure 1.3: Model setup, model domain, hypocenter, receiver location, fault model

1.5.4 Afterschocks

Use aftershocks to constrain our fault planes. In theory, aftershock locations should lie in the vicinity of reconstructed fault planes.

Most aftershocks occur on or near the main shock's fault plane, in practice, one can easily distinguish which is the fault plane and which is the auxiliary plane by looking at their locations. The fault area can also be estimated from the aftershock locations. Figure 2.1 shows the spatial distribution of the 2017 Botswana earthquake's aftershocks and the geometry of two purposed fault planes. In our opinion, the two fault planes fit quiet well with the aftershock locations, the most aftershocks locate near the fault planes. Due to the complexity of the aftershock's pattern, it is not possible to fit the aftershock locations with a single fault plane.

Most of aftershocks occur soon after the main shock, and decay quasi-hyperbolically with time. This decay relation is described by Omori's Law. It is widely accepted that the aftershock decay reflects stress readjustment following the stress changes due to the main shock. The depth of the main shock is thought to be at least 20km. Deep earthquakes usually do not obey the Omori's Law as they often have many fewer or even none detectable earthquakes, means that unlike friction sliding, the deep earthquakes resulting from phase change in mantle minerals, which could only produce slip once and cannot recur. (Stein)

The fact that large amount of aftershocks associated with the main shock at deep depth is interesting. However, due to limited time and incomplete data, we will not investigate further about the aftershocks in this thesis.

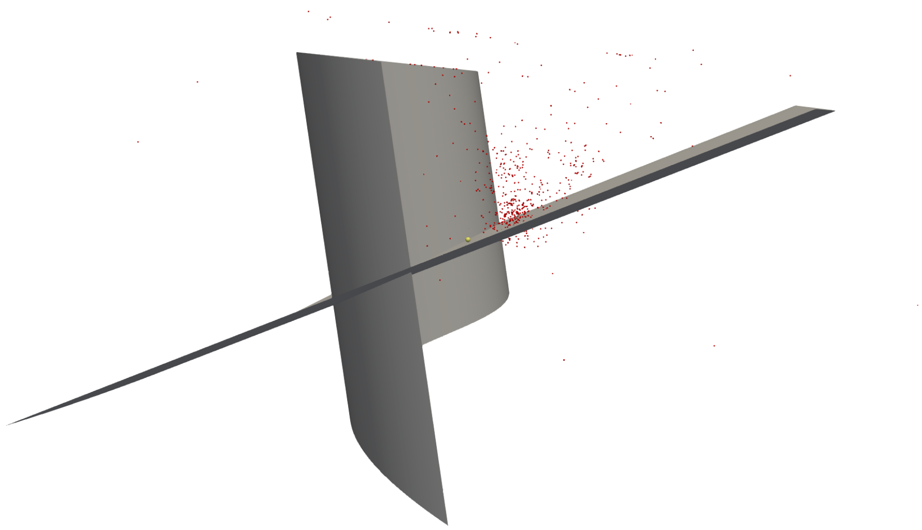


Figure 1.4: Aftershocks fit fault planes, yellow ball represents the hypocenter, small red dots represent the aftershocks

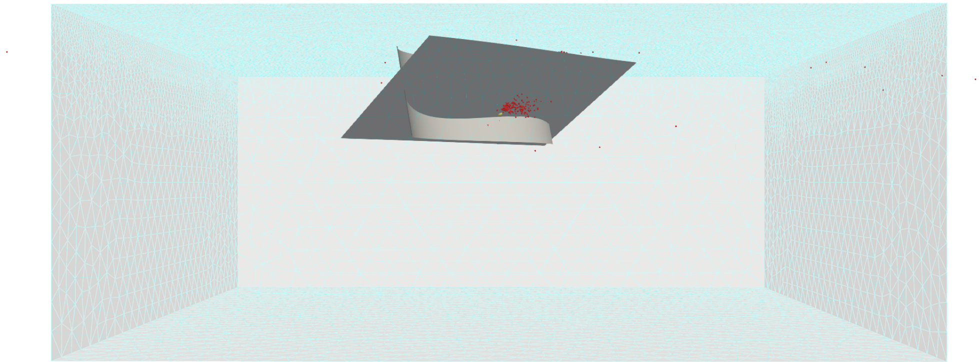


Figure 1.5: Fault planes inside the mesh with the red dots indicates the location of the aftershocks

1.5.5 Fault geometry values from published literature

Compare our purposed Two Faults model to published literature (Fadel et al. 2017) dip and strike angle...

Chapter 2

Results

If geophysics requires mathematics for its treatment, it is the Earth that is responsible, not the geophysicist.

- *Sir Harold Jeffreys, Cambridge university*

2.1 Simulation results

2.1.1 Ground movement

InSAR

High vertical deformation in the epicentral area of the Bhuj earthquake.[19]

Vertical deformation suggests buildup of stress at these locations, may interpret the structures where these stresses are builtup to be LSCs.[19]

