The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2053-23

Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa

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Modeling of volcanic and tectonic phenomena

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USA

Simple Models of Dikes and Faults

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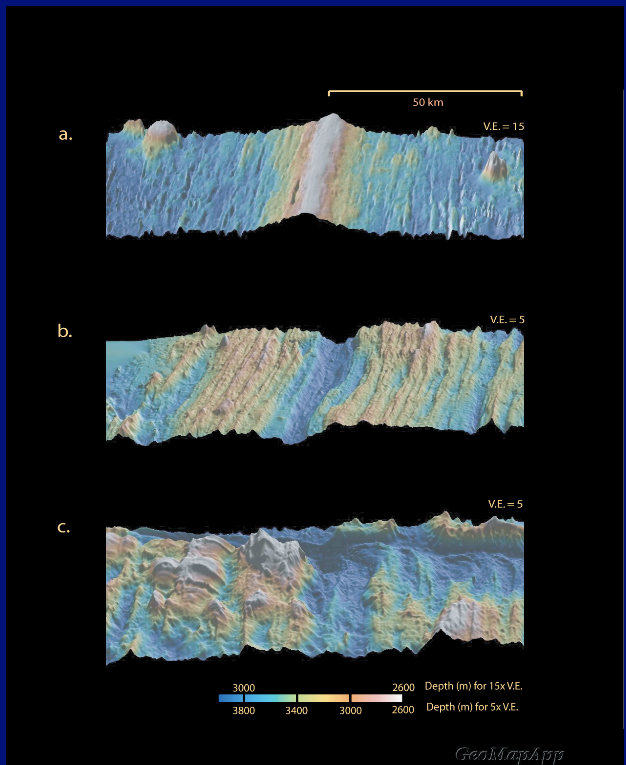
1.The 1975-1984 dike sequence at Krafla, Iceland



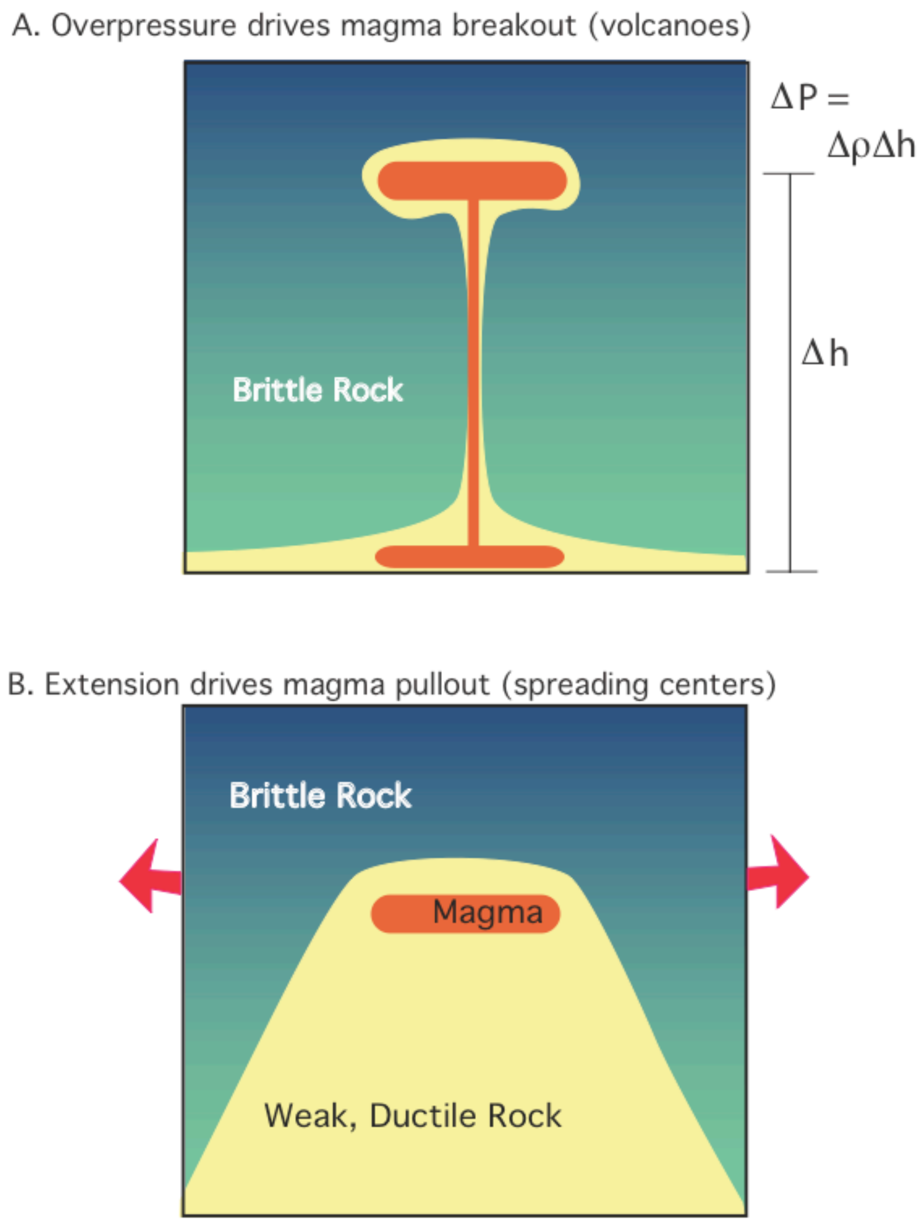
2. Controls on the offset of normal faults

3. Diking and faulting at spreading centers

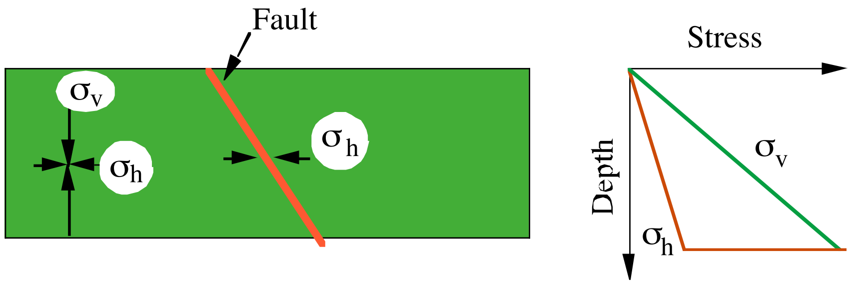
A major difference between volcanoes and rifts/spreading centers may be how magma is forced out of a magma chamber.

This talk is concerned with a how the stresses at a spreading are relieved by dike intrusions.

The pattern of dikes may reflect the changing stress field.



Minimum Stress Difference for Fault Slip

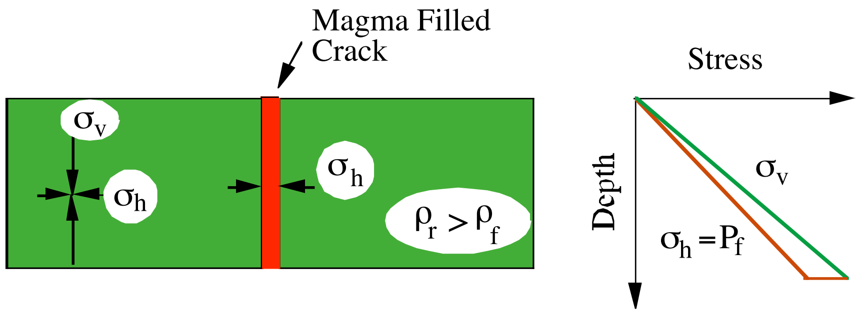


ρ_r = rock density

$$\sigma_v(z) = \rho_r\, g\, z$$

$$\sigma_h(z) = \left[\frac{(1+\mu^2)^{1/2} - \mu}{(1+\mu^2)^{1/2} + \mu}\right]\sigma_v(z) \sim [1/4]\,\sigma_v(z)$$

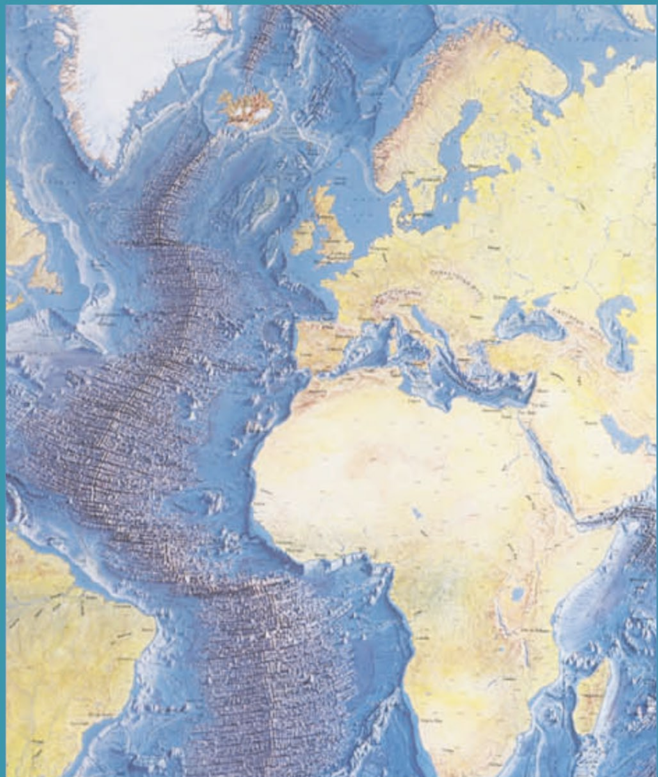
Minimum Stress Difference for Opening Dike

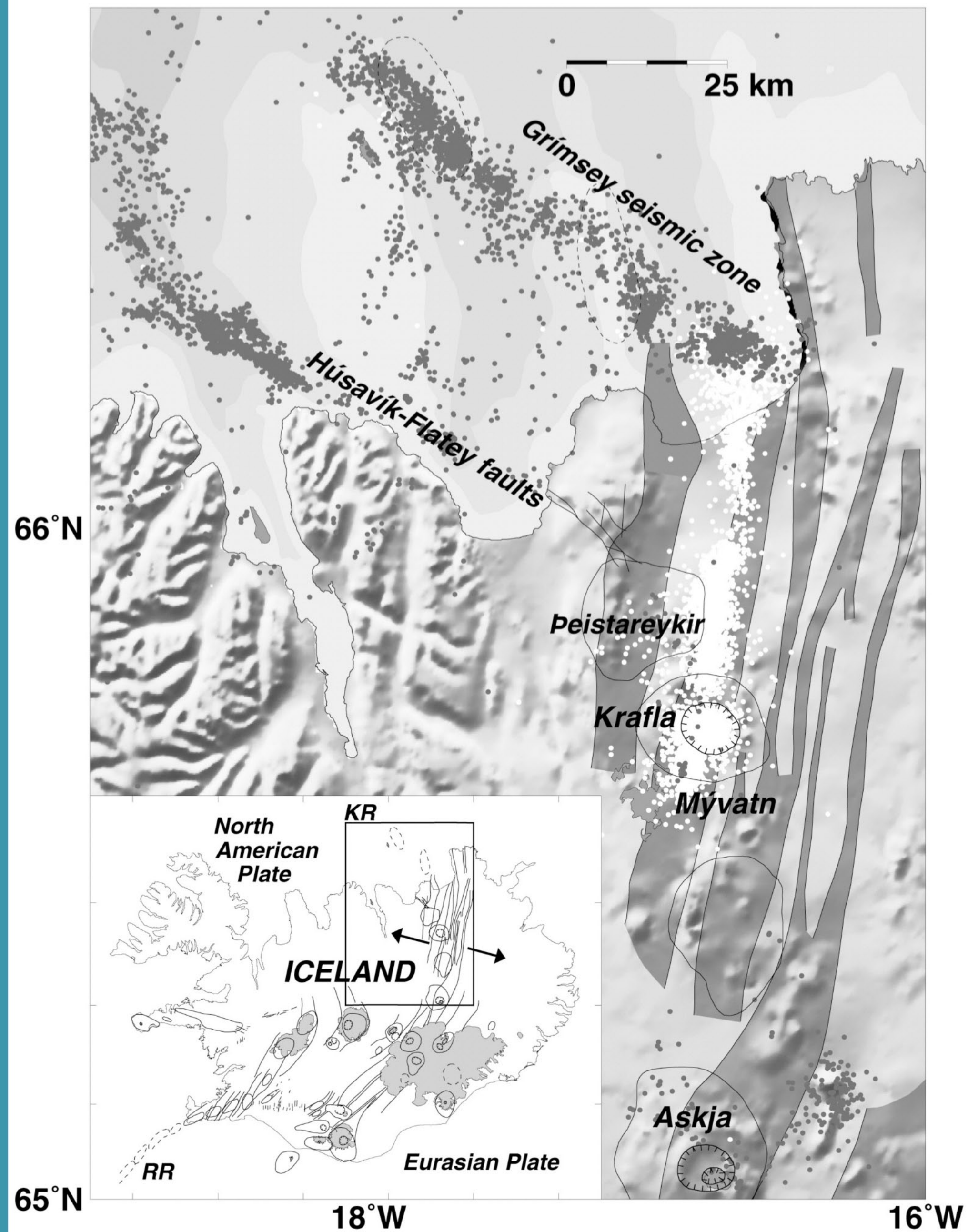


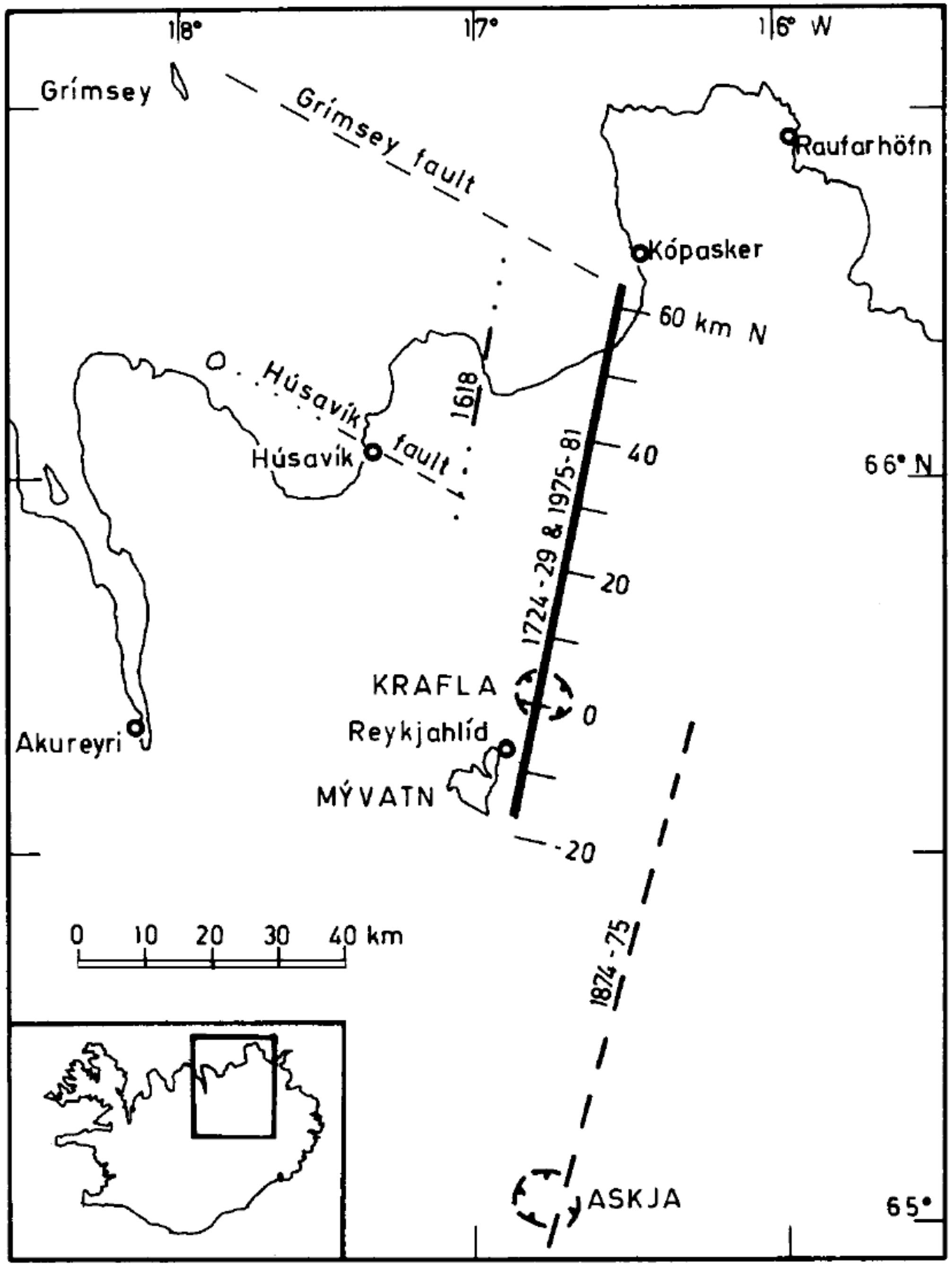
$$\sigma_v(z) = \rho_r\, g\, z$$

$$\sigma_h(z) = P_f = \rho_f\, g\, z$$

Krafla, Iceland
Earthquake and Fissure Locations
(by Bryndis Brandsdottir)

