The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

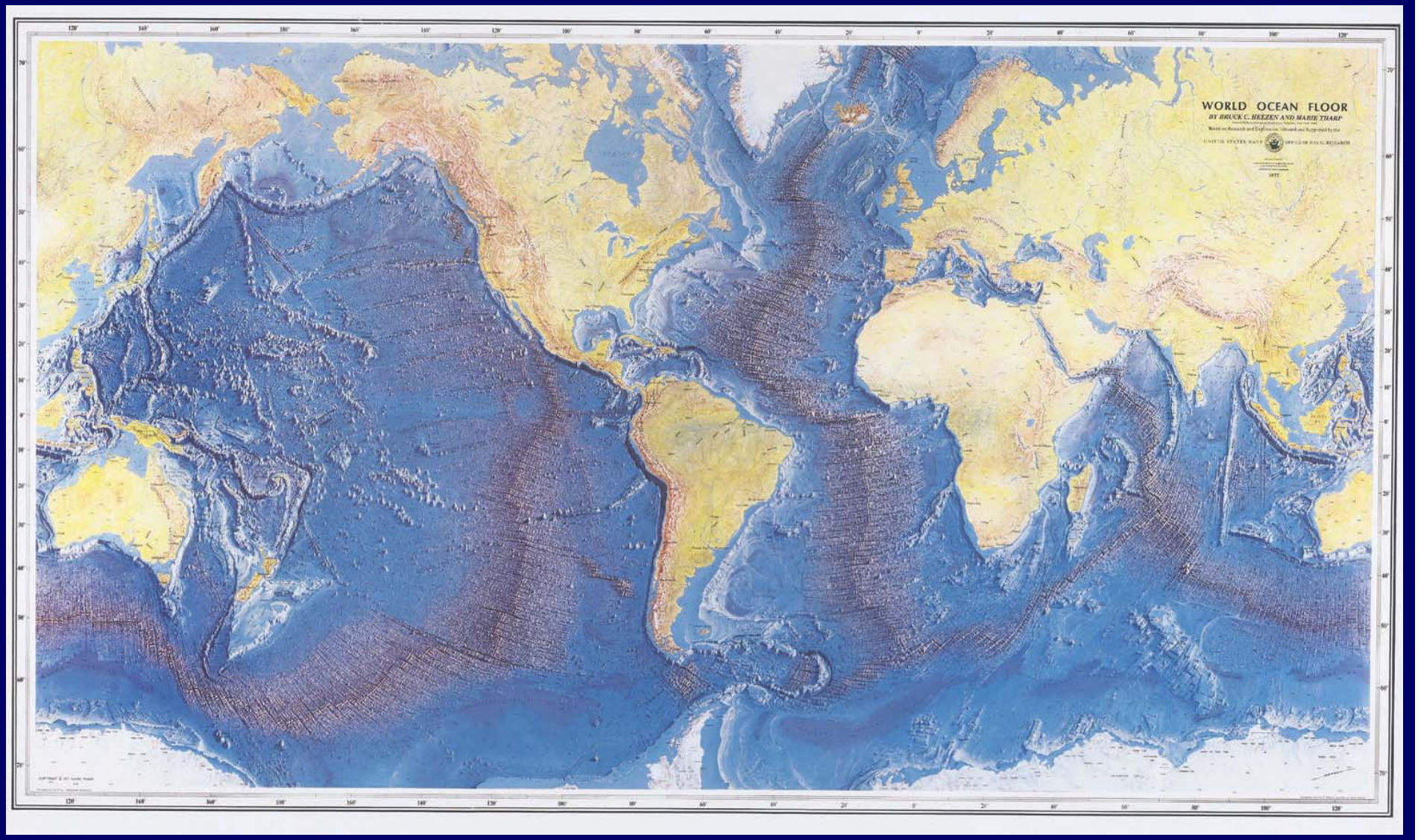
2053-9

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

17 - 28 August 2009

Magma intrusion – implications for 'hidden risks' in youthful as well as evolved rifts?

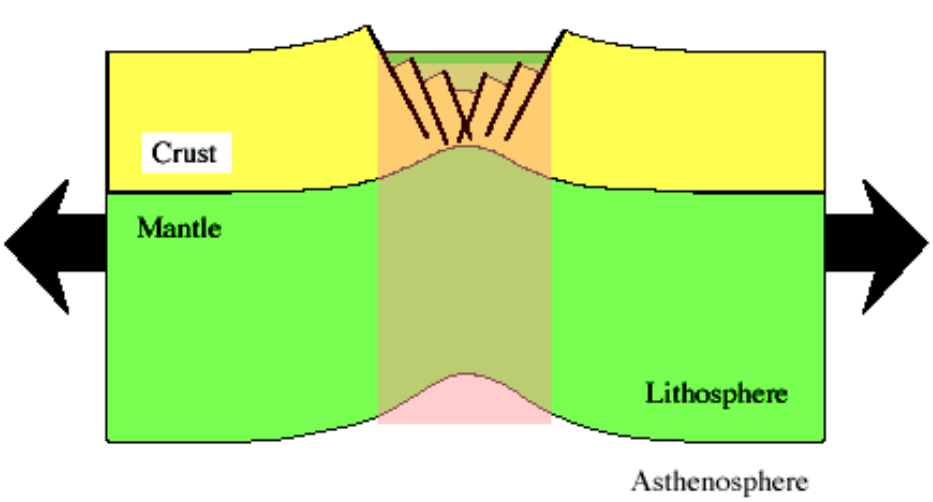
Roger Buck
Lamont Doherty Earth Observatory
New York
USA

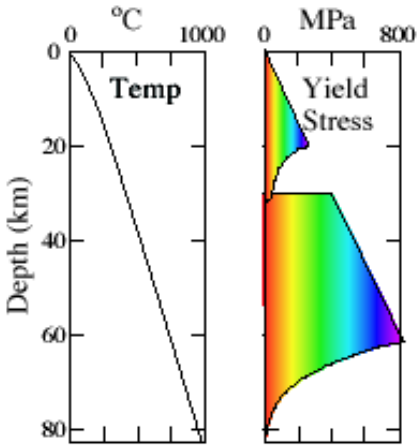

WORLD OCEAN FLOOR
BY BRUCE C. HEEZEN AND MARIE THARP

Problem For Extensional Models:

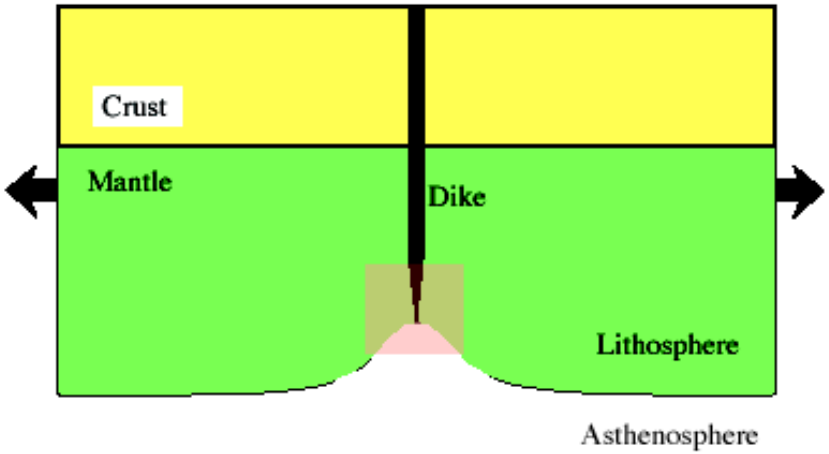
- 95% of models are amagmatic
- 95% of plate separation is by dikes