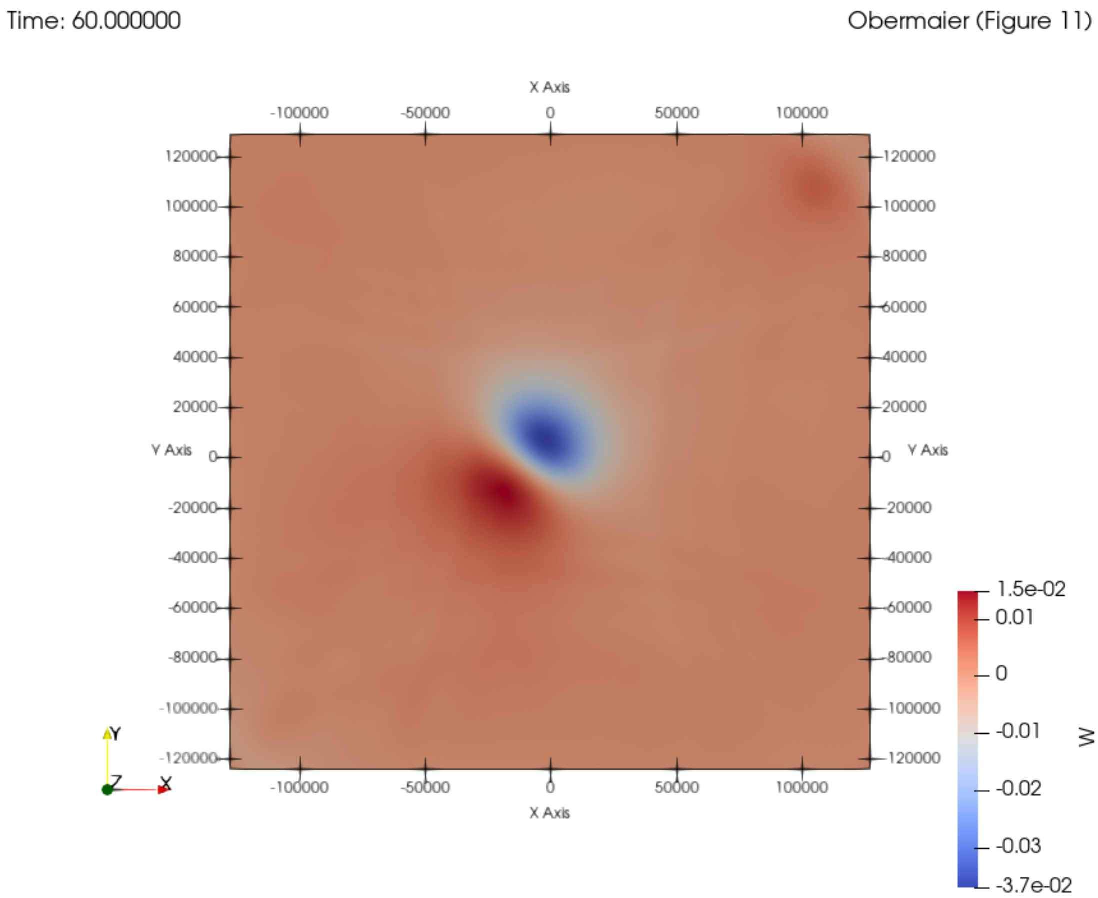


Figure 2.1: Surface displacement, vertical

Absolute Slip

The simulation shows that the absolute slip is 3.6 meters, which is unrealistic.

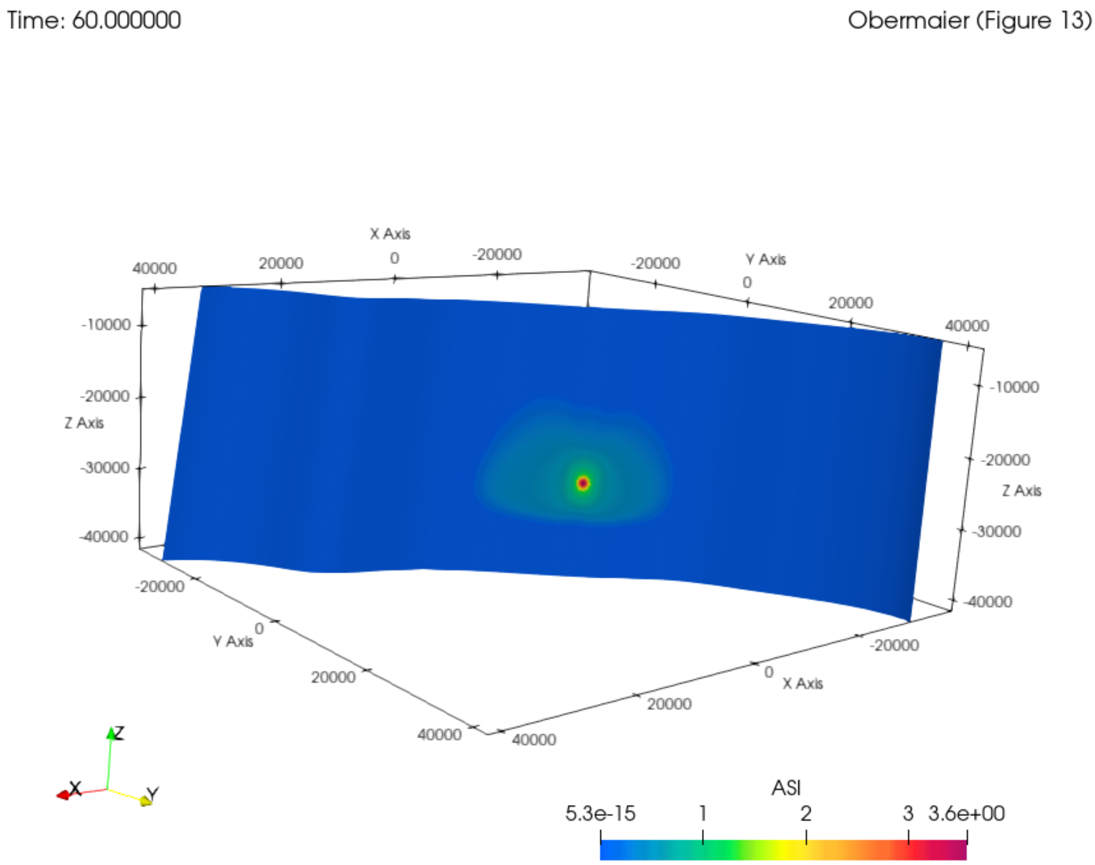
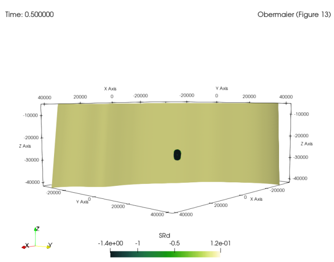
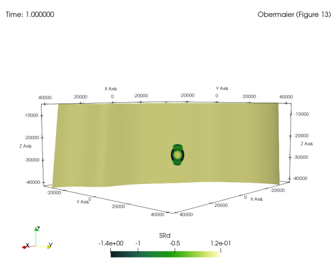
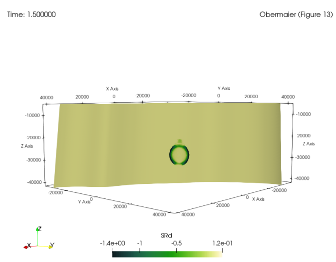


Figure 2.2: Absolute Slip

2.1.2 Dynamic Rupture Process







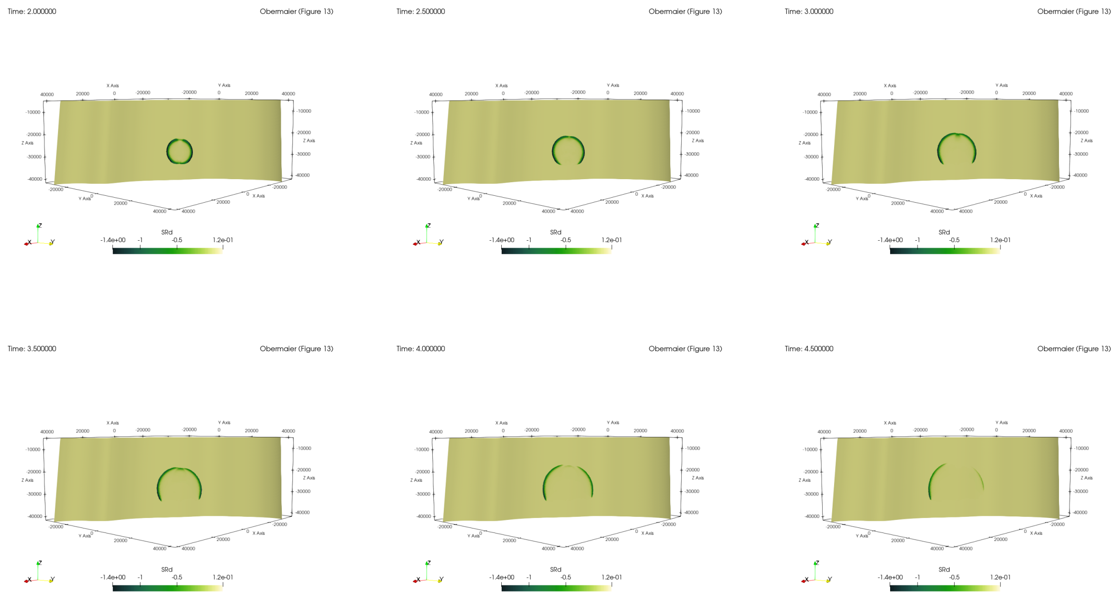


Figure 2.5: Rupture Process on the first fault plane

0.5 to 4.5 seconds out of 60.0 seconds simulation from Obermaier on the first fault plane. SRd means slip rate in dip direction.

