Constant Nubia-Somalia kinematics controls a polyphase volcano-tectonic evolution of the Main Ethiopian Rift, East Africa

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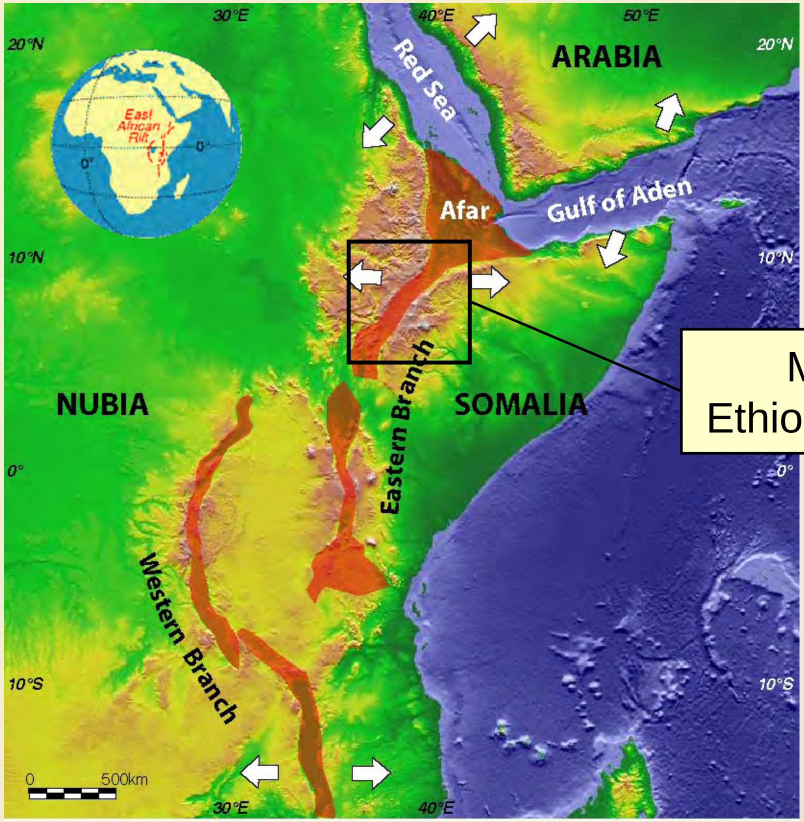
Rifting & magmatism

East African Rift System



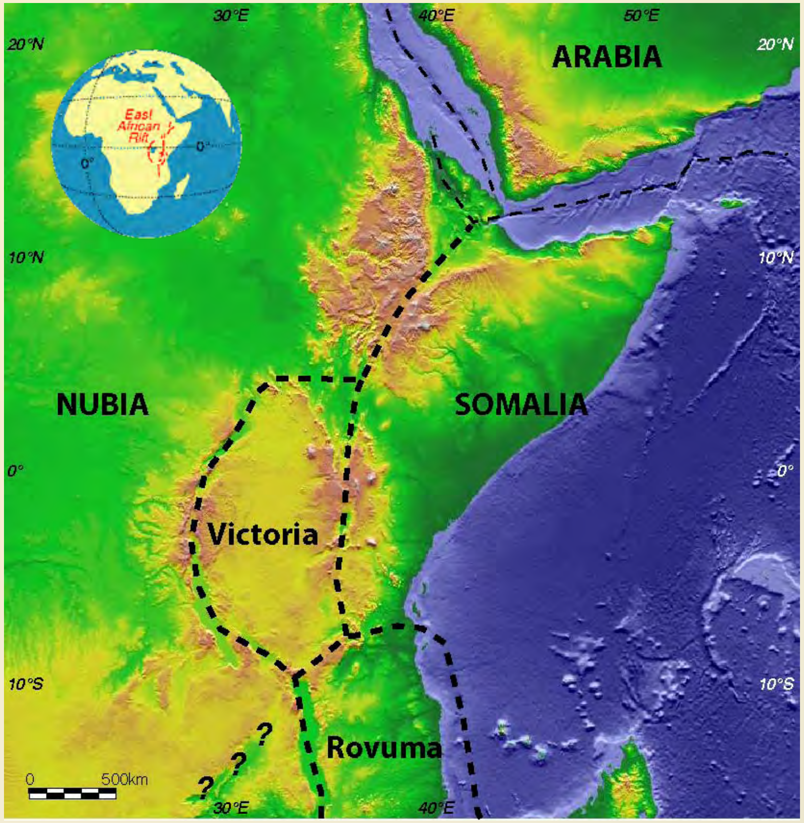
Main Ethiopian Rift

MER ideal place to study:

-the evolution of continental rifting (magmatic rift that records different stages of rifting from initiation to incipient oceanic spreading)

Rifting & magmatism

East African Rift System



MER ideal place to study:

-the evolution of continental rifting (magmatic rift that records different stages of rifting from initiation to incipient oceanic spreading)

-the Nubia-Somalia kinematics (southwards the two-plate model for the East African Rift is too simplistic)

Outline of the presentation

1. Evolution of rifting in the Main Ethiopian Rift
   - -patterns of faulting
   - -volcano-tectonic evolution
   - -Nubia-Somalia kinematics

2. Analogue modelling of continental rifting
   - -oblique rifting
   - -results:
     - evolution of the MER
     - plate kinematics

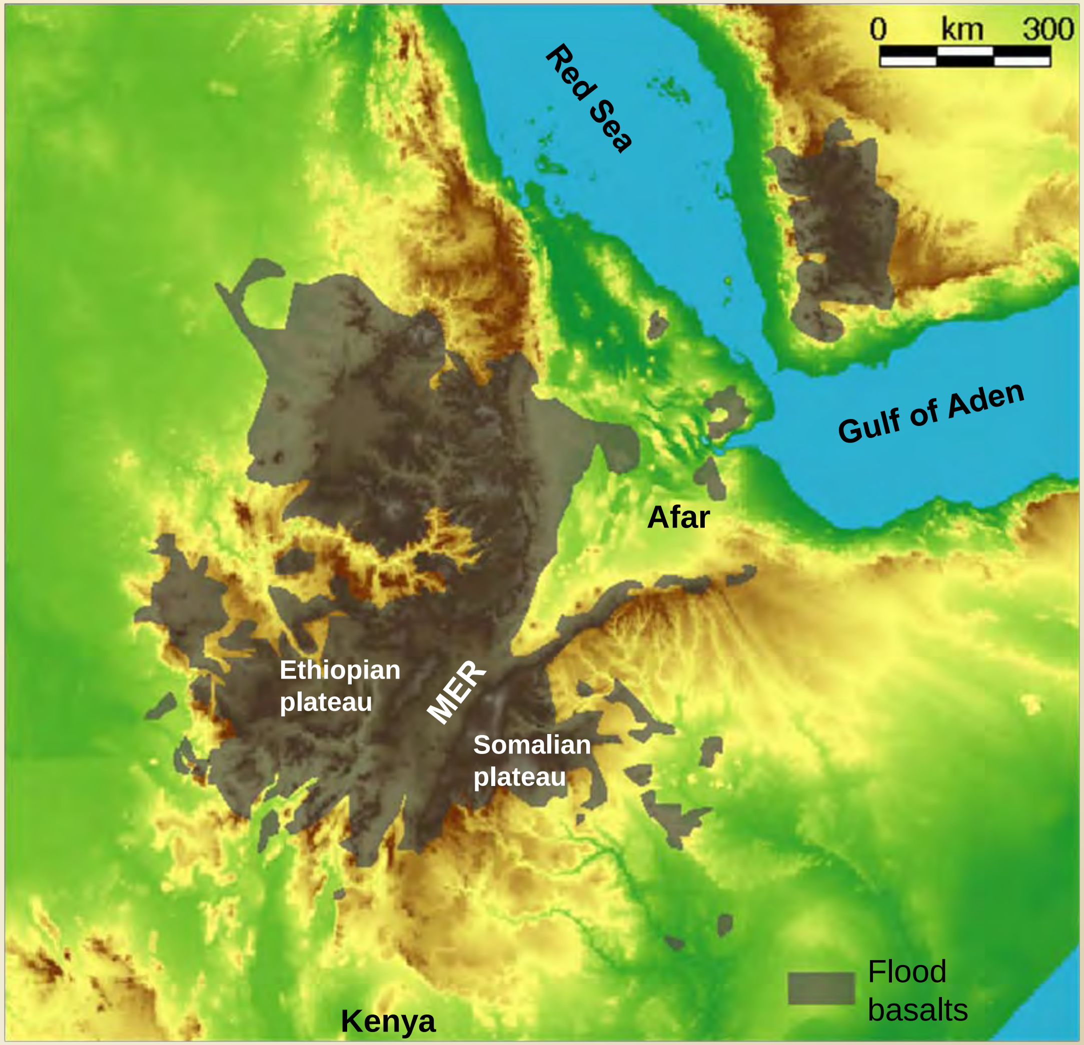
3. From rifting to break-up in the MER
   - -relations (feedback) deformation/magmatism
   - -lithospheric weakening and rupture

(Pre-rift) Flood basalt event

Voluminous flood basalt activity (→ Afar plume activity)

-emplaced at ~30 My
-uplift (?)
-underplating (10km)

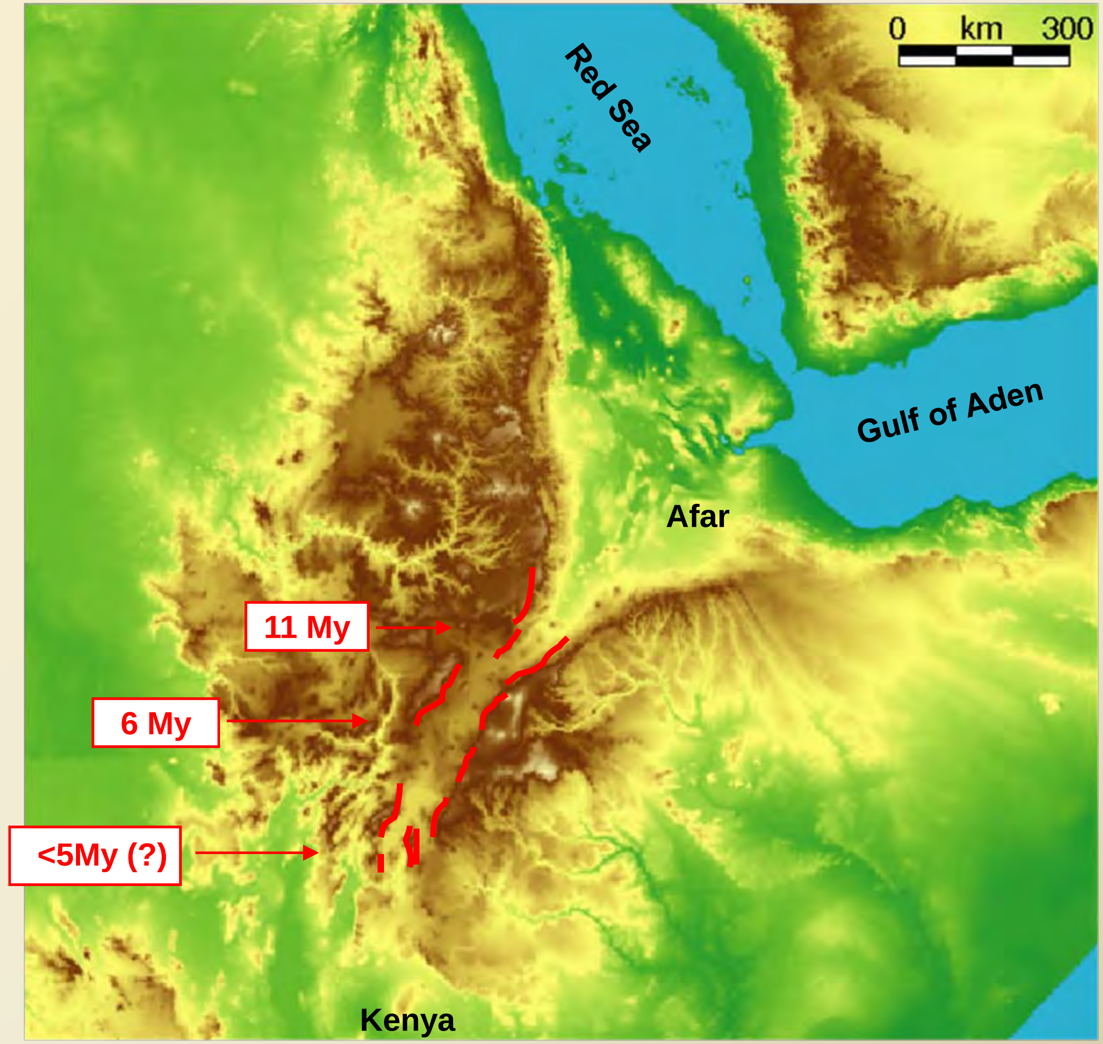
No significant extension (rifting started about 20 My later)



