The relations between magmatism and deformation during continental rifting: examples from the Main Ethiopian Rift, East Africa

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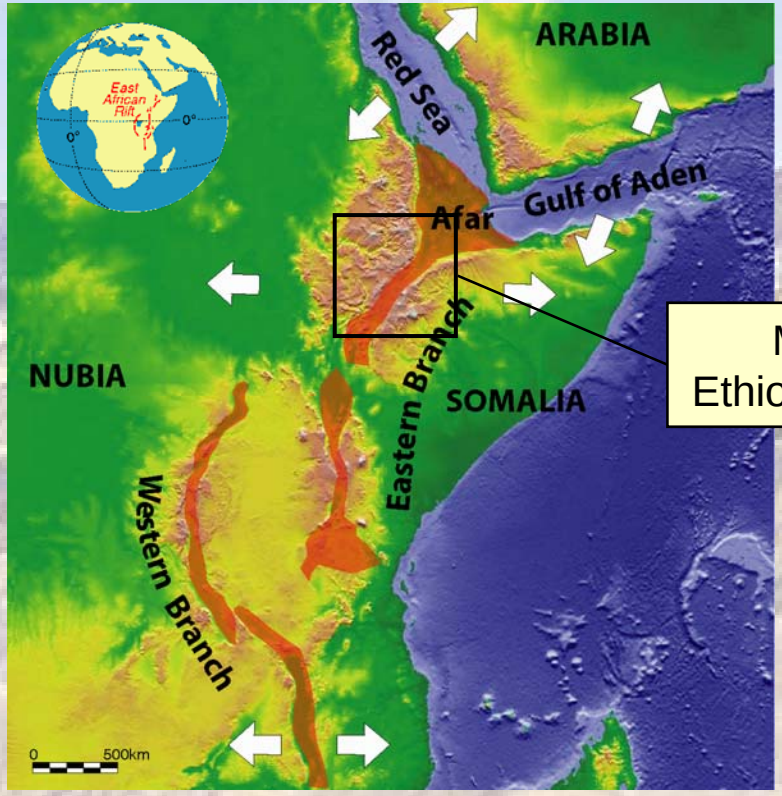
Rifting & magmatism

East African Rift System



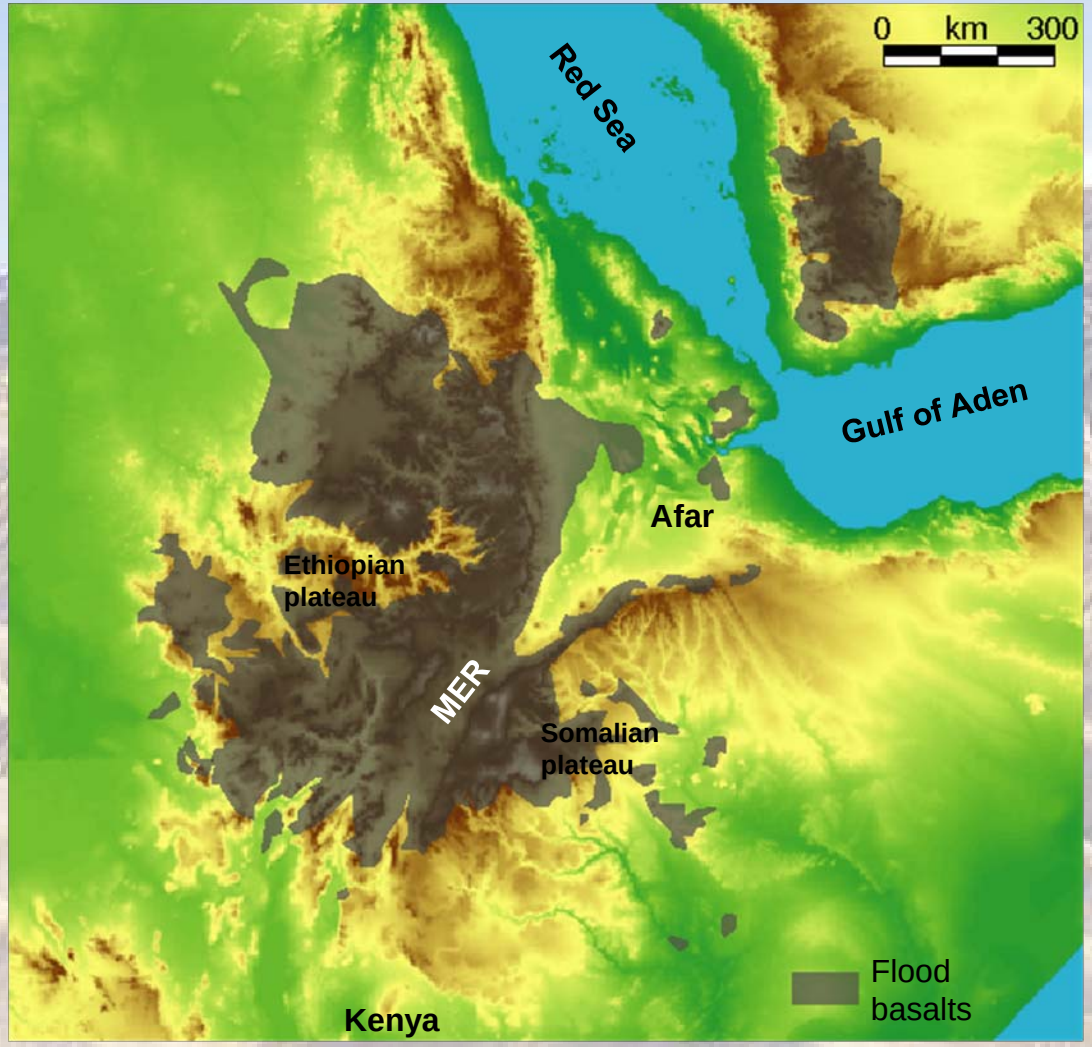
Magmatic rift that records different stages of rift evolution from rift initiation to incipient oceanic spreading
→ ideal place to study the interaction between magmatism and deformation

(Pre-rift) Flood basalt event

Voluminous flood basalt activity (→ Afar plume activity)