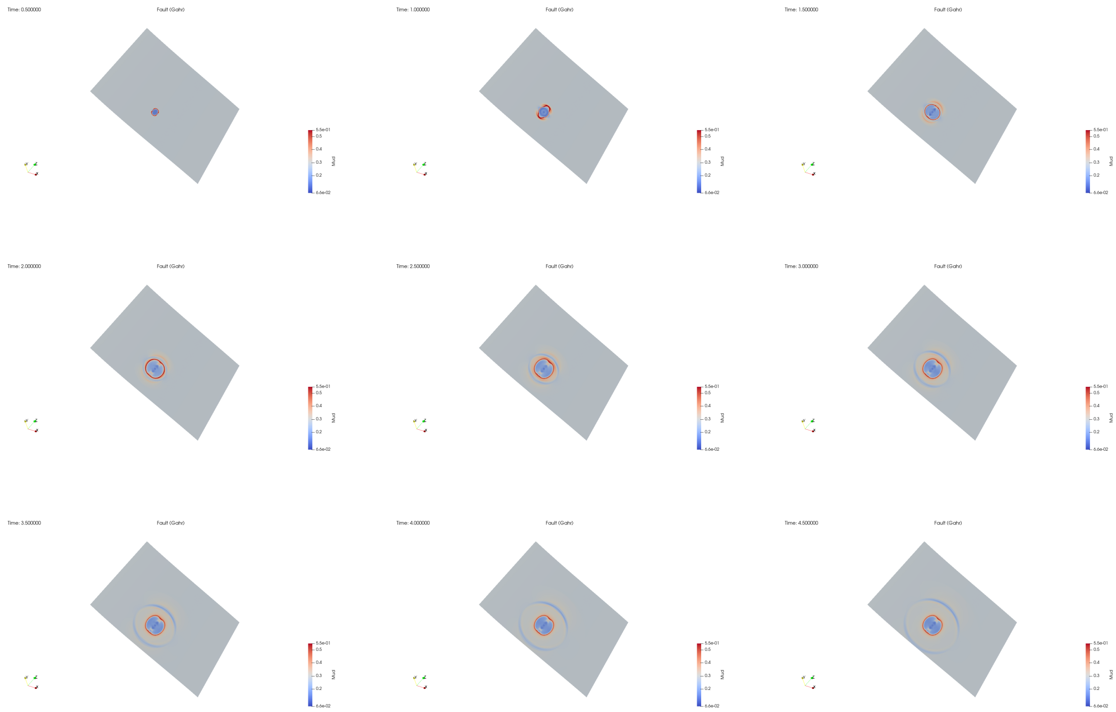


Figure 2.8: Rupture Process on the second fault plane

0.5 to 4.5 seconds out of 6.0 seconds simulation from Gahr on the second fault plane. Mud is current friction.

2.1.3 Synthetic seismic data

- Instrument correction (preprocessing) need to be done for the observational data, note that the magnitude is an order of 8 different between obs and syn;
- Need to apply a shift in time domain for observational or synthetic data in order to compare them;
- spectrum: obs scale down by 10e8