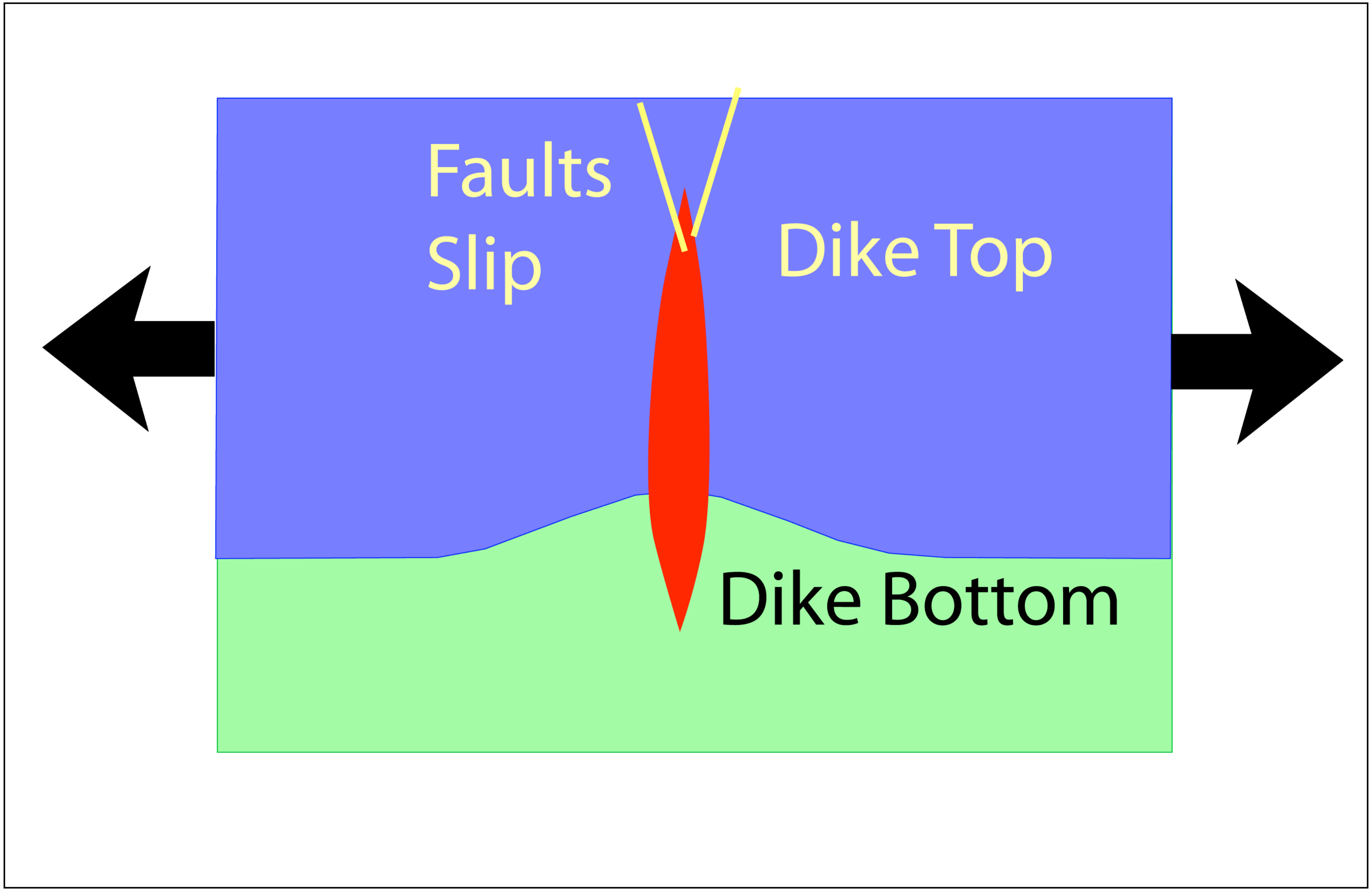






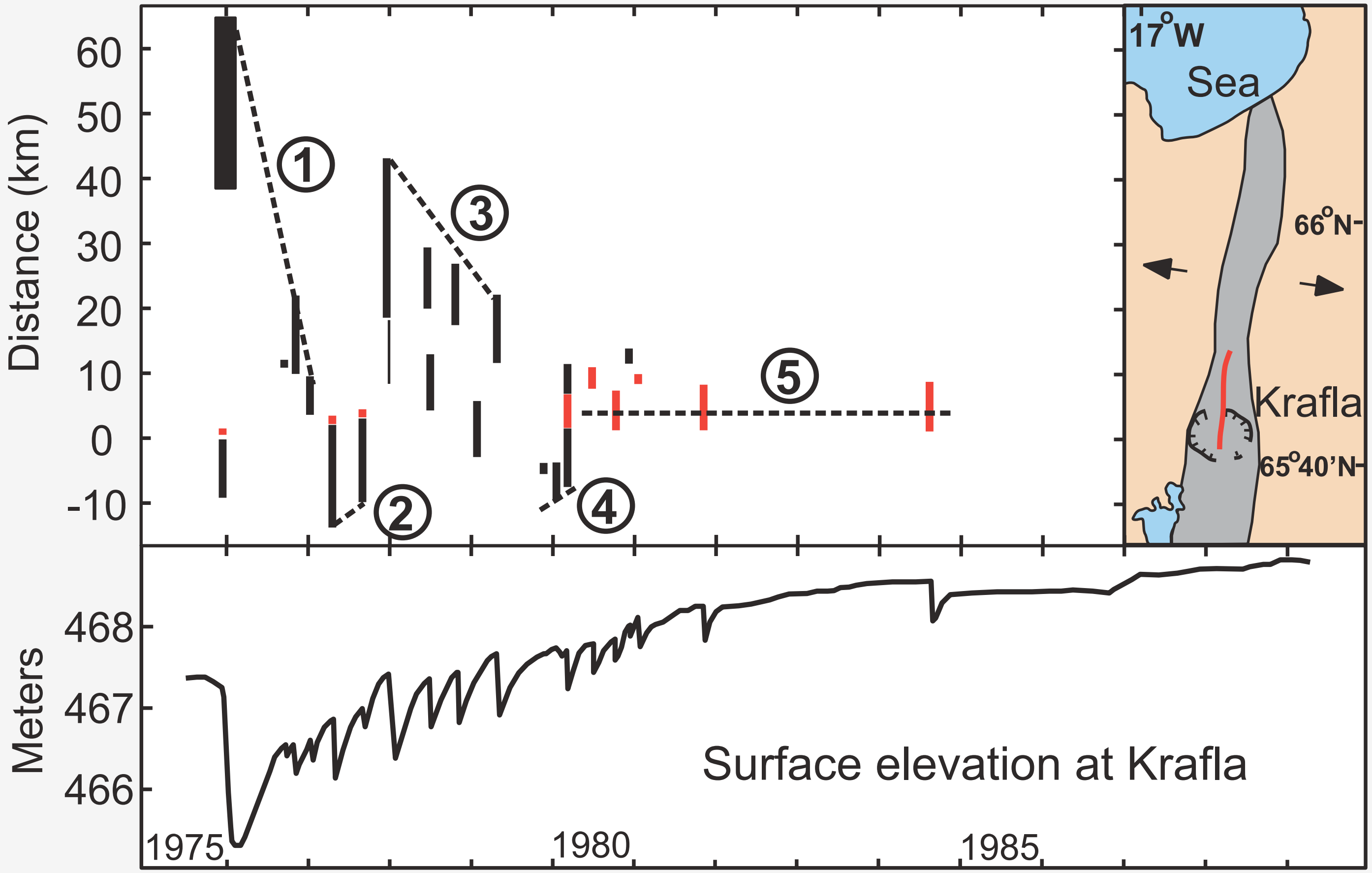
18°
17°
16° W
Grímsey
Grímsey fault
Raufarhöfn
Kópasker
60 km N
Húsavík fault
1618
Húsavík
40
66° N
1724-29 & 1975-81
20
KRAFLA
0
Reykjahlíd
Akureyri
MÝVATN
-20
0 10 20 30 40 km
1874-75
ASKJA
65°

Dike Opening Makes Faults

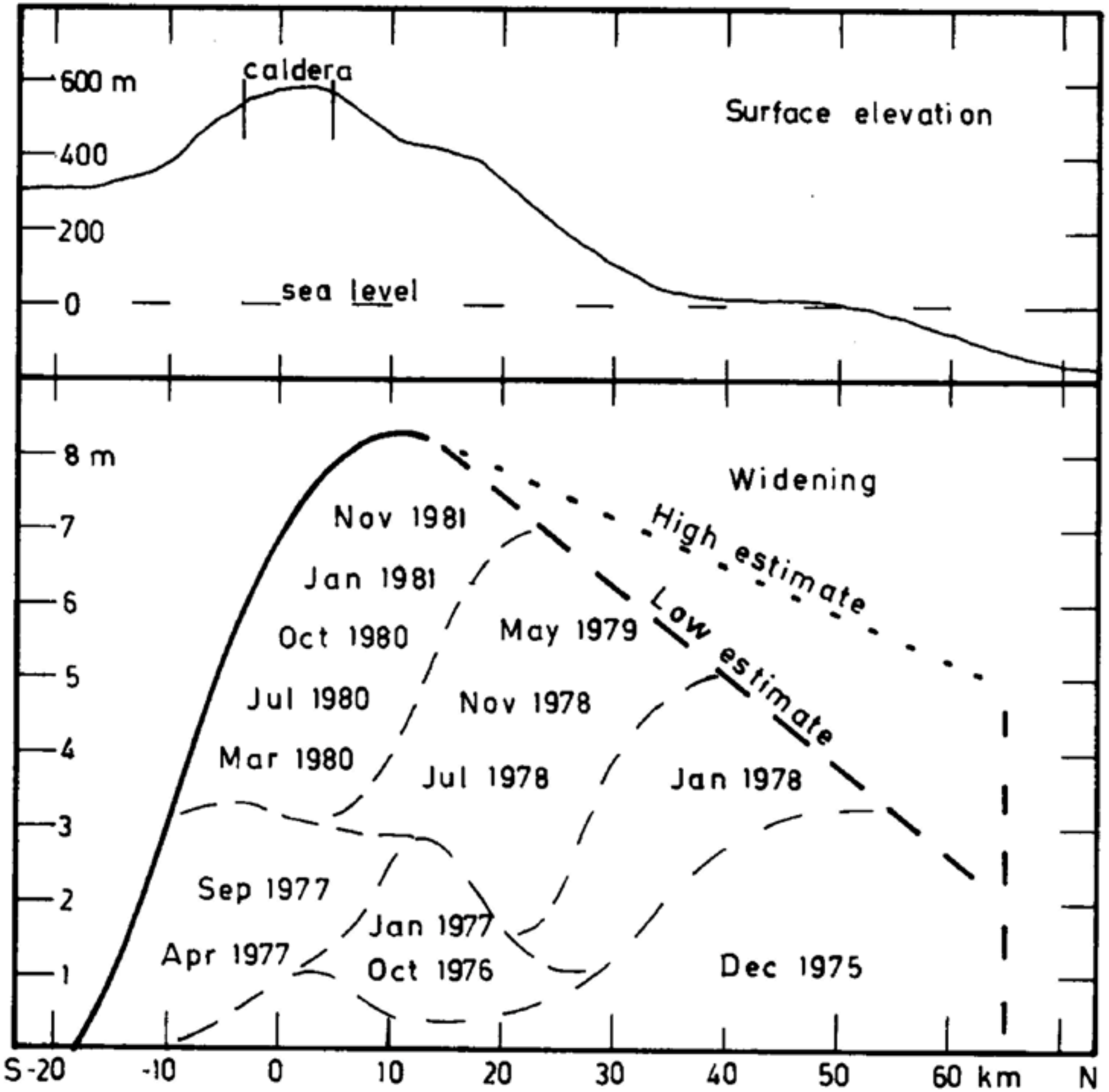



Thorarinsson September 8, 1977

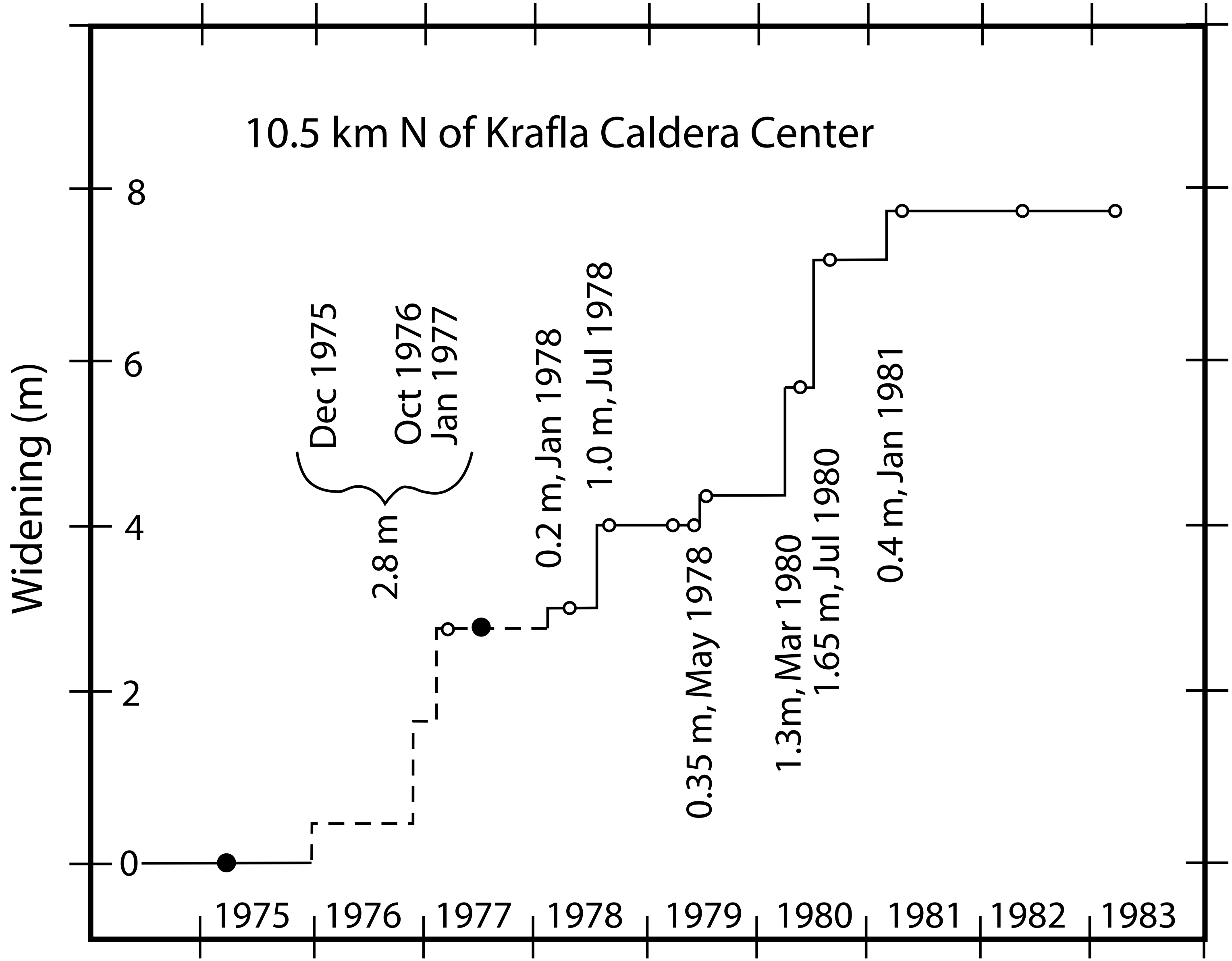
1975-1984 Krafla Rifting Episode



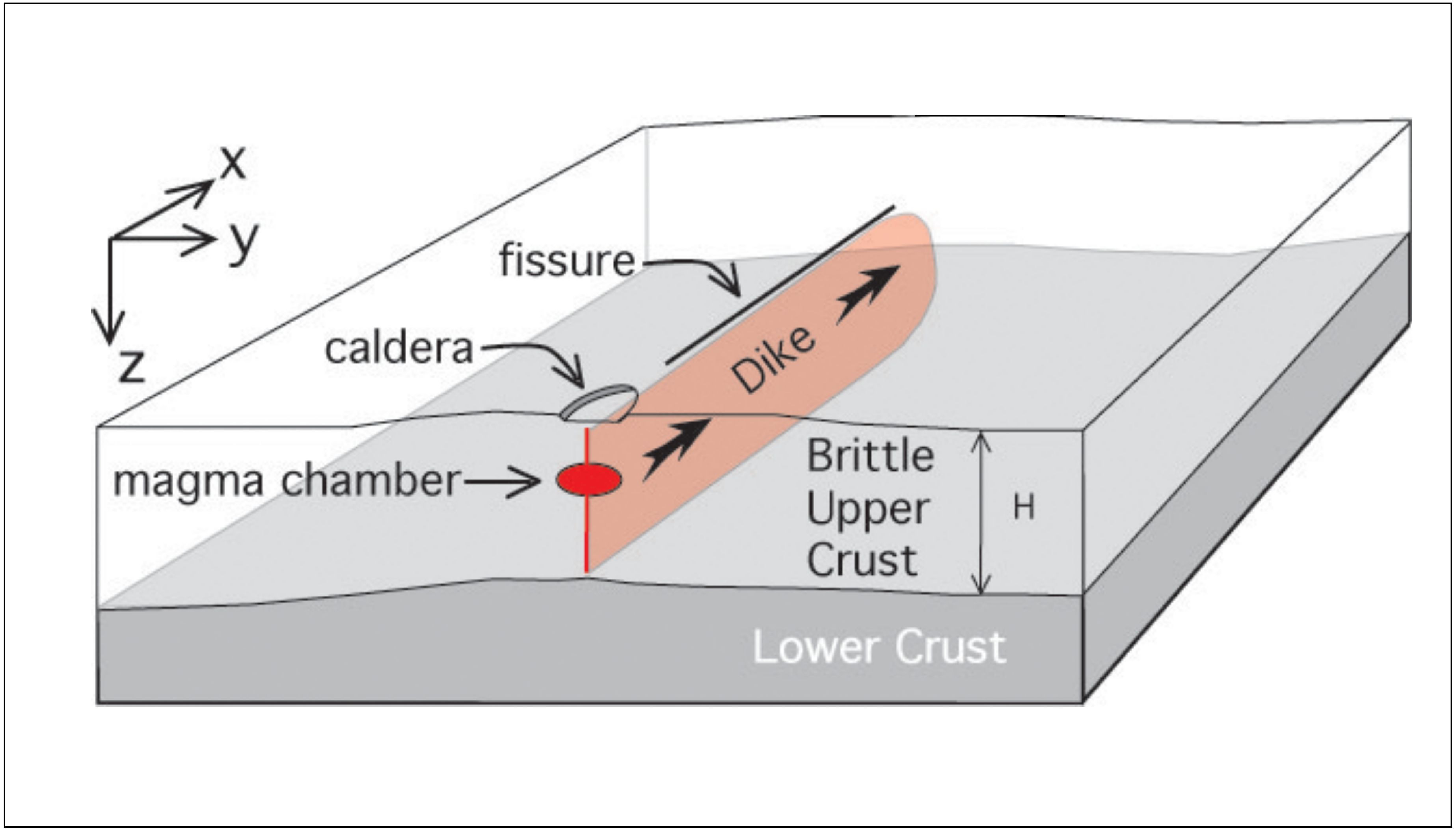
(Adapted from Einarsson, 1991)

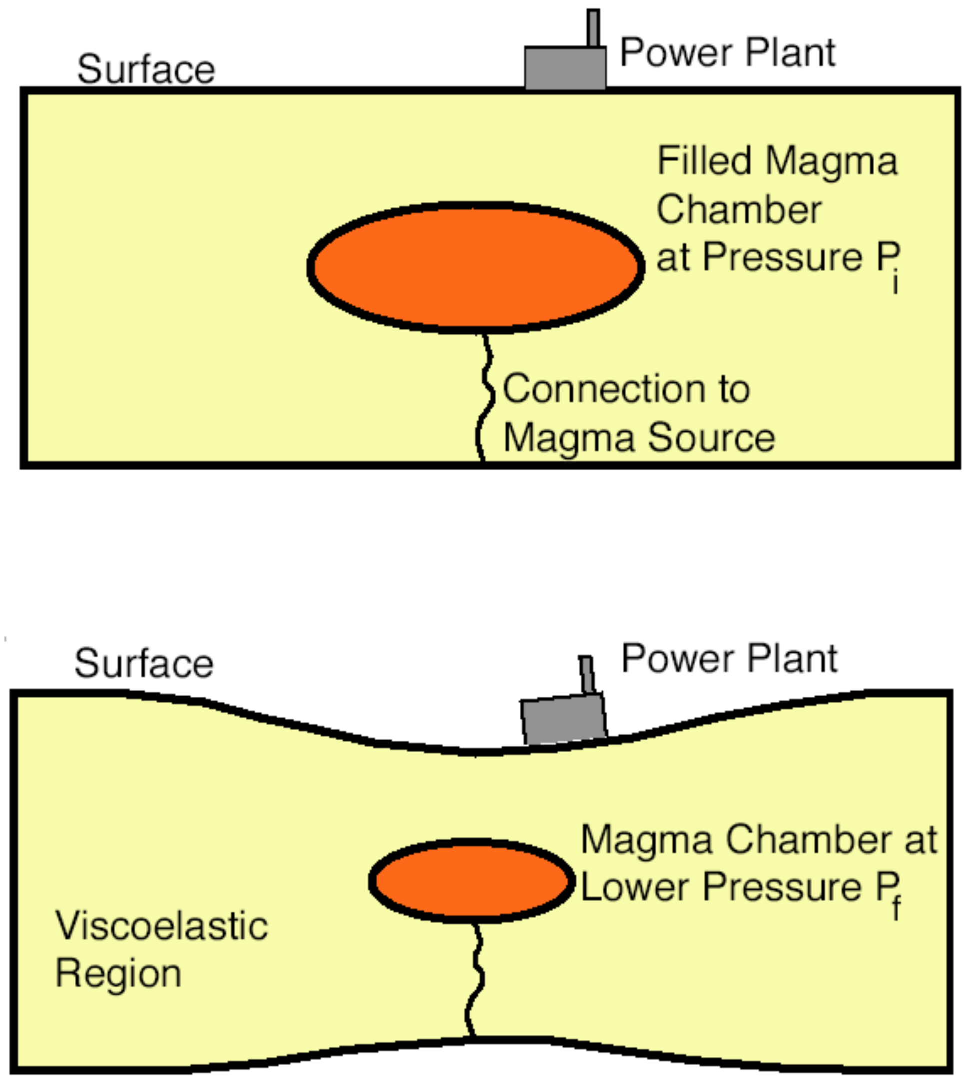


caldera
600 m
400
200
0
sea level
Surface elevation
8 m
7
6
5
4
3
2
1
Widening
High estimate
Low estimate
Nov 1981
Jan 1981
Oct 1980
Jul 1980
Mar 1980
May 1979
Nov 1978
Jul 1978
Jan 1978
Sep 1977
Jan 1977
Apr 1977
Oct 1976
Dec 1975
S -20
-10
0
10
20
30
40
50
60 km
N