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

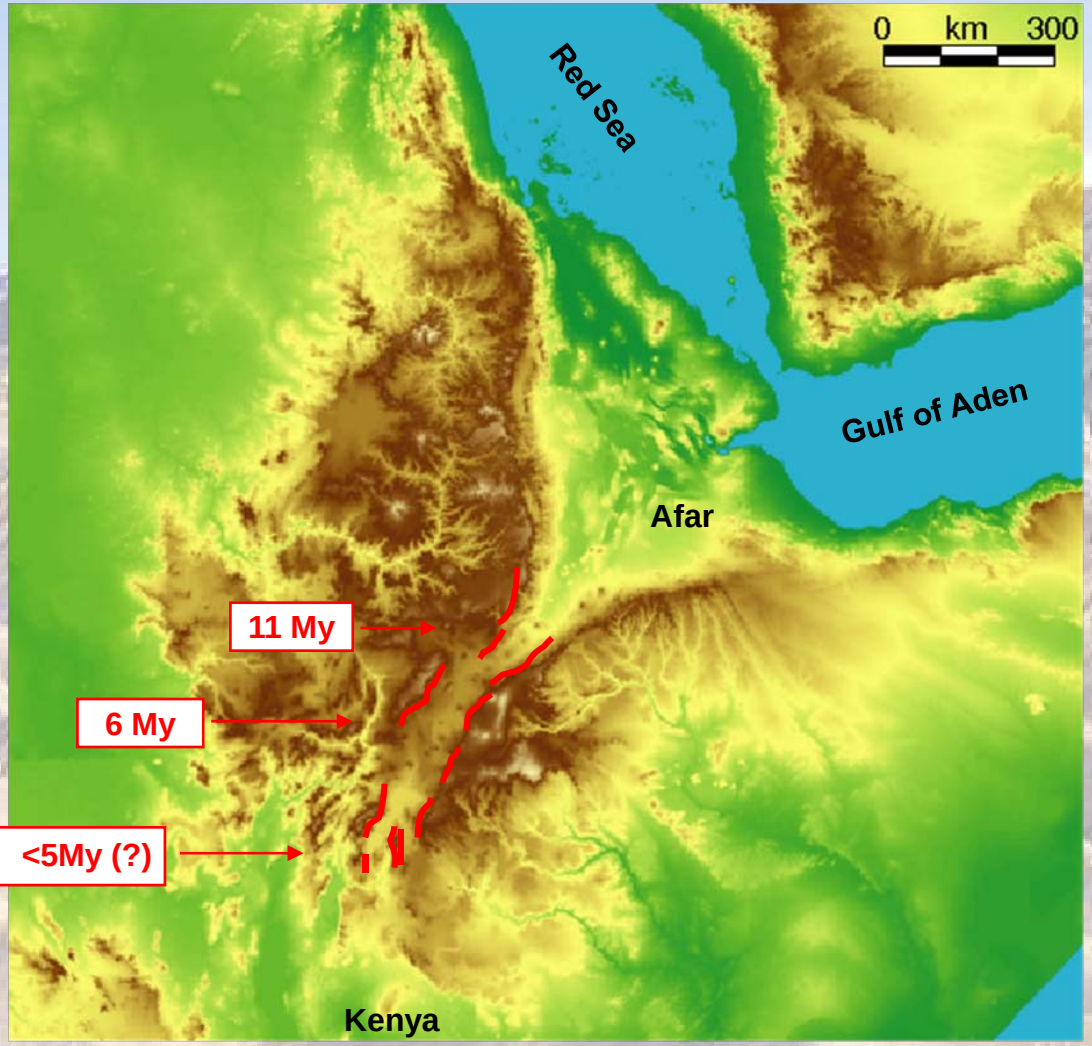
No significant extension (rifting started about 20 My later)



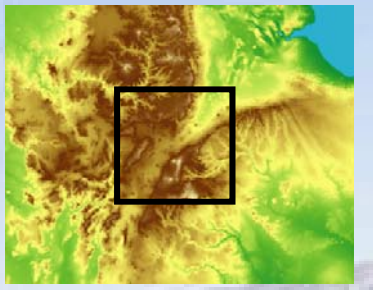
Tertiary rifting: activation of large boundary faults