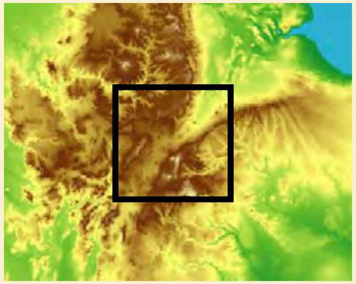
Tertiary rifting: activation of large boundary faults

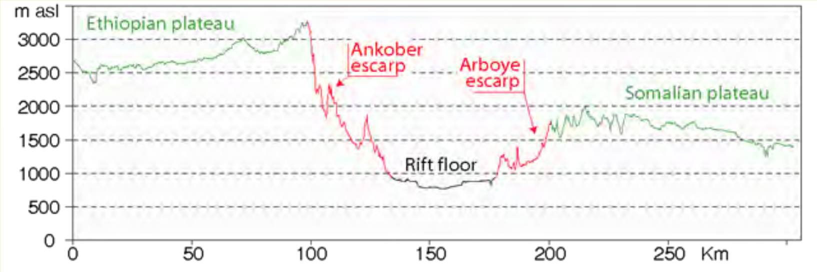
First rifting phase

diachronous activation of large boundary faults in the different rift segments (e.g., Wolfenden et al., 2004 EPSL; Bonini et al., 2005 Tectonics)



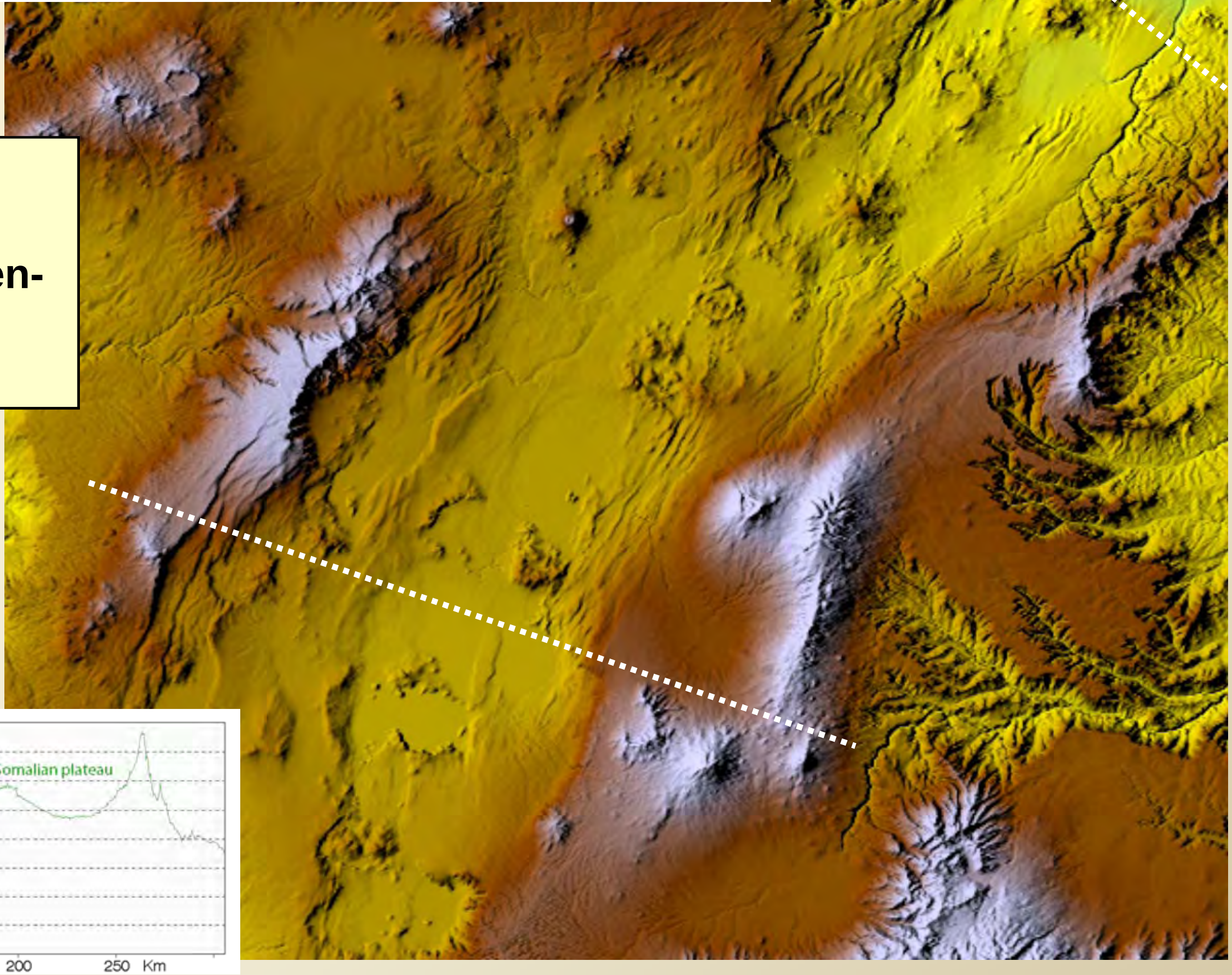
Boundary faults characteristics

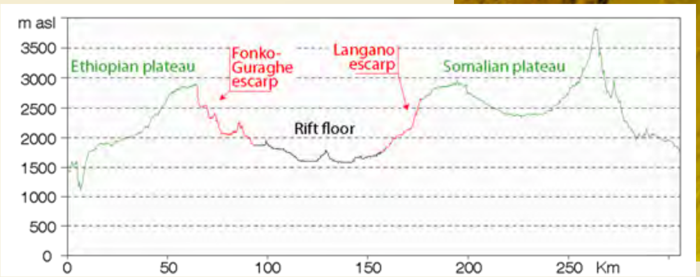




Trend around NE-SW

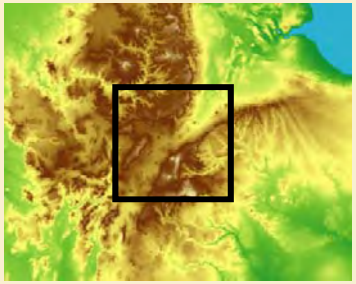
Few widely-spaced, en-echelon, long faults with large offset

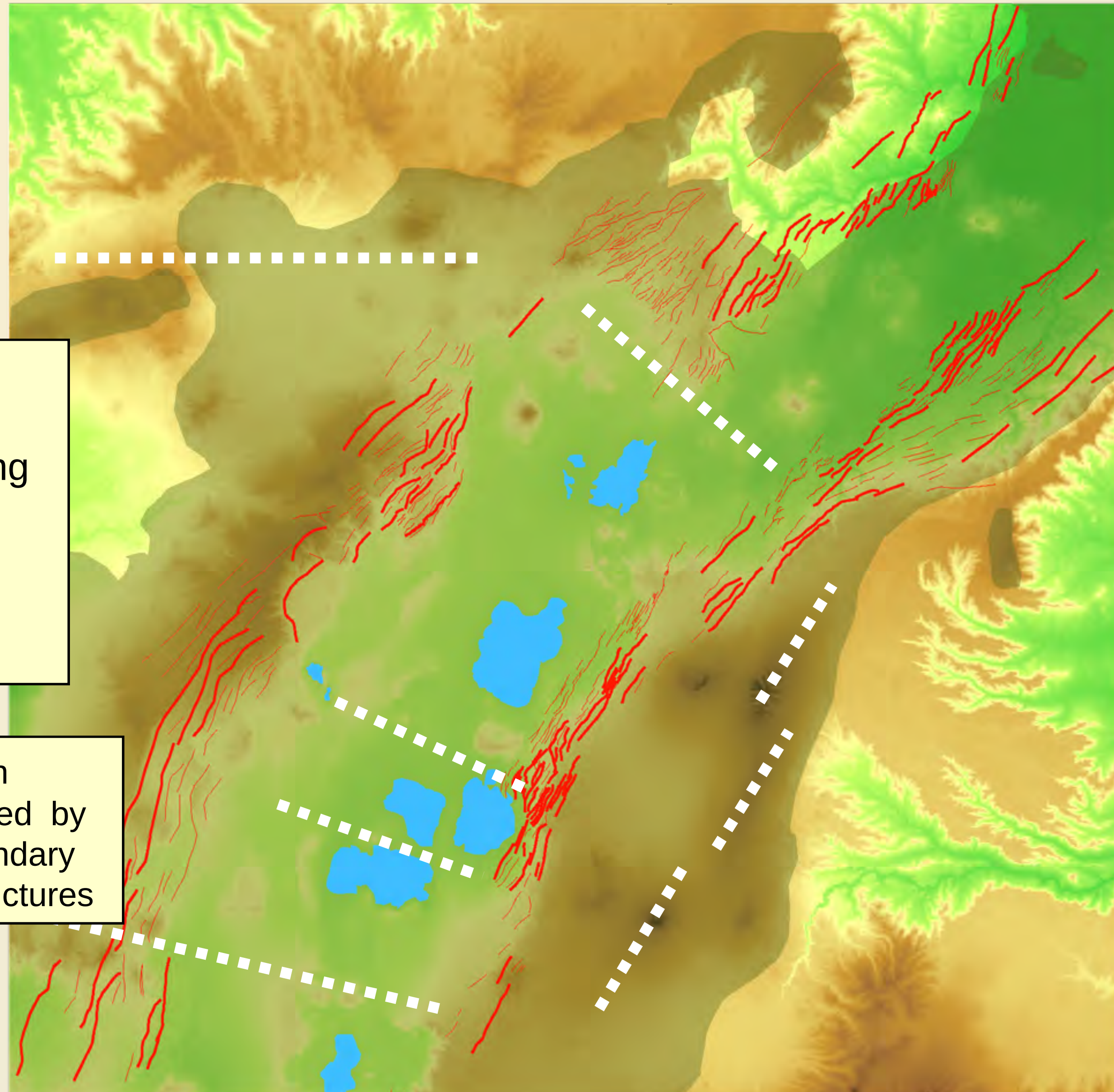




Boundary faults characteristics

Boundary faults characteristics





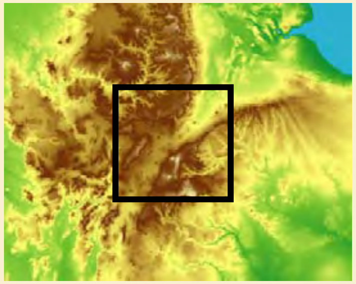
Trend around NE-SW

Few widely-spaced, long faults, en-echelon, with large offset

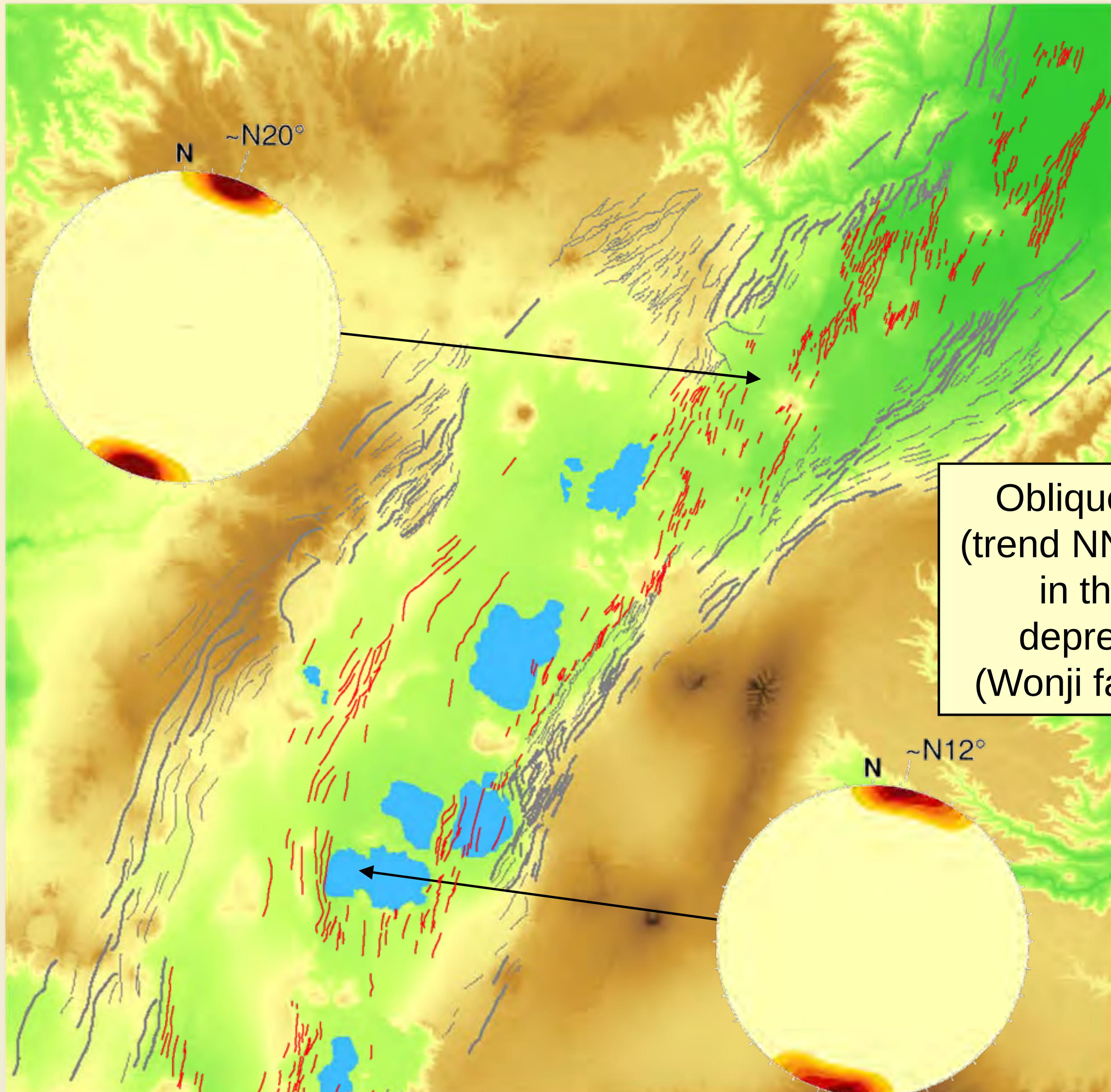
Asymmetric basins

Diffuse volcanism with spatial distribution controlled by a complex network of boundary faults and pre-existing structures

