

3D NUMERICAL MODELS FOR ALONG-AXIS VARIATIONS IN DIKING AT  
MID-OCEAN RIDGES

by

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### ***Dedication***

I would like to dedicate this thesis to my mother, 田霞 (Tian, Xia). I wouldn't have a chance to experience this wonderful world without her giving birth to me. She rears me up by herself with her great love, optimism and peseverence. Without her guidance and support, I will not become who I am.

I also want to dedicate this thesis toward my major thesis advisor: Professor Eunseo Choi. His mentorship defines what a great advisor is like. Without his guidance, neither this thesis nor my fast personal development during these two years is possible. He has kindled a flame that illuminates the way for my future career as a geodynamic modeler.

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Thank you my dear mother, 田霞 (Tian, Xia). You are always a great mother to me. Thank you so much for rearing me up by yourself with your great courage, optimism, love and care. Without you, there is no me.

“In the midst of winter, I found there was, within me, an invincible summer.”

—Albert Camus

“People have no higher calling than to strive for the greater good of humankind and society and that the future of humanity can be assured only when there is a balance between scientific development and the enrichment of the human spirit.”

—Kazuo Inamori

“不失其所者久，死而不亡者寿。”

—《道德经》

### *Abstract*

Tian, Xiaochuan. M.S. The University of Memphis. May 2015 Master of Science.  
3D Numerical Models for Along-axis Variations in Diking at Mid-Ocean Ridges. Major  
Professor: Dr. Eunseo Choi.

Bathymetry of ocean floors reveals a great variety of morphologies at Mid-ocean Ridges (MORs). Previous studies showed that the morphologies at slow spreading MORs are mainly controlled by the ratio between rates of magma supply and plate extension. 2D models for the across-ridge cross-sections have been successful in explaining many of the observed morphological features such as abyssal hills and oceanic core complexes. However, the magma supply varies along the ridge and the interaction between the tectonic plates and magmatism at MORs are inevitably 3D processes. We propose to investigate the consequences of the along-axis variability in diking in terms of faulting pattern and the associated structures. This work will include implementation of an algorithm of parameterizing repeated diking in a 3D parallel geodynamic modeling code.

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# 1 Introduction

## 1.1 Review of Literature

Geodynamic modeling as well as a variety of geological, geophysical observations and lab experiments have provided insight into the processes occurring at the mid-ocean ridges (MORs) [e.g., Tucholke and Lin, 1994, Blackman et al., 2002, Behn et al., 2006, Behn and Ito, 2008, Ito and Behn, 2008, Baines et al., 2008, Escartín et al., 2008, Canales et al., 2008, Dick et al., 2008, Dannowski et al., 2010, Olive et al., 2010, Reston and Ranero, 2011, Reston and McDermott, 2011]. In particular, the advent of high-resolution multi-beam bathymetric data has made it possible to discover differences in axial topography between slow and fast spreading ridges and morphological transition from the center of a ridge segment to the tip of the ridge segment.

Variations in morphologies among different MORs are mainly controlled by four factors: magma supply, tectonic strain, hydrothermal circulation and spreading rate [Fowler, 2004]. Among them, the spreading rate shows the strongest correlation with the ridge morphology. Slow-to-intermediate spreading ridges (half spreading rate less than 4 cm/yr) produce median valleys that are typically 10~20 km wide and 1~2 km deep (e.g., Mid-Atlantic Ridges, Figure 1a). Fast-spreading ridges (half spreading rate greater than 5 cm/yr) like the East Pacific Rise have axial highs that are 10~20 km wide, 0.3~0.5 km high (Figure 1b).

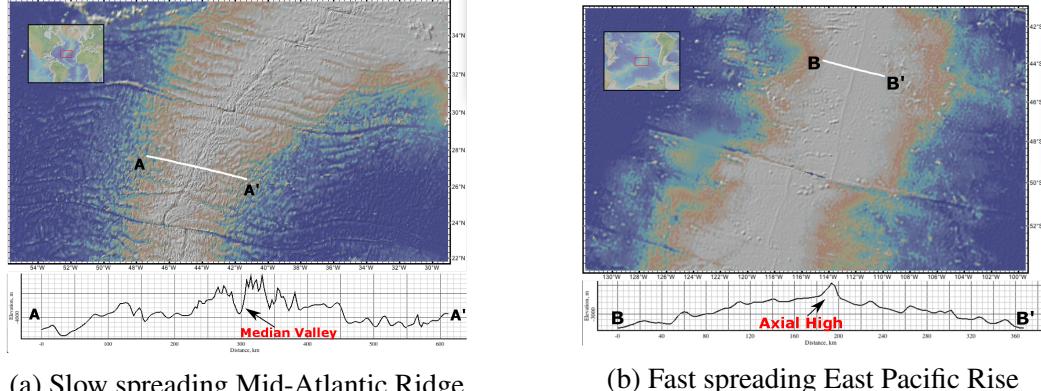


Figure 1: Profiles of bathymetry across MORs.

Slow spreading ridges exhibit along-axis variations in off-axis morphology, the width and depth of median valleys and crustal thickness. Figure 2 shows that the topographic profile near to the center of the ridge segment (A-A') is rather symmetric and has higher frequency with a median valley  $\sim$ 12 km wide and  $\sim$ 1 km deep. In contrast, the near-tip profile (B-B') is asymmetric and has a much lower frequency with a median valley wider than 30 km and shows a greater relief ( $\sim$ 3 km). The maximum along-axis variation in crustal thickness  $\Delta H_c$  is linearly increasing with segment length L [Chen and Lin, 1999] and the relationship is  $\Delta H_c(L) = 0.0206L$  (Figure 3).

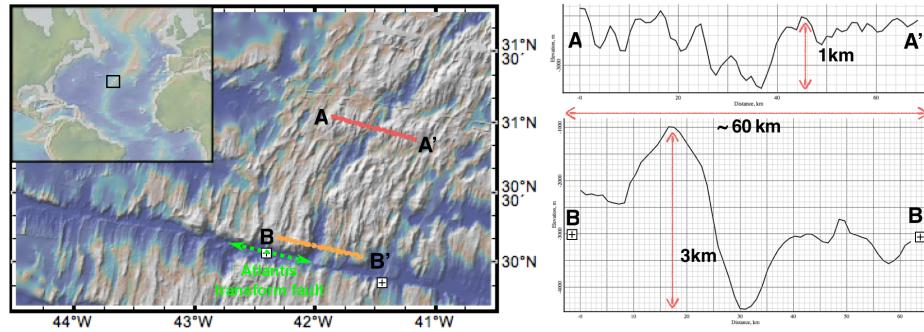


Figure 2: Two bathymetric profiles across the Mid-Atlantic Ridge around  $30^{\circ}\text{N}$  with vertical exaggeration of 10. A-A' is closer to the segment center while B-B' is at the tip of the segment.  
EC: [I can't clearly see the label, Atlantis transform fault.]

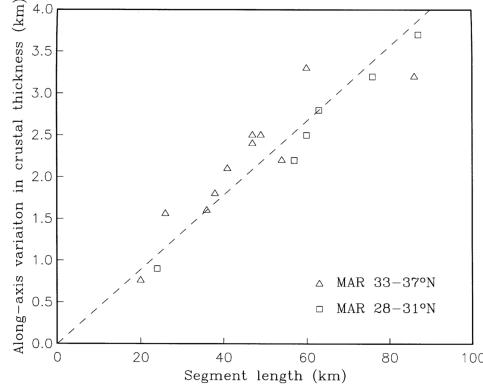


Figure 3: Relationship between the maximum crustal thickness variations ( $\Delta H_c$ ) along a ridge segment and the segment length (L). The dashed line is the best-fit linear regression of the combined data. [Chen and Lin, 1999]

Magma supply at the MORs is mostly a passive process when no hot plume is present [Fowler, 2004]. Driven by both vertical pressure difference and buoyancy due to horizontal density difference, hot mantle rises up to fill the vacated room produced by the plate separation. Decompression of the upwelling hot mantle results in partial melting. The generated magma upwells to the upper crust and feeds the dikes at the ridge center.

The passive nature of the melting process at the MORs leads to the major difference between fast and slow spreading ridges. At fast spreading ridges, magma is generated at a higher rate than at slow spreading ridges. Thus, fast spreading ridges can sustain more frequent diking, which efficiently release stresses generated by far-field forces driving the plate motion. In contrast, diking is less frequent at slow spreading ridges and can only partially releases the stresses associated with plate motion. The plates associated with slow-spreading ridges experiences internal deformations (e.g. tectonics process like normal faulting) when the accumulated extensional stress exceeds the strength of the crust.

Buck et al. [2005] defined the ratio between the rate of plate separation by diking and spreading rate as  $M = V_{dx}/2V_x$ , where  $V_{dx}$  is the rate of opening by diking at a MOR and  $V_x$  is the half spreading rate of the MOR. According to this definition,  $M = 1$  represents the case where dike injection is so frequent that magma supply is sufficient to release all the tensional stresses from plate separation.  $M = 0$  corresponds to the case of no magma

supply, in which diking does not account for any of the plate motion and therefore plates kinematics requires plates to go through internal deformations. As shown in Figure 4, an axial high forms at a fast spreading ridge ( $M = 1$ ) due to buoyancy from lateral density difference across ridge axis but a median valley forms at a slow-spreading ridge ( $M = 0.5$ ) due to near-axis normal faulting, which is in turn caused by the stretching of oceanic lithosphere.

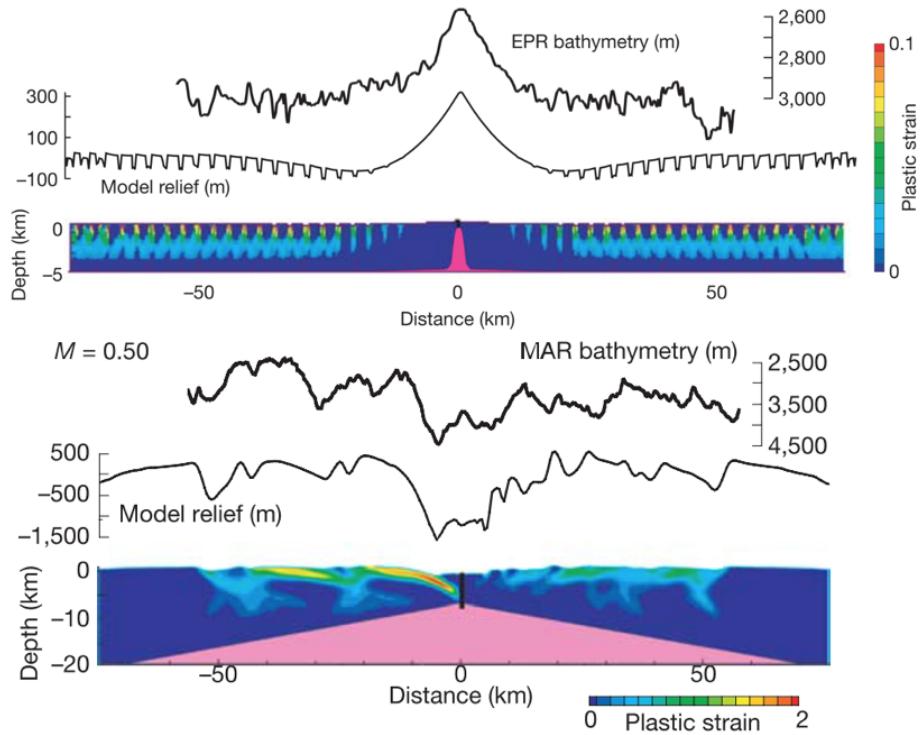


Figure 4: Upper one: modeling result for fast spreading agrees well with the observation of East Pacific Rise. Lower one: modeling result for slow spreading ridges agrees well with the bathymetry of Mid Atlantic Ridge. [Buck et al., 2005]

Tucholke et al. [2008] expand the investigation on the role of  $M$  in the mid-ocean ridge mechanics. They focus on the faulting behaviors of slow spreading ridges and find that the OCCs are most likely to form when  $M$  varies from 0.3 to 0.5. When  $M = 0.7$  (Fig. 5), repeated diking pushes faults that have formed at the spreading center away from the ridge axis. Since the thickness of the brittle layer increases away from the ridge axis due to cooling effects, frictional and bending energy for maintaining the fault also in-

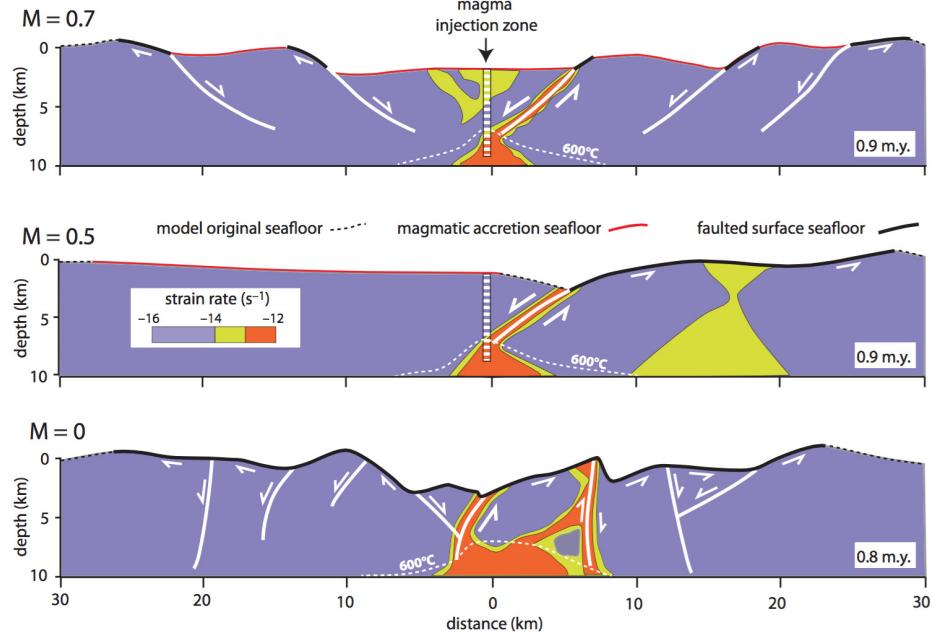


Figure 5: Snapshots of modeled fault behavior and seafloor morphology for values  $M = 0, 0.5$ , and  $0.7$ ; model allows thermal evolution. Structural interpretation is superimposed on modeled distribution of strain rate; model time is indicated in panels at lower right; dashed white line at bottom is  $600\text{ }^{\circ}\text{C}$  isotherm and approximates the brittle-ductile transition; dashed seafloor is original model seafloor, red seafloor is that formed dominantly by magmatic accretion, and solid bold seafloor is fault surface.[[Tucholke et al., 2008](#), [Whitney et al., 2012](#)]

creases. When the energy needed for maintaining an existing fault exceeds the energy for breaking a new near-axis fault, the old fault is replaced by the new one and most of the extension is accommodated by the new fault. When  $M = 0.3 \sim 0.5$ , the normal fault remains active for a long time and rotates to a very low angle normal fault (detachment fault), exhuming the lower crust and mantle materials to the seafloor. When  $M < 0.3$ , most of the tension is accommodated by intra-plate deformations rather than by diking and as a result, faulting pattern is more complicated and unsteady.

*EC:* [In the publication we will be writing, you'll also need to mention the works by Ito and Behn and Olive et al.]

## 1.2 Statement of Research Purpose

The M-factor formulation used in the previous 2D models [e.g., Tucholke et al., 2008, Buck et al., 2005] successfully explained major features found in across-ridge profiles of seafloor bathymetry. However, 2D models have limitations in studying the along-ridge variations in morphology and faulting patterns. Magma supply at fast spreading ridges seems always sufficient for accommodating plate motions with little variation along the ridge axis. The relatively uniform topography along fast spreading ridges is considered to be consistent with the uniform abundance of the magma supply. However, along the slow spreading ridges, bathymetry, gravity anomaly and results from reflection and refraction seismology show strong correlation with variation in crustal thickness [Ryan et al., 2009, Chen and Lin, 1999, Lin et al., 1990, Tolstoy et al., 1993]. Because oceanic crust is mainly formed by upwelled magma at the ridge, variation in the thickness of the crust implies variation in magma supply. At slow spreading ridges, the degree of cooling by hydrothermal circulation, thermal structures and even local spreading rate [Baines et al., 2008] also varies both along and across the ridge axis and they appear interrelated. Thus, for slow-to-intermediate spreading ridges, the interactions between tectonics and magmatism at MORs are inevitably 3D processes and 3D numerical models are desirable for better understanding factors controlling both across- and along-ridge topography variations.

The purpose of this thesis is to extend the M-factor formulation originally developed for 2D models to three dimensions (3D) by implementing it into a 3D numerical modeling code SNAC (StGermaiN Analysis of Continua) [Choi et al., 2008]. By systematically exploring the behaviors of the 3D models and comparing them with observations, we aim to better understand how the mid-ocean ridge magmatism and tectonic deformations interact.

## 2 Methods

### 2.1 Method of approach

The numerical modeling code, SNAC (StGermaiN Analysis of Continua), is an explicit Lagrangian finite element code that solves the force and energy ~~XT: find out which one is energy balance equation~~ balance equations for elasto-visco-plastic materials. Figure 6 shows major components of SNAC.

For each time step, strain and strain rates are updated based on the initial or previous velocity fields under the constraints from boundary conditions. A constitutive model returns updated stresses corresponding to these deformation measures. Internal forces are then calculated from the updated stresses, which is plugged into the momentum balance equation together with the body force term. Then, the damped ~~XT: better understand the damped force~~ net force divided by inertial mass yields acceleration at a node point, which is time-integrated to velocity and displacement.

A 3D domain is discretized into hexahedral elements, each of which is in turn divided into two sets of tetrahedra. This symmetric discretization prevents faulting from favoring a specific direction or “mesh grains”.