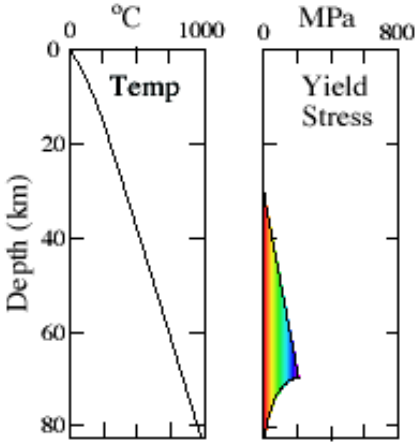
Tectonic Stretching

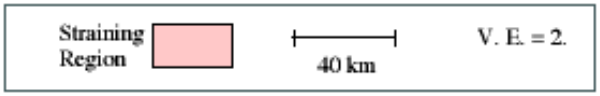


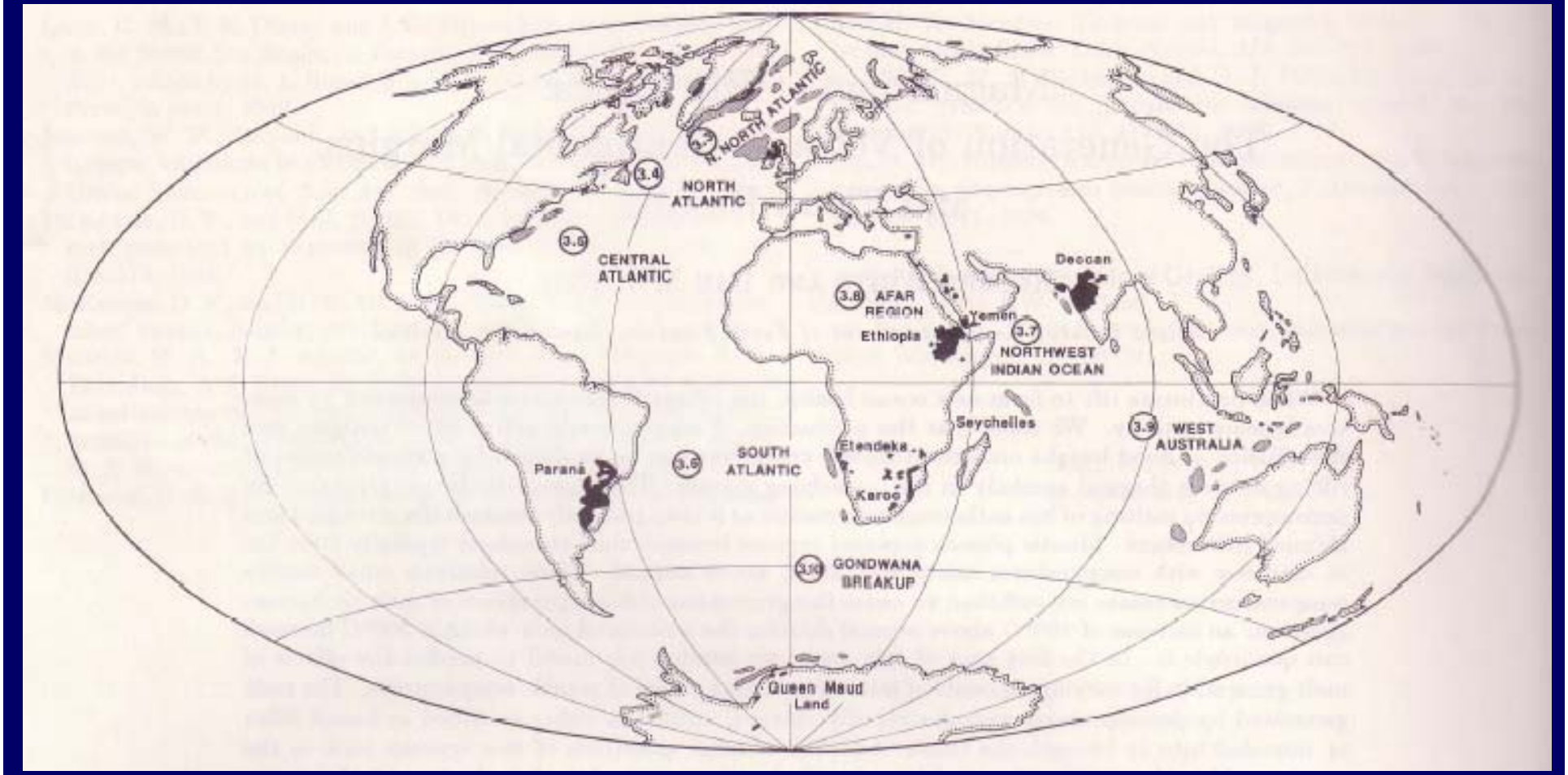


Magmatic Extension

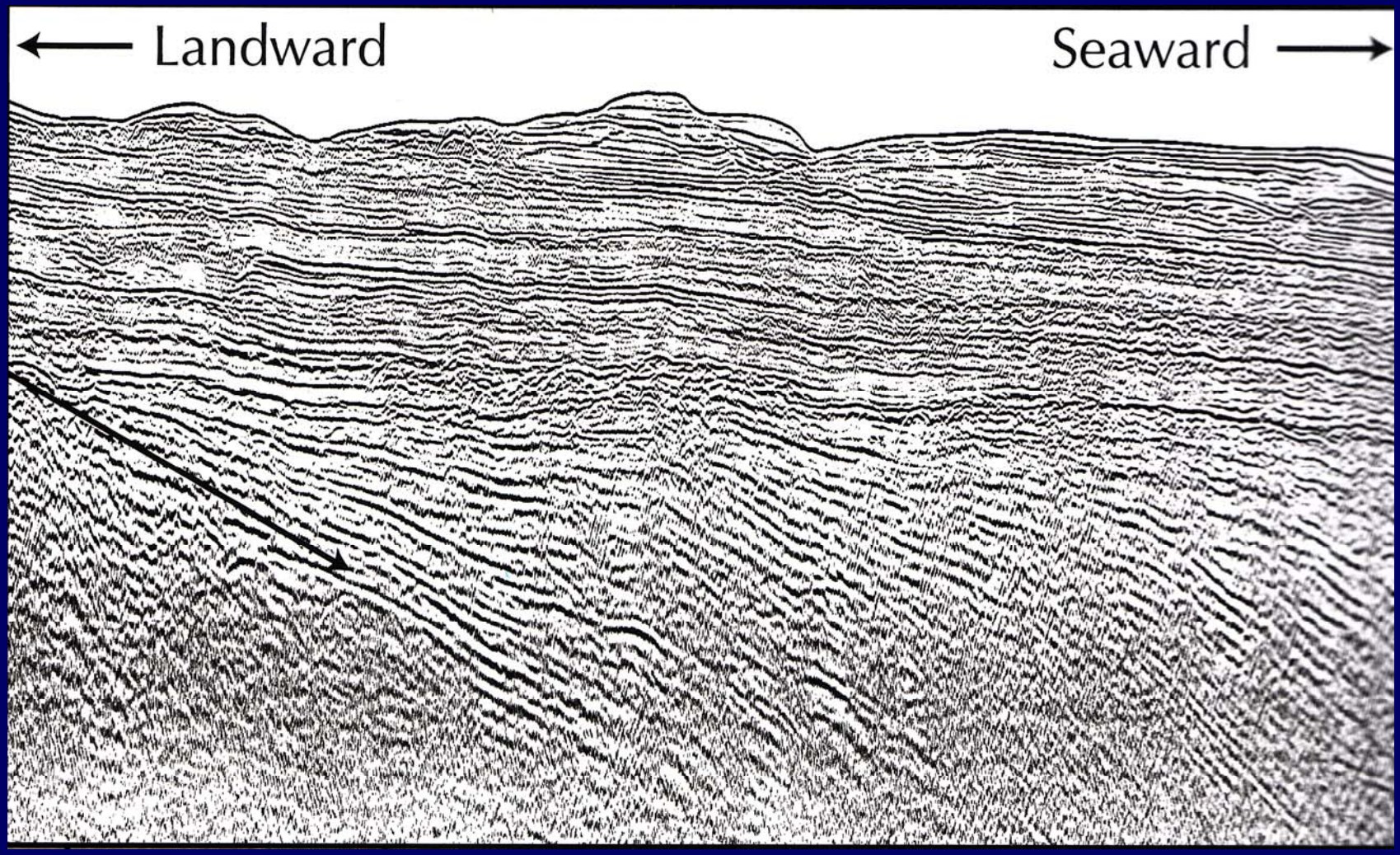


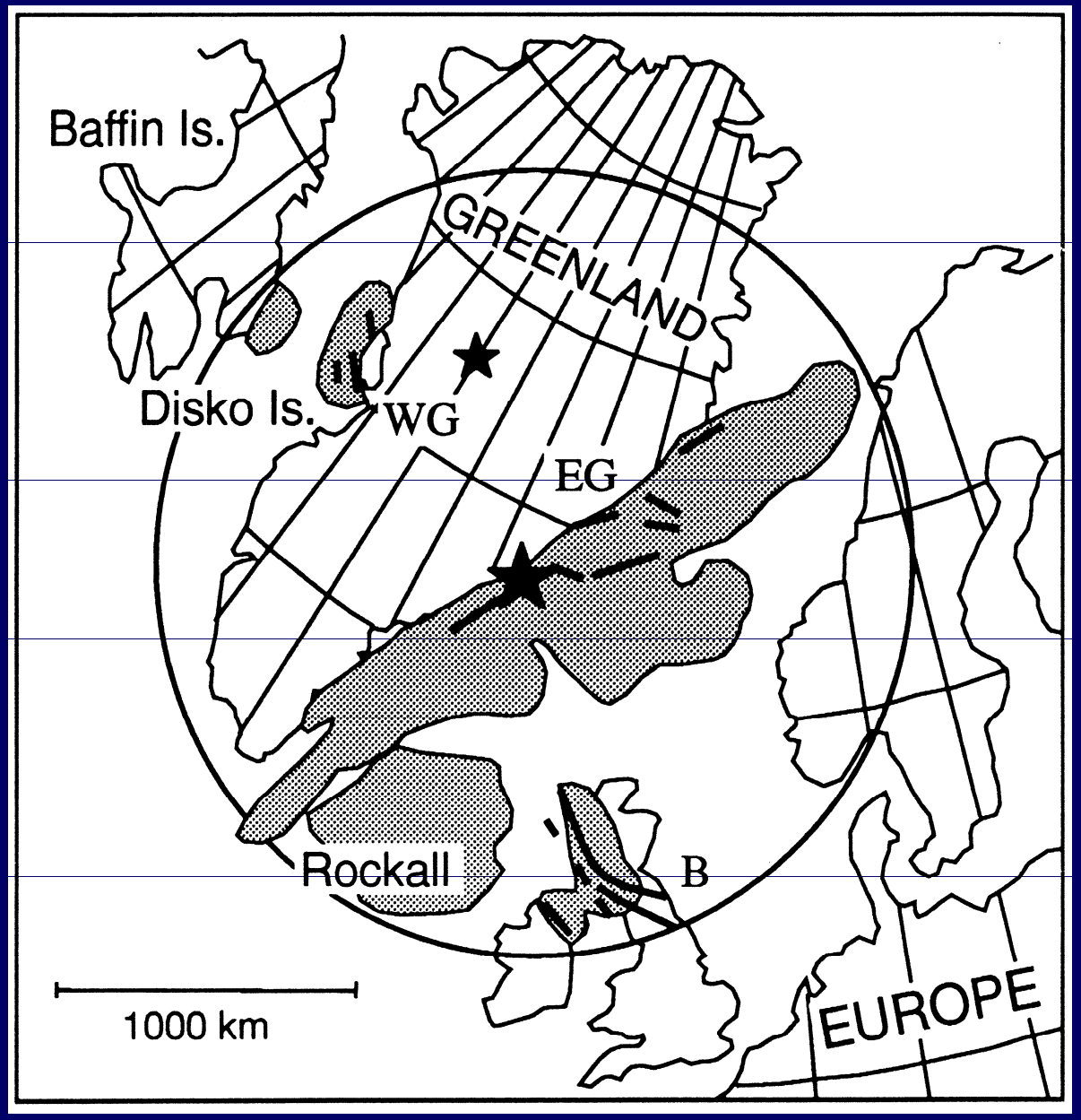


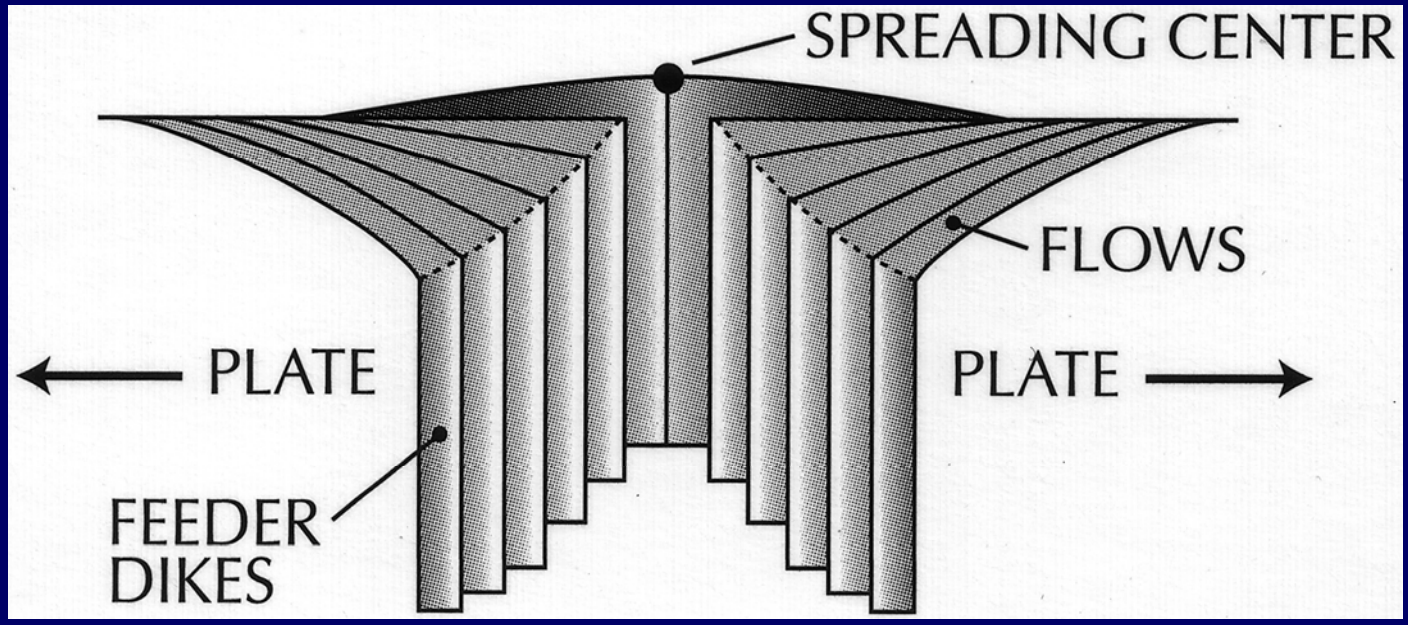


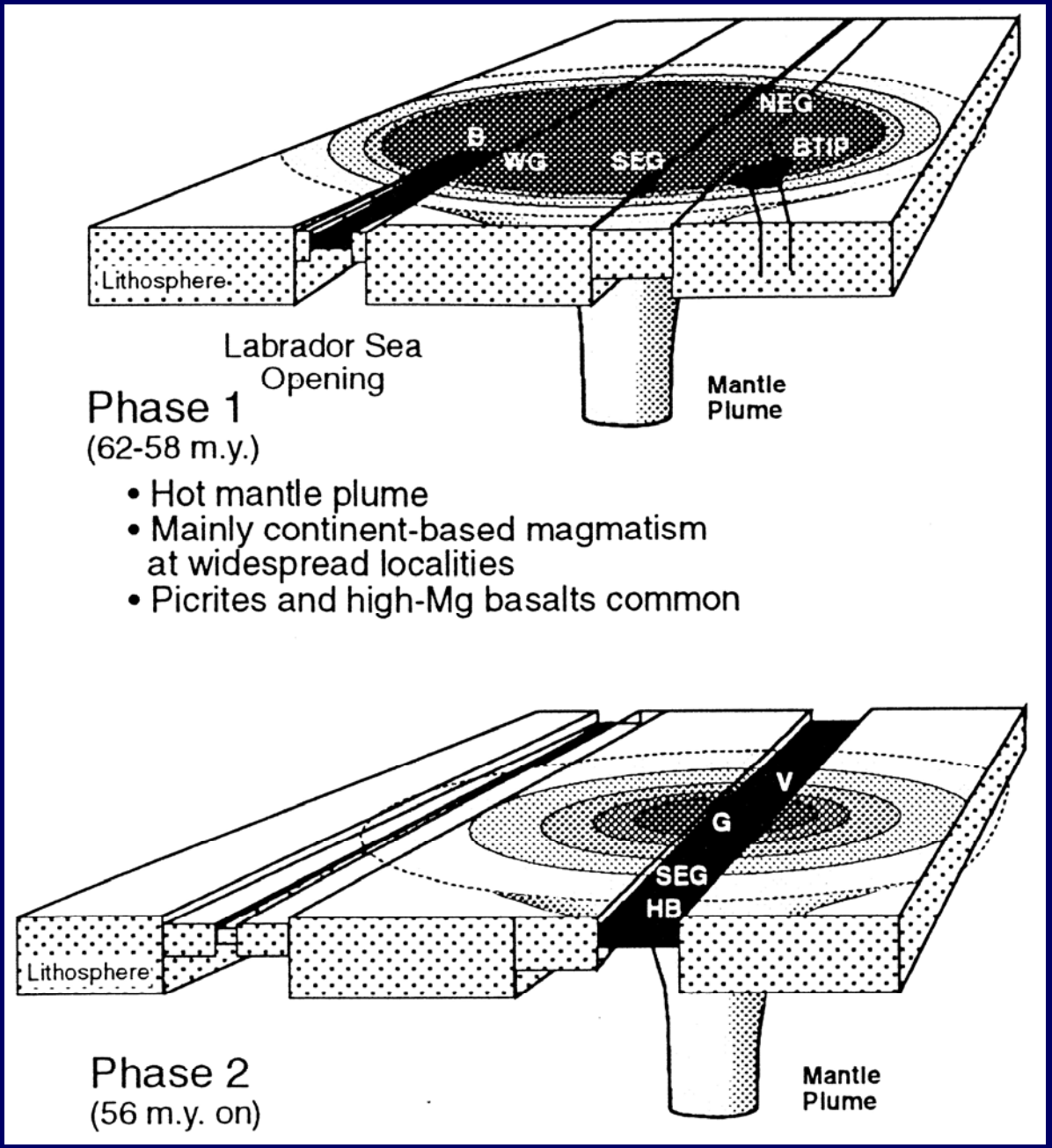


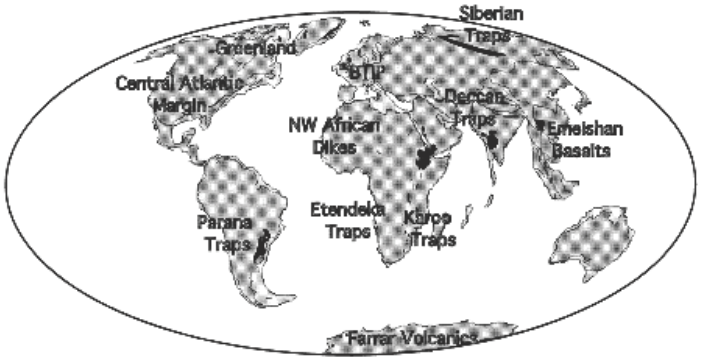
WHITE AND McKENZIE: MAGMATISM AT RIFT ZONES

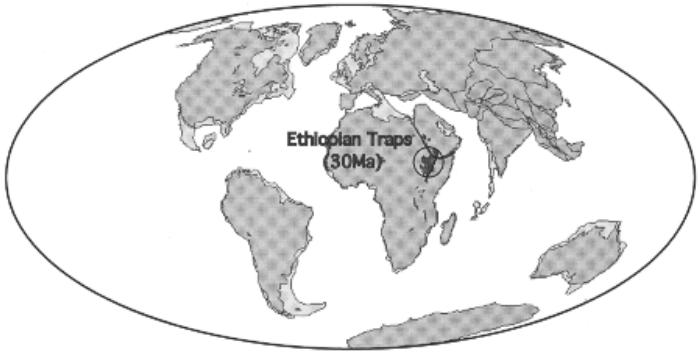

Landward
Seaward

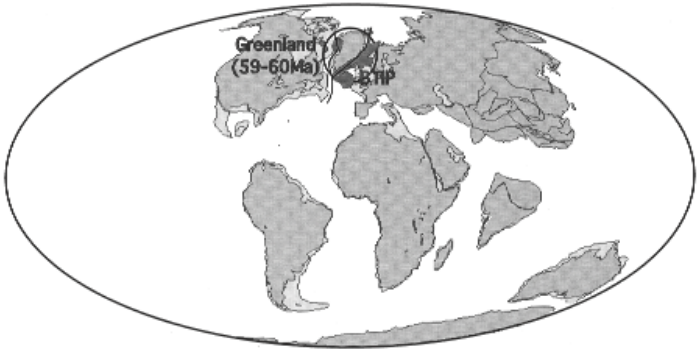

Baffin Is.
GREENLAND
Disko Is.
WG
EG
Rockall
B
1000 km
EUROPE

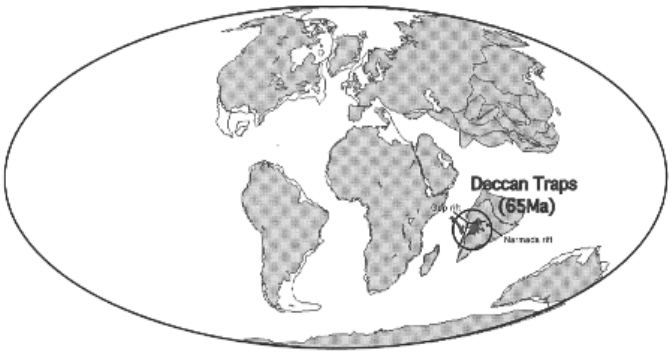

SPREADING CENTER
FLOWS
PLATE
PLATE
FEEDER
DIKES

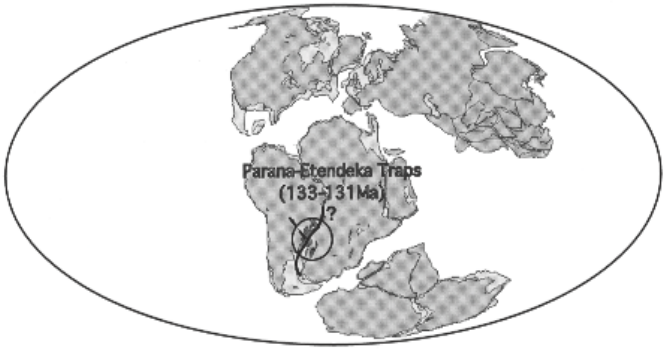

B
WG
SEG
NEG
BTIP
Lithosphere
Labrador Sea
Opening
Mantle
Plume
Phase 1
(62-58 m.y.)
• Hot mantle plume
• Mainly continent-based magmatism
at widespread localities
• Picrites and high-Mg basalts common
V
G
SEG
HB
Lithosphere
Phase 2
(56 m.y. on)
Mantle
Plume