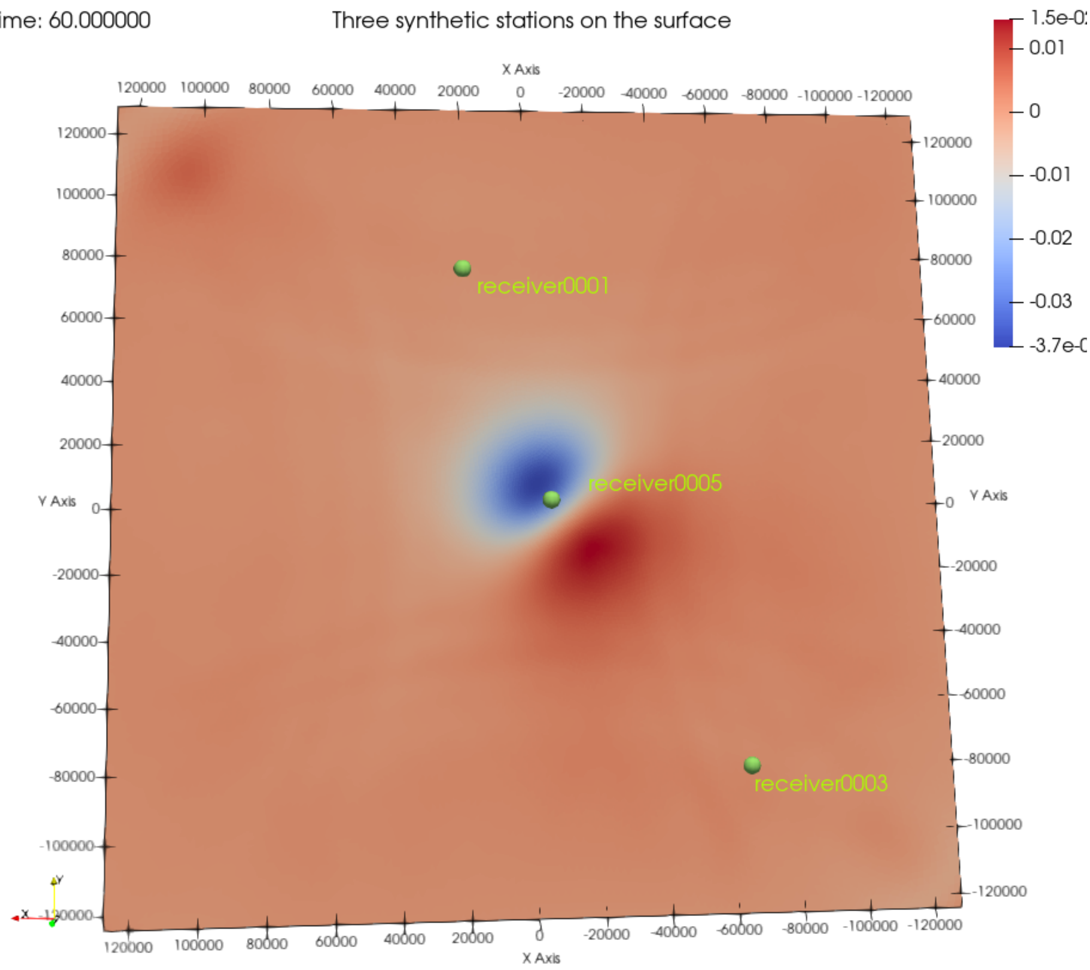


Figure 2.9: Location of the synthetic receivers

Request and processing Observational data

This piece of Python code is what I used for processing the observational data, thanks to *Obspy* Project, I have saved a lot of time !

```
for sta in station_list:
    #request 1 minuate data
    st = client.get_waveforms(network="NR", station=sta, location="", channel="BH?",
    #cut it in 40 sec
    st1=st.slice(starttime=t, endtime=t+40)
    st1.plot();#Plot RAW data
    #get instrument response
    inv = client.get_stations(network="NR", station=sta, location="", channel="BH?",
                    starttime=t, endtime=t+40, level="response")
    #instrument removed + filter[bandpass, 0.2-0,6]
```

```
st2 = st1.copy()
st2.detrend(type='demean')
st2.detrend(type='linear')
st2 = st2.remove_response(inventory=inv).filter("bandpass", freqmin=0.2, freqmax=
st2.plot();
for i, tr in enumerate(st2):
    mdict = {k: str(v) for k, v in tr.stats.items()} #change iteritems to items
    mdict['data'] = tr.data
    savemat("data-" + str(sta) + "_" + str(i) +".mat", mdict) #change like this
```

Obs vs Syn seismogram

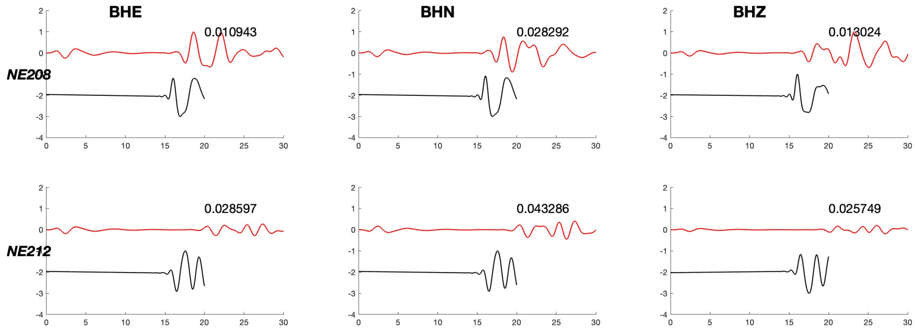


Figure 2.10: Observational and Synthetic seismogram after applied [0.2, 0.6] band pass with order 4 Butterworth filter, cut in 30 seconds

