Curvature blindness, “fabric” and free air gravity data speaks for itself

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Finding Petroleum, New Geophysical Approaches, 24th April 2018, Geological Society, London

An Introduction

Data sanity

Method, use

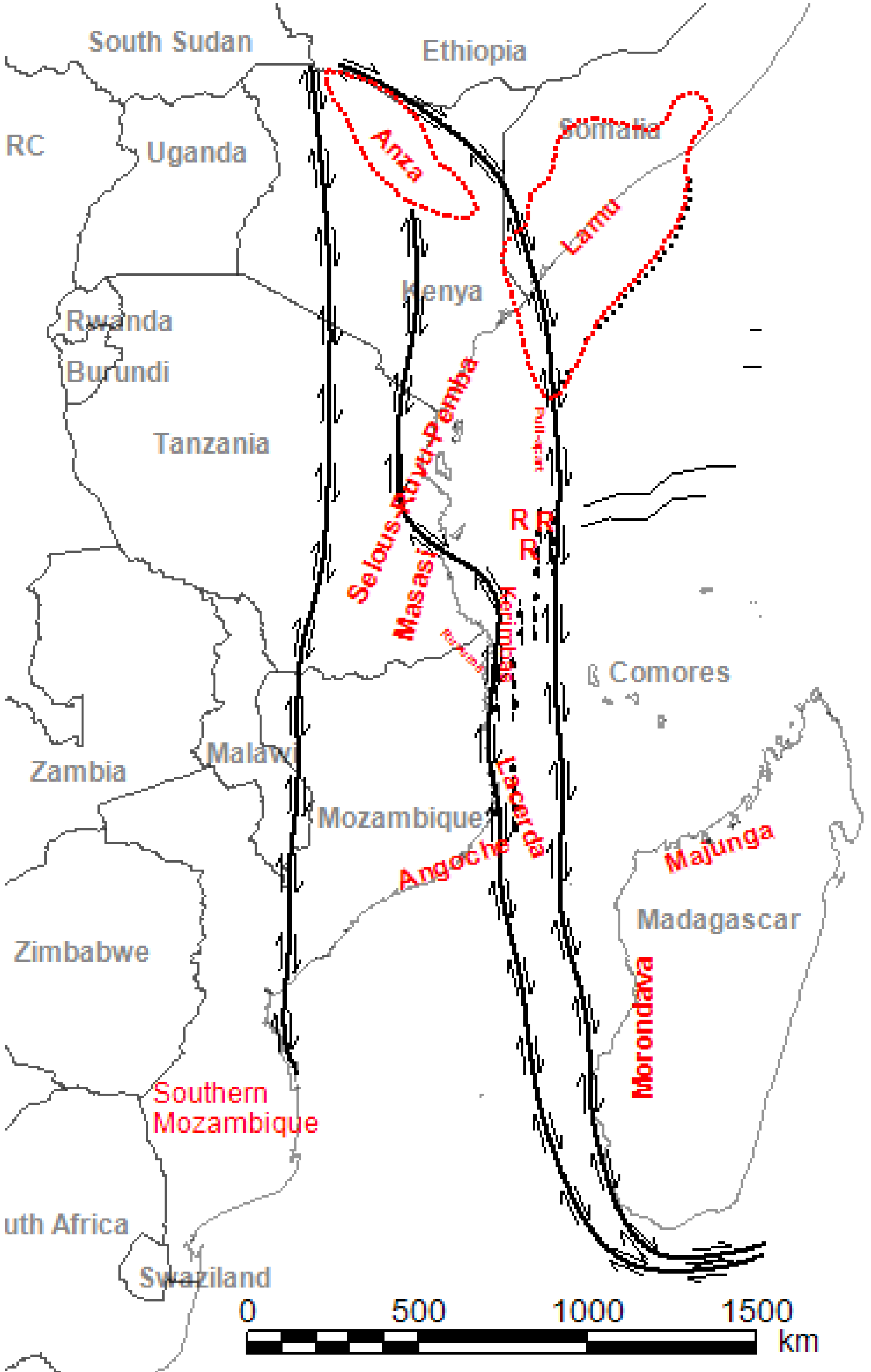
Echelon structure

Fabric, +/- geological structure

East Africa strike slip tectonics (EAOG)

A Conclusion

Two further examples: constructive and destructive margins



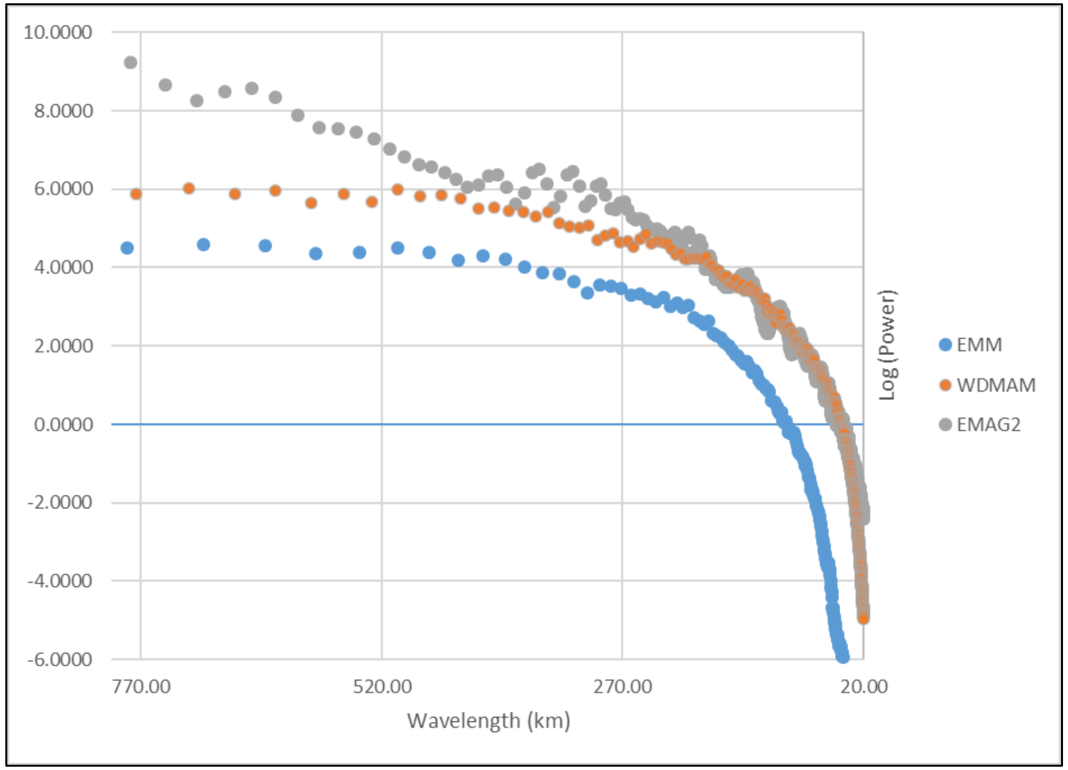
Data description

Enhanced Magnetic Field model (EMM, Chulliat et al, 2015),

Limited resolution to order 720 (30 minutes or ~56km wavelength), incorporates aeromagnetic, marine and *ESA swarm satellite data (amongst other satellite measurements)*

Lacks krigged interpolated areas of EMAG2 and associated high frequency noise. ***Better regional crustal field*** representation, without poorly sampled local field in Western Indian Ocean

Processed for IGRF correction, reduced to pole and amplitude gain corrected to enhance crustal magnetizations. Internal core and external field removed in IGRF process



Above: 1D radial average spectral comparison of EMM, WDMAM, and EMAG2

Sandwell Free Air Gravity (**Sandwell et al, 2014**), presented at **1 minute offshore resolution** has been processed and a decompensative correction applied to yield residual gravity. The new residual gravity products provide better control crustal structure and correlates well with the EMM processed magnetics. **Processed and *corrected for Simple Bouguer, terrain, Bullard Earth curvature, Airy isostasy, and residual taken from upward continuation to 40km.*** Refer LaFehr, 91, Cordell et al 91, and Hinze et al 2013 for example.

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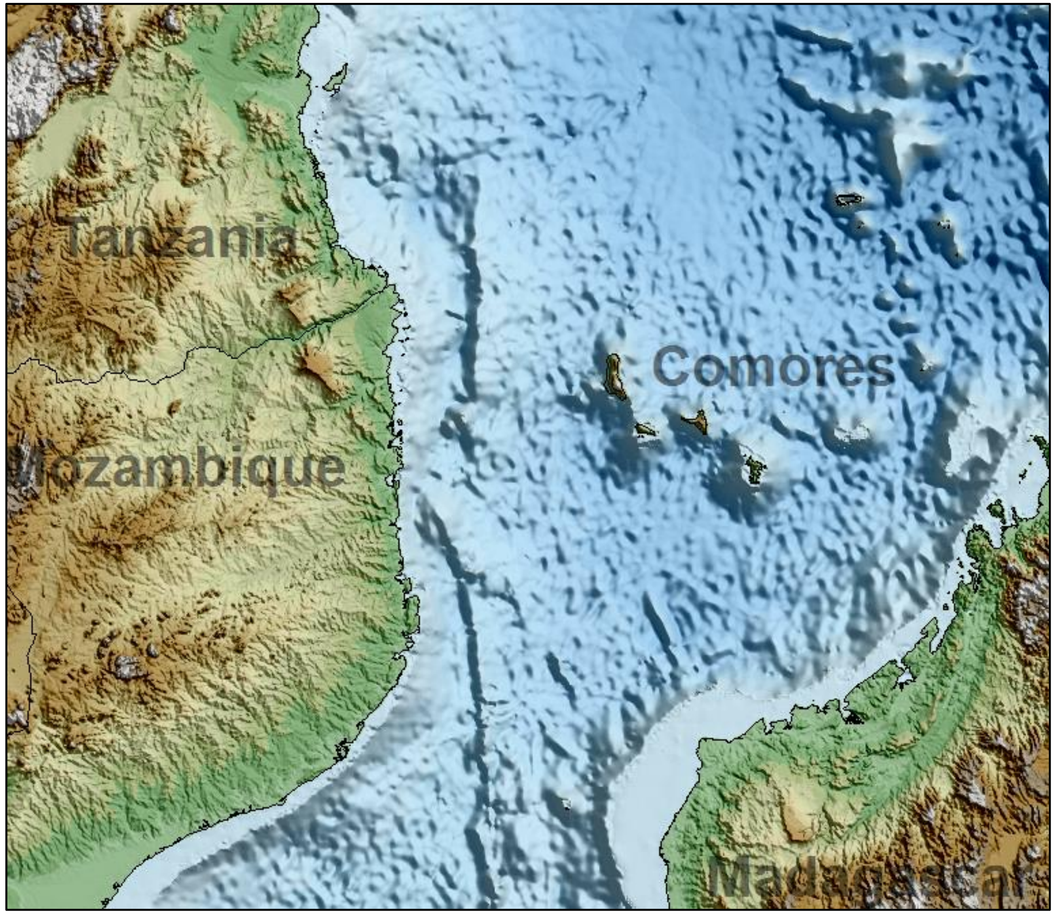
Use of Sandwell Free Air Gravity

Free air gravity correlates with topo-bathymetric relief, neither:

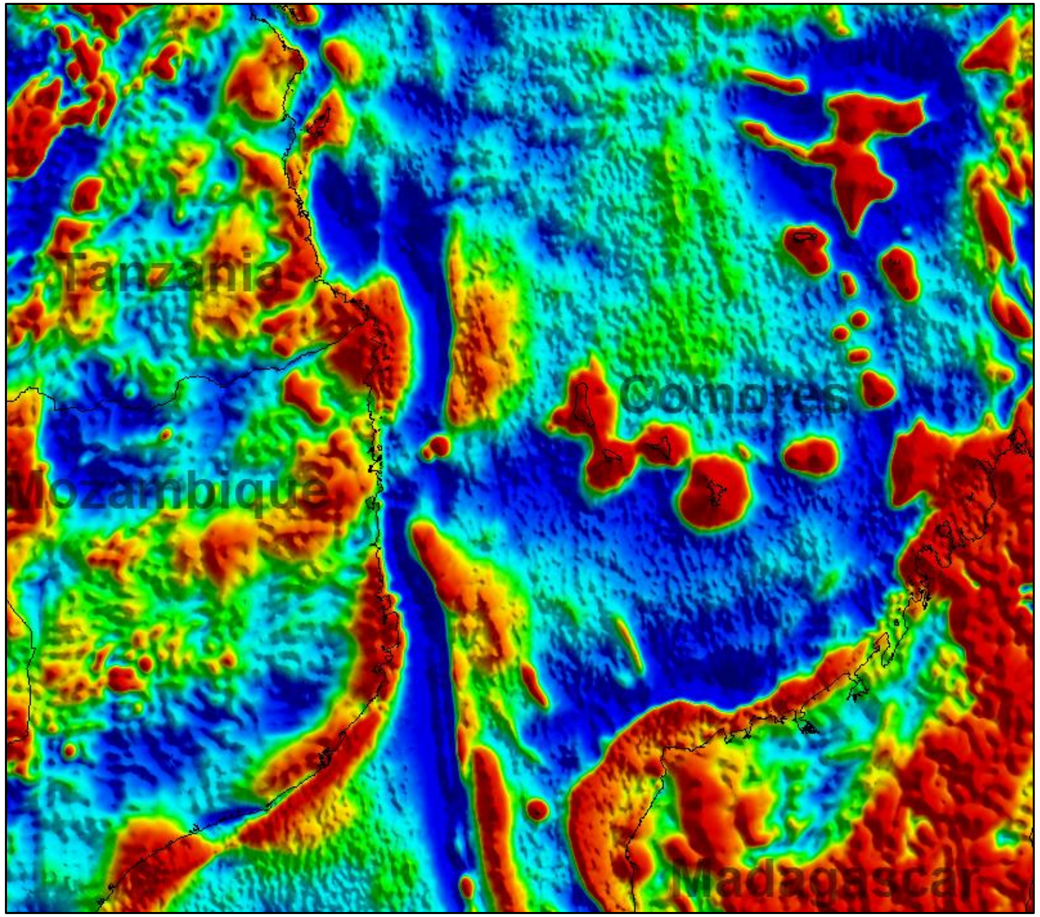
1 geology, nor

2 shallow crustal density variation

But most useful application in geodesy



Left: Etopo-1 topo-bathymetry



Right: Sandwell's v23 Free Air Gravity, _correlates to topo-bathymetric relief_ (Sandwell et al, 2014)

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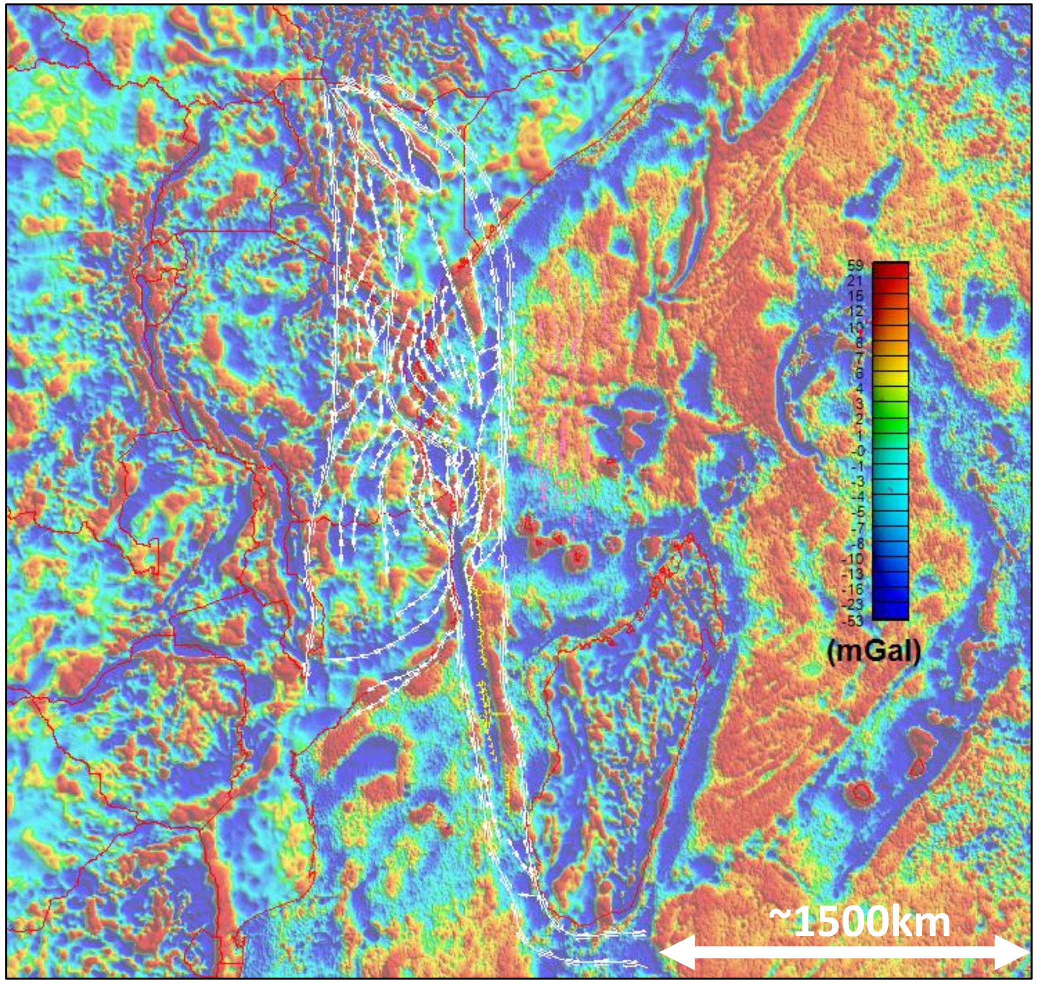
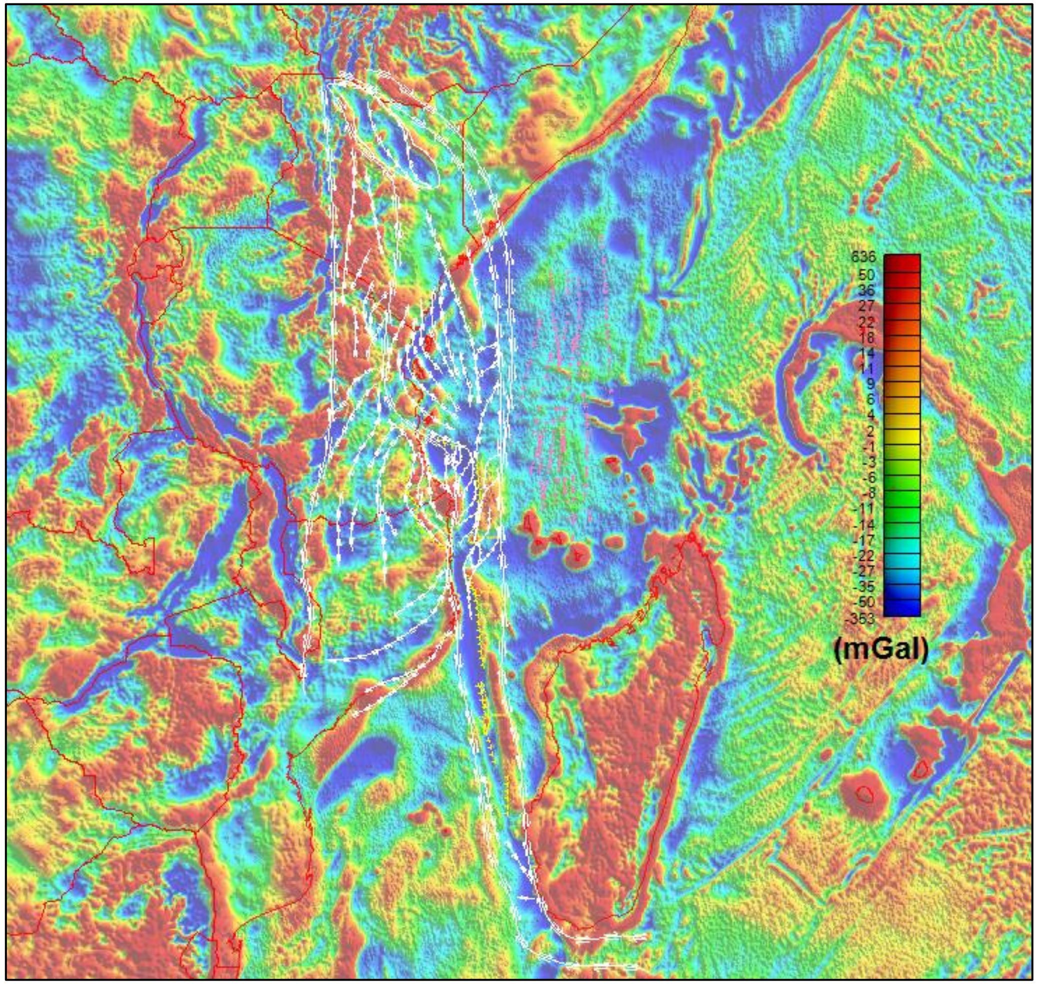
Use of Sandwell Free Air Gravity

Free air gravity must be processed to yield useful residualized products for shallow crustal interpretation

Let the data speak for itself: rather than model potential fields to support a preconceived model/ idea



Left: Decompensative gravity (*corrected for Free Air, Simple Bouguer, terrain, Bullard Earth curvature, isostasy, and residual taken from upward continuation to 40km)*



Right: Sandwell's v23 Free Air Gravity, *correlates to topo-bathymetric relief (***Sandwell et al, 2014***)*

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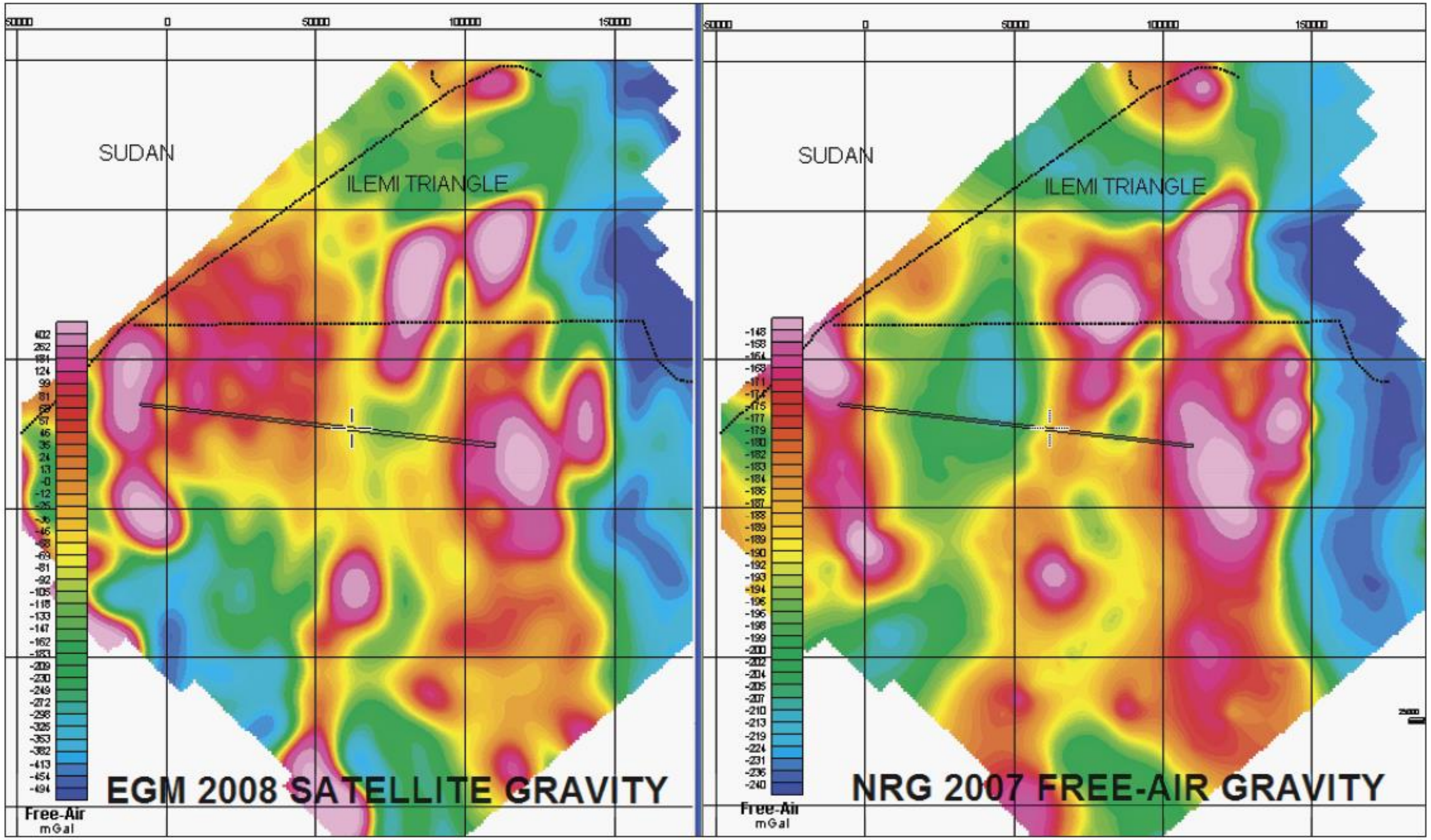
Onshore Sandwell = EGM 2008, Ilemi triangle