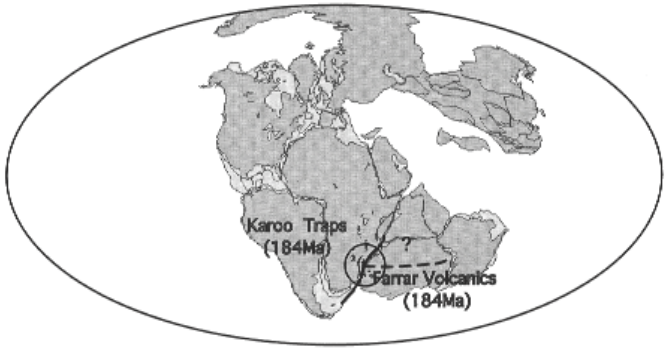

Siberian
Traps
Greenland
BTP
Central Atlantic
Margin
Deccan
Traps
NW African
Dikes
Emeishan
Basalts
Etendeka
Traps
Karoo
Traps
Parana
Traps
Ferrar Volcanics


Ethiopian Traps
(30Ma)


Greenland
(59-60Ma)
BTP

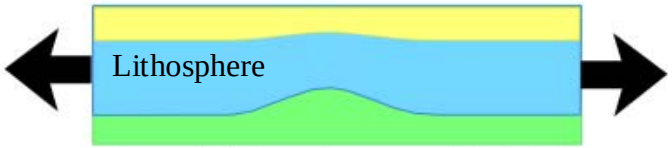

Deccan Traps
(65Ma)


Parana-Etendeka Traps
(133-131Ma)
?

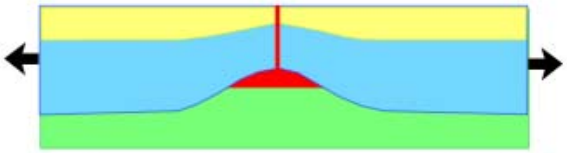

Karoo Traps
(184Ma)
?
Ferrar Volcanics
(184Ma)

Rifting and Magmatism: A Chicken and Egg Problem

Petrologic View: Rift Chicken lays magmatic egg

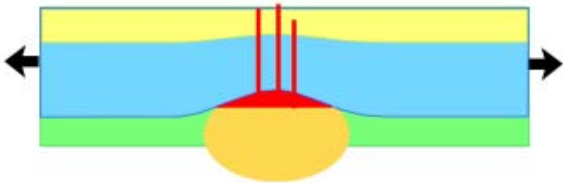


1. Stretch lithosphere and thin it



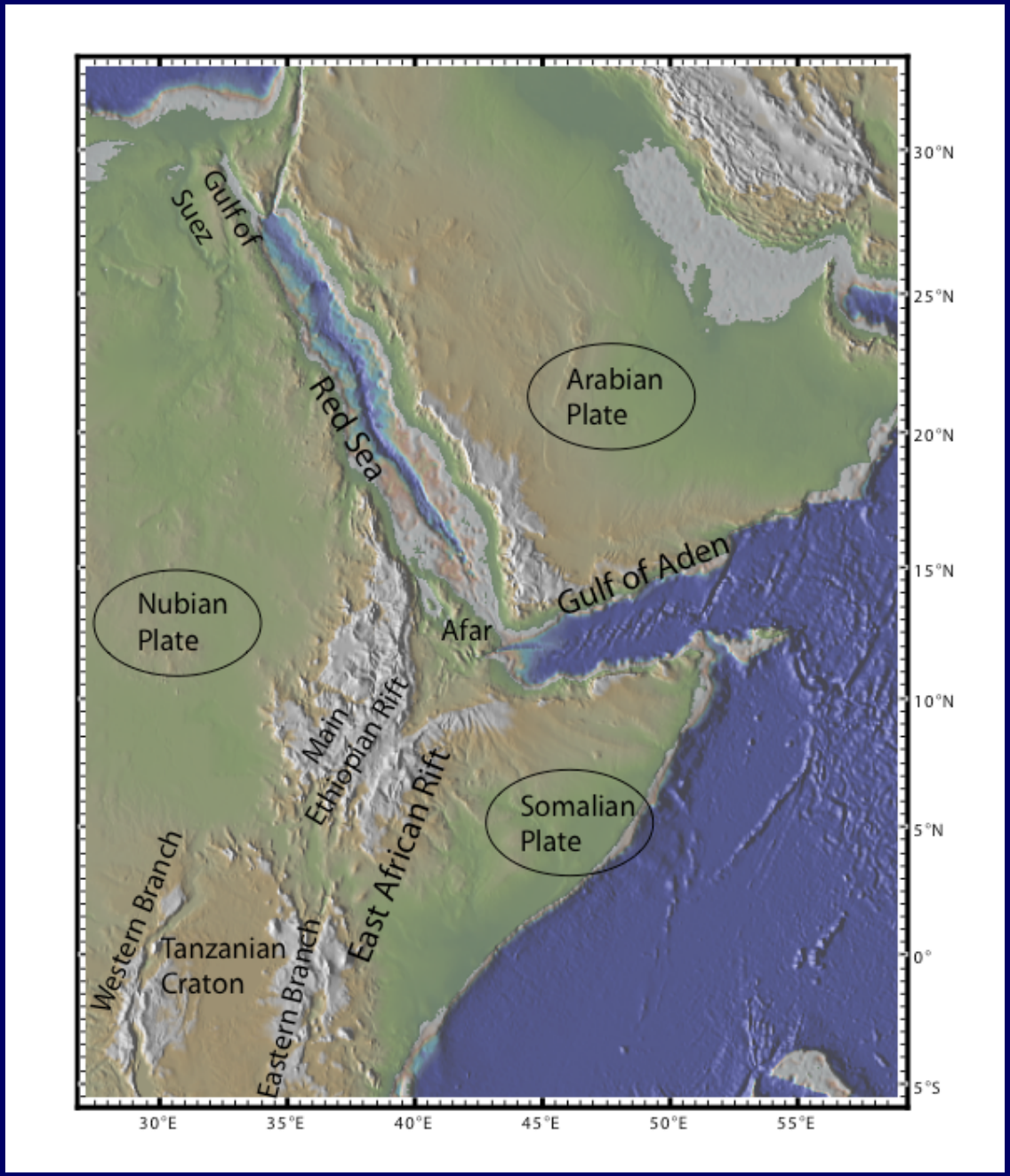
2. Pull up asthenosphere and melt it

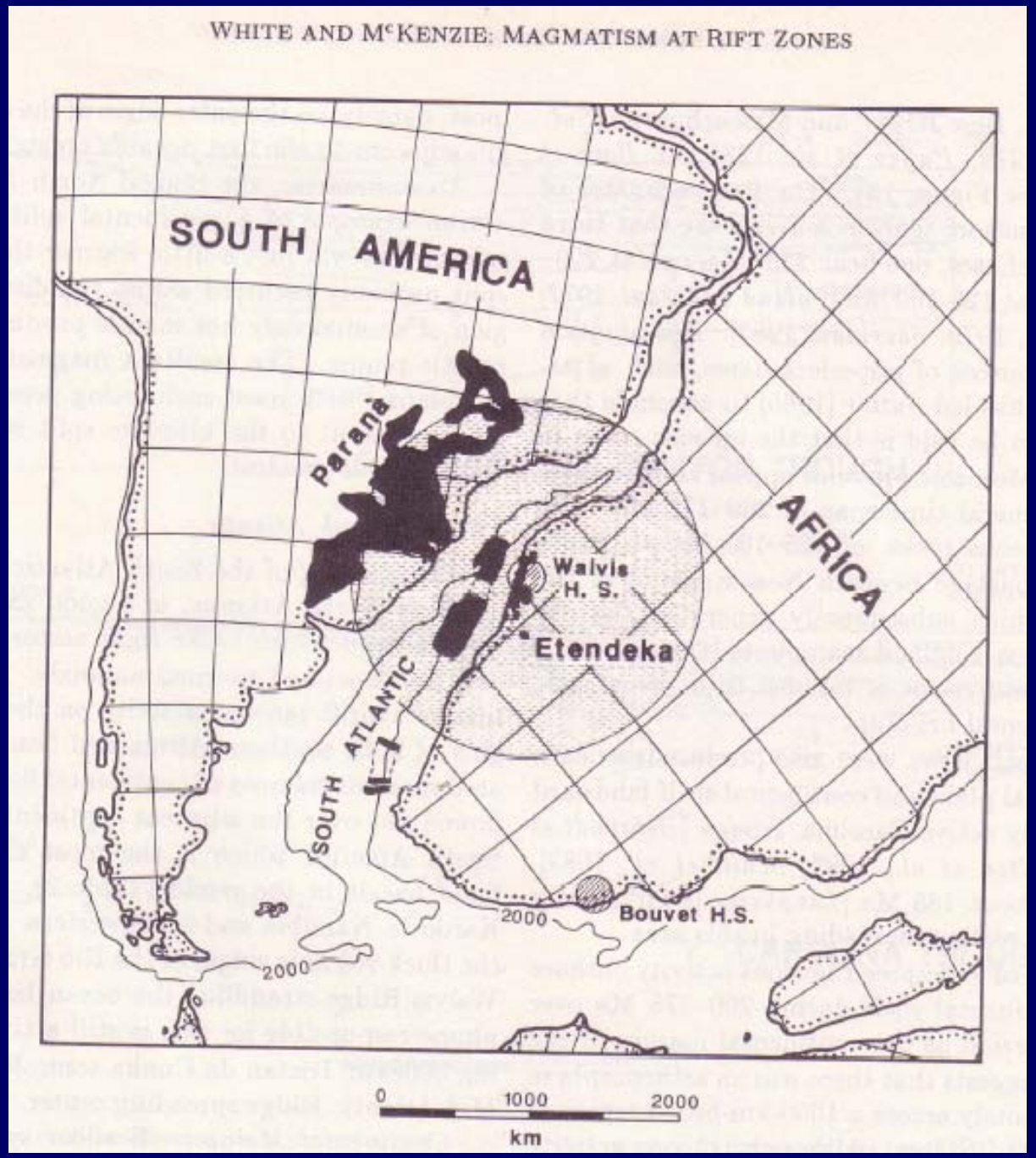
Mechanical View: Magmatic Egg grows into Rift