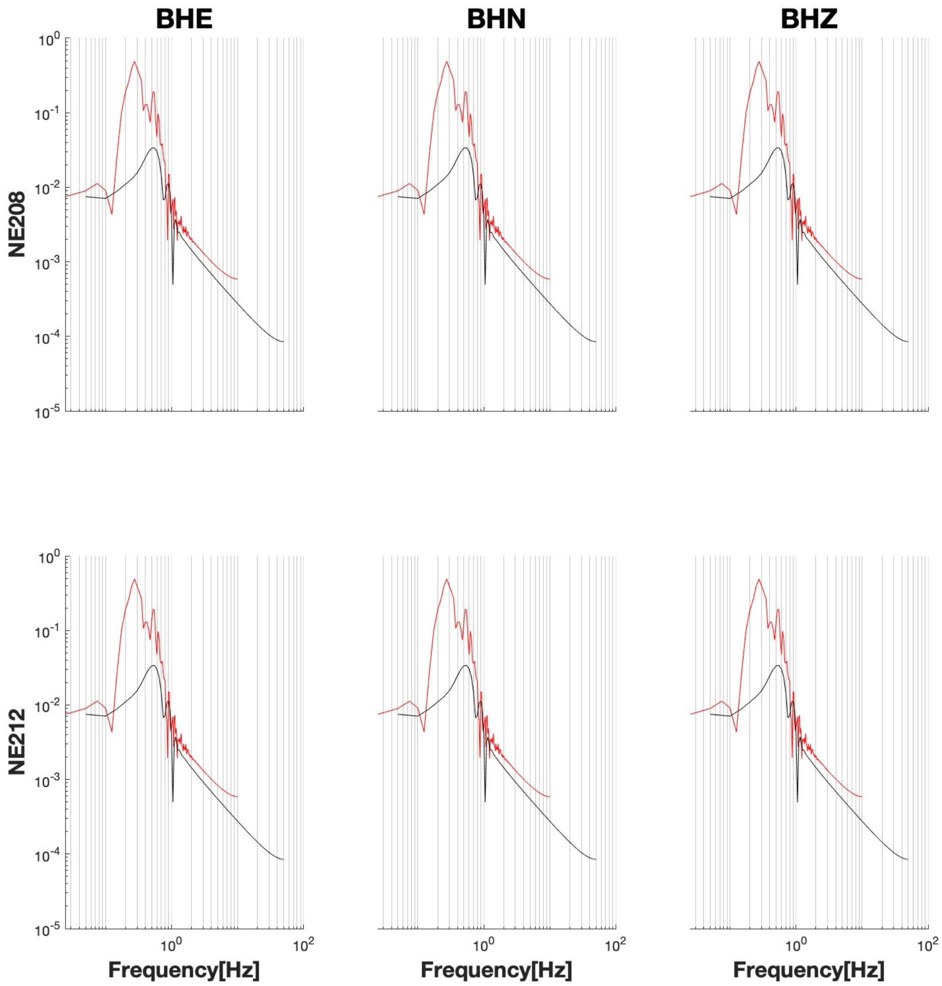


Figure 2.11: Observational and Synthetic spectrum after some scaling, red is obs

2.1.4 Stress distribution: Autocoulomb

Appendix A

Supporting Material for Chapter 1

A.0.1 Observations - Rotation of the regional stress field

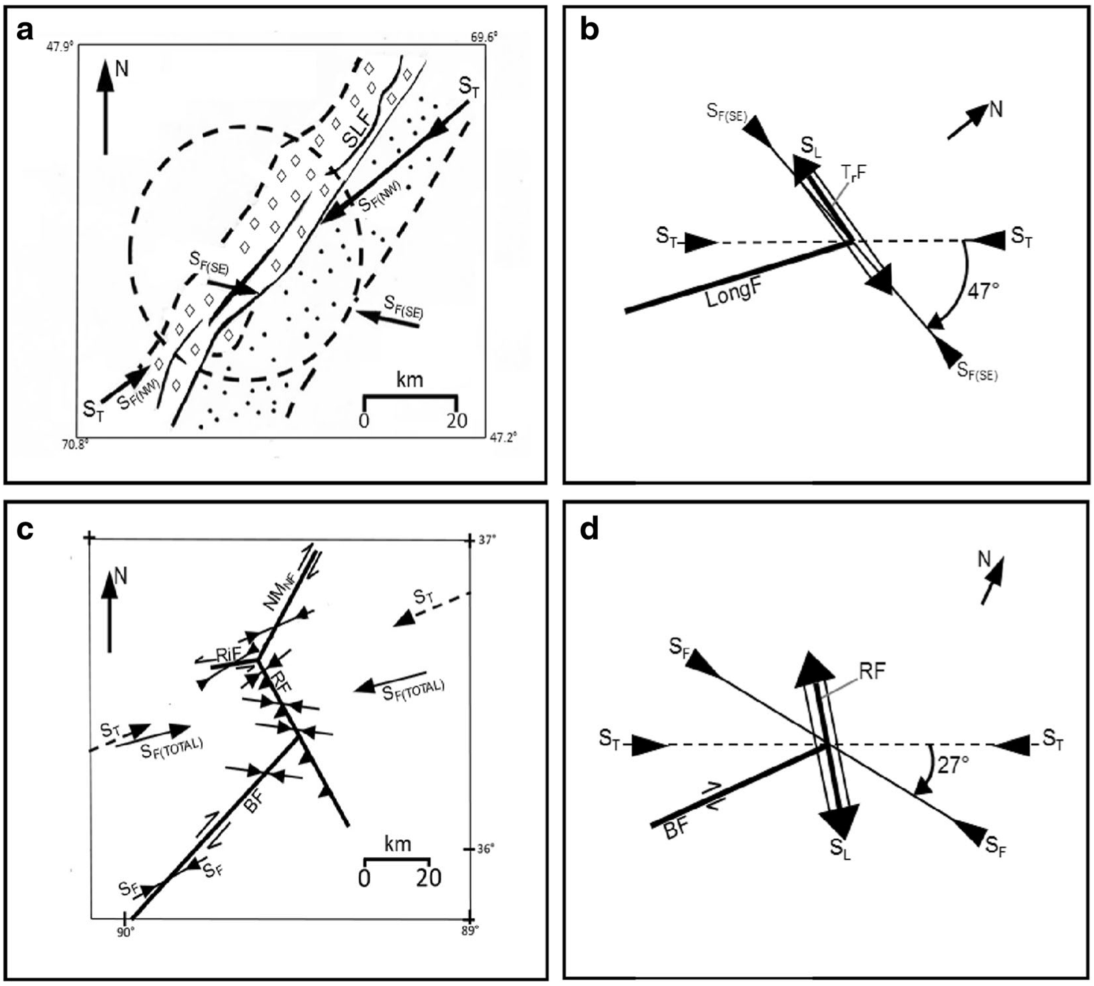


Figure A.1: Rotation of the regional stress field at St. Lawrence and New Madrid [19]

A.0.2 Observations - Large uplifts were observed in the vicinity of faults from InSAR image

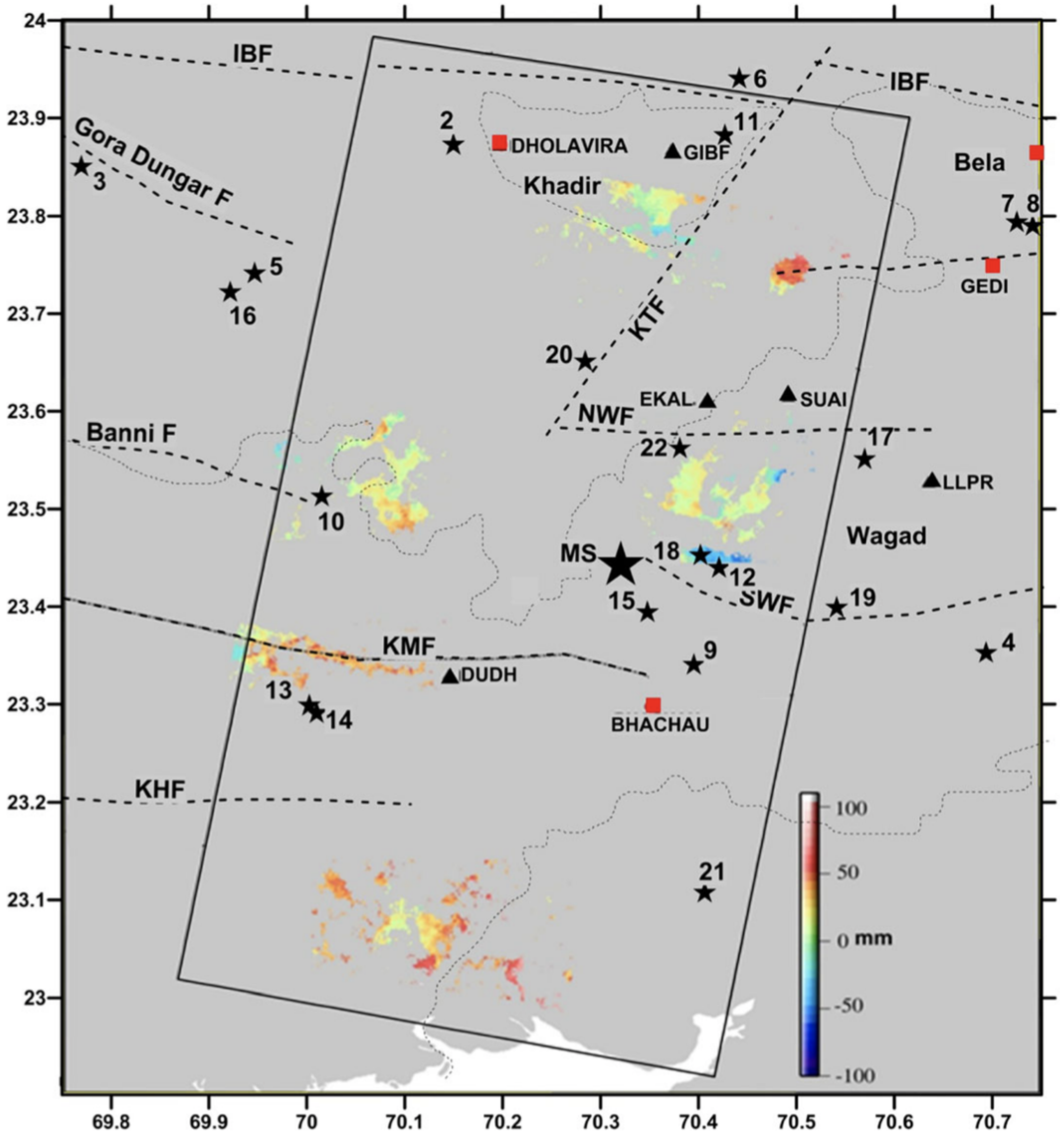


Figure A.2: InSAR showing deviations in LOS in the surrounding area of epicentre of M 7.7 Bhuj earthquake [19]

Large uplifts were observed in the vicinity of faults. Triangles show location of GPS stations. Locations of vertical deformations (colour) are compared with M ≥ 4.0 aftershocks [19]