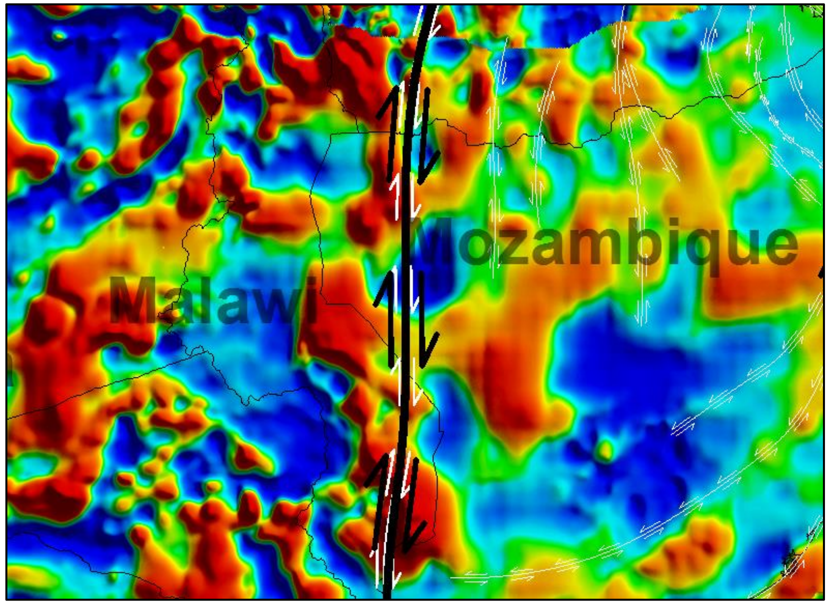
Long and Njuguna, 2011, Free Air comparison between Sandwell (with onshore EGM2008) 2009 (left) and Airborne gravity (right), Lotikipi Basin, west of Turkana, (Ilemi Traingle)

There are areas of fill-in

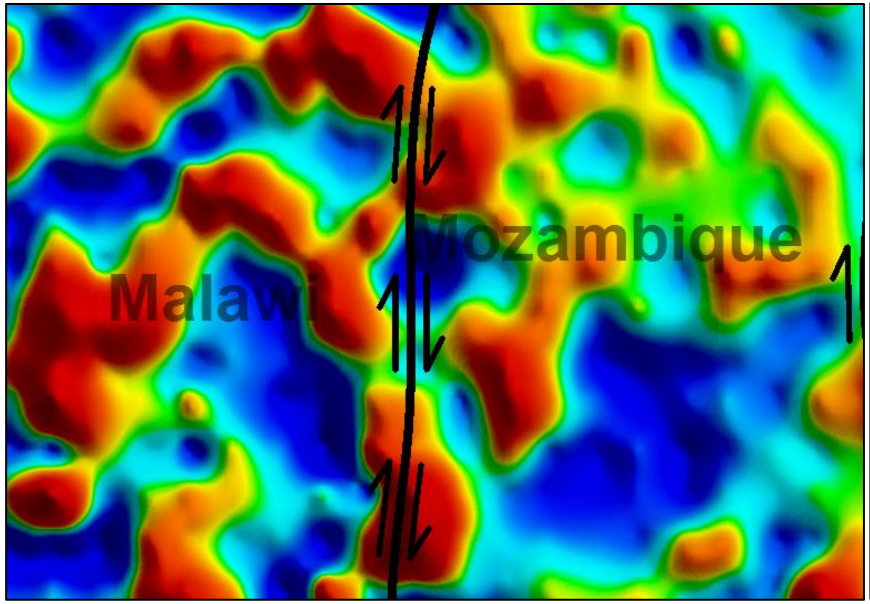
Presented at 5 minutes onshore

Pavlis paper 2012, most of world covered by fitting to onshore measurements, though some areas proprietary (e.g. Somalia, and central part of the reworked northern Mozambique belt.

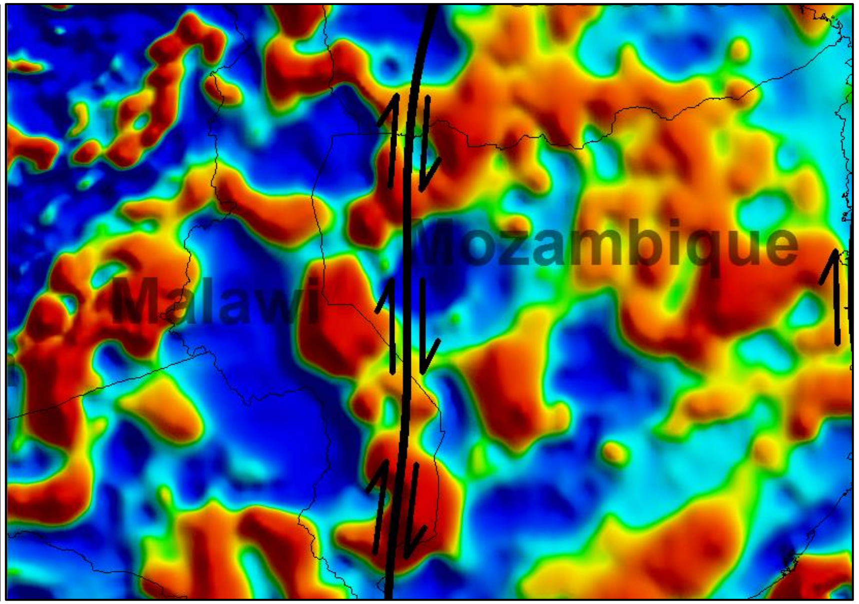
Onshore correlative satmag



EMAG 2 version 3, reduced to pole magnetics, Meyer et al, 2017
~4km resolution

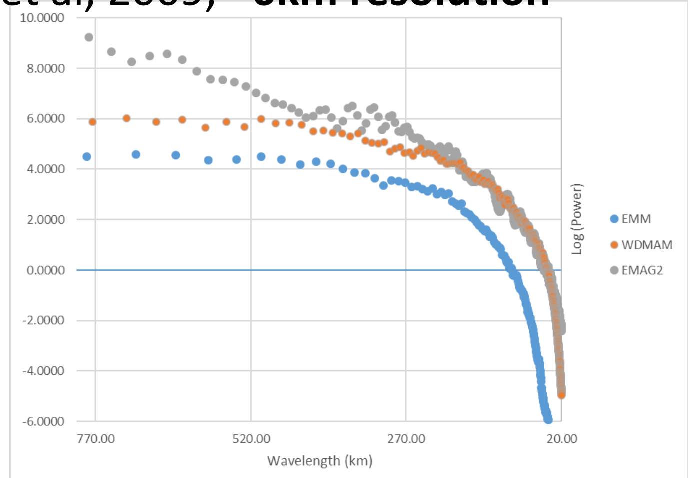


EMM 2015 IGRF corrected, reduced to pole magnetics, Chuillat et al, 2015
~56km resolution



WDMAM2, reduced to pole magnetics
Quesnel et al, 2009, **~6km resolution**

- Swarm Satellite Data
- CHAMP Satellite Data
- ORSTED Satellite Data
- INTERMAGNET Observatory Data
- GEODAS magnetic data



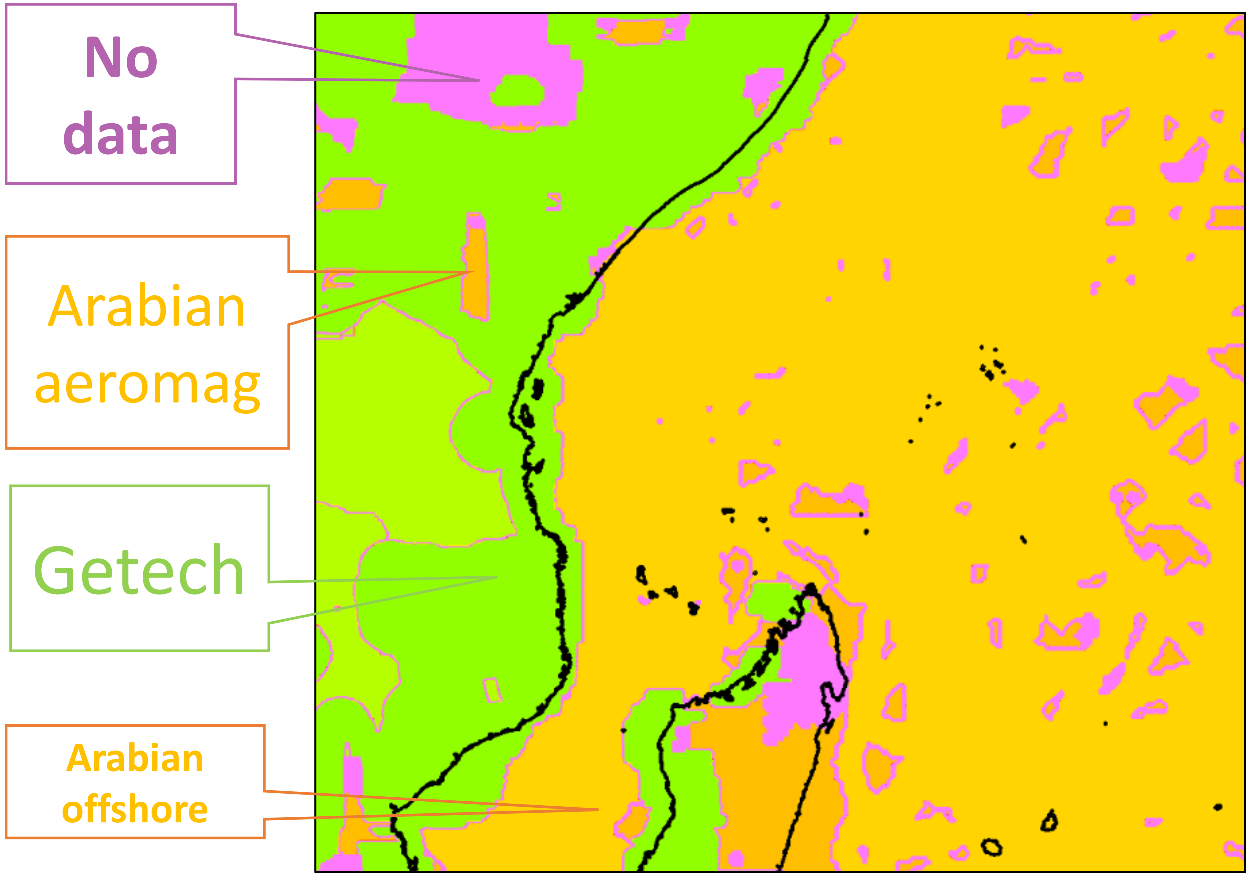
Right: 1D radial average spectral comparison

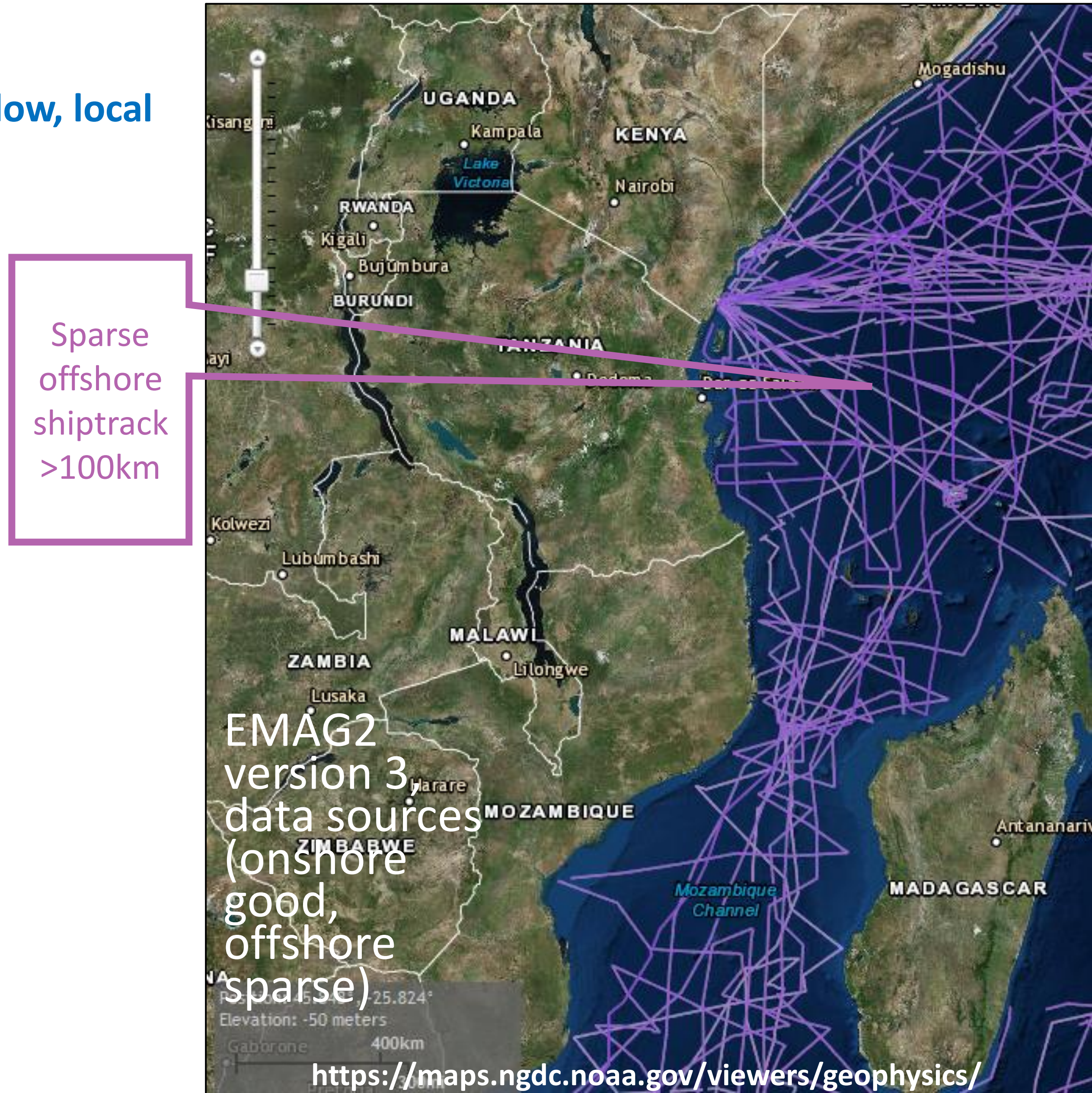
Use of EMAG2 version 3 – offshore not correlative

Krigged (i.e. interpolated) in areas of sparse shiptrack data

Not spatially homogeneous and continuous sampling of shallow, local crustal field, at 2 minute resolution

Below: EMAG2 version 3 data sources (**Meyer et al 2017)**





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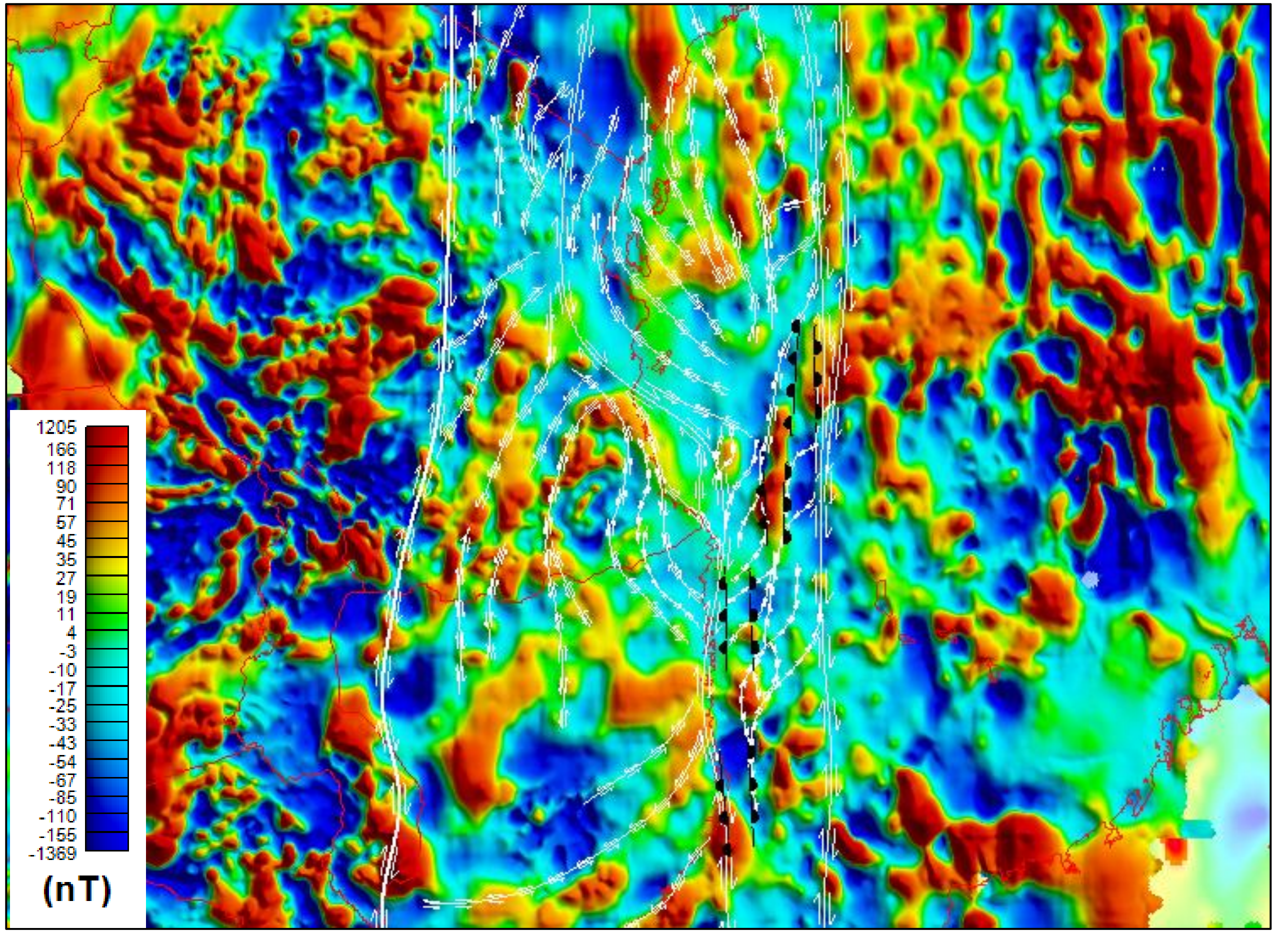
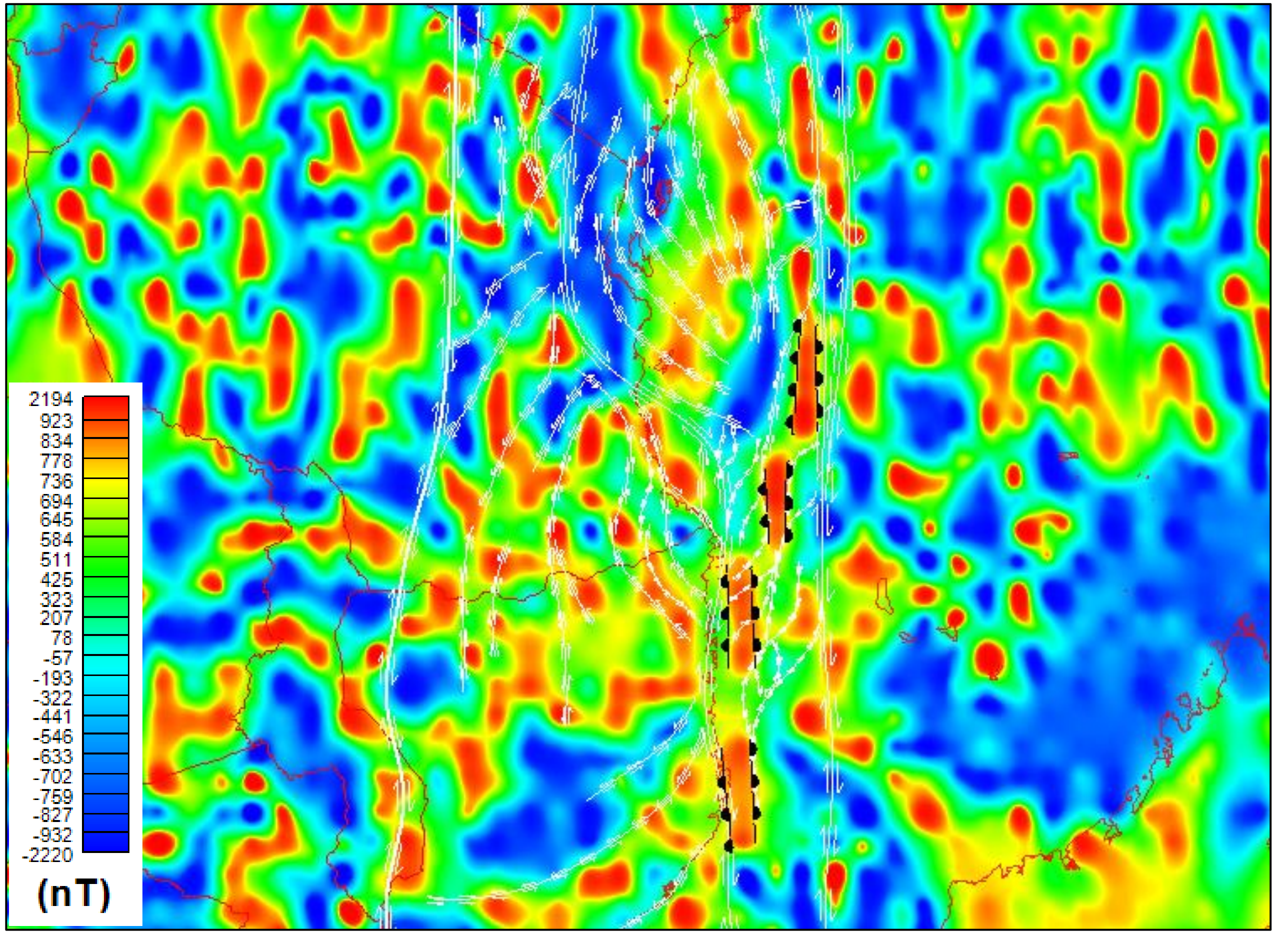
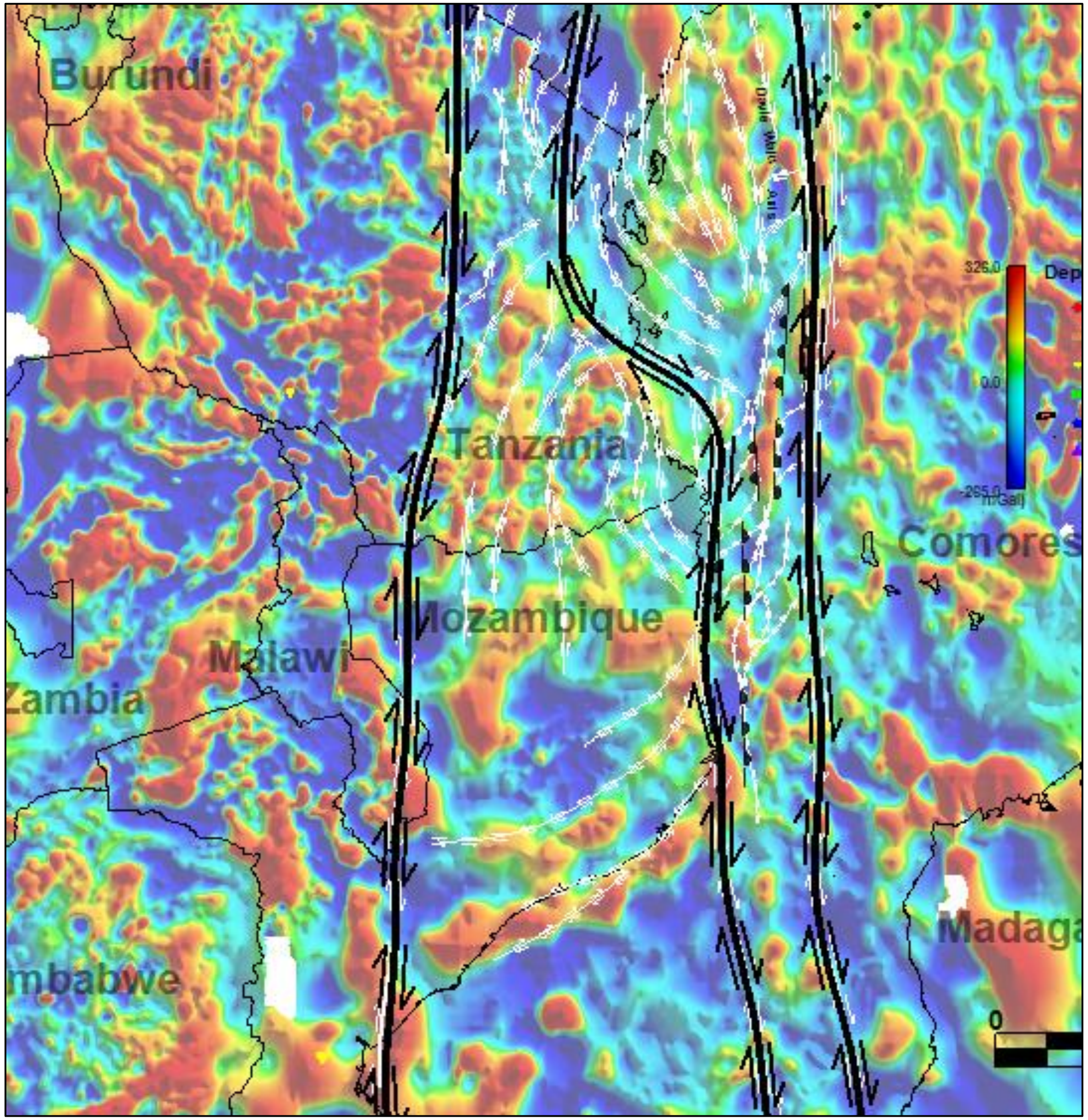
EMAG2 version 3 (left) versus EMM2015 (right)

EMAG2: Krigged (i.e. interpolated) in areas of sparse shiptrack data, **better onshore correlations** where higher resolution aeromagnetic surveys exist.