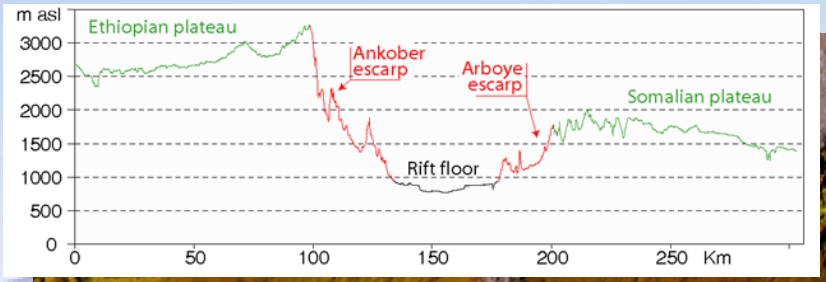
First rifting phase

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



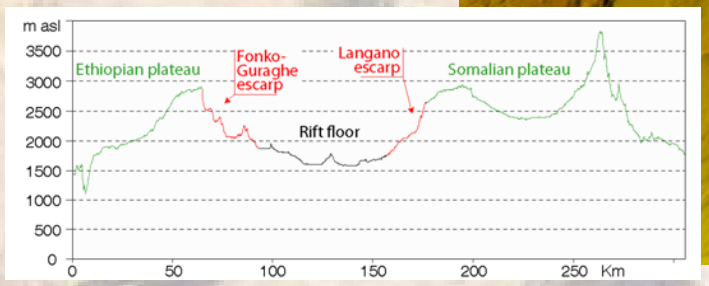
Boundary faults characteristics





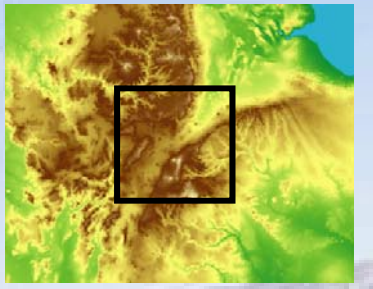
Trend around NE-SW

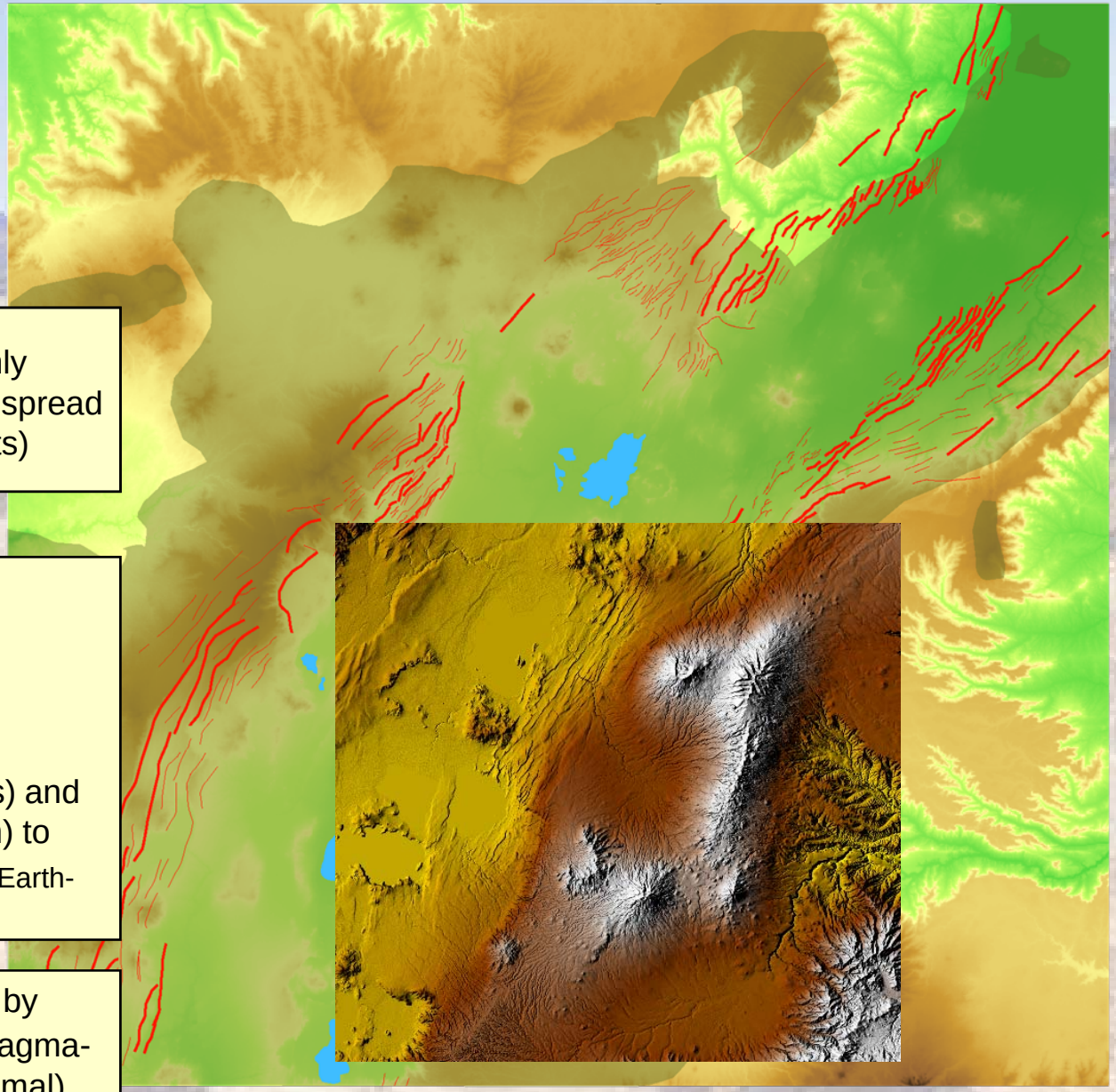
Few widely-spaced, long faults with large offset



Boundary faults characteristics

Boundary faults and volcanism





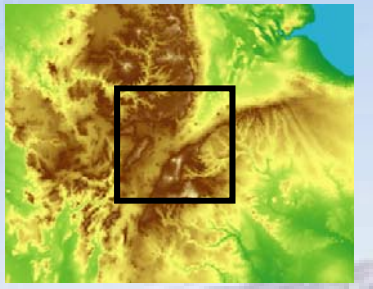
Diffuse volcanism (mainly bimodal composition: widespread rhyolitic ignimbrites, basalts)

Spatial distribution controlled by:

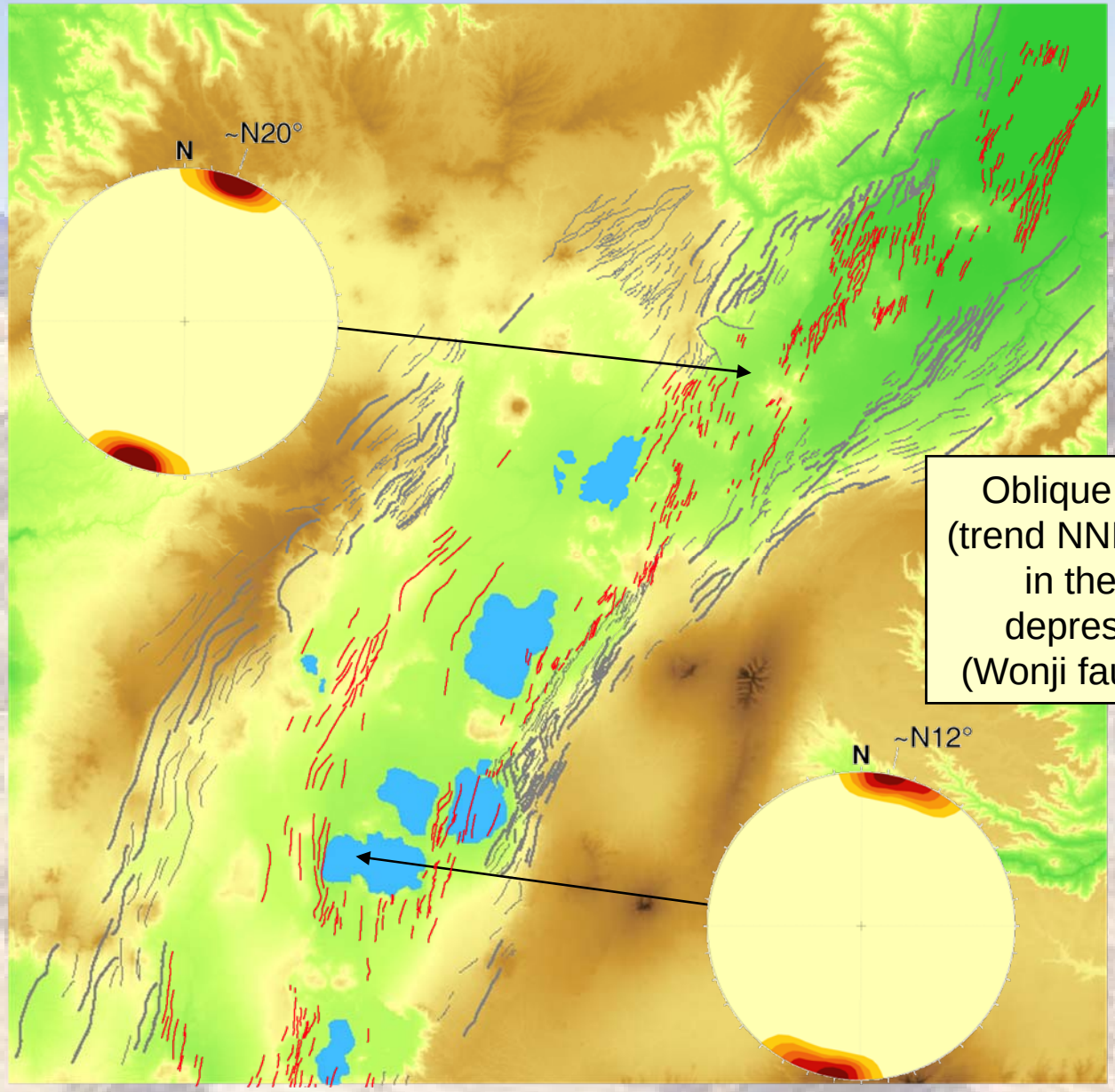
-boundary faults
-pre-existing fabrics, both transversal (transfer zones) and parallel (off-axis volcanism) to the rift (e.g. Corti et al., 2003 Earth-Sci. Rev.)