Rheology for the oceanic lithosphere is assumed to be elasto-visco-plastic (EVP). When viscosity is high at low temperature, the EVP rheology implemented in SNAC essentially becomes the Mohr-Coulomb plasticity with strain softening that can create shear bands that behave like faults. Strain softening is realized by cohesion decreasing with increasing amount of permanent (i.e., plastic) strain. I assume this relationship is linear for simplicity. It is sufficient for a full description of such a linear strain weakening to define initial and final values of cohesion and a critical plastic strain at which cohesion becomes the final value. I define the rate of strain weakening as the cohesion difference divided by the critical plastic strain and use it as one of the model parameters. When temperature is high and viscosity is low, the rheology becomes the Maxwell viscoelasticity and can

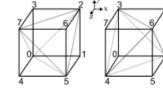
model creeping flow. This property of the EVP model makes it possible to set up a structure with a brittle lithosphere and a ductile asthenosphere through a proper temperature distribution. Rheological parameters are taken from previous studies that use a similar rheology [e.g., [Buck et al., 2005](#); [Tucholke et al., 2008](#)] or from lab experiments [e.g., [Kirby and Kronenberg, 1987](#)].

For 3D diking processs, the strain  $\Delta\varepsilon_{xx}$  associated with diking leads to stresses changes,  $\Delta\sigma_{xx}$ ,  $\Delta\sigma_{yy}$  and  $\Delta\sigma_{zz}$ . These stress changes due to diking are computed according to the linear elastic constitutive equations  $\sigma_{ij} = \lambda\varepsilon_{kk}\delta_{ij} + 2\mu\varepsilon_{ij}$ .

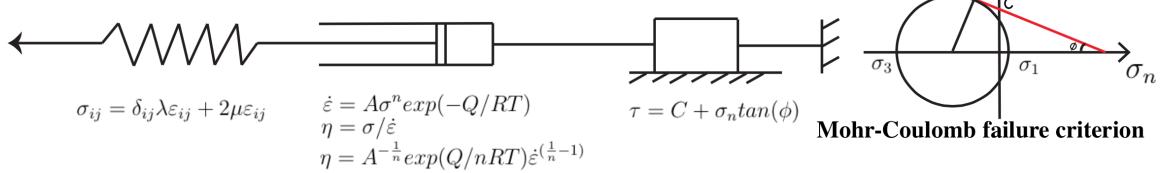
**SNAC:** a 3D, MPI parallelized, updated Lagrangian explicit finite difference code for modeling long-term tectonic evolution of the Earth's elasto-visco-plastic crust and mantle. (Choi et al., 2008)

$$\text{Momentum Balance Equation: } \frac{\partial\sigma_{ij}}{\partial x_j} + \rho g_i = \rho \frac{Dv_i}{Dt}$$

**Spatial Decritization:** A 3D domain is discretized into hexahedral elements, each of which is filled with two sets of 5 tetrahedra.



**Elasto-Visco-Plastic (EVP) Rheology:**



**Diking M Formulation:**  $M = Vdx / 2Vx$  (Vdx is the diking velocity in x direction, 2Vx is the full spreading velocity)

Stresses introduced by a dike accretion strain(dike widening) $\Delta\varepsilon_{xx}$  in each time step dt:

$$\Delta\sigma_{xx} = (\lambda + 2\mu)\Delta\varepsilon_{xx} \quad \Delta\sigma_{yy} = \lambda\Delta\varepsilon_{xx} \quad \Delta\sigma_{zz} = \lambda\Delta\varepsilon_{xx}$$

Figure 6: Essential components of the numerical method.

## 2.2 Model Setup

The 3D models have a common geometry of  $60 \text{ km} \times 20 \text{ km} \times 20 \text{ km}$  in  $x$ ,  $y$  and  $z$  axes respectively with a resolution ( $\Delta x$ ) of 1 km (i.e.,  $\Delta x$  is the size of each hexahedron element). The initial temperature field linearly increases from  $0^\circ\text{C}$  at the top surface to  $240^\circ\text{C}$  at the depth of 6 km, reflecting enhanced cooling due to hydrothermal circulation (Fig. 7). Below 6 km, the temperature profile follows the semi-infinite half-space cooling model of moving plates [e.g., [Turcotte and Schubert, 2002](#)]. Two sides perpendicular

to the  $z$  coordinate axis are free-slip. The top surface has vertical tractions from water columns, of which heights are locally determined as  $(4000 - h(x, z))$  m, where  $h(x, z)$  is the topography at a location,  $(x, z)$ . The bottom surface is supported by the Winkler foundation. Temperature is fixed at 0 °C on the top surface and at 1300 °C on the bottom surface.

Diking, represented by the factor  $M$  as described above, is assumed to occur in the middle of the domain (Fig. 7), where the lithosphere is the thinnest.

We adopt the linear isotropic elasticity, power-law viscosity of dry diabase [e.g., Kirby and Kronenberg, 1987, Buck et al., 2005] and the Mohr-Coulomb plastic model. The complete list of model parameters are given in Table 1.

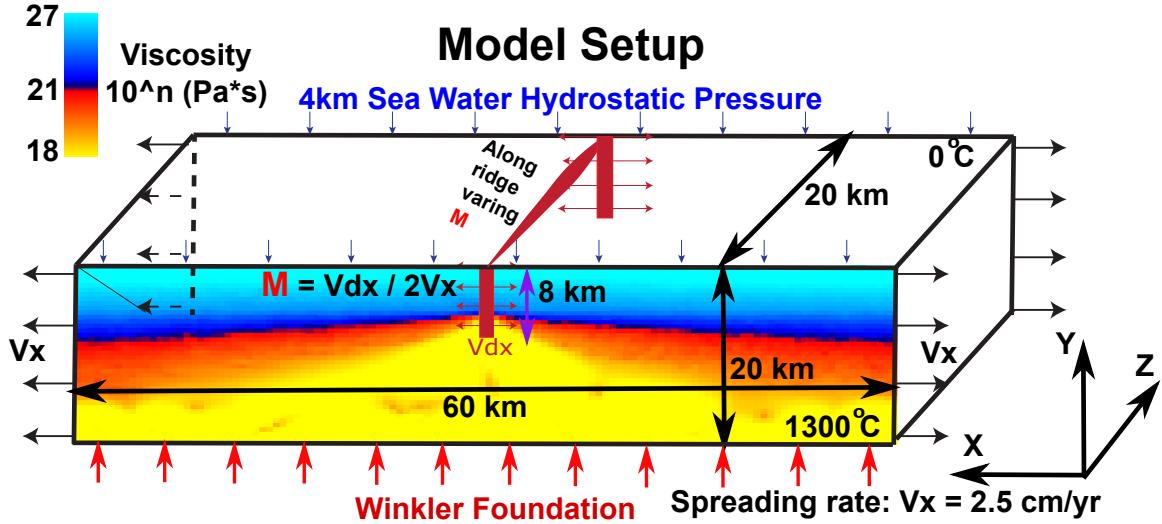


Figure 7: Model setup

Before running 3D models, I have run hundreds of pseudo-2D models for initial setup and benchmarking with previous studies [e.g., Buck et al., 2005, Tucholke et al., 2008]. Preliminary pseudo-2D results show that the model behavior in faulting pattern is sensitive to the rate of strain weakening. Two cases of strain weakening are tested in the 3D models. In one case (denoted as Type 1 weakening), cohesion linearly decreases from 44 MPa (denoted as  $C_i$ ) to 4 MPa ( $C_e$ ) for plastic strain accumulating from 0 ( $\varepsilon_{p_i}^1$ ) to 0.1 ( $\varepsilon_{p_e}^1$ ). It has a characteristic fault slip of 150 m for pseudo-2D models and 300 m for 3D

models. The other case (Type 2 weakening) assumes cohesion linearly decreasing from 44 MPa ( $C_i$ ) to 4 MPa ( $C_e$ ) for plastic strain accumulating from 0 ( $\varepsilon_{p_i}^2$ ) to 0.33 ( $\varepsilon_{p_e}^2$ ). In this case, the characteristic fault slip for pseudo-2D models is 500 m and for 3D models is 1 km. The characteristic fault slip is defined as  $\Delta X_c = 3\Delta x \varepsilon_{p_e}$  where  $3\Delta x$  represents the thickness of the shear bands which is usually 2 to 4 times  $\Delta x$  (size of a hexahedron element) [Lavier et al., 2000]. When  $\Delta X_c$  amount of slip takes place at the fault interface, the cohesion of the material at the faulting interface decreases to  $C_e$ . In this way, under the same amount of  $\Delta X_c$ , models with different resolution should produce the same faulting patterns.

Although how to estimate the M values from observations is a subject of on-going research, constraints are available from a large dataset of bathymetry, gravity and seismic surveys as well as geological drilling. Generally, at slow spreading ridges, magma supplies mostly at the center of the ridge segment and decreases towards the tip of the segment [Tolstoy et al., 1993, Chen and Lin, 1999, Carbotte et al., 2015]. There is also evidence for shorter wavelength of 10 to 20 km discrete focus of magma accretion along the ridge axis [Lin et al., 1990].

The numerical cost of a 3D model is non-trivial. For 2 Myr of model time, each model usually runs on 192 cores for about 48 hours (i.e., around  $10^4$  core-hours). *EC:* Add some more details about the hardware you used. CPU maker, model, clock speed. Also, information about networking hardware of the cluster, since it's relevant to the numerical cost.

Based on these observational constraints and computational cost, I start considering a few scenarios of variations in M along the ridge axis. They are 1) three types of functional forms, linear, sinusoidal and square root; 2) three ranges of M variation along the ridge axis, 0.5 to 0.7, 0.5 to 0.8 and 0.2 to 0.8; and 3) two types of weakening rate, type 1 and type 2 *EC:* [I think I suggested to use more explicit names like fast and slow but looks like you decided to stick to type 1 and 2.].

While 18 models are possible, I could run 11 models with the available computational resources. The complete list of the models is given in Table 2.

Table 1: Summary of 3D Model Parameters

Number	Variable	Description	Value	Units
1	$W_{dike}$	Dike width	2	km
2	$D_{dike}$	Dike depth	8	km
3	$H$	Crustal thickness at dike	6	km
4	$dT/dy$	Crustal thermal gradient	40	K/km
5	$T_1$	Temperature at lower boundary of crust	240	°C
6	$g$	Gravity acceleration	10	m/s <sup>2</sup>
7	$demf$	Dimensionless force damping factor	0.8	N/A
8	$dt$	Time step	1.5768e+07	second
9	$topokappa$	Parameter for topography smoothing	0	N/A
10	$shadowDepth$	Ghost elements for parallel computing	2	N/A
11	$meshI$	Mesh number in X direction	60	N/A
12	$meshJ$	Mesh number in Y direction	20	N/A
13	$meshK$	Mesh number in Z direction	20	N/A
14	$L_I$	Length in X direction	20	km
15	$L_J$	Length in Y direction	20	km
16	$L_K$	Length in Z direction	20	km
17	$\rho$	Density	3000	kg/m <sup>3</sup>
18	$\lambda$	Lamé's constant	30	Gpa
19	$\mu$	Shear modulus	30	Gpa
20	$refvisc$	Reference viscosity	0.125e-17	Pa <sup>-n</sup> /s
21	$activationE$	Activation Energy	276.0e+3	kJ/mol
22	$vis_{min}$	viscosity minimum cutoff	1.0e+18	Pa * s
23	$vis_{max}$	viscosity maximum cutoff	1.0e+27	Pa * s
24	$srexponent$	Power of power law in viscosity	3.05	N/A
25	$\varepsilon_{p_i}^1$	initial plastic strain for piecewise Type 1 weakening	0	N/A
26	$\varepsilon_{p_i}^2$	initial plastic strain for piecewise Type 2 weakening	0	N/A
27	$\varepsilon_{p_e}^1$	end plastic strain for piecewise Type 1 weakening	0.1	N/A
28	$\varepsilon_{p_e}^2$	end plastic strain for piecewise Type 2 weakening	0.33	N/A
29	$C_i$	initial Cohesion for piecewise weakening	44	Mpa
30	$C_e$	end Cohesion for piecewise weakening	4	Mpa
31	$\phi$	Friction angle	30	°
32	$remesh_{timestep}$	Remesh when timestep reach its value	400000	N/A
33	$remesh_{length}$	Remesh when the global minimum of the ratio of the volume of a tetrahedron to one of its surface area	0.6	N/A
34	$topTemp$	Surface temperature	0	°C
35	$bottomTemp$	Bottom temperature	1300	°C
36	$V_x$	Half spreading rate	7.9e-10	m/s

Table 2: List of 3D numerical experiments.

Model	M range	Functional Form	Type of weakening	For short
1	0.2-0.8	Linear	Type 1	M28LinT1
2	0.2-0.8	Sinusoidal	Type 1	M28SinT1
3	0.2-0.8	Square Root	Type 1	M28SqrtT1
4	0.5-0.7	Linear	Type 1	M57LinT1
5	0.5-0.7	Sinusoidal	Type 1	M57SinT1
6	0.5-0.7	Sinusoidal	Type 2	M57SinT2
7	0.5-0.7	Square Root	Type 2	M57SqrtT2
8	0.5-0.8	Sinusoidal	Type 1	M58SinT1
9	0.5-0.8	Sinusoidal	Type 2	M58SinT2
10	0.5-0.8	Square Root	Type 1	M58SqrtT1
11	0.5-0.8	Square Root	Type 2	M58SqrtT2

### 3 Results

#### 3.1 Reference model

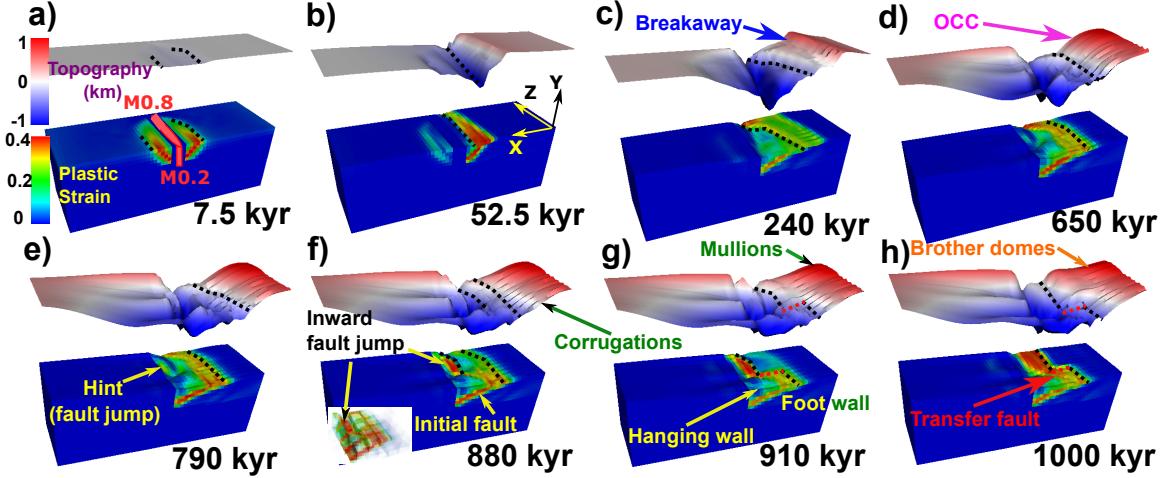


Figure 8: Evolution of plastic strain and surface topography of the reference model M28LinT1. Each snapshot shows plastic strain plotted on the model domain, the five times exaggerated topography and the time at which it is taken. The initial seafloor is at 0 km of elevation. The black dashed lines are the terminations of faults. The red dashed lines in g) and h) are the transfer faults that connect the terminations. The inset in f) plots plastic strain with opacity linearly proportional to plastic strain value.

I consider the model with  $M$  varying linearly from 0.2 to 0.8 along the ridge axis with type 1 weakening rate as the reference model and denote it as M28LinT1 following the shorthand notations given in Table??<sup>EC</sup>: [I couldn't make this reference work... Please take care of it.]. I describe the general model behaviors in this section and then provide details and mechanisms of the major structural features of the model in the next section.

For the first 7.5 kyr (Figure 8.a), normal faults, represented by localized plastic strain, begin to form near the ridge axis. Because stresses due to plate extension accumulate faster at the lower  $M$  side than at the higher  $M$  side, faults first initiate at the lower  $M$  side and then propagate to the higher  $M$  side. Such an asynchronous initiation of faults along the ridge axis creates offset in breakaway at later stages. Likewise, the model produces a median valley that widens and deepens with rates inversely proportional to the  $M$  value (i.e. rate of local magma supply) (Fig. 8a-c).

By 52.5 kyr (Figure 8.b), the normal fault on the right hand side of the ridge axis remains active while the one on the left becomes inactive. The upper part of the active fault plane (shown as plastic strain in the model) is exposed to the seafloor.

The active normal fault on the right rotates to a lower dip of  $\sim 30^\circ$  at the root of the fault and to  $\sim 0^\circ$  at the exposed fault interface after about 240 kyrs (Fig. 8.c). However, the normal fault at the higher M side (especially for  $M > 0.7$ ) experiences less fault rotation and the termination of the fault is closer to the ridge axis. The maximum relief between the breakaway and the EC: trough [Mark this on Fig. 8.] inside the EC: median valley [Mark this on Fig. 8.] becomes larger than 1 km. In addition,  $\sim 2$  km wavelength EC: corrugations [Since you mention this here first, you should mark it on Fig. 8c, not on 8f.] begin to form between the breakaway and termination at the lower M side ( $M < 0.3$ ). I discuss the formation mechanism for the corrugations in Discussion.

By 650 kyr (Figure 8.d), the detachment fault reaches its lowest dip angle and its termination stops moving away from the ridge axis. The original breakaway of this detachment has already moved out of the model domain. The total fault offset at this point is greater than the thickness of the crust and thus would be sufficient for exhuming the upper mantle materials.

A new near-axis fault first appears at the center of the model domain with  $M \in (0.5, 0.65)$  and then propagates in a positive  $z$  direction (Fig. 8.d,e). At this time, the initial detachment fault is still active and takes up most of the extension.