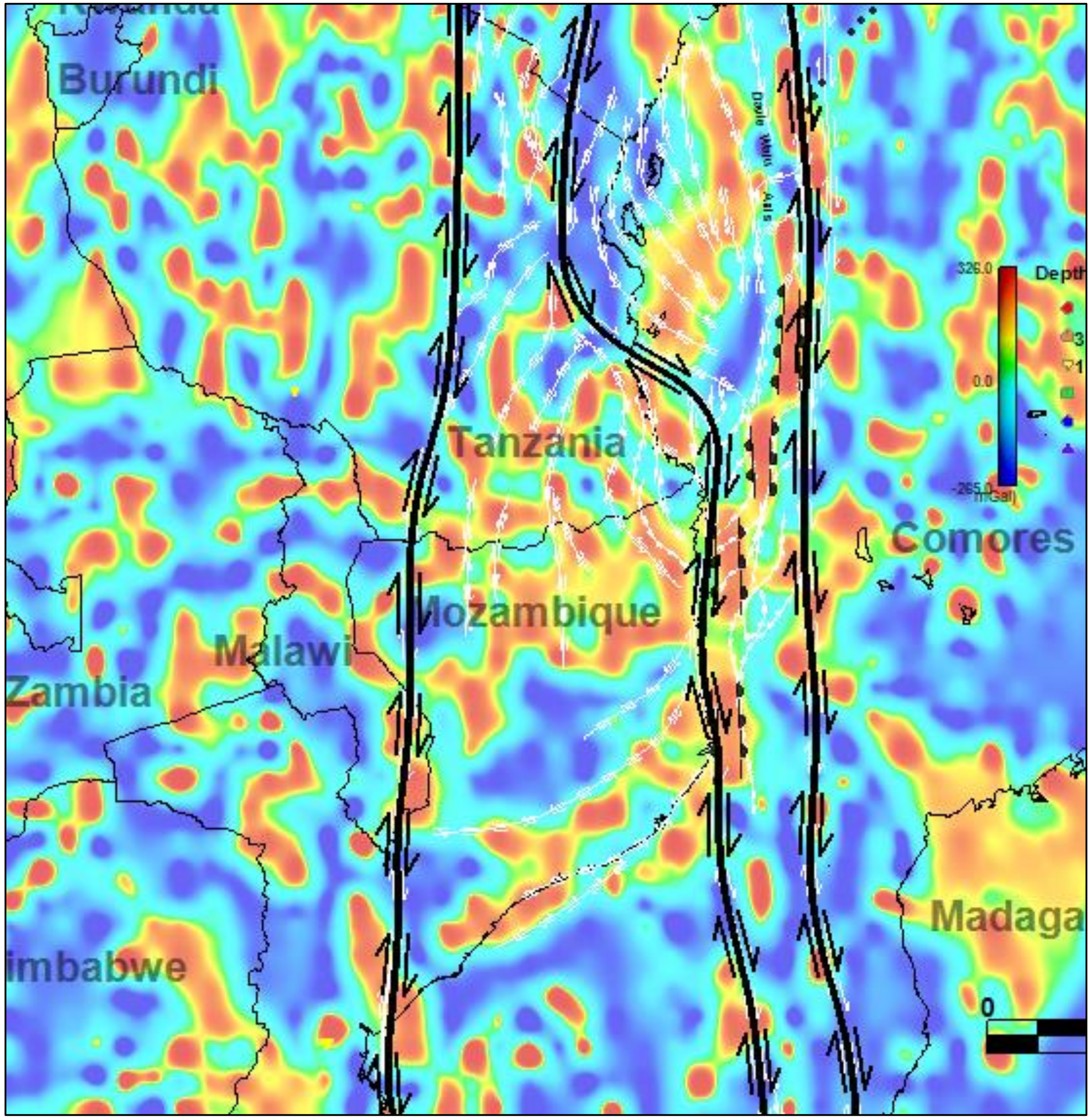
EMM 2015: **Better sampling** of **regional** (deeper) crustal magnetization, limited to spherical harmonic order 720, without krigging or interpolation of 2 minute cells across 100s kms.







EMAG 2 version 3, reduced to pole magnetics



EMM 2015 IGRF corrected, reduced to pole magnetics, amplitude gain corrected (Rajagopalan and Millegan, 1994)

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An example from Senegal, Long and Cameron 2016

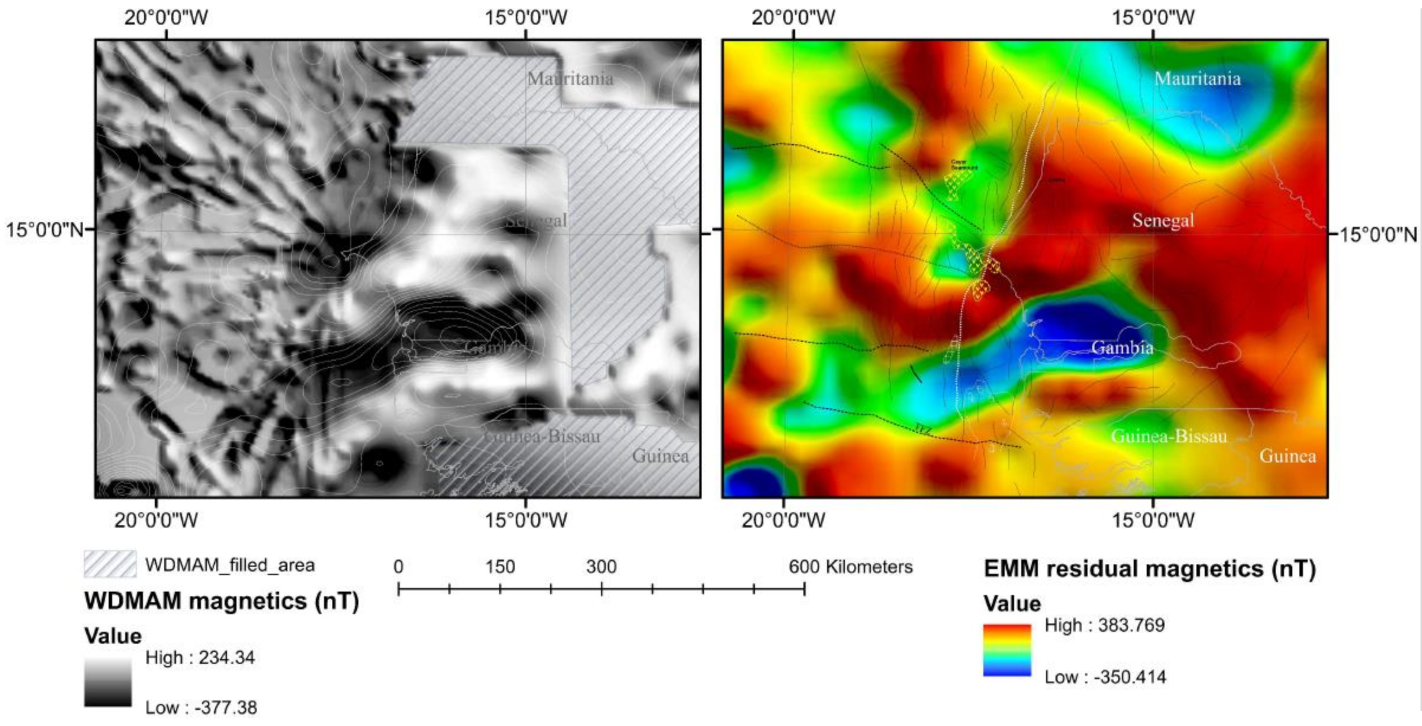

Figure 6: Left: World Digital Magnetic Anomaly Map (WDMAM) showing areas of interpolated field. White contours of Enhanced Magnetic Model (EMM). Right: EMM residual magnetics with gravity interpretation overlain from above.

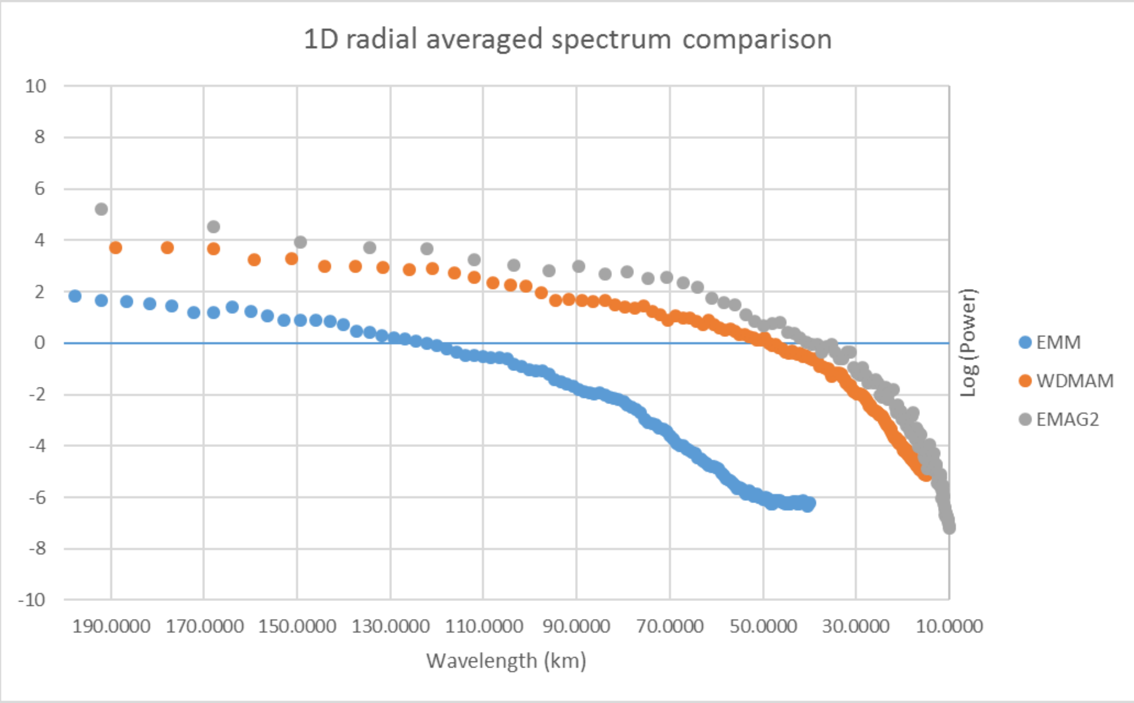

Figure 3: Radial averaged spectra comparison of magnetic datasets. EMAG2 not used in this study.

*"The EMM provides continuous coverage versus areas of onshore interpolation in the WDMAM (see **figure 6**) . The data were extracted at a vertical datum of the WGS84 ellipsoid. The magnetic field at ground level is a combination of the main magnetic field (outer core), the crustal magnetic field, and temporal variation of the external magnetic field. The EMM was processed to create a residual corrected magnetics product to resemble crustal magnetization source anomalies by removing an approximation of the inducing field strength, as an IGRF correction."*

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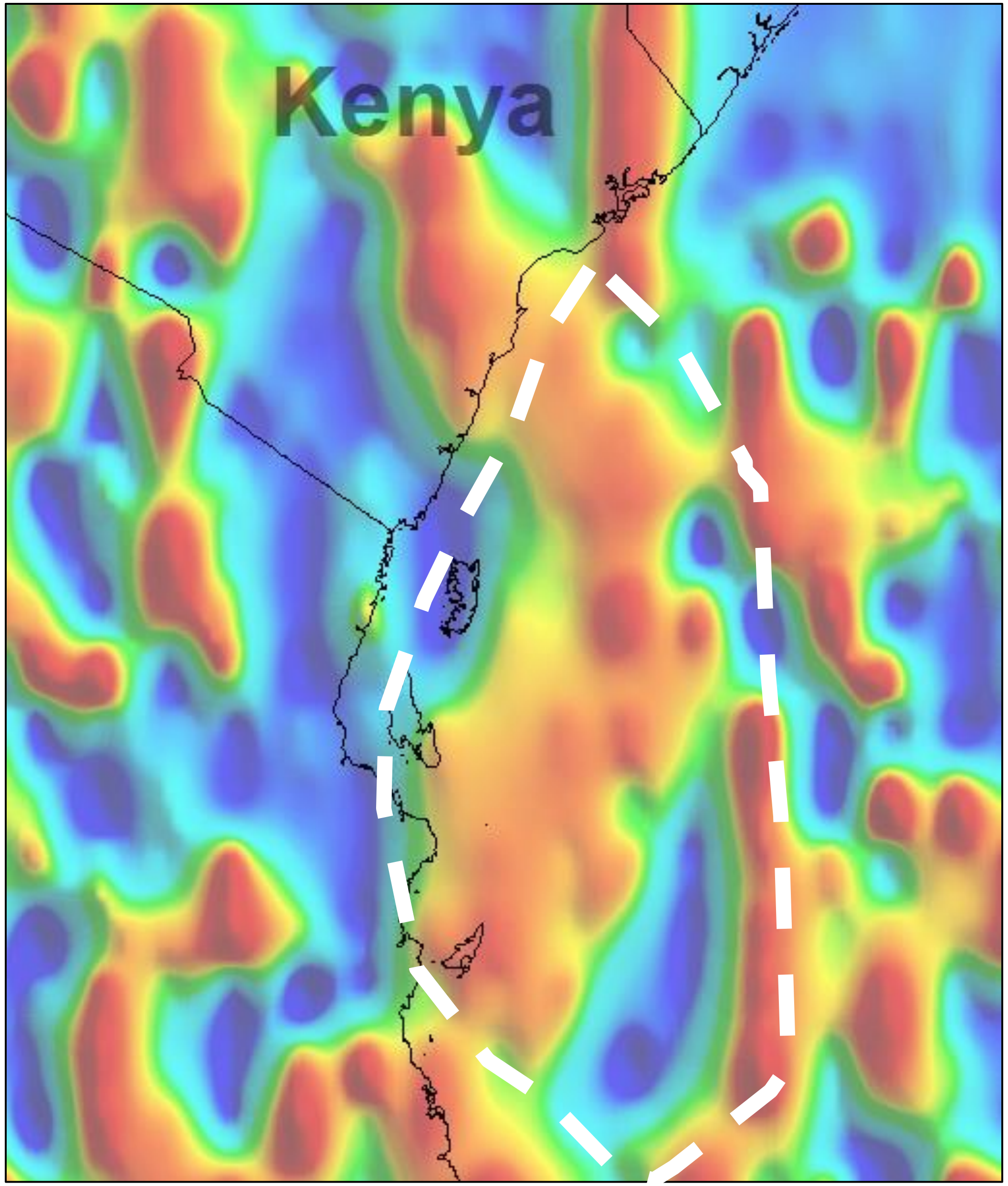
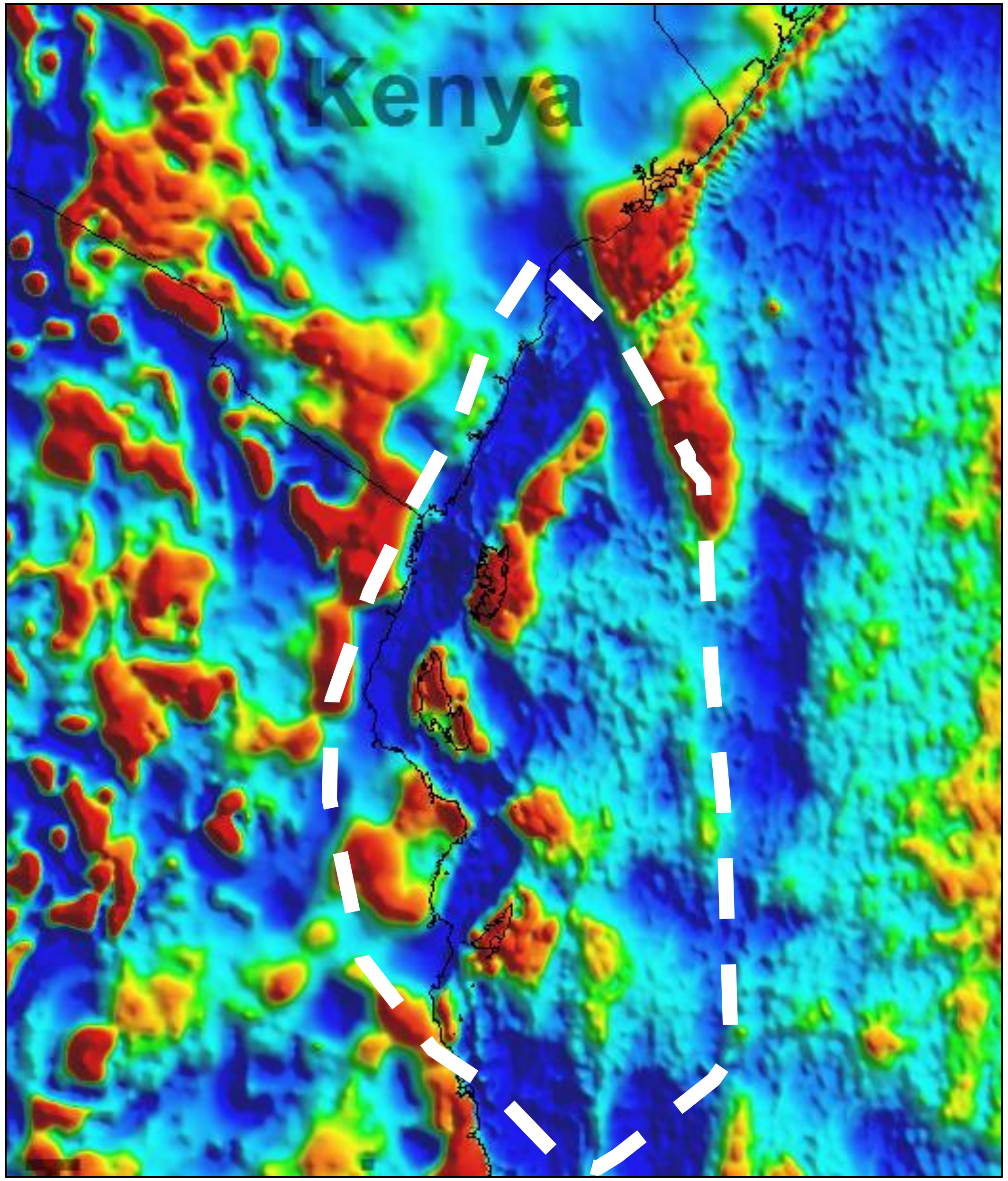
Fabric





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Above (l): IGRF corrected, reduced to pole magnetics Above (r): Decompensative gravity residual

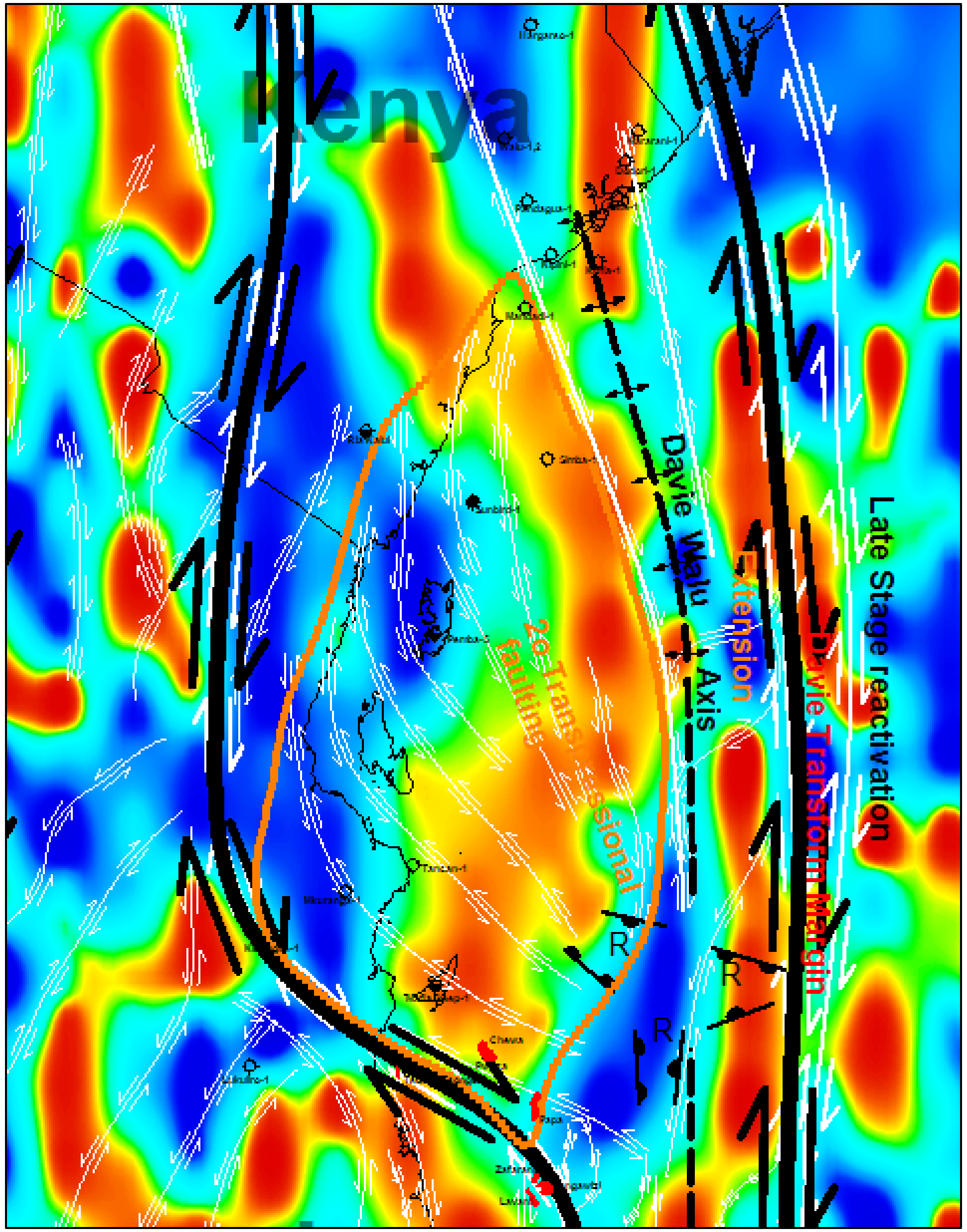
Structure

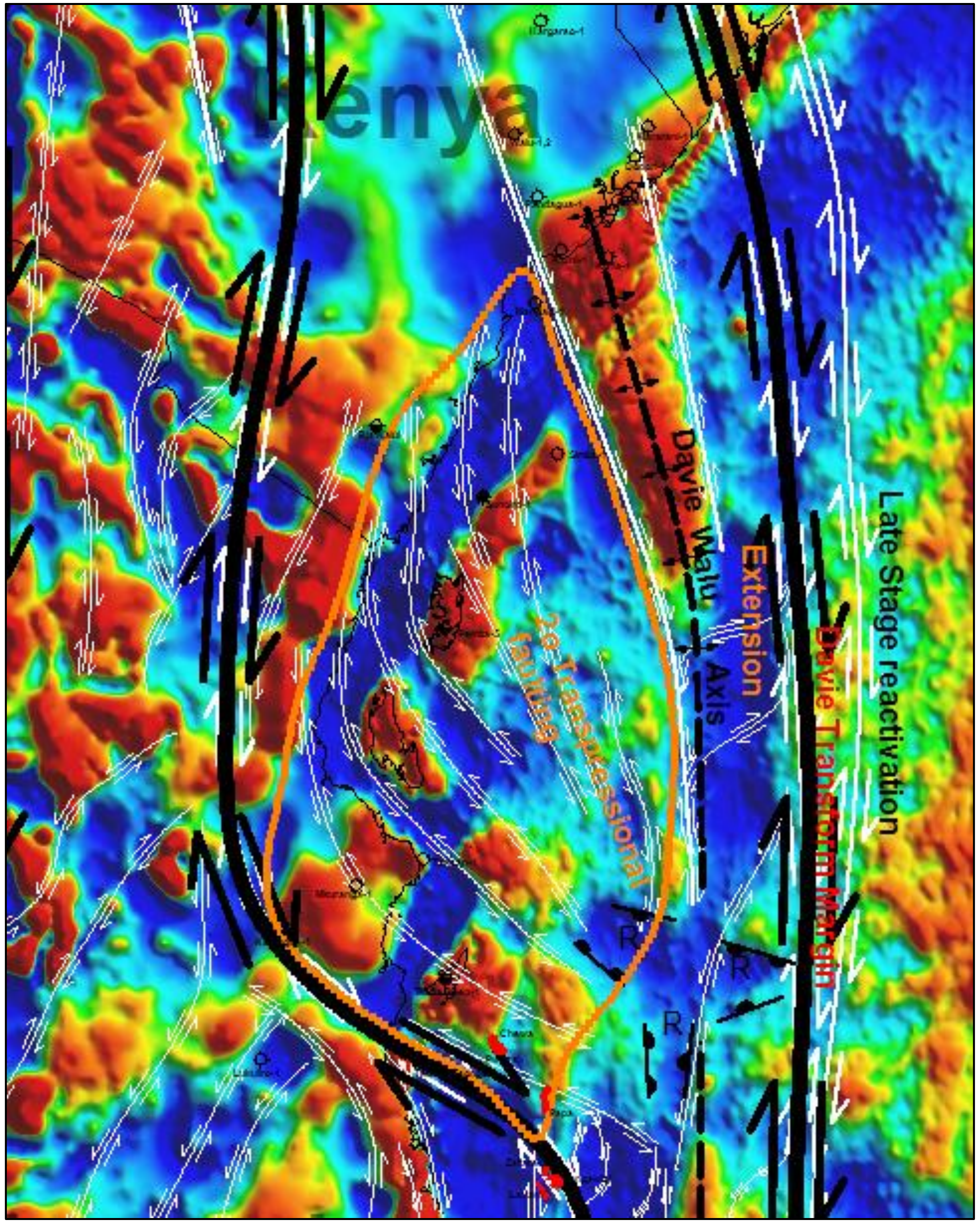
Geological context: Indicative of strike slip deformation