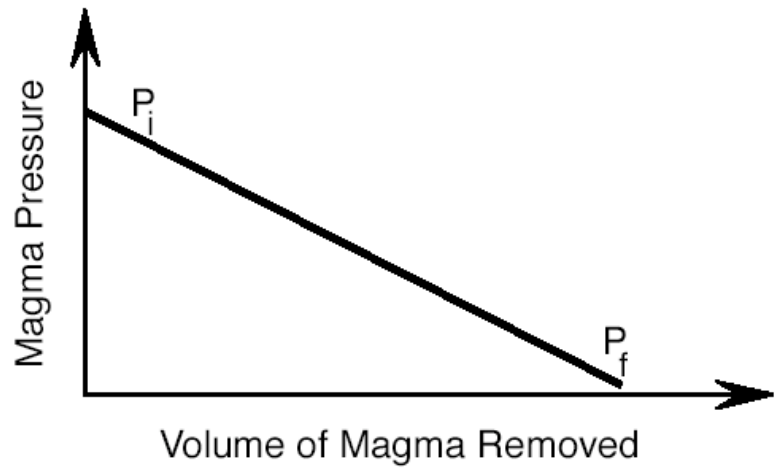


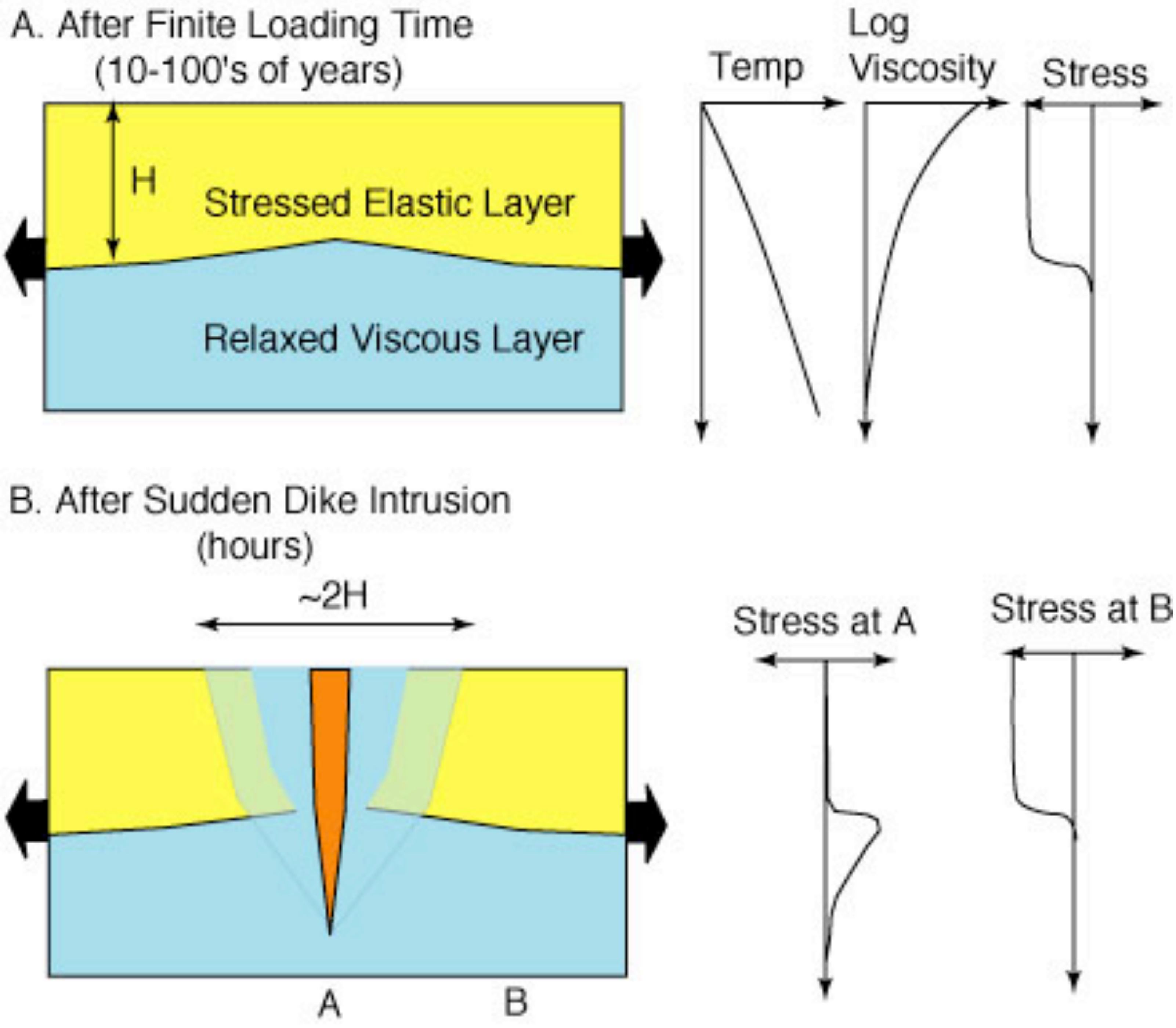
10.5 km N of Krafla Caldera Center
Widening (m)
0
2
4
6
8
1975
1976
1977
1978
1979
1980
1981
1982
1983
Dec 1975
Oct 1976
Jan 1977
2.8 m
0.2 m, Jan 1978
1.0 m, Jul 1978
0.35 m, May 1978
1.3m, Mar 1980
1.65 m, Jul 1980
0.4 m, Jan 1981


x
y
z
fissure
caldera
Dike
magma chamber
Brittle
Upper
Crust
H
Lower Crust



Assumption 1: The system is closed during an event. As magma is pulled from the magma chamber its pressure is reduced.

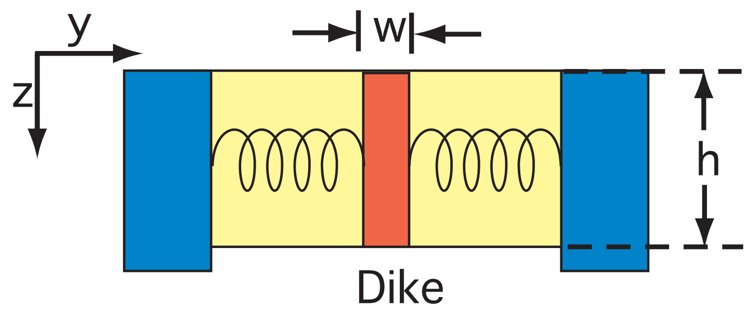




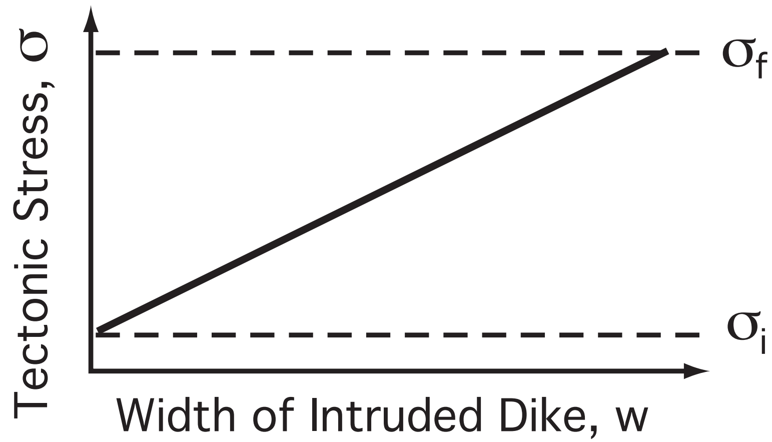
C. After Partial Freezing of Dike

Assumption 2: Dike opening relieves tectonic stresses in a finite width region.

A.



B.



Assumption 3: For magma to breakout of a chamber the driving pressure (magma pressure - local tectonic stress) must be larger than ΔP_b

Assumption 4: Dike propagation will stop when the driving pressure drops below ΔP_s.

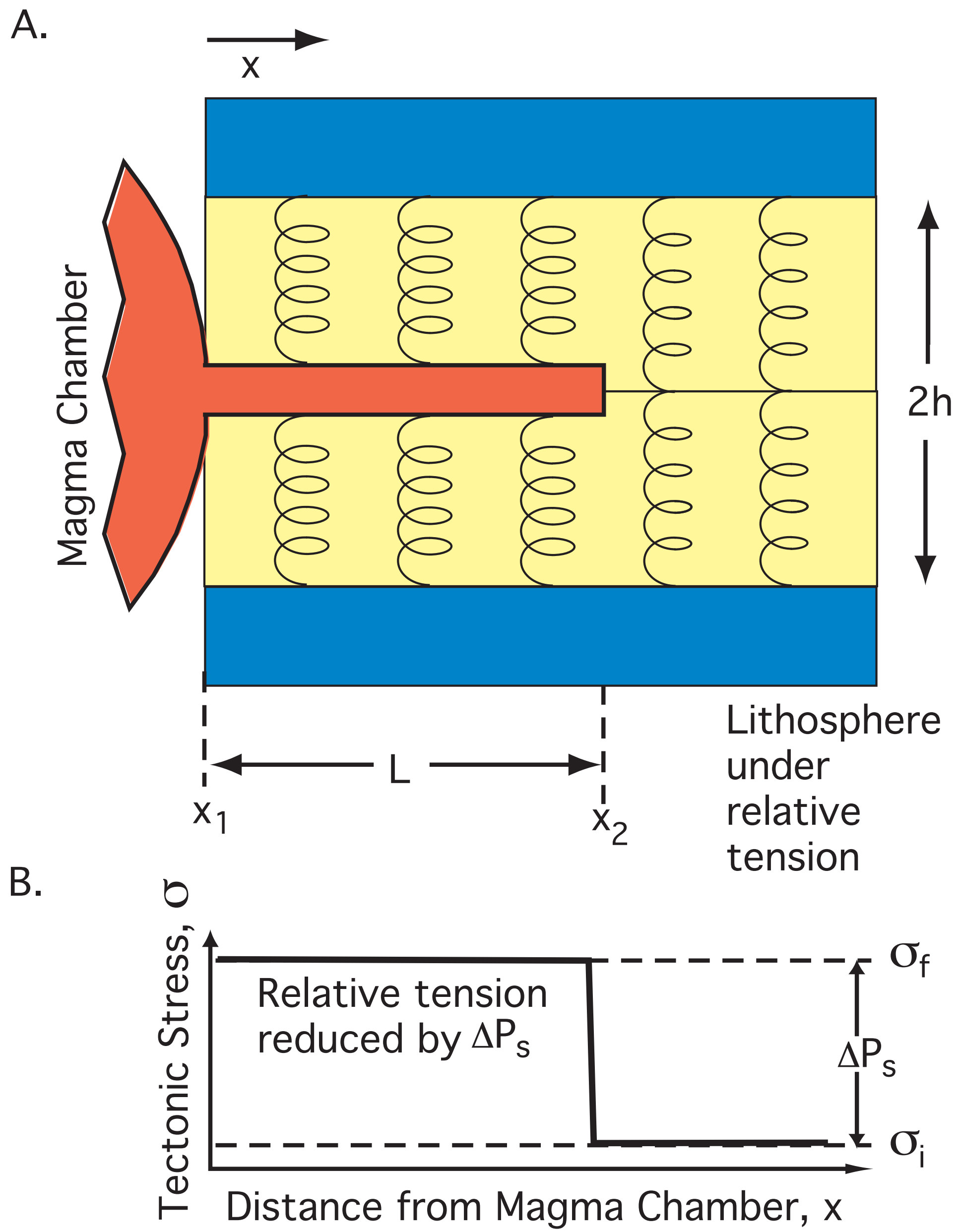
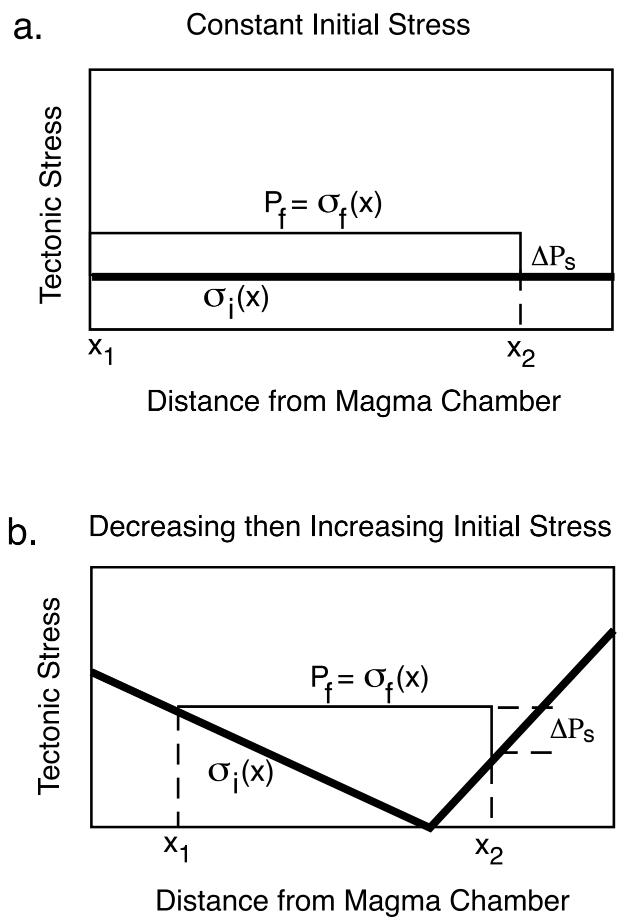
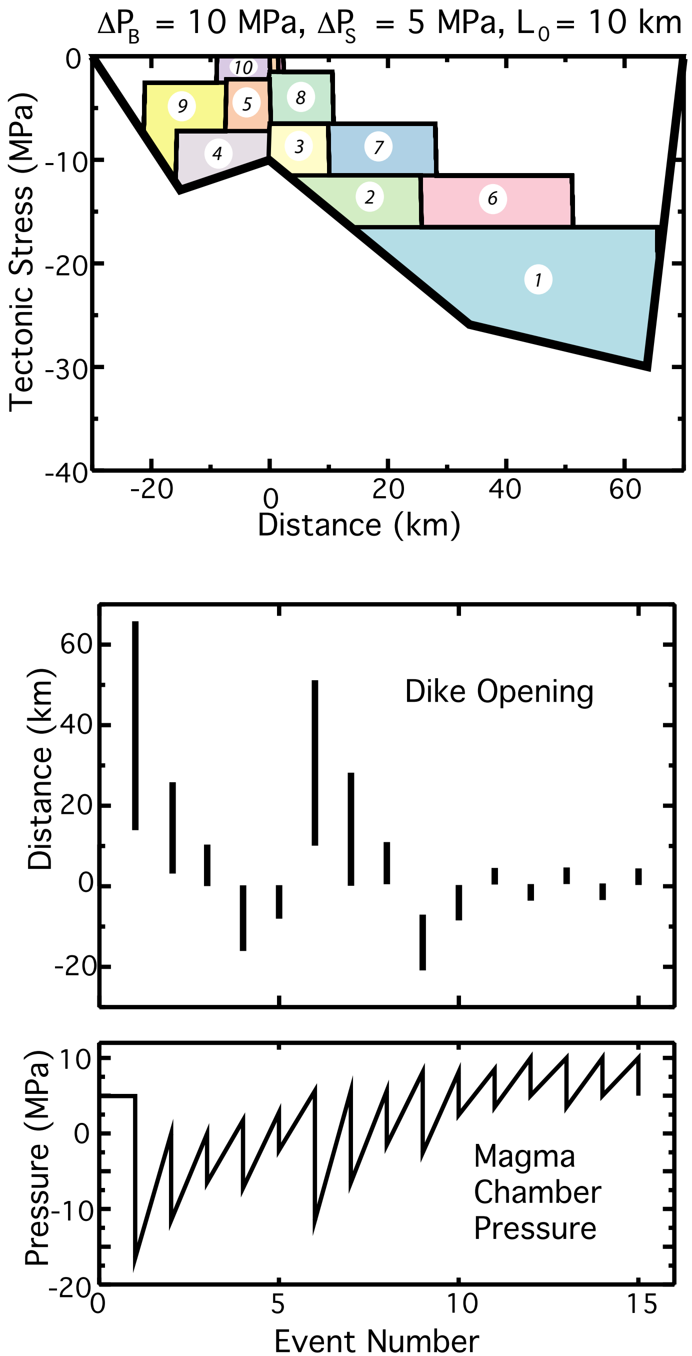


Figure 9.

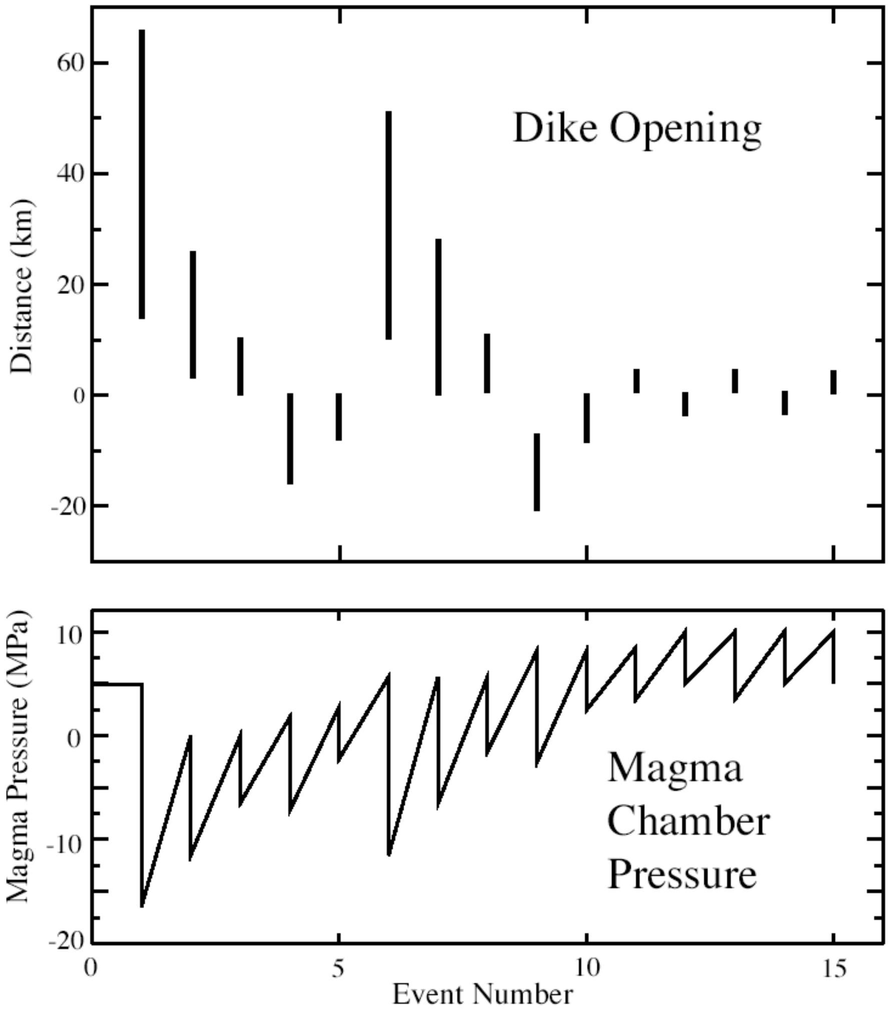


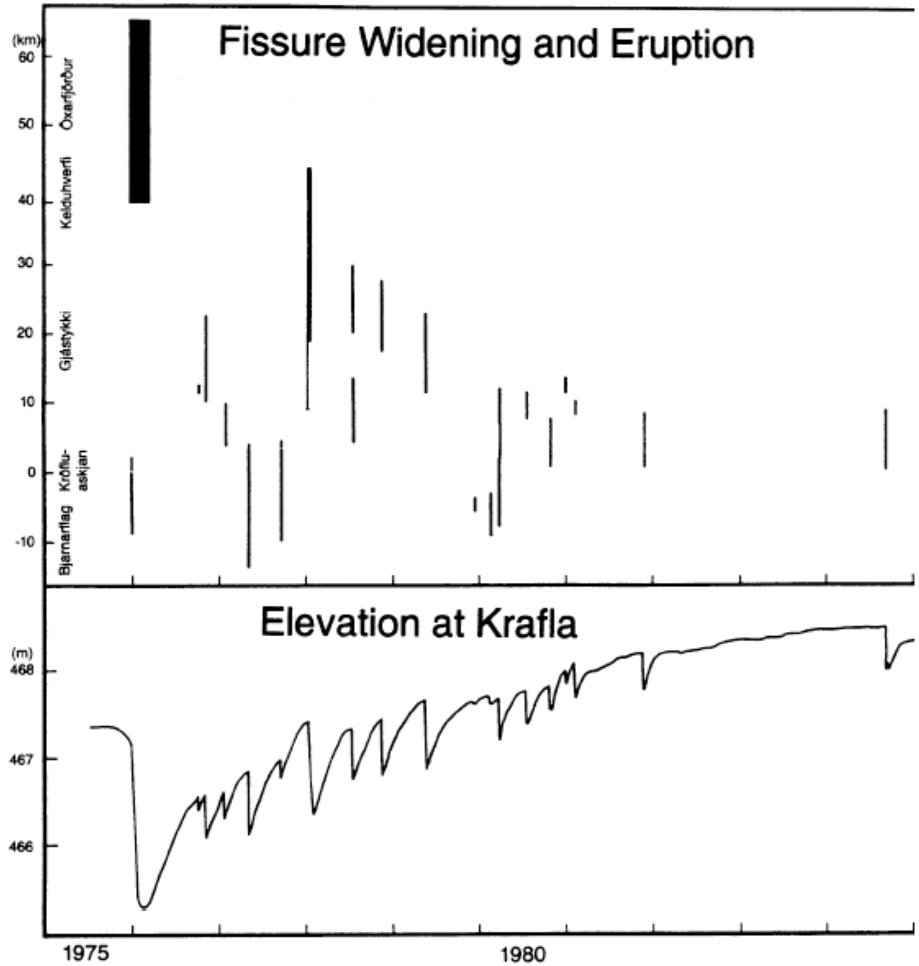
a.
Constant Initial Stress
Tectonic Stress
$P_f = \sigma_f(x)$
ΔP_s
$\sigma_i(x)$
x_1
x_2
Distance from Magma Chamber
b.
Decreasing then Increasing Initial Stress
Tectonic Stress
$P_f = \sigma_f(x)$
ΔP_s
$\sigma_i(x)$
x_1
x_2
Distance from Magma Chamber