Extension accommodated by **brittle deformation** (magma-related deformation is minimal)

Tertiary rifting: activation of internal (Wonji) faults

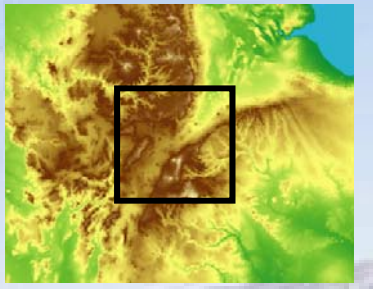


Change in deformation style at around 2 My



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

Tertiary rifting: activation of internal (Wonji) faults



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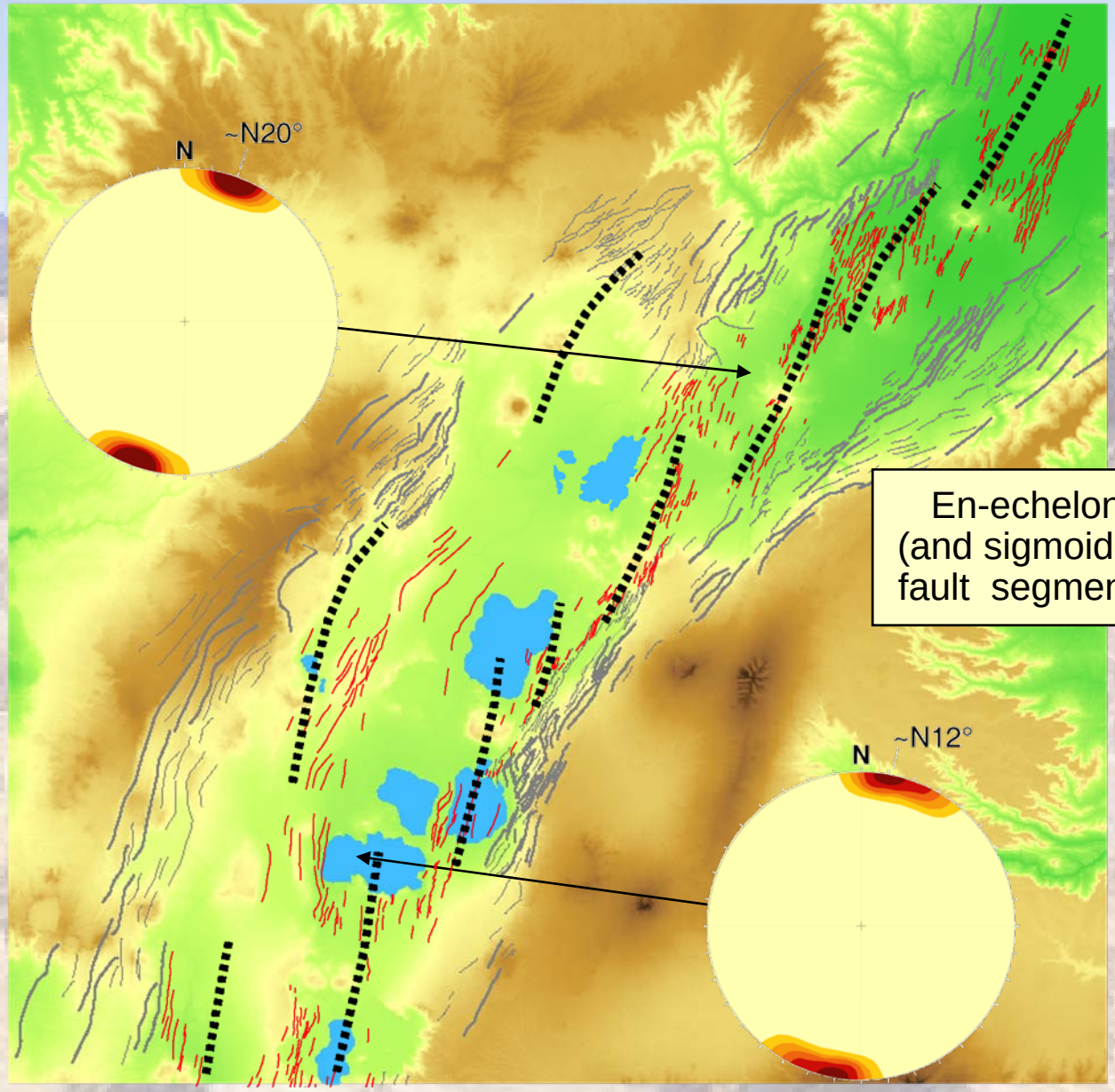


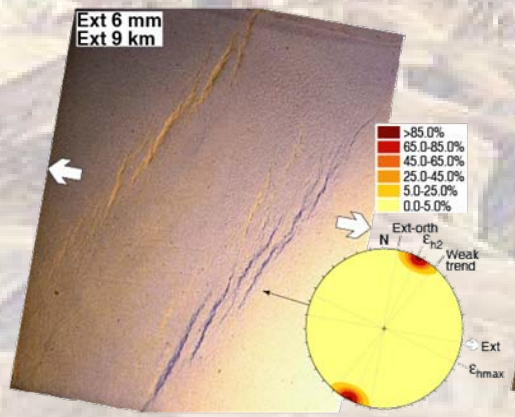
En-echelon (and sigmoidal) fault segments

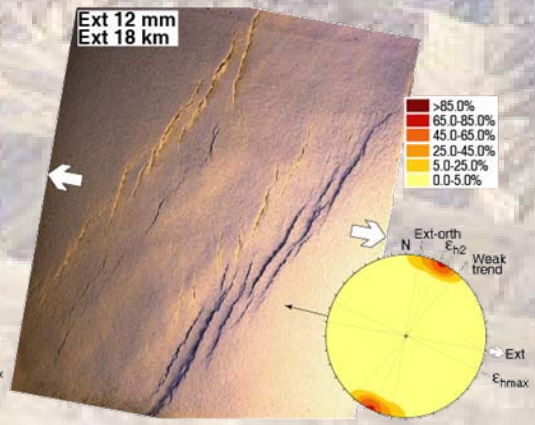
Activation of internal (Wonji) faults: why?

Analogue experiments suggest that **oblique rifting** may be responsible for the diachronous development of the two fault different systems (1st: boundary faults, 2nd: en-echelon oblique faults; Corti, 2008 Nature geosc).