The new near-axis normal fault at the higher M side cuts through the hanging wall of the detachment fault at 880 kyr (Fig. 8.f). It coexists with the initial detachment fault and begins to accommodate most of the intra-plate extension. This event is called the “inward fault jump” [Tucholke et al., 1998; Dick et al., 2008].

By 910 kyr (Fig. 8.g), the inward fault jump completes in the  $M > 0.5$  region: the new high-angle fault takes up all the extension and the initial detachment fault becomes completely inactive. The block that was previously a hanging wall to the detachment becomes

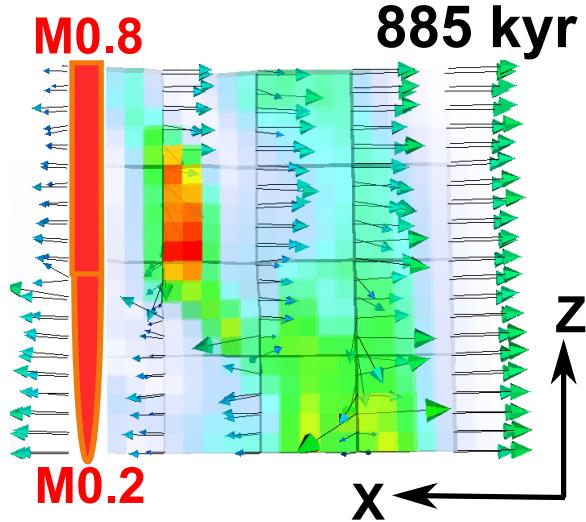


Figure 9: Bird's-eye view of velocity field with plastic strain plotted with opacity linearly proportional to its value. (color scale is the same as Figure 8.a))

a footwall of the new fault, passively moving with the plate to the negative  $x$ -axis direction. At the lower M side, the detachments is still active and the hanging wall continues to move toward the positive  $x$ -axis direction (Figure 9). This opposite sense of relative motions between the high and the low M side produces a region of dextral shear and eventually creates a transfer fault (Fig. 8.h). As the inward jumped fault evolves, another dome adjacent to the initial OCC is produced at the higher M side by 1000 kyr<sup>EC:</sup> [Not sure if What the arrow points to is really another dome.].

### 3.1.1 Constant M model M88ConT2

<sup>XT:</sup> I still prefer to have M88ConT2 because: 1. As a comparison to the varying M model, it help to show the importance of M variation (corrugation, mullion, median valley variation, inward fault jump etc. 2. it itself is a mode of MORs topography formation mechanism, those higher frequency symmetrical abyssal hills. <sup>EC:</sup> I don't agree. This section can be simply summarized as, "a constant M shows similar behaviors with a corresponding 2D model from the previous studies and (obviously) does not show along-ridge variations in terms of morphology and faulting". If you really want, say something like this upfront, like, where you first introduce the reference model.

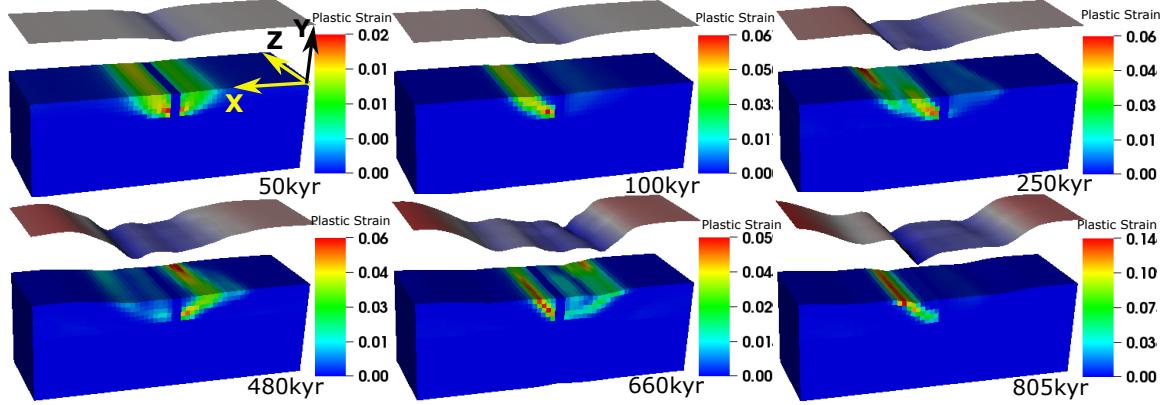


Figure 10: Evolution of plastic strain and surface topography of the model: M88ConT2 (Table 2). (color scale of topography is the same as Figure 8.a)

As a comparison to the varying M models, a constant M model is run.

As shown in Figure 10, model M88ConT2 produces a  $\sim 20$  km wide and  $1\sim 2$  km deep median valley, which is similar to the generally observation of the Mid-Atlantic Ridges. The width and depth of the median valley is almost constant along the ridge as contrast to the varying M models. The variation of the location of the breakaway and termination along the ridge that is mentioned in the reference model (M28LinT1) does not show up. Because the magma supply is constant along the ridge with  $M = 0.8$ , there is no stress perturbation along the ridge. Thus, the normal faults along the ridge initiate at the same time and the slipping rate of the fault is also constant along the ridge axis. The synchronized fault initiation results in no offset between breakaways and the constant slipping rate produces no along ridge axis variation in the position of the termination. In addition, neither corrugations nor mullion structures are generated. Normal faults alternate on each side of the ridge axis with a period of  $\sim 300$  kyr due to the mechanism mentioned in the “Introduction” section for the 2D models of  $M > 0.5$ . This fault alternation produces symmetrical high frequency abyssal hills. For 3D models, why and how fault alternates on each side of the ridge axis is different from the previous 2D studies and is described in the following sections.

### 3.2 Main structural characteristics

I identify seven features that are identified in the reference model and found common to most of the models: Location of the termination, geometry of the trough, inward fault jump, fault alternation, mass wasting, hourglass-shaped median valley and corrugations and mullion structures. Since the details of these features differ among the models, they are useful for delineating and contrasting complicated model behaviors.

#### 3.2.1 Location of termination

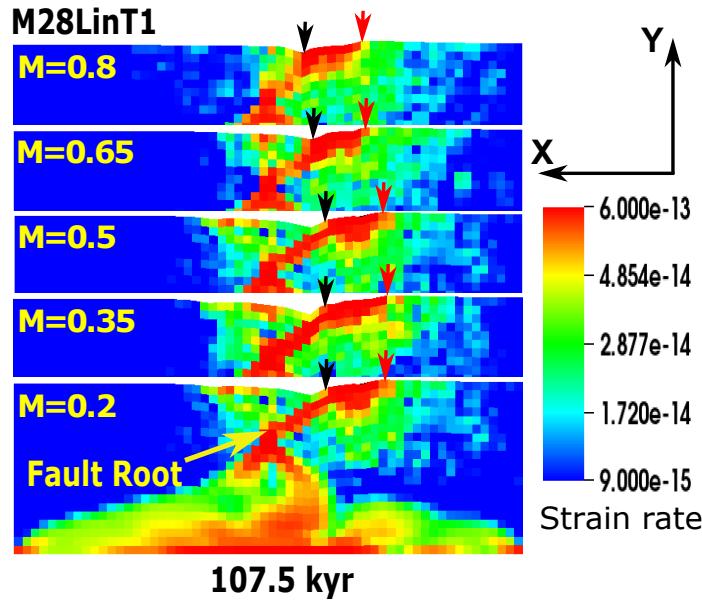


Figure 11: The second invariant of strain rates plotted on the reference model's vertical cross-sections along the ridge at 107.5 kyr. Terminations and breakaways are marked by black and red arrows.

Location of a fault termination varies along the ridge as faulting behaviors change according to the variation in  $M$  values, as shown by black dashed lines in Figure 8 and black arrows in Figure 11). When  $M \leq 0.5$ , the distance between the termination and the ridge axis as well as the dip angle of the fault are similar. Because the rotation rate of the detachment fault is determined by how fast the termination moves away from the fault root. Since the detachment faults for the ridge region of  $M < 0.5$  root at the same place

at the intersection between the center dike and the brittle-ductile transition (BDT) and the moving rate of the termination has a maximum value that is restricted by the far field extension rate  $V_x$ , the distances between the terminations and fault roots of the detachment faults is similar among the three slices of  $M \leq 0.5$ . In addition, in order to spend least frictional energy during faulting, the detachment fault interface between the two ends (termination and fault root) tends to be a straight line. Thus, the dip angle of the detachment fault is inversely proportional to the distance between the termination and the root of the fault when  $M < 0.5$ . Since the termination at the lower M side ( $M < 0.5$ ) moves with the spreading plate with same velocity  $V_x$ , and the initiation time difference of the normal faults at the lower M side is similar (Figure 8.a), the distances between the terminations and the roots of the faults are the same. Thus the dip angles as well as the distance between the termination and the ridge axis of the faults at the lower M side are similar. However, when  $M > 0.5$  (Figure 11, (M = 0.65, 0.8)), the amount of fault slip decreases as M increases. The crust at the footwall experiences less bending and the detachment fault remains in a higher angle as well as that the terminations are closer to the ridge axis. Because the root of the fault is slowly pushed away from ridge axis while the termination of the faults are closer to ridge axis due to a later initiation of the fault. One thing needs to be noted is that the trough at the higher M side correspond to the terminations but detached from the terminations at the low M side ( $M < 0.5$ ) as shown in Figure 11.

### 3.2.2 Geometry of trough

The depressed narrow region that develops in the median valley is termed as “trough”. The reference model showed that its shape in the map view evolves from a straight line parallel to the ridge axis to a line oblique to the ridge axis (Figure ??). Initially, the trough along the ridge corresponds to the termination. However, at the lower M side ( $M < 0.5$ ), as the normal fault rotates to a lower dip at the lower M side, the trough is no longer coincident with the fault termination and is moving slowly to the left because the hanging wall

is pulled by the conjugate plate. However, the trough on the higher M side ( $M > 0.5$ ) is pushed away from the ridge axis [Tucholke et al., 2008]. But since the trough cannot bypass the termination, the trough at  $M = 0.8$  is restricted closer to the ridge axis. Together it generates the curved shape of the trough (Figure ??).

### 3.2.3 Inward fault jump

The inward fault jump occurs in all the models when an old fault locks and a new one forms near the ridge axis (e.g., Fig. 8). *<sup>XT</sup>:for the description of the previous commented out paragraph, please refer to:[Lavier et al., 2000; Olive et al., 2014]*

The new fault usually forms on the high M side first and it connects to the existing detachment developing on the lower M side ( $M < 0.5$ ), producing a curved fault termination. Unlike fault alternation, the inward fault jump occurs on the same side of the ridge axis with its along-axis extent corresponds to the  $M > 0.5$  region.

### 3.2.4 Fault alternation

When  $M$  is high enough, a normal fault first forms on one side of the ridge axis but another fault forms on the other side when the first one locks (Fig. 10) [Buck et al., 2005, Tucholke et al., 2008]. This behavior is termed as “fault alternation”.

### 3.2.5 Mass wasting

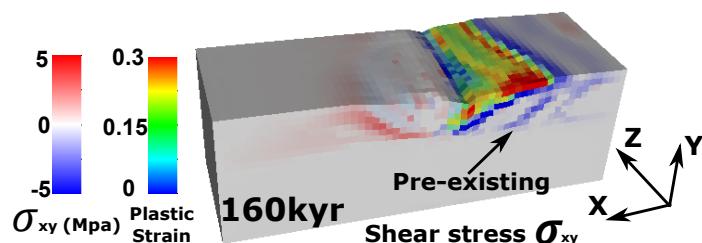


Figure 12: The weak detachment fault tip reaches the pre-existing shear stress. Plastic strain is plotted with opacity linearly proportional to its value.

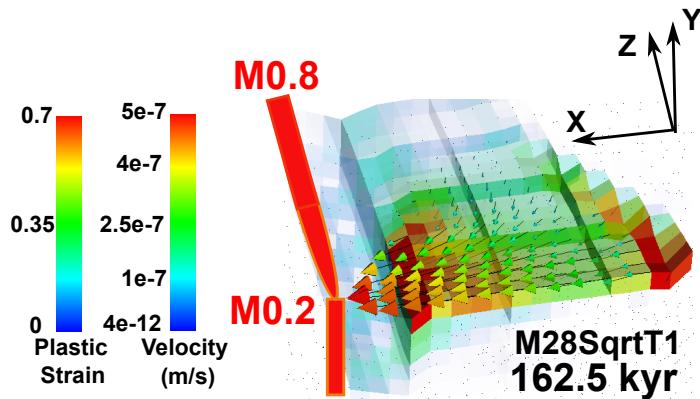


Figure 13: Velocity of the mass wasting hanging wall. Magnitudes of the velocity are shown by the colors of the arrow heads. Plastic strain is plotted with opacity linearly proportional to its value.

Mass wasting occurs on the exposed surface of a low-angle normal fault. When a layer of weak fault interface becomes gravitationally unstable and is detached from the underlying material, the detached layer flows towards the ridge axis and the lower M side with a velocity  $\sim 10$  times faster than the half spreading rate (Figure 13; Figure 14.b,e (first row))). The mass wasting produces a continuous fault scarp with a relief of  $\sim 1$  km along the initial breakaway.

Immediately after an event of mass wasting, the fault trace jumps towards the ridge axis (Figure 14.d versus f (third row: plastic strain)). Then,  $\sigma_{xy}$  and  $\sigma_{xz}$  soon <sup>EC:</sup> fill in the area [What do you mean by “stresses filling an area”?] between cut-back created fault scarp and the new termination (Figure 14.f (fourth and fifth row:  $\sigma_{xy}$  and  $\sigma_{xz}$ )). <sup>EC:</sup> [don’t understand the rest of this paragraph.] After that, the termination at the higher M side extends faster and further than the lower M side (Figure 17.a~d). This is because during the cut-back, tensional stress due to bending is released at the lower M side but continues to accumulate at the higher M side. At the lower M side, it needs time to reach the previous tensional stress state and then starts from there to pull the new termination away from the ridge axis. While at the higher M side the increasing tensional stress directly leads to a fast extending termination.

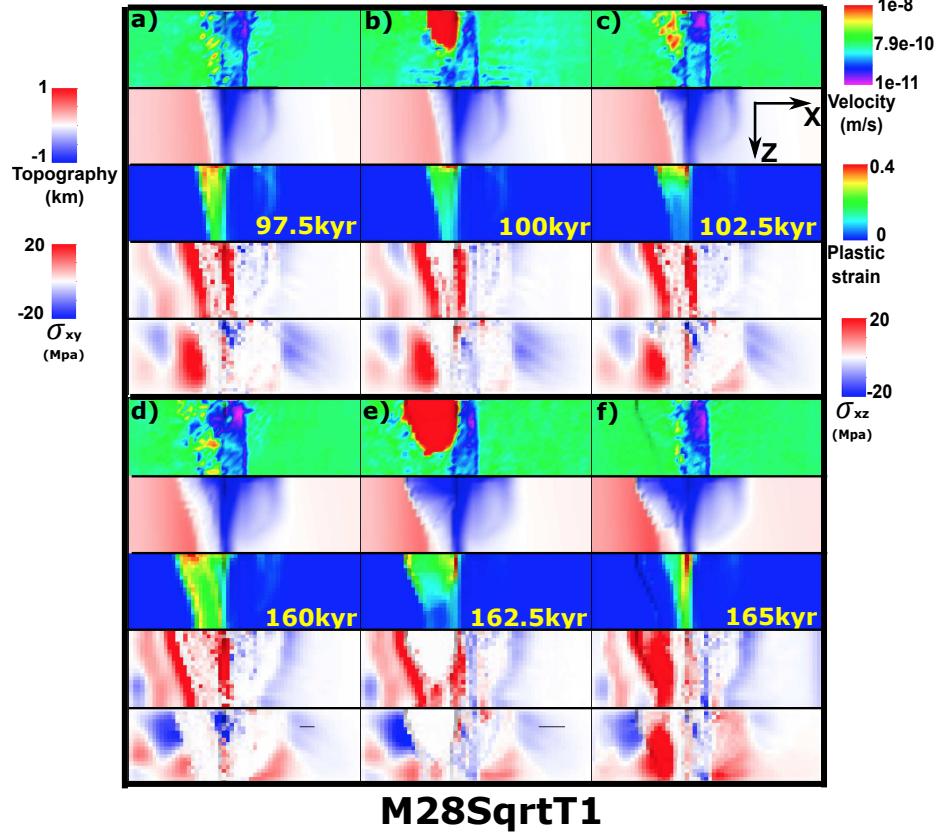


Figure 14: Plastic strain, topography and stresses evolution for M28SqrtT1.