Spatially correlative

"Data speaks for itself"

Reconciliatory to other observations





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Above (l): EMM 2015, reduced to pole magnetics

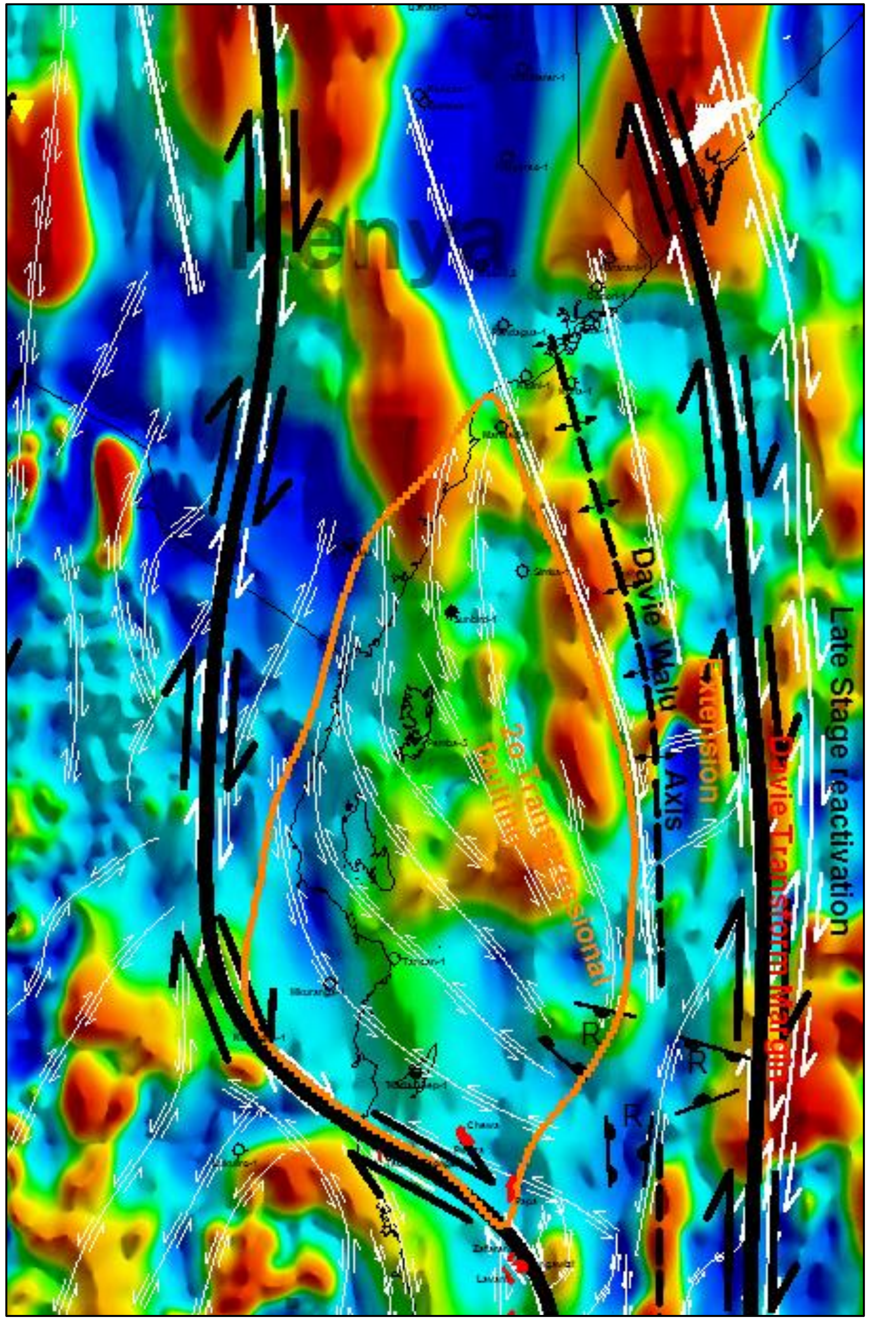
Above (r): Sandwell Decompensative gravity residual

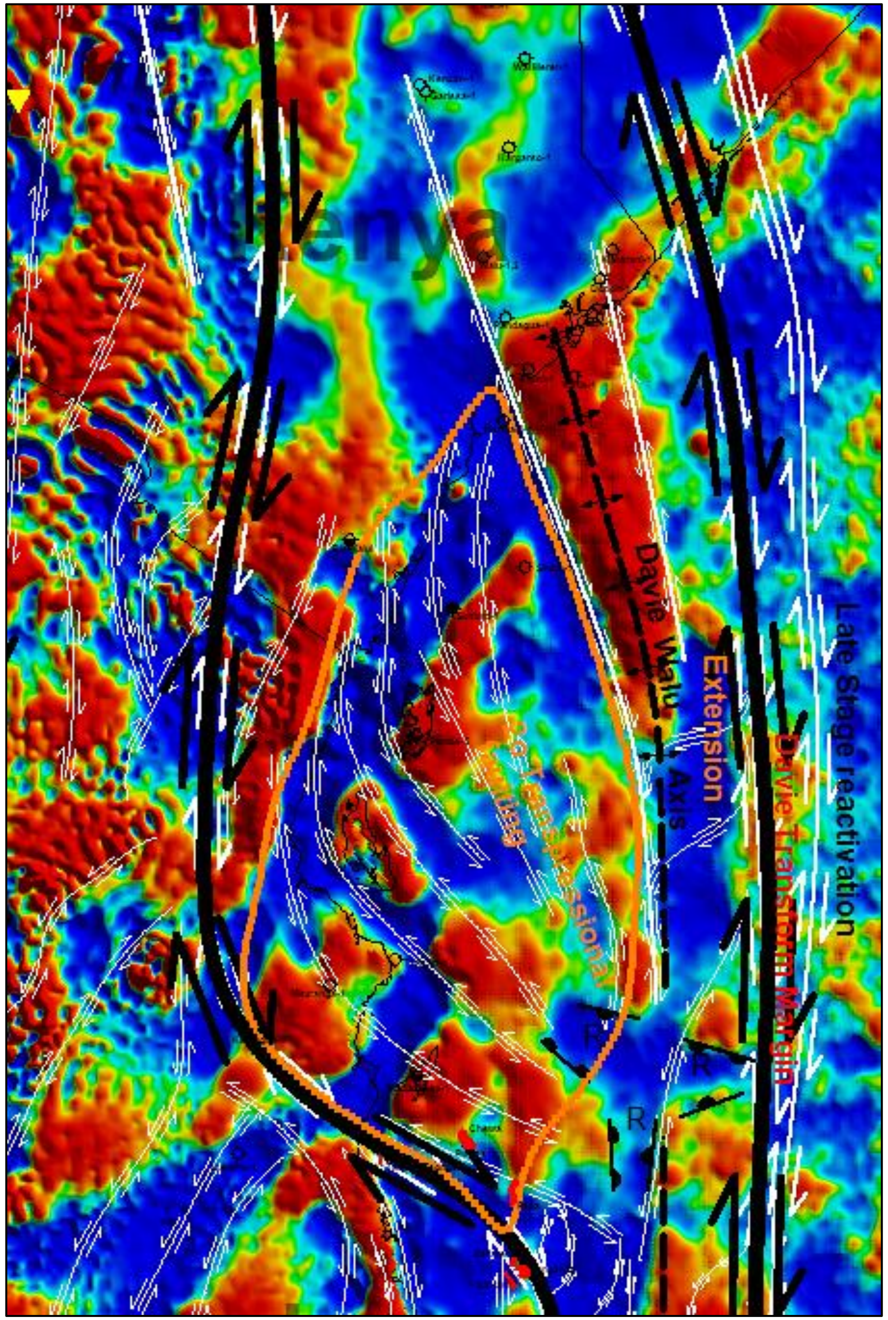
Structure

<u>Consistent reproducable processed residual anomalies</u>

<u>Different data sources</u>

EMAG2 v3 and DTU 13 (both 2 arc minute resolution)





Above (l): EMAG 2 v3., reduced to pole magnetics Above (r): DTU13 Decompensative gravity residual

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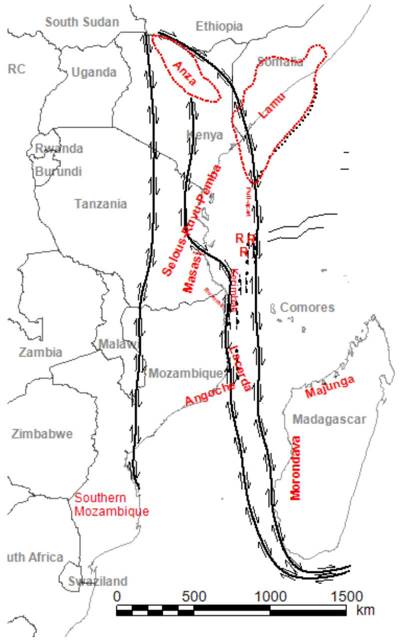
EAST AFRICA OIL GROUP



East African Margin

A few unknowns, to name some:

Anza Basement, what is the overburden fill

COB boundaries –structural controls on basin evolution

Extent of Somali Basin oceanic spreading – early heat flow

Formation of the Davie Ridge – petroleum systems opportunities

Structural definition of Davie…Davie Ridge, Davie Walu, Davie Fracture Zone, Davie Transform Margin

The crustal composition of the Beira High

Pre-breakup configuration of Madagascar/ East Gondwana versus West Gondwana

…and is there any significant oil?

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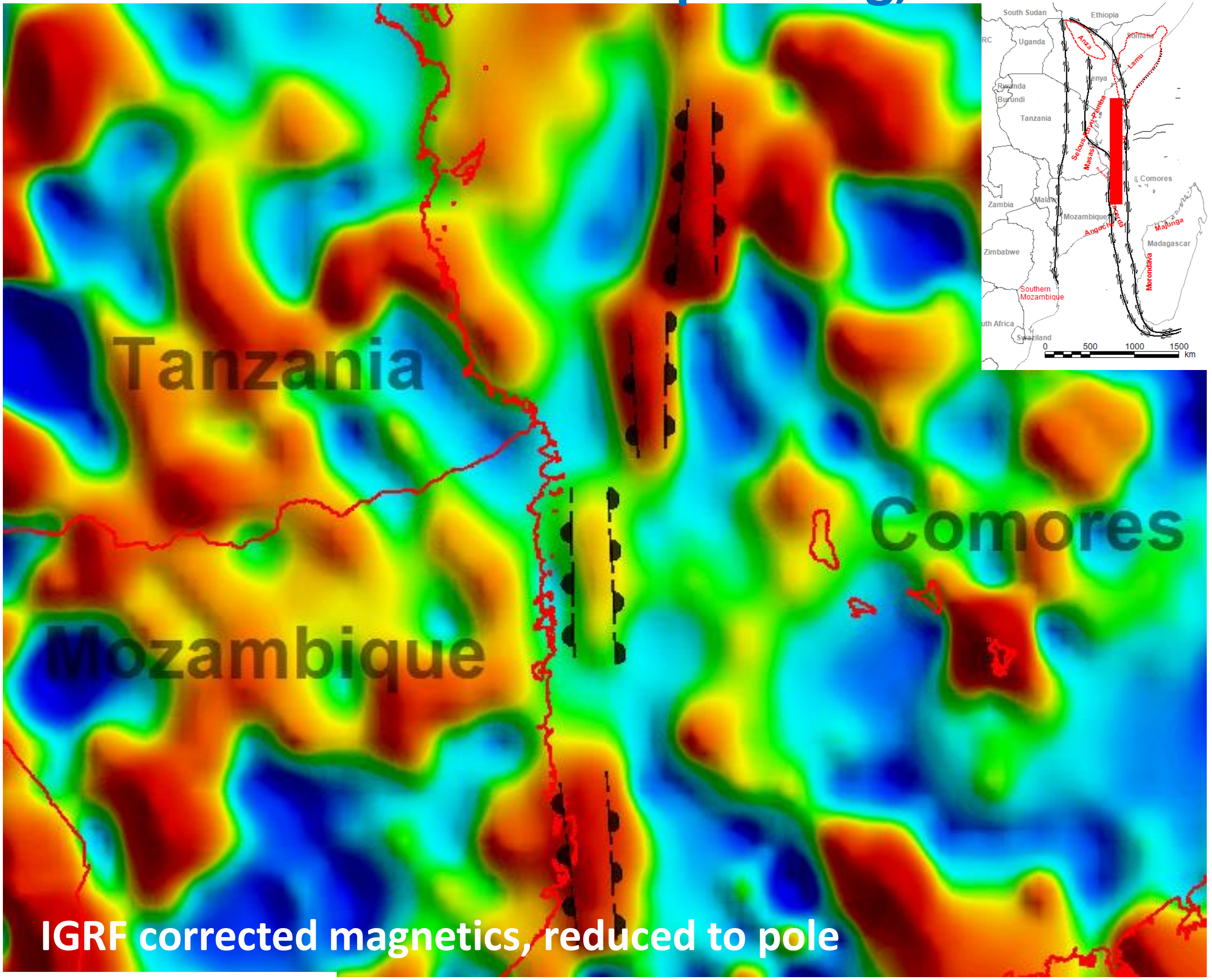
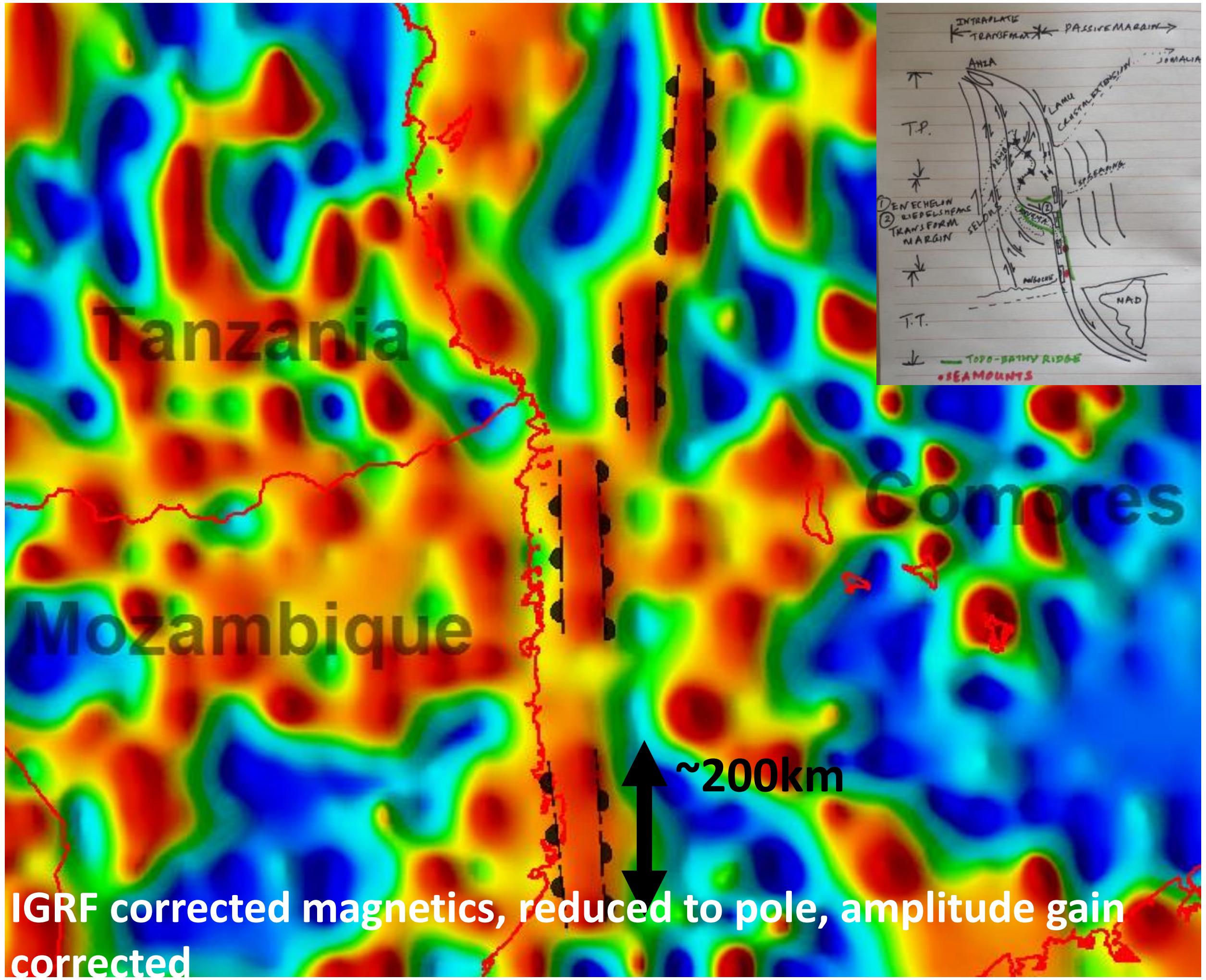
EMM2015 magnetics - Echelon crustal blocks

In a dextral strike slip setting, indicative of duplexing (e.g. **Woodcock and Fischer, 1986**)





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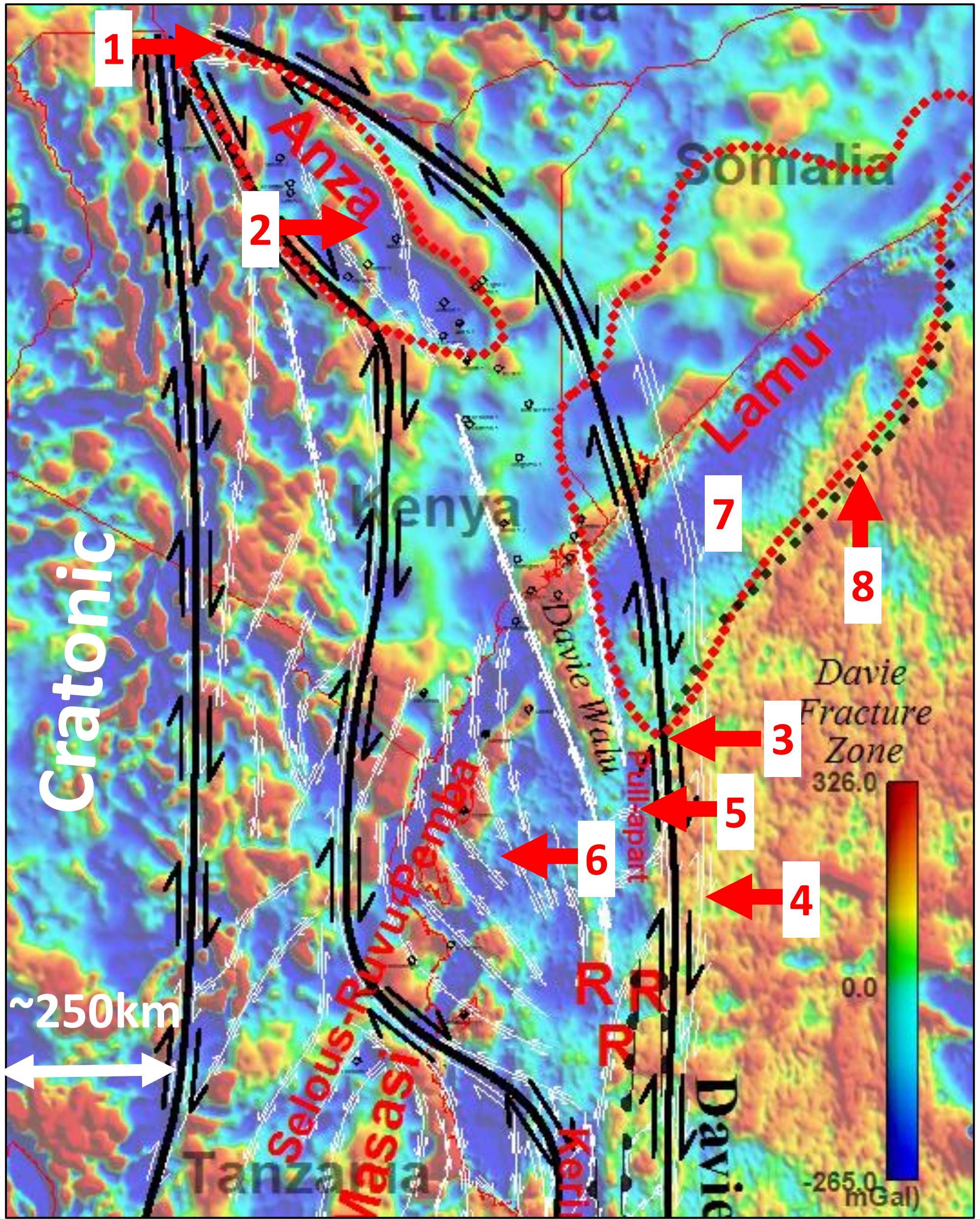
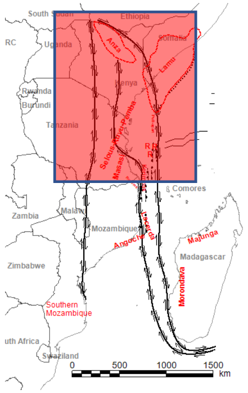
Anza – the northern strike slip closure by rotation