Tertiary rifting: activation of internal (Wonji) faults

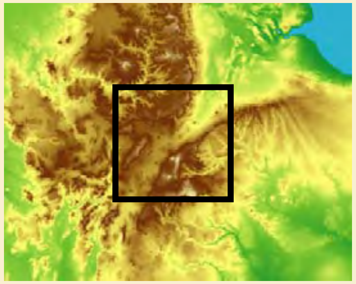


Change in deformation style at around 2 My



Oblique faults (trend NNE-SSW) in the rift depression (Wonji fault belt)

Tertiary rifting: activation of internal (Wonji) faults



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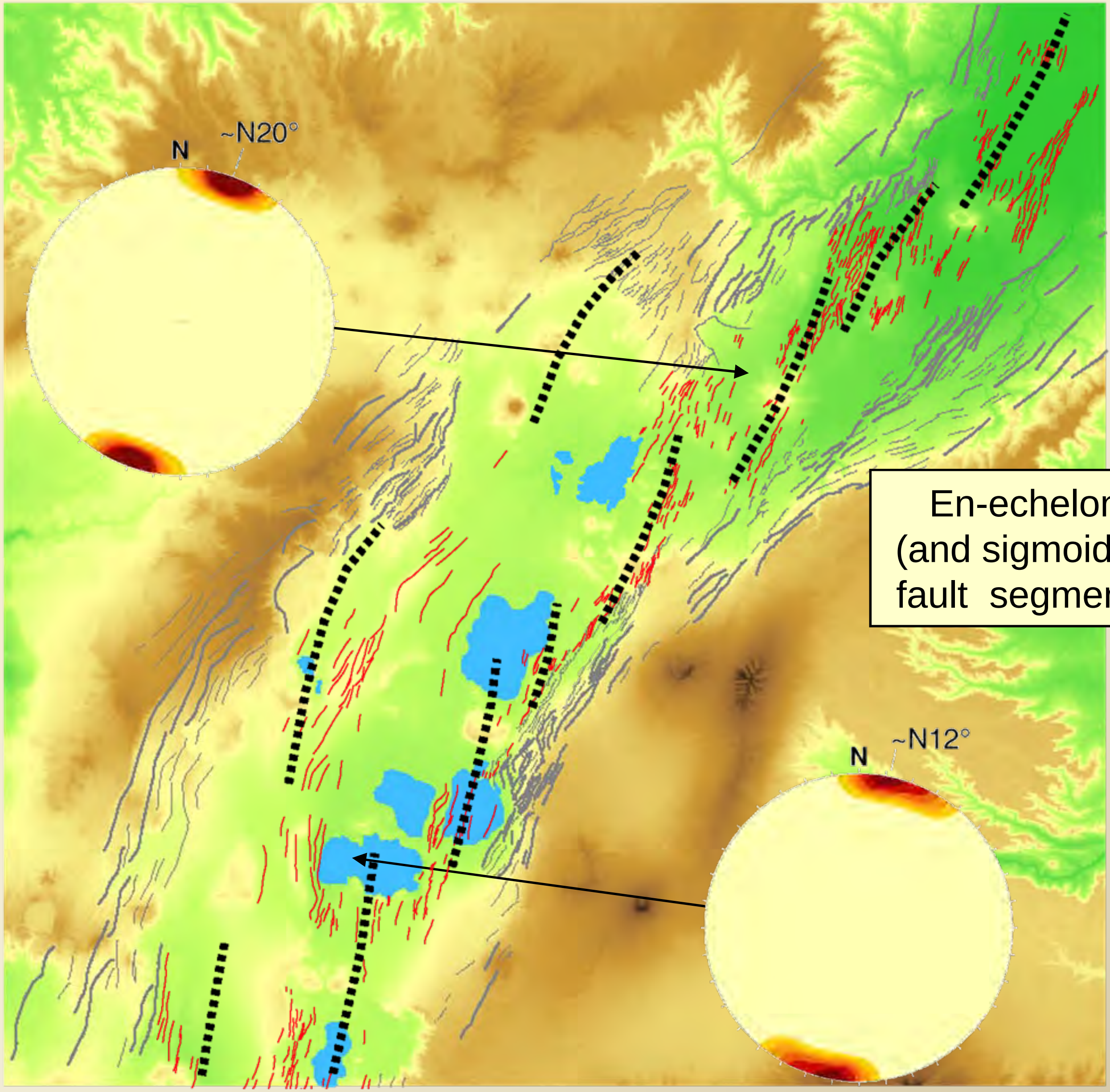


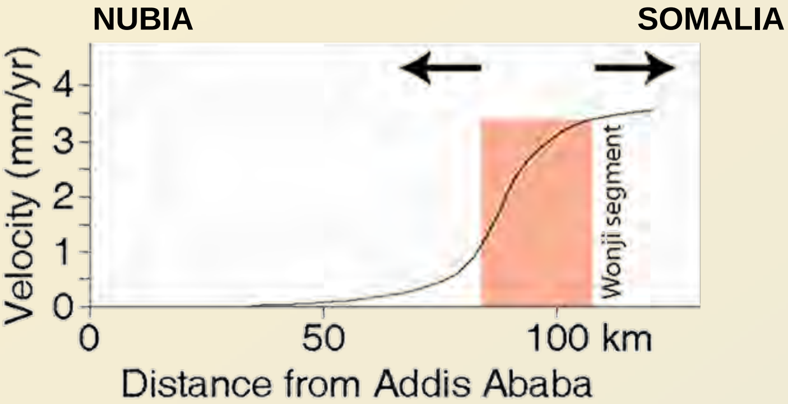
En-echelon (and sigmoidal) fault segments

Wonji faults characteristics

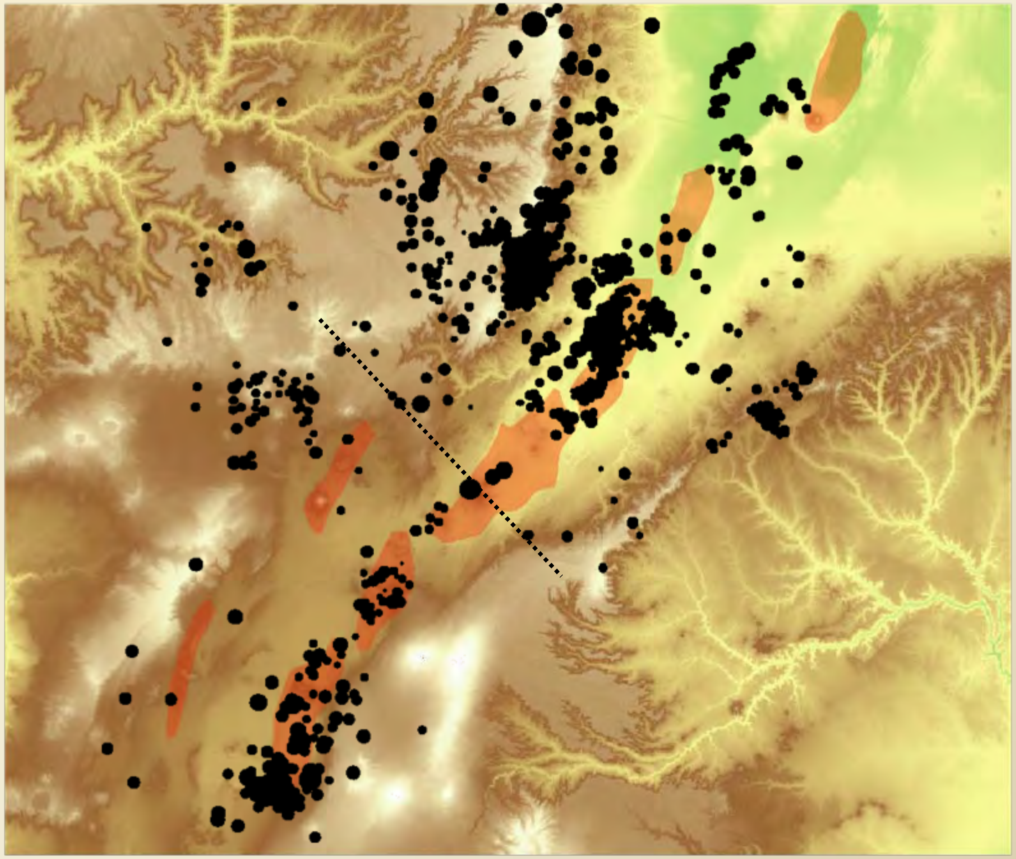
Dense swarms of short faults with small displacement

Lithospheric weakening and strain localisation

Seismicity and geodetical data indicate a strongly localised deformation within Wonji segments

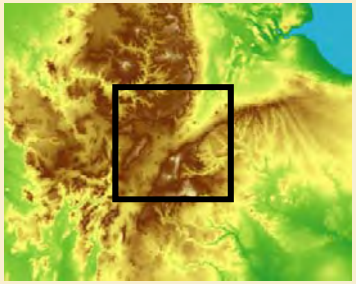


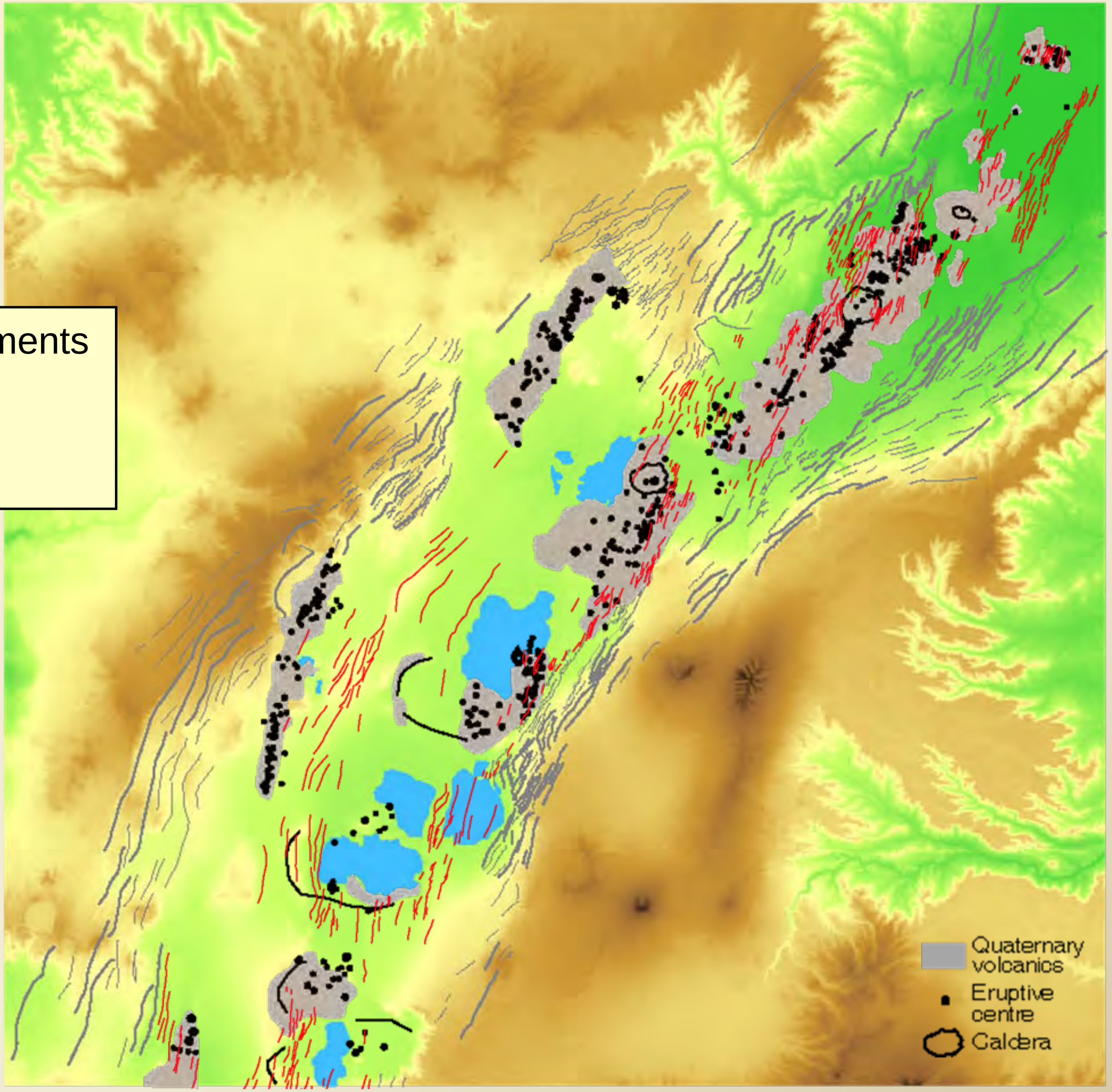
Velocity profile from geodetical data in the MER (after Billham et al, 1999 Geophys Res Lett)