### 3.2.6 Hourglass-shaped median valley

A median valley takes a hourglass shape whenever  $M$  varies along the ridge. The hourglass shapes vary with time and the functional form of  $M$  variation. A median valley initially has similar width along the ridge but is deeper on the lower  $M$  side where normal faults first form. By  $\sim 100$  kyr (Figure 18.b), the fault on the negative  $x$ -axis direction of the ridge axis doesn't propagate to the higher  $M$  side of the ridge and becomes inactive. It produces a depressed topography curve following the inactive fault trace, which is further away from the ridge axis at the lower  $M$  side but closer to ridge axis at the higher  $M$  side. On the other side of the ridge axis, as the active fault rotates to a lower dip angle, it generates breakaways that are further away from the ridge axis at the lower  $M$  side while closer to the ridge axis at the higher  $M$  side. This along ridge variation in the location of the breakaways act as another boundary of the hourglass. Both boundaries are extended

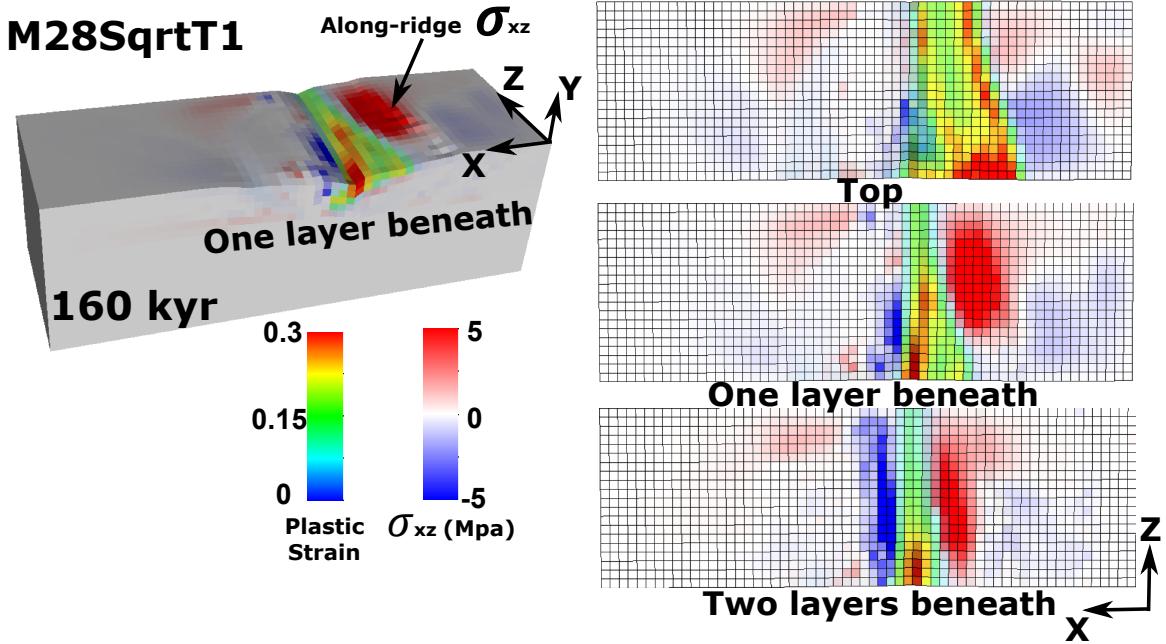


Figure 15: Along ridge axis  $\sigma_{xz}$  (bird's-eye view of three layers of model domain) (positive(red) means clockwise). Plastic strain is plotted with opacity linearly proportional to its value.

following the spreading plates. By  $\sim 170$  kyr (Figure 18.c), the hourglass become wider and deeper. Since the area of the cross-section along the ridge inside the hourglass shape median valley is approximately inversely proportional to the local M values, the shape of the hourglass varies with different M variations.

The further depression inside the median valley is mostly due to the elastic deformation from crustal extension. As shown in Figure 19, the  $\sigma_{xx}$  in the median valley is higher because that the brittle crust is the thinnest at the median valley, when same amount of force propagates from far field extension to the median valley, the stress increases. This increased  $\sigma_{xx}$  is responsible for the further depression and extension of the median valley on the negative  $x$ -axis direction of the ridge axis (Figure 18.d). For the median valley on the other side of the ridge axis, cut-back triggered mass wasting between the breakaways and the ridge axis results in the further lowering in topography (Figure 14.d versus e (topography)).

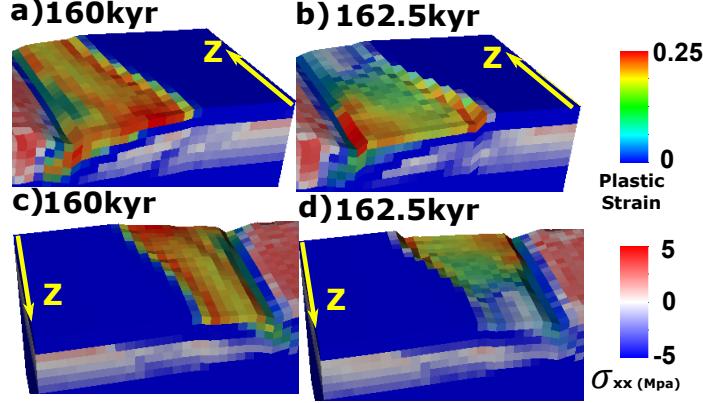


Figure 16: M28SqrtT1 (Table 2). Bending stress drop (a versus b) at the lower M side due to the cut-back. No bending stress drop (c versus d) at the higher M side as a comparison.

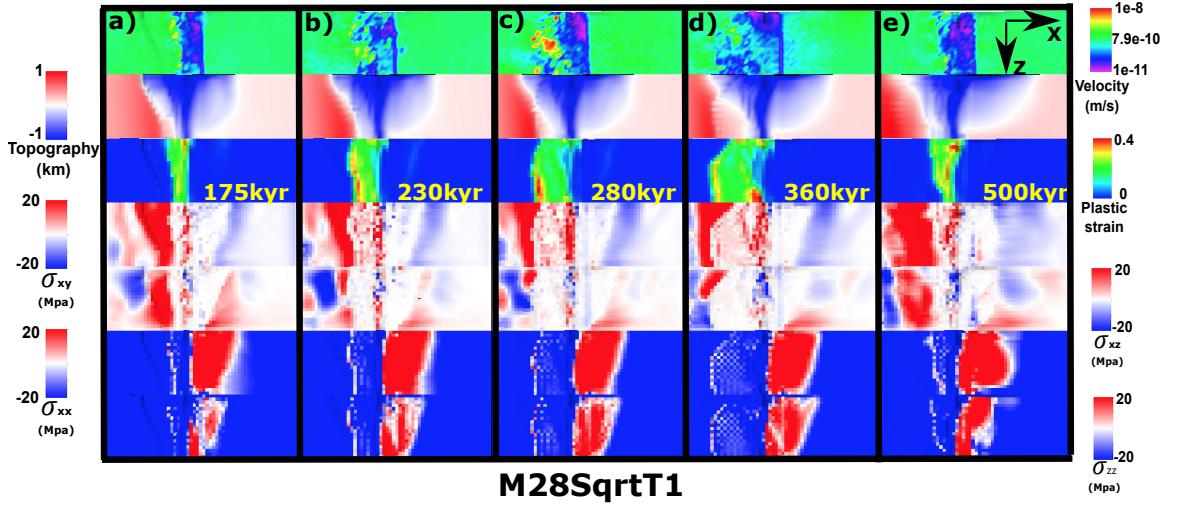


Figure 17: New fault front chase after cut-back.

### 3.2.7 Corrugations and mullion structures

Both corrugations and mullion structures are linear structures parallel to the spreading direction. As shown in Figure 8.f, at the  $M < 0.5$  area on top of the OCC surface, corrugations show a uniform wavelength of  $\sim 2$  km with hundreds meters in amplitude. While at the higher M side of the ridge (Figure 8.g), a mullion structure of a wavelength of  $\sim 7$  km. In spite of morphological similarity, corrugations and mullion structures have different formation mechanisms.

#### Corrugations

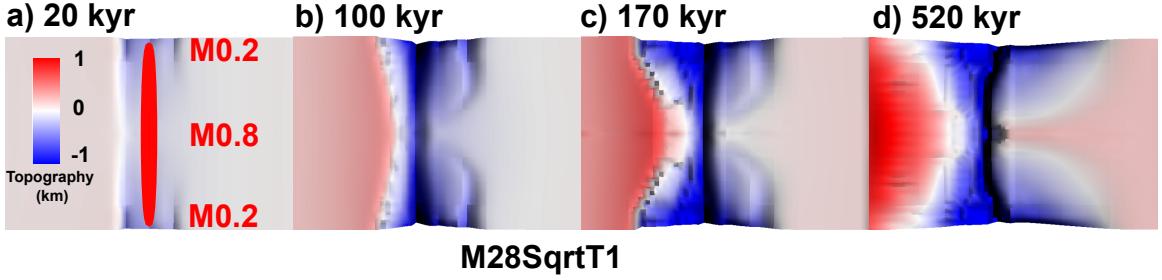


Figure 18: Bird's-eye view of the evolution of the hourglass shape median valley. It is generated by attaching the topography of the M28SqrtT1 model to its mirror reflection by assuming symmetrical M variation (0.2 to 0.8 to 0.2).

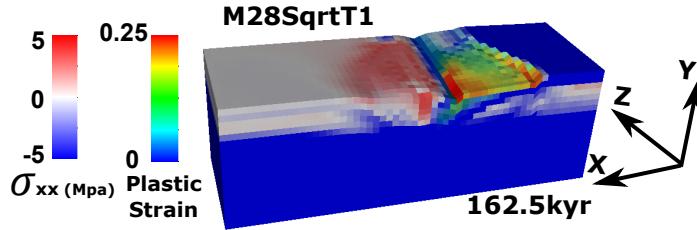


Figure 19: Higher  $\sigma_{xx}$  shows inside the median valley on the negative  $x$ -axis direction of the ridge axis.

The corrugation starts at the breakaway as a response to tensile stress in the  $z$ -axis direction. As shown in Figure 20, when the plastic strain reaches or exceeds 0.1 (red color), based on type 1 weakening, the cohesion decreases to 4 MPa. With a  $30^\circ$  friction angle, tensile failure is declared when the  $\sigma_{zz}$  reaches  $\sim 7$  MPa (yellow color). The tensile stress is due to the asynchronous faulting along the ridge. Faulting initiates earlier at the lower M side of the ridge. As the fault offsets more on the low M side than on the high M side, the footwall of the fault rotates and gets uplifted more on the low M side. The footwalls along the ridge generate the isochron-parallel tectonic stress  $\sigma_{zz}$ . Since  $\sigma_{zz}$  follows along the moving tip of the plastic strain, the plastic strain together with  $\sigma_{zz}$  generate tensile failure that extends away from the ridge axis and thus produces the linear corrugations that are parallel to the spreading velocity. Detail analysis along with simpler model experiments are given in the “Discussion” section.

## Mullion structures

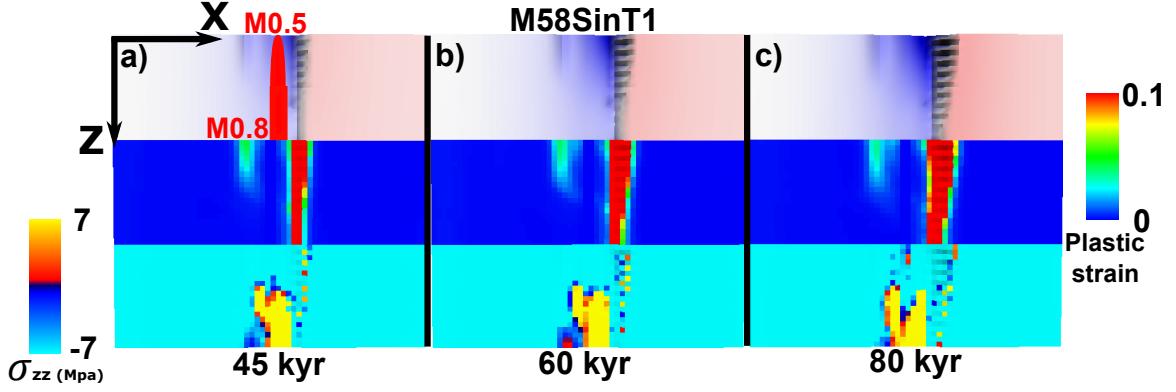


Figure 20: Bird's-eye view of the evolution of the corrugations. Color scales for the topography is the same as Figure 8.

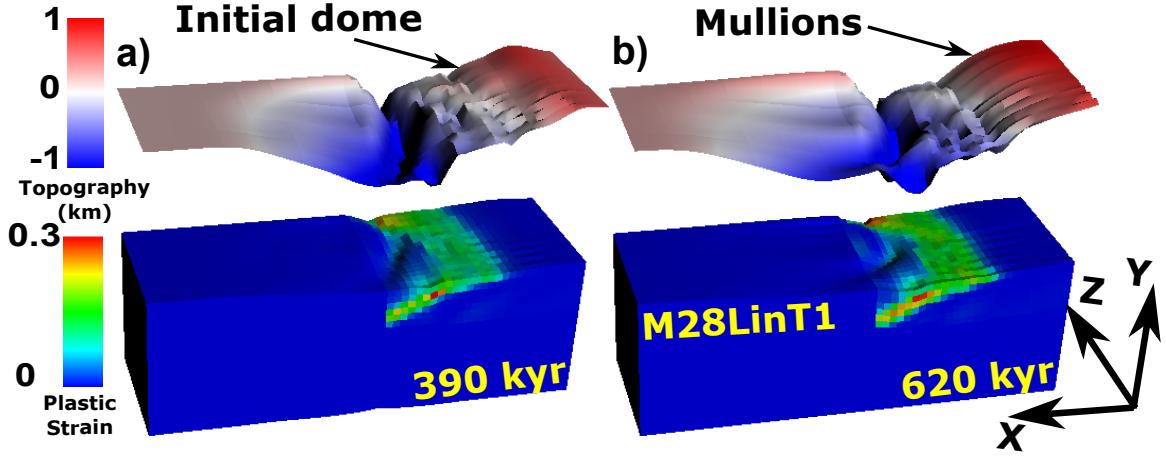


Figure 21: Evolution of mullion structures.

Mullion structures observed in the models are formed by the along ridge variation in the location of the termination due to the evolution of faulting. They usually appear at where the termination is closer to the ridge axis. The shape of the footwall follows the trace of the termination as it is exhumed to the surface. At where the termination is bent inward to the ridge axis, an “initial dome” (Figure 21.a)) is produced once the hanging wall is exhumed to the seafloor. The wavelength of the mullion structure is determined by the shape of the termination. If the pattern of the termination lasts for a long time and the footwall of the detachment fault keeps being exhumed to the surface following the trace of the detachment fault termination, a mullion structure is produced (Figure 21.b)).

### 3.3 Effects of the functional forms of M variation

#### 3.3.1 M28(Lin, Sin, Sqrt)T1

Comparing M28LinT1, M28SinT1 and M28SqrtT1, major differences lie in the model behaviors of the “inward fault jump”, the “cut-back” and the “hourglass shape median valley”. All three models have no fault alternation.

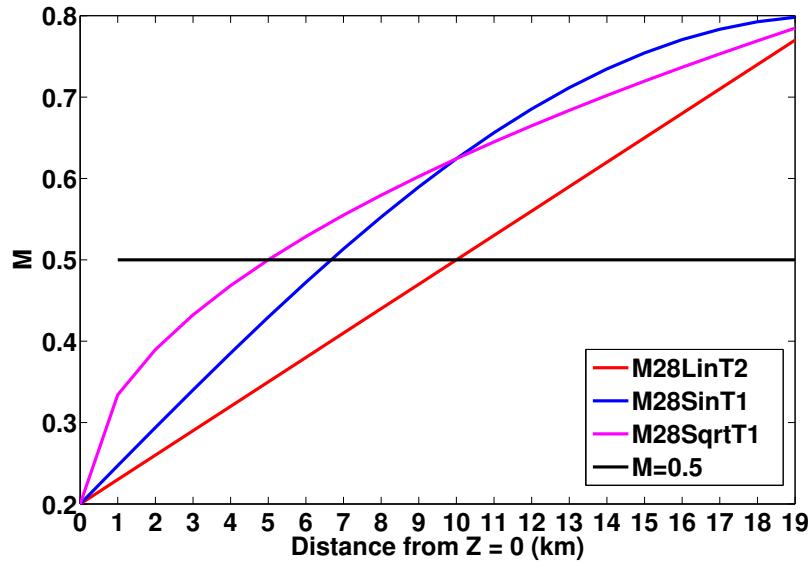


Figure 22: Three functional forms of M variation. M begins to exceed the  $M = 0.5$  black line at  $Z=10$  km, 7 km, 5 km for M28LinT1, M28SinT1 and M28SqrtT1 respectively.

#### Inward fault jump

Only linear and sinusoidal models have inward fault jump. Square root model shows no inward fault jump because during cut-back, termination of the detachment fault retreats backward toward the ridge axis and the detachment fault is maintained near the ridge axis.

Between linear and sinusoidal models, timing and dimension of the inward jumping faults are different. For the linear functional form, the inward fault jump at the higher M side starts accommodating most of the extension at  $\sim 900$  kyr and replaces the initial detachment fault (Figure 23, Figure 8.f). It nucleates from the ridge center where  $M = 0.5$

and then propagates to the  $M = 0.8$  end with a length of  $\sim 11$  km. For the sinusoidal functional form, the inward fault jump takes the place of the initial detachment fault earlier at  $\sim 550$  kyr with a length of  $\sim 14$  km (Figure 23).

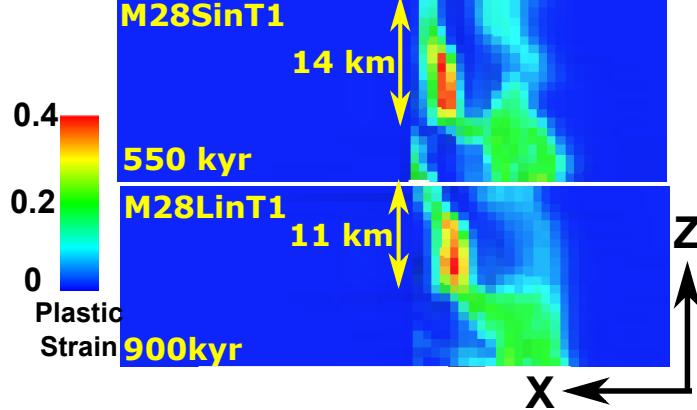


Figure 23: Bird's-eye view for comparing the length and timing of inward fault jump.

The timing difference between the linear and sinusoidal models is because M28SinT1 consistently has a higher  $M$  values than the M28LinT1 (Figure 22), which results in that the initial detachment fault at the higher  $M$  side ( $M > 0.5$ ) of M28SinT1 is pushed off axis faster than M28LinT1 and thus forming an earlier inward fault jump. The length difference is because M28SinT1 has a greater length along the ridge axis of  $M \geq 0.5$  (Figure 22).

### Cut-back

Cut-back only happens in the M28SqrtT1 model. Qualitatively, it is because M28Sqrt has a much higher value of  $\frac{\partial M}{\partial Z}$  at the lower  $M$  side (Figure 24), which implies a larger along ridge shear stress  $\sigma_{xz}$  as well as a larger difference in  $\sigma_{xy}$  along the ridge that result in the decoupling between the higher and lower  $M$  sides hanging walls.