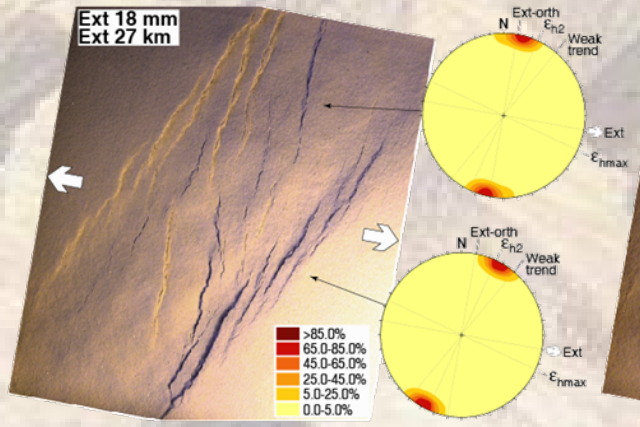
Boundary faults can accommodate only a limited amount of displacement; with progressive extension deformation shifts in the weakest part of the rift (i.e. in the thinned rift depression)

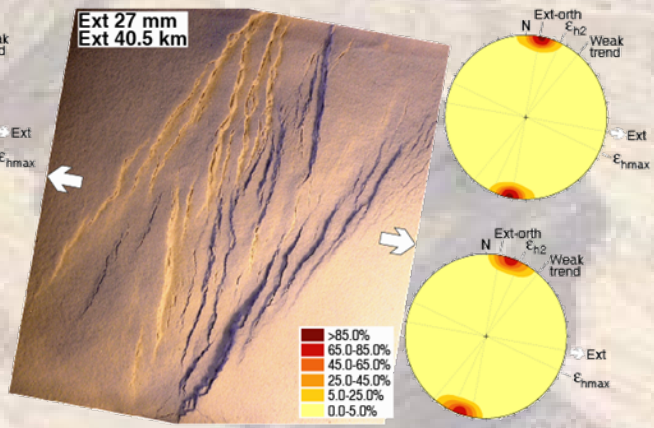
Corti, 2008
Nature Geosc





BOUNDARY FAULTS STAGE



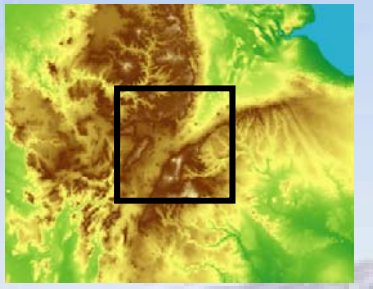


INTERNAL FAULTS STAGE

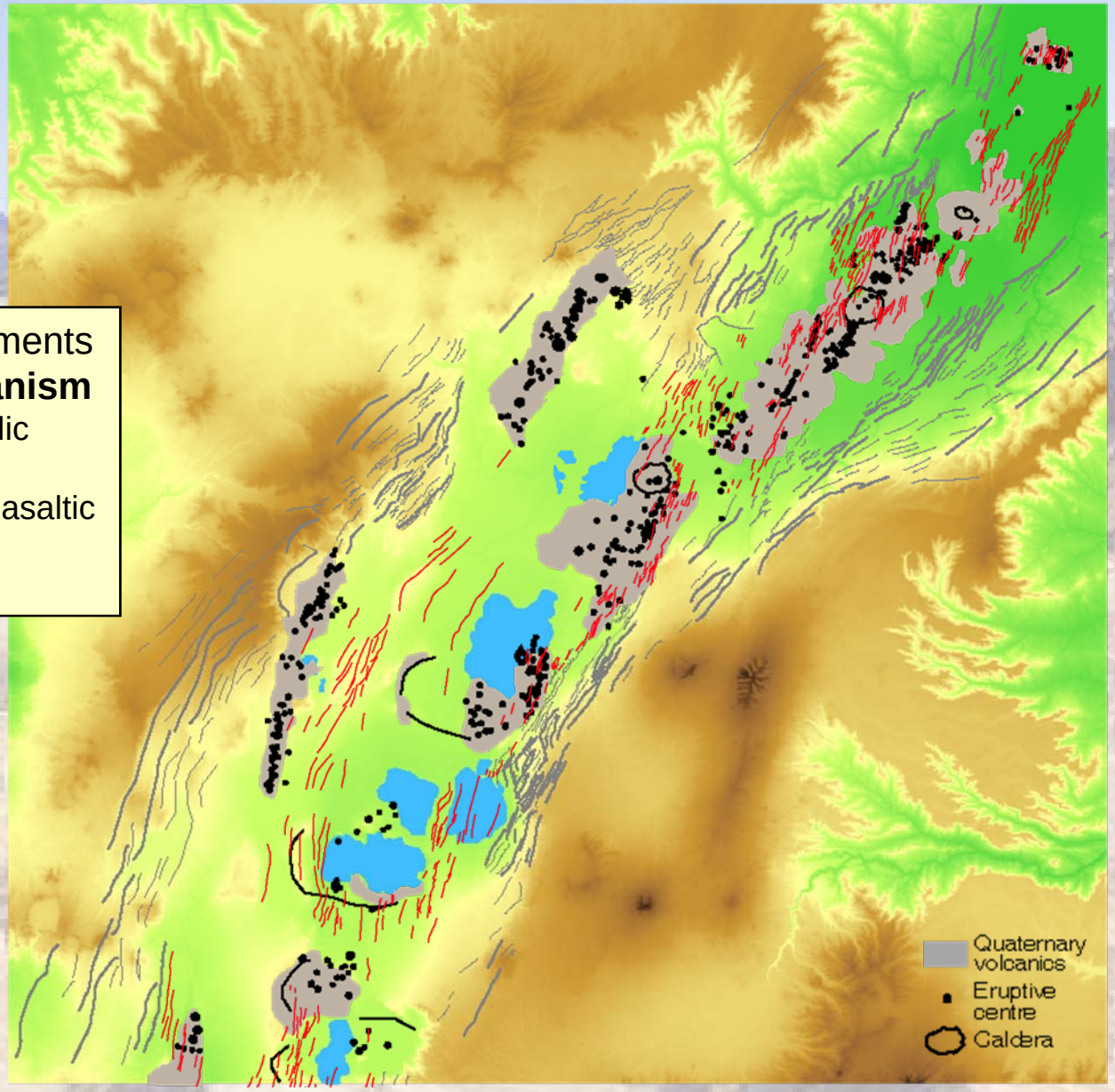
Wonji faults characteristics

Dense swarms of short faults with small displacement

Wonji faults and volcanism



En-echelon Wonji segments strongly **localise volcanism** (bimodal composition: acidic central volcanoes, fissural basalts & cinder cones – basaltic volcanism increases with increasing extension)