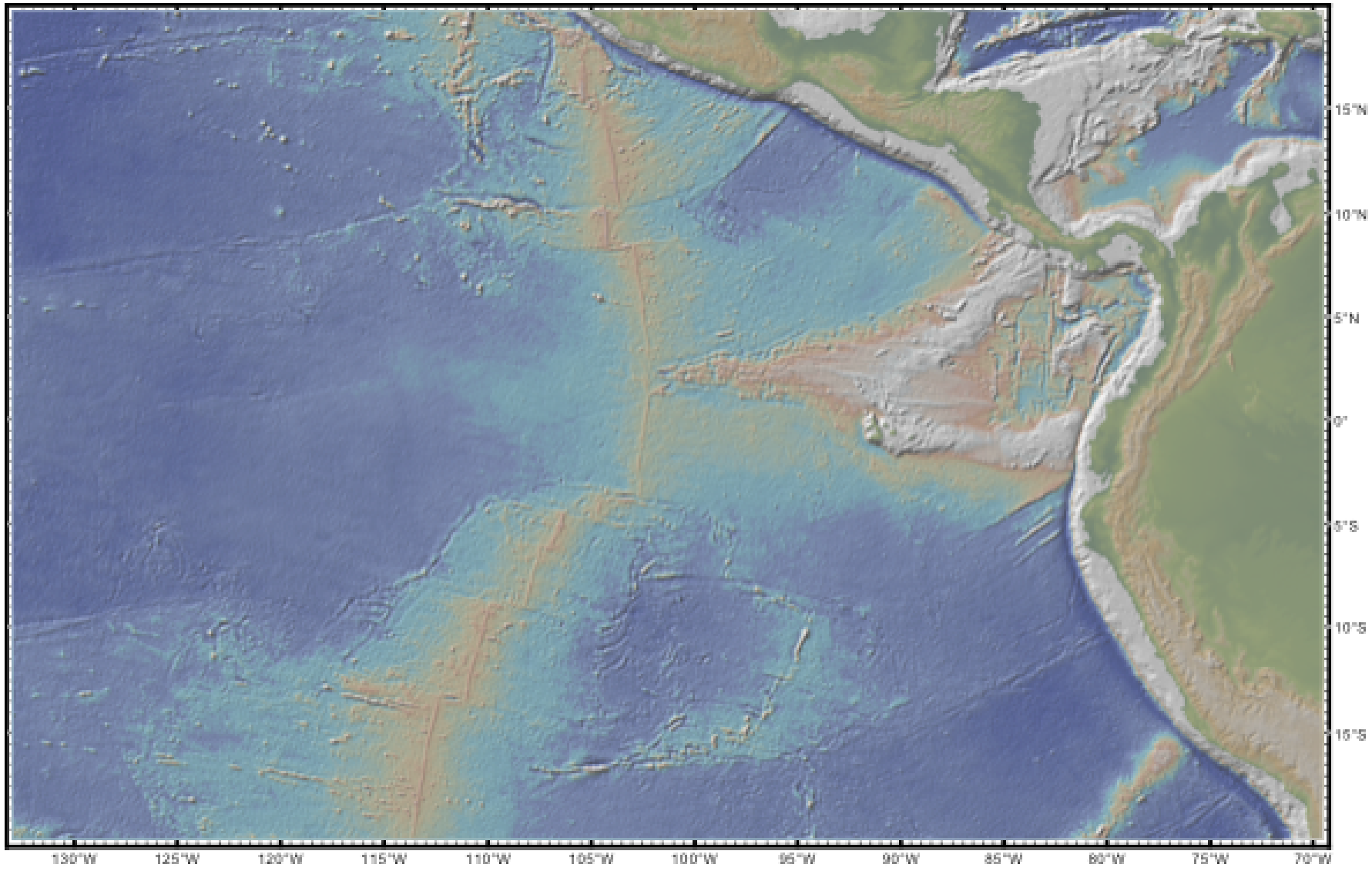


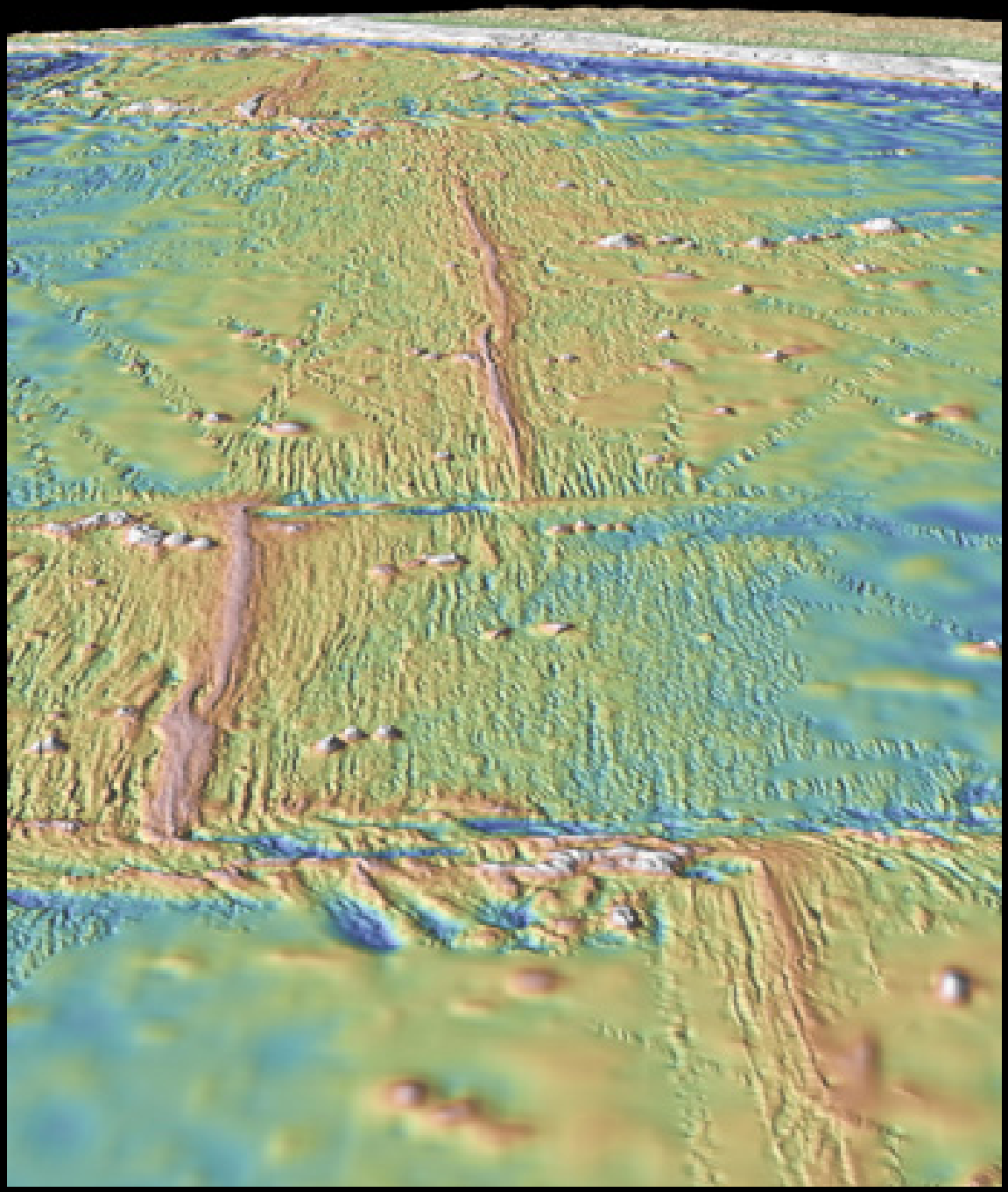
1. Intrude lithosphere and heat it

2. Stretch weakened lithosphere

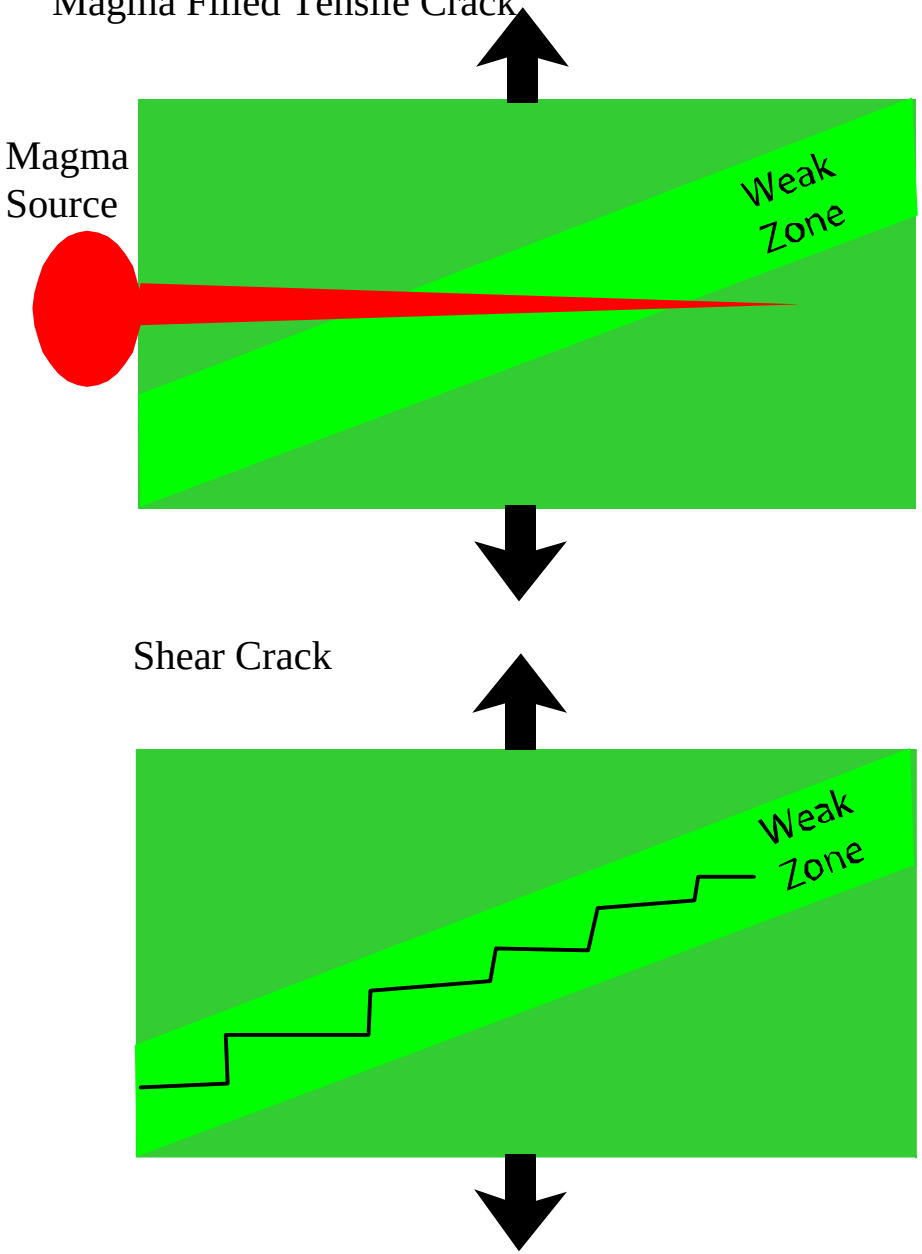

Gulf of Suez
Red Sea
Arabian Plate
Nubian Plate
Gulf of Aden
Afar
Main Ethiopian Rift
East African Rift
Somalian Plate
Western Branch
Tanzanian Craton
Eastern Branch
30°N
25°N
20°N
15°N
10°N
5°N
0°
5°S
30°E
35°E
40°E
45°E
50°E
55°E


SOUTH AMERICA
Paraná
AFRICA
Walvis
H. S.
Etendeka
SOUTH ATLANTIC
2000
Bouvet H.S.
2000
0
1000
2000
km


15°N
10°N
5°N
0°
5°S
10°S
15°S
130°W
125°W
120°W
115°W
110°W
105°W
100°W
95°W
90°W
85°W
80°W
75°W
70°W
2005/09/07 15:04:22