### Hourglass shape median valley

As shown in Figure 25, differences among the three models are identified. At 160 kyr, median valley for M28SinT1 has the smallest cross-section ( $x-y$ ) area at the higher  $M$

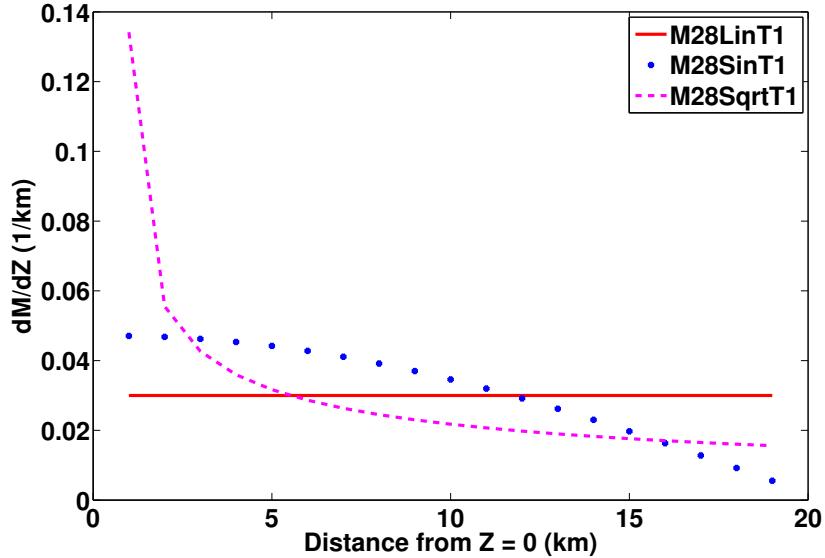


Figure 24:  $\partial M / \partial Z$  comparision.

side. While at the lower M side, M28SqrtT1 has the smallest area of the cross-section. This is because the cross-section area inside the median valley is inversely proportional to the local M value along the ridge. Moreover, the breakaways at the lower M sides for M28LinT1 and M28SinT1 bend to parallel to the ridge axis while the breakaway for M28SqrtT1 extends further away from the ridge axis. In addition, M28SinT1 has a trough inside the median valley with the highest curvature. At 500 kyr, M28SinT1 has the narrowest median valley at the higher M side and the high topography zone on the left hand side of the ridge axis is the widest. Integrating the topography at the left hand side of the ridge axis of the three models, M28Sqrt has the largest value of integration since it has the largest integration of M along the ridge axis. In addition, the termination of the detachment fault of M28SqrtT1 has the highest curvature at the lower M sides. All these observations correspond to the M variation (Figure 22).

### 3.3.2 M58(Lin,Sin,Sqrt)T2

Among M58LinT2, M58SinT2 and M58SqrtT2, the major difference lies in whether it has “fault alternation”. Except for the constant M model M88ContT2, among all the mod-

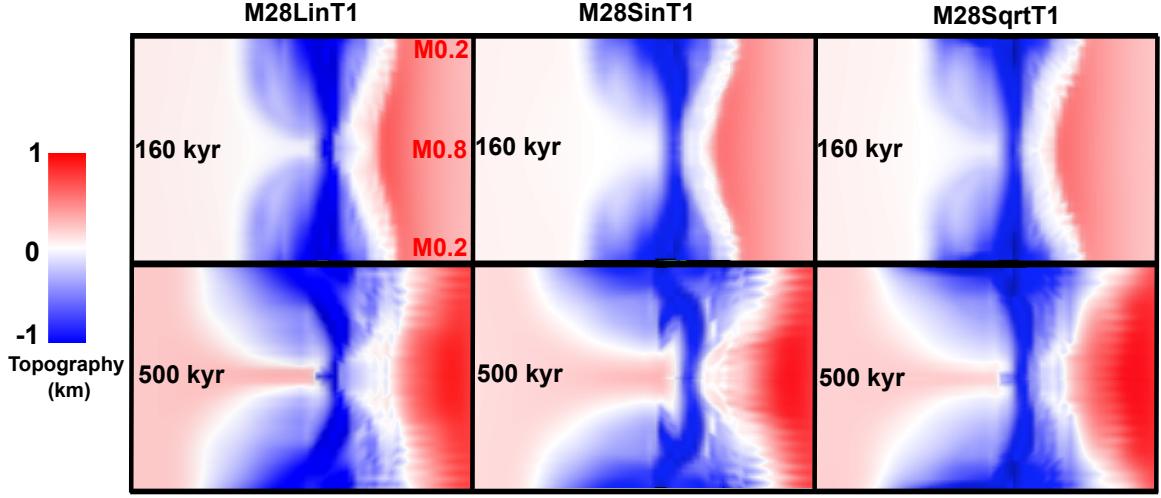


Figure 25: Bird’s-eye view of the topography. (without vertical exaggeration.)

Table 3: Average M values of the 20 km segment. (The value is calculated by integrating M along the ridge axis and divided by the length of the model domain in  $z$ -axis.)

M range Function \	M28	M57	M58
Linear	0.4850	0.5950	0.6425
Sinusoidal	0.5668	0.6223	0.6834
Square root	0.5837	0.6279	0.6918

els, only the models with type 2 weakening and M ranges from 0.5 to 0.8 (M58) have fault alternation. However, M58LinT2 does not produce alternating fault during the 1.1 Myr model time. Instead, one detachment fault lasts until  $\sim 300$  kyr when the inward fault jump happens at the higher M side ( $0.65 < M < 0.8$ ) and replaces the initial detachment fault. This provides an upper limit of average M value of the whole segment that prevent fault alternation and allows a long-lived detachment fault to produce a OCC. As shown in Table 3, the upper limit for the average M value is 0.6425 for M58LinT2. Detail analysis of the fault alternation is given in “Discussion”.

### 3.4 Effects of the weakening rate

Among the twelve 3D models, three pairs of models have both type 1 and type 2 weakening while the range of M and functional form are maintained to be the same. They are

M57SinT1/T2, M58SinT1/T2 and M58SqrtT1/T2.

### 3.4.1 M57SinT1 versus M57SinT2

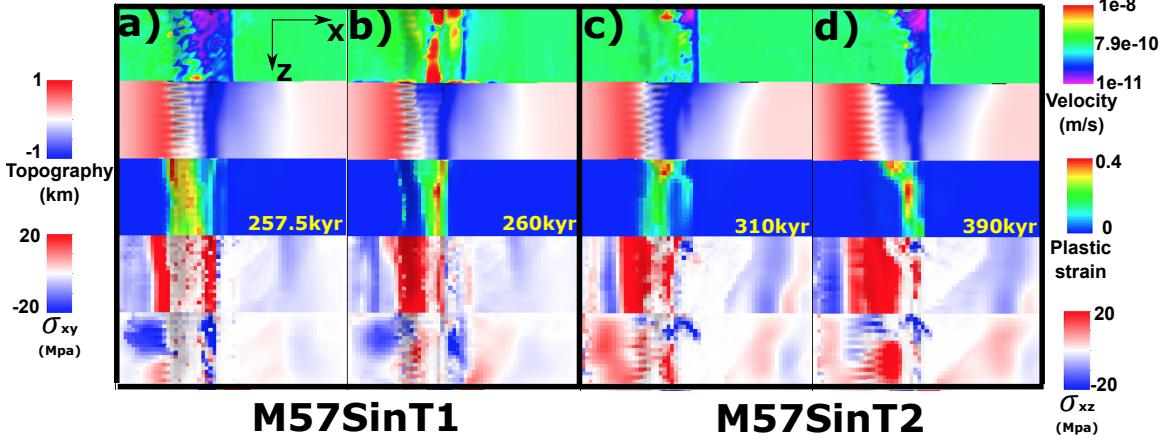


Figure 26: M57SinT2 versus M57SinT1 (Table 2)

Initially, both models develop normal faults on both sides of the ridge axis at the lower M side. In the model with the faster weakening rate (M57SinT1), faults propagate toward the higher M side and cut through the whole crust by 25 kyr but this process completes later by 50 kyr in the model with the slower weakening rate (M57SinT2). By  $\sim 310$  kyr, the inward fault jump appears at the higher M side ( $M > 0.55$ ) of M57SinT2 while at where  $M \leq 0.55$ , the initial fault remains active (Figure 26.c and d). However, when the weakening is fast (M57SinT1), cut-back happens at  $\sim 260$  kyr and helps to maintain a relative higher angle fault with a termination closer to the ridge axis. The initial fault remains, no inward fault jump forming (Figure 26.a and b). In addition, the width of median valley at the lower M side is wider for M57SinT2 than M57SinT1 (Figure 26.c, d versus a, b) because slower weakening (type 2) allows a more distributed tensional stress  $\sigma_{xx}$  rather than fast weakening that once a fault establishes, larger amount of the tensional stress  $\sigma_{xx}$  is released at the fault. The amplitude of the corrugations of M57SinT1 is larger than that of slower weakening M57SinT2. This is because faster weakening rate

allows a faster decrease in the cohesion. As the cohesion reaches its minimum of 4 MPa earlier when the plastic strain accumulates to 0.1, tensile failure is easy to happen in the isochron parallel direction and produces the corrugations.

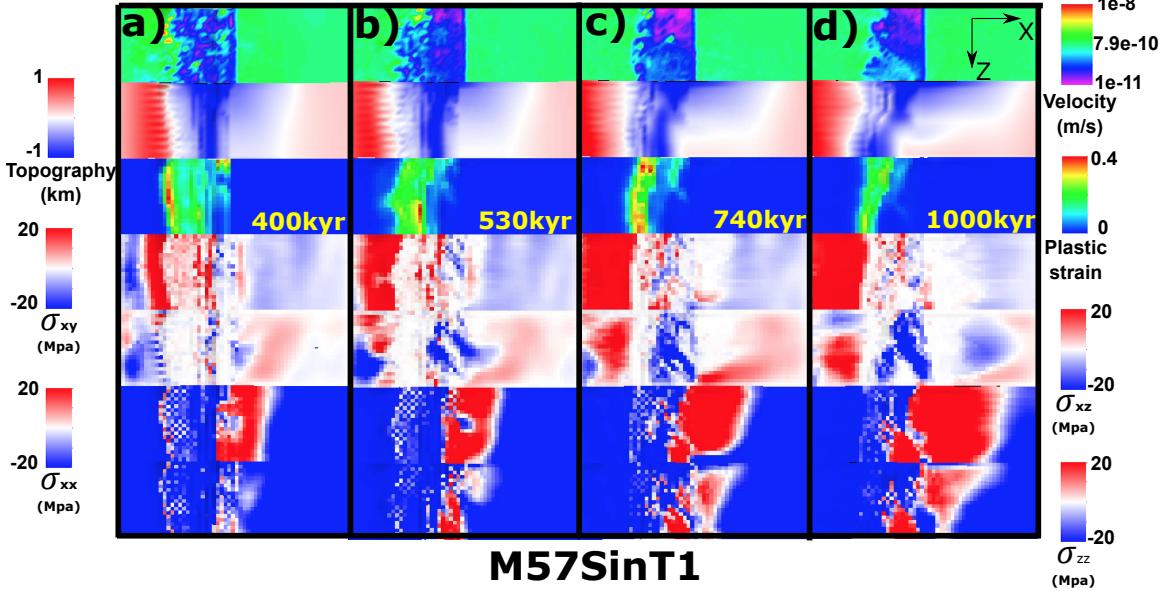


Figure 27: Faulting and stress evolution for M57SinT1.

### M57SinT1

For M57SinT1, by 400 kyr (Figure 27.a), two antithetic fault forms at the lower M side ( $0.5 < M < 0.58$ ) accommodating part of the plates extension. This makes the termination at the lower M side retreat backward to the ridge axis. The hanging walls of the antithetic faults slide down into the trough and lower the topography. By 530 kyr, the termination at the center of the ridge segment ( $M = 0.61\sim0.63$ ) extends further (Figure 27.b). This curved termination leads to a curved topography aligns with it (white curve in the second row). By 740 kyr, another antithetic fault forms at the lower M side (Figure 27.c). It doesn't take the place of initial fault and disappear soon, however, it again releases tensional stress and helps maintain a closer to ridge axis termination at the lower M side. By 1000 kyr (Figure 27.d), an Atlantiss Massif shape OCC is produced (lower M side has a wider dome and higher M side has a narrower dome) due to the along ridge termination

evolution. Corrugations with wavelength varying from hundreds to kilometers are also produced.

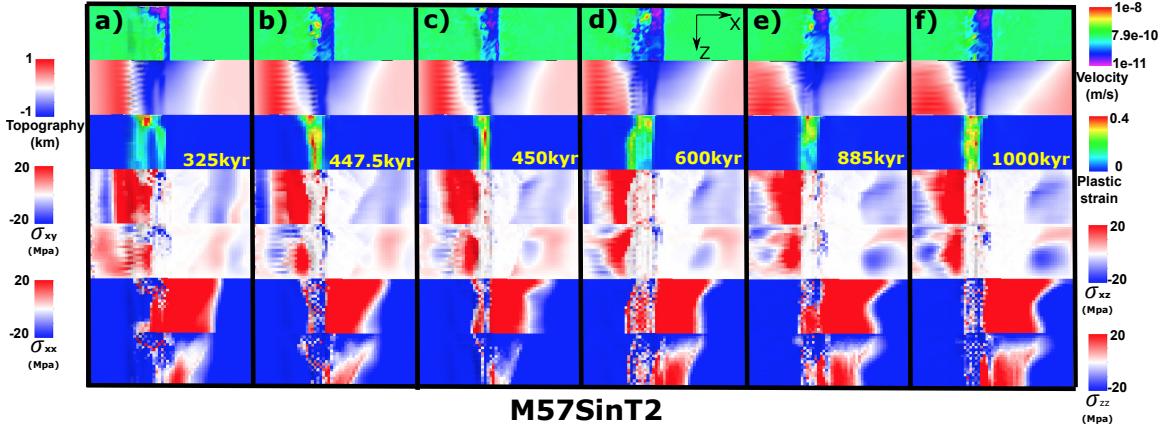


Figure 28: M57SinT2 (Table 2) faulting and stress evolution with respect to time.

## M57SinT2

For M57SinT2, instead of maintaining a detachment fault like M57SinT1, it produces inward fault jump at the higher M side. By 325 kyr (Figure 28.a), an inward fault jump happens and takes the place of the initial detachment fault at the higher M side. Between 447.5 kyr (Figure 28.b) and 450 kyr (Figure 28.c), a small scale cut-back happens and the termination recedes backward. By 600 kyr, the termination at the higher M side extends further (Figure 28.d). By 885 kyr, an inward fault jump happens at the higher M side ( $0.62 < M < 0.7$ ) (Figure 28.e). The width of the median valley at the lower M side keeps increasing due to the distributed  $\sigma_{xx}$  (Figure 28.a~d).

### 3.4.2 M58SinT1 versus M58SinT2

A major difference between M58SinT1 and M58SinT2 is that only M58SinT2 has fault alternation.

## M58SinT1

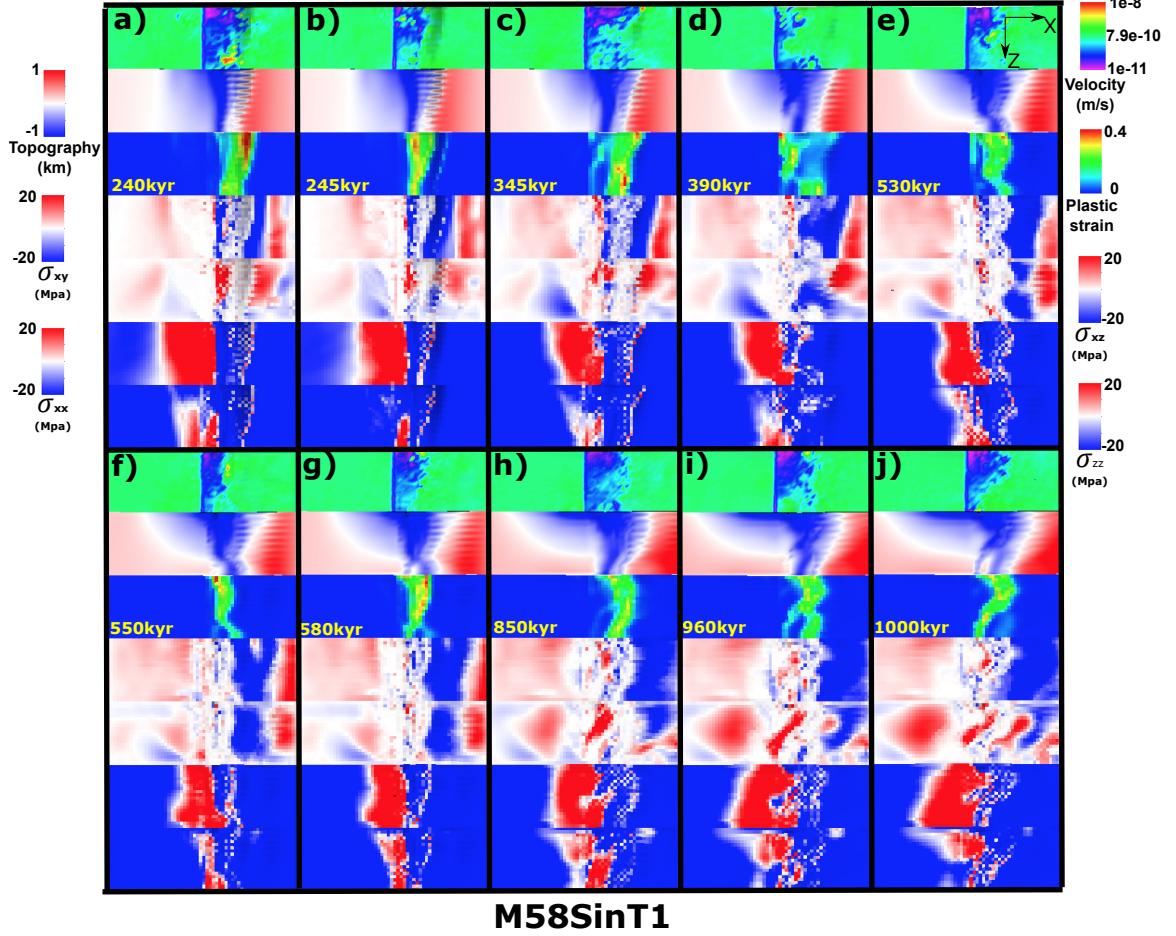


Figure 29: Faulting and stresses evolution (M58SinT1).