Seismicity of the MER from October 2001 to January 2003 (note that earthquakes mostly occur above mafic intrusions) [after Keir et al, 2006 JGR]

Wonji faults and volcanism

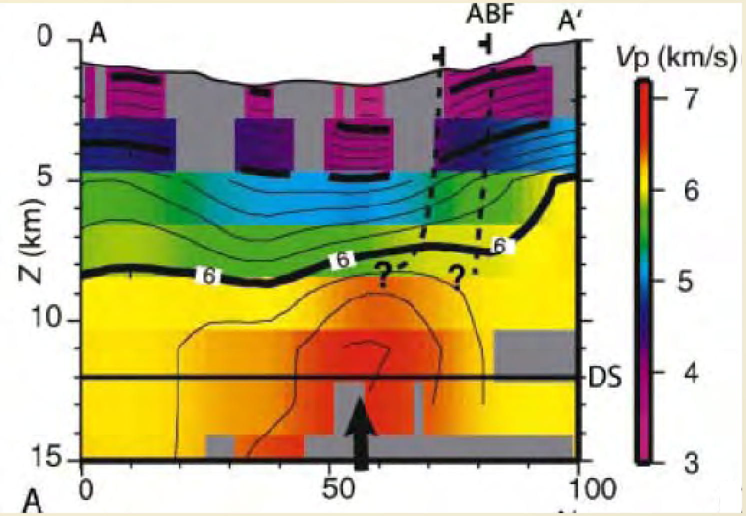




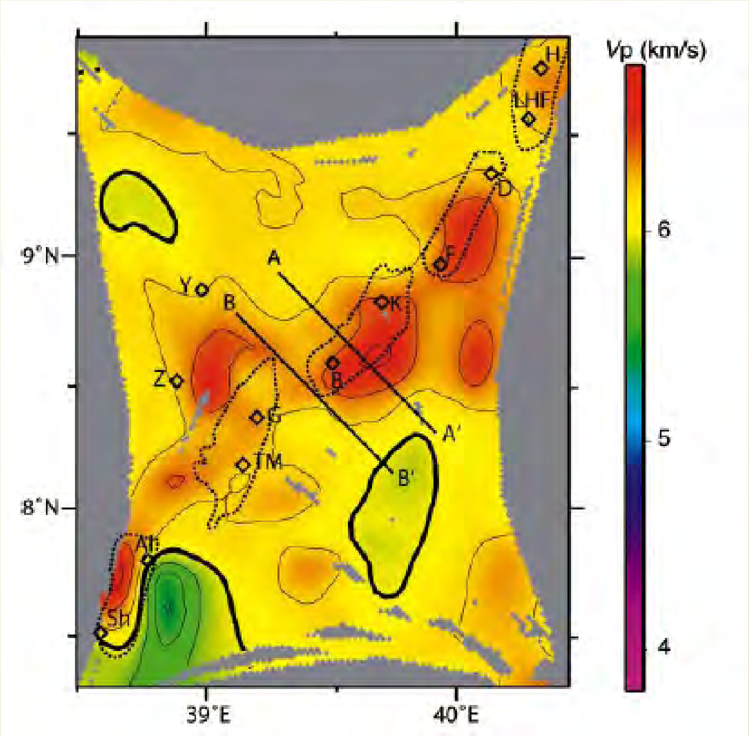
En-echelon Wonji segments strongly **localise Quaternary volcanic activity**

Wonji faults and magma intrusion

Geophysical data (Ethiopia Afar Geoscientific Lithospheric Experiment, EAGLE project; Maguire et al., 2003EOS) evidence strong magma intrusion in the lithosphere below Quaternary volcanic centres



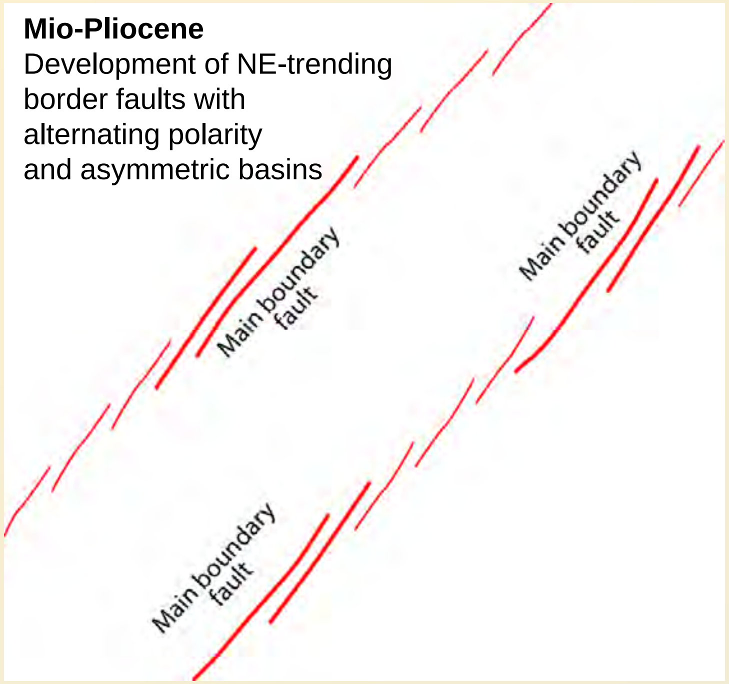
Magma intrusion has a segmented nature and occurs in right-stepping, en echelon pattern mimicking the surface segmentation of Wonji segments



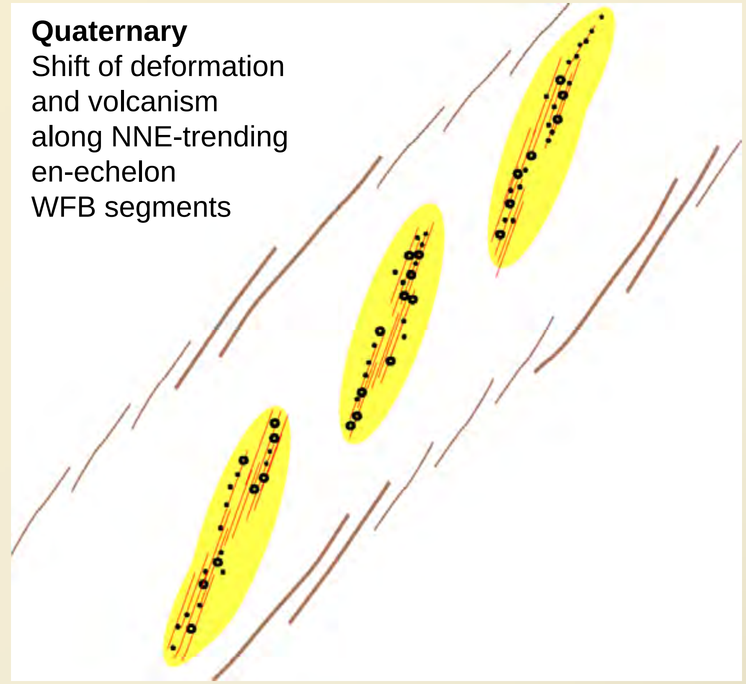
Controlled-source tomography at 10 km below the rift valley (after Keranen et al, 2004 Geology)

Summary of evolution

Mio-Pliocene
Development of NE-trending
border faults with
alternating polarity
and asymmetric basins

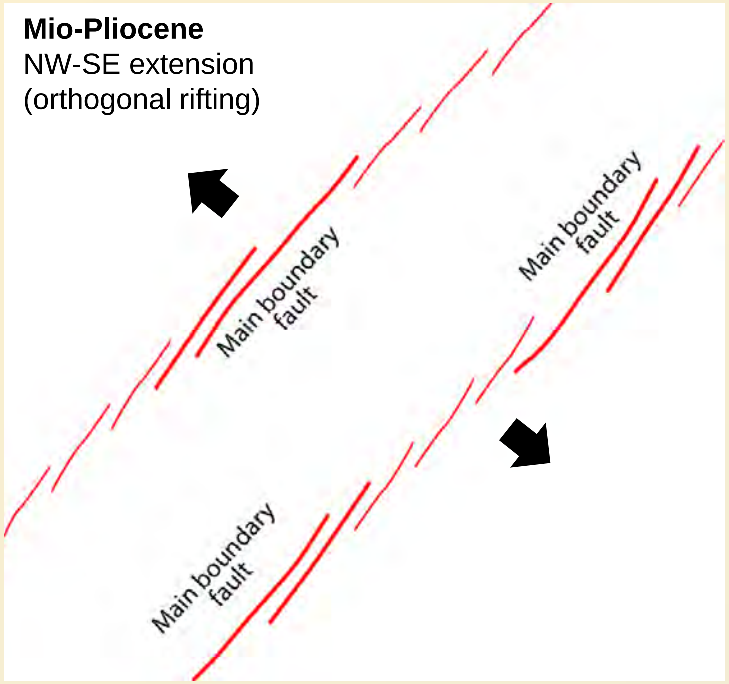


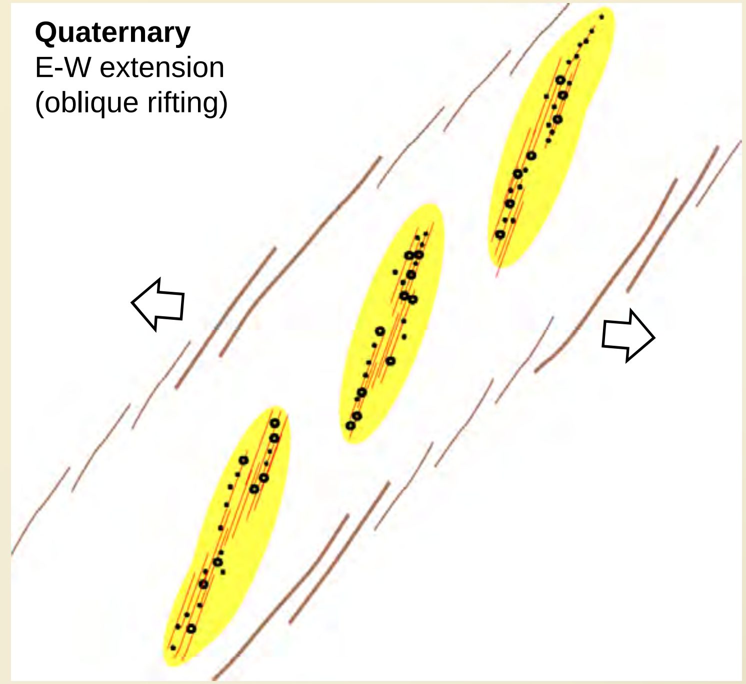
Quaternary
Shift of deformation
and volcanism
along NNE-trending
en-echelon
WFB segments

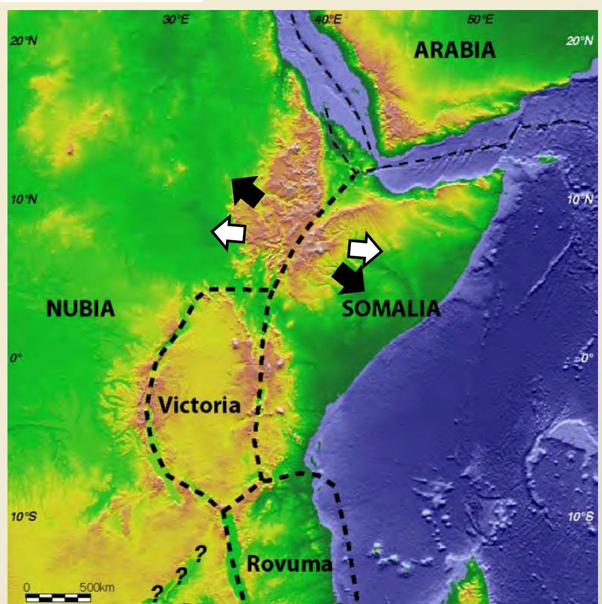


2-phase evolution, with activation of different fault systems (with different trend)