Plan View of Tensile Crack vs. Shear Crack



Diking and Faulting Mechanics

How Dikes Make Faults

-Force for splitting plates

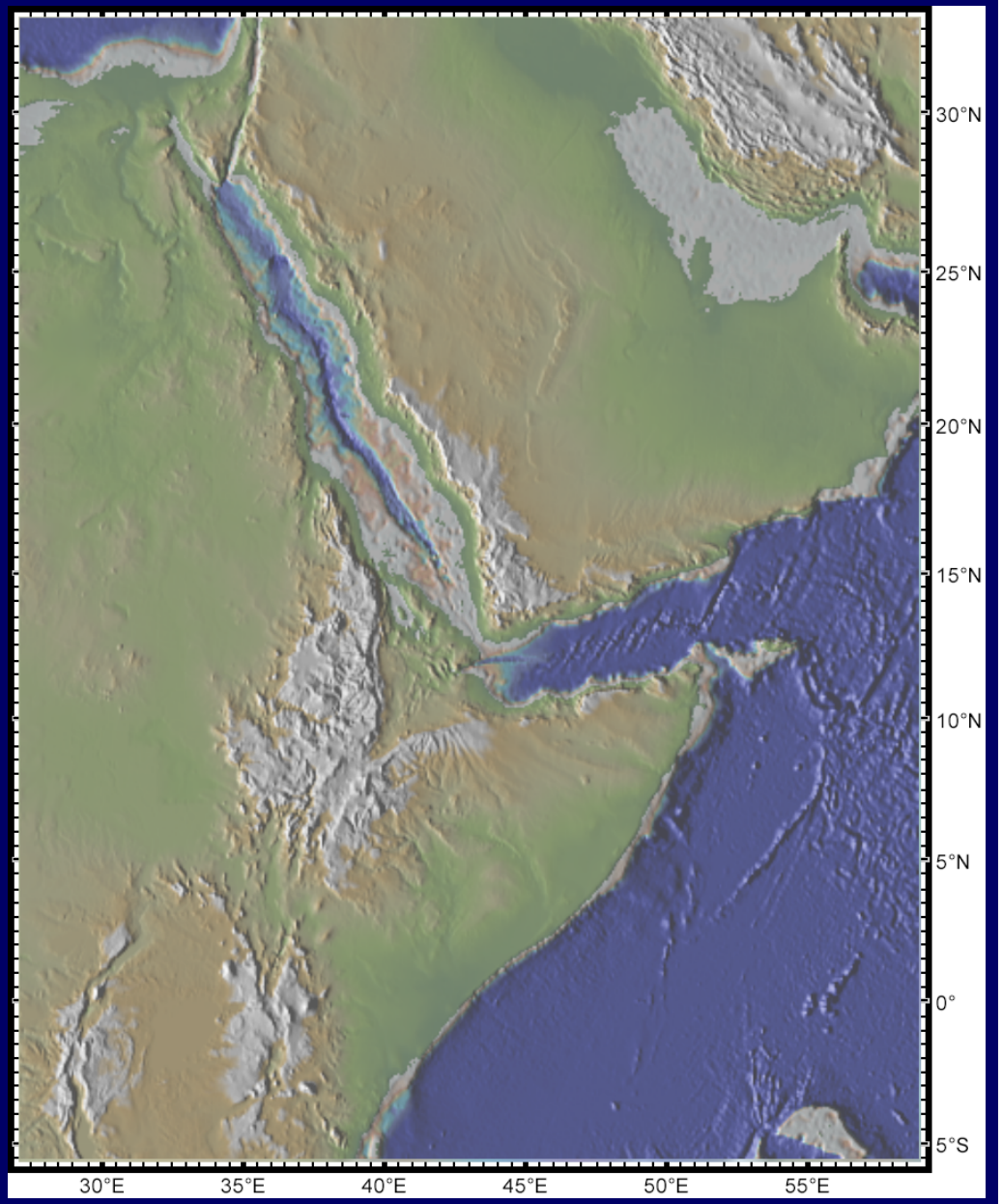
-Straight rifts/ridges = magmatic

-Amount of magma to rift

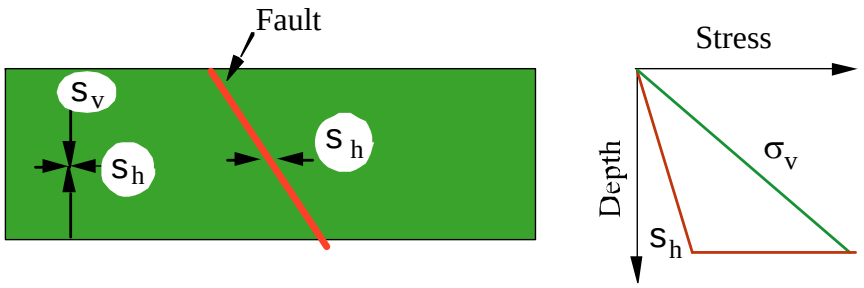
Segment-Scale Dike Observations

- Krafla, Icland 1975-1984

- Afar, Ethiopia 2005



Minimum Stress Difference for Fault Slip

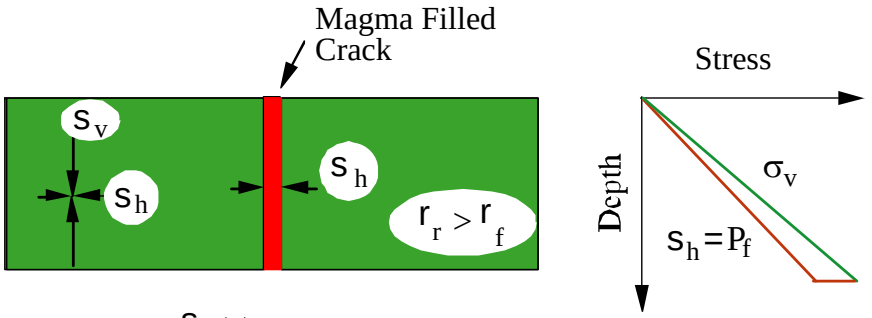


r_r = rock density

$s_v(z) = r_r g z$

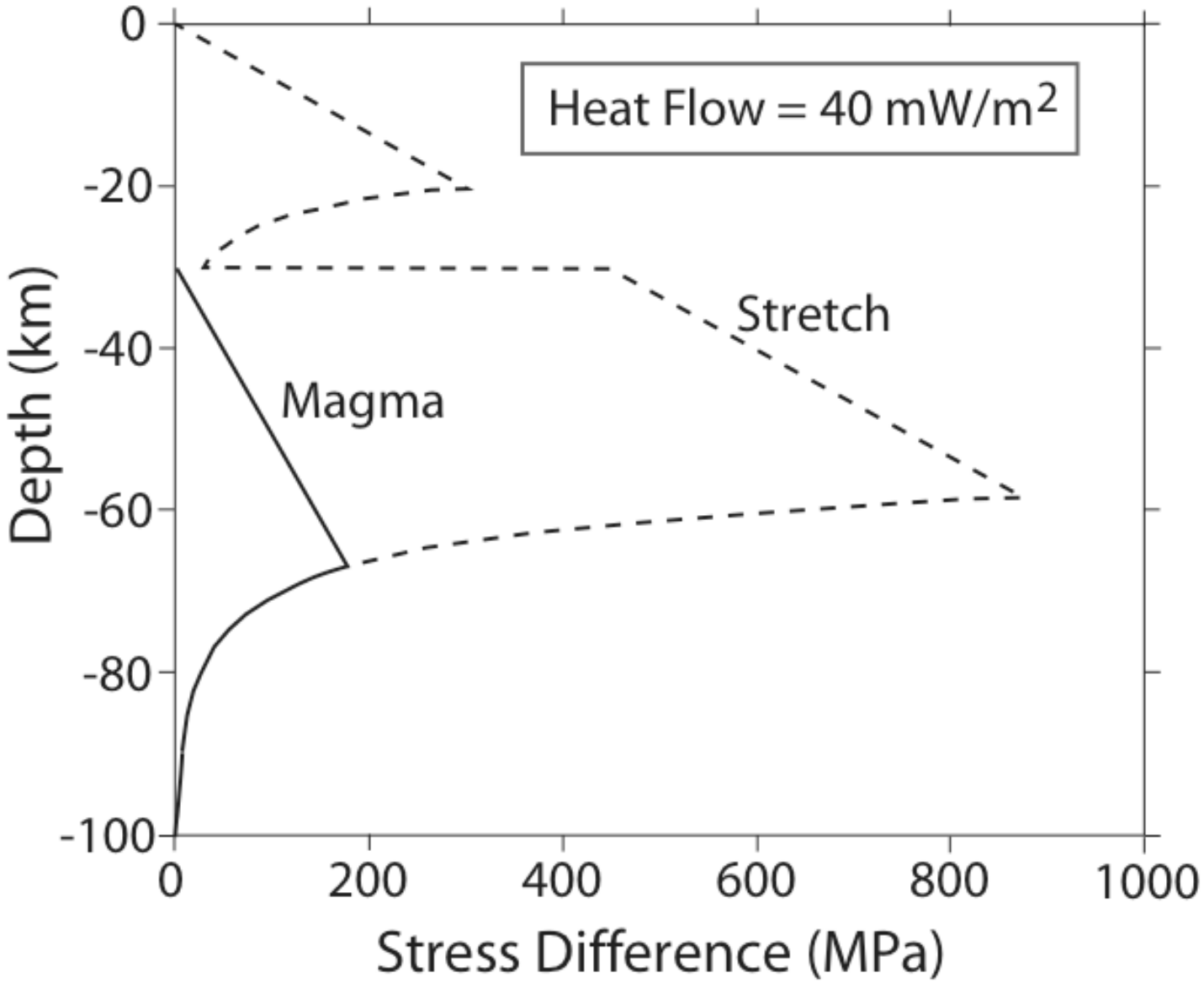
$$s_h(z) = \left[\frac{(1+m^2)^{1/2} - m}{(1+m^2)^{1/2} + m}\right] s_v(z) \sim [1/4] s_v(z)$$

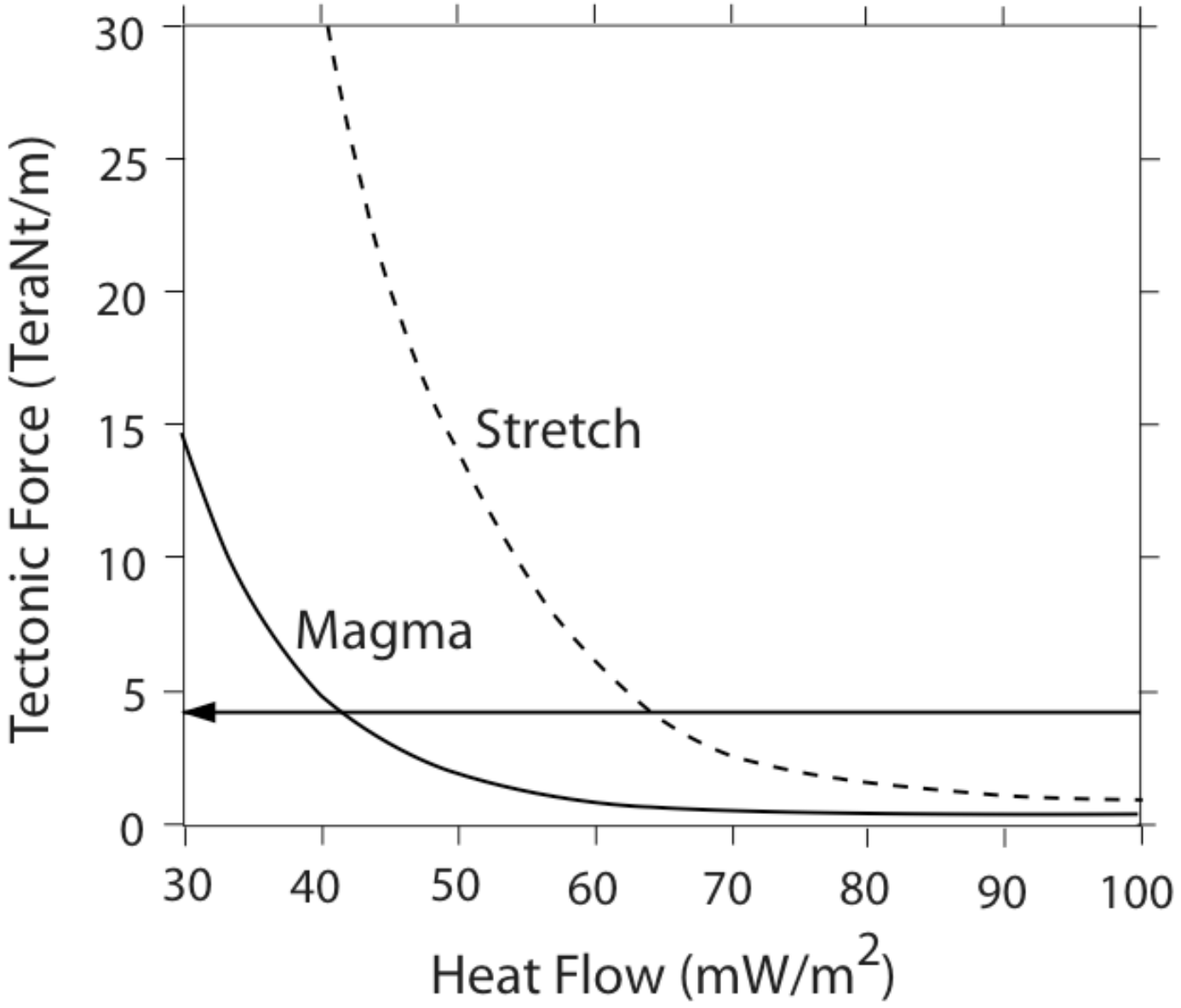
Minimum Stress Difference for Opening Dike



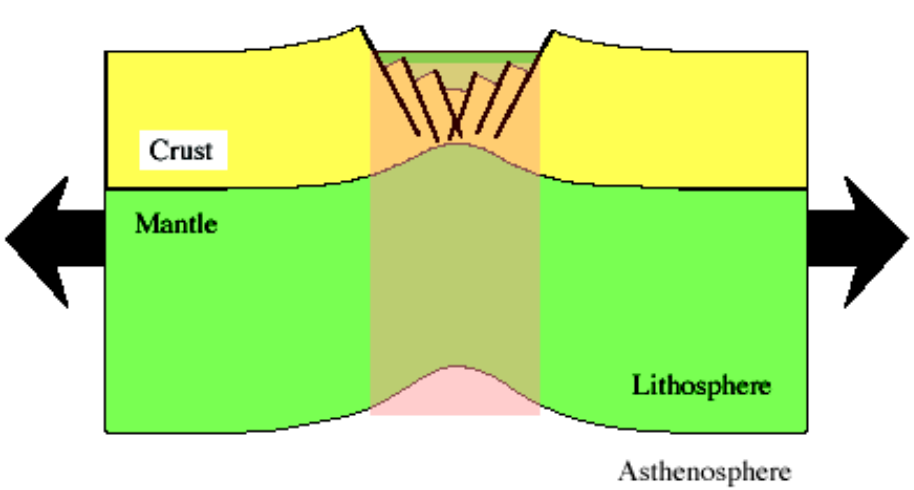
$s_v(z) = r_r g z$

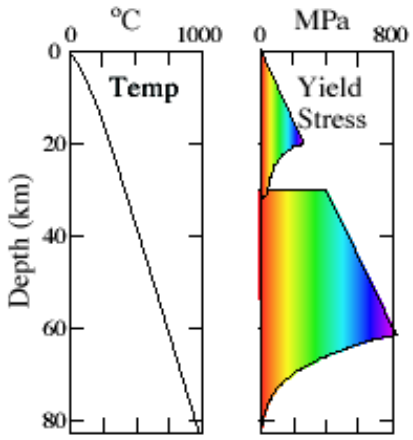
$s_h(z) = P_f = r_f g z$


Heat Flow = 40 mW/m2
Stretch
Magma
Depth (km)
0
-20
-40
-60
-80
-100
0
200
400
600
800
1000
Stress Difference (MPa)

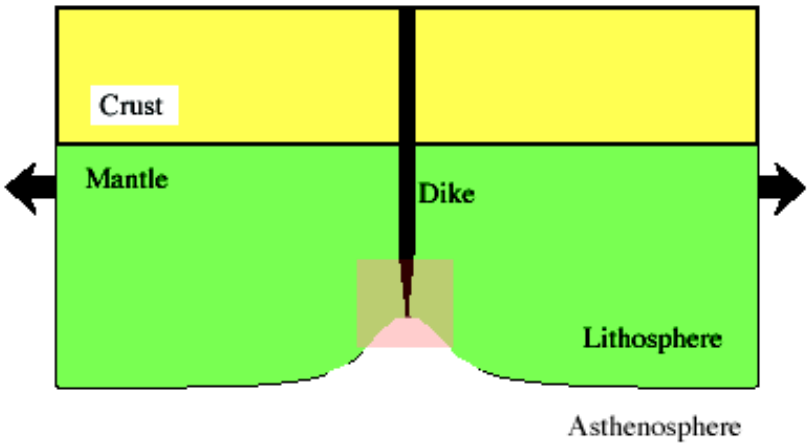

Tectonic Force (TeraNt/m)
30
25
20
15
10
5
0
Stretch
Magma
30
40
50
60
70
80
90
100
Heat Flow (mW/m2)