Appendix B

Supporting Material for Chapter 2

B.0.1 Resistivity model

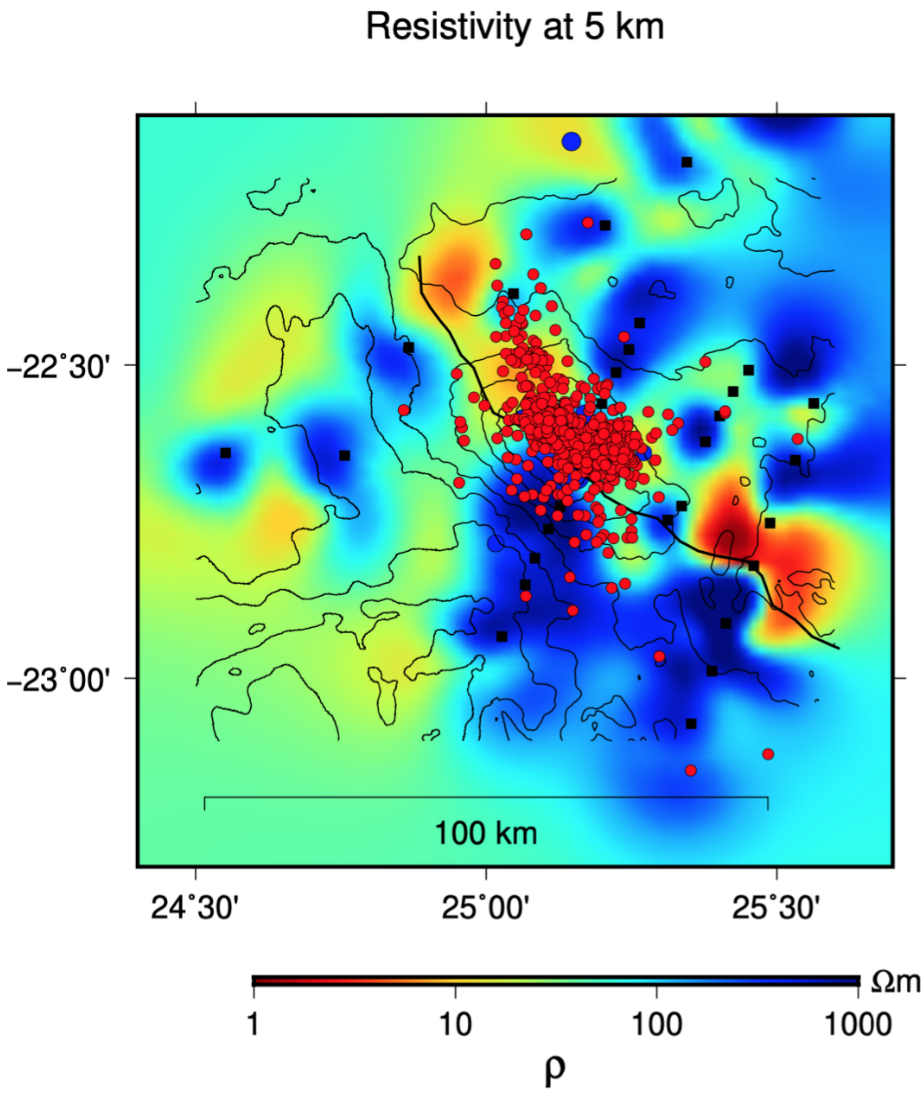


Figure B.1: Estimated fault trace from Moorkamp's resistivity model [15]

B.0.2 Define a fault model - botswan_fault_6e3.yaml

```
!Switch
[rs_a]: !ConstantMap
  map:
    rs_a: 0.01
[RS_sl0]: !ConstantMap
  map:
    RS_sl0: 0.1
[rs_srW]: !ConstantMap
  map:
    rs_srW: 0.1
[s_xx, s_yy, s_zz, s_xy, s_yz, s_xz]:!Include initial_stress.yaml
[nuc_xx,nuc_yy,nuc_zz,nuc_xy, nuc_yz,nuc_xz]:!Include nucleation_stress.yaml
```

B.0.3 Setup initial stress - botswana_initial_stress.yaml

```
!EvalModel     #Provides values by evaluating another easi tree.
parameters: [Omega, eCS, b_xx, b_yy, b_zz, b_xy, b_yz, b_xz]
model: !Switch
  [Omega]: !FunctionMap          #Implements a mapping described by an ImpalaJIT funct
    map:
      Omega: |
        zStressDecreaseStart = -33000.;
        zStressDecreaseStop = -37000.;
        zStressDecreaseWidth = zStressDecreaseStart - zStressDecreaseStop;
        if  (z>=zStressDecreaseStart) {
            return 1.0;
        } else {
            if (z>=zStressDecreaseStop) {
               a = 1.0-(z-zStressDecreaseStop)/zStressDecreaseWidth;
               Sx = (3.0*a*a-2.0*a*a*a);
               return 1.0-Sx;
            } else {
              return 0.001;
            }
        }
  [b_xx, b_yy, b_zz, b_xy, b_yz, b_xz]: !EvalModel
    parameters: [sig_zz,S]
    model: !FunctionMap
      map:
        sig_zz: |
          return 2670.0*(1.0-0.8645)*9.8*min(-5000.0,z);
        S: |
          R = 0.7;
          return (1.0/R-1.0);
    components: !AndersonianStress       #This function allows computing Andersonian s
      constants:
        mu_d:       0.1
        mu_s:       0.6
```

```
        SH_max:    132.0
        cohesion:  0.0
        s2ratio:   0.5
        S_v: 1
  [eCS]: !FunctionMap
    map:
      eCS: |
        return 2670.0*(1.0-0.8645)*9.8*min(-5000.0,z);
components: !FunctionMap #implements a mapping described by an ImpalaJIT function.
  map:
    s_xx:     return Omega*b_xx + (1.0-Omega)*eCS;
    s_yy:     return Omega*b_yy + (1.0-Omega)*eCS;
    s_zz:     return Omega*b_zz + (1.0-Omega)*eCS;
    s_xy:     return Omega*b_xy;
    s_yz:     return Omega*b_yz;
    s_xz:     return Omega*b_xz;
```