Summary of evolution







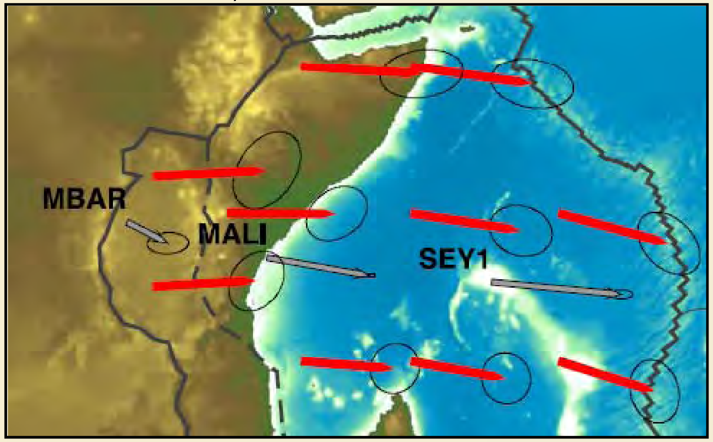
Related to a change in Nubia-Somalia kinematics

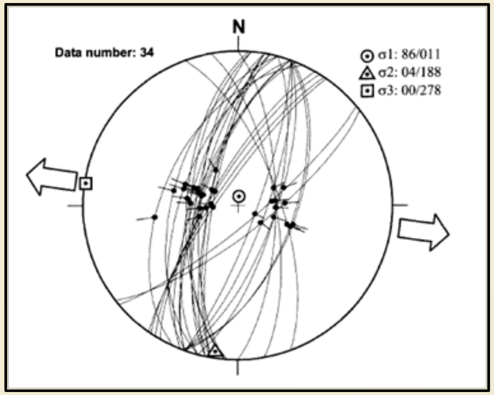
(e.g., Bonini et al., 1997; Boccaletti et al., 1998; Wolfenden et al., 2004)

Nubia-Somalia kinematics and MER evolution

Current E-W Nubia-Somalia motion → oblique rifting kinematics (geodetic data, slip vectors of Late Quaternary-Holocene faults)

Fernandes et al, 2004 EPSL





Pizzi et al, 2006 Geol Soc Spec Publ

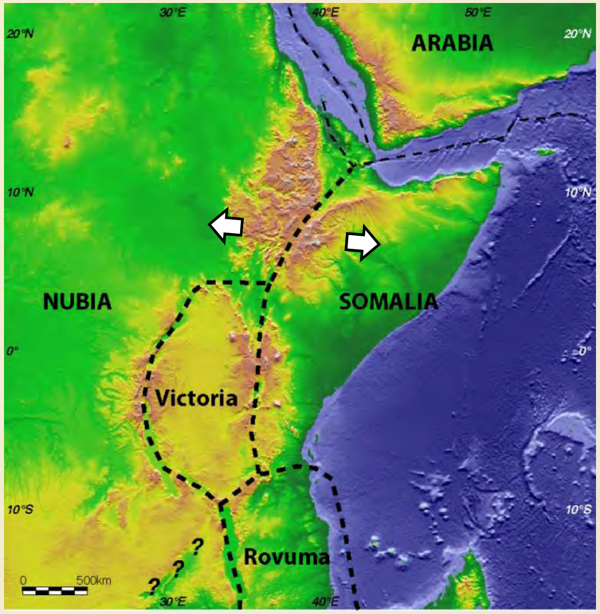


Plate kinematic models:

constant (roughly E-W) Nubia-Somalia motion since 11Ma (e.g., Royer et al., 2006 Geology)

Constant oblique rifting controls the two-phase evolution in the MER **?**

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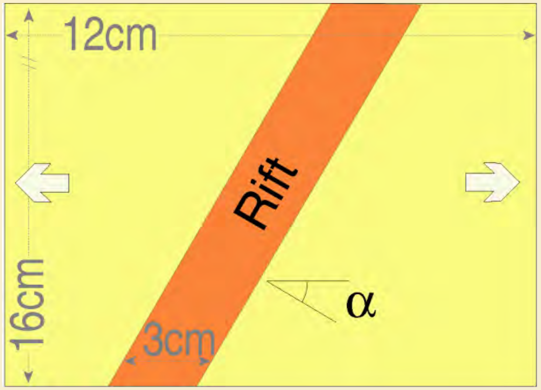
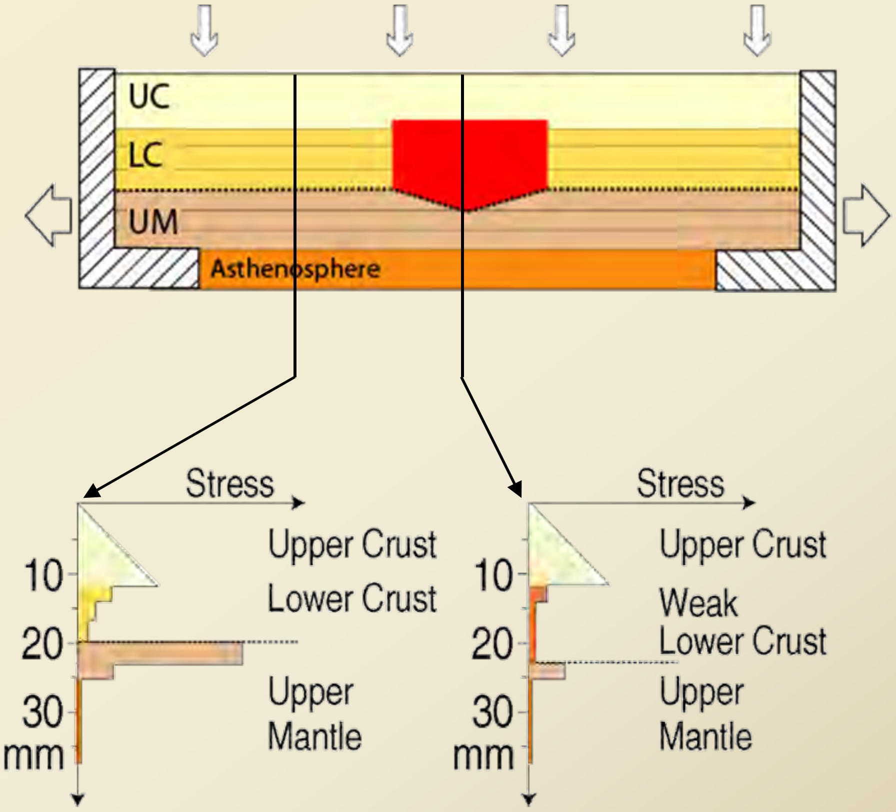
Analogue (physical) models of (oblique) rift development: set-up





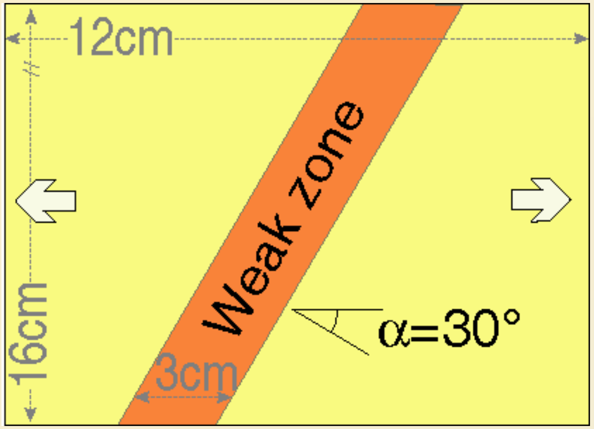
Strength profiles and set-up based on numerical models by Van Wijk, 2005 GRL

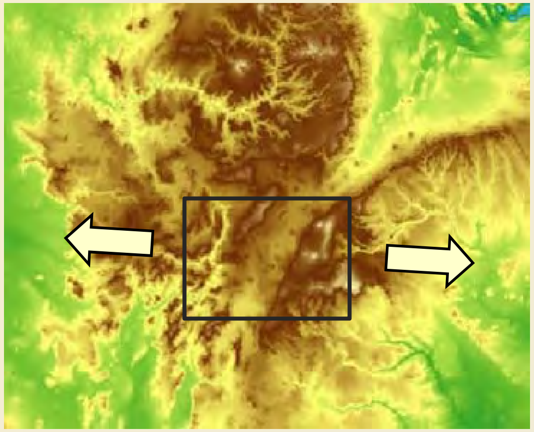
Materials: K-Feld powder, Plastilina-silicone mixtures

Syn-rift sedimentation

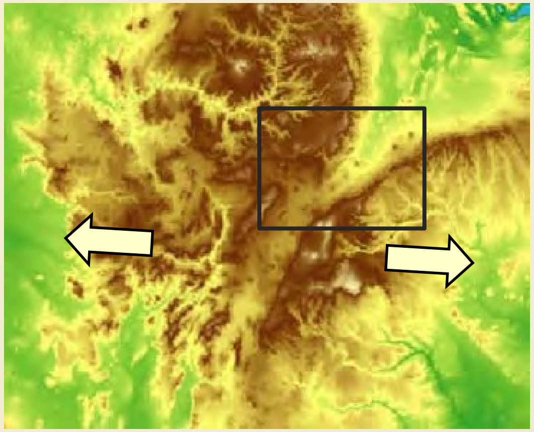
Corti, 2008
Nature geosc

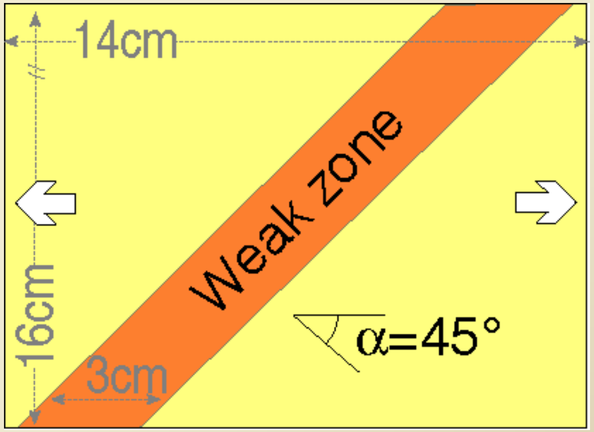
Analogue (physical) models of (oblique) rift development: set-up