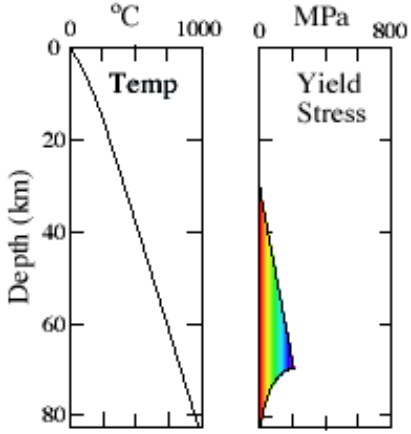
Tectonic Stretching

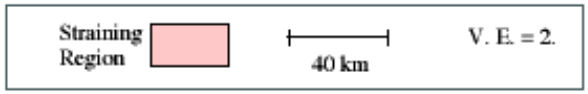




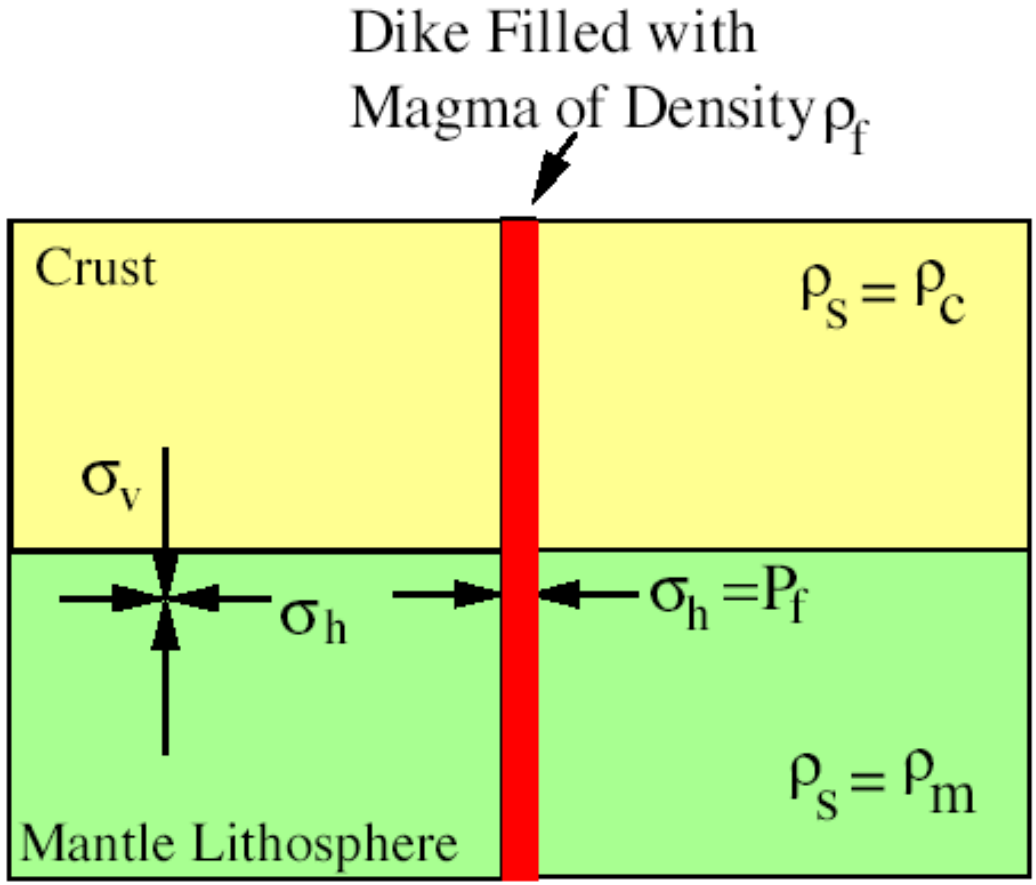
Magmatic Extension

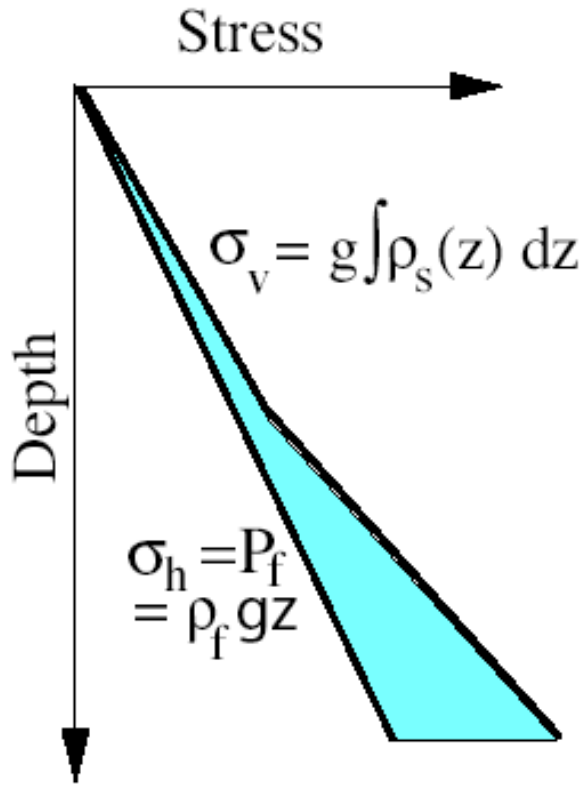


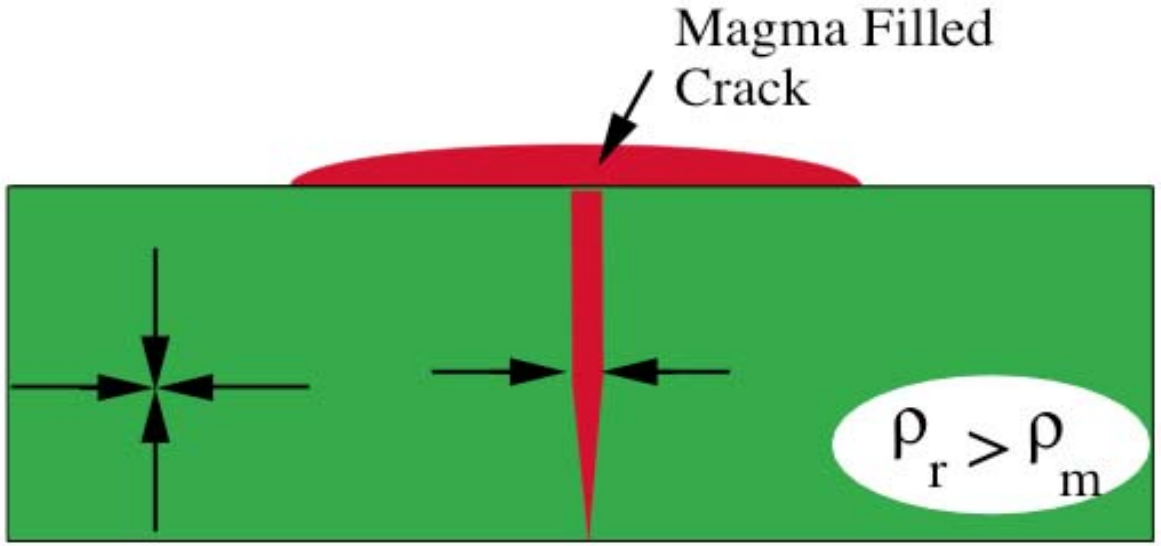




Minimum Stress for Opening Dike






Magma Filled
Crack
$\rho_r > \rho_m$

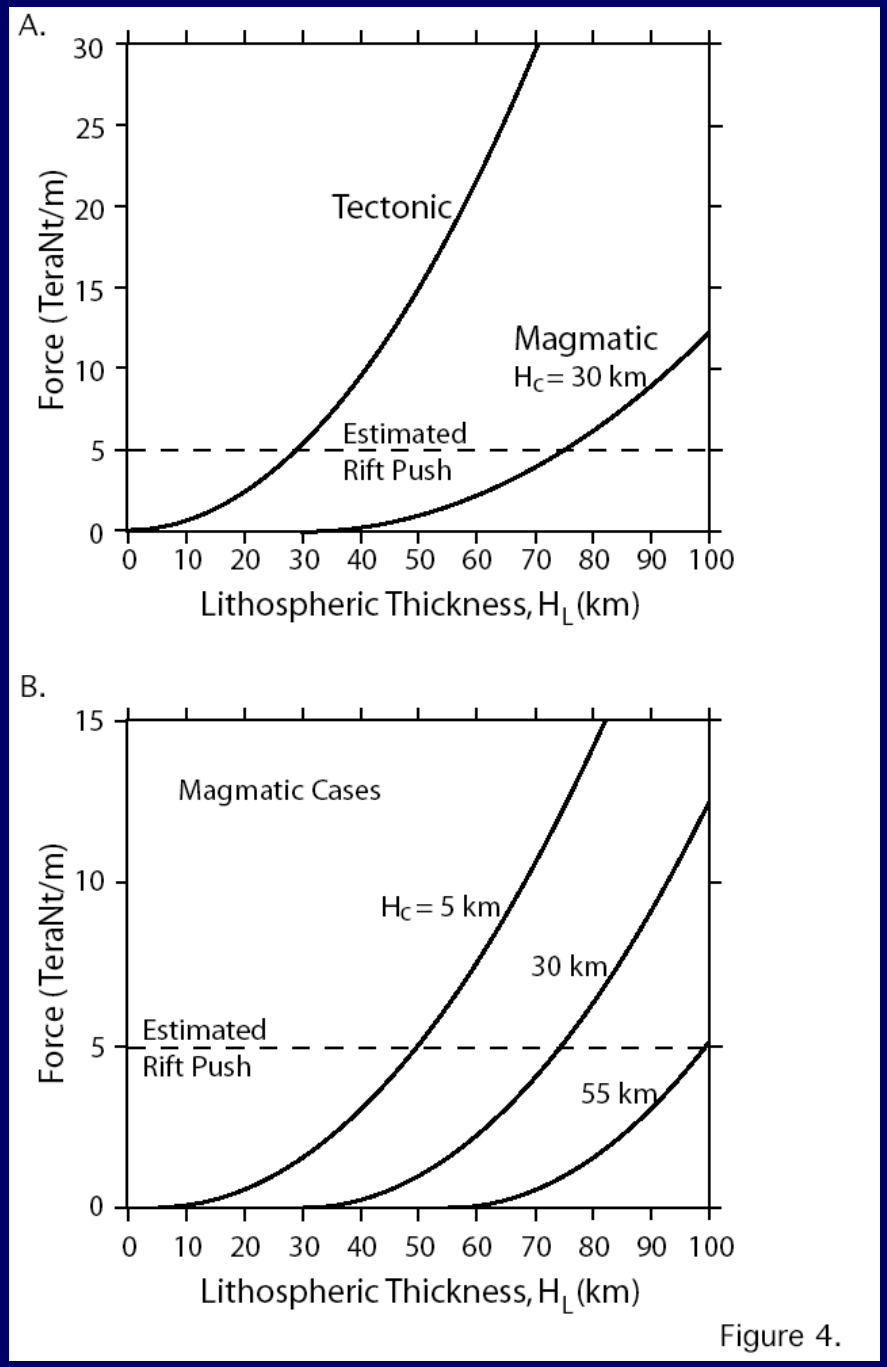
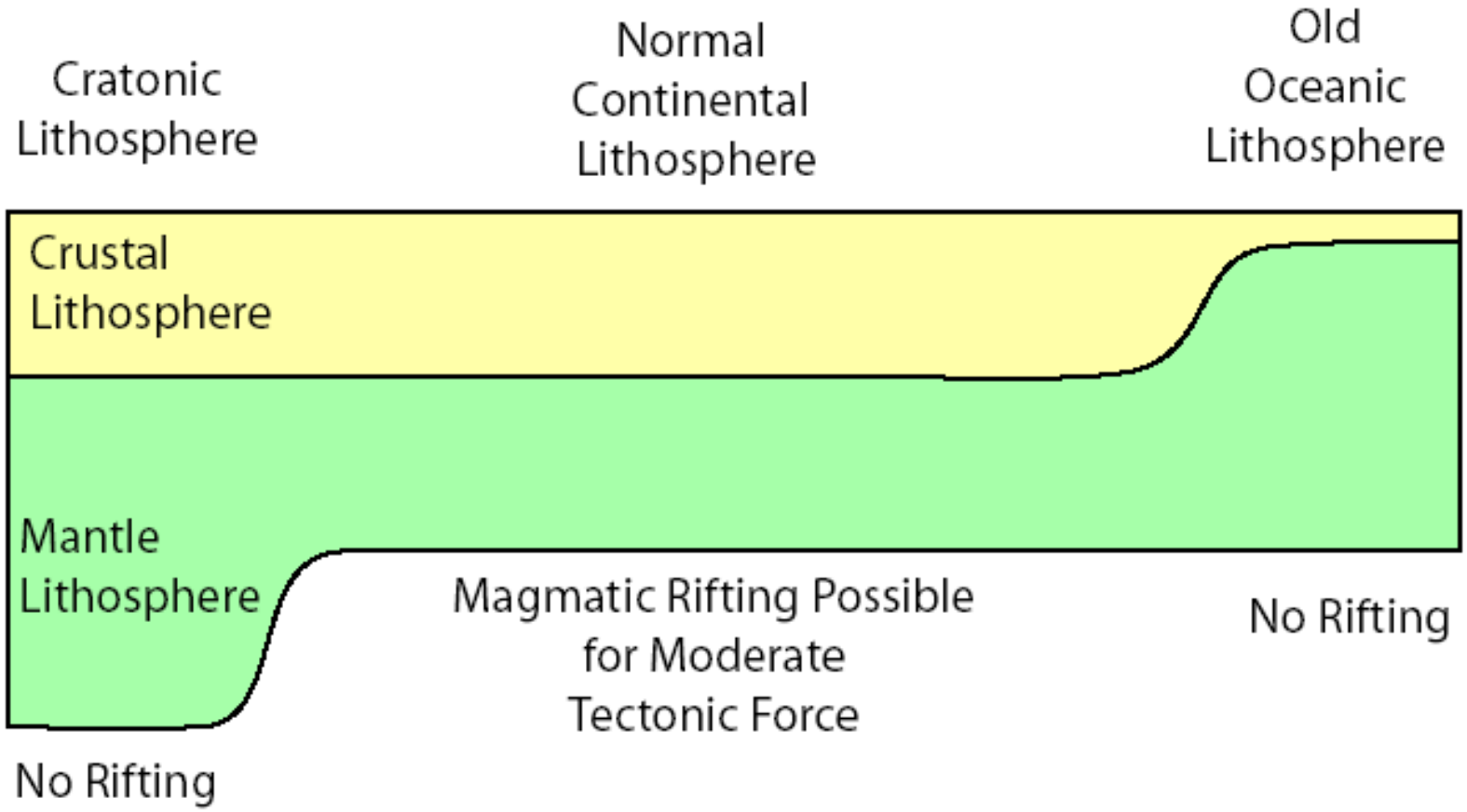
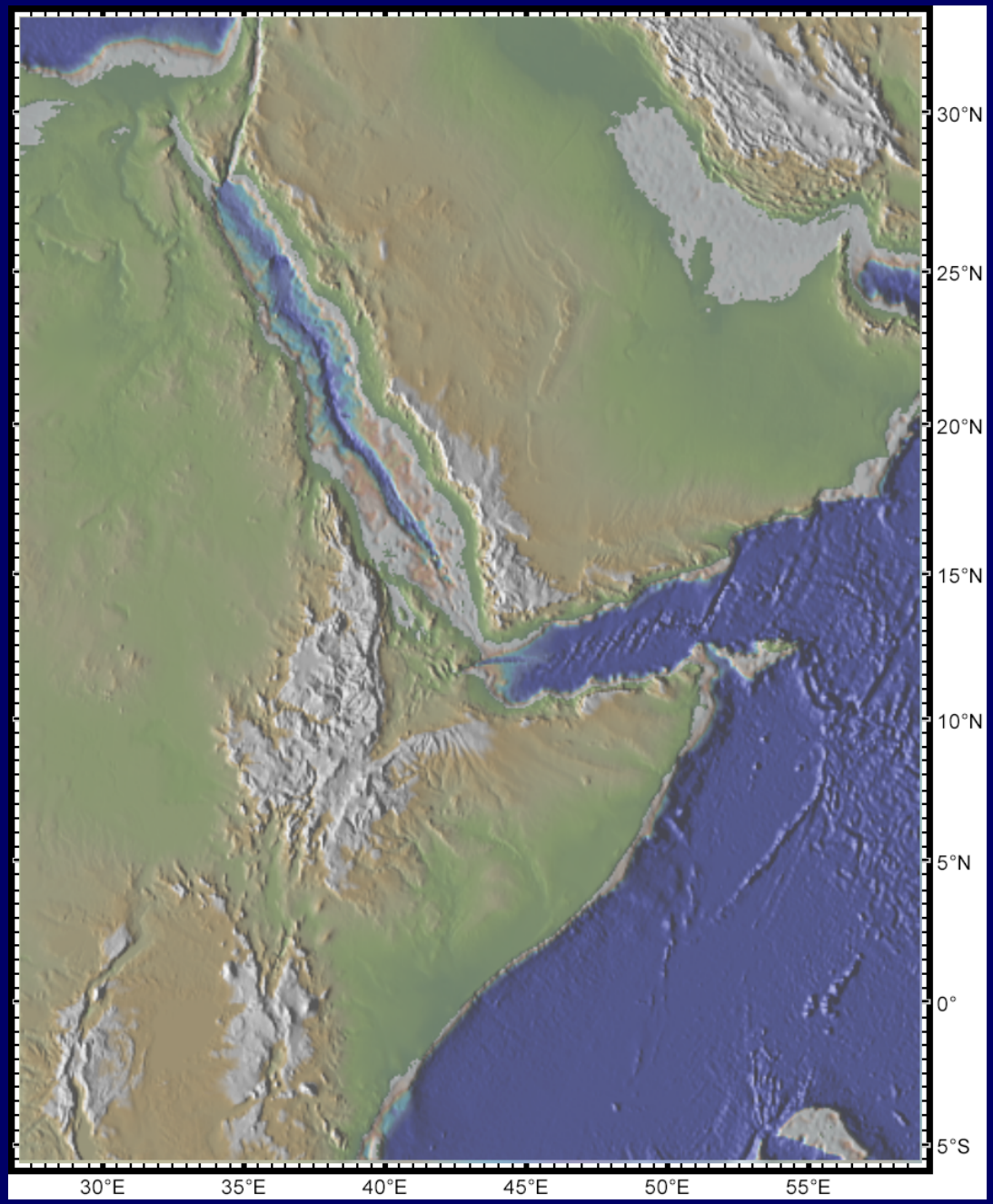
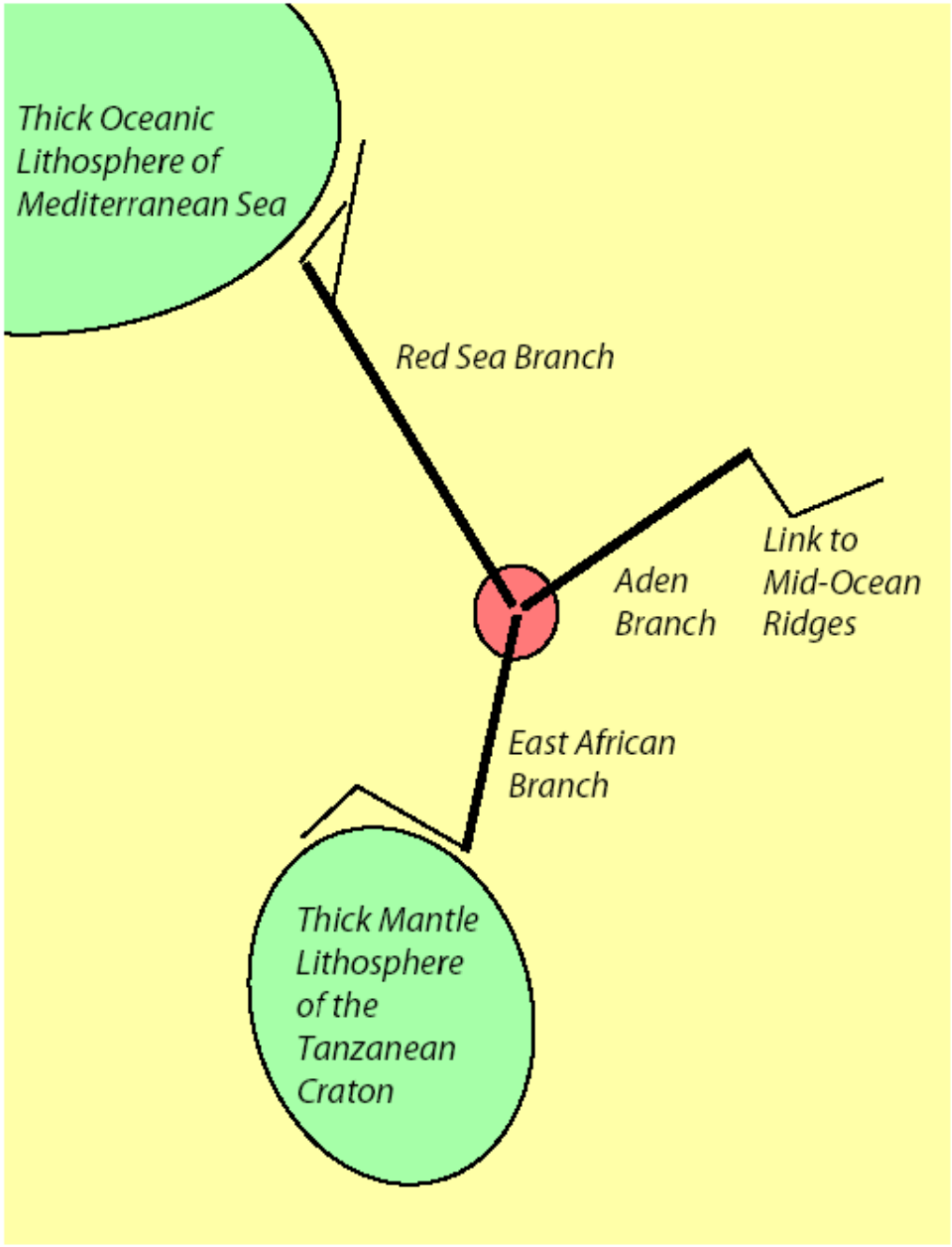