ΔP_B = 10 MPa, ΔP_S = 5 MPa, L_0 = 10 km
Tectonic Stress (MPa)
Distance (km)
Dike Opening
Distance (km)
Magma Chamber Pressure
Pressure (MPa)
Event Number

T = 5 MPa, ΔP =10 MPa



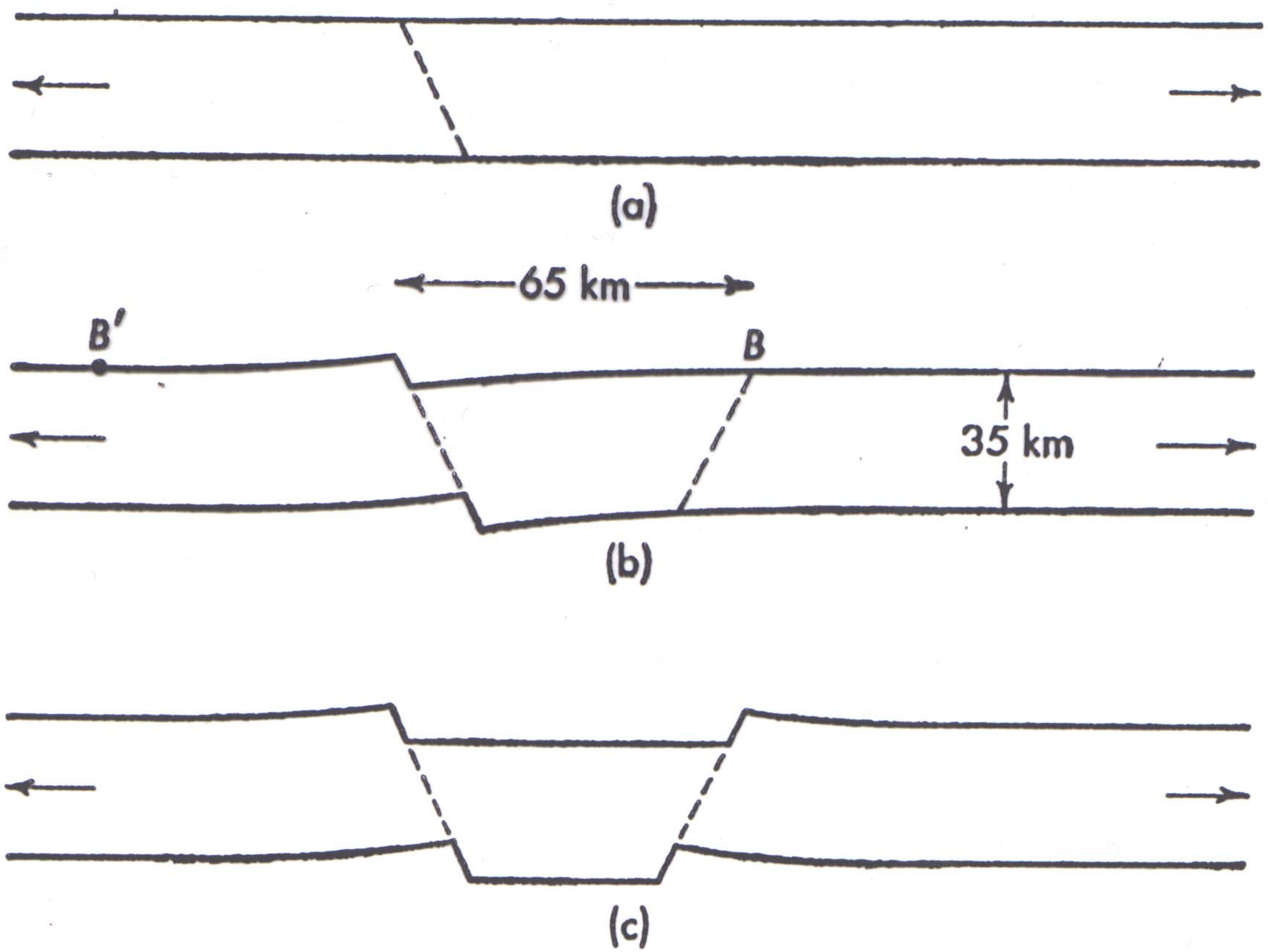


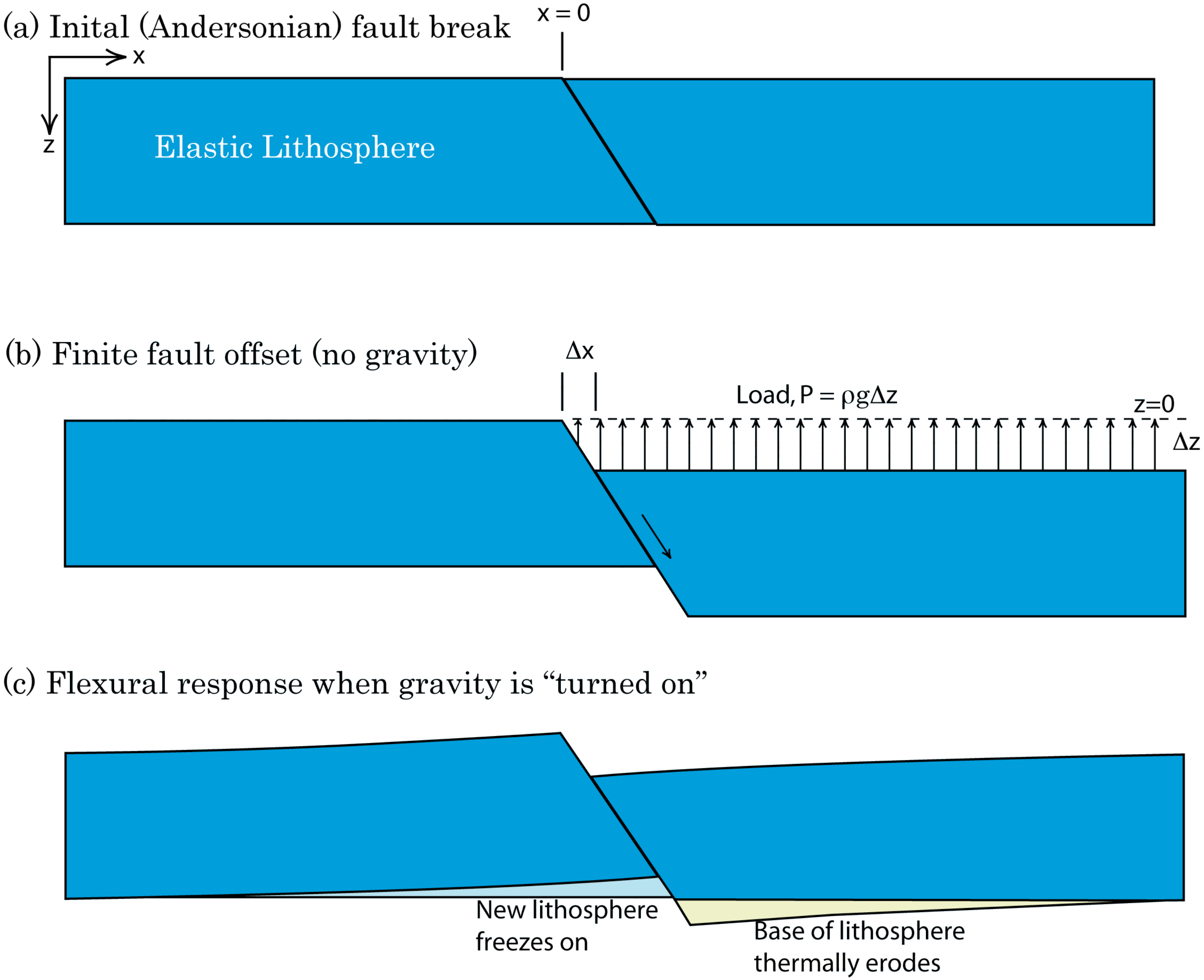
Simple models of Normal Faulting

Big Question: How far can a normal fault slip before another fault takes over.

Motivation: A few normal faults slip a huge amount.

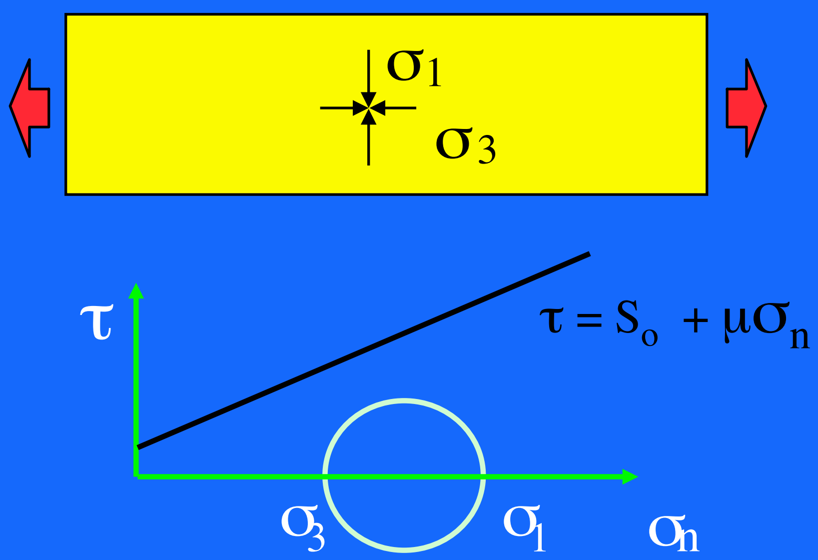
Gravitational Stress on a Flexing Layer Scale



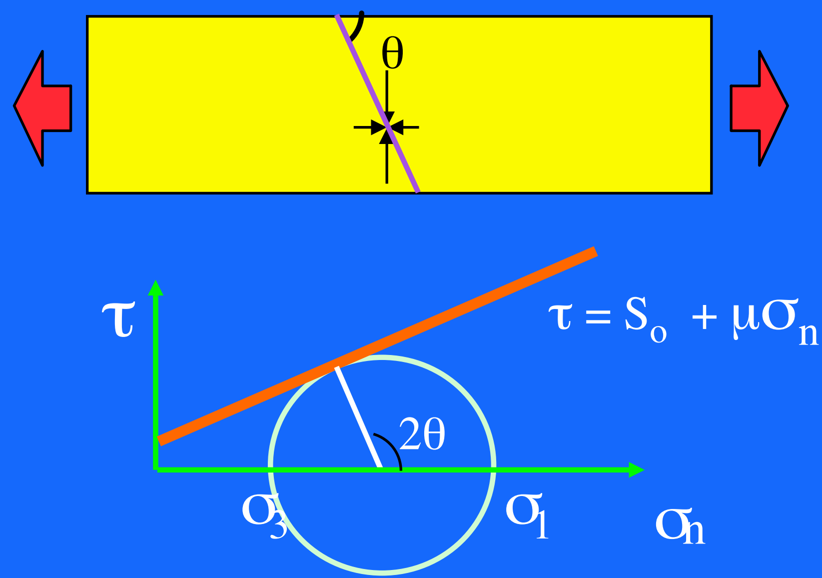


(a) Inital (Andersonian) fault break
x = 0
x
z
Elastic Lithosphere
(b) Finite fault offset (no gravity)
Δx
Load, P = ρgΔz
z=0
Δz
(c) Flexural response when gravity is "turned on"
New lithosphere
freezes on
Base of lithosphere
thermally erodes

Andersonian Stress State



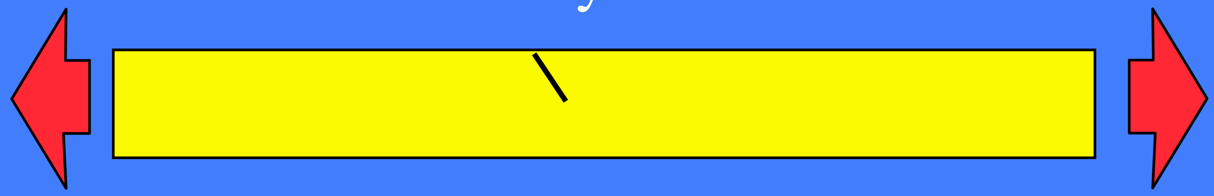
Andersonian Breaking State

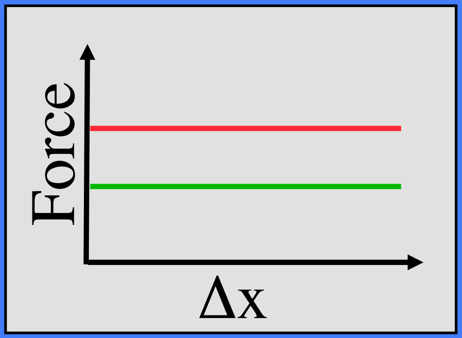


Finite Offset of Elastic Layer

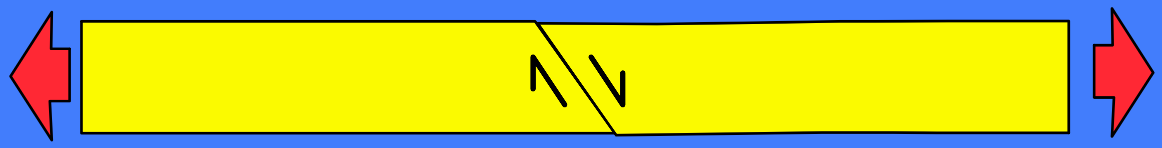
(after Forsyth, Geology, 1992)

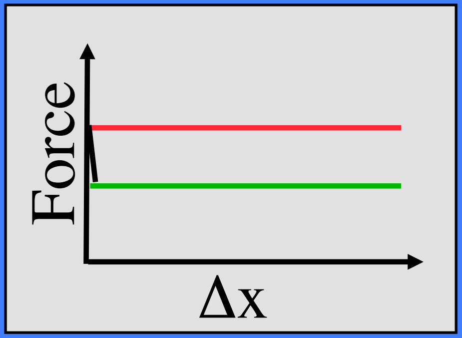
Fault Breaks Layer





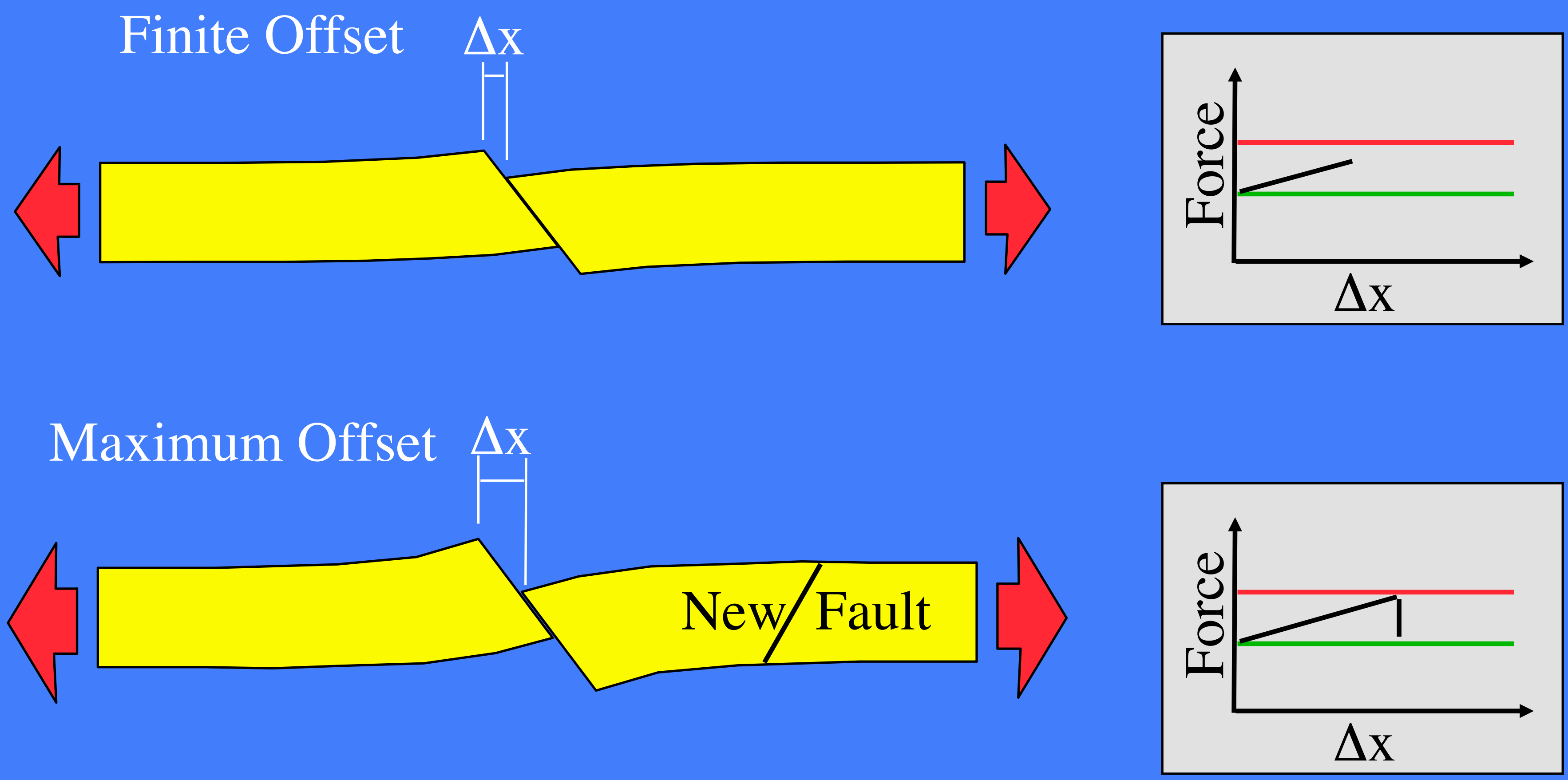
Fault Begins to Slip

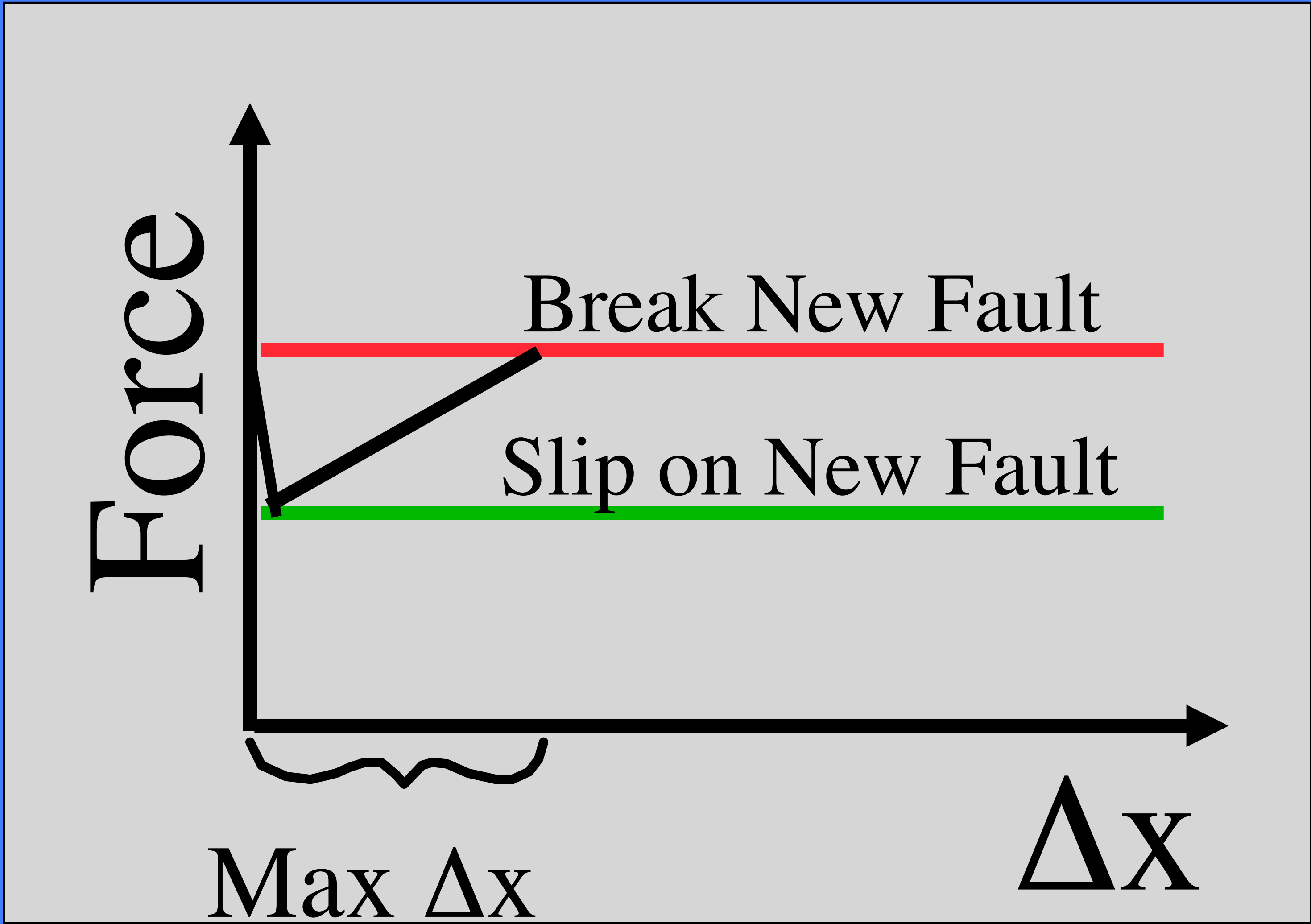




Finite Offset of Elastic Layer

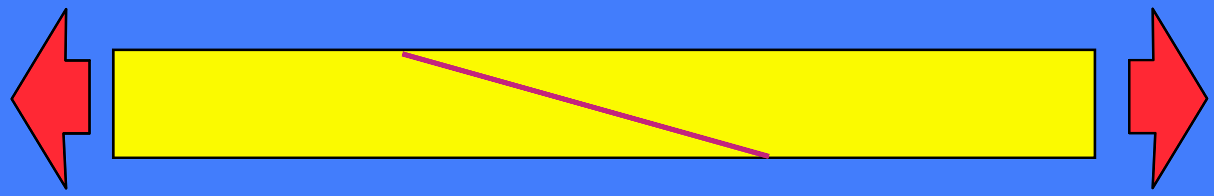
(after Forsyth, Geology, 1992)