Central MER



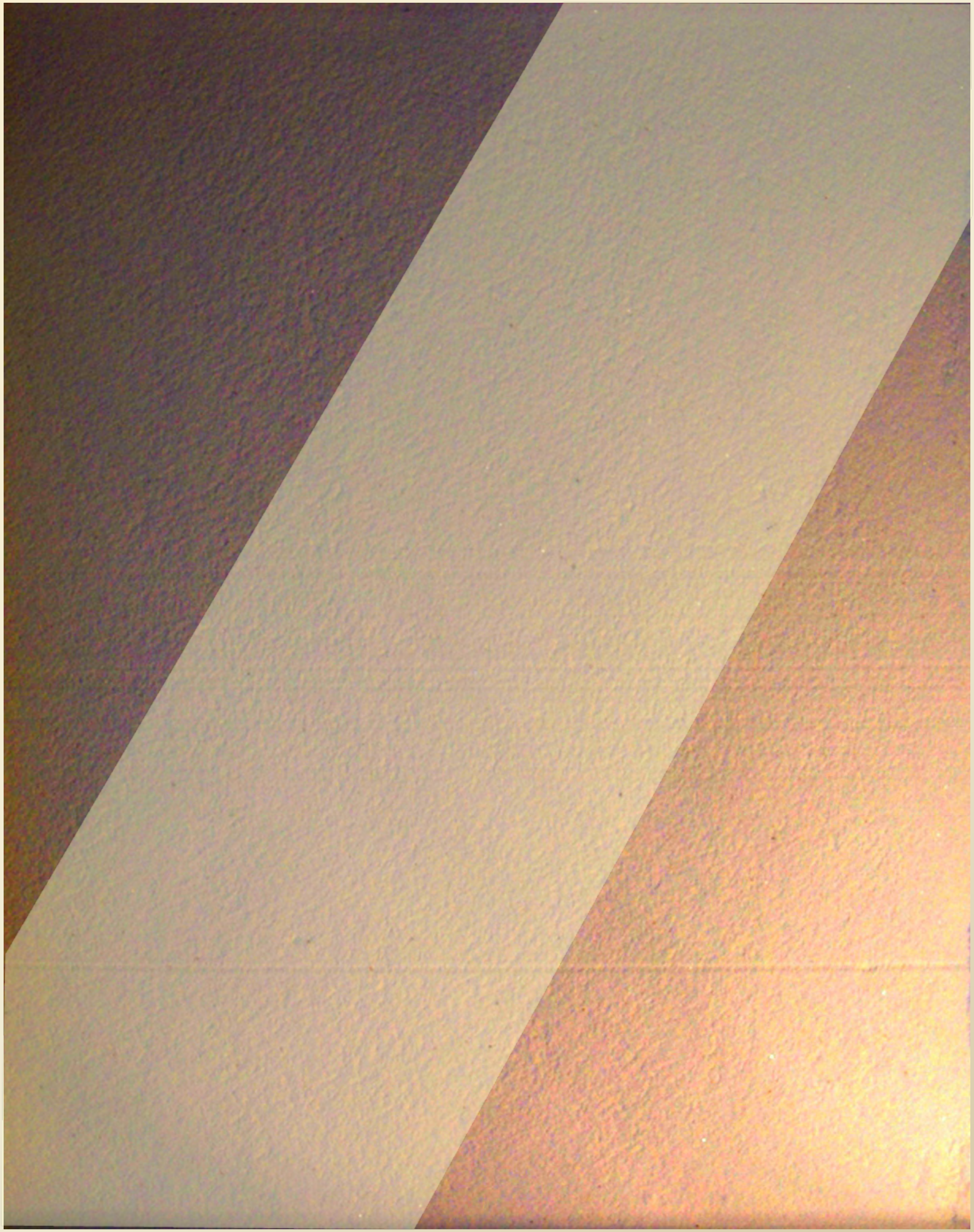


Northern MER

Model ext 28032007

EXT 0 mm
EXT 0 km

5 cm



Model ext 28032007

EXT 12 mm
EXT 18 km

SEDIMENTATION

5 cm

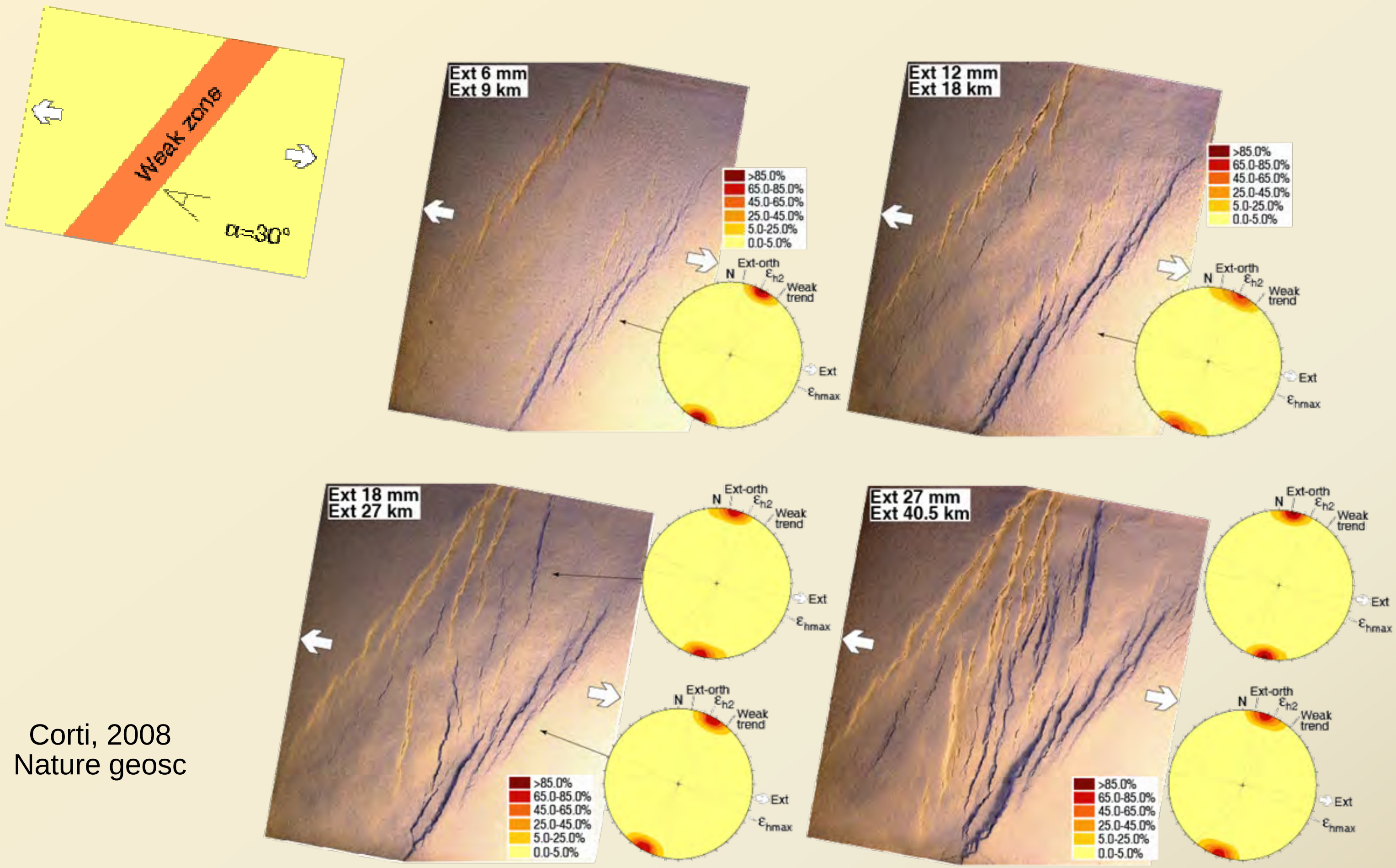
Model ext 28032007

EXT 27 mm
EXT 40.5 km

SEDIMENTATION

5 cm

Analogue modelling of oblique rifting: results



BOUNDARY FAULTS STAGE

INTERNAL FAULTS STAGE

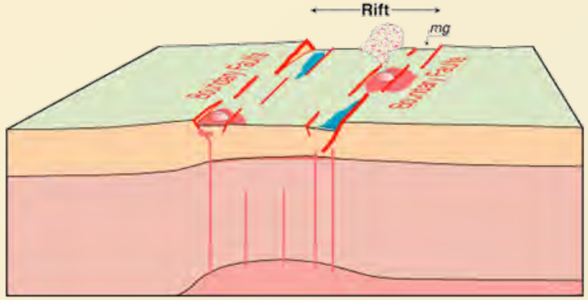
Corti, 2008
Nature geosc

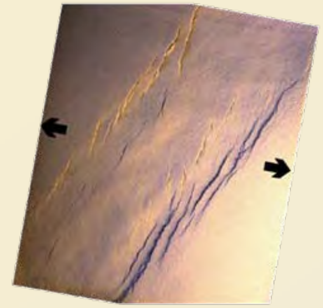
Constant oblique rifting is responsible for the diachronous development of the two fault different systems (1st: boundary faults, 2nd: en-echelon oblique faults; Corti, 2008 Nature geosc).

Boundary faults can accommodate only a limited amount of displacement; with progressive extension deformation shifts in the weakest part of the rift (i.e. in the thinned rift depression)

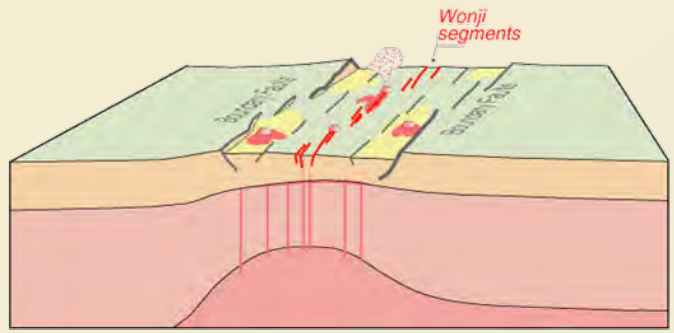
Analogue modelling of oblique rifting: application to the MER

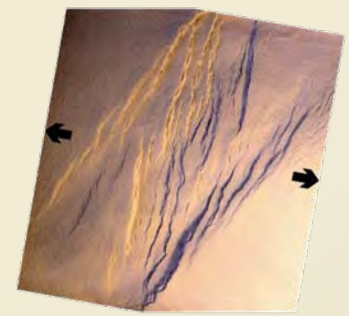
Border faults (11My-2My)





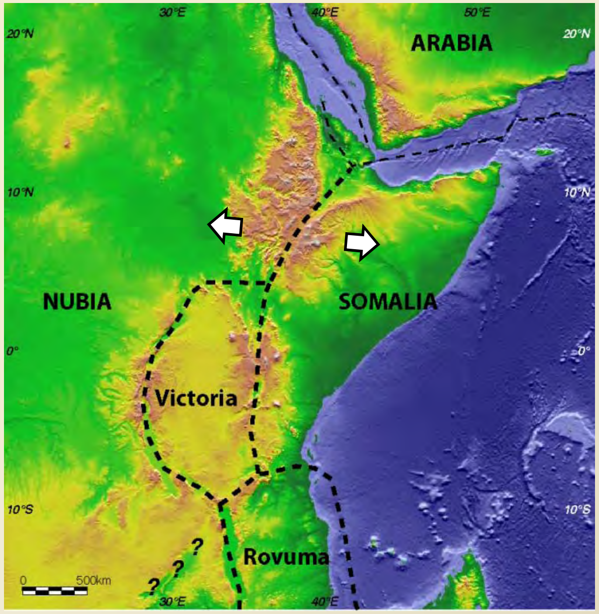
Localised deformation on Wonji segments (2My)





No change in kinematics required

Constant (simple) Nubia-Somalia kinematics, two-phase (complex) evolution of the MER

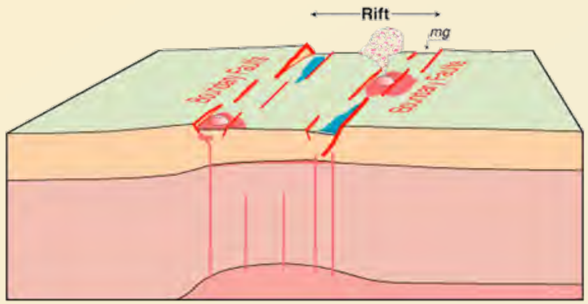


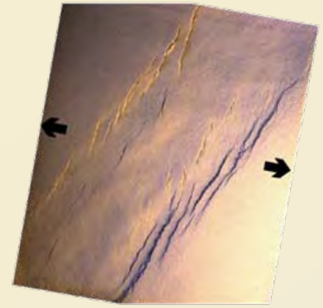
Best-fit of fault patterns in models and nature suggests a N100°E Nubia-Somalia extension in the MER
(Corti, 2008 Nature geosc)

modified from Ebinger, 2005 A&G; see also Corti, 2008 Nature geosc

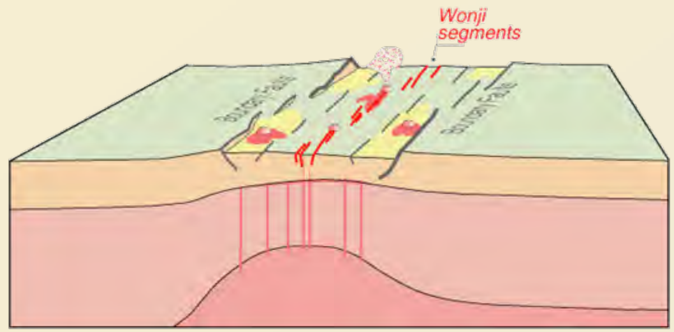
Analogue modelling of oblique rifting: application to the MER

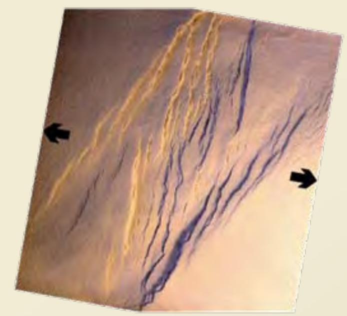
Border faults (11My-2My)



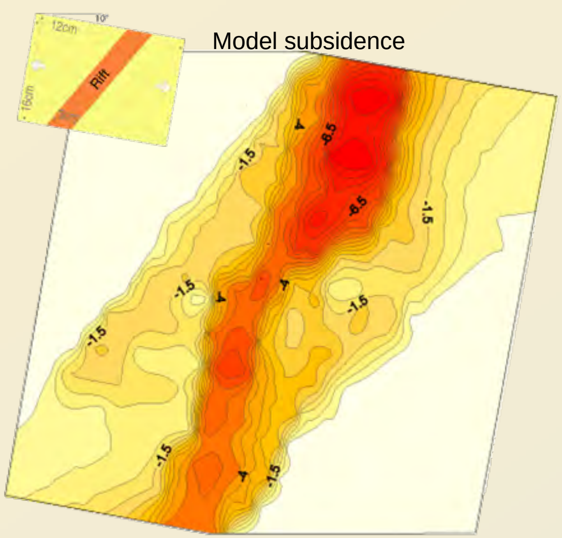


Localised deformation on Wonji segments (2My)