B.0.4 Define a nucleation patch - botswana_nucleation_stress.yaml

```
!EvalModel
parameters: [b_xx, b_yy, b_zz, b_xy, b_yz, b_xz, ShapeNucleation]
model: !Switch
  [b_xx, b_yy, b_zz, b_xy, b_yz, b_xz]: !EvalModel
    parameters: [S, sig_zz]
    model: !FunctionMap
      map:
        sig_zz: |
          return -2670.0*(1.0-0.8645)*9.8*29000;
        S: |
          R = 4.0;
          return (1.0/R-1.0);
    components: !AndersonianStress
      constants:
        mu_d:      0.1
        mu_s:      0.6
        SH_max:    132.0
        cohesion:  0.0
        s2ratio:   0.5
        S_v: 1
  [ShapeNucleation]: !FunctionMap
          map:
            ShapeNucleation: |
              xc = -3446.35;
              yc= 5.21499;
              zc=-29000;
              r_crit = 1000.0;
              r = sqrt(pow(x-xc, 2.0) + pow(y-yc, 2.0) + pow(z-zc, 2.0));
              if (r < r_crit) {
                return exp(pow(r,2.0)/(pow(r,2.0)-pow(r_crit,2.0)));
```

```
                }
                return 0.0;
components: !FunctionMap
  map:
    nuc_xx:     return ShapeNucleation*b_xx;
    nuc_yy:     return ShapeNucleation*b_yy;
    nuc_zz:     return ShapeNucleation*b_zz;
    nuc_xy:     return ShapeNucleation*b_xy;
    nuc_yz:     return ShapeNucleation*b_yz;
    nuc_xz:     return ShapeNucleation*b_xz;
```

B.0.5 Include a material model - botswan_material.yaml

```
!Any
  components:
    - !ASAGI
      file: botswana_RhoMuLambda.nc
      parameters: [rho, mu, lambda]
      var: data
    - !ConstantMap
        map:
          rho: 3330.
          mu: 65942325000.
          lambda: 81235350000.
```

botswana_RhoMuLambda.nc

```
netcdf botswana_RhoMuLambda {
types:
  compound material {
    float rho ;
    float mu ;
    float lambda ;
  };
dimensions:
        x = 220 ;
        y = 218 ;
        z = 20 ;
variables:
        float x(x) ;
        float y(y) ;
        float z(z) ;
        material data(z, y, x) ;
}
```

B.0.6 Parameter File - parameter.par

```
&equations

 MaterialFileName = 'botswana_material.yaml'
 Plasticity=0                                !ignore Tv if Plasticity =0, off-fault plasti
Tv = 0.05
/
&IniCondition
/
&Boundaries
BC_fs = 1                                    ! Enable free surface boundary conditions
BC_dr = 1                                    ! Enable dynamic rupture boundary conditions
BC_of = 1                                    ! Enable absorbing boundary conditions
/
&DynamicRupture
FL = 103                                     ! Friction law: 103 use Rate-and-State fricit
BackgroundType = 0                           ! ?
ModelFileName = 'botswana_fault_6e.yaml'!  0.863, yaml file defining spatial depandanc

!define fault friciton parameters, "borrowed" from [Numerical method:TABLE A1, Palgur
RS_f0 = 0.6                                  ! Steady-state friction coefficient at V_0
RS_sr0 = 1d-6                                ! Reference slip velocity, V_0
RS_b = 0.014                                 ! Evolution effect parameter
Mu_W=0.1                                     ! Fully weakened friction coefficient
RS_iniSlipRate1 = 1d-16                      ! Initial Slip rate
RS_iniSlipRate2 = 0d0                        ! ?
t_0 =0.4                                     ! rise time?

GPwise=1  !initial condition projection on every points?

XRef = 0.1                  ! Reference point for defining strike and dip direction
YRef = 0.1
ZRef = -1.0
refPointMethod = 1

RF_output_on = 0            ! Rupture front ascii output
magnitude_output_on = 1     ! Moment magnitude output, e.g. Mw=6.5; Mw=2/3*(log10(M_0
energy_rate_output_on = 1   ! moment rate output
OutputPointType = 5         ! Type (0: no output, 3: ascii file, 4: paraview file, 5:
SlipRateOutputType = 0      ! 0: (smoother) slip rate output evaluated from the diffe
                            ! 1: slip rate output evaluated from the fault tractions
/

&Elementwise

!see: https://seissol.readthedocs.io/en/latest/fault-output.html

printIntervalCriterion = 2       ! 1=iteration, 2=time
                                 ! if printIntervalCriterion=1, the output is generate
                                 ! this only works with Global time stepping
```

```
printtimeinterval_sec = 0.5      ! Time interval at which output will be written
OutputMask = 1 1 1 1 1 1 1 1 1 1 0 1   ! 1/ slip rates in strike and dip direction , i
                                       ! 2/ transient shear stress in strike and dip
                                       ! 3/ normal velocity , u_n
                                       ! 4/ Mud, current friction , StV, state varible
                                       ! 5/ Ts0, Td0, Pn0: total stress , including in
                                       ! 6/ Sls and Sld: slip in strike and dip direc
                                       ! 7/ Vr: rupture velocity , computed from the s
                                       ! 8/ ASI: absolute slip
                                       ! 9/ PSR: peak slip rate
                                       ! 10/ RT: rupture time
                                       ! 11/ DS only with LSW, time at which ASI> D_c
                                       ! P_f and Tmp: pore pressure and temperature ,
refinement = 1              ! refinement=0, one triangle for each mesh cell;
                            ! refinement=1, subdivides each triangles
refinement_strategy =  2    ! refinement_strategy=1, splits each triangle into 3 triang
                            ! refinement_strategy=2, splits each triangle into 4 triang
/
&Pickpoint
printtimeinterval = 0.1                ! Index of printed info at timesteps
OutputMask = 1 1 1 1 1 1 1 1 1 1 1 1   ! turn on/off fault outputs , same as before?
nOutpoints = 2
PPFileName = 'recevier_35K_center.dat'
/


&SourceType
/

&SpongeLayer
/

&MeshNml
MeshFile = '../mesh_hsu/mesh3/mesh3_case2'              ! name of my mesh, 14mio only v
(updated)
meshgenerator = 'PUML'           ! Name of meshgenerator (format) Gambit3D-fast , Netc
/


&Discretization
CFL = 0.5                             ! CFL number (<=1.0)
FixTimeStep = 5                       ! Manualy chosen maximum time step
ClusteredLTS = 2                      ! Local time stepping
                                      ! 1 for Global time stepping , 2,3,5,... Local tim
                                      ! ClusteredLTS defines the multi-rate for the tim
                                      ! use LTS > speed up
/

&Output
```

```
OutputFile = '../output_6e/botswana_model_6e'      !output in this folder
Format = 6                                 ! Format (0=IDL, 1=TECPLOT, 2=IBM DX, 4=GiD, 6=h
!              |stress      |vel
iOutputMask = 0 0 0 0 0 0 1 1 1
printIntervalCriterion= 2                  ! Criterion for index of printed info: 1=timeste
TimeInterval = 0.5                         ! Index of printed info at time
refinement = 1                             ! (?)

!off-fault ascii receivers
nRecordPoints = 2                           !number of receivers in the file
RFileName = 'recevier_35K_center.dat'
pickdt = 0.01                              ! Pickpoint Sampling, sampling rate, i.e. sampli
pickDtType = 1                             ! Pickpoint Type
ReceiverOutputInterval = 0.5               ! (Optional) Synchronization point for receivers

!Free surface output
SurfaceOutput = 1
SurfaceOutputRefinement = 2                ! (?)1 > 4 triangle, 2 > 16 triangle
SurfaceOutputInterval = 0.5
/
&AbortCriteria
EndTime = 20.0                             ! Simulation time 8.75*30 = 262.5, 150 = 8.75*t
/

&Analysis
/

&Debugging
/
```

B.0.7 SeisSol Shell script - parallel computing with MPI

```
#!/bin/bash
ulimit -Ss unlimited
nohup mpirun -n 8 SeisSol_Release_drome_4_elastic parameters_6e3.par
&>output_6e3.log&
```

SeisSol supports parallel computing with MPI (Message-Passing Interface standard). MPI consists of libraries that can be called from Fortan, C, C++ and Python (pyMPI).

n indicates the number of processors allocated for the specific model setup configured in *parameters_6e3.par*. How large should n be in order to achieve optimal performance? To answer this question, we need to consider scaling because adding more processors does not necessarily mean more speed-up for even high percentages of parallelizability (Percentage of the code that can be parallelized).