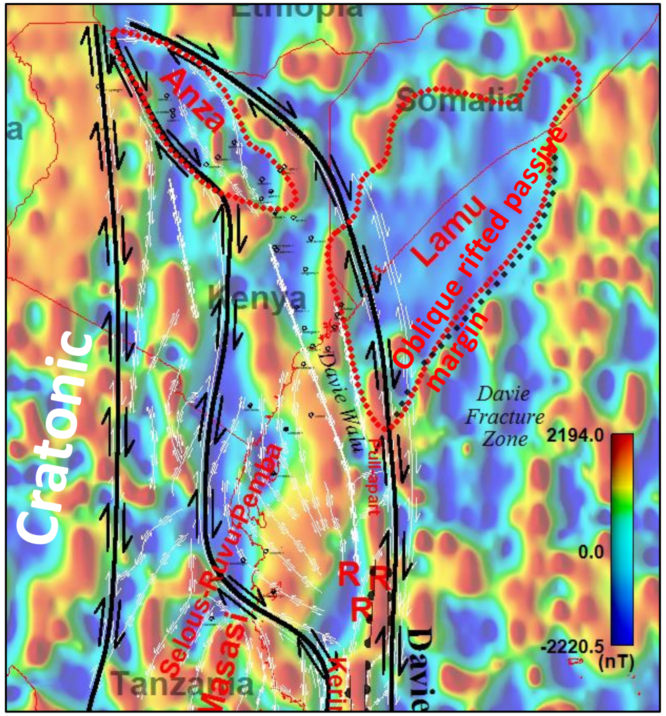
Left: Decompensative gravity, *below right*: IGRF corrected, reduced to pole magnetics

Correlative strike slip fault offsets, transform margin, crustal extension, and oceanic boundary

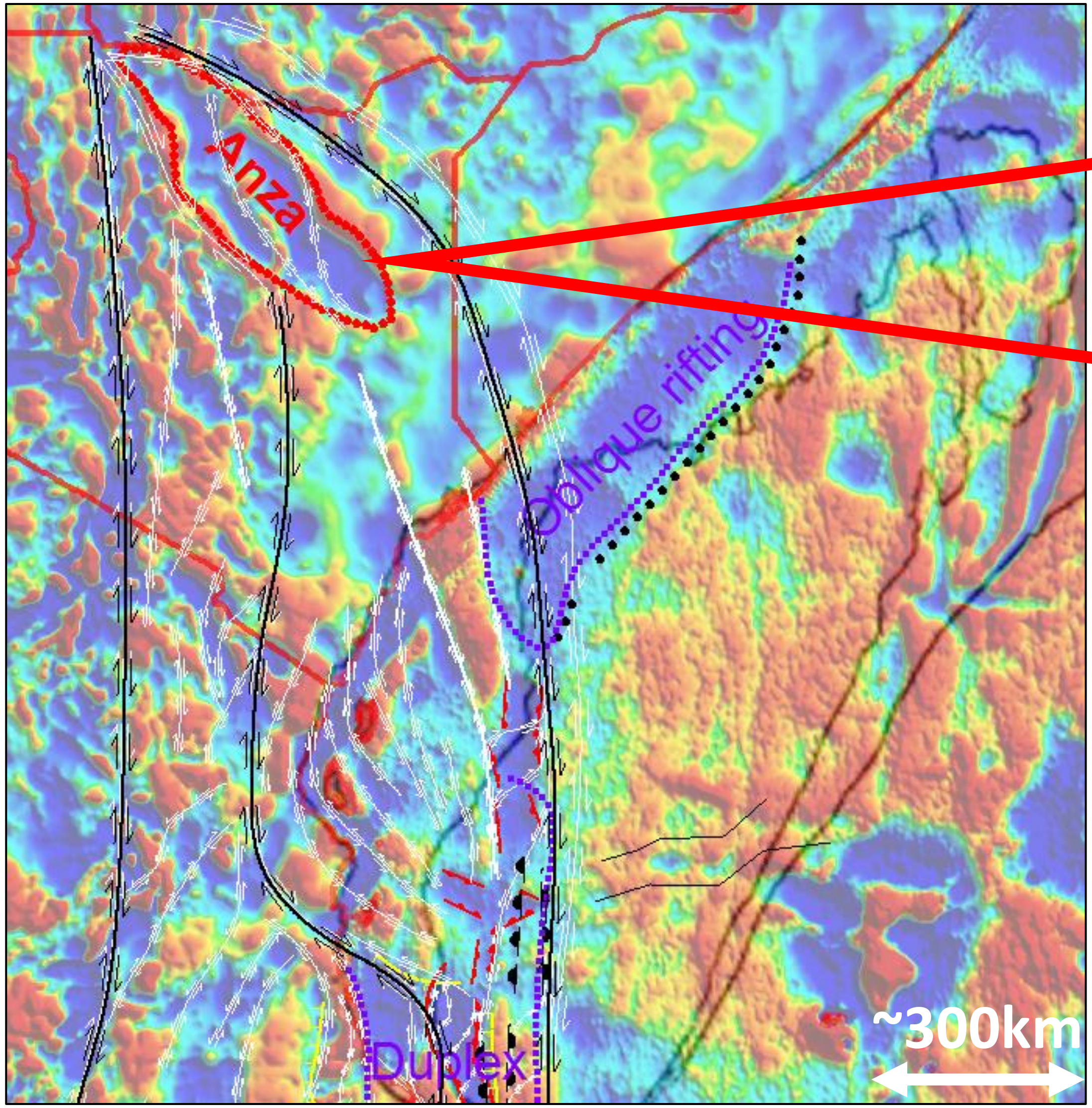
Storti et al, 2003 - On intraplate strike slip tectonics:

"During divergence, they act as transfer zones that segment rifts, passive continental margins and, ultimately, oceanic spreading ridges… form major persistent zones of apparent weakness whose influence may be felt over many hundreds or even thousands of million years."

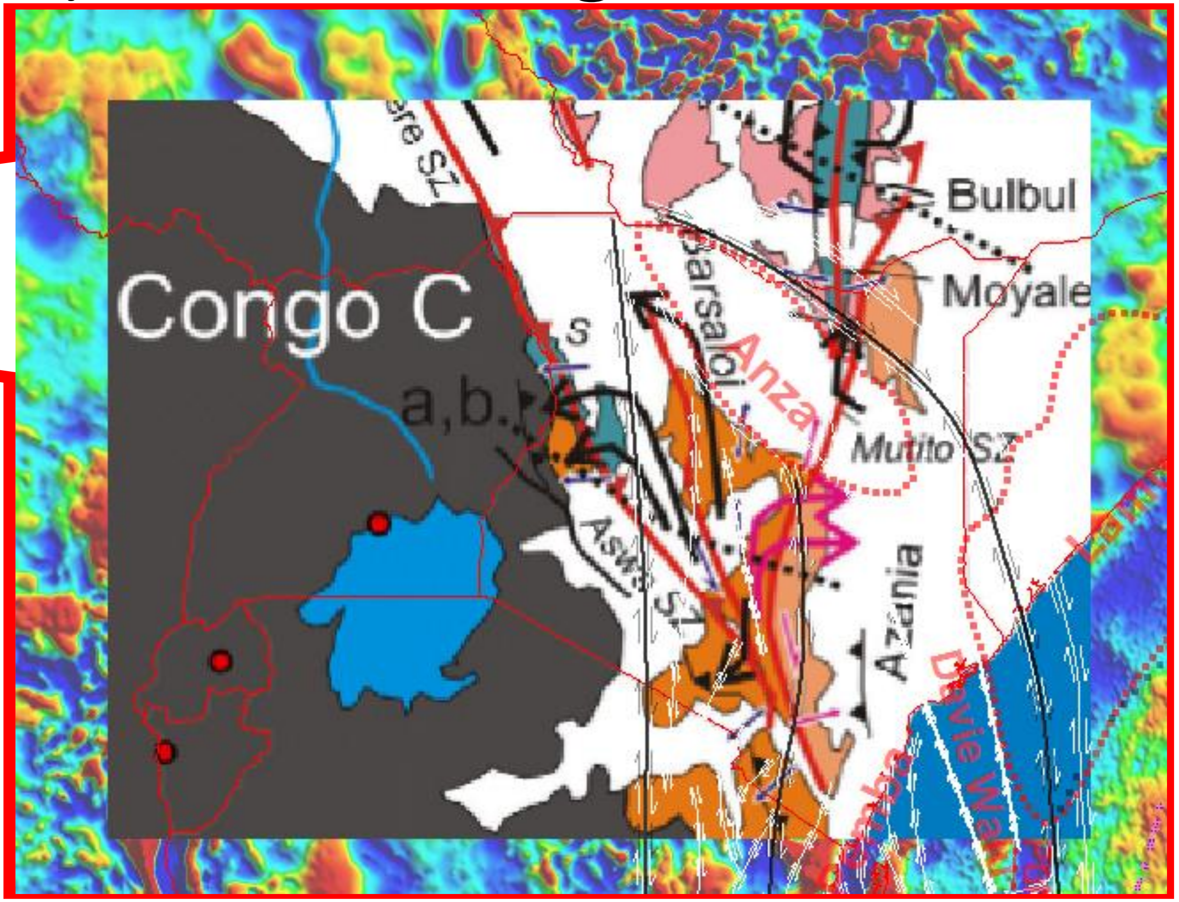
1 Closure by rotation
2 Seismic evidence of Neogene inversion + earlier
3 Main transform margin
4 Oceanic transform segment
5 Seismic evidence of Jurassic pull-apart basin
6 Transpression, several episodes
7 Oblique rifted passive margin
8 Continent-Ocean boundary



Precambrian Suture (E-W Gondwana) to Anza Neogene inversion:



Above: Decompensative gravity residual overlain by **David Boote's Triassic Karoo reconstruction**, 2017, based on rigorous well correlations



Above: After Fritz, 2013. Anza occupies Neoproterozoic Barsaloi suture between the Congo cratonic margin and the relic Azania margin as part of the East African Orogen.

Relic faults and sutures remain lines of weakness, note western cratonic strike margin.

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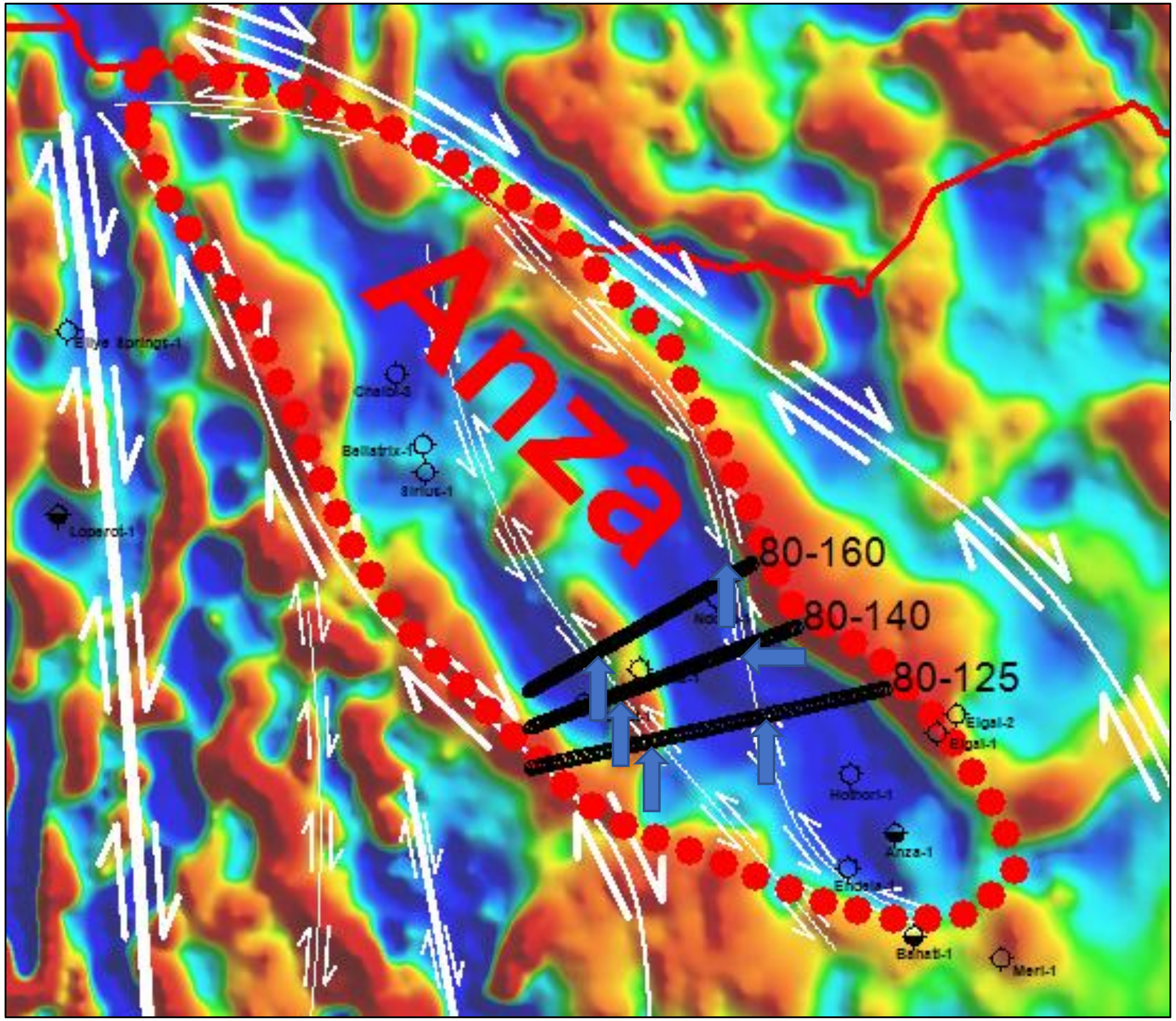
Kaisut-Central Anza: seismic



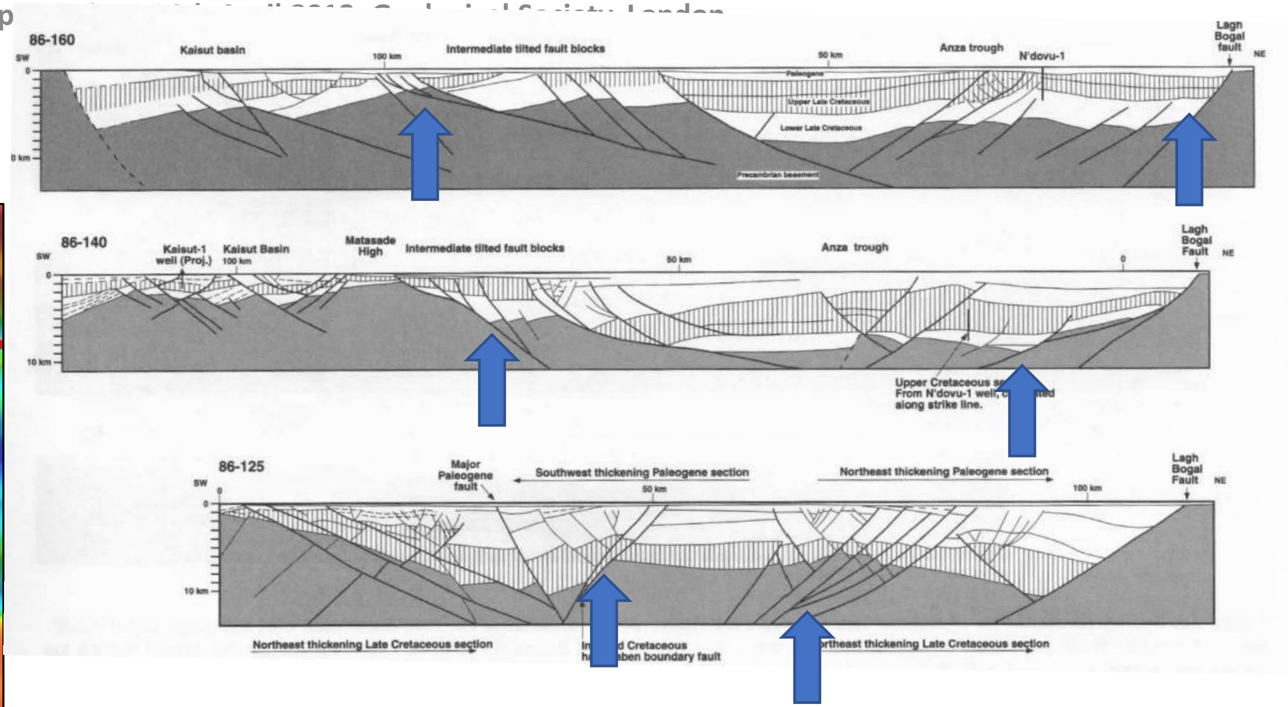


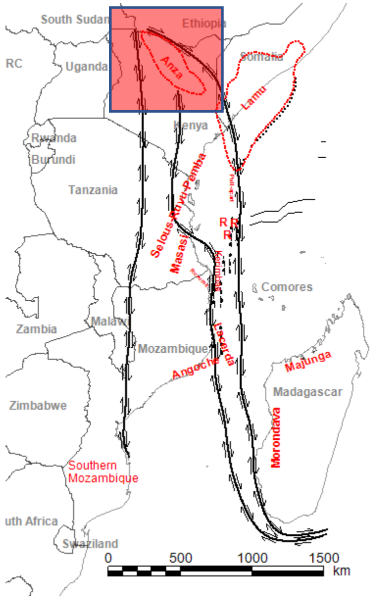
Figure 15, Morley, 1999

Kaisut (west central Anza): correlative deep basement faults

<u>**Highly rotated Cretaceous lower section, less rotated Palaeogene upper section (Morley, 1999)**</u>

Early strike slip \ oblique rifting\ transform margin propagates

Later reactivation as inversion



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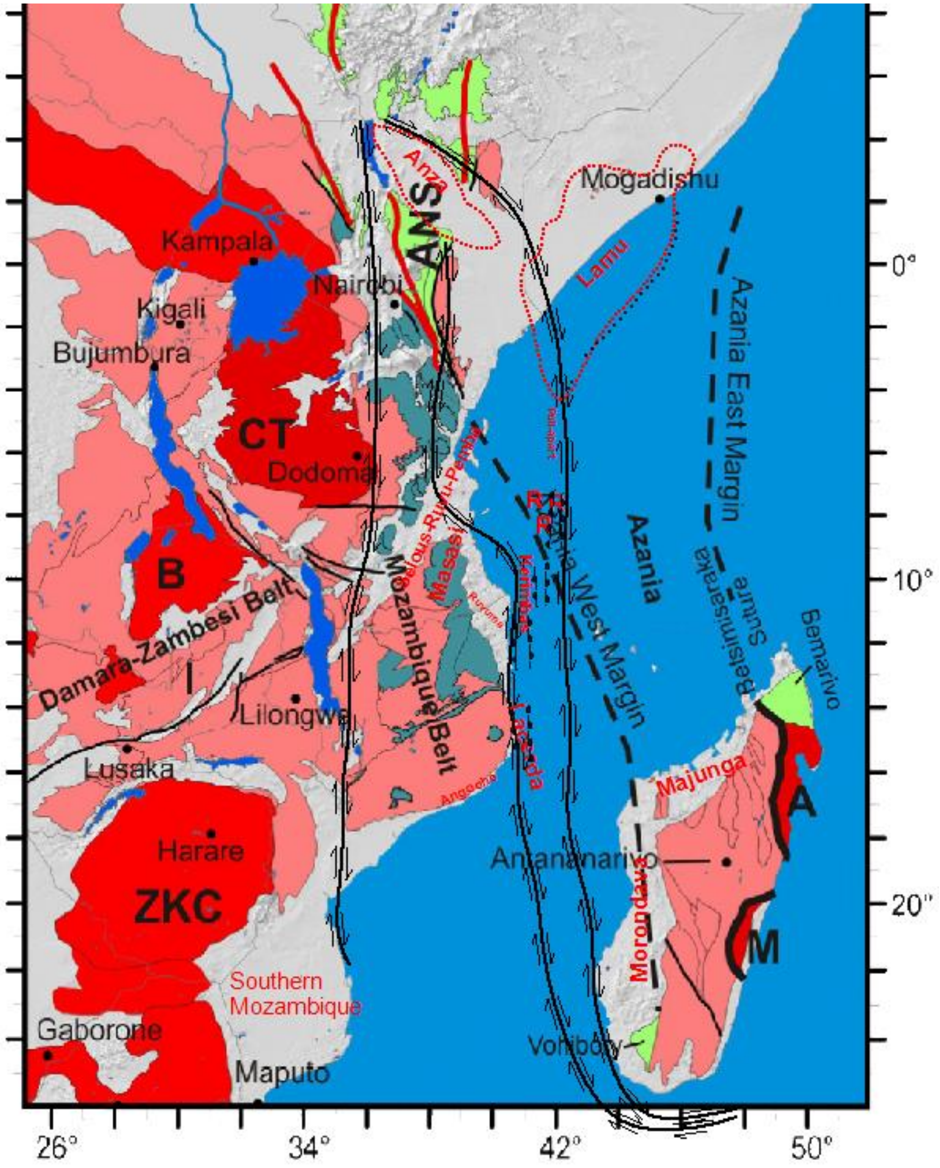
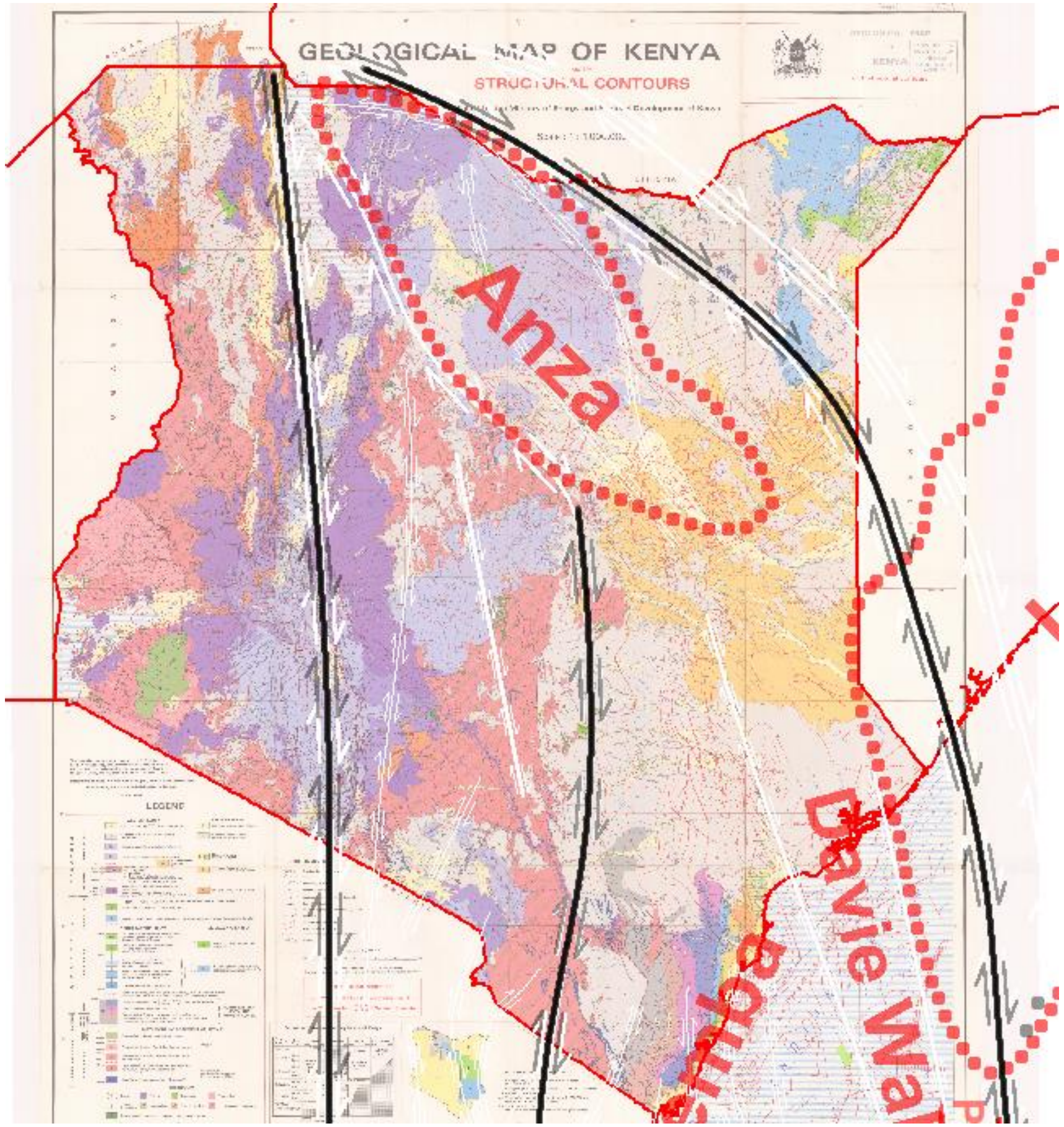
Precambrian Suture (E-W Gondwana) to Anza Neogene inversion:

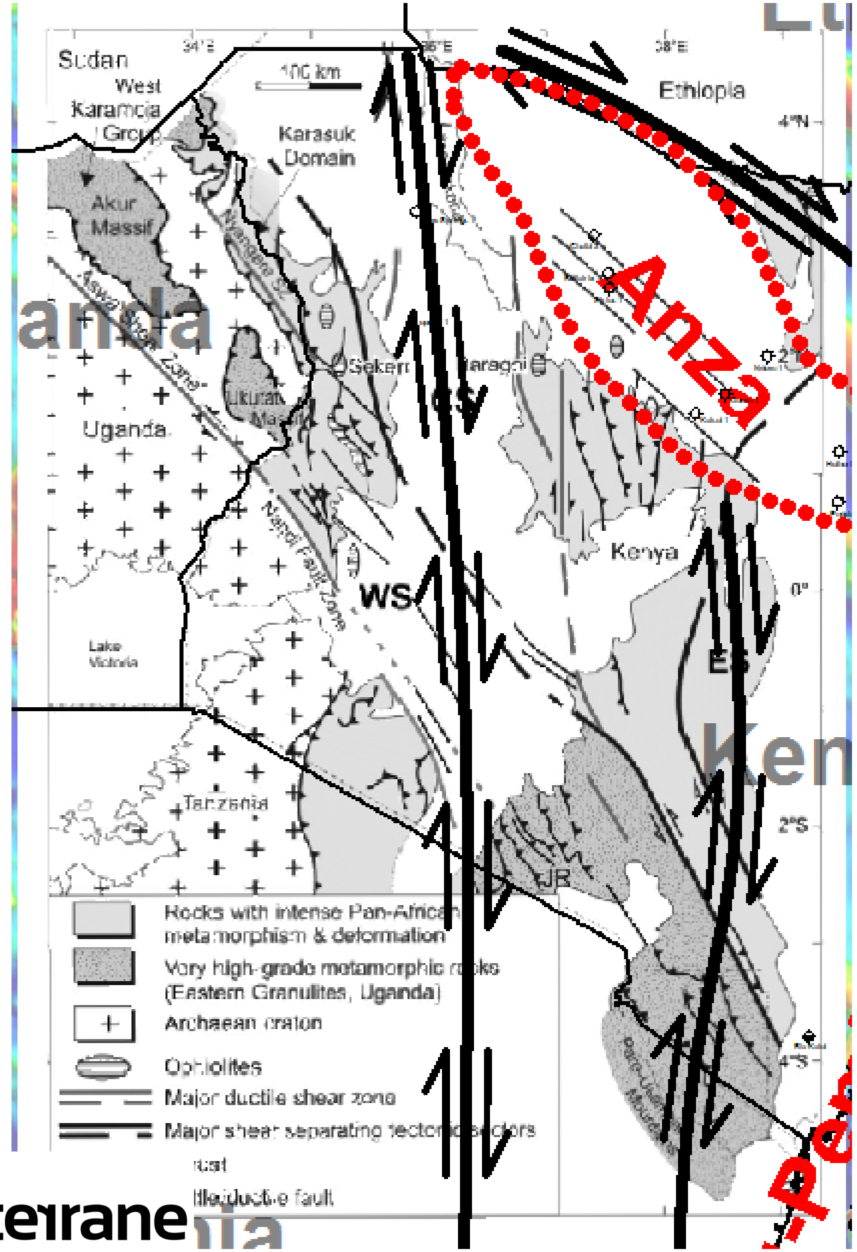
Below: Azanian western margin is found in Madagascar (**Fritz et al , 2013**)



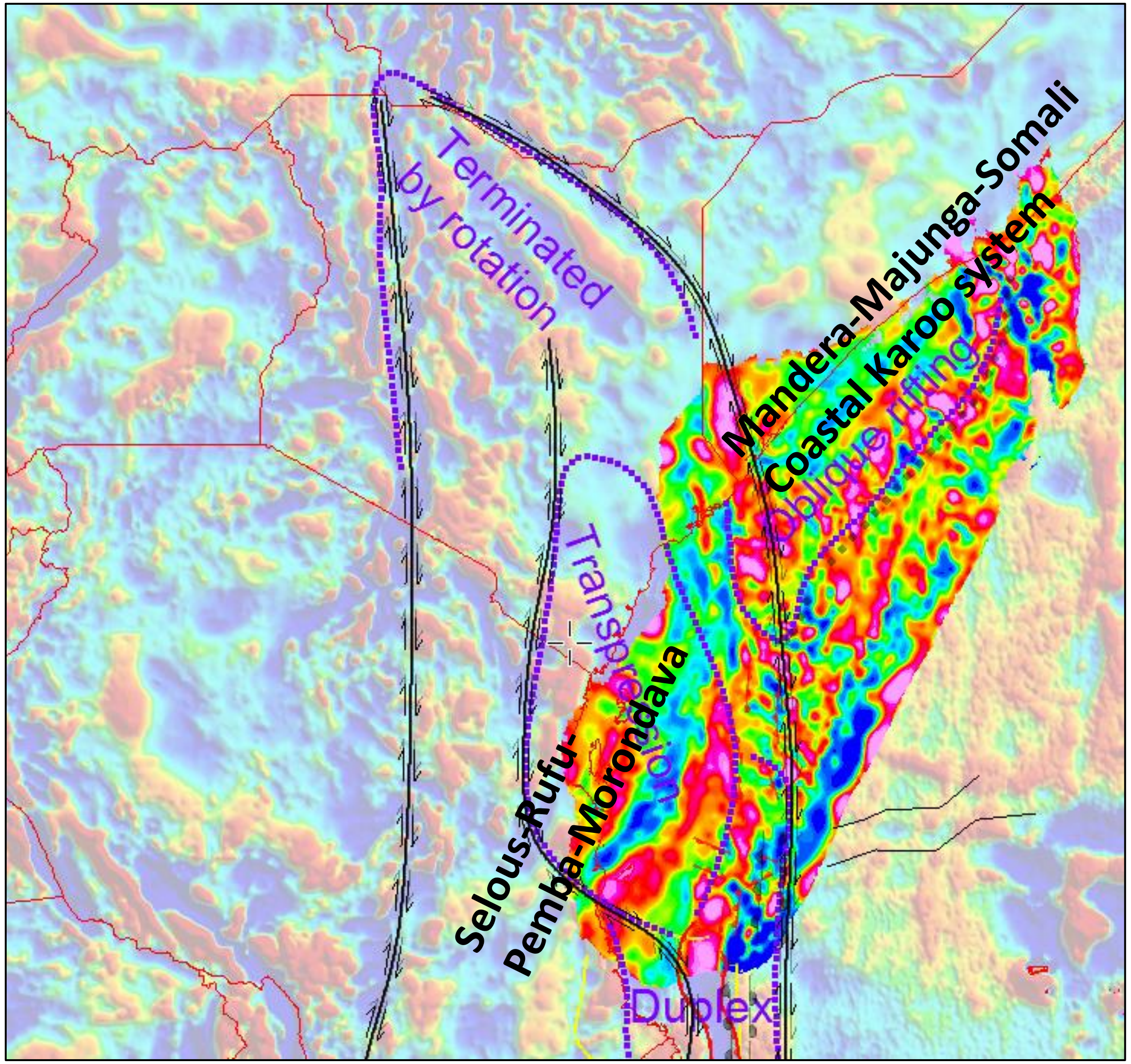
Below: The structure over Kenya Surface Geology, MoE Kenya



Karoo- extensional rifting prior to Gondwana breakup



Left: Supplemented after (**Salmaan et al , 2016**) – Aswa shear zone is a synthetic Riedel shear

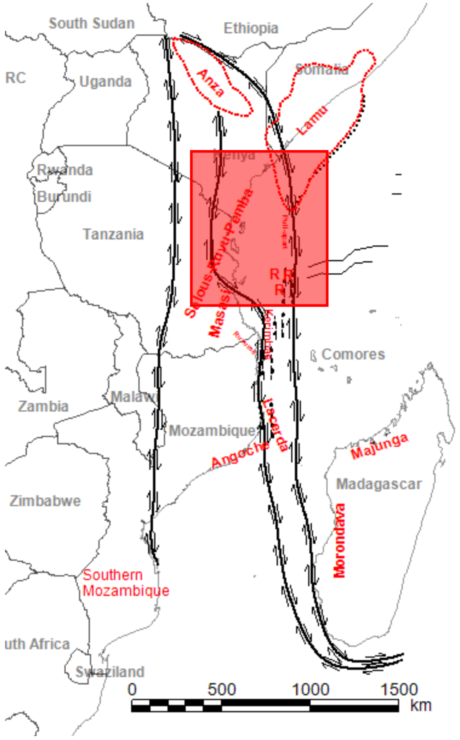


Above: Madagascar circa Gondwana breakup, Karoo syn-extensional rifting

Davie Walu & Mafia-Zanzibar-Pemba restraining bend

Compressional bend – ‘horsetail splay’, folding and synthetic sinistral strike slip faulting gives way to dextral extension east of Davie Walu Axis

Right: Decompensative gravity
With Seton magnetic chron picks



1 Pemba High

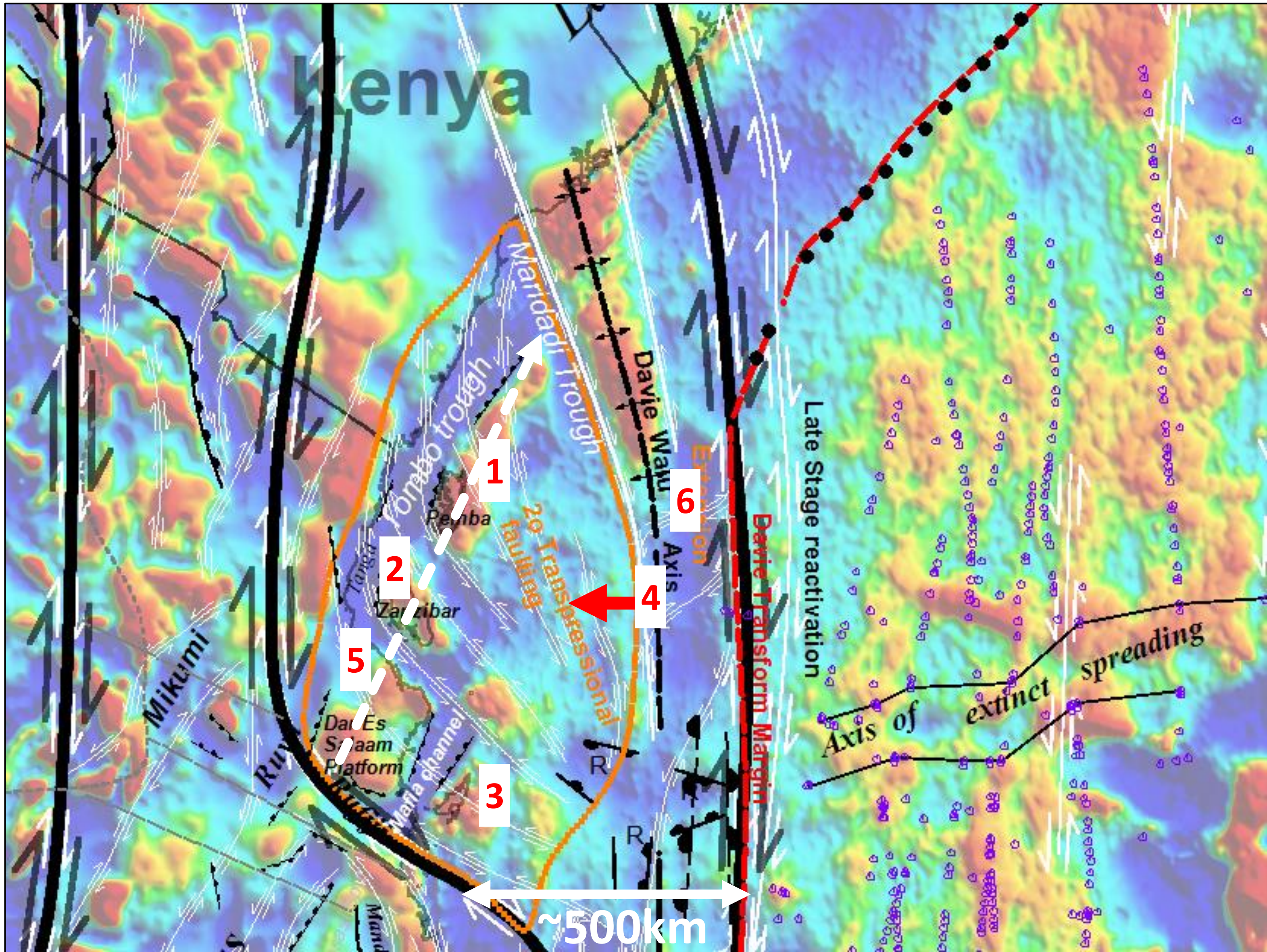
2 Zanzibar High

3 Mafia High

4 Synthetic strike slip faulting

5 Oblique fold axis correlates with seismic

6 Jurassic pull-apart



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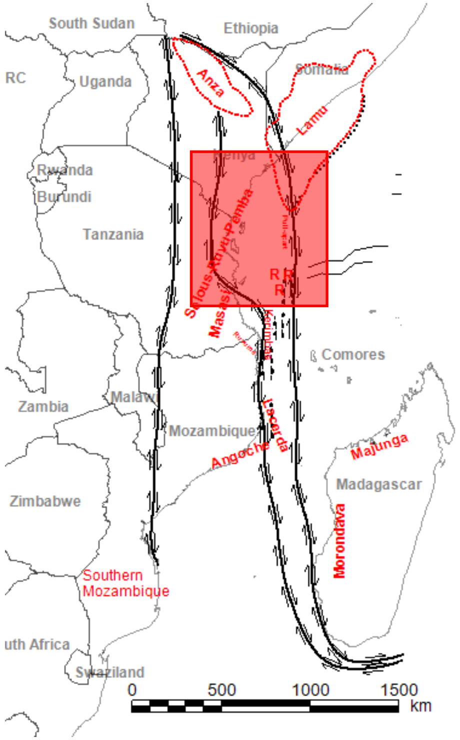
Davie Walu & Mafia-Zanzibar-Pemba restraining bend

Compressional bend – 'horsetail splay', folding and synthetic sinistral strike slip faulting gives way to dextral extension east of Davie Walu Axis

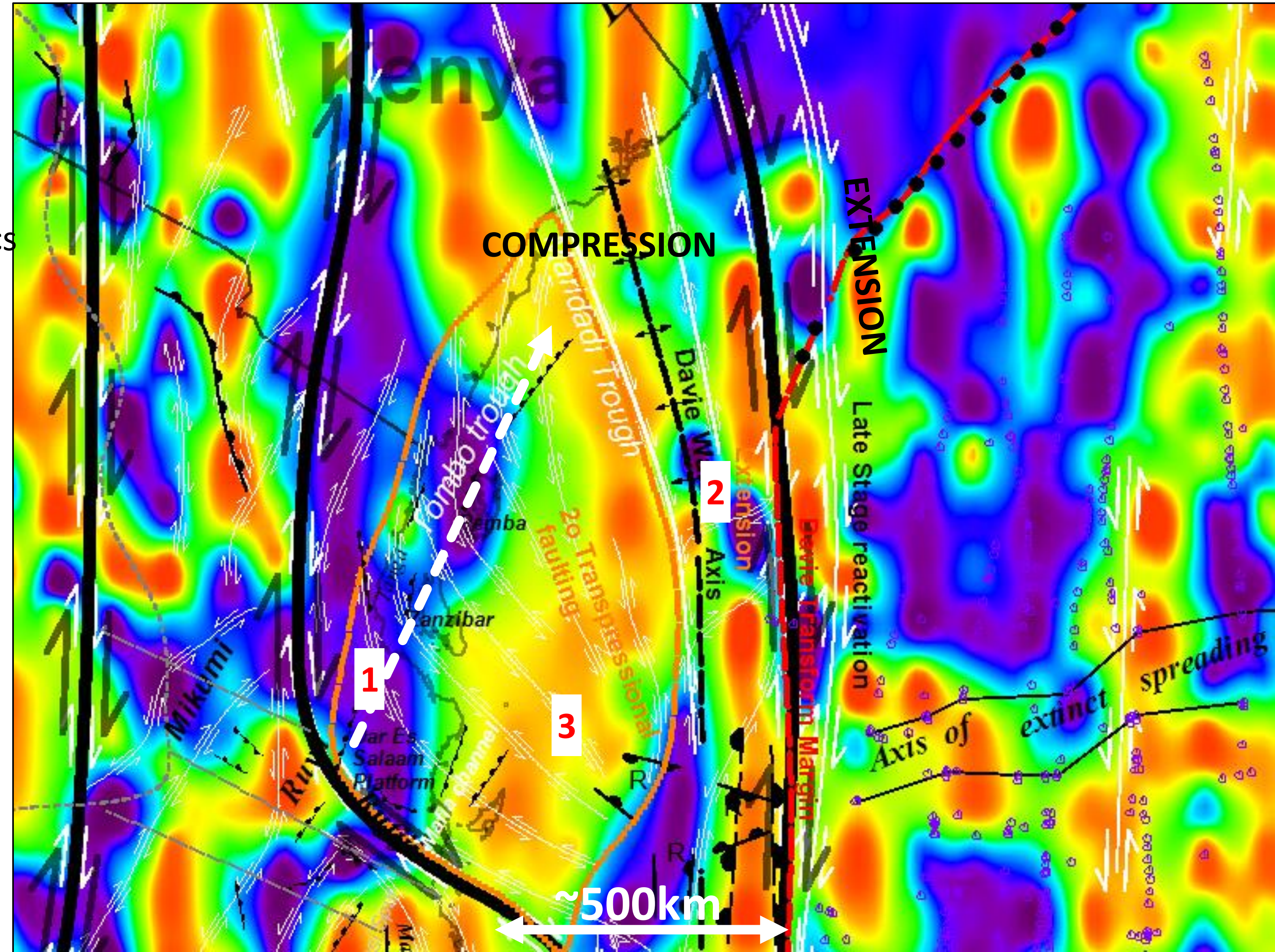
Right: IGRF corrected, reduced to pole magnetics



1 Antithetic fold axis deformed by later synthetic faulting

2 Jurassic pull apart

3 Second order transpressional synthetic faulting



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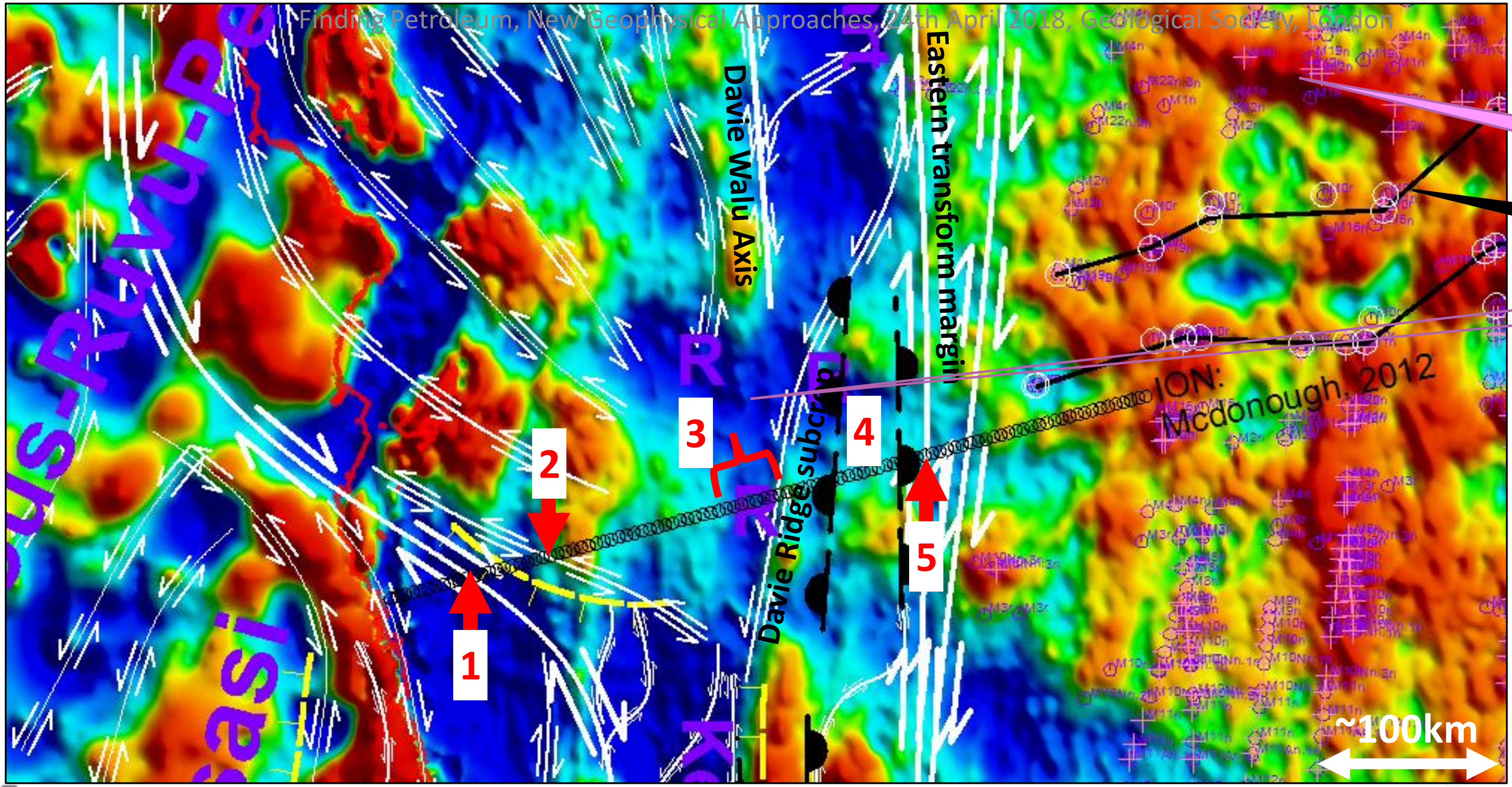
Offshore Tanzania, failed rifting and onset of early extensional duplexing

