Origin of σ3 re-orientation during oblique magma-assisted rifting. Example of the Main Ethiopian Rift

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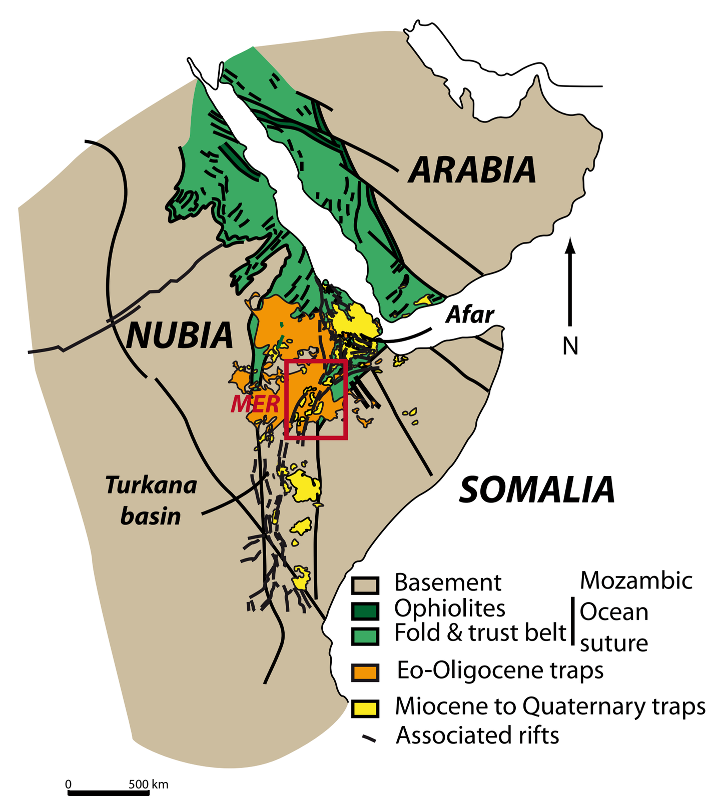
Introduction



In East Africa horn, continental breakup leads to the individualization of Nubia, Arabia and Somalia plates that occurred along the Mozambic Ocean Suture Zone (MOSZ) that trends NNW-SSE (Kazmin et al., 1978, Stern 1994).

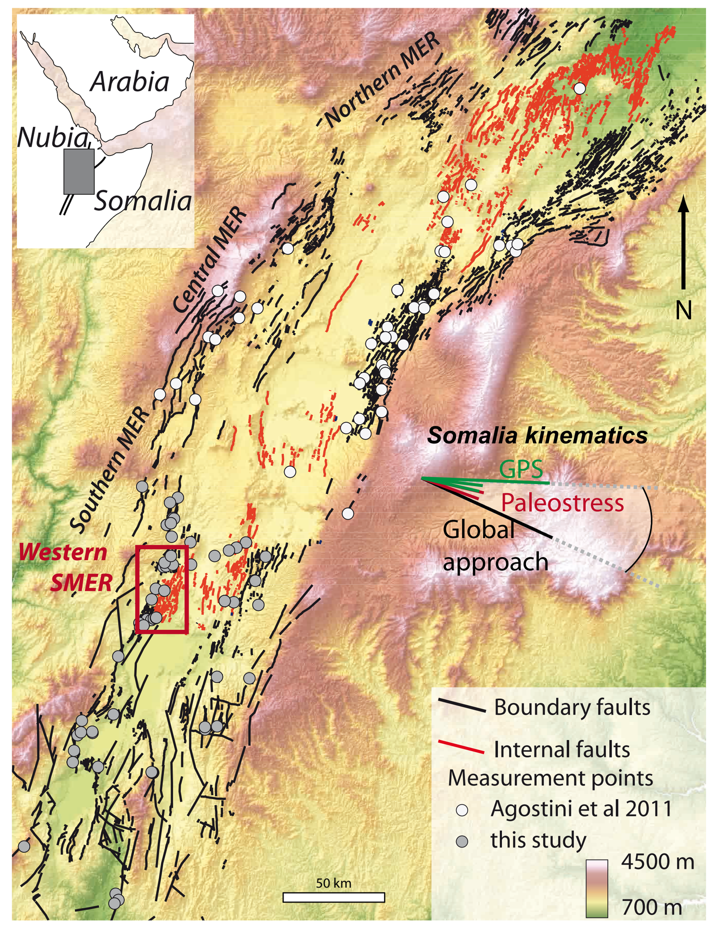
During Eocene, the evolution from collision to active subduction of the boundary conditions at the northern convergent margin of the African plate (Bellahsen et al., 2003) , coupled with the presence of the Afar plume, helped strain localization along the MOSZ and lead to the Red Sea sea opening (Gass, 1977) and Nubia and Arabia's continental break up. Contemporaneously, up to 3km of basaltic floods have been emplaced above the plume in the Afar region (Mohr and Zanettin 1988).