During the 1 Myr extension of the model M58SinT1, 10 phases of the evolution of faulting are identified (Figure 29.a~j). Antithetic faults, inward fault jumps, cut-backs happens and a rider block, corrugations and mullion structures are produced.

By 240 kyr (Figure 29.a), due to fast weakening (type 1), cohesion along the termination is low. Stress  $\sigma_{zz}$  takes the advantage and generates  $\sim 2$  km wavelength corrugations parallel to the spreading direction as the termination extends further away from the ridge axis. Between 240 kyr (Figure 29.a) and 245 kyr (Figure 29.b), a cut-back happens with mass wasting at the lower M side. The termination recedes toward the ridge axis during the cut-back. By 345 kyr (Figure 29.c), an antithetic fault forms at the lower M side ( $0.5 < M < 0.545$ ) with an inward fault jump happens at at ridge segment with  $M \in (0.575, 0.635)$  (Figure 30). 45 kyr later, the two weak zone connect to each other and take the

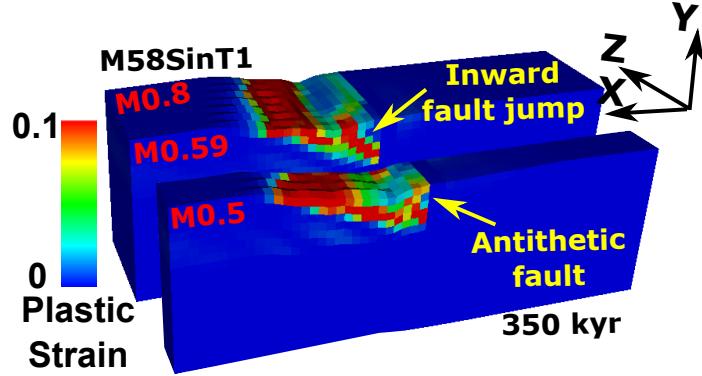


Figure 30: Plastic strain for M58SinT1 at 350 kyr.

place of the initial detachment fault at the lower M side (Figure 29.d). Due to this inward fault jump, a dextral  $\sigma_{xz}$  zone (blue area in the  $\sigma_{xz}$  panel) forms and is bounded by the termination of the inward fault jump near the ridge axis at the lower M side and the termination of the initial detachment fault at the higher M side. By 530 kyr (Figure 29.e), the termination of the inward fault jump at the lower M side evolves to a curve with its center extends further away from the ridge axis because the inward fault jump initiates at the center and starts extending away from the ridge axis earlier, however, the lower M side of the curve remains closer to the ridge axis due to the antithetic fault and the other end of the curve is also closer to the ridge axis because the fault initiates later. This curved termination at the lower M side also connects to the initial detachment fault at the higher M side which is further away from the ridge axis. Together, the curved termination is like a mirror reflected letter “S”. This flipped “S” shape termination is also reflected in topography. As the curved termination at the higher M side lasts for  $\sim 300$  kyr since  $\sim 390$  kyr, following the shape, a  $\sim 10$  km in wavelength and  $\sim 7$  km in along spreading direction mullion structure is formed (Figure 31). By  $\sim 680$  kyr, an inward fault jump happens at the higher M side ( $0.74 < M < 0.8$ ). It perturbs the curved shape termination and ceases the further exhumation of the mullion structure. This inward fault jump also produces a rider block that covers the inactive detachment fault and moves off axis following the exhuming footwall of the inward jumped fault.

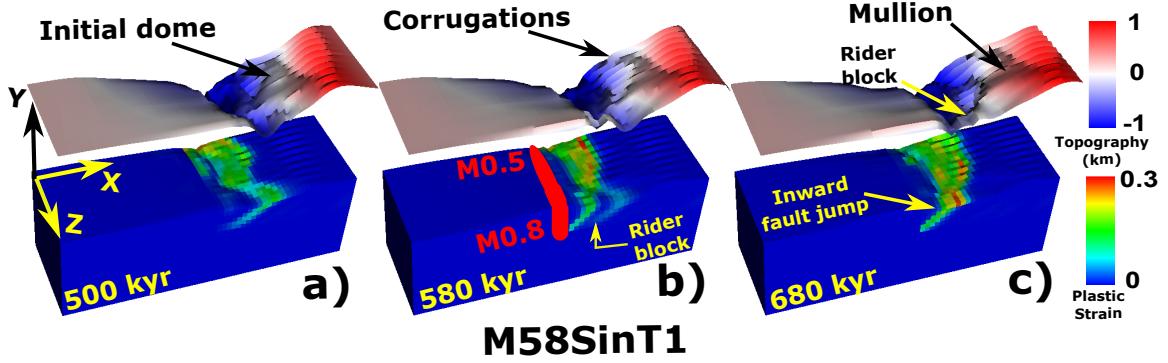


Figure 31: Evolution of faulting and morphologies of M58SinT1.

Between 530 kyr (Figure 29.e) and 550 kyr (Figure 29.f), another cut-back happens at the lower M side ( $0.5 < M < 0.545$ ) where a slump block with an area of  $\sim 9 \text{ km}^2$  flows down the topography slope into the trough. Terminations recedes backward to the ridge axis. By 580 kyr, termination at the lower M side extends further away from the ridge axis due to less magma supply. Between 580 kyr and 850 kyr, due to two antithetic faults at the lower M side ( $M \in (0.5, 0.53) \cup (0.56, 0.605)$ ), the termination at the lower M side recedes and the previous mirror reflected “S” shape termination evolves to a half circle curve (Figure 29.h). The shape is also reflected in the topography. By 960 kyr (Figure 29.i)), at the ridge segment with  $M \in (0.62, 0.665)$ , another inward fault jump replaces the detachment fault away from the ridge axis and retreats the termination backward to the ridge axis forming two half circle curves with wavelengths of around half of the model domain in  $z$ -axis. A large sinistral shear zone (red region  $\sim 40^\circ$  oblique to ridge axis) is seen in the  $\sigma_{xz}$  panel. The shear stress  $\sigma_{xz}$  results from the inward fault jump at the center of the ridge segment that previous hanging wall changes to the footwall of the inward jumped fault and generates a offset between the old hangingwall at the lower M end and the new footwall of the inward jumped fault. By 1000 kyr, due to the along ridge coupling, the inward fault jump propagates to the higher M side (Figure 29.j).

## M58SinT2

As shown in Figure 32, a fault initiates on the left hand side of the ridge axis (Fig-

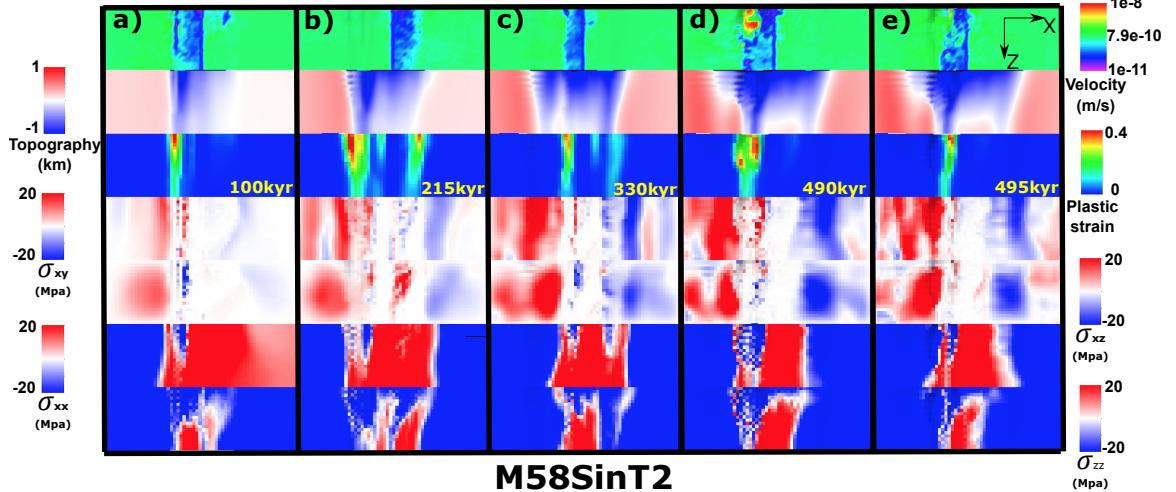


Figure 32: Faulting and stresses evolution of M58SinT2.

ure 32.a). The breakaway at the lower M side extends further than that of the higher M side. It takes longer time of  $\sim 100$  kyr to form a localized fault plane through the whole ridge segment due to the slower rate of weakening (type 2). By 215 kyr (Figure 32.b), fault alternates to the conjugate plate and gradually replaces the initial one. Corrulations are only produced at the lower M side ( $M \in (0.5, 0.62)$ ). By 330 kyr, fault alternates again. Between 490 kyr (Figure 32.d) and 495 kyr (Figure 32.e), a cut-back happens with mass wasting and termination receding. A slump block of an area of  $\sim 16$   $\text{km}^2$  flows down the topography slope into the trough. With fault alternation, the shape of the median valley is no longer an hourglass. However, at the lower M side, the median valley is still wider and deeper. High frequency abyssal hills are produced at the higher M side. In addition, M58SinT2 has a fault alternation frequency of  $\sim 150$  kyr which is higher than that of M88ConT2. <sup>XT:</sup>Reason for this difference needs further discussion.

### 3.4.3 M58SqrtT1 versus M58SqrtT2

The major difference between M58SqrtT1 and M58SqrtT2 is also whether the normal fault alternates or not.

### M58SqrtT1

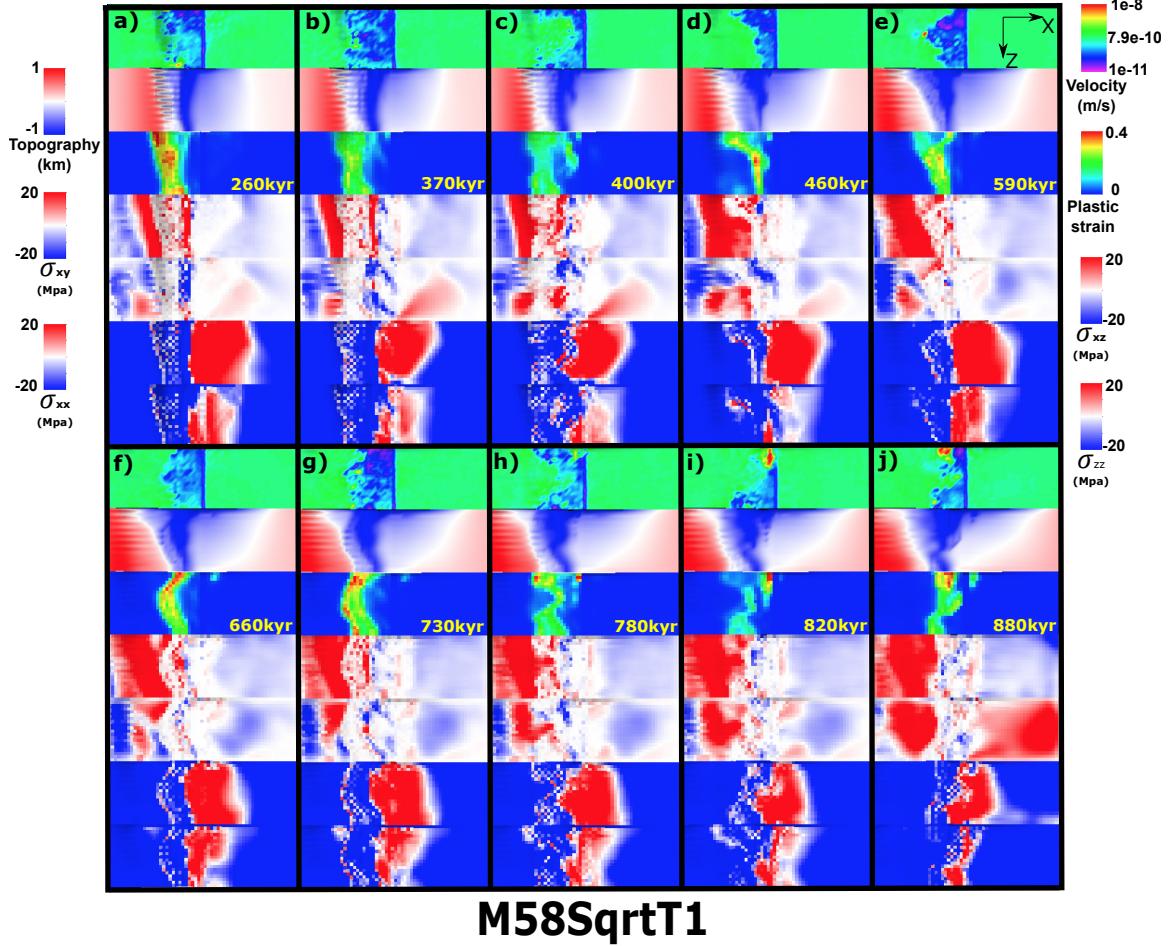


Figure 33: M58SqrtT1 (Table 2) faulting and stress evolution with respect to time.

By 260 kyr, breakaway at  $M = 0.5$  extends  $\sim 5$  km further away from the ridge axis than that of the higher  $M$  end (Figure 33.a). Corrugations of a wavelength of  $\sim 2$  km ~~XT: 2 km is the correct wavelength for corrugations, change previous wrong ones of 1 km~~ are produced along the ridge. By 370 kyr (Figure 33.b), due to larger value of  $\frac{\partial M}{\partial Z}$  at the lower  $M$  side, a vertical tensile failure takes place at  $M \in (0.5, 0.5949)$  ~~XT: previous M range for Sin and Sqrt models should be revised, I used linear to calculate with respect to number of elements in Z. Start from this and the later ones are ok~~. Two parallel dextral shear stress zones (blue) are seen in the  $\sigma_{xz}$  panel. By 400 kyr (Figure 33.c), an inward fault jump happens at where  $M \in (0.5949, 0.7121)$  and it propagates to the higher  $M$  end and replaces the initial detachment fault at the higher  $M$  side by 460 kyr (Figure 33.d). By 590

kyr (Figure 33.e), an inward fault jump happens at the lower M side ( $M < 0.5949$ ) and connect with the normal fault at the higher M side replacing the initial detachment fault. An  $\sim 18 \text{ km}^2$  triangular shape (bird's-eye view) rider block is produced at the lower M side. Termination at the center of the ridge segment extends furthest away from the ridge axis. This is because the previous inward fault jump first initiates there, so the fault starts slipping earlier and because the value of M is lower at the segment center than the higher M end. By 660 kyr (Figure 33.f), as the previous inward jumped fault at the higher M side evolves, another dome is produced. There is a hint of high angle normal fault at where  $M < 0.5949$  on the conjugate plate. But it doesn't develop. By 730 kyr (Figure 33.g), the termination evolves to a "half circle" and the shape is also seen in the topography. By 780 kyr (Figure 33.h), another inward fault jump appears at the ridge segment with  $M \in (0.6342, 0.7121)$  and produced a curved termination with a wavelength of  $\sim 10 \text{ km}$ . It has the potential to create a large wavelength mullion structure. Meanwhile, at the lower M side ( $M < 0.5949$ ) near the ridge axis, an antithetic fault forms and propagates toward the higher M side (Figure 33.i). It triggers another inward fault jump to happen at the lower M side and produces another rider block. The inward jumped fault later connects with the detachment fault at the higher M side (Figure 33.j). In addition, a tensile failure shows its hint at the lower M side ( $M < 0.6342$ ) of the conjugate plate.

## M58SqrtT2

By 195 kyr (Figure 34.a), breakaway at the lower M side extends further away from the ridge axis. Three corrugations begin to show up due to tensile failure. Median valley on the conjugate plate is wider at the lower M side because slow weakening allows a more distributed  $\sigma_{xx}$  that results in the elastic depression of the conjugate plate. Between 195 kyr (Figure 34.a) and 200 kyr (Figure 34.b), a cut-back happens with mass wasting along the ridge and is followed by the termination retreat. By 270 kyr fault alternates (Figure 34.c). The shape of the alternated fault follows the curved shape shear

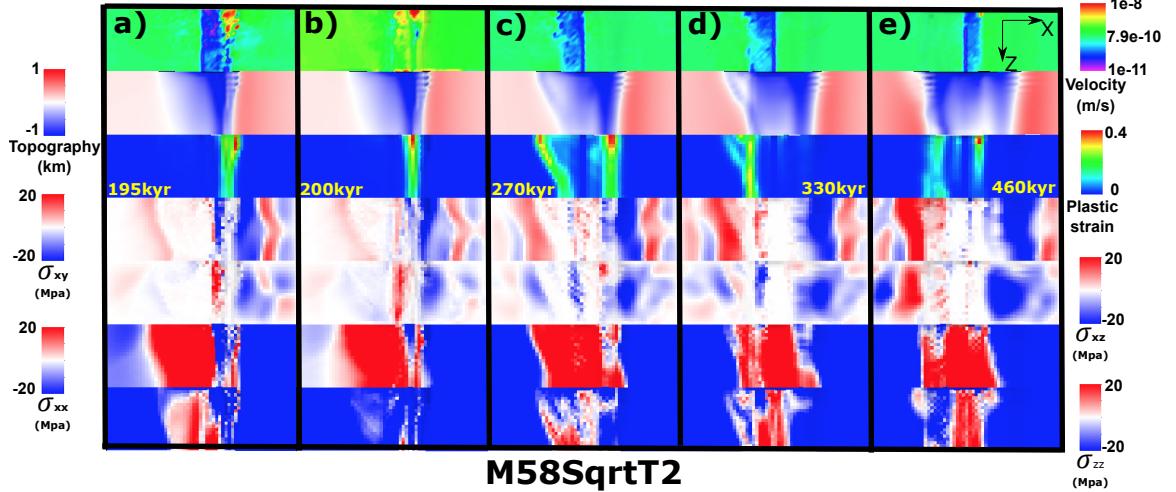


Figure 34: Faulting and stresses evolution for M58SqrtT2.