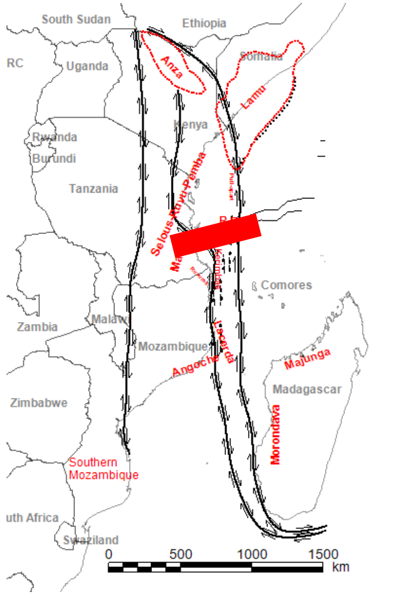


Left: Decompensative gravity

Published magnetic chron picks

Davis, 2016, M0 trace

Triple R failed aulacogen on M0 axis



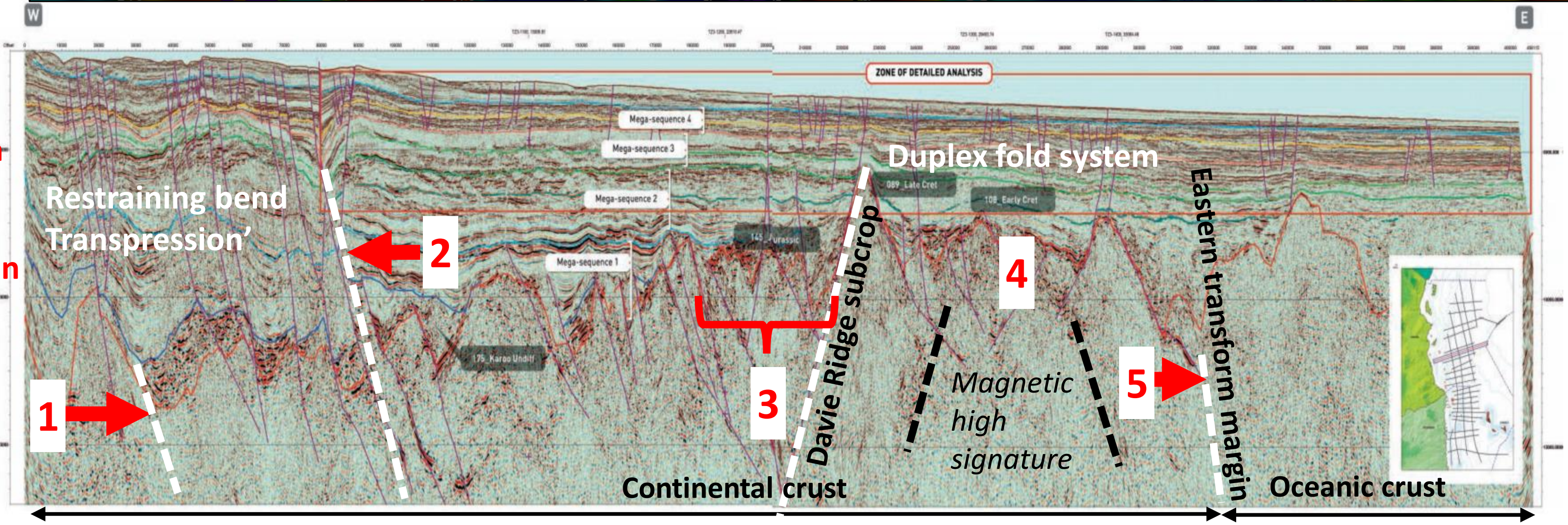
1 Transpression restraining fault

2 Transpression restraining fault

3 Failed triple R aulacogen

4 Outer high

5 Eastern Transform Margin



Left: ION line: *TZ3-2700 after* **McDonough et al, 2012**

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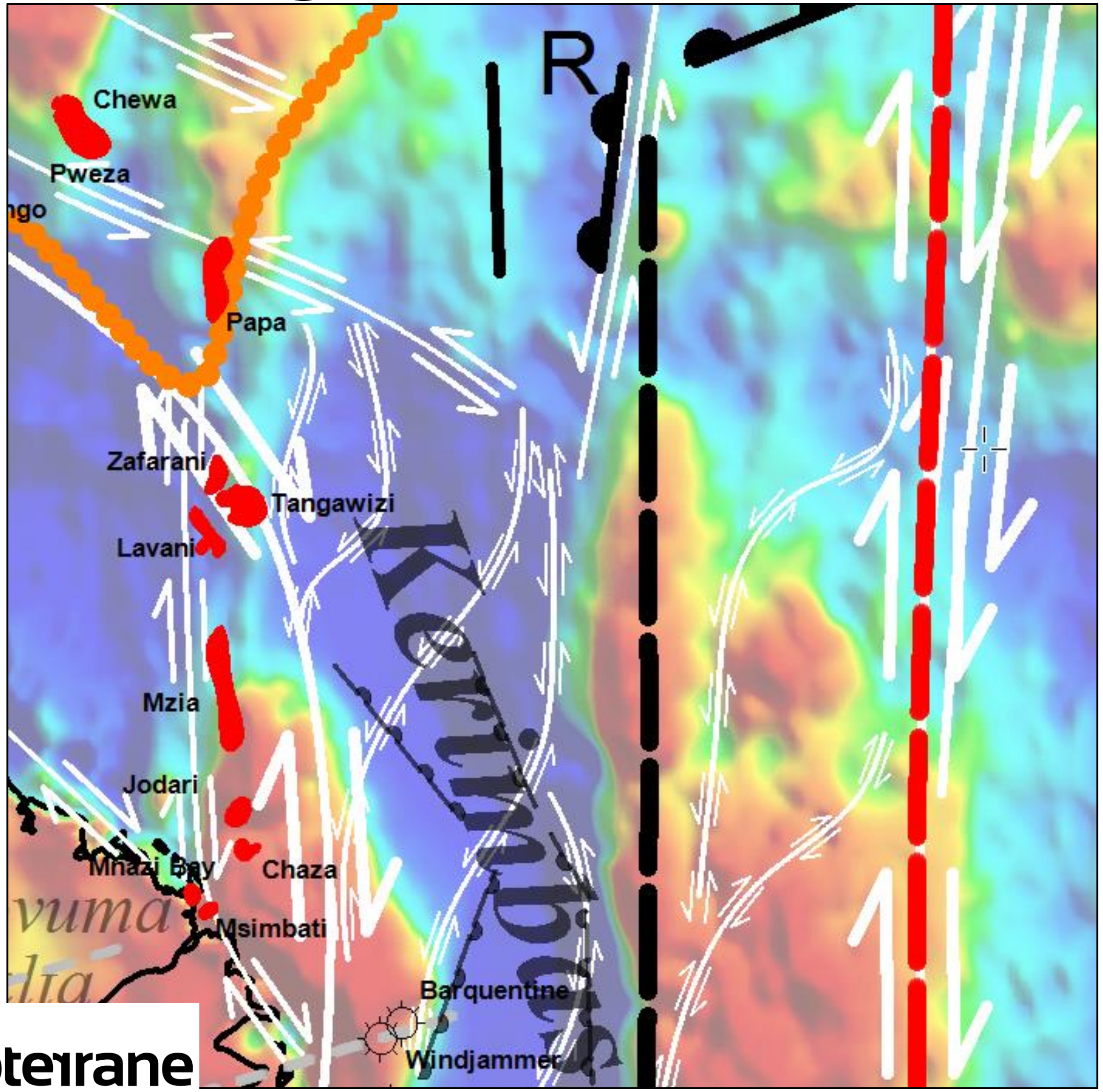
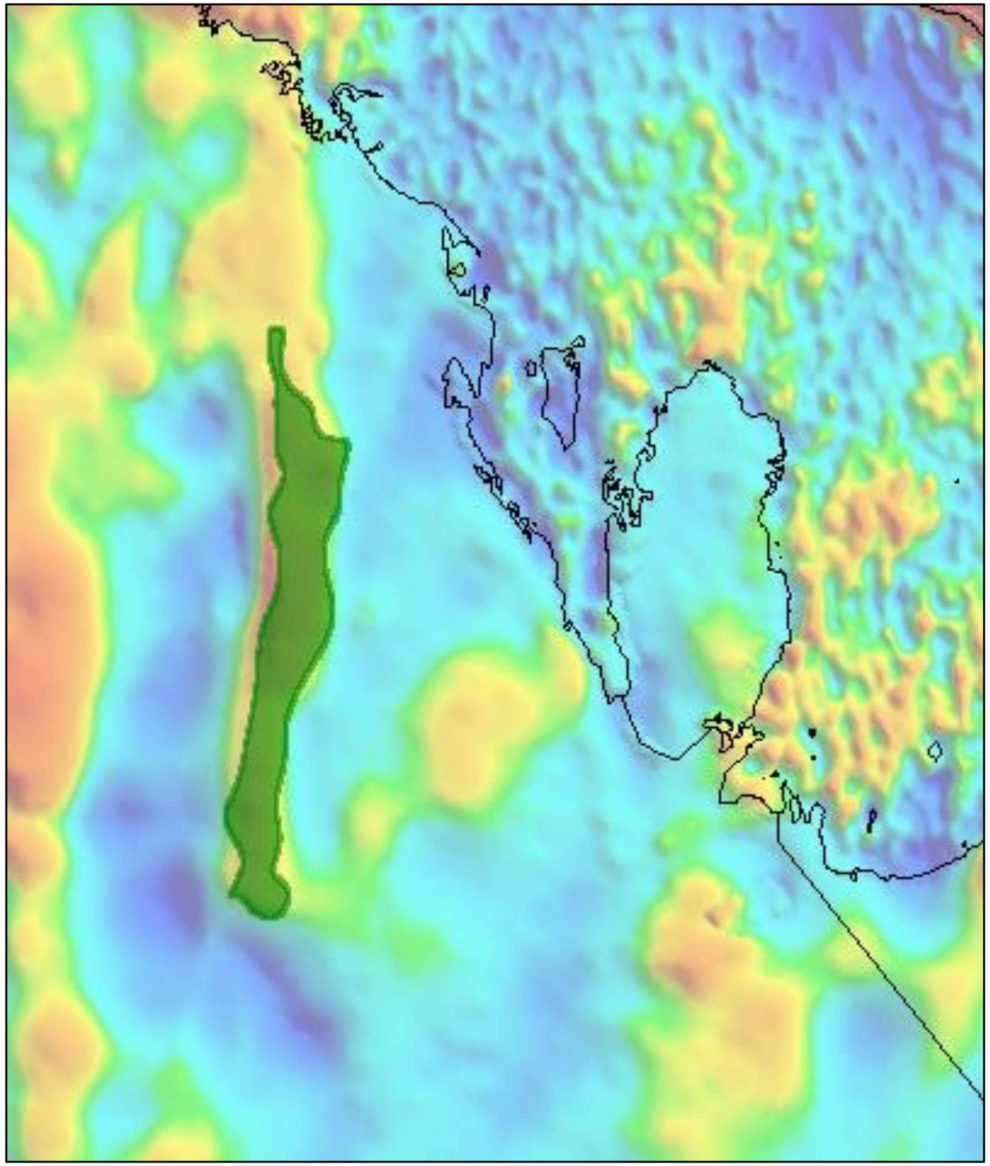
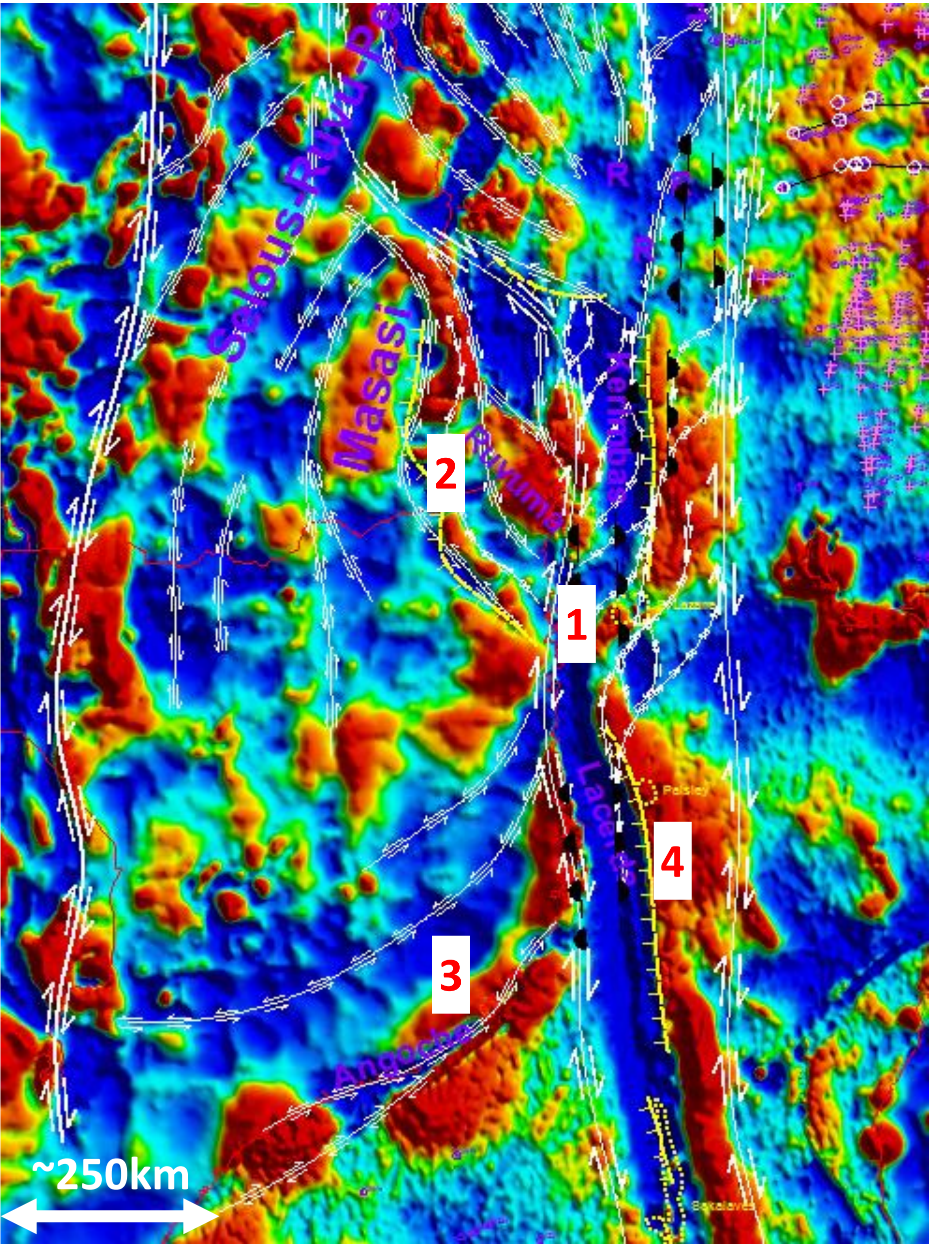
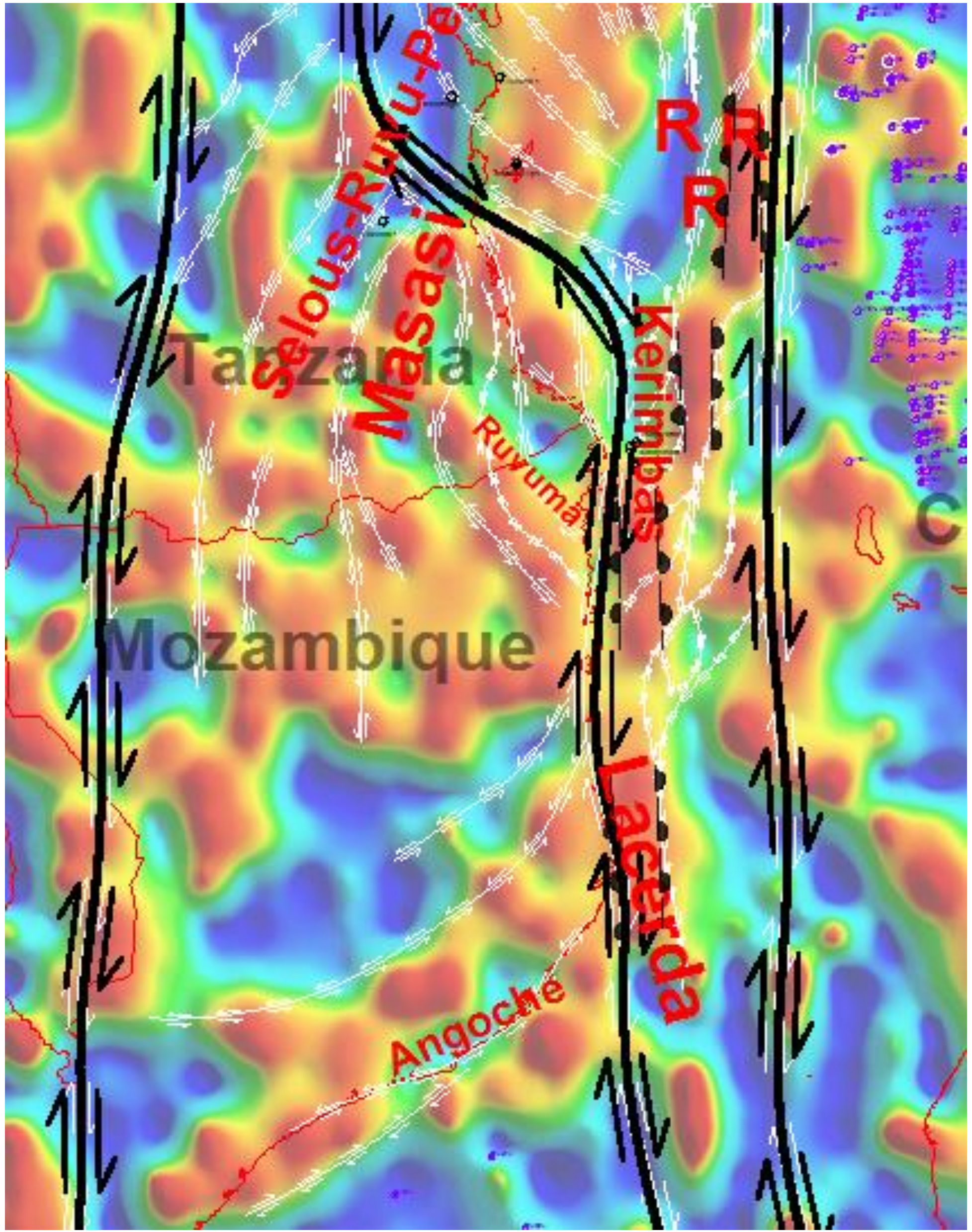
57 tcf gas– 10 Billion BOE ~50-100 Billion BO



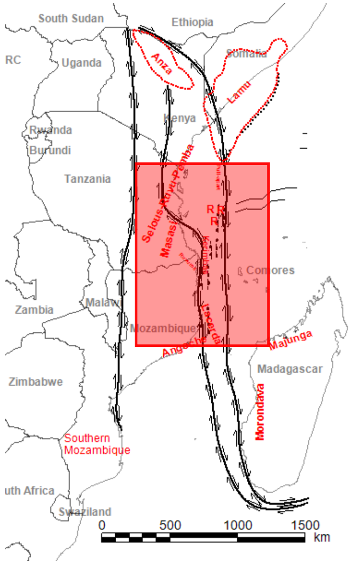


Kerimbas-Lacerda duplex to transtension





Left: Decompensative gravity
Right: EMM, IGRF corrected, reduced to pole

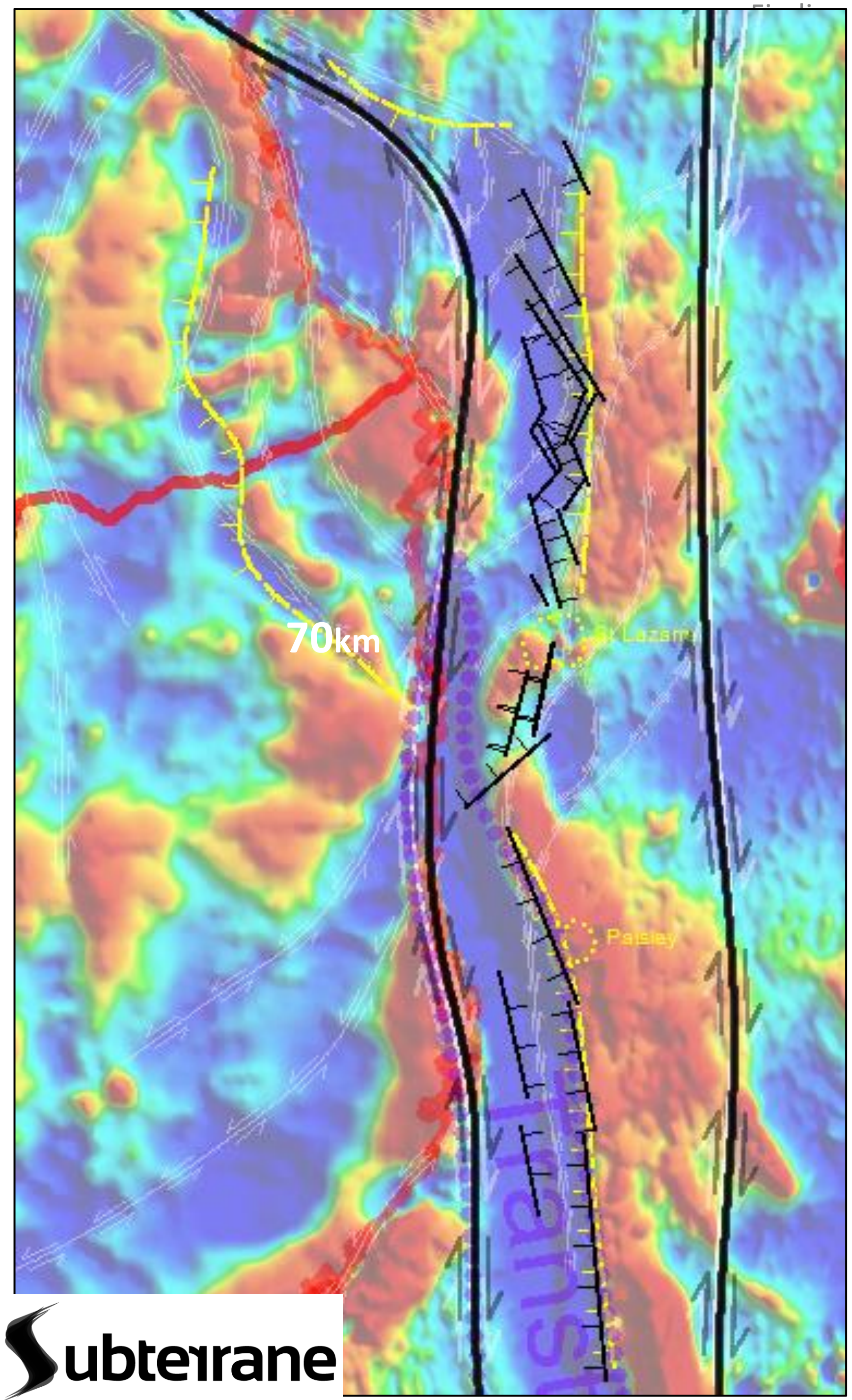


1 Southern onset of narrow transtensional zone (Lacerda basin)

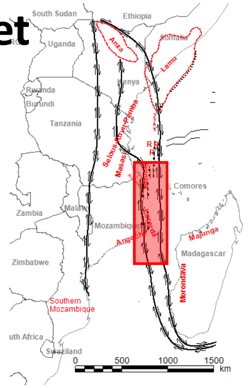
2 Rotation of Rovuma

3 Angoche pull-apart, antithetic fault zone

4 Offshore Tertiary uplift - easterly bound by deep basement blocks, form bathymetric ridges (yellow lineaments) binds Davie Ridge to east

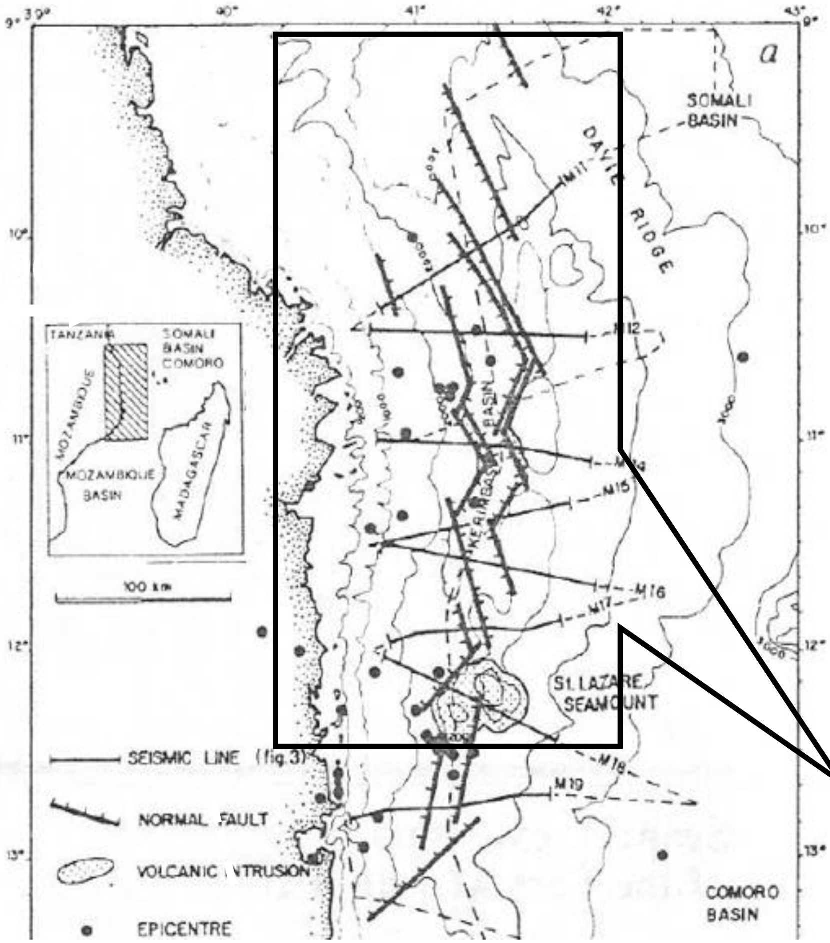


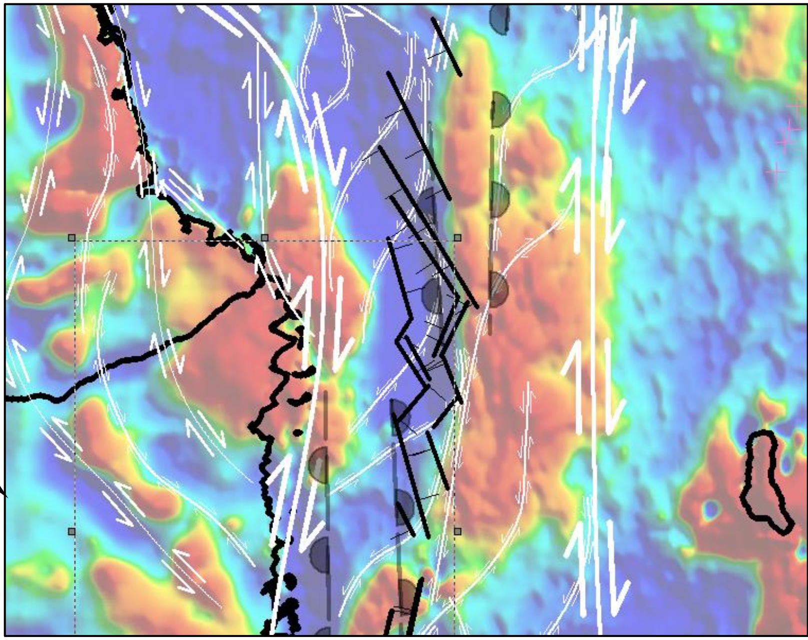
Right and below: Mougenot et al, 1986 mapped en echelon synthetic Riedel shears, these are related to reactivation, within the corridor as can be seen they straddle the bathymetric ridge



Mougenot's faults- evidence of Tertiary reactivation

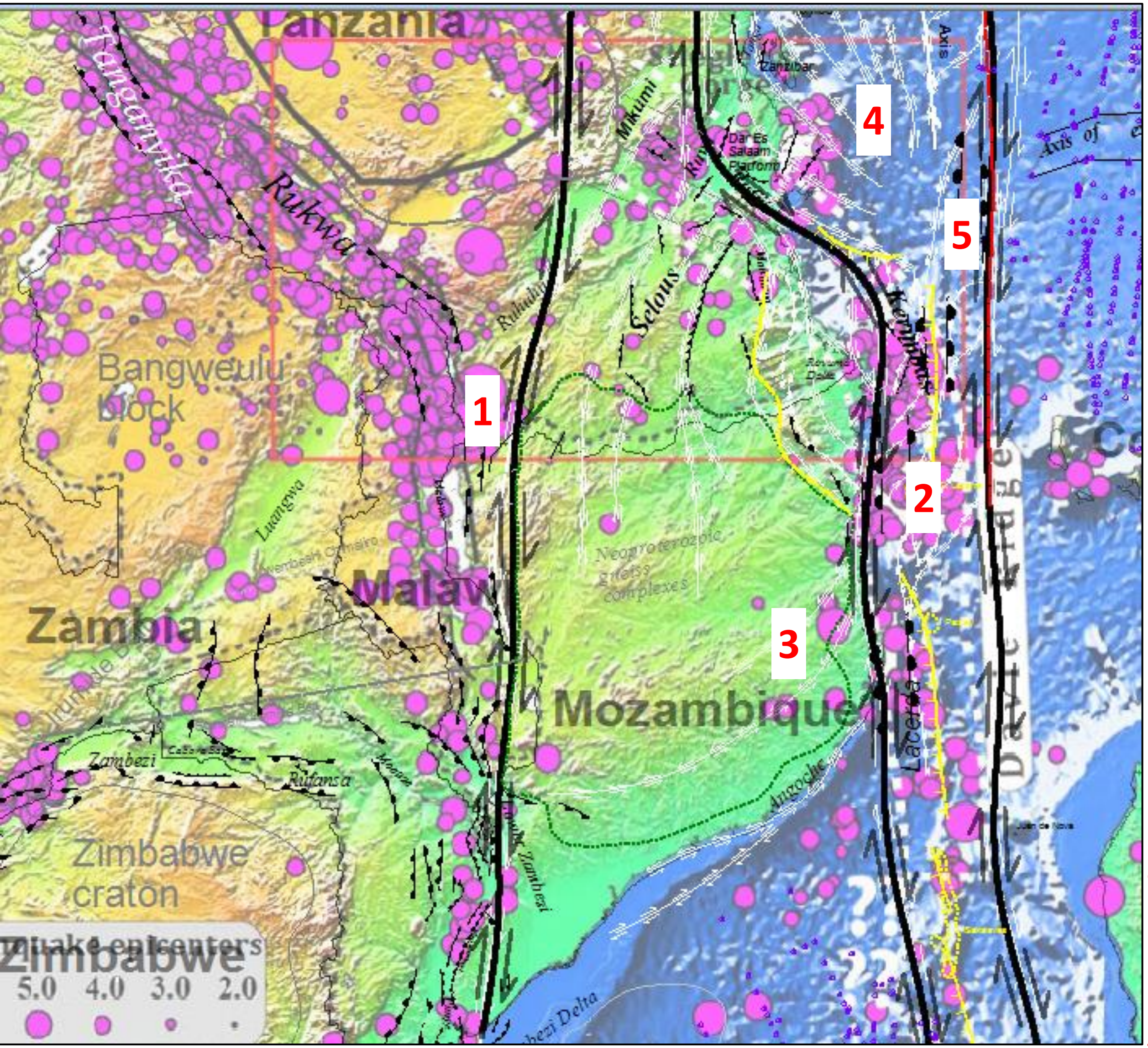
The strike slip corridor, in extension, narrows, and south of St Lazarre seamount transitions from the duplex system to a narrow, deep, extensional system, bound to the east by the tightly folded Davie Ridge.





EAST AFRICA OIL GROUP

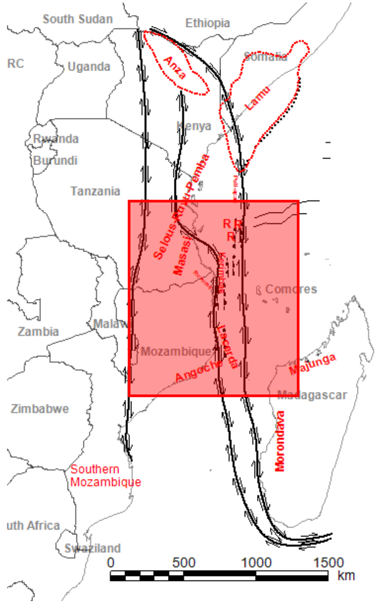
Seismicity locked by strike slip corridor



Modified after Mulibo et al, 2016

Left: Seismicity (Mulibo et al, 2016) over decompensative gravity

The transform margin and associated strike slip zones have influenced the development of later rift systems. Focal solutions for the seismicity support the strike slip fault configuration, *below right* (refer Mulibo et al, 2016) and indicate the transform margin is still active.



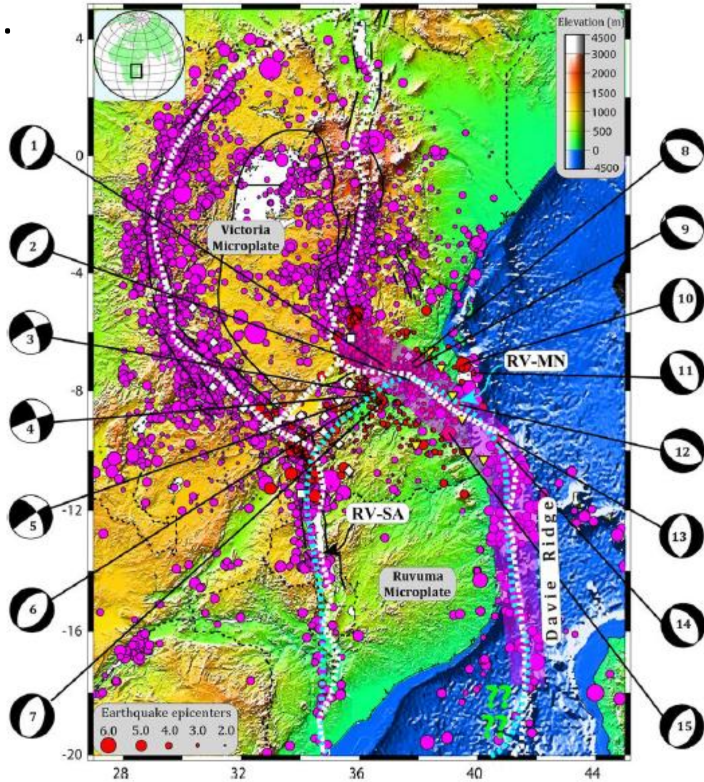
1 Western branch of East African Rift System, and associated seismicity, locked by western intraplate strike slip

2 Transform margin locks “offshore EARS” related seismicity

3 Associated seismicity along Riedel antithetic fault

4 Seismicity associated with sinistral movement in zone of transpression

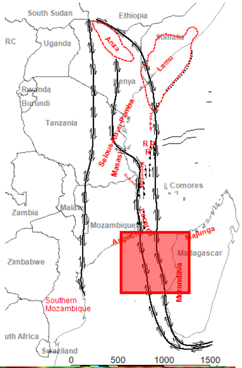
5 Present topographic ridges mark the northern extent of the offshore Tertiary uplift

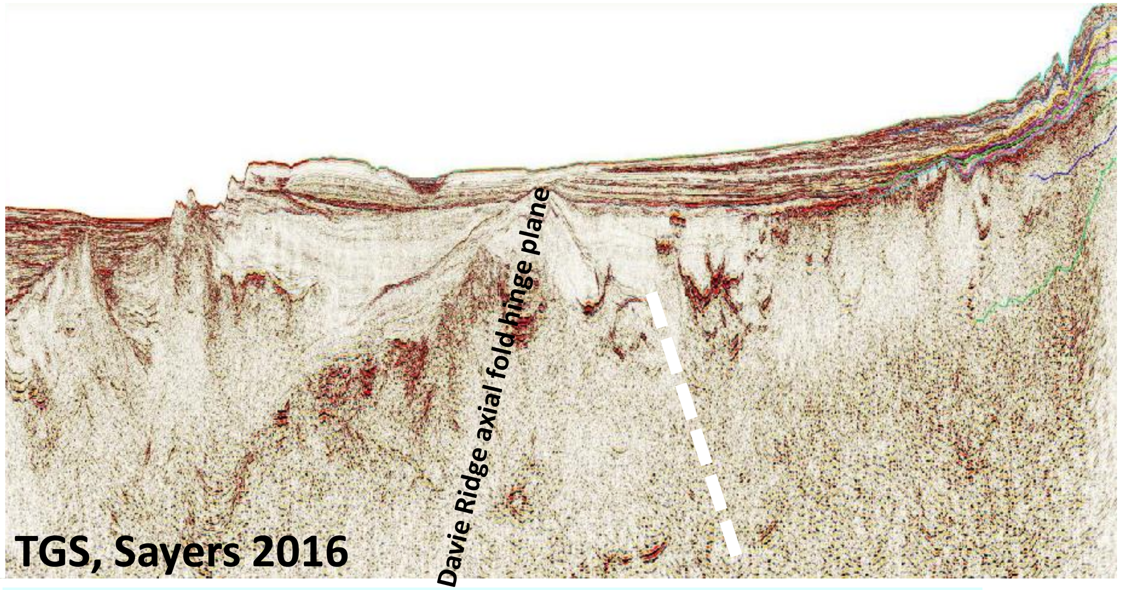


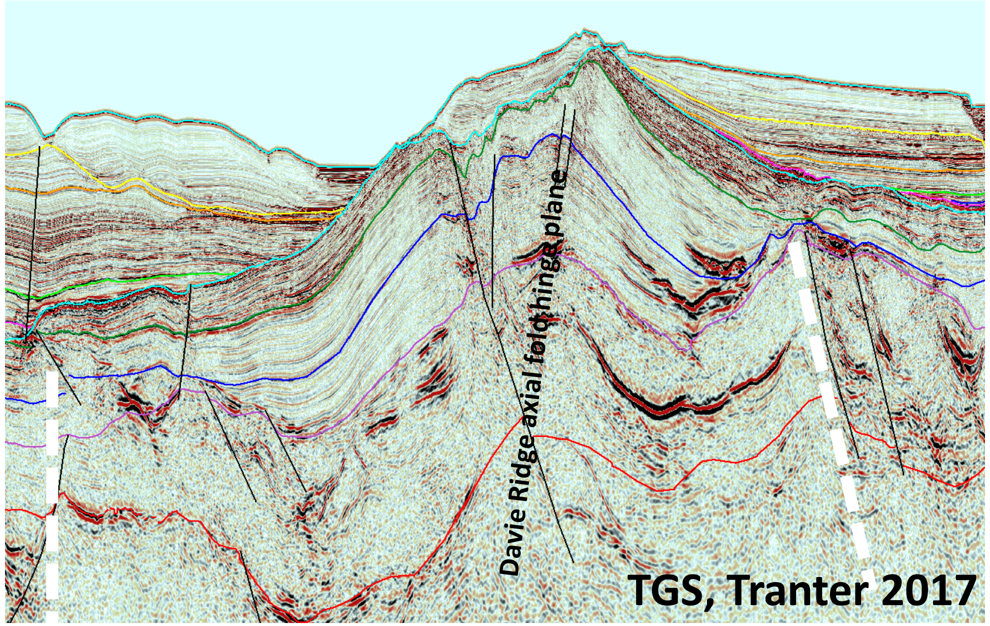
Mulibo et al, 2016

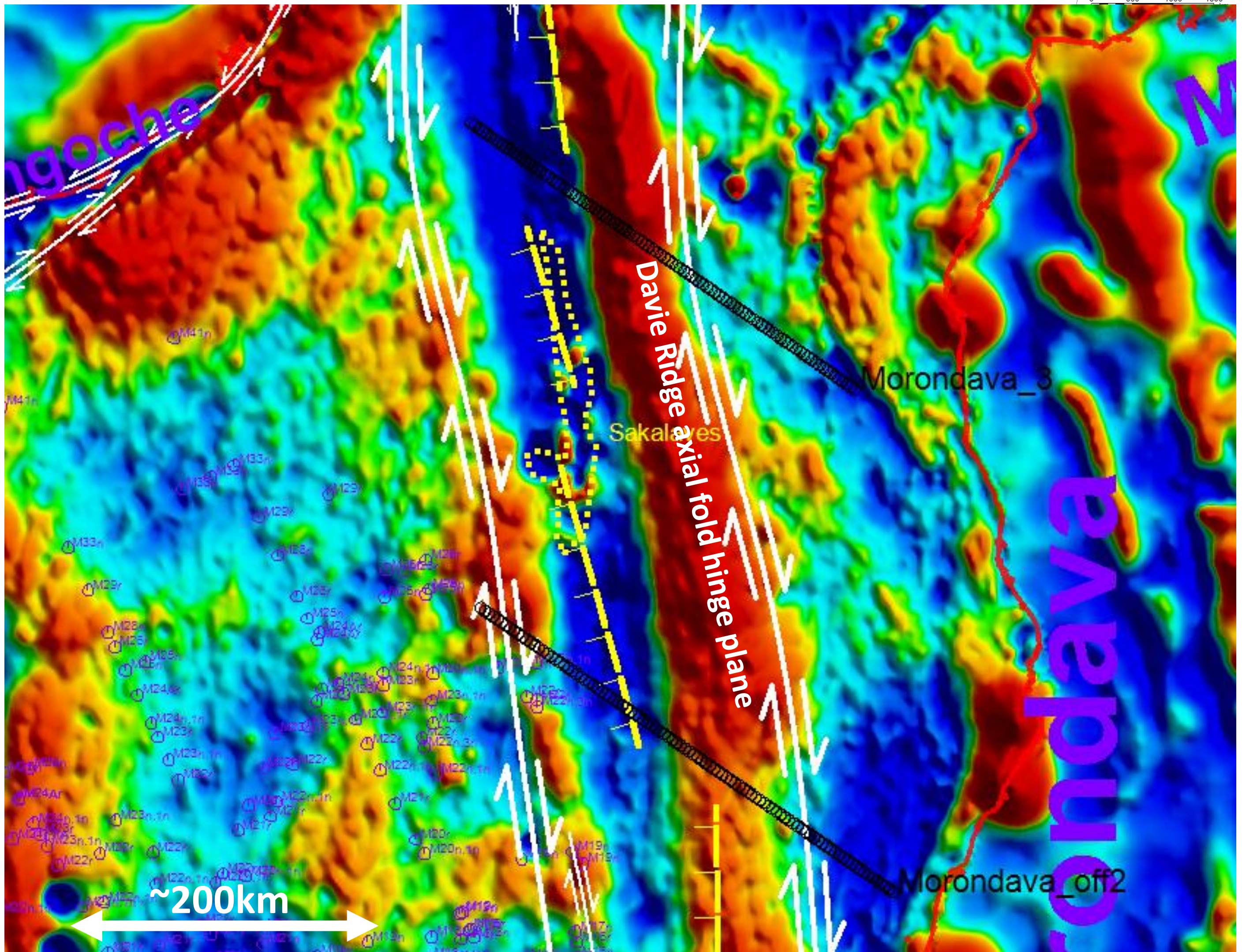
Morondava- Davie Ridge

North of Sakalaves, the TGS line shows the major fold axis of the Davie Ridge, evidence of compressional strike slip reactivation, further south Tertiary related pull-apart deformation dissipates in the transtensional zone of the strike slip corridor of the Transform margin



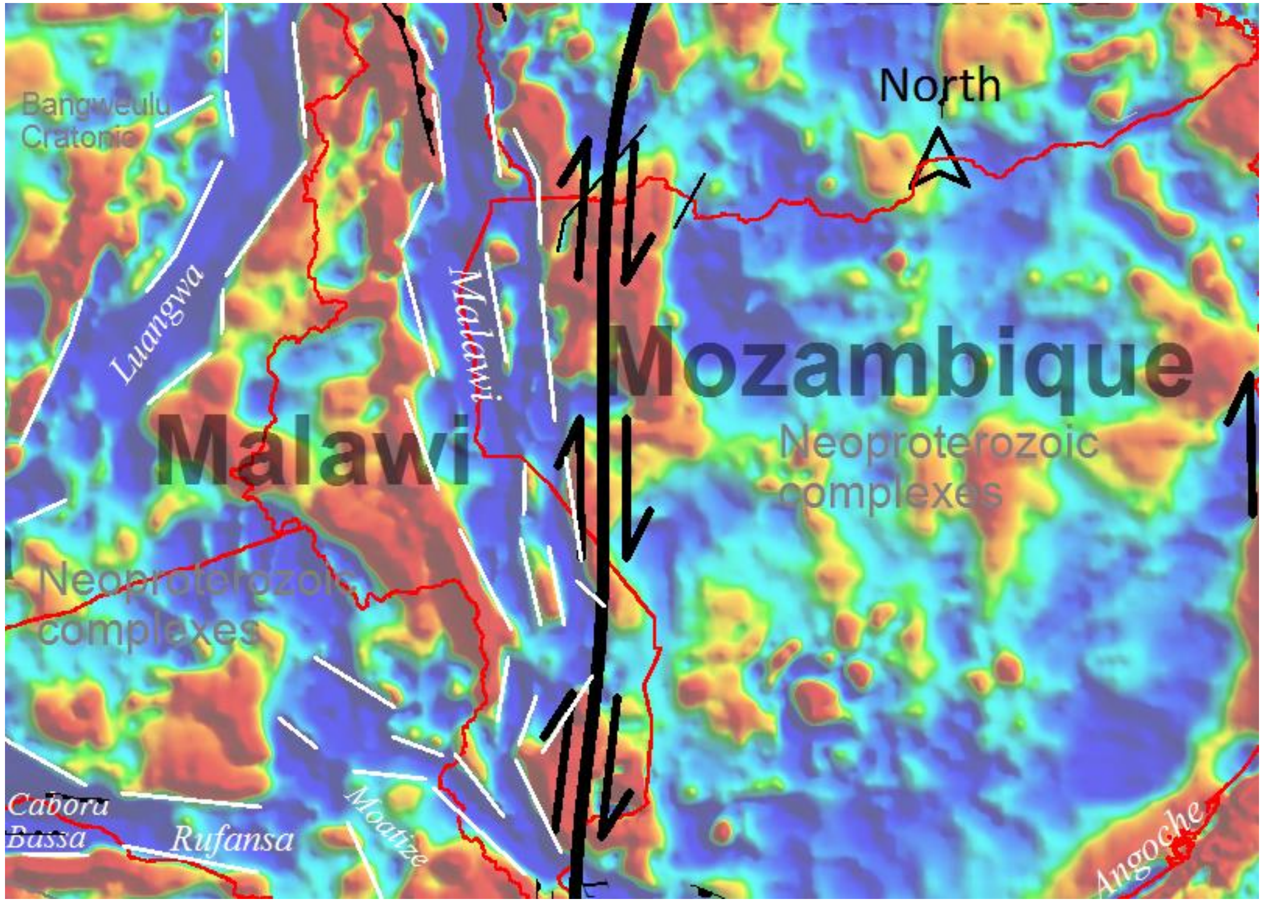




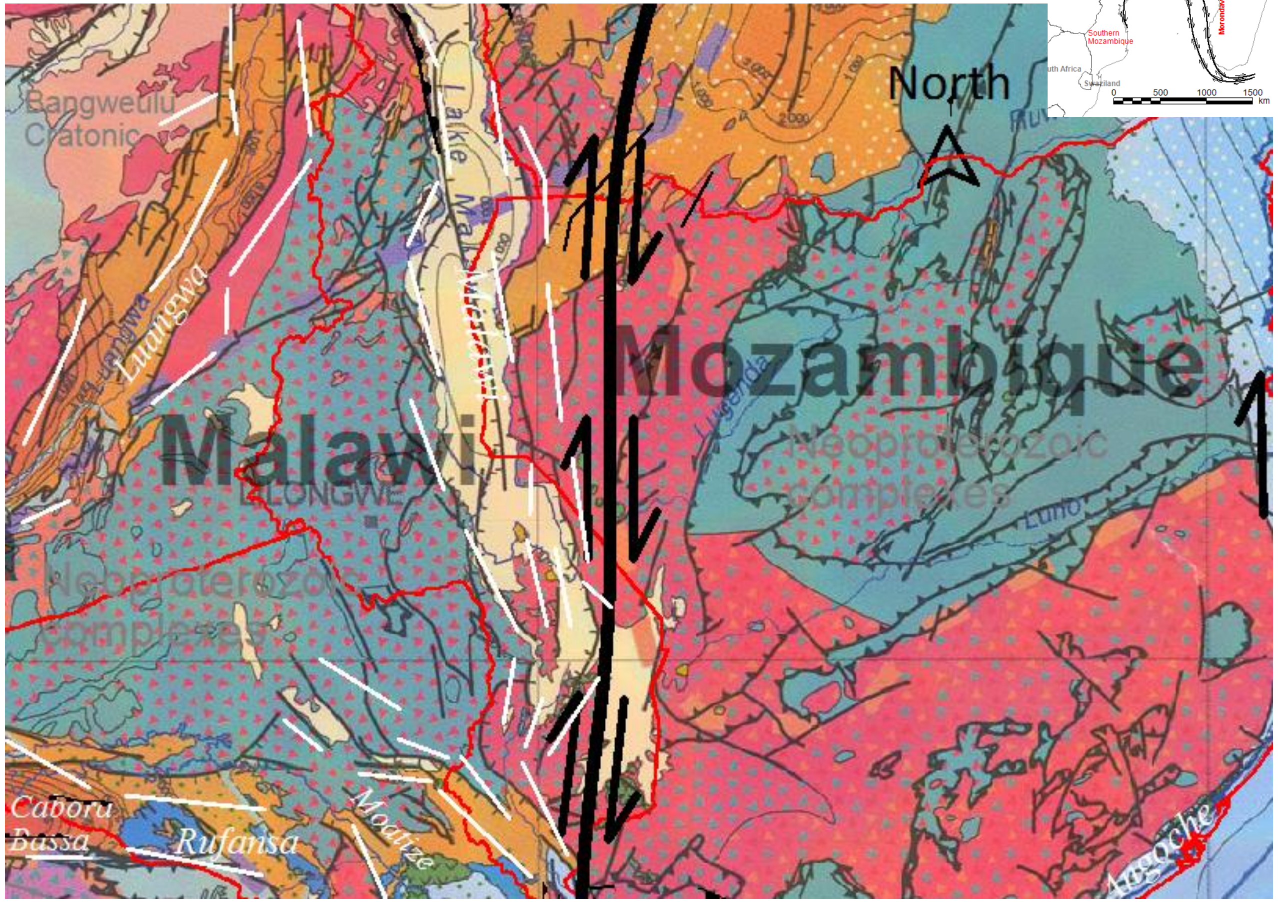


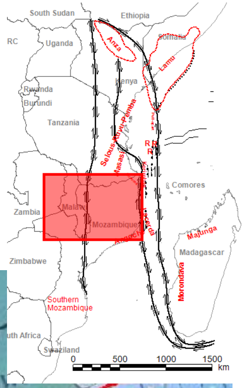
EAST AFRICA OIL GROUP

Onshore Karoo-EARS real geological correlations



Decompensative gravity with Karoo and EARS rifting bound at depth to the western margin of strike slip corridor