A.
Force (TeraNt/m)
Tectonic
Magmatic
H_C = 30 km
Estimated
Rift Push
Lithospheric Thickness, H_L (km)
B.
Force (TeraNt/m)
Magmatic Cases
H_C = 5 km
30 km
55 km
Estimated
Rift Push
Lithospheric Thickness, H_L (km)

Figure 4.

Limits on Magmatic Rifting



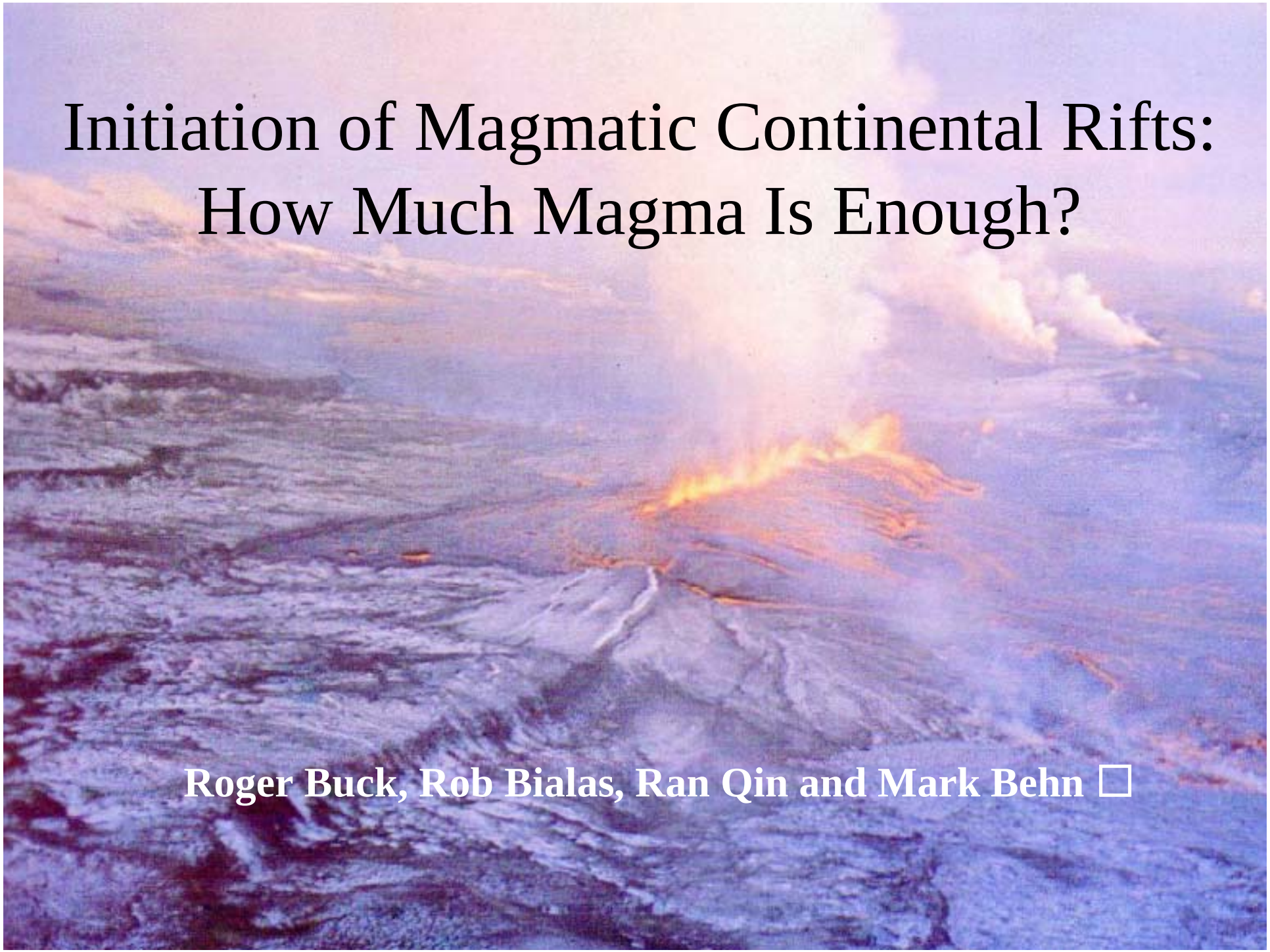

30°N
25°N
20°N
15°N
10°N
5°N
0°
5°S
30°E
35°E
40°E
45°E
50°E
55°E


Thick Oceanic Lithosphere of Mediterranean Sea
Red Sea Branch
Aden Branch
Link to Mid-Ocean Ridges
East African Branch
Thick Mantle Lithosphere of the Tanzanean Craton

Big Unknowns about Dike at Rifts/Ridges:

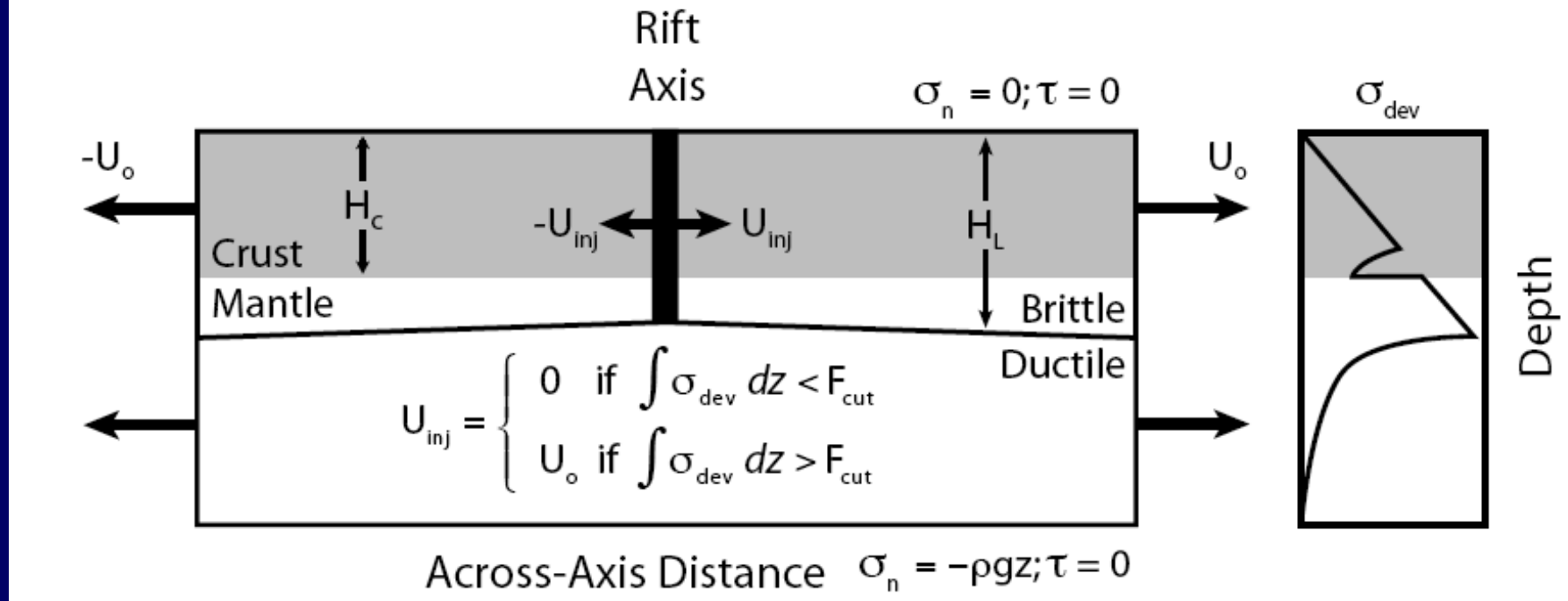
- What controls dike length?
- What controls dike width and frequency?