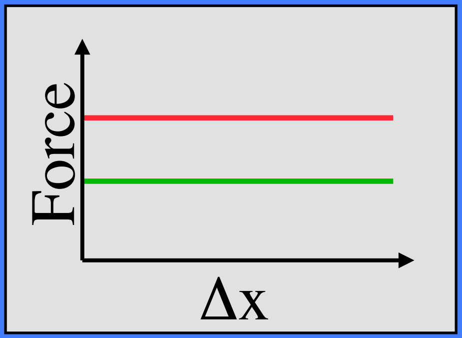



Force
Break New Fault
Slip on New Fault
Max Δx
Δx

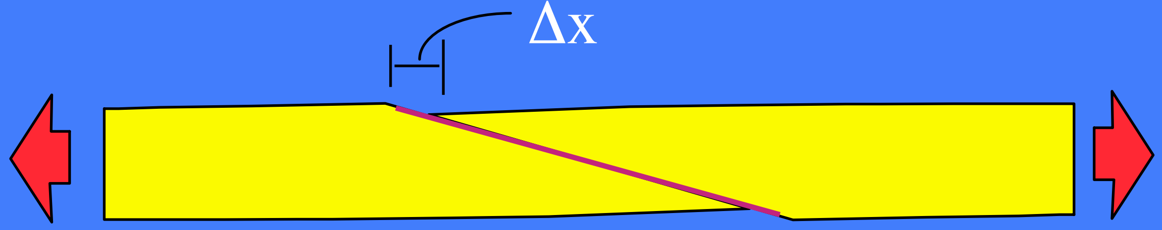
Finite Offset of Elastic Layer
(after Forsyth, Geology, 1992)

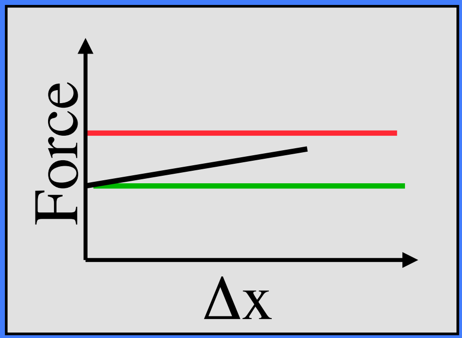
Assume Pre-existing Weak Fault



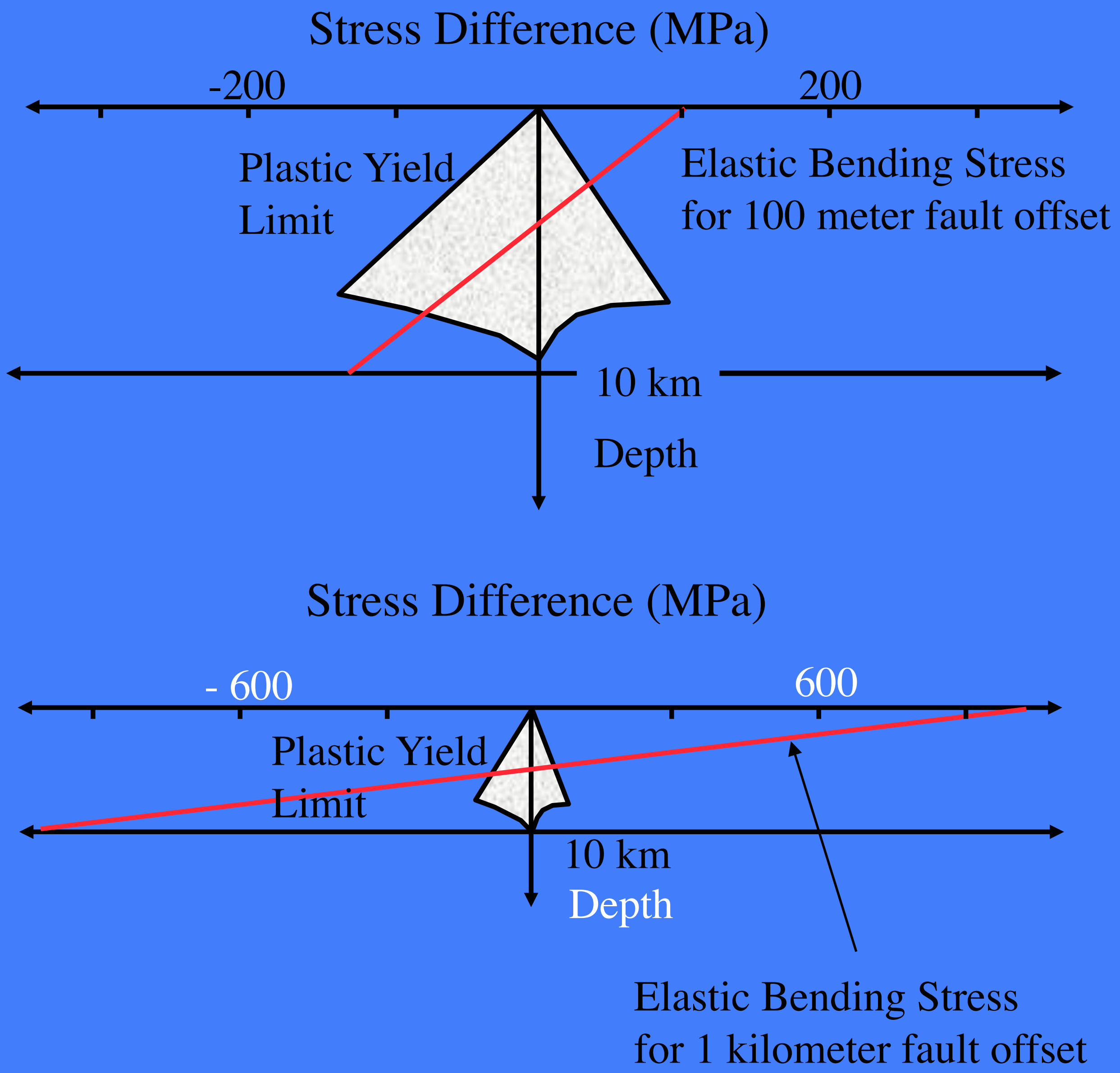


Slip on Low-angle Weak Fault





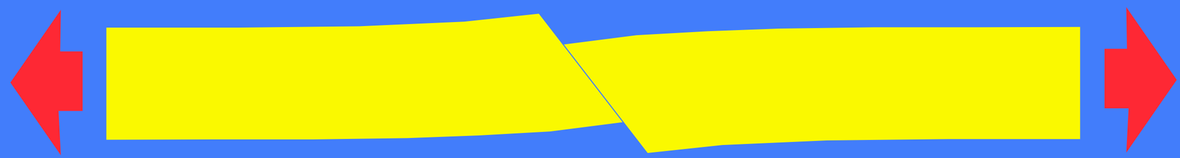
Stresses due to Plate Bending

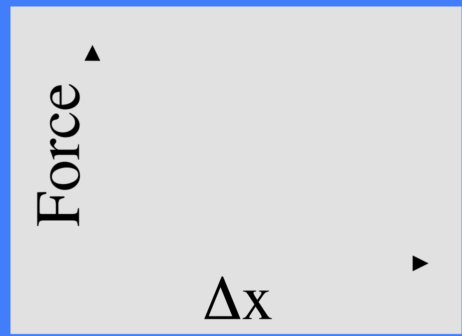


Finite Offset of Elastic-Plastic Layer

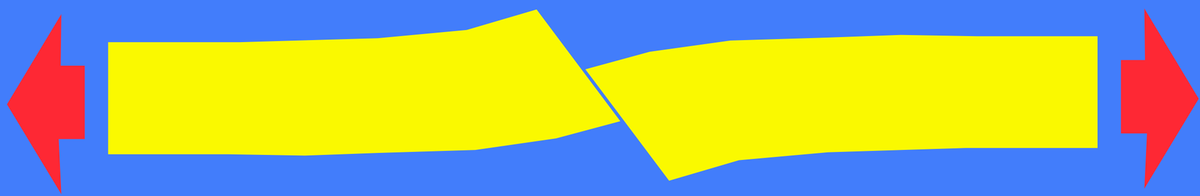
(after Buck, Geology, 1993)

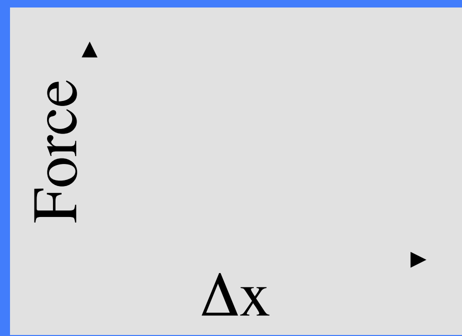
Finite Offset Δx



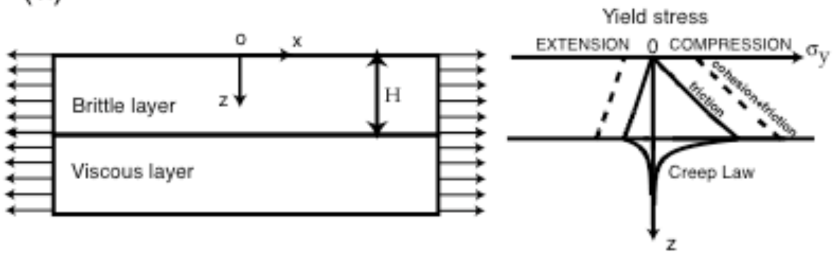


Offset Δx taking Maximum Force



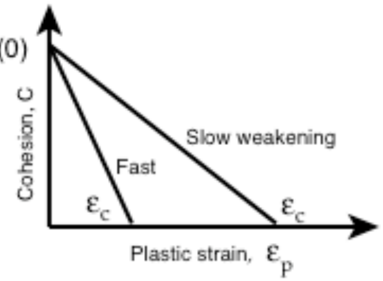


(a)

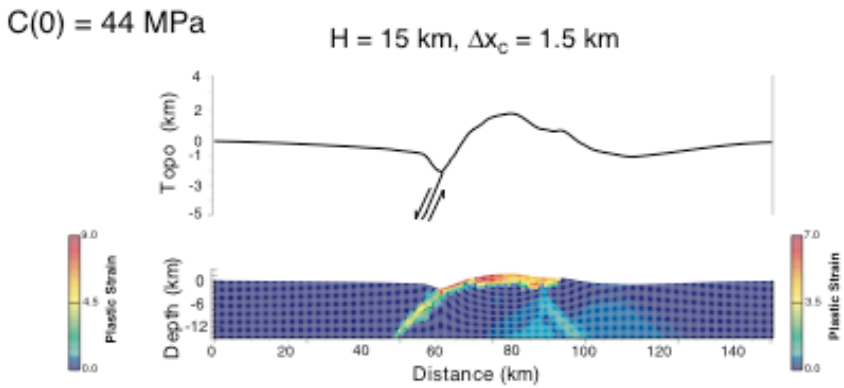


o
x
z
H
Brittle layer
Viscous layer
Yield stress
EXTENSION
0
COMPRESSION
σ_y
cohesion+friction
friction
Creep Law
z

(b)

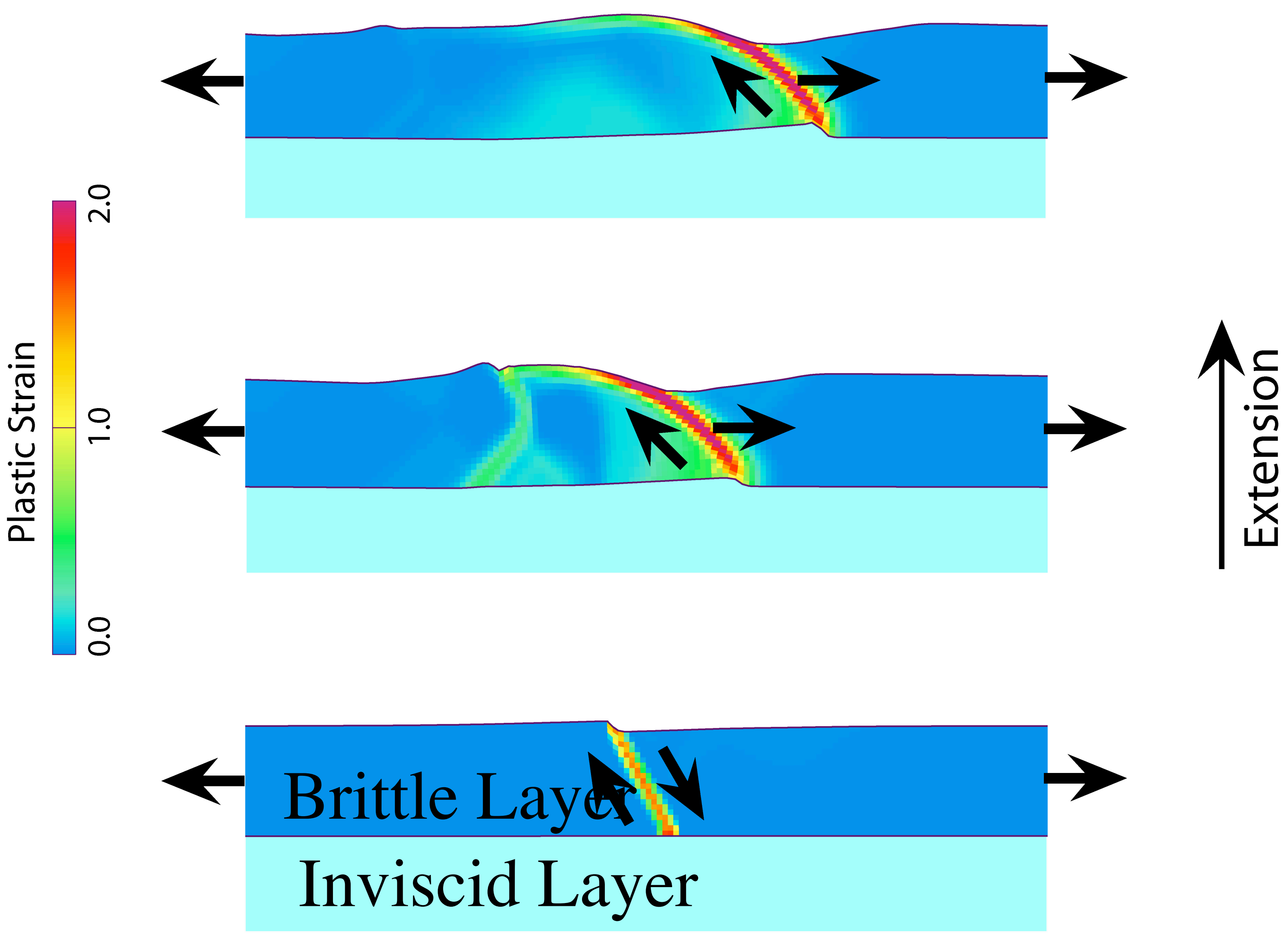


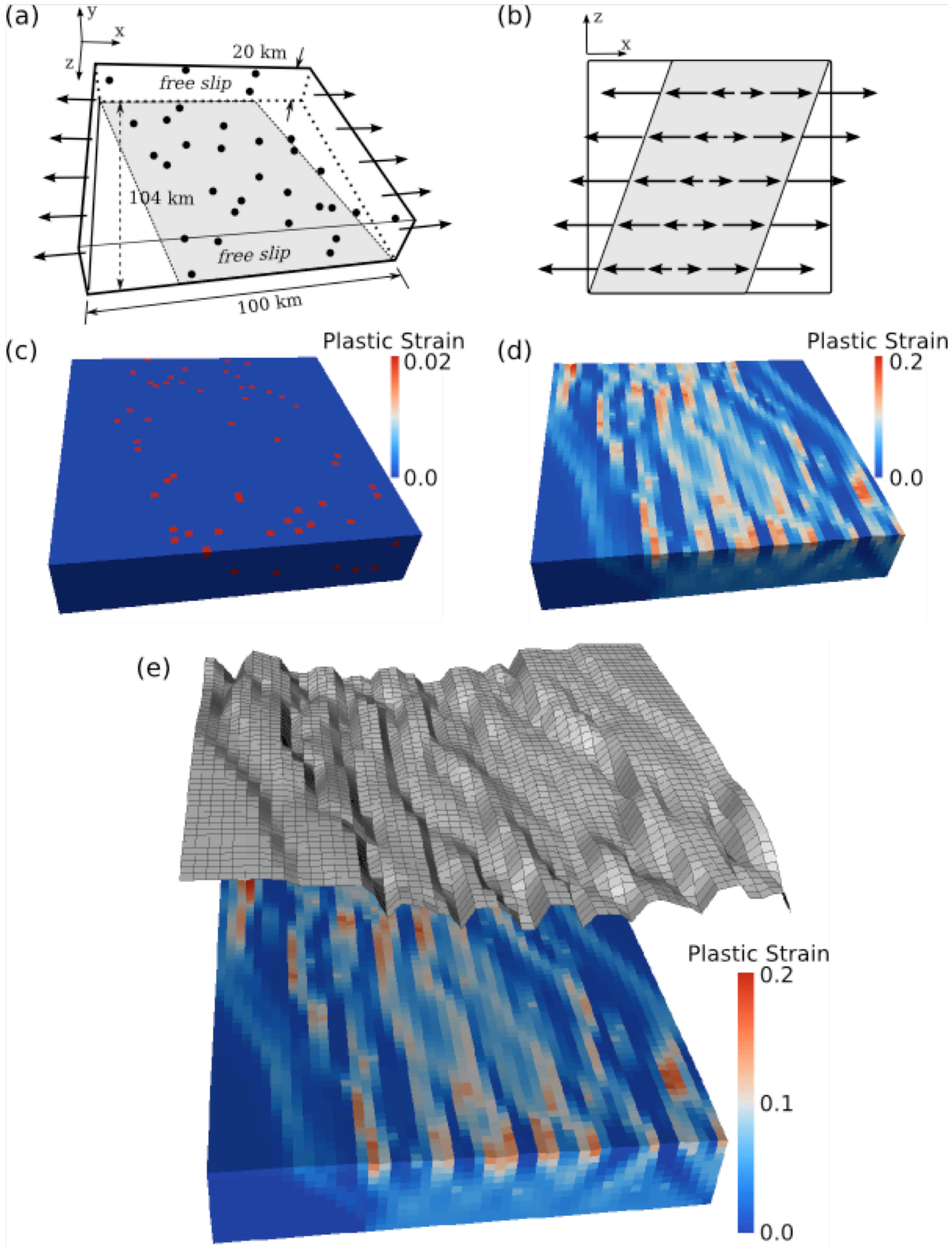
C(0)
Cohesion, C
Slow weakening
Fast
ε_c
ε_c
Plastic strain, ε_p