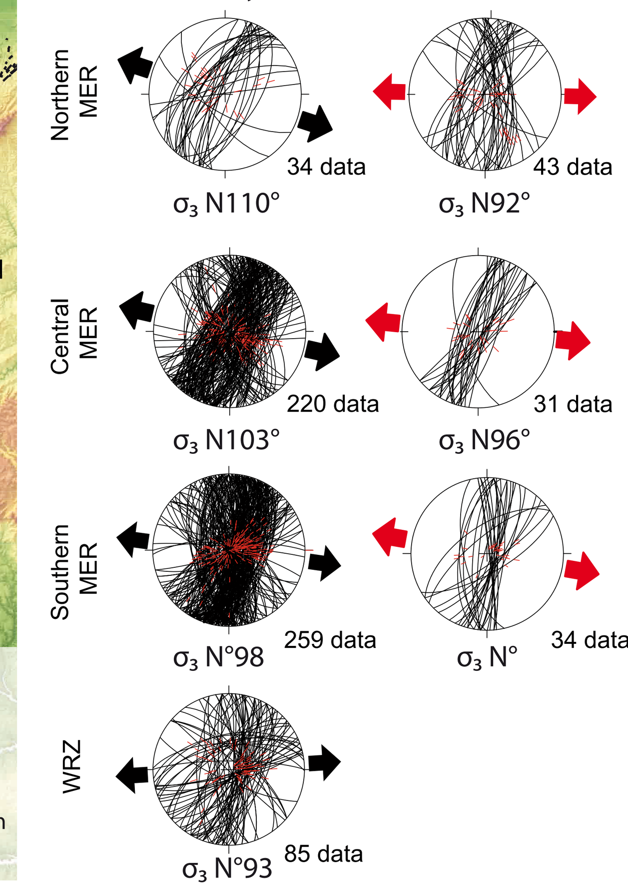
During Miocene, a second episode of "pre-rift" basaltic flood were emplaced and predates the Main Etiopian Rift opening (MER)(Zanettin et al.,1978; Ebinger et al., 1993). The MER develops south of the Afar region, and separates the Nubia and Somalia plates. Different scenarii are exposed concerning the timing and development of the MER:

1/ A northward propagation starting at 18 Ma in the south and reaching the Afar at 11Ma (Wolfenden et al., 2004).

2/ A southward migration from Miocene to present day (Bonini et al., 2005, Keranen & Klemperer 2007).

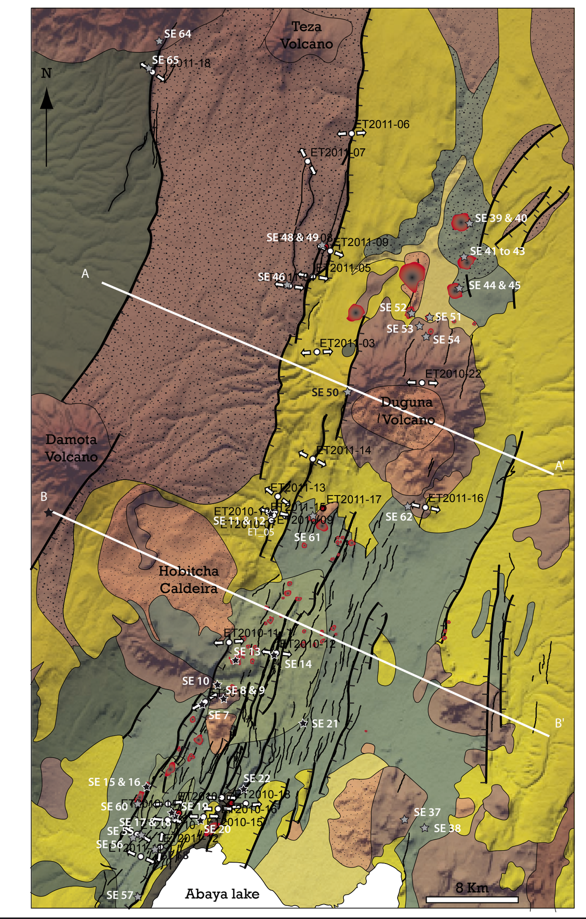
The rift presents a curved shape at angle with the direction of Somalia plate's motion, making it a prefect example to study how the fault develops and accommodates oblique extension.





At regional scale

Oblique rifting in the central and northern Main Ethiopian Rift (MER) has resulted in a complex structural pattern characterized by two differently oriented fault systems (e.g., Corti, 2009): a set of NE-SW-trending boundary faults and a system of roughly NNE-SSW-oriented fault swarms affecting the rift floor (Wonji faults). Boundary faults formed oblique to the regional extension vector, likely as a result of the oblique reactivation of a pre-existing deep-seated rheological anisotropy, whereas internal Wonji faults developed sub-orthogonal to the stretching direction. Previous works have successfully reconciled this rift architecture and fault distribution with the long-term plate kinematics (e.g., Corti, 2008); however, at a more local scale, fault-slip data reveal significant variations in the orientation the minimum principal stress and related fault-slip direction across the rift valley (Agostini et al., 2011). Whereas fault measurements indicate a roughly N95°E extension on the axial Wonji faults, a N105°E to N110°E directed minimum principal stress and slip direction is observed along boundary faults, pointing to a stress (and slip) reorientation supported by the available focal mechanism solutions of earthquakes. Both fault-slip data and analysis of seismicity indicate a roughly pure dip-slip motion on the boundary faults, despite their orientation (oblique to the regional extension vector) should result in an oblique displacement. To shed light on the process driving the variability of data derived from fault-slip (and seismicity) analysis we present crustal-scale analogue models of obliquity rifting.