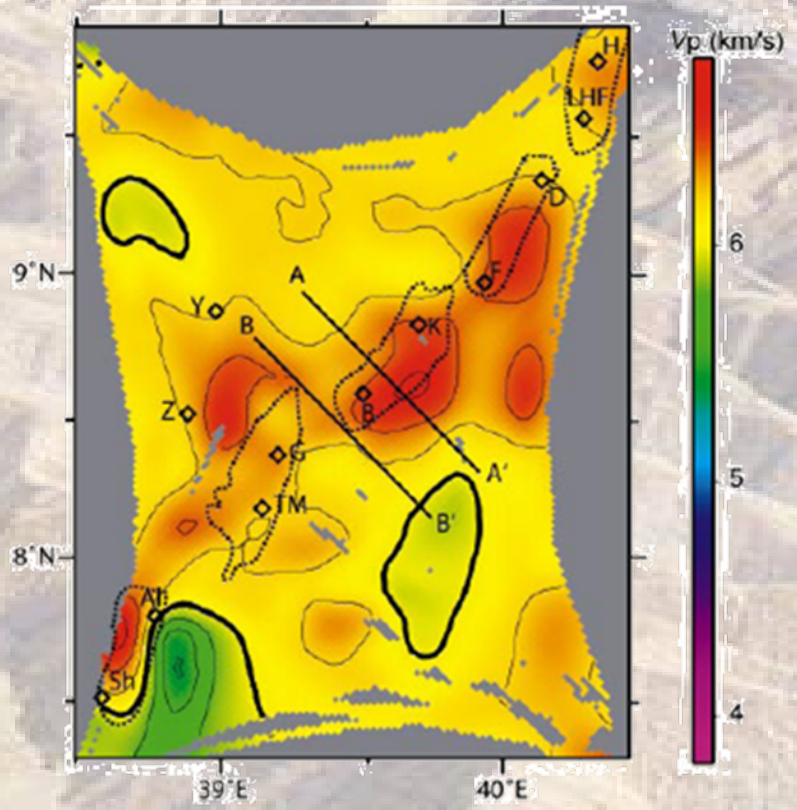


Wonji faults and magma intrusion

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

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

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

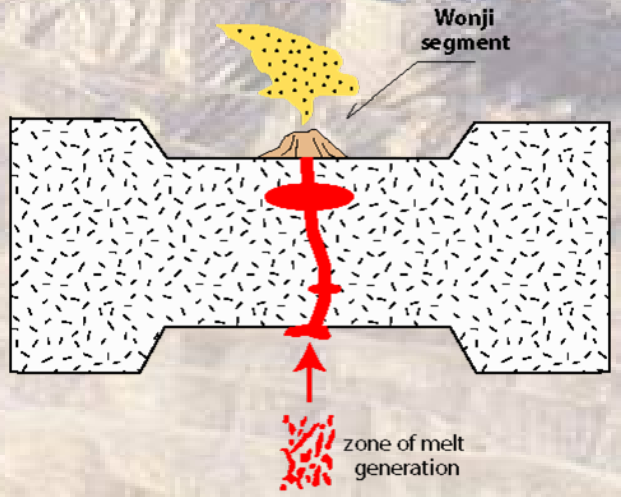


Controlled-source tomography at 10 km below the rift valley (after Keranen et al, 2004 Geology)

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

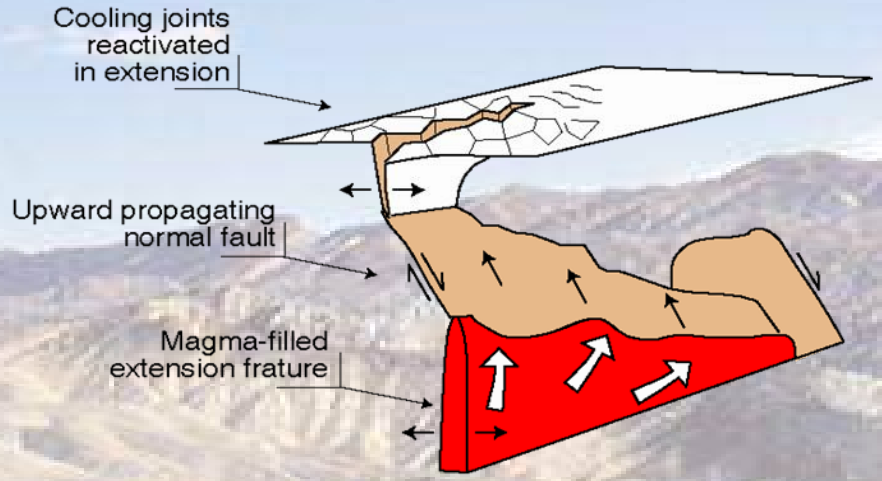
EAGLE data → Pervasive magma intrusion in the entire lithosphere (melt-filled cracks and dykes cutting through the uppermost 75km; e.g., Kendall et al., 2004 Nature; Keir et al., 2005 Geophys Res Lett)



Geochemical/petrological data suggest a well connected magmatic system from melt generation zones (50-90km) to the surface beneath the Wonji segments (Rooney et al 2007 JGR)

Wonji faults and magma intrusion

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**

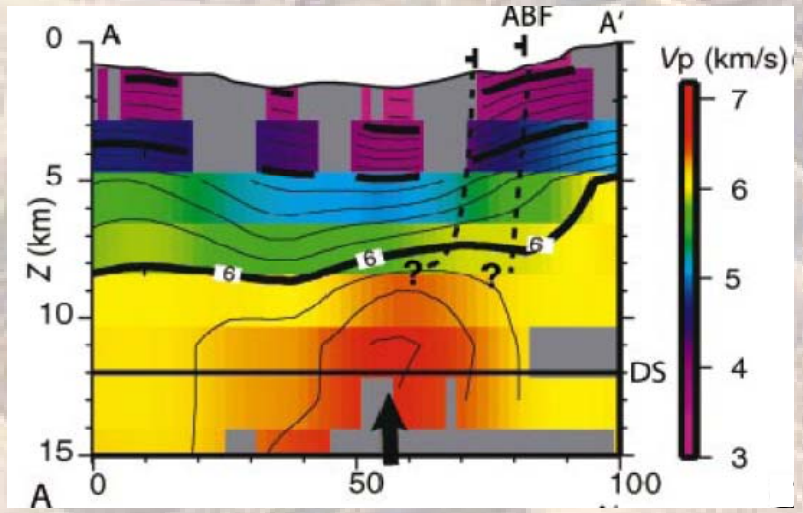
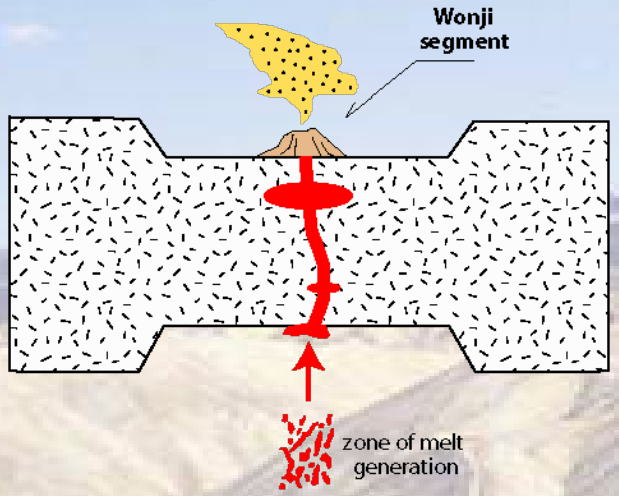
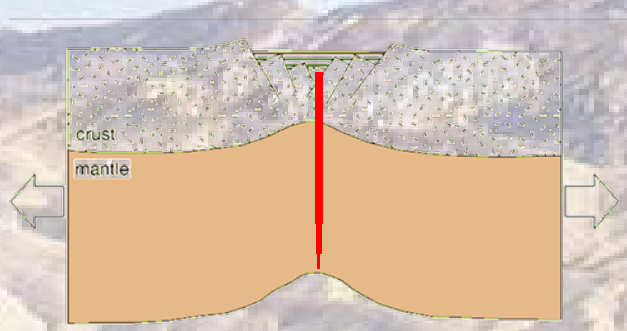
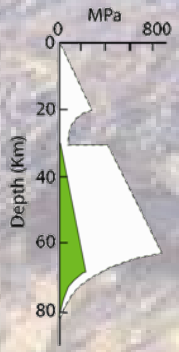