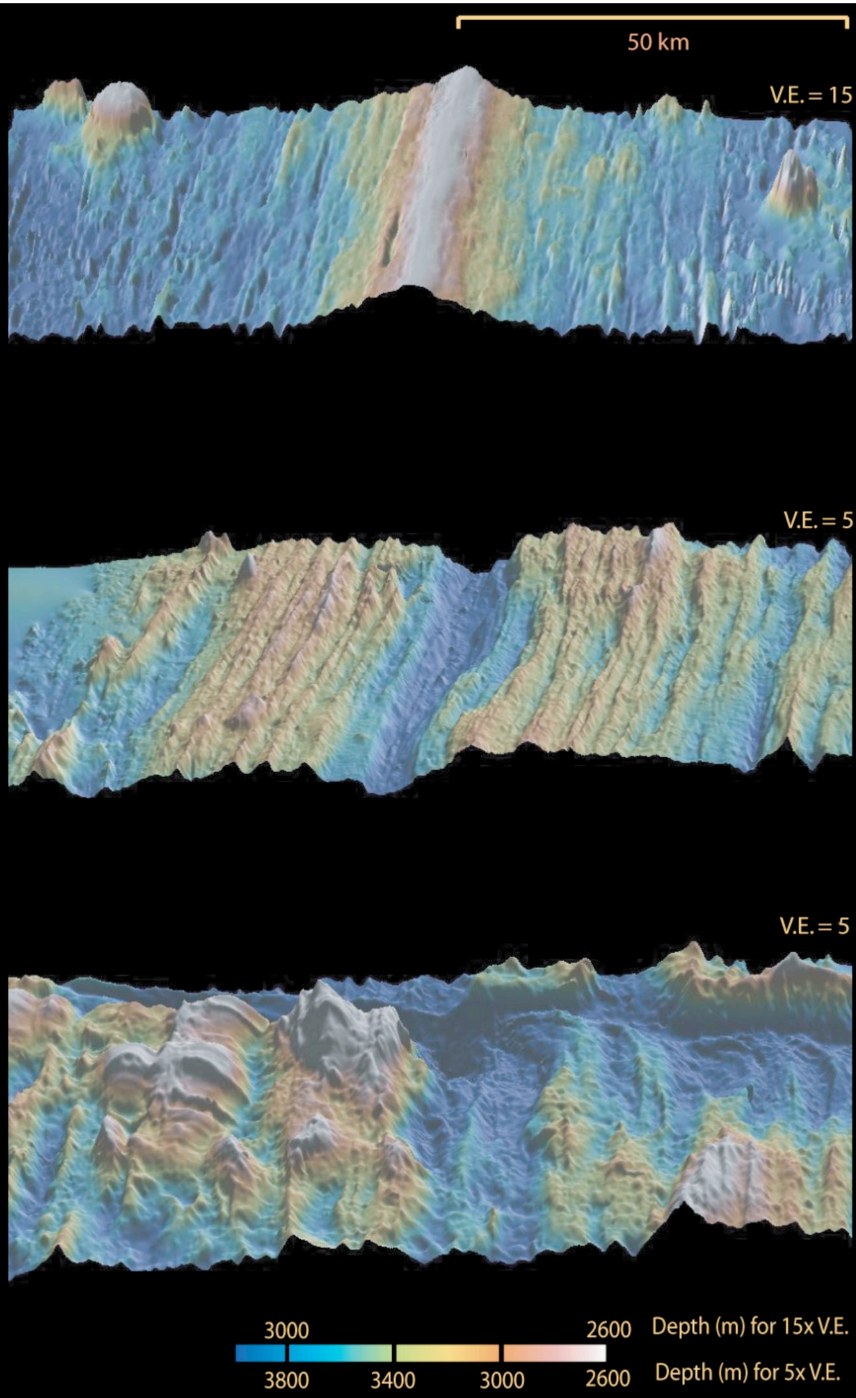
C(0) = 44 MPa
H = 15 km, Δx_c = 1.5 km
Topo (km)
Depth (km)
Distance (km)
Plastic Strain
Plastic Strain

Extension of Floating Brittle Layers:
Single ***Fault*** Moves with ***Upper Plate***





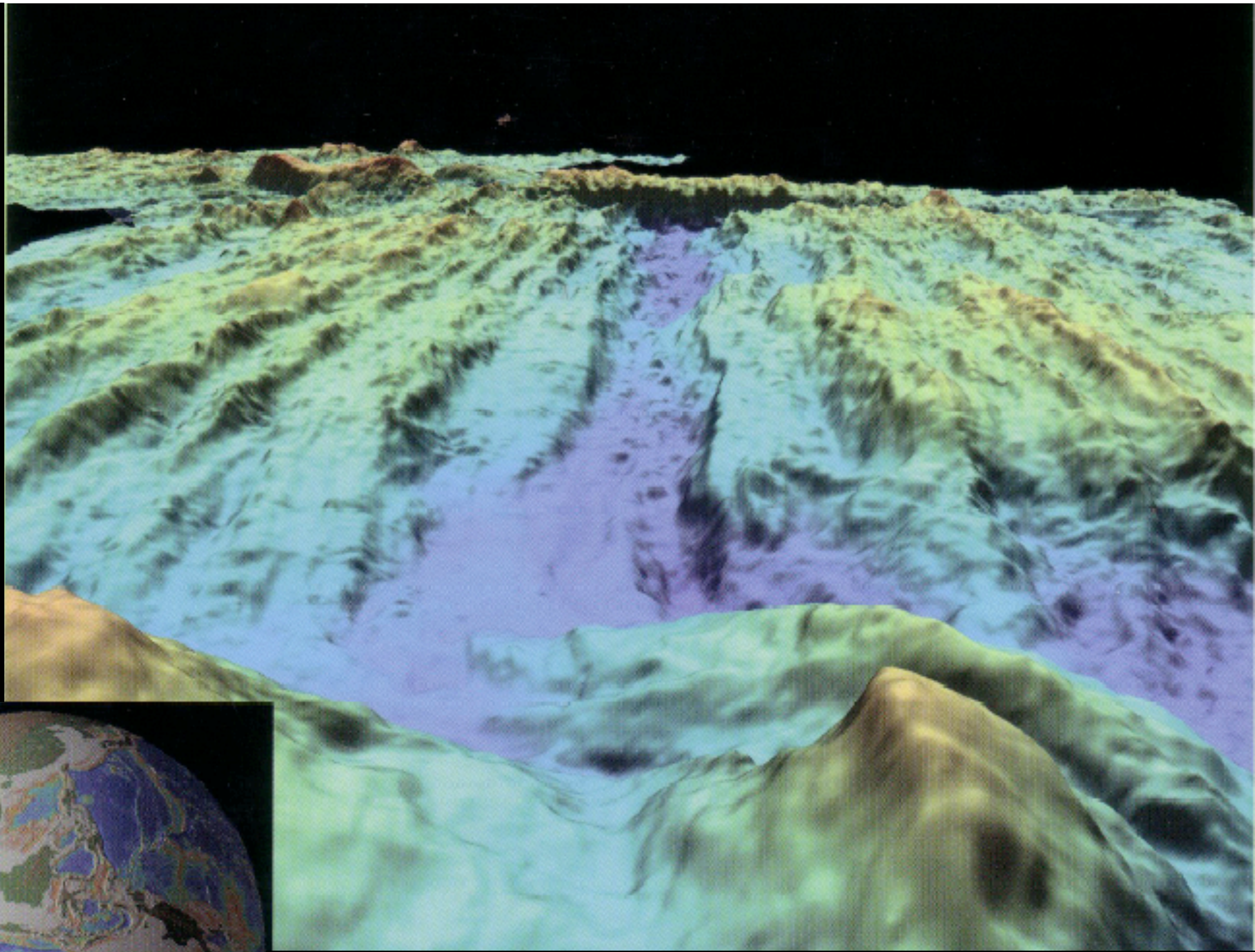
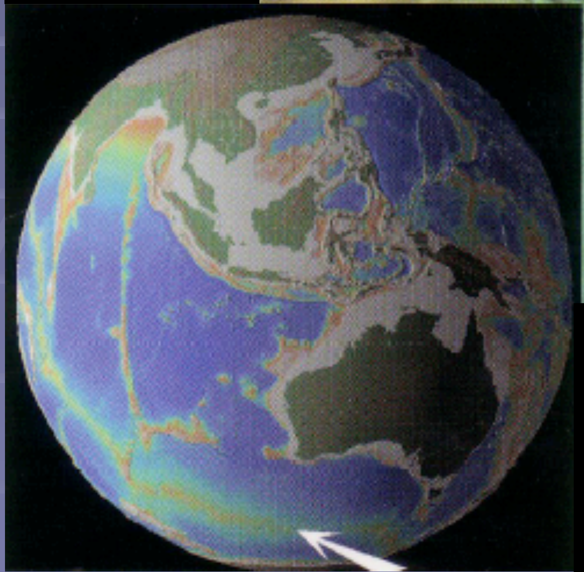
From Eunseo Choi