At local scale

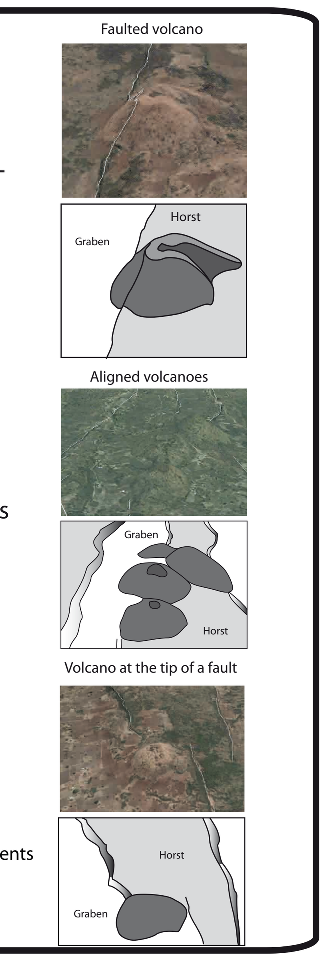
Strain partitioning is observed at regional scale as a result of oblique rifting. At local scale, perturbation of the stress field induced by volcanic activity may also lead to strain re orientation along faults. Therefore we investigate one of the tectono-magmatic segments along the MER., in order to constrain the kinematics and timing of the deformation as well as the timing of volcanic eruptions.

The western SMER margin is a magmatic margin that shows a well-developed faults network that trend NNE-SSW. Numerous volcanic edifices are observed along the margin.

Volcanoes show three different kind of relationship with faults:
1/ cut by fault
2/ Aligned above a blind fault
3/ at the tip of the fault

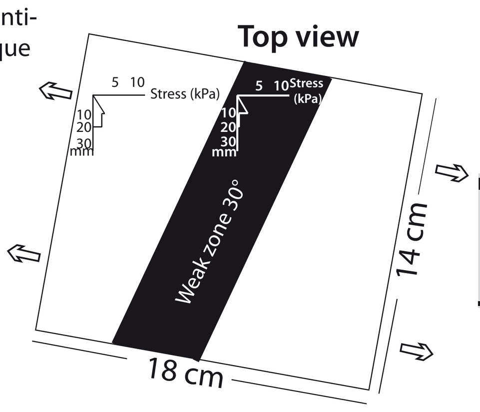
The geological map is a compilation fieldwork, google earth images analyses, satellite images and SRTM 90, Kazmin 1979, Chernet 2011and google earth images analyses (volcanoes occurrences), satellite images and SRTM 90 (fault pattern & lava flows). Our preliminary geochemical analyses confirm the nature of the mapped lithologies.

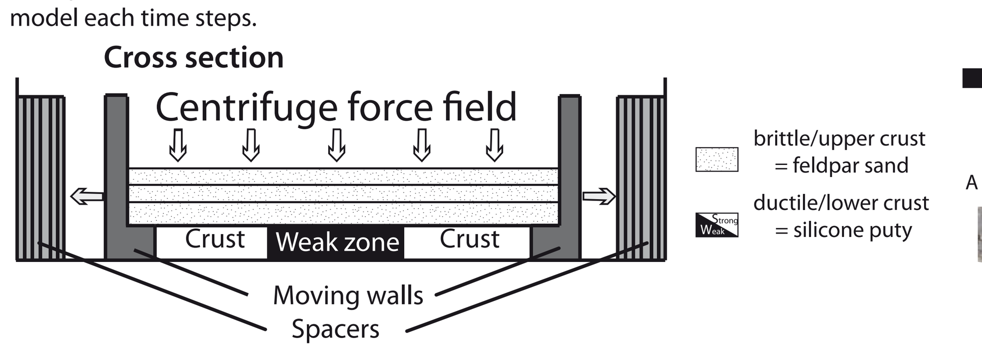
	ACID LAVAS	BASIC LAVAS	
Holocene	Rhyolite dome; Pyroclatic flow	Scoria cone	Major normal fault
Pleistocene	Rhyolite dome; Ignimbrites	Basaltic / yaloclastites; Basalt	Volcanic edifice
Pliocene	Trachite		Minor normal fault
Mio-Pliocene	Rhyolites, Ignimbrites & trachytes		Quaternary volcao-sediments
Miocene		Basalts	
Oligo-Miocene	Rhyolite & Trachite		Quaternary aluvions



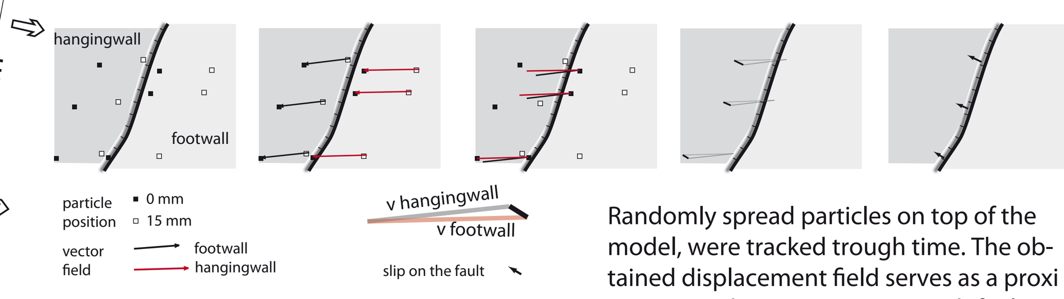
Analogue modeling of strain partitioning during oblique rifting

The models reproduced extension of a continental crust containing a weak zone oblique to the stretching direction (0° to 45° of obliquity by increment of 15°, in order to compare the analogue modeling results with the northern, central and southern MER). The top to bottom vertical layering of the experiments consisted of brittle (feldspar powder), analogue to the upper crust and ductile material (plasticine mixture) analogue to the lower crust. 3 mm of symmetric extension was performed removing 1,5 mm spacers on both side of the model each time steps.