$\sigma_{xy}$  zone (red) as seen since  $\sim 195$  kyr on the left hand side of the ridge axis. By 330 kyr (Figure 34.d), at the lower M side, an inward fault jump happens and takes the place of the old fault further away from the ridge axis. By 460 kyr (Figure 34.e), fault alternates again to the right hand side of the ridge axis.

### 3.5 Effects of the range of M variation

Generally, M57 and M58 models create a median valley much narrower and shallower than that of M28 models.

#### 3.5.1 (M28 M57 M58)SinT1

##### M57SinT1 versus M58SinT1

For description of M57SinT1 evolution with respect to time, please refer to Section 3.4.1 and Figure 27. For description of M58SinT1 evolution with respect to time, please refer to Section 3.4.2 and Figure 29. Comparing M57SinT1 and M58SinT1, the major difference is that the faulting pattern evolution for M58SinT1 is much more dynamic with a higher frequency of inward fault jumps, cut-backs and connection of the offsetted fault zones. For M58SinT1, the inward fault jumps and antithetic faults usually replace the old

ones. However, for M57SinT1, diking is not strong enough to create big enough stress perturbation along the ridge axis for inward fault jumps or antithetic faults to take the place of the original one. At the lower M side, antithetic faults only help to accommodate tensional stress which assists in maintaining a termination near the ridge axis while the termination at the higher M side gradually moves off axis. This produces an OCC with larger dome at the lower M side than that of higher M side which is opposite to the shape of the OCC produced by M58SinT1.

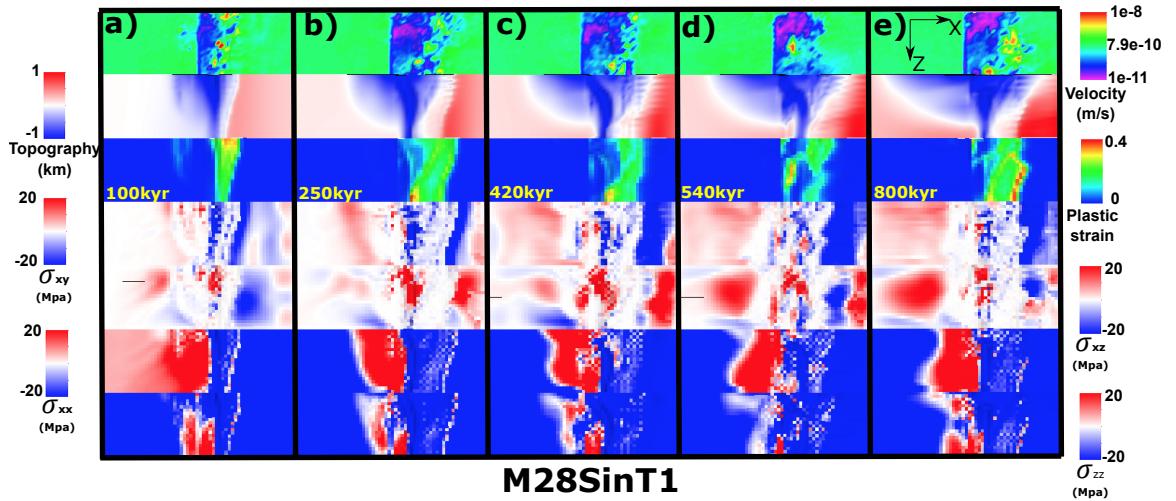


Figure 35: M28SinT1 (Table 2) faulting and stress evolution with respect to time.

### M28SinT1

As shown in Figure 35, faulting evolution is much less dynamic than that of M58SinT1. One detachment fault keeps active on the right hand side of the ridge axis. Only inward fault jump happens  $\sim 540$  kyr (Figure 35.d). By  $\sim 100$  kyr (Figure 35.a), breakaway at the lower M side extends  $\sim 4$  km further away from ridge axis than the higher M side. By 250 kyr (Figure 35.b),  $\sim 4$  corrugations begin to evolve at the lower M side ( $M \in (0.2, 0.5135)$ ). By 420 kyr, at the higher M side, a hint of inward fault jump begins to show up. It develops into an inward fault jump by 540 kyr (Figure 35.d) and propagates toward higher M side. At the lower M side ( $M \in (0.2, 0.2939)$ ), a tensile failure takes up part of the plate extension and helps maintain a closer to ridge axis termination than the

extending termination at the region with  $M \in (0.4724, 0.6562)$  (Figure 35.e). The curved in termination at the lower M side produces a mullion structure.

### 3.5.2 M57SinT2 versus M58SinT2

For description of M57SinT2 evolution with respect to time, please refer to Section 3.4.1 and Figure 28. For description of M58SinT1 evolution with respect to time, please refer to Section 3.4.2 and Figure 32. A major difference is that M57SinT2 has no fault alternation while M58SinT2 has.

### 3.5.3 M28LinT1 versus M57LinT1

For description of M28LinT1 evolution with respect to time, please refer to Section 3.1.

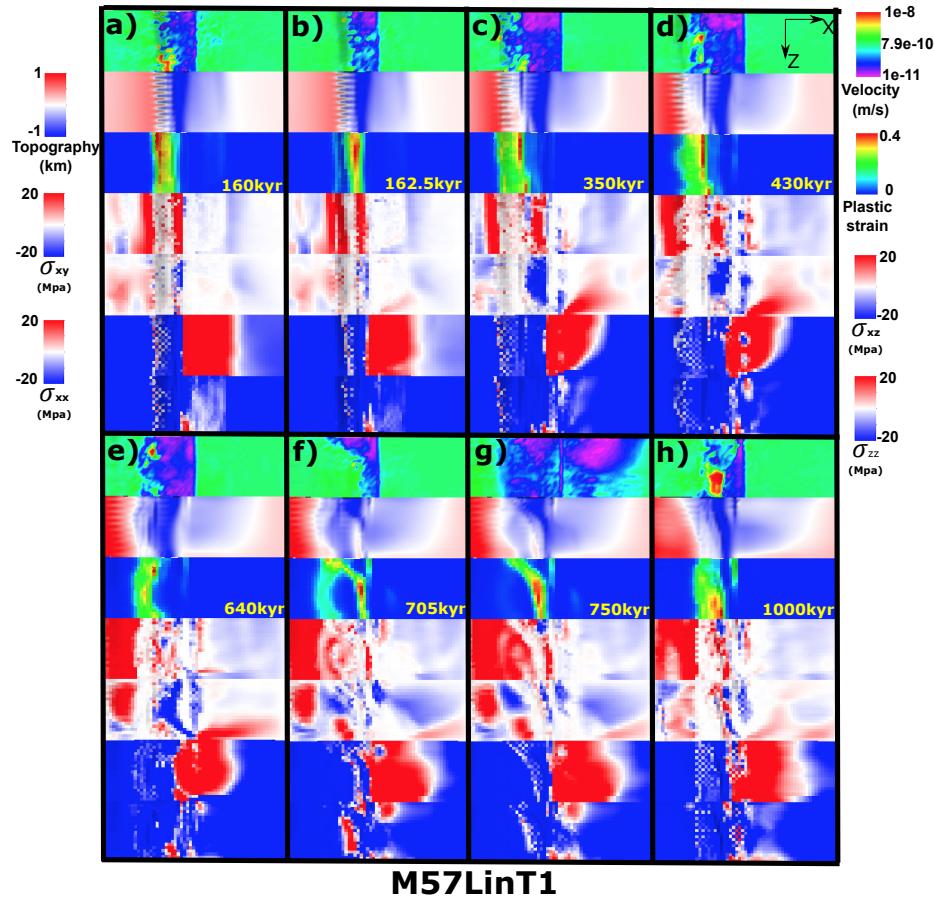


Figure 36: M57LinT1 (Table 2) faulting and stress evolution with respect to time.

## **M57LinT1**

As shown in Figure 36, between 160 kyr (Figure 36.a) and 162.5 kyr (Figure 36.b), a cut-back happens. The corrugations have a relatively high amplitude. Due to less M variation (0.2), the along ridge offset in breakaways is smaller. The median valley almost has a constant width along the ridge. By 350 kyr (Figure 36.c), a tensile failure happens at the region with  $M \in (0.5, 0.61)$  and generates a linear topography low. Another shorter tensile failure at the higher M side ( $M > 0.64$ ) helps maintain a high angle normal fault near the ridge axis. By 430 kyr (Figure 36.d), the tensile failure at the lower M side ( $M < 0.52$ ) is responsible for the retreat of the termination. While at where  $M \in (0.54, 0.59)$ , the termination extends further away from the ridge axis. This curved termination results in a “dog bone” shape topography as seen at 640 kyr (Figure 36.e) and is also responsible for the large dextral shear (blue) stress  $\sigma_{xz}$ . By 705 kyr (Figure 36.f), an inward fault jump happens and replaces the original detachment fault at the higher M side with a length of  $\sim 15$  km. This inward jumped fault connects with the detachment fault at the lower M side. The new “L” shape termination is responsible for the topography seen at 1000 kyr (Figure 36.h). The termination at the higher M side soon catches up the further extended termination at the lower M side due to the presence of a tensile failure.

### **3.5.4 M28SqrtT1 versus M58SqrtT1**

For description of the evolution of M28SqrtT1, please refer to Paragraph 3.2.5. For description of evolution of M58SqrtT1, please refer to Paragraph 3.4.3. Generally the faulting evolution for M58SqrtT1 is more dynamic with several inward fault jumps, antithetic faults, connection between offsetted faults along the ridge while M28SqrtT1 is simpler with only two cut-backs.

### **3.5.5 M57SqrtT2 versus M58SqrtT2**

For description of evolutio of M58SqrtT2, please refer to Paragraph 2.

The major difference between M57SqrtT2 and M58SqrtT2 is that only M58SqrtT2 has fault alternation.

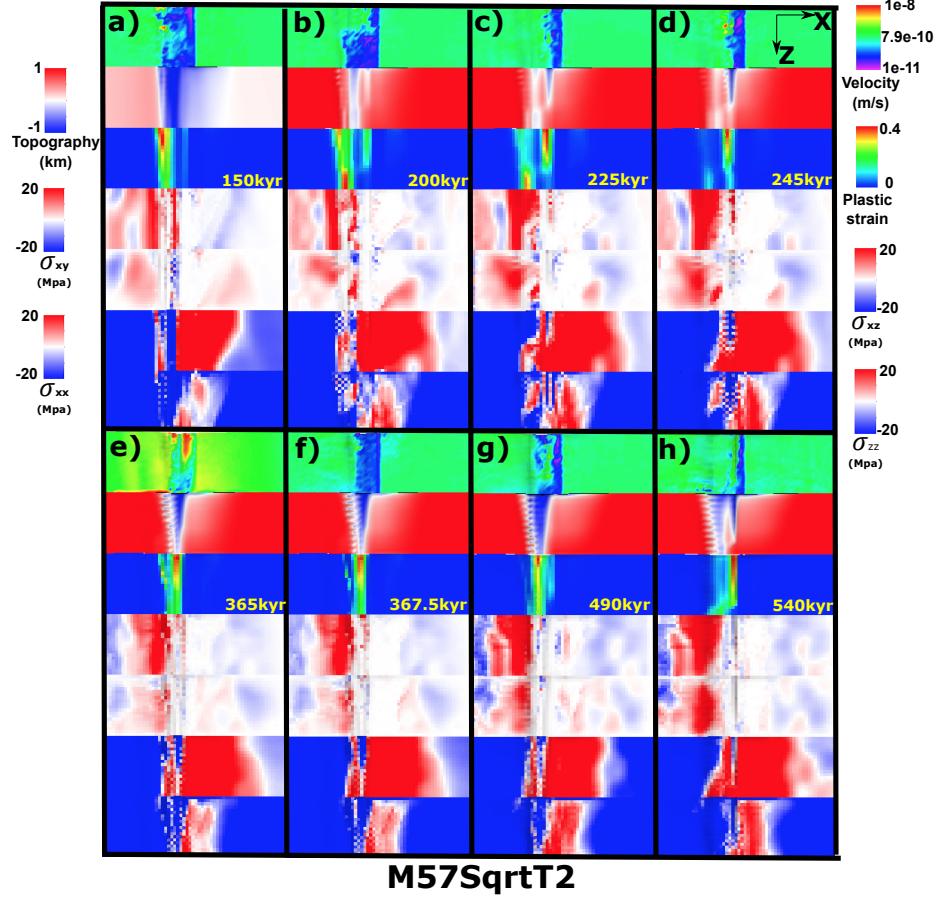


Figure 37: M57SqrtT2 (Table 2) faulting and stress evolution with respect to time.

### M57SqrtT2

For M57SqrtT2, six small scale cut-back happen at 282.5 kyr, 290 kyr, 365 kyr, 452.5 kyr, 482.5 kyr and 540 kyr respectively. As shown in Figure 37, the fault keeps on the left hand side of the ridge axis. By 200 kyr (Figure 37.b), an inward fault jump begins to evolve and takes the place of the initial fault. As the fault evolves, a stage of discontinuous abyssal hill is produced at the lower M side (Figure 37.c). The fault propagates toward the higher M side and cuts through the plate by  $\sim$ 245 kyr (Figure 37.d) when corrugations at the lower M side are produced. Between 365 kyr (Figure 37.e) and 367.5 kyr

(Figure 37.f), a cut-back happens. By 490 kyr (Figure 37.g), an antithetic fault begins to evolve and terminates the old fault. It then develops into a vertical tensile failure at 540 kyr (Figure 37.h). *XT* for M57SqrtT2, the topography since 200 kyr uplifted, I suspect there might be some runtime error for this model. Consider to abandon this model and if possible, rerun it.

## 4 Discussion

In this “Discussion” section, I first briefly summarize the results. Then I discuss the model features by comparing them with nature observations.

### 4.1 Summary of Results

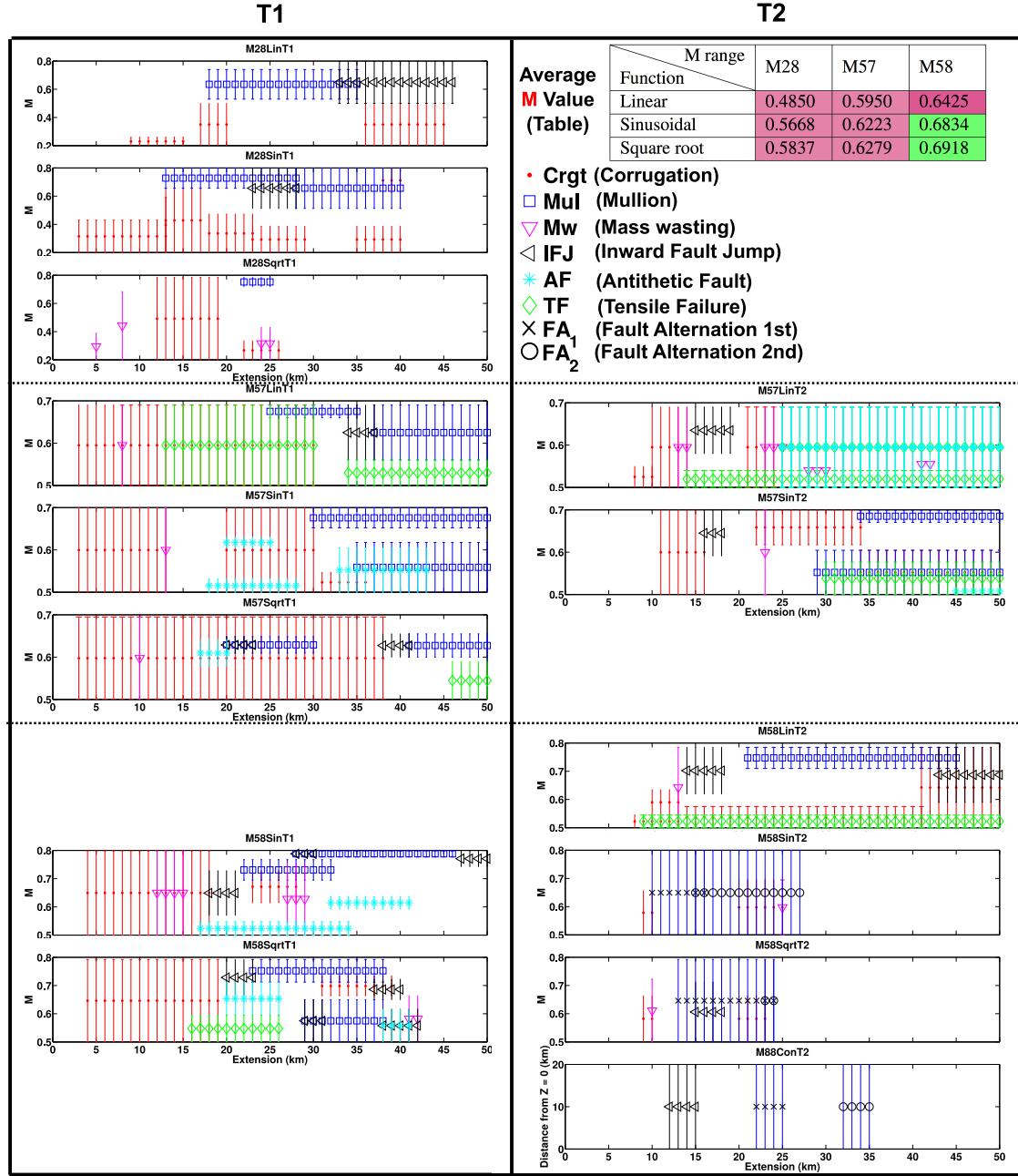


Figure 38: Results summary. Model evolution with increasing plate extension.