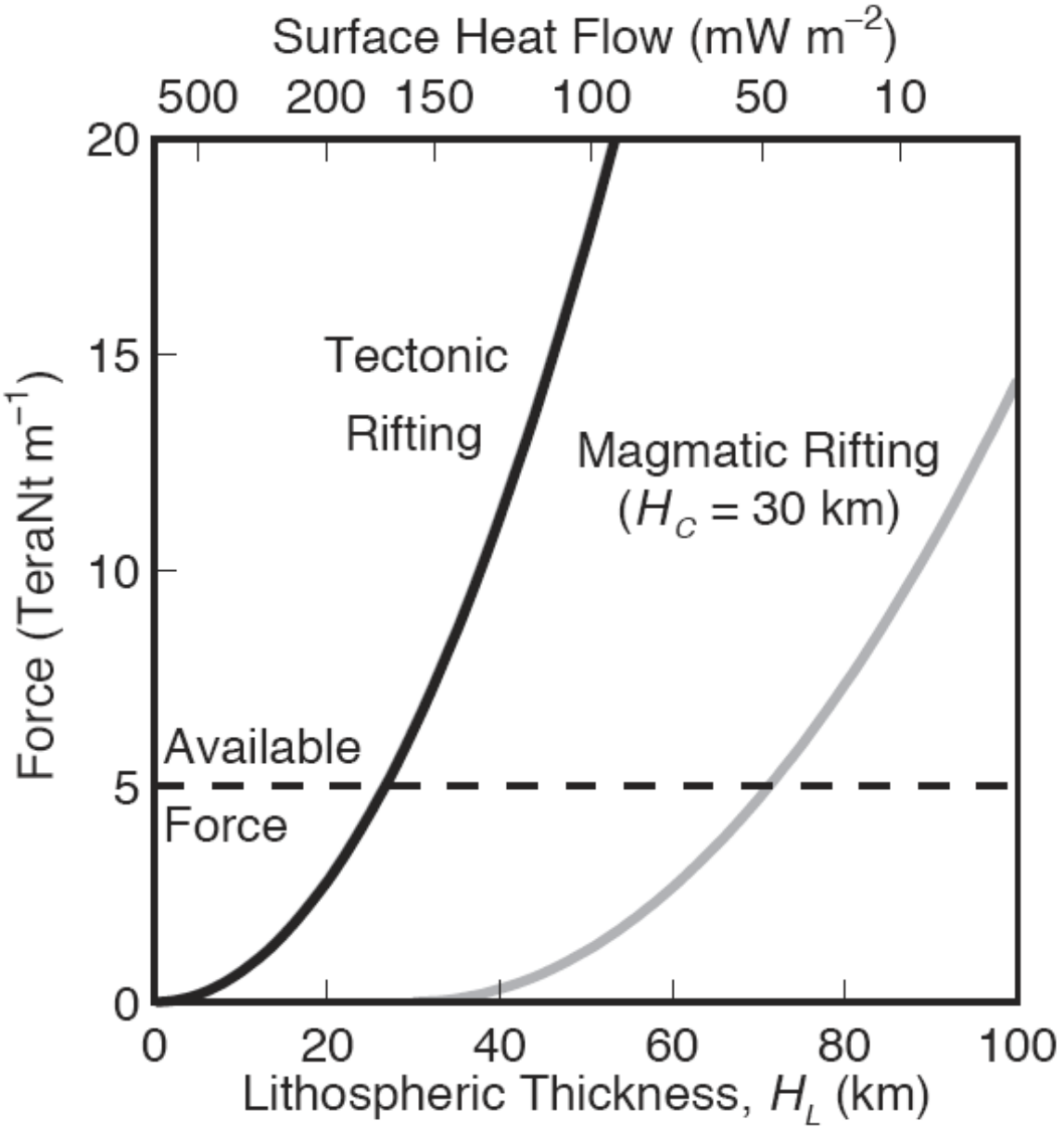
Need to look at active dikes

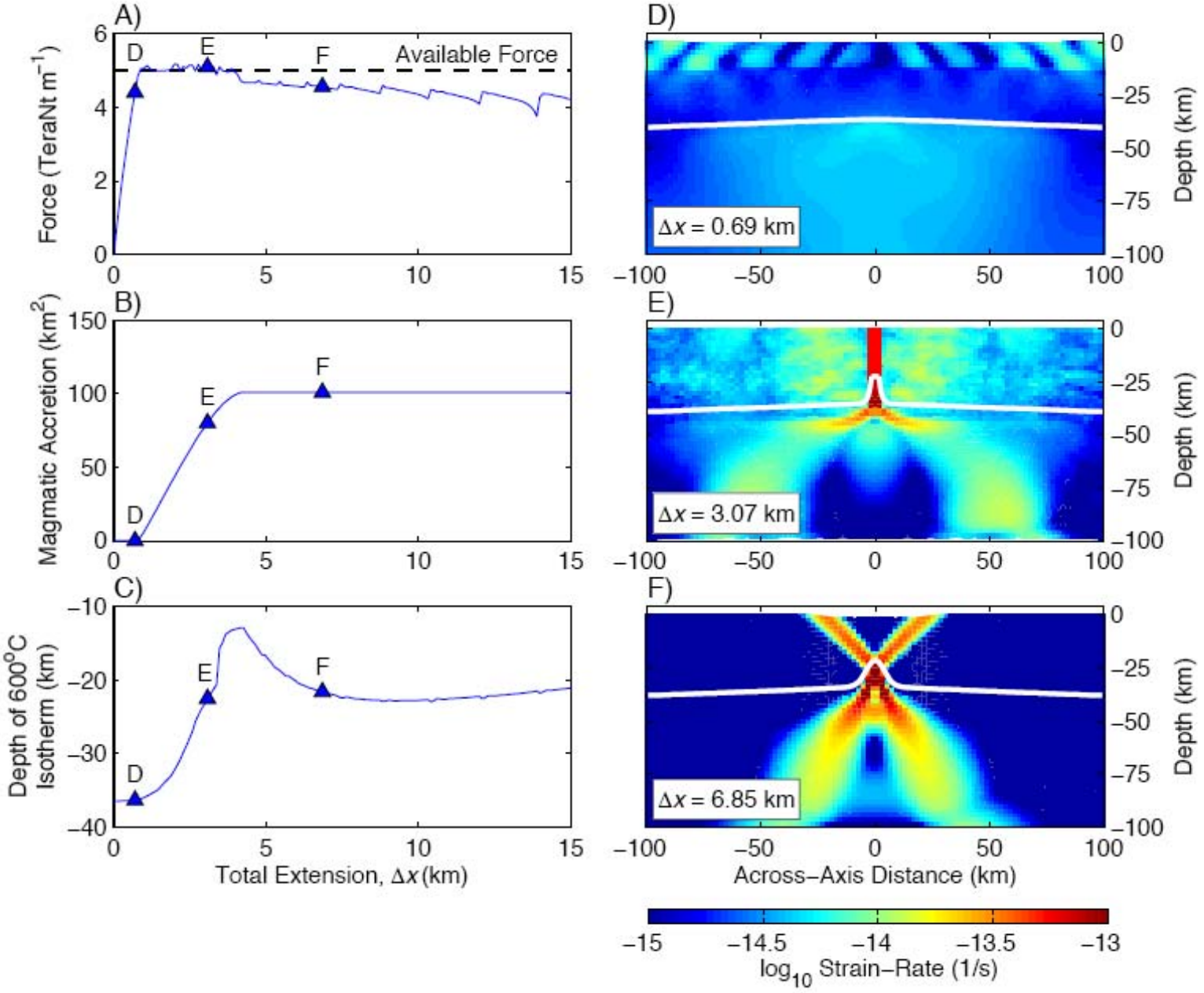


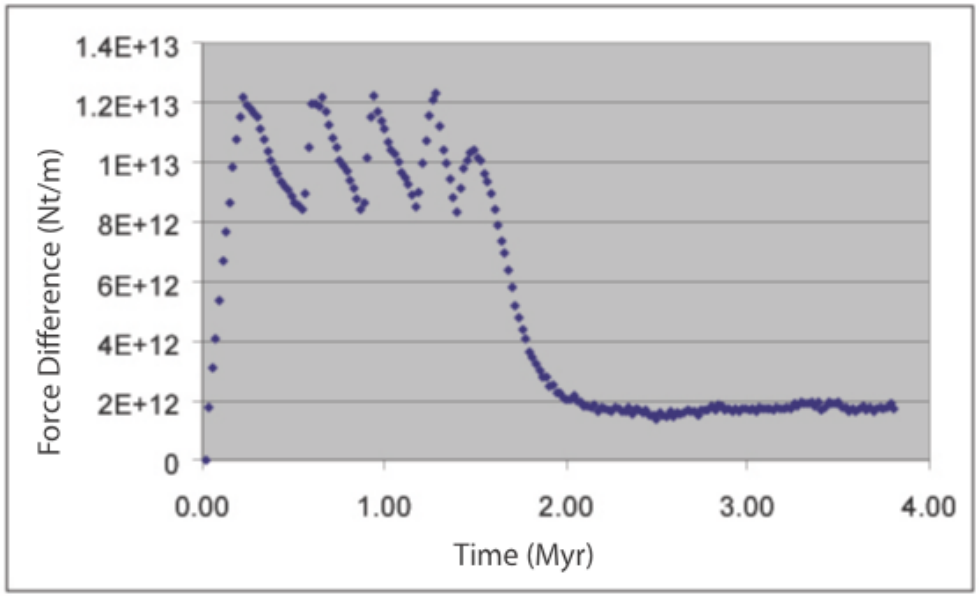
Initiation of Magmatic Continental Rifts: How Much Magma Is Enough?

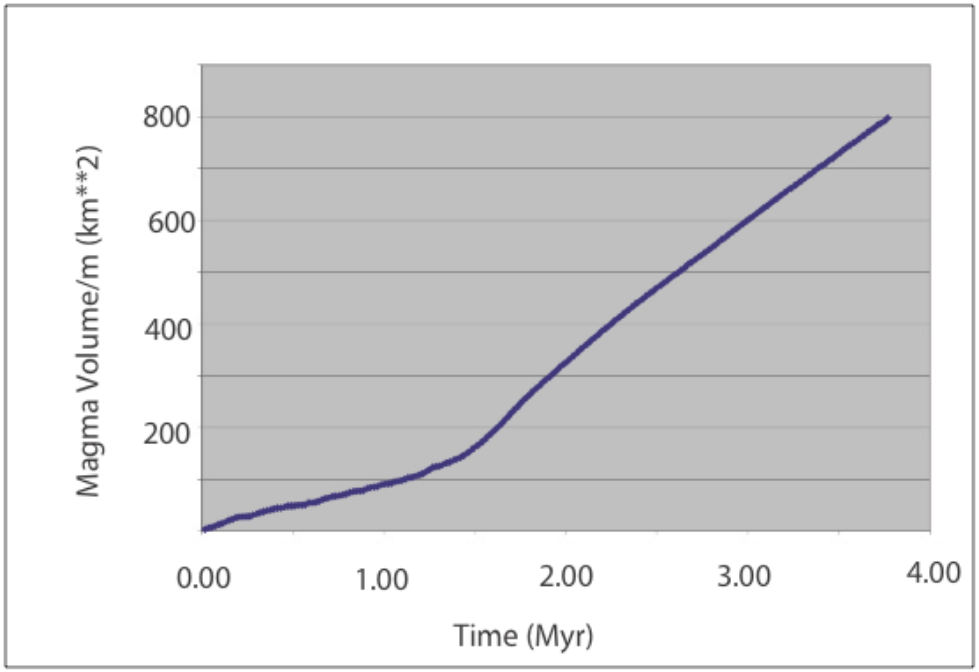
Roger Buck, Rob Bialas, Ran Qin and Mark Behn ☐


Rift
Axis
$\sigma_n = 0; \tau = 0$
σ_{dev}
$-U_o$
U_o
H_c
$-U_{inj}$
U_{inj}
H_L
Crust
Mantle
Brittle
Ductile
$U_{inj} = \begin{cases} 0 & \text{if } \int \sigma_{dev}\, dz < F_{cut} \\ U_o & \text{if } \int \sigma_{dev}\, dz > F_{cut} \end{cases}$
Depth
Across-Axis Distance
$\sigma_n = -\rho g z; \tau = 0$

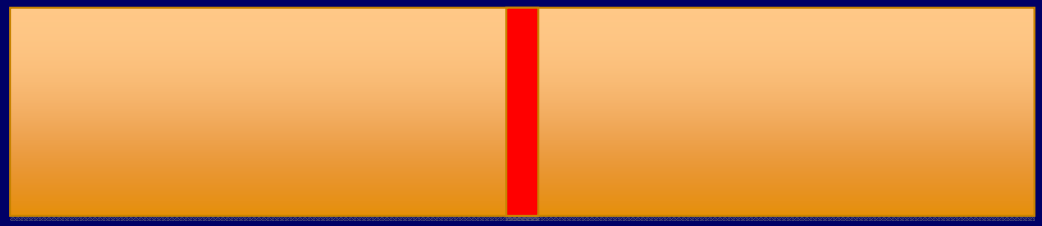

Surface Heat Flow (mW m^{-2})
500
200
150
100
50
10
20
15
10
5
0
Force (TeraNt m^{-1})
Tectonic
Rifting
Magmatic Rifting
(H_C = 30 km)
Available
Force
0
20
40
60
80
100
Lithospheric Thickness, H_L (km)


A)
B)
C)
D)
E)
F)
Force (TeraNt m^{-1})
Available Force
D
E
F
Magmatic Accretion (km^2)
Depth of 600°C Isotherm (km)
Total Extension, Δx (km)
Δx = 0.69 km
Δx = 3.07 km
Δx = 6.85 km
Depth (km)
Across–Axis Distance (km)
log$_{10}$ Strain–Rate (1/s)

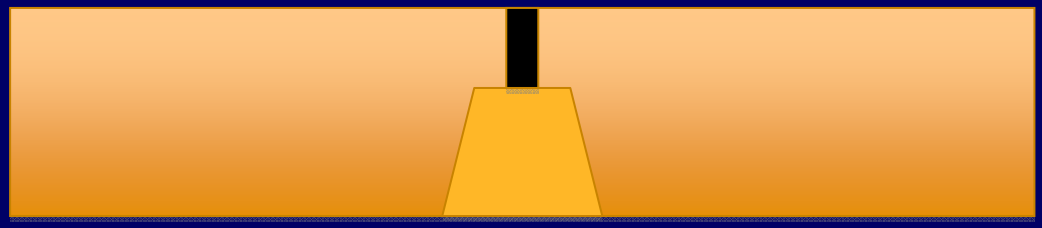

1.4E+13
1.2E+13
1E+13
8E+12
6E+12
4E+12
2E+12
0
Force Difference (Nt/m)
0.00
1.00
2.00
3.00
4.00
Time (Myr)


800
600
400
200
Magma Volume/m (km**2)
0.00
1.00
2.00
3.00
4.00
Time (Myr)

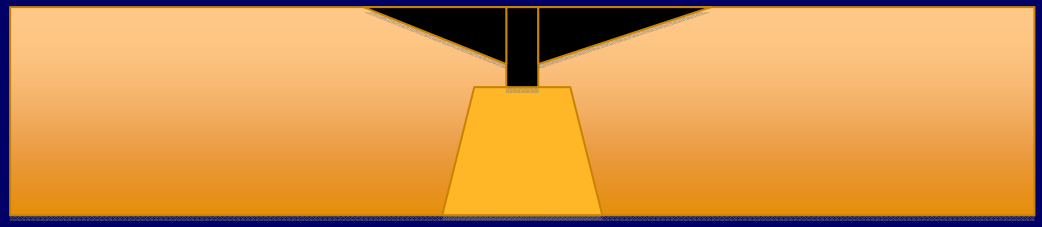
Magma Injection Weakens Lithosphere



Weak Lithosphere Extends Tectonically



Sometimes a Pulse of Extrusion Makes a Volcanic Margin



Intrusion of giant dikes explains:

1. Opening of rifts in normal continental areas

2. Reduced subsidence during magmatic rifting

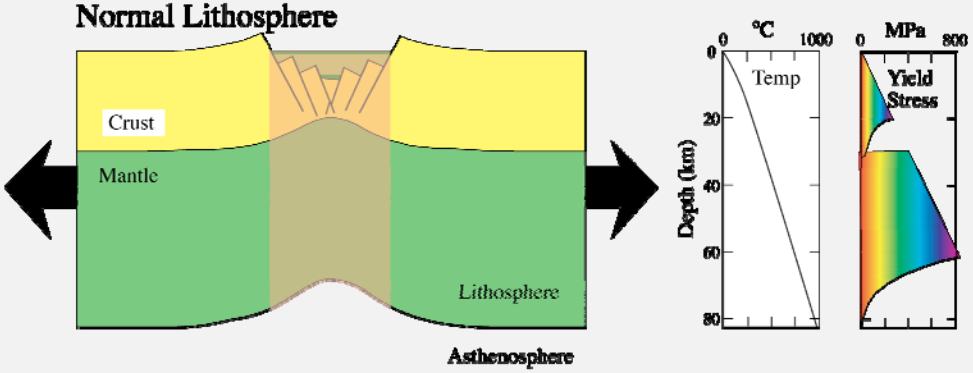
3. No opening of rifts where mantle lithosphere is thick: Cratons or old oceanic crust

4. Only a few kilometers of magmatic rifting may weaken lithosphere enough for extension to continue at moderate stress levels

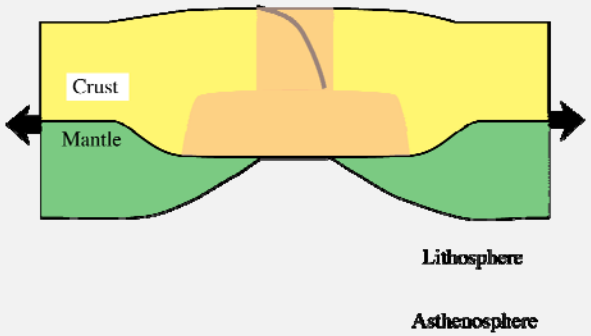
5. Magma does not have to reach the surface to affect rifting. Need seismics to 'see' magma

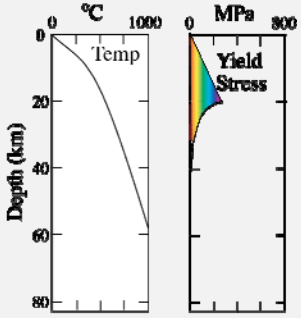
Tectonic Stretching

Normal Lithosphere

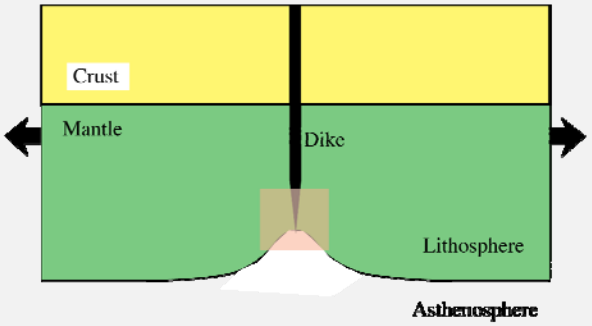


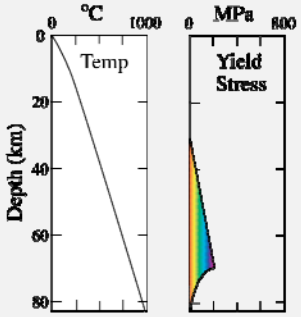
Orogenic Lithosphere





Magmatic Extension





Big Challenges for Extensional Modeling

- 3D Dike and fault propagation
- Distance of dike propagation
- Effect of dike stress changes on fault patterns
- Thermal effect of diking