At the end of the experiment, after 15 mm of extension, the surface of all the models show two sets of faults: large boundary faults that develop above the weak/strong ductile discontinuity and internal fault that develops in the mean time but above the homogenous/weak ductile crust



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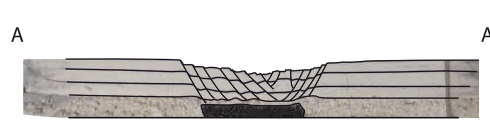

Randomly spread particles on top of the model, were tracked trough time. The obtained displacement field serves as a proxi to recover the motion across each fault. This, coupled with the dip of the faults, obtained via the cross section allow us to compute the paleostress tensor on each fault plane of the model using WinTensor (Delvaux et al., 2003).

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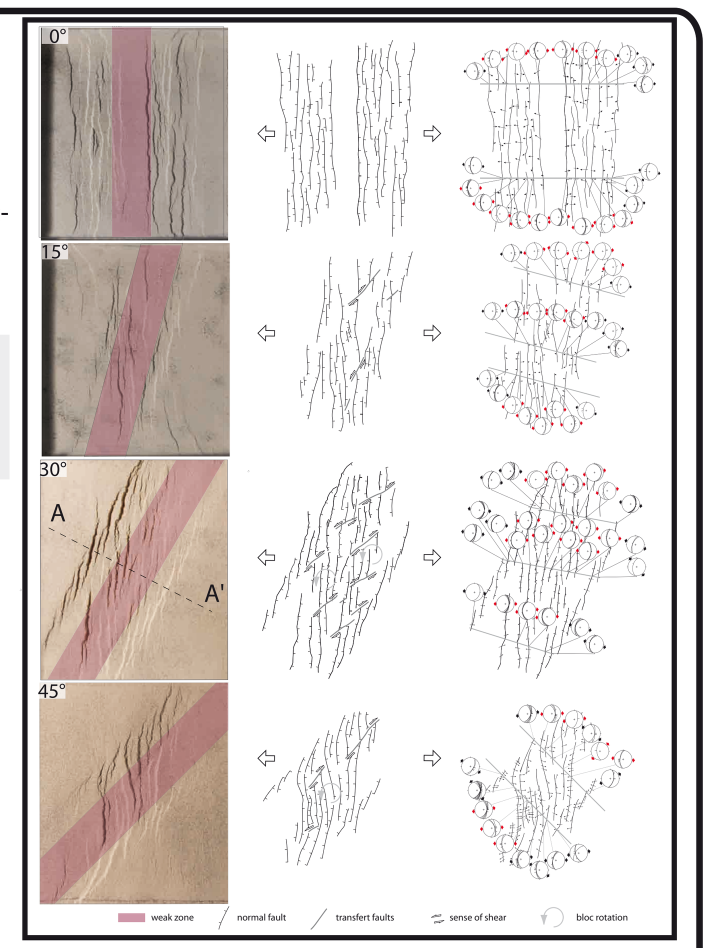
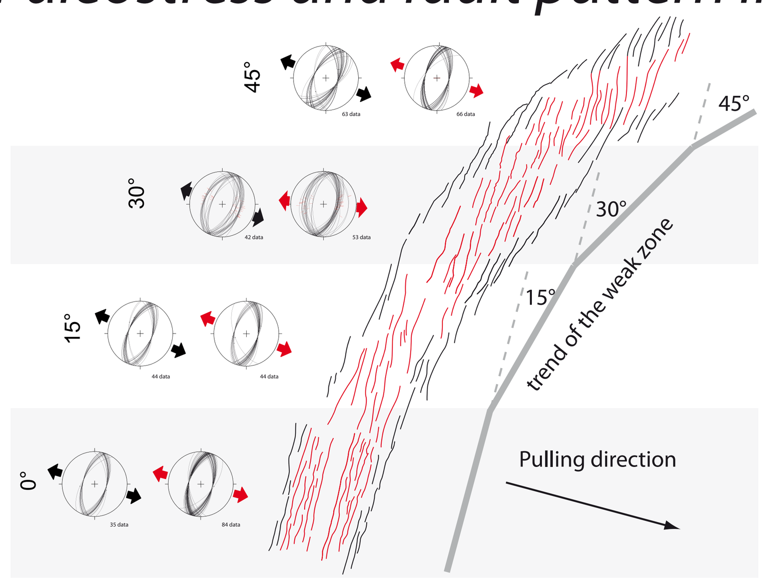
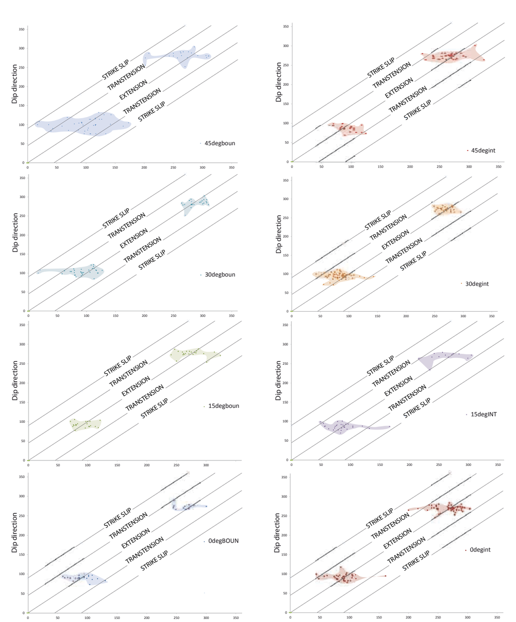