SeisSol code recently reached a remarkable strong scaling (How the run time varies with the number of processors for a fixed size problem), and also obtained peak performance at 1.09

PFlops. After years of performance optimization, *SeisSol* code based on the discontinuous Galerkin method was recognized by being nominated as a finalist of the Gordon Bell Prize in 2014. [2]

Bibliography

[1] Stephen Hawking. *A brief history of time: from big bang to black holes.* Random House, 2009.

[2] Heiner Igel. *Computational seismology: a practical introduction.* Oxford University Press, 2017.

[3] Seth Stein and Michael Wysession. *An introduction to seismology, earthquakes, and earth structure.* John Wiley & Sons, 2009.

[4] Hideo Aochi and Eiichi Fukuyama. Three-dimensional nonplanar simulation of the 1992 landers earthquake. *Journal of Geophysical Research: Solid Earth*, 107(B2):ESE–4, 2002.

[5] James R Rice. Fault stress states, pore pressure distributions, and the weakness of the san andreas fault. In *International geophysics*, volume 51, pages 475–503. Elsevier, 1992.

[6] Marlon Ramos, Prithvi Thakur, Yihe Huang, Ruth Harris, and Kenneth Ryan. Working with dynamic earthquake rupture models: A practical guide. 03 2022. doi: 10.31223/X5KD16.

[7] Calistus D Ramotoroko, Rubeni T Ranganai, and Peter Nyabeze. Extension of the archaean madibe-kraaipan granite-greenstone terrane in southeast botswana: Constraints from gravity and magnetic data. *Journal of African Earth Sciences*, 123:39–56, 2016.

[8] A-A Gabriel, J-P Ampuero, Luis A Dalguer, and Paul Martin Mai. The transition of dynamic rupture styles in elastic media under velocity-weakening friction. *Journal of Geophysical Research: Solid Earth*, 117(B9), 2012.

[9] Giulio Di Toro, Raehee Han, Takehiro Hirose, Nicola De Paola, Stefan Nielsen, Kazuo Mizoguchi, Fabio Ferri, Massimo Cocco, and Tosihiko Shimamoto. Fault lubrication during earthquakes. *Nature*, 471(7339):494–498, 2011.

[10] Ruth A Harris, Michael Barall, David A Lockner, Diane E Moore, David A Ponce, RW Graymer, G Funning, Carolyn A Morrow, Christodoulos Kyriakopoulos, and Donna Eberhart-Phillips. A geology and geodesy based model of dynamic earthquake rupture on the rodgers creek-hayward-calaveras fault system, california. *Journal of Geophysical Research: Solid Earth*, 126(3):e2020JB020577, 2021.

[11] James Byerlee. Friction of rocks. In *Rock friction and earthquake prediction*, pages 615–626. Springer, 1978.

[12] Thomas Ulrich, Alice-Agnes Gabriel, Jean-Paul Ampuero, and Wenbin Xu. Dynamic viability of the 2016 mw 7.8 kaikōura earthquake cascade on weak crustal faults. *Nature communications*, 10(1):1–16, 2019.

[13] Thomas Obermaier. *Mechanisms of intraplate earthquakes: The 2017 Botswana event . BS Thesis at LMU München*, October 2020.

[14] Sophia Gahr. *The 2017 Intraplate Earthquake in Botswana: Computational Modeling of the Rupture Dynamics . BS Thesis at LMU München*, May 2021.

[15] Max Moorkamp, Stewart Fishwick, Richard J Walker, and Alan G Jones. Geophysical evidence for crustal and mantle weak zones controlling intra-plate seismicity–the 2017 botswana earthquake sequence. *Earth and Planetary Science Letters*, 506:175–183, 2019.

[16] Thomas Ulrich, Stefan Vater, Elizabeth H Madden, Jörn Behrens, Ylona van Dinther, Iris Van Zelst, Eric J Fielding, Cunren Liang, and A-A Gabriel. Coupled, physics-based modeling reveals earthquake displacements are critical to the 2018 palu, sulawesi tsunami. *Pure and Applied Geophysics*, 176(10):4069–4109, 2019.

[17] Kadek Hendrawan Palgunadi, Alice-Agnes Gabriel, Thomas Ulrich, José Ángel López-Comino, and Paul Martin Mai. Dynamic fault interaction during a fluid-injection-induced earthquake: The 2017 m w 5.5 pohang event. *Bulletin of the Seismological Society of America*, 110(5):2328–2349, 2020.

[18] Kathryn Materna, Shengji Wei, Xin Wang, Luo Heng, Teng Wang, Weiwen Chen, Rino Salman, and Roland Bürgmann. Source characteristics of the 2017 mw6. 4 moijabana, botswana earthquake, a rare lower-crustal event within an ancient zone of weakness. *Earth and Planetary Science Letters*, 506:348–359, 2019.

[19] Pradeep Talwani. On the nature of intraplate earthquakes. *Journal of Seismology*, 21(1): 47–68, 2017.

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Nomenclature

	Symbols and Abbreviations	Meaning	Note
1	IPEs	Intraplate Earthquakes	
2	LSCs	Local Stress Concentrators	
3	S_v	Vertical stress	
4	S_{Hmax}	Maximum continental horizontal stress	
5	S_F	Final stress	Unified model
6	S_T	Regional stress	Unified model
7	S_L	Local stress	Unified model
8	R	relative prestress ratio	SeisSol
9	SHmax	the direction of maximum horizontal stress	SeisSol

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Statement of Authorship

With this statement I certify that this master thesis has been composed by myself. Unless otherwise acknowledged in the text, it describes my own work. All references have been quoted and all sources of information have been specifically acknowledged. This thesis has not been accepted in any previous application for a degree.

Selbständigkeitserklärung

Hiermit versichere ich, diese Masterarbeit selbständig und lediglich unter Benutzung der angegebenen Quellen und Hilfsmittel verfasst zu haben. Ich erkläre weiterhin, dass die vorliegende Arbeit noch nicht im Rahmen eines anderen Prüfungsverfahrens eingereicht wurde.