Model results show systematic changes when the average M value ( $\bar{M}$ ) increases.  $\bar{M}$  is the value of integration of M along the ridge divided by the length of the ridge segment. As seen in the table of Figure 38,  $\bar{M}_{M58} > \bar{M}_{M57} > \bar{M}_{M28}$  and within each M range,  $\bar{M}$  for functional form with square root is higher than that for sinusoidal and linear.

Comparing the models with slower weakening rate (type 1) (left column of Figure 38), when  $\bar{M}$  increases, faulting (i.e. inward fault jump, antithetic fault) as well as other main model behaviors (i.e. corrugation, mullion, mass wasting, tensile failure) become more complex and dynamical with higher recurrence frequencies.

Comparing M28SinT1 and M28LinT1 shows that the inward fault jump for M28SinT1 (with higher  $\bar{M}$ ) happens earlier and lasts a shorter period of time. As  $\bar{M}$  increases to 0.5837 for M28SqrtT1, mass wasting first shows up. During the mass wasting, a curved fault scarp with  $\sim 1$  km relief is produced and it has a shape very similar to 13 °N, Mid-Atlantic Ridge (please refer to a detailed discussion in the next section).

When M57 are compared to M28 models, corrugations show up earlier along the whole 20 km ridge segment. All three models have mass wasting. Tensile failures and antithetic faults begin to show up. For M57LinT1 ( $\bar{M} = 0.5950$ ), it begins to have tensile failure which releases tensional stress in the hanging wall and results in the delay of inward fault jump. For M57SinT1 ( $\bar{M} = 0.6223$ ), antithetic fault first shows up and together with mass wasting lead to the absence of inward fault jump. The antithetic fault at the lower M side helps to maintain a closer to ridge axis termination which results in a larger mullion structure at the lower M side and thus produces an OCC with a shape similar to the Atlantis Massif at 31 °N Mid-Atlantic Ridge. For M57SqrtT1 ( $\bar{M} = 0.6279$ ), it has twice of inward fault jumps and each of them is followed by a small scale mullion structure.

Comparing M58 and M57 models shows that the two M58 models have 3 and 4 times of inward fault jump respectively while M57 models have at most twice of that. Also, corrugations of M57 show up earlier and it might imply that corrugation favors specific

range of  $\frac{\partial M}{\partial Z}$ , neither too higher, nor too low. Between M58SinT1 ( $\bar{M} = 0.6834$ ) and M58SqrtT1 ( $\bar{M} = 0.6918$ ), the major difference is M28SqrtT1 has twice inward fault jumps at the lower M side because M values are higher at the lower M side.

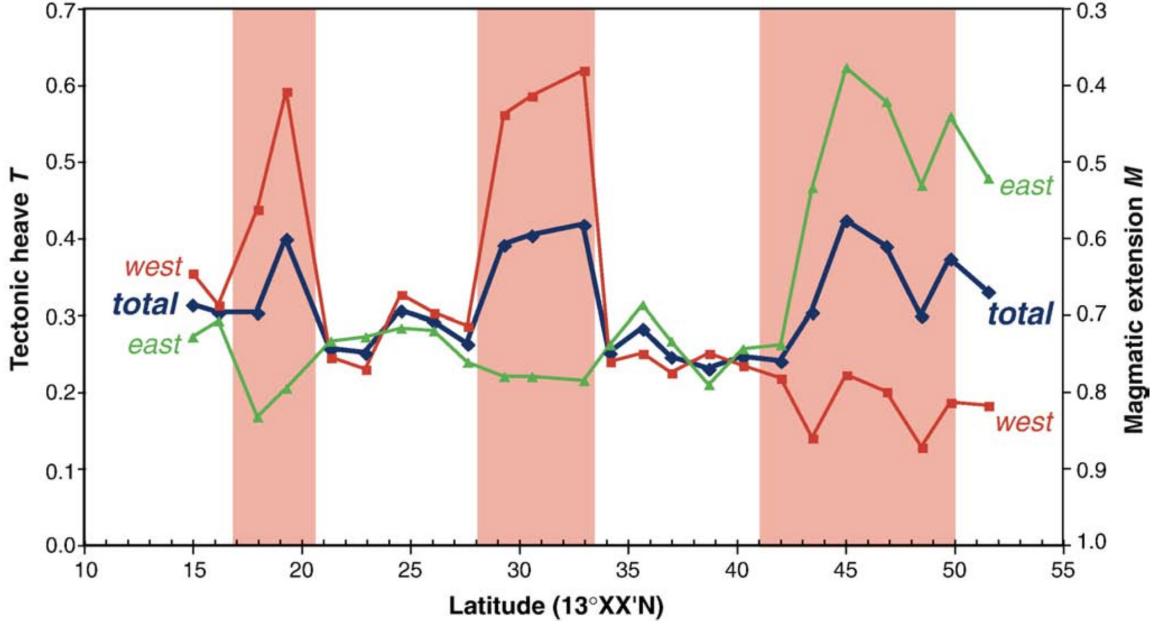


Figure 39: Along-axis variations in total accumulated tectonic heave  $T$  in the past 1.86 Ma (since chron C2n), and consequent inferred magmatic component  $M$  ( $= 1 - T$ ) as a proportion of total plate separation (blue line). Pink shaded areas delineate loci of the active or recently active OCCs. The relative contributions of tectonic strain from the western and eastern flanks of the axis that give rise to the total heave  $T$  are shown by red and green lines respectively. Adapted from [MacLeod et al., 2009].

When comparing models with different weakening rate (type 1 versus type 2), the most obvious difference is that only two of type 2 models with  $\bar{M} > 0.6425$  generates alternating faults, they are M58SinT2 and M58SqrtT2. They don't have mullion structure because the high frequency of fault alternation allows a specific pattern of termination to last for a shorter period of time. Also, they neither have tensile failure nor antithetic fault. This provides an upper limit in our 3D models for producing long lasting detachment fault that can generate OCCs. Comparing M57T2 and M57T1 models shows that M57T2 models generally have earlier inward fault jump but later corrugations. For the model with constant  $M = 0.8$  along the ridge axis, the inward fault jump and fault alterna-

tions have a period of  $\sim 10$  km of extension. Corrugation, mullion structures, mass wasting, antithetic fault and tensile failure are not produced in this model which implies that varying  $M$  is necessary for producing those features.

In addition, the upper limit of  $\bar{M} = 0.6425$  for allowing a long lasting detachment fault to produce an OCC in our model is consistent to the results from a near-bottom sidescan bathymetric profiler survey and sampling study of the Mid-Atlantic Ridge near  $13^{\circ}\text{N}$  [MacLeod et al., 2009]. As shown in Figure 39, the average  $M$  value  $\bar{M} = 0.63 \pm 0.05$  for the pink area where OCCs are present while when there is no OCC,  $\bar{M} = 0.73 \pm 0.03$ .

## 4.2 Fault Alteration

### 4.2.1 Trade-off between bending and weakening

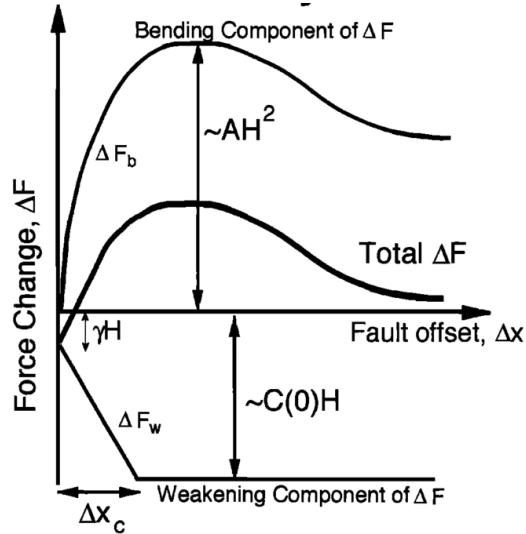


Figure 40: Trade-off between change in bending force  $\Delta F_b$  and weakening in the fault interface  $\Delta F_w$ .  $H$  is the thickness of the brittle crust and  $\gamma$  is the size of initial weak perturbation and  $A$  defines the maximum bending force change. (For more details, please refer to [Lavier et al., 2000])

Before we move on to each of the pairs, the framework studied by [Lavier et al., 2000] needs to be mentioned here for better understanding the model behaviors observed in our

model results. There is a trade-off between change in bending force  $\Delta F_b$  as a function of fault offset  $\Delta X$  and force change  $\Delta F_w$  as a function of  $\Delta X$  due to strain weakening. As described in [Lavier et al., 2000], higher characteristic fault offset ( $\Delta X_c$ ) or slower strain weakening results in multiple faults rather than only one fault lasting. Whether conjugate fault and even multiple faults can be produced depends on the local stress condition. The strength weakening of the existed fault combines with how much bending force resists the fault to keep offsetting play a major role in determining the stress state at the other areas. As the sea-floor keeps spreading and  $\Delta X$  increasing, the change in bending force  $\Delta F_b$  increases and the strength at the fault interface decreases due to weakening  $\Delta F_w$  (Figure 40). If the net force change  $\Delta F = \Delta F_b + \Delta F_w$  is positive, it means that it is getting harder and harder to maintain the existing fault and stress will begin to accumulate at the other areas which eventually break another fault.  $\Delta F_b$  initially increases fast with respect to  $\Delta X$  and then when the breakaway bends over, it reaches its peak value and begins to decrease a little and maintains at a constant value. If the strain weakening is fast enough that the net effect force  $\Delta F$  is always negative, then most of the stress will be released by the existing fault and thus no conjugate or multiple faults will be created.

Our model results verify this analysis that only Type two weakening (slower weakening with higher  $\Delta X_c$ ) can produce an alternating normal fault on the conjugate plate.

Based on the previous experience in pseudo-2D models and [Lavier et al., 2000], when  $M > 0.5$ , the frequency of normal faulting alternation is higher for higher characteristic fault offset ( $\Delta X_c$ ) of Type two weakening compared to Type one weakening. However, for the reference model two, M88ConT2 (Table 2), interesting enough, when comparing pseudo-2D and 3D models with Type two weakening under case of  $M = 0.8$ , even though the 3D Model has a larger  $\Delta X_c$  of 1km than that of pseudo-2D model of 0.5km, the 3D model M88ConT2 has a lower frequency of faulting alternation. Since  $M$  is constant 0.8 along the ridge-axis, the effect of along ridge coupling that resists alternation need not be considered. One possibility is that the resisting bending force increase in

a higher rate than linear with respect to increasing the length of the ridge segment ( $Z_{max}$  km).

#### 4.2.2 Alternating on conjugate plate

The fault alternation behavior observed in pseudo-2D models in cases  $M > 0.5$  is much more complicated in 3D models. The results shows that only Type two weakening with M58 will result in a alternating faulting pattern. <sup>XT:</sup>integrate the area of  $M > 0.5$  with respect to Z to see if there is any quantatative analysis available.

#### 4.2.3 Secondary near-axis normal fault

The secondary near axis high angle normal fault is another common observation of the models. As shown in Figure 8, at the ridge axis with  $M > 0.5$  (i.e.  $Z > 10$ ), the existing normal fault will be pushed away from the ridge-axis due to excessive diking, as its mechanism has been mentioned in the introduction chapter, another new near axis normal fault is created at around 650kyr. As it evolve, the initial detachment fault become inactive (the transparent view of plastic strain shown in the rigth corner inset of time 880kyr). This secondary fault creates another dome and its composition is more likely to be volcanic rather than ultramafic, however, as it evolves, if it can last long, lower crust and upper mantle material can be exhumed to the surface. The composition of the domes observed at Kane magamullions is similar to this mechanism that ultramafic Babel dome is on the West and crustal inside-corner high on the East.

#### 4.2.4 Effect of along ridge-axis coupling

The along ridge-axis coupling allowed the normal fault at the high M side ( $M > 0.5$ ) to last for a long time and become a detachment that can produce a OCC. This behavior is different from previous 2D studies that only  $M=0.3 \sim 0.5$  can make OCCs and it also provides an alternative explanation for reconciling the gap between 2D model and obser-

vation described in [Olive et al., 2010]. Instead of magma injecting below brittle dutile transition, even injecting in the crust, due to along ridge coupling, model can still create OCC for high magma supply. Find the observation evidence for high M OCC from refs of Olive2010. As mentioned in the abstract of Olive2010, ref4-11 show a spectrum of magma supply.

### 4.3 Corrugations

There are two contributing factors, for one, trans-extenstional stresses are created due to offset of the breakaway as well as the variation in fault displacements along the ridge axis; for the other, the variation of the positions of the terminations of the detachment faults along the ridge-axis creates anastomosing faults that is mentioned in [Smith et al., 2014]. This anastomosing faulting behavior is largely responsible for corrugations in our models.

The stress at the tips of the breakaways is generally tensional in both parallel and orthogonal directions to the ridge-axis. (Figure ??f,g)

#### 4.3.1 Wavelength of corrugations

### 4.4 Comparing model results with nature observation

#### 4.4.1 Cut back at 13°N Mid-Atlantic Ridge (M28SqrtT1)

The cut back behavior in M28SqrtT1 model creates a fault scarp of  $\sim$ 1km in relief, 40km in length along the Z axis. Note that the fault scarp corresponds to initial formed break-away. The topography at 13°N Mid-Atlantic Ridge also has a fault scarp with very similar geometry with  $\sim$ 1km in relief. Due to the variation in diking along the ridge-axis, a sandglass shape of median valley is also produced in the model where the narrowest center corresponds to the region with high magma supply ( $M=0.8$ ). This sandglass shape is also frequently observed in the nature along the Mid-Atlantic Ridges.

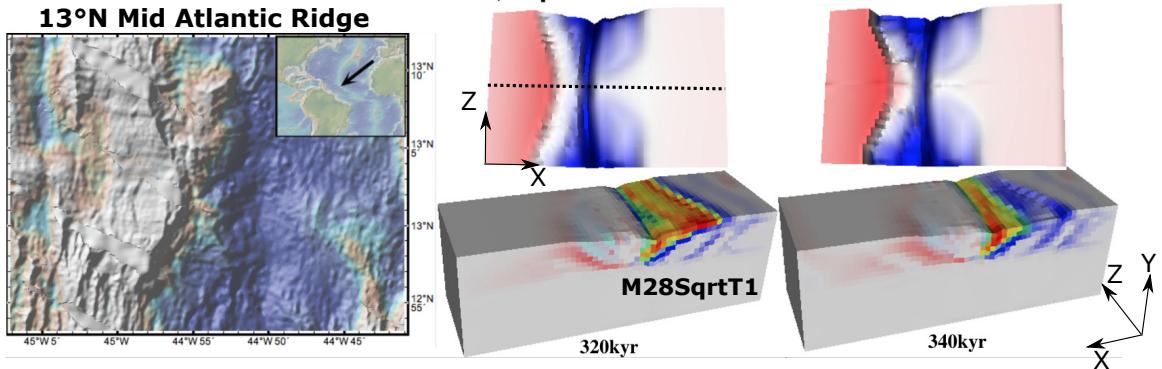


Figure 41: Comparing nature observation at 13°N Mid-Atlantic Ridge to the Cut back behavior of model M28SqrtT1. The model topography is a mirror symmetric flip according to the dash line, it reveals the case of  $M$  varies in a square root functional form from 0.2 to 0.8 to 0.2. For discussion on cut back formation mechanism, please refer to Section ???. The bathymetry is from GeoMapApp [Ryan et al., 2009].

#### 4.4.2 Double dome at 23°N Mid-Atlantic Ridge (Kane Megamullions) (Several models)

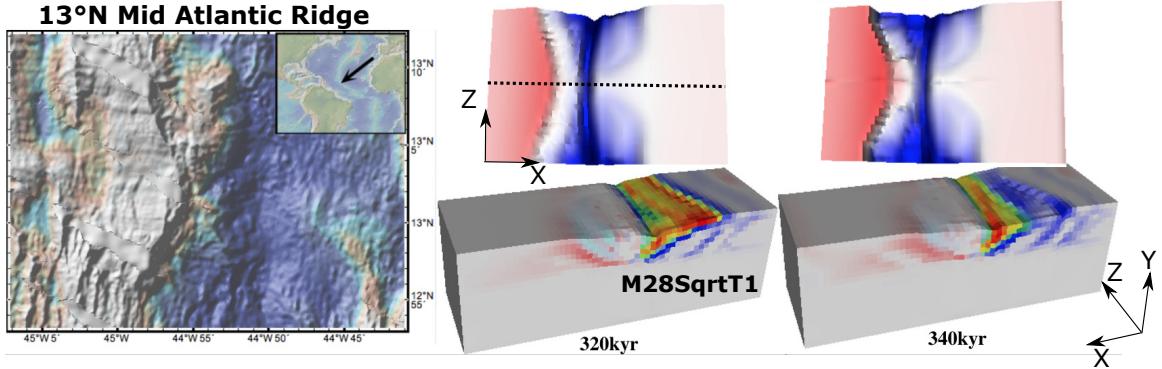


Figure 42: Comparing nature observation at 13°N Mid-Atlantic Ridge to the Cut back behavior of model M28SqrtT1. The model topography is a mirror symmetric flip according to the dash line, it reveals the case of  $M$  varies in a square root functional form from 0.2 to 0.8 to 0.2. For discussion on cut back formation mechanism, please refer to Section ???.

#### **4.4.3 Atlantis Massif Shape at 30°N Mid-Atlantic Ridge ()**

#### **4.4.4 Shear low**

#### **4.4.5 Corrugations**

### **4.5 Influence of healing**

### **4.6 Model Limitation**

#### **4.6.1 Fixed thermal structure effects and justification**

Thermal conduction rate for  $\kappa = 6\text{mm}^2/\text{s}$  material is  $1.8\text{e}5 \text{ km/Myr}$ , four magnitude faster compared to spreading rate of  $2.5\text{km/Myr}$ .

### **4.7 Recommendation for Future Research**

## **5 Conclusions**

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