Paleostress and fault pattern in the model

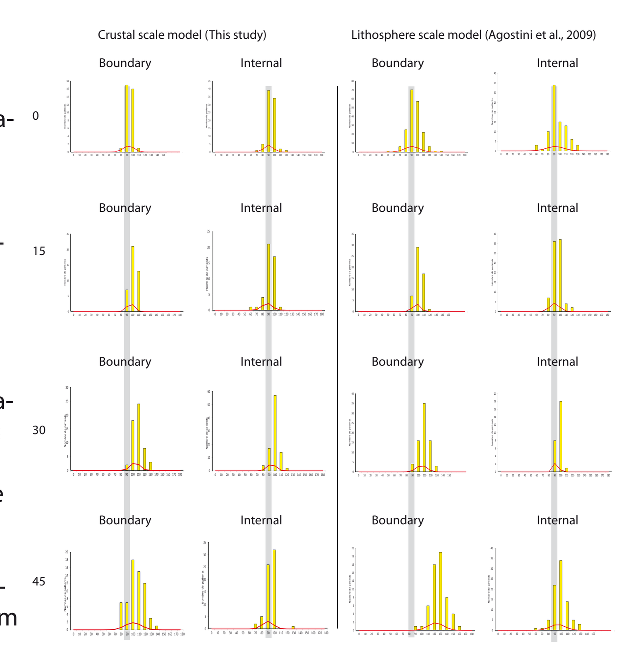


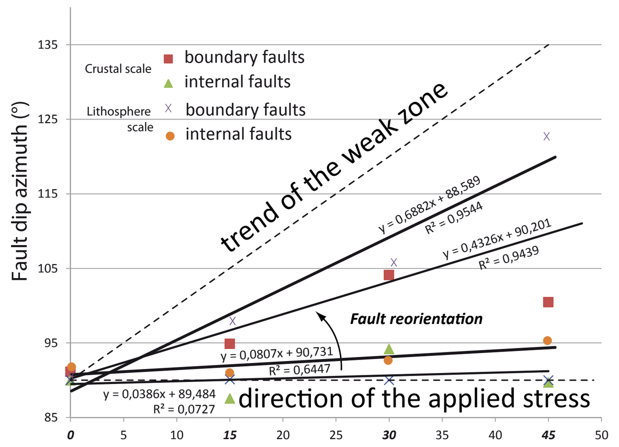
The fault pattern obtained in models is similar to the observed fault pattern in the MER. Paleostress reconstruction separating boundary and internal faults shows that a similar to nature strain partitioning is observed. In our models as well as in nature, both boundary and internal faults are activated in pure extension.



Fault kinematics range from pure extension to strike slip, whatever the degree of obliquity. This could reflect the material properties as well as the maturity of the faults. Indeed, it has been shown that faults kinematics vary through time and that a non-mature fault system have a different behavior that a mature fault system that show kinematics that are responding directly to the applied stretching (Leever et al., 2011).

Statistical analysis of the trend of the faults has been performed. The two afford mentioned sets of faults were separated: boundary and internal faults. The grey bar indicates the direction of applied stretching. A first order observation is that the internal mean fault dip trend is close to the applied stretching direction whereas the mean trend of boundary faults shows an increasing angle with the applied stretching when obliquity increases. This effect is enhanced in lithosphere scale models (analyzed data are from Agostini et al 2009).

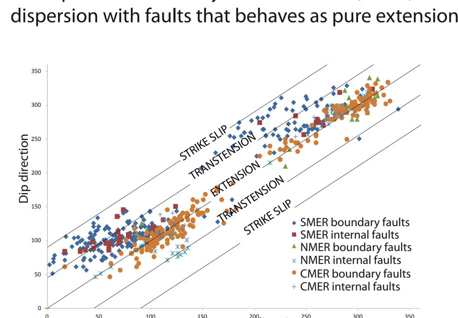




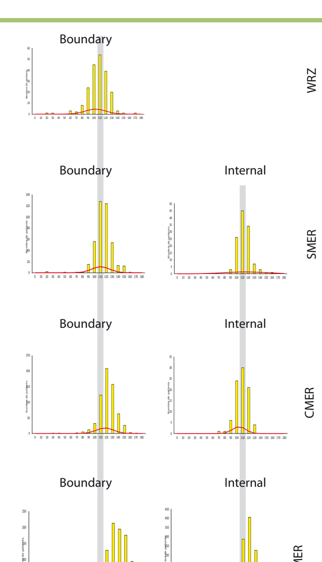
The mean trend of boundary fault dip direction is not parallel to the weak zone but trend in between the applied stretching direction and the trend of the weak zone. Whereas the mean trend of internal fault dip direction show no correlation with the amount of obliquity trend parallel to the applied stretching direction.