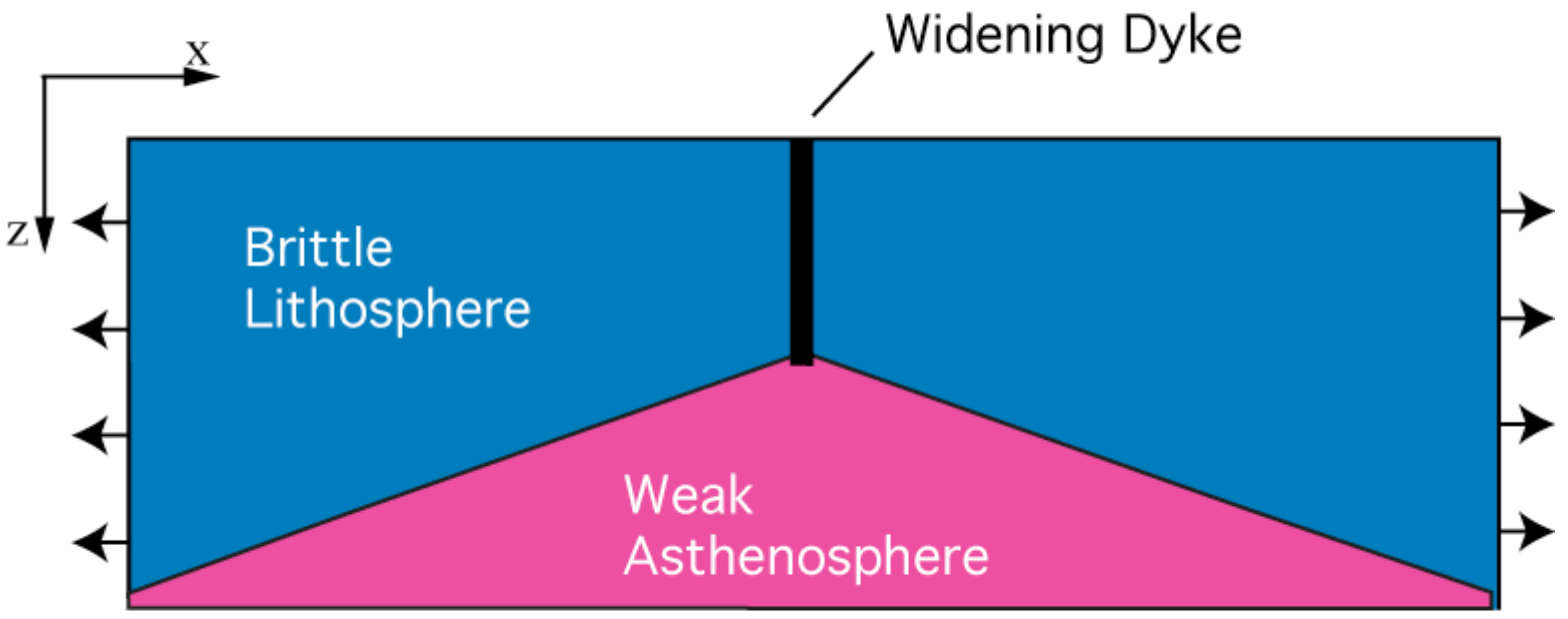
AXIAL HIGH

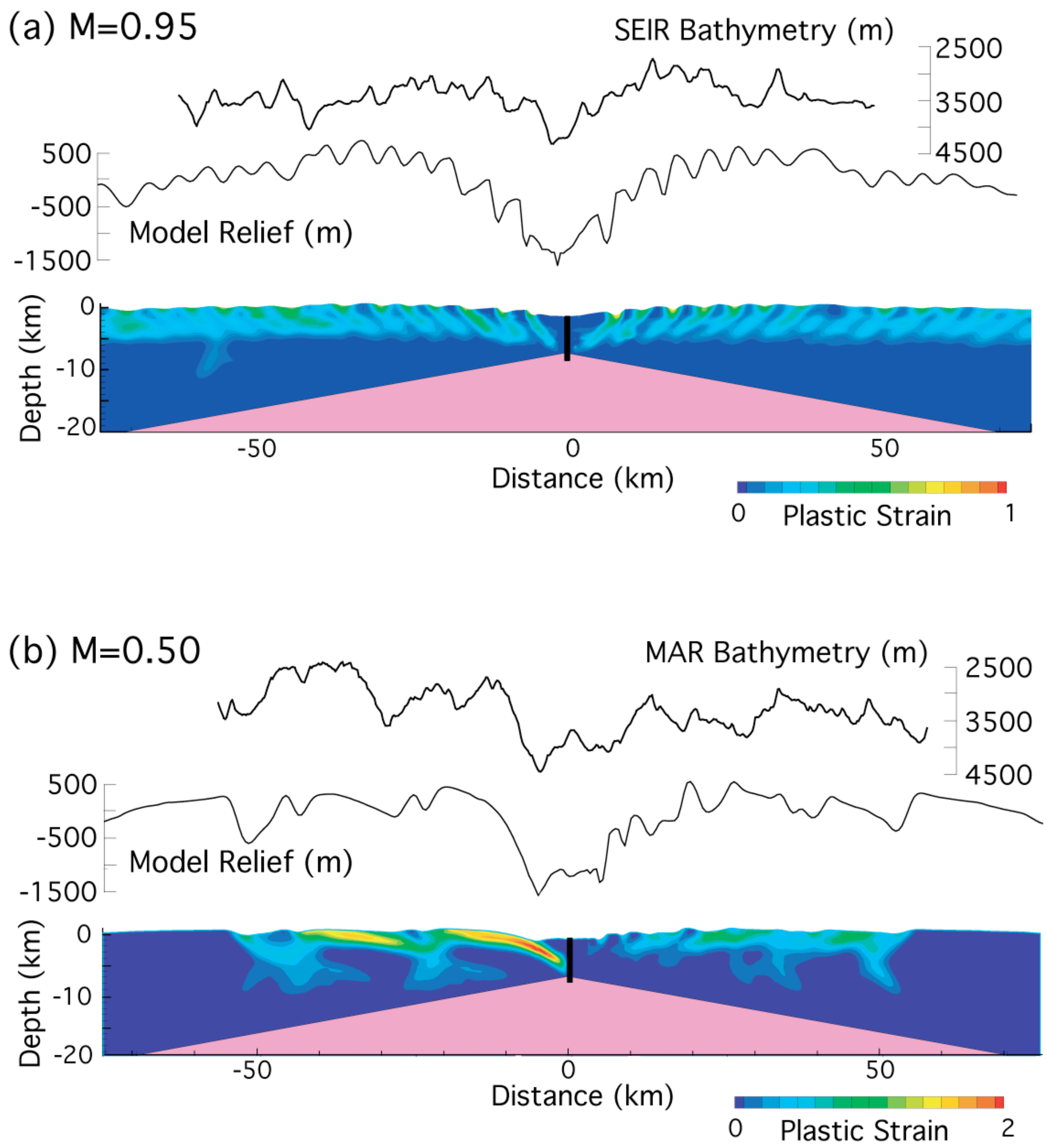
AXIAL VALLEY

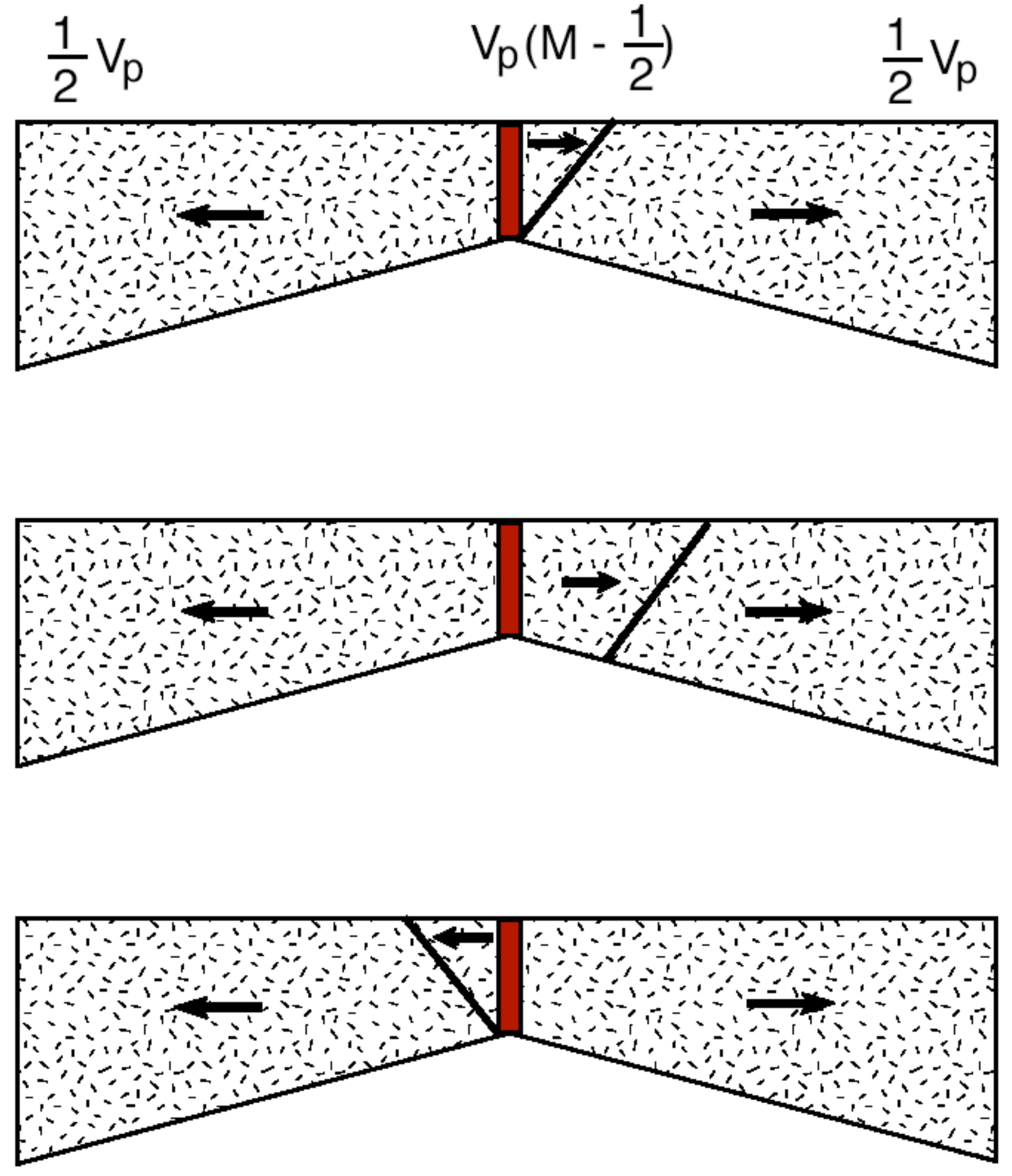
OCEANIC
CORE COMPLEX

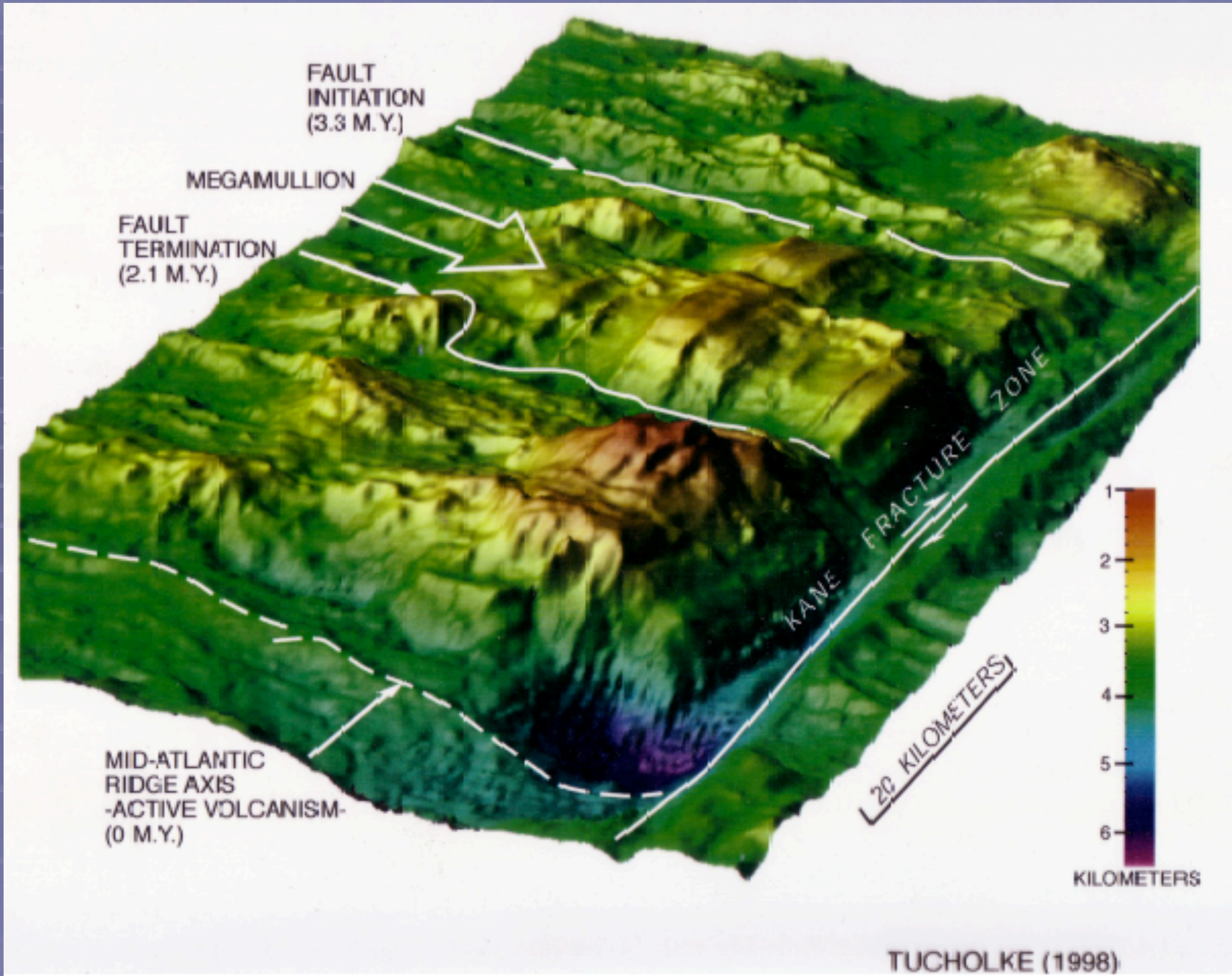
Model Setup



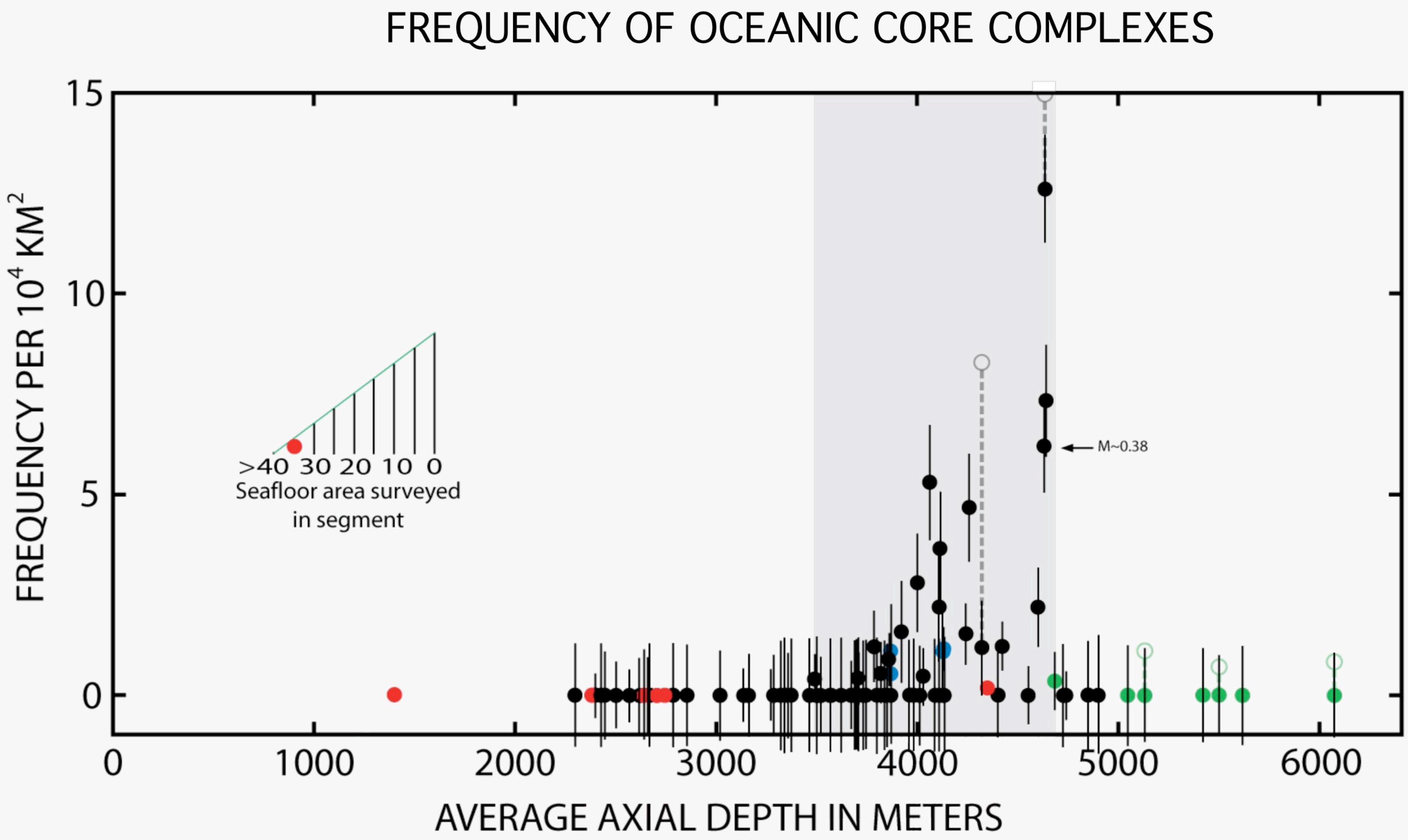

(a) M=0.95
SEIR Bathymetry (m)
2500
3500
4500
500
-500
-1500
Model Relief (m)
Depth (km)
0
-10
-20
-50
0
50
Distance (km)
0
Plastic Strain
1
(b) M=0.50
MAR Bathymetry (m)
2500
3500
4500
500
-500
-1500
Model Relief (m)
Depth (km)
0
-10
-20
-50
0
50
Distance (km)
0
Plastic Strain
2



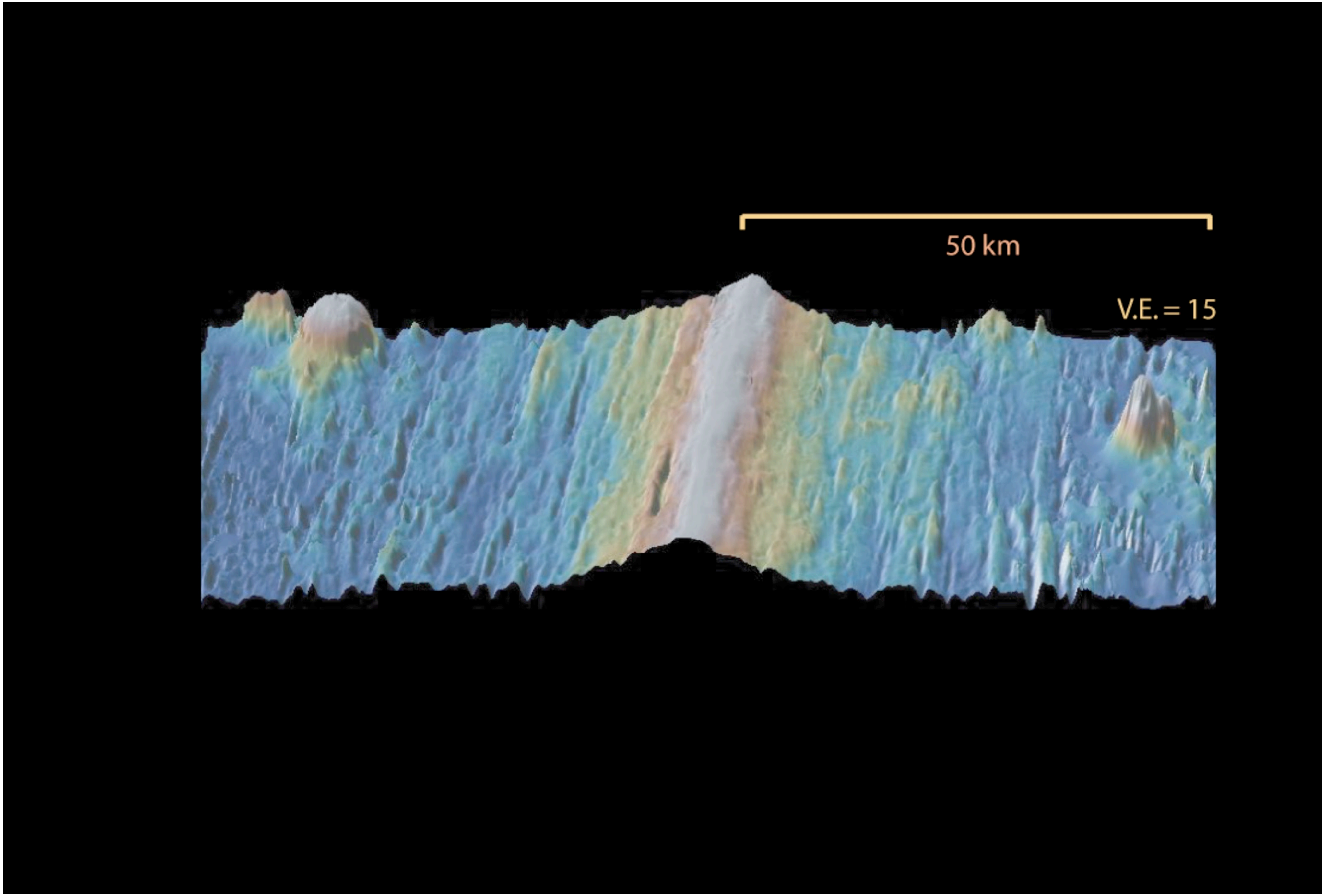
$\frac{1}{2}V_p$
$V_p(M - \frac{1}{2})$
$\frac{1}{2}V_p$

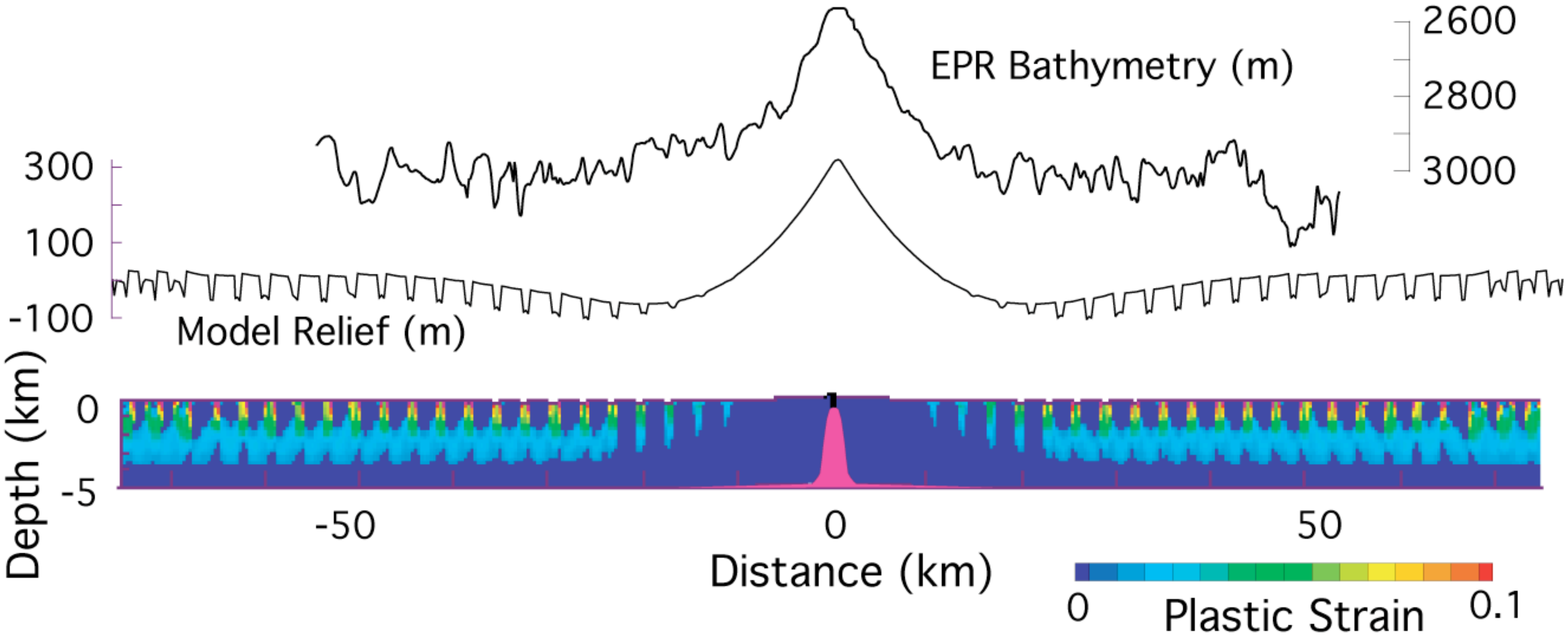

FAULT
INITIATION
(3.3 M.Y.)
MEGAMULLION
FAULT
TERMINATION
(2.1 M.Y.)
KANE FRACTURE ZONE
MID-ATLANTIC
RIDGE AXIS
-ACTIVE VOLCANISM-
(0 M.Y.)
20 KILOMETERS
1
2
3
4
5
6
KILOMETERS
TUCHOLKE (1998)

Data is consistent with the 'Goldilocks Hypothesis'



Tucholke, Behn, Buck and Lin, Geology (2008)

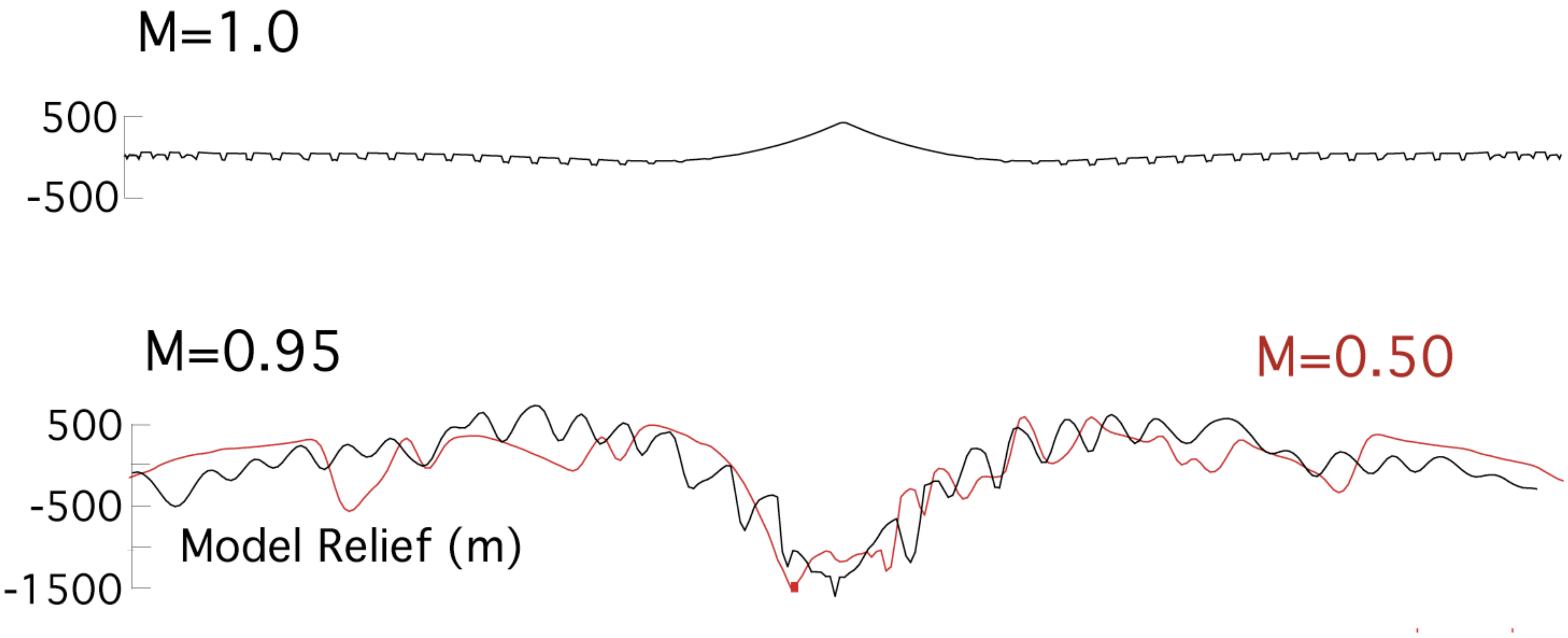

50 km
V.E. = 15



2600
EPR Bathymetry (m)
2800
3000
300
100
-100
Model Relief (m)
Depth (km)
0
-5
-50
0
50
Distance (km)
0
Plastic Strain
0.1

Problem: For fixed M

Model gives either a high for M=1 or a very deep low for M<1

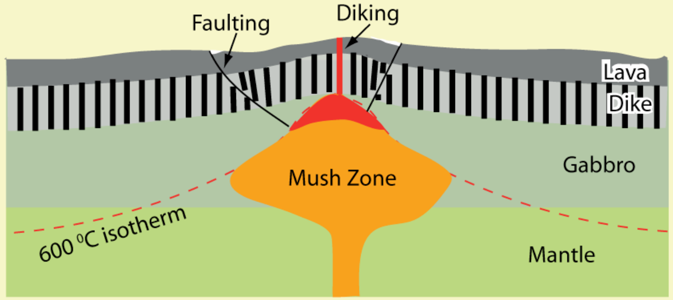


New Model

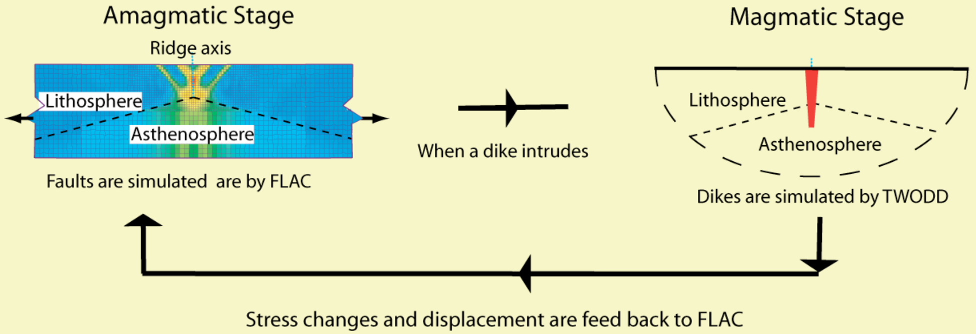
Possible Solution

Magma input, and so *M*, increases with axial depth.

Rationale: More magma is pulled into a deeper section of ridge axis where pressures are lower.