Image of large mafic intrusion (after Keranen et al, 2004 Geology)

Wonji faults and magma intrusion: lithospheric weakening







Strength

(after Buck 2006 Geol Soc Spec Pap)

EAGLE data: Magmatic processes have fundamentally modified the crust and mantle lithosphere beneath the rift

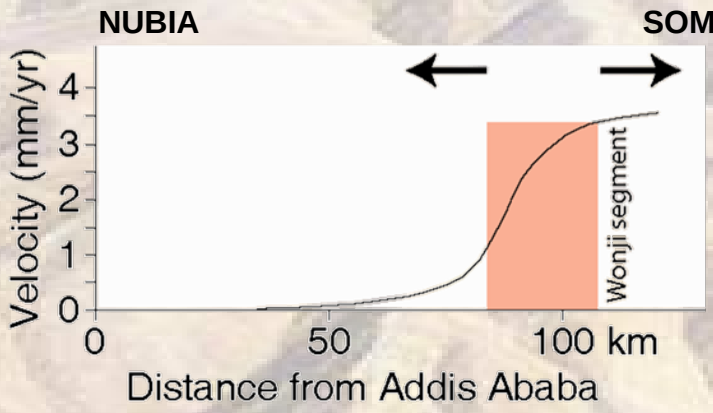
Decrease in lith strength up to one order of magnitude

Weakening

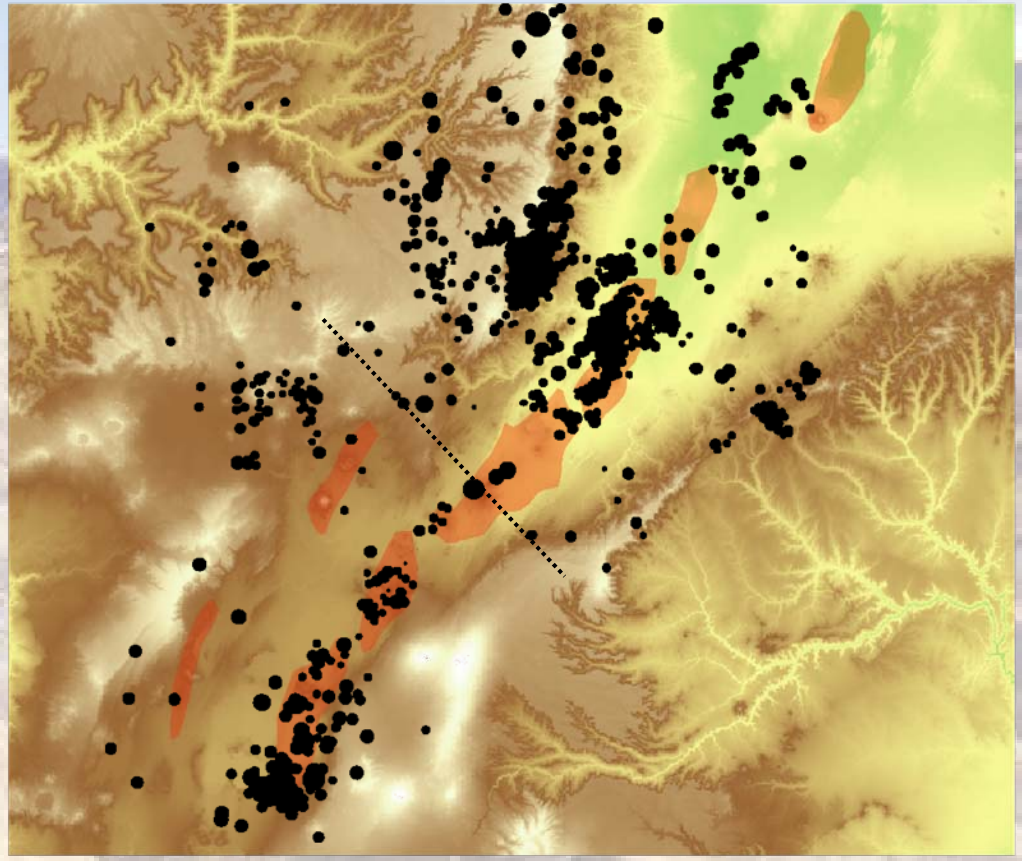
strain localisation (e.g., Corti et al. 2007 JGeodyn)

Lithospheric weakening and strain localisation

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



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

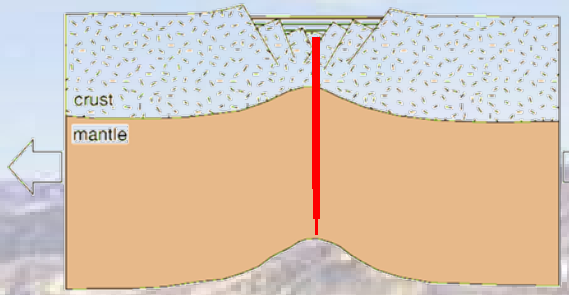


Seismicity of the MER from October 2001 to January 2003 (note that earthquakes mostly occur above mafic intrusions) [after Keir et al, 2006 JGR]

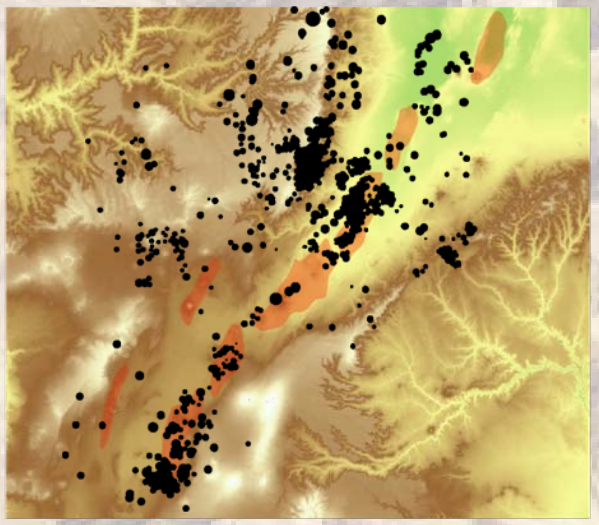
Lithospheric weakening and strain localisation