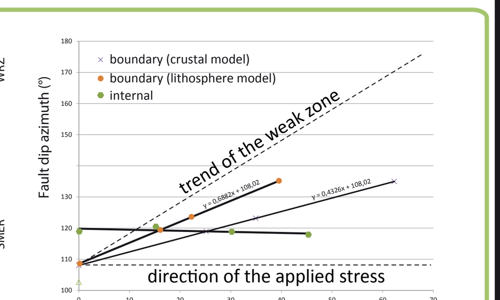
Analyse of the MER

The same analysis has been performed with field data and fault trend data acquired thanks to satellite images. Field data collected along the MER over the years confirm that the NMER and CMER are mature and accommodate deformation in pure extension (for a concept of fault maturity see Leever et al., 2011, whereas the SMER still display a strong dispersion with faults that behaves as pure extensional to almost pure strike slip.



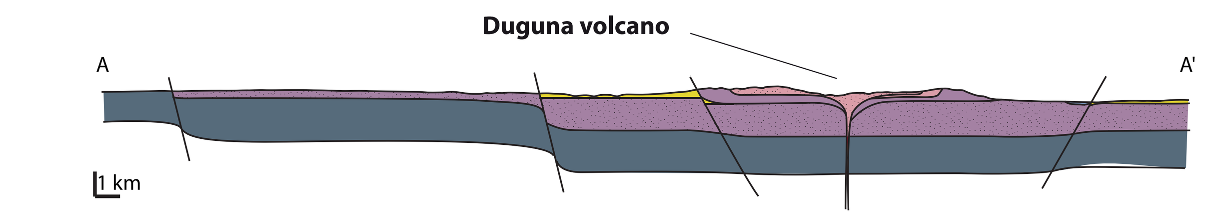
Statistical analysis of the fault trend, separating boundary and internal faults show:
1/ The mean trend of the internal fault are centered around a peak oriented N120°
2/ Boundary faults show an increasing offset from the N120° of the value from north to south with the increasing of the degree of obliquity.



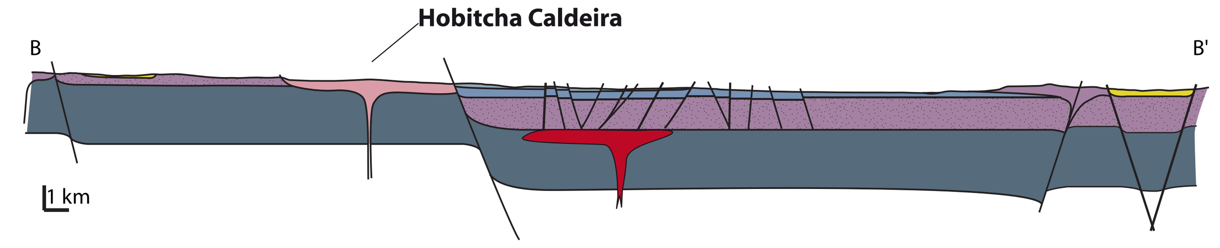


The WFB (internal faults) developed above a weak homogeneous material as they form the so-called tectono-magmatic segments of the MER. This fault system is 2 Ma, and develop under N122° stretching.
The boundary faults are older and developed under N108° stretching.
Following a lithosphere scale model, the orientation of the weak zone in depth can be (re) covered.