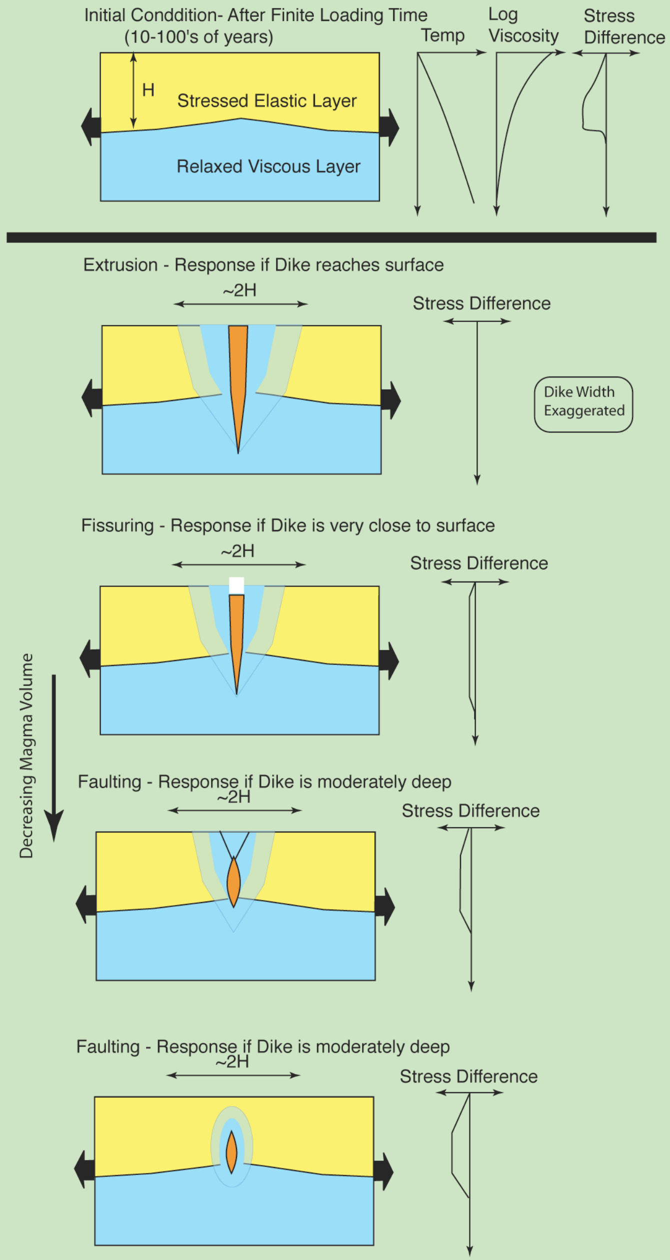


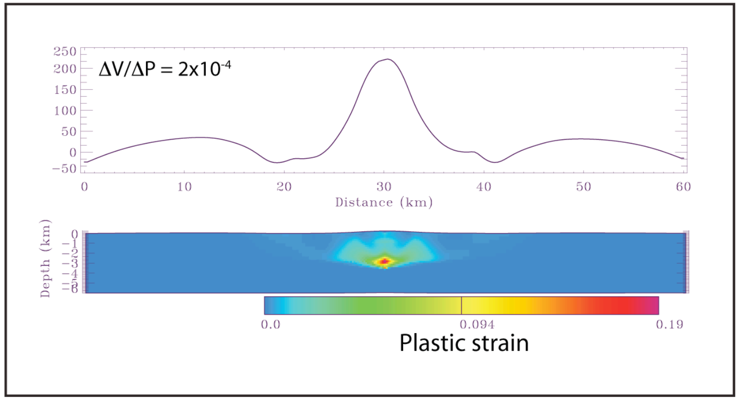
We simulate periodic dike opening and fault offset in response to an evolving stress field produced by plate separation.

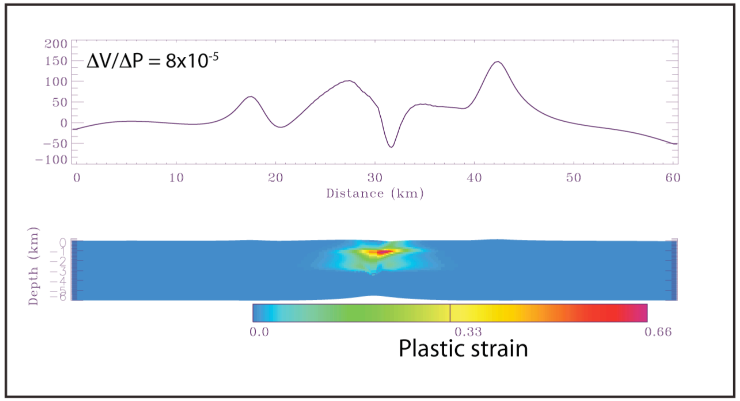


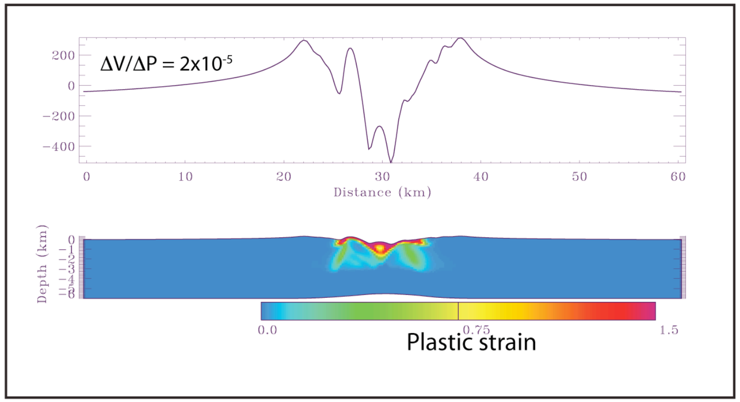
Magma input increases with decreasing axial depth by a set relation between magma volume injected in a dike episode and magma pressure (ΔV/ΔP). Magma that does not fill a dike is extruded.

Effect of Magma Volume on the Type of Dike Intrusion
(cases allowed in the new model)

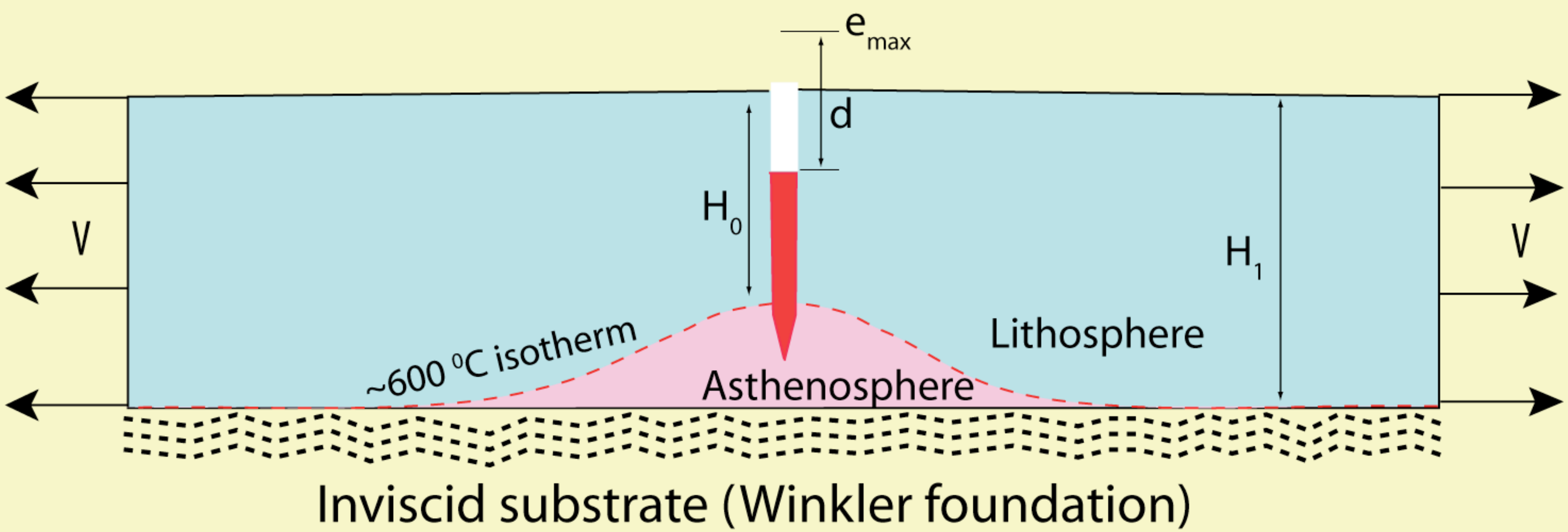


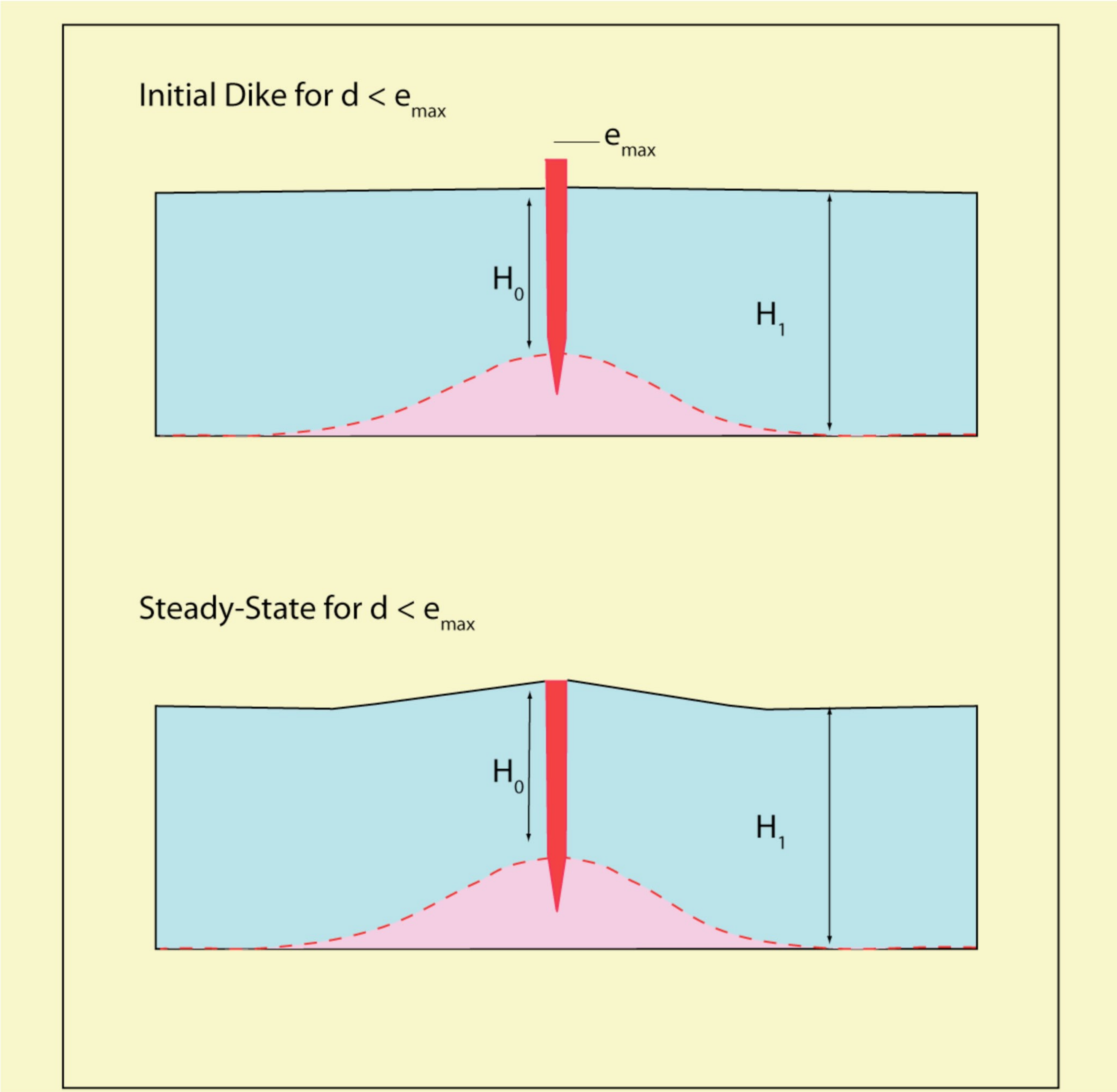

ΔV/ΔP = 2x10-4
250
200
150
100
50
0
−50
0
10
20
30
40
50
60
Distance (km)
Depth (km)
0.0
0.094
0.19
Plastic strain

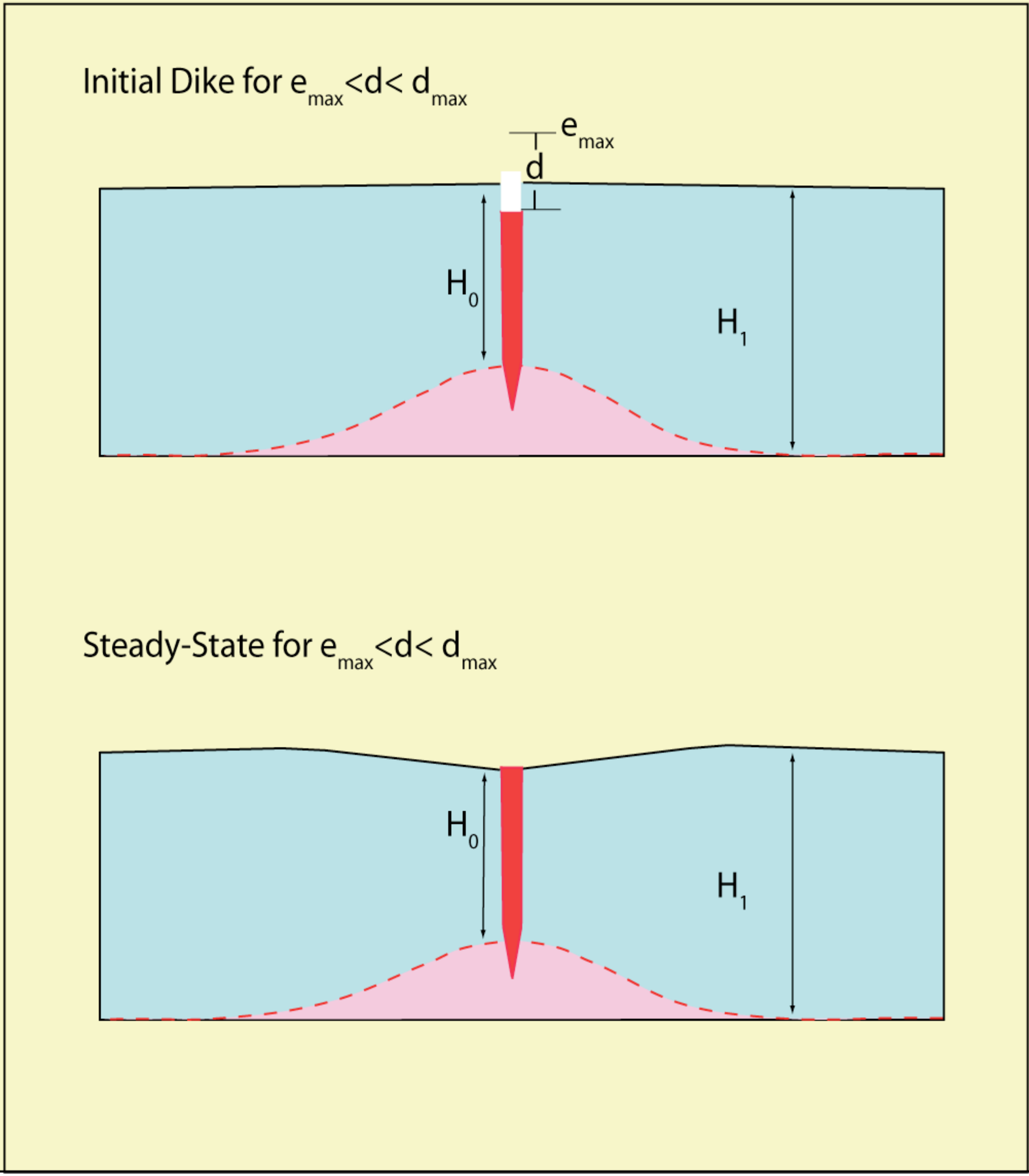

ΔV/ΔP = 8x10-5
200
150
100
50
0
−50
−100
0
10
20
30
40
50
60
Distance (km)
Depth (km)
0.0
0.33
0.66
Plastic strain


ΔV/ΔP = 2x10-5
200
0
−200
−400
0
10
20
30
40
50
60
Distance (km)
Depth (km)
0.0
0.75
1.5
Plastic strain

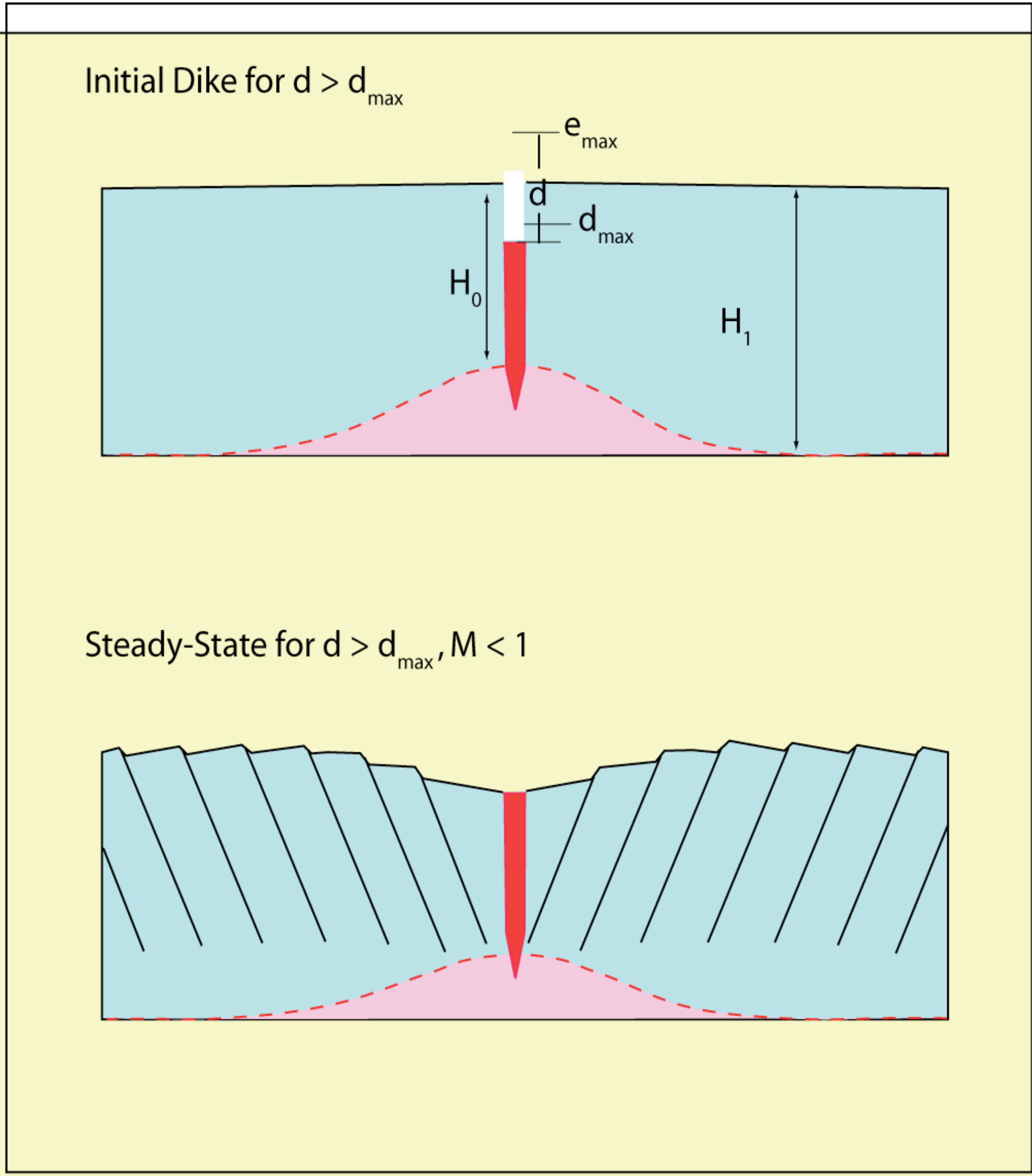
Interpretation of Model Results




Initial Dike for d < e_{max}
e_{max}
H_0
H_1
Steady-State for d < e_{max}
H_0
H_1



Initial Dike for e_max<d< d_max
e_max
d
H_0
H_1
Steady-State for e_max<d< d_max
H_0
H_1



Initial Dike for d > d max
e max
d
d max
H 0
H 1
Steady-State for d > d max , M < 1

Conclusions

1. *M* must be a function of axial depth (*d*) to get the observed range of axial depths.

2. If the axial depth is less than the maximum tectonic-controlled depth (d_{max}) then M=1.

3. For M=1 axial valleys the extrusve layer thickness should be proportional to fault stretching.

4. For M<1 the axial depth equals d_{max}.

5. For M~0.5 the model gives oceanic core complex-like structures on one side of the axis.