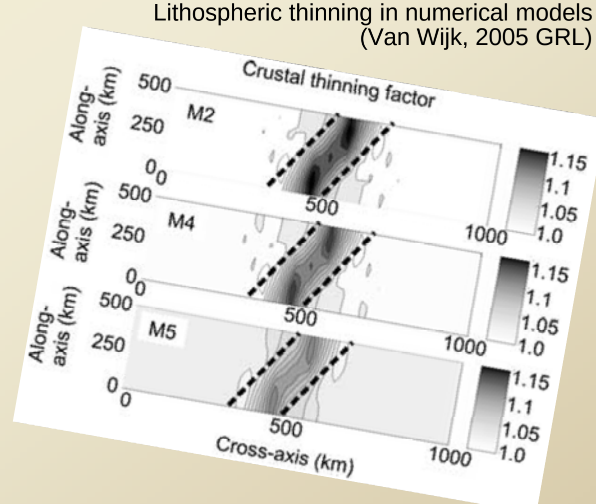


Model subsidence



Scheme of deformation distribution

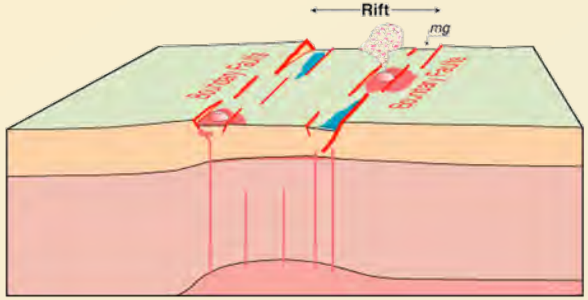
Lithospheric thinning in numerical models (Van Wijk, 2005 GRL)

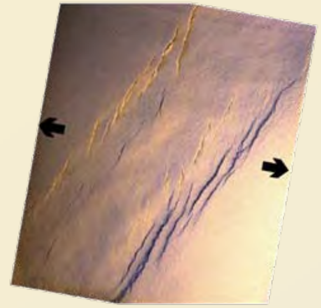


Oblique rifting results in a typical en-echelon arrangement deformation segments, with max lithospheric thinning and focused magma production (numerical models)

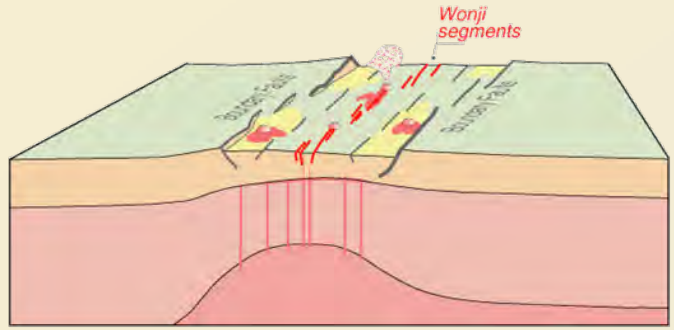
Analogue modelling of oblique rifting: application to the MER

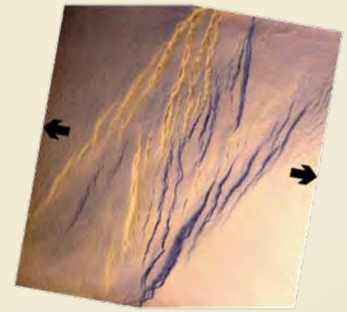
Border faults (11My-2My)



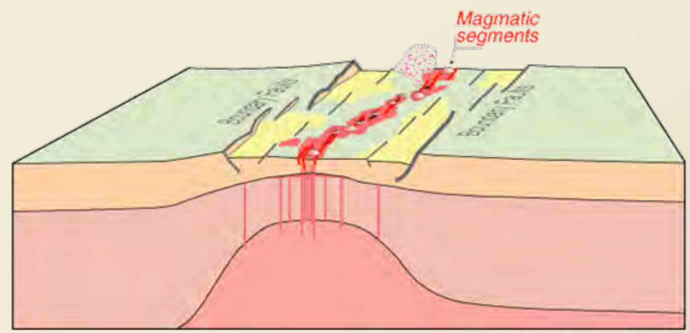


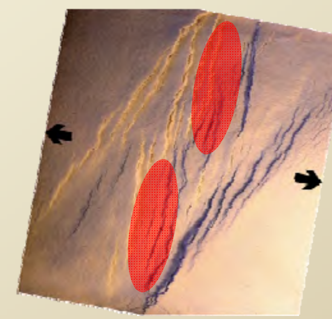
Localised deformation on Wonji segments (2My)





Focusing of magmatism on Wonji segments (2My-present)



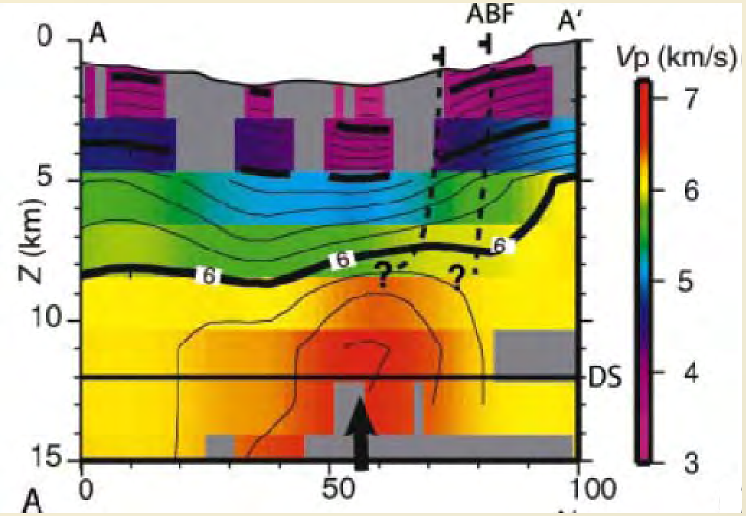


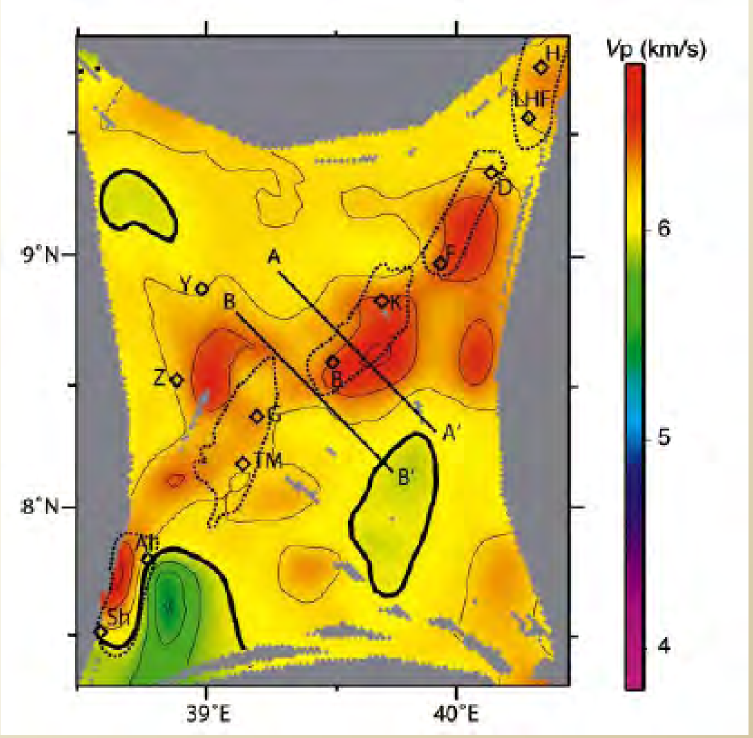
Deformation and (Quaternary) magmatism in the MER

Geophysical data (Ethiopia Afar Geoscientific Lithospheric Experiment, EAGLE project; Maguire et al., 2003EOS) evidence strong magma intrusion in the lithosphere below Wonji segments

Large mafic intrusions (mid-lower crust), melt-filled cracks/dykes (crust, upper mantle), magma chambers (upper crust)
below Quaternary volcanic centres

Pervasive magma intrusion in the entire lithosphere (uppermost 75km; e.g., Kendall et al., 2004 Nature; Keir et al., 2005 Geophys Res Lett)
→ Magmatic processes have fundamentally modified the crust and mantle lithosphere beneath the rift





Keranen et al, 2004
Geology

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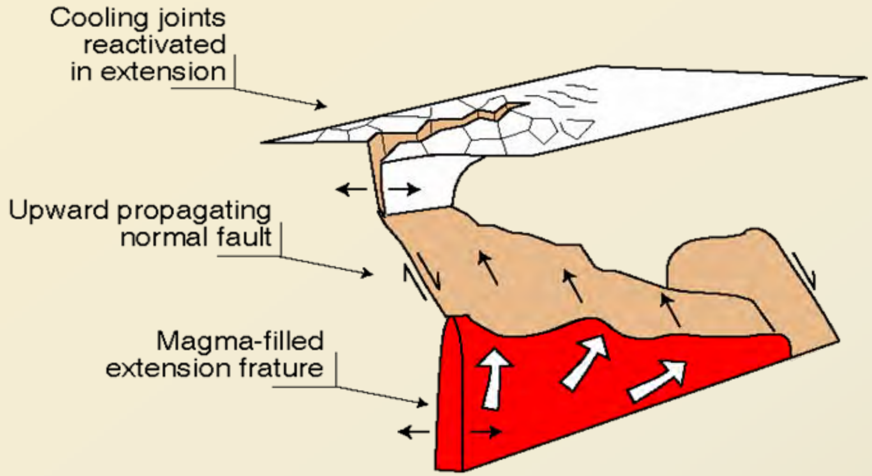
Deformation and (Quaternary) magmatism in the MER

Dyke-induced growth of normal faults (above mafic intrusions)



Model of fault growth during the 2005 Dabbahu magmatic rifting episode (after Rowland et al, 2007 GJI)

Extension accommodated

(seismically) by a combination of dyking/faulting in the **upper crust**

(aseismically) by magma injection within a narrow zone in the **mid/lower crust** and **upper mantle**

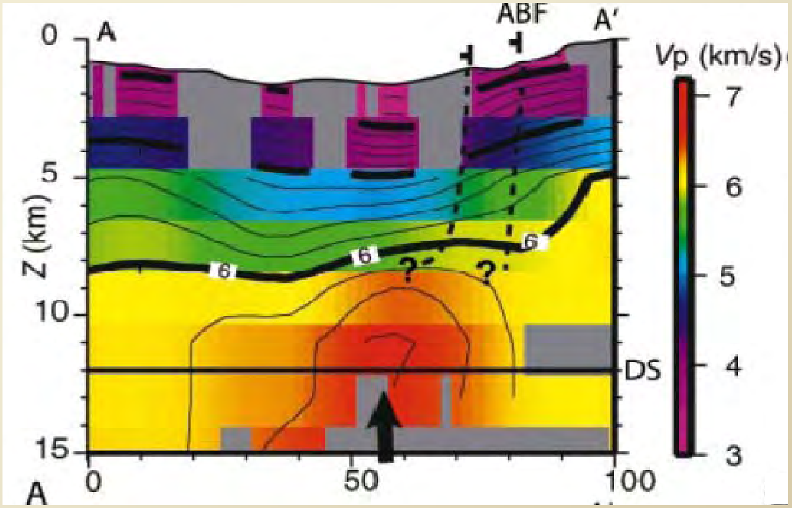
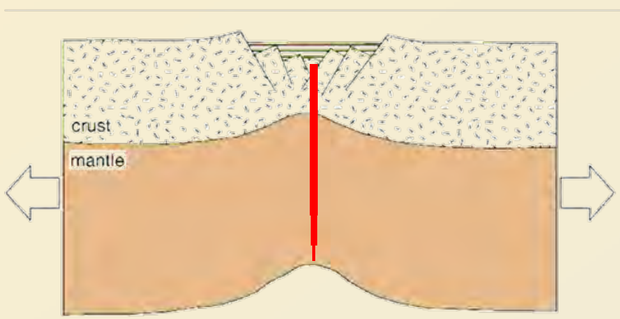
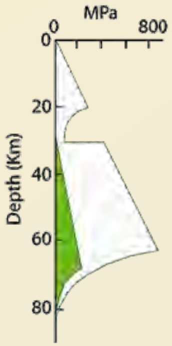


Image of large mafic intrusion (after Keranen et al, 2004 Geology)

Wonji faults and magma intrusion: lithospheric weakening



(after Buck 2006 Geol Soc Spec Pap)