Feedback deformation-magmatism

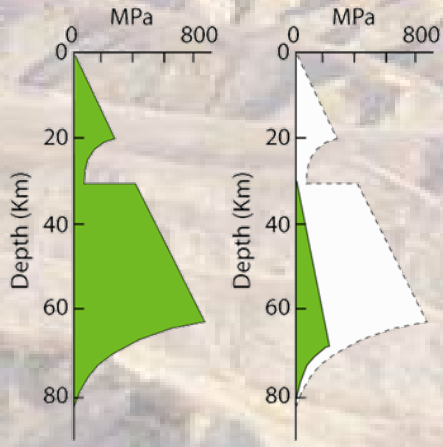
Focused magma intrusion



Localised deformation



Pronounced weakening



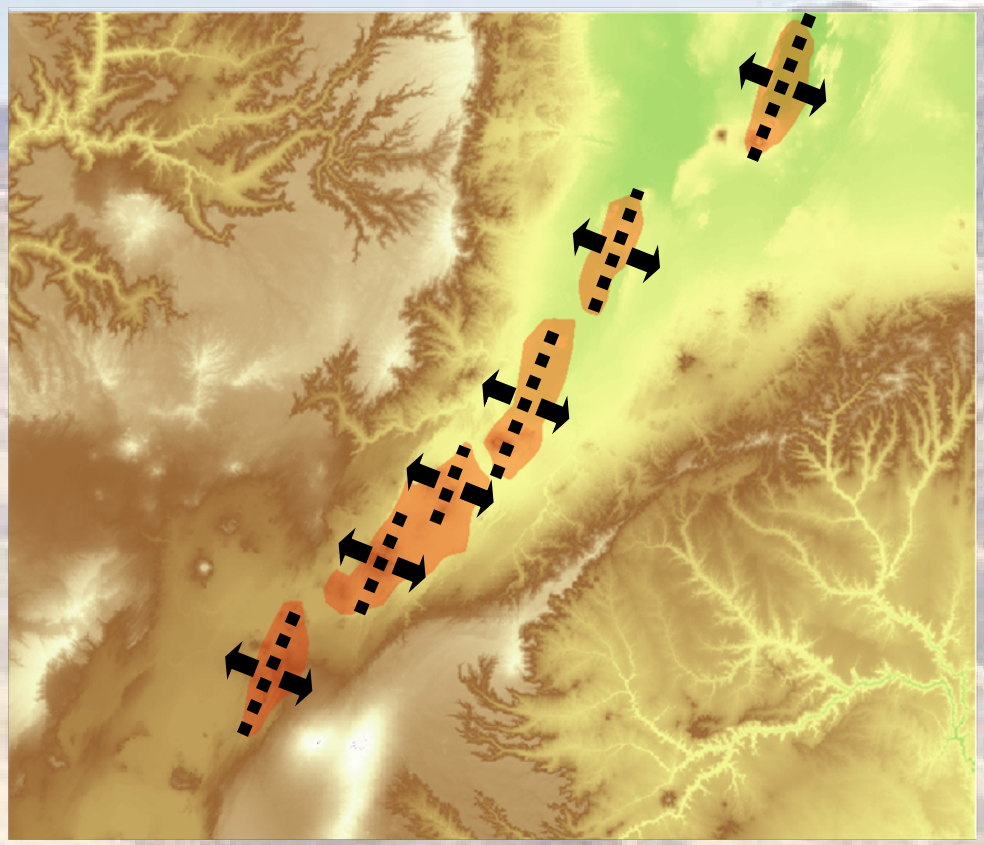
see also Corti et al., 2007 JGeodyn

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

Continental break-up

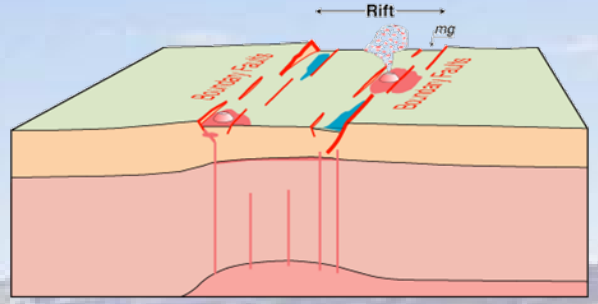
Characteristics of Wonji volcano-tectonic segments (extensive mafic addition to the crust within a narrow zone of localized strain, dyking/faulting, seismic activity, low elastic thickness, morphology & segmentation,…) typical of **slow-spreading ridges**

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

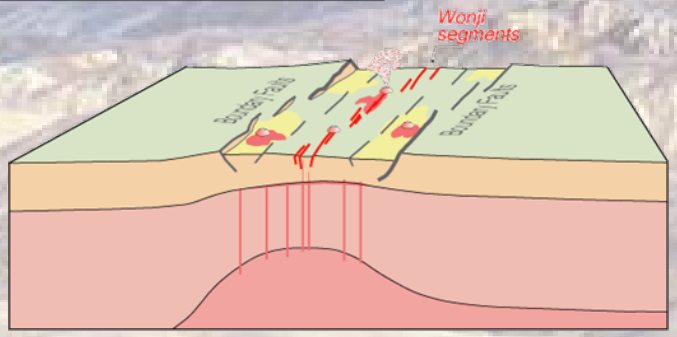


Summary and conclusions: from rifting to break-up in the Main Ethiopian Rift

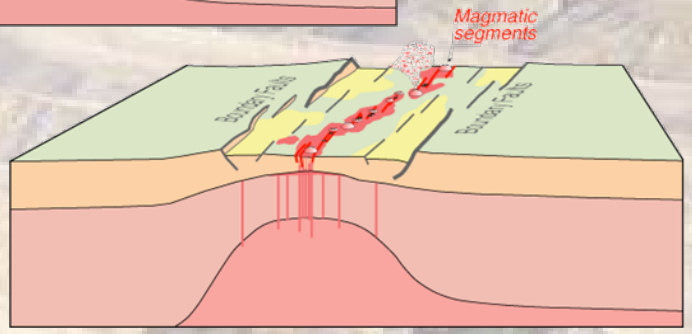
Border faults, diffuse magmatism (11My-2My)



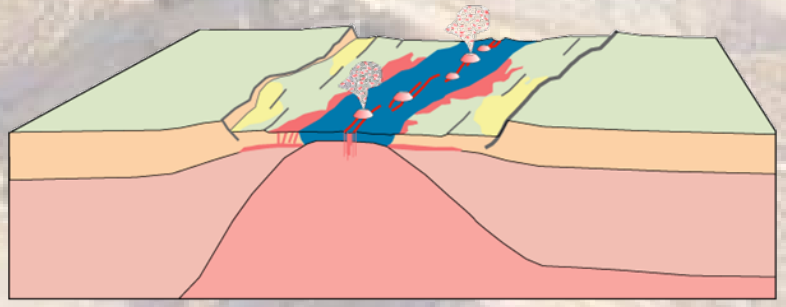
Localised deformation on Wonji segments (2My)



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



Break-up and incipient spreading on Wonji segments



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

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

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