Fieldwork along the Southwestern volcanic margin of the Main Ehtiopian Rift

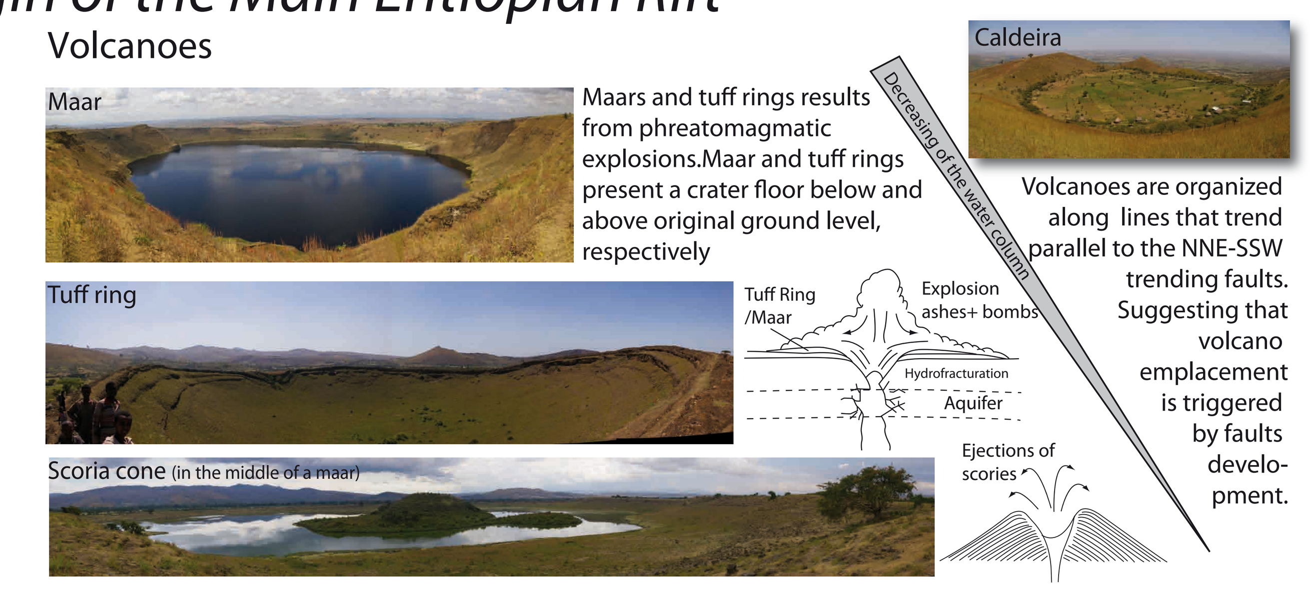


Duguna volcano is located on the rift floor and is a relatively young feature as it is not affected by faults. Its western boundary is controlled by an east-dipping fault.



Hobitcha caldera is located on the western rift shoulder and the rift floor is affected by a well developed fault pattern and volcanic system comprising numerous scoria cones.

Volcanoes

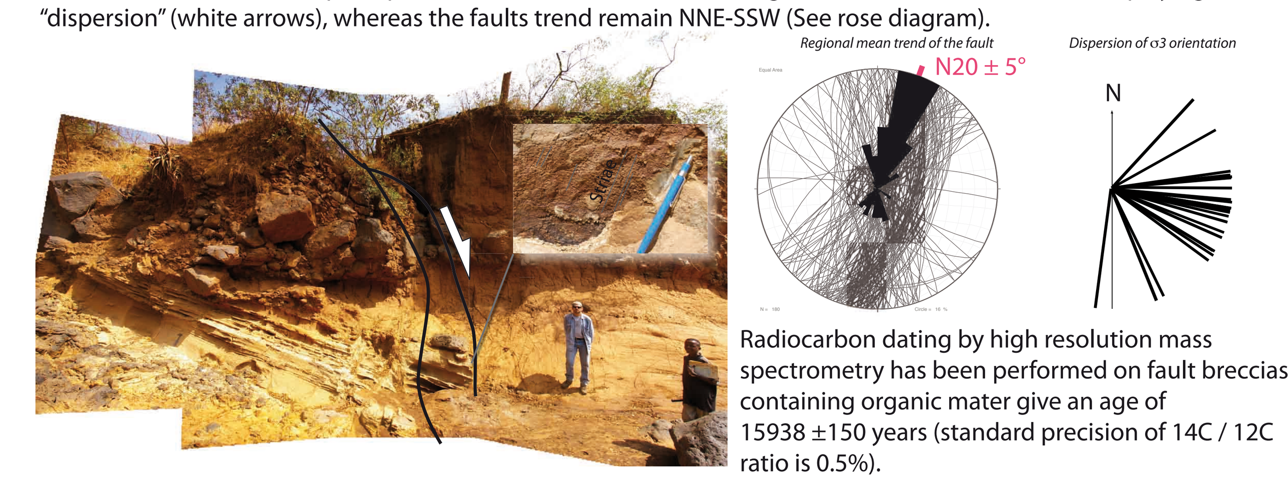


Maars and tuff rings results from phreatomagmatic explosions.Maar and tuff rings present a crater floor below and above original ground level, respectively

Volcanoes are organized along lines that trend parallel to the NNE-SSW trending faults. Suggesting that volcano emplacement is triggered by faults development.

Normal faulting

The western SMER margin shows a well-developed NNE-SSW trending, SE dipping fault pattern. Paleostress reconstruction of the least principal stress axis σ3 from field data range between N30° and N105° *, displaying a wild "dispersion" (white arrows), whereas the faults trend remain NNE-SSW (See rose diagram).

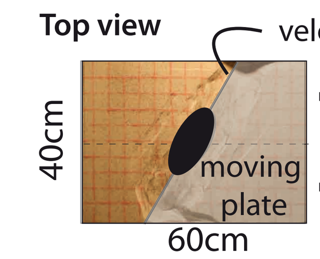


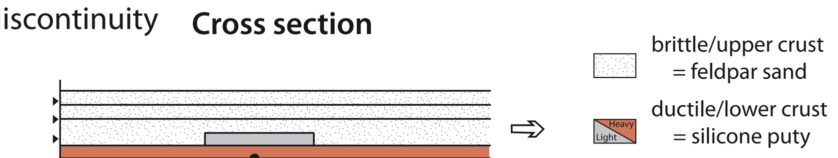
Radiocarbon dating by high resolution mass spectrometry has been performed on fault breccias containing organic mater give an age of 15938 ±150 years (standard precision of 14C / 12C ratio is 0.5%).