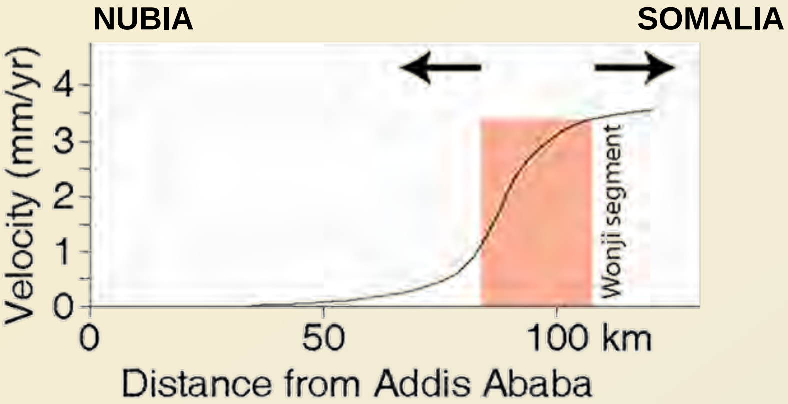
Strength

Decrease in lith strength up to one order of magnitude

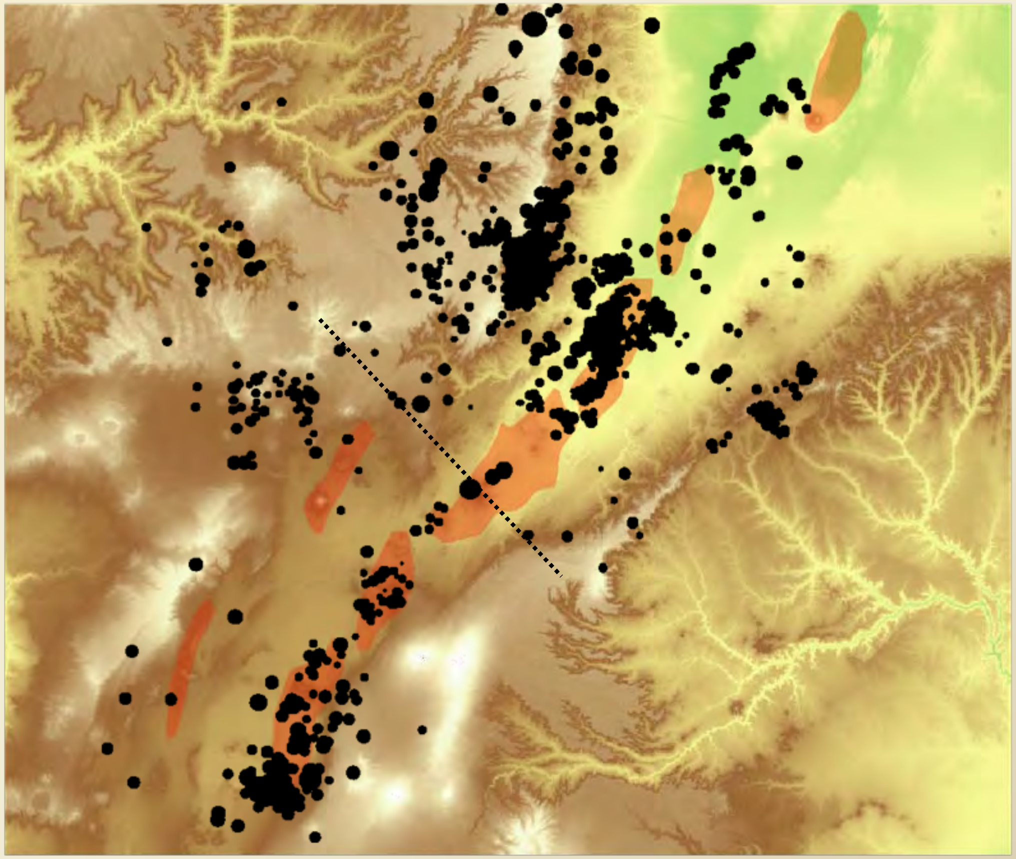
Increase in **strain localisation** (e.g., Corti et al. 2007 JGeodyn)

Lithospheric weakening and strain localisation

Deformation is localised in a very narrow region (about 10km-wide in the Northern MER; Keir et al., 2006 JGR) within Wonji segments



Velocity profile from geodetical data in the MER (after Billham et al, 1999 Geophys Res Lett)

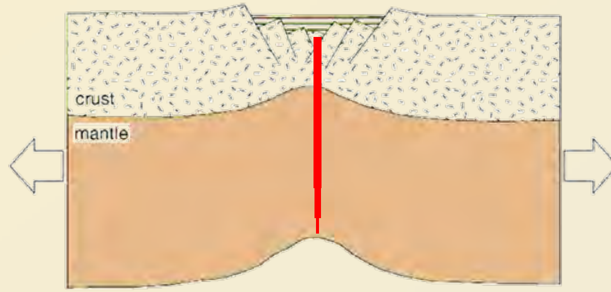


Seismicity of the MER from October 2001 to January 2003 (note that earthquakes mostly occur above mafic intrusions) [after Keir et al, 2006 JGR]

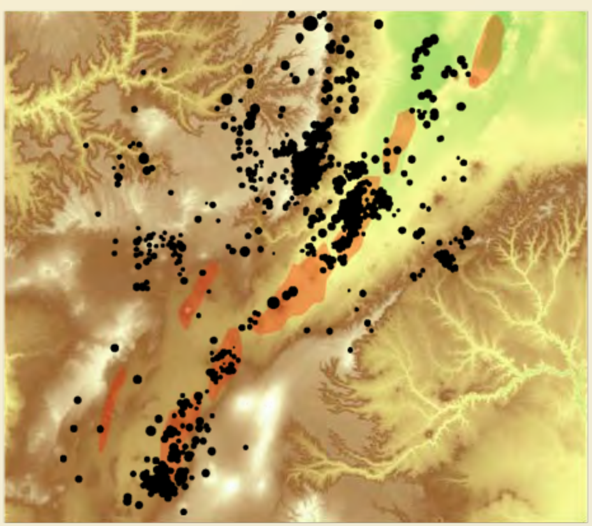
Lithospheric weakening and strain localisation

Feedback deformation-magmatism

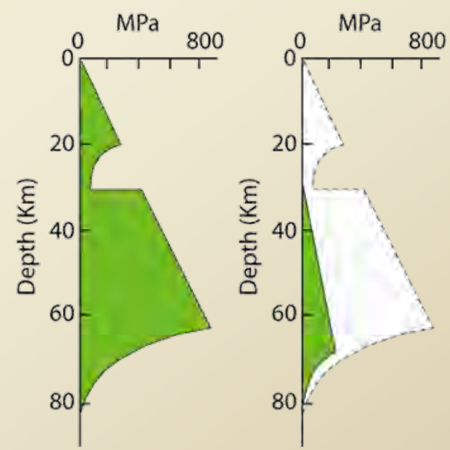
Focused magma intrusion



Localised deformation



Pronounced weakening



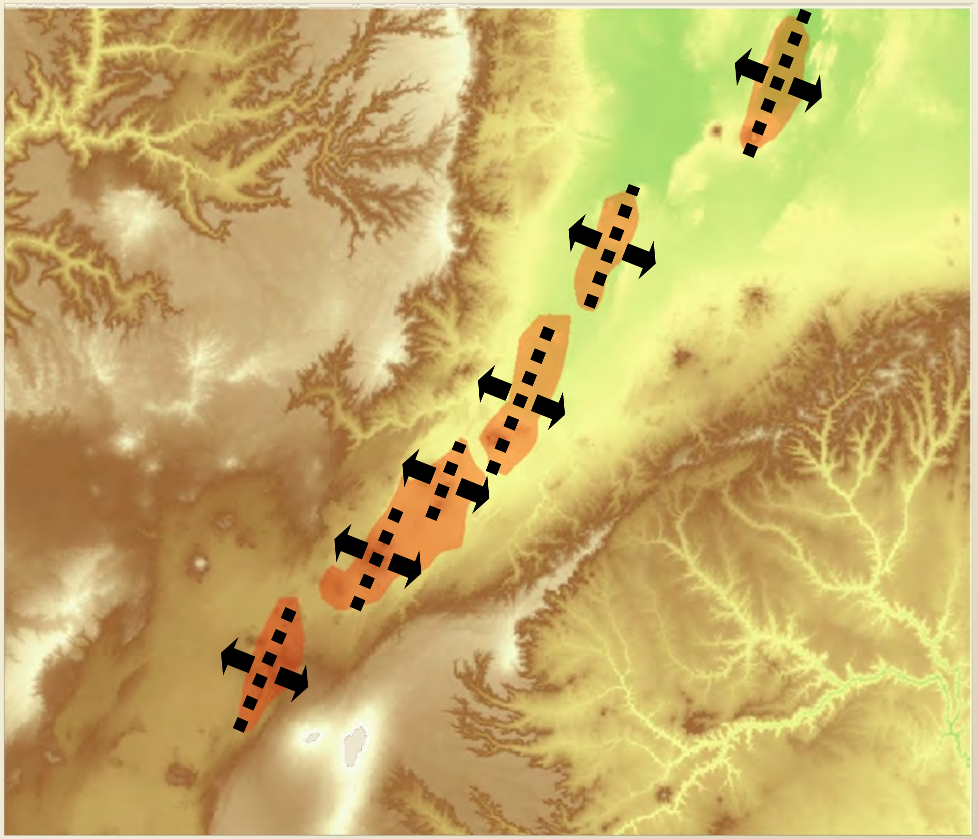
see also Corti et al., 2007 JGeodyn

The self-reinforcing process allows the **break-up** of the continental lithosphere

Continental break-up

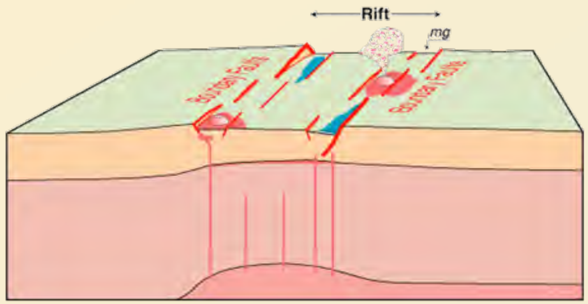
Characteristics of Wonji volcano-tectonic segments (extensive mafic addition to the crust within a narrow zone of localized strain, dyking/faulting, seismic activity, low elastic thickness, morphology & segmentation,…) typical of **slow-spreading ridges**

(Northern) MER is in the break-up stage, Wonji segments act as incipient mid-ocean spreading centres (e.g., Ebinger, 2005A&G)



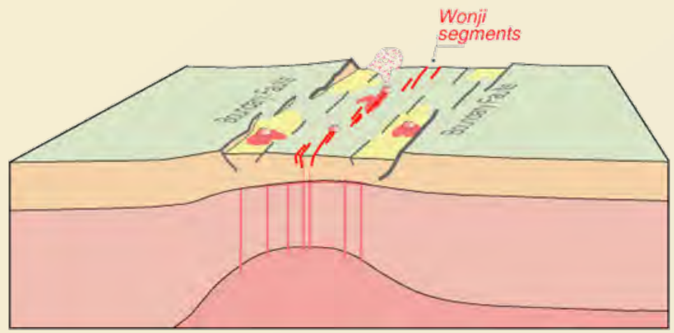
Summary and conclusions: from rifting to break-up in the MER

Border faults, diffuse magmatism (11My-2My)

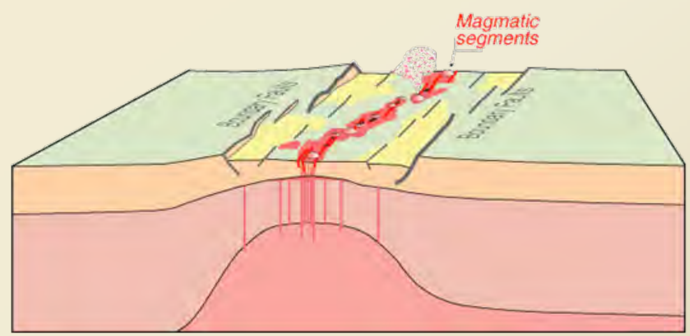


Transition from fault dominated rift morphology toward magma assisted-rifting during break-up (increase in coupling deformation-magmatism with extension)

Localised deformation on Wonji segments (2My)

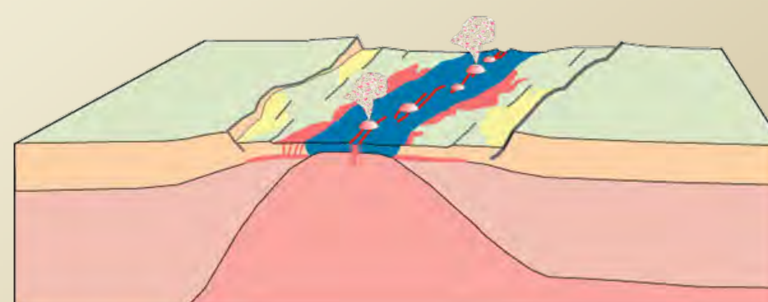


Focusing of magmatism on Wonji segments (2My-present)



Feedback magmatism-deformation → Lithosphere strongly modified by magmatism → Weakening & and strain localisation

Break-up and incipient spreading on Wonji segments



modified from Ebinger, 2005 A&G; see also Corti, 2008 Nature geosc