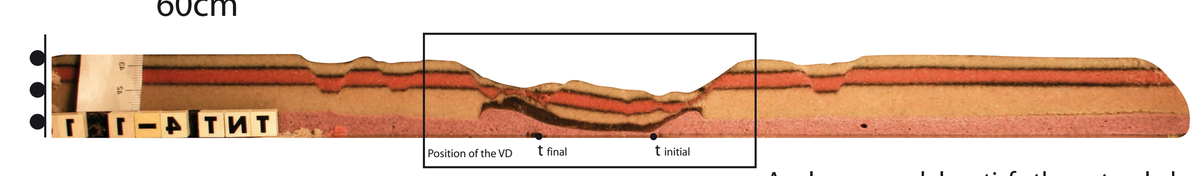
* were obtained using Win-TENSOR, a software developed by Dr. Damien Delvaux of the Royal Museum for Central Africa, Tervuren, Belgium.

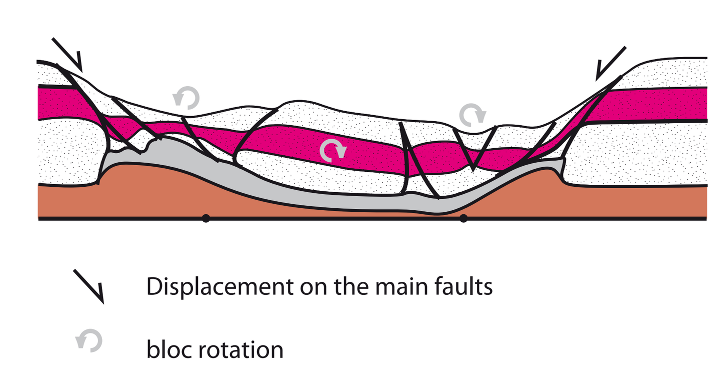
Analogue and numerical modeling

The models reproduced the extension of a brittle upper crust (quartz sand) containing a magma chamber (light PDMS putty), lying on a decollement layer (heavy pink putty) (analogue either to a lithological interface or to the brittle ductile transition). We test the influence of the geometry of the magma chamber (a/b ratio of the ellipse) and the angle of the velocity discontinuity (0° to 45° of obliquity by increment of 15°). In this case the model has been stretched only on one side to satisfy the natural case of the MER: asymmetric extension toward the east. We present here one of the experiment for an obliquity of 30° and an a/b ratio of 1/2.







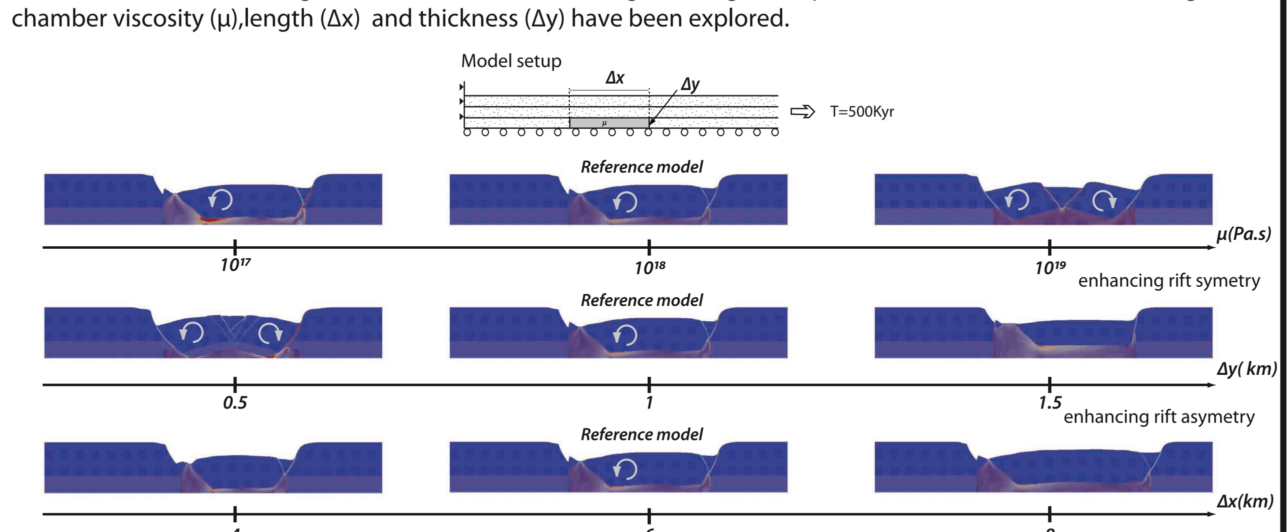


Analogue models satisfy the natural observations in term of geometry of the fault that are observed above the magma chamber in nature. Two sets of opposite dipping faults developed at each side of the magma chamber defining a main graben. Inside the graben floor, a set of smaller faults formed, along which the light putty tend to rise.

Work in progress:

The next step, is to analyze how the faults above the light putty accommodate the deformation and to see the contribution of the up rising material (light putty) to the observed deformation pattern

We also investigate this problem by the means of 2D numerical models with the ELEFANT code (http://www.cedricthieulot.net/elefant.html), an improved version of FANTOM (Thieulot, 2011). Numerical modeling is a complementary tool that allows us for the monitoring the material strain and strength during the experiments. The influence of the magma chamber viscosity (μ),length (Δx) and thickness (Δy) have been explored.



These results are prliminary and the ultimate goal of this study is under progress and addresses the 3D influence of a magma chamber on fault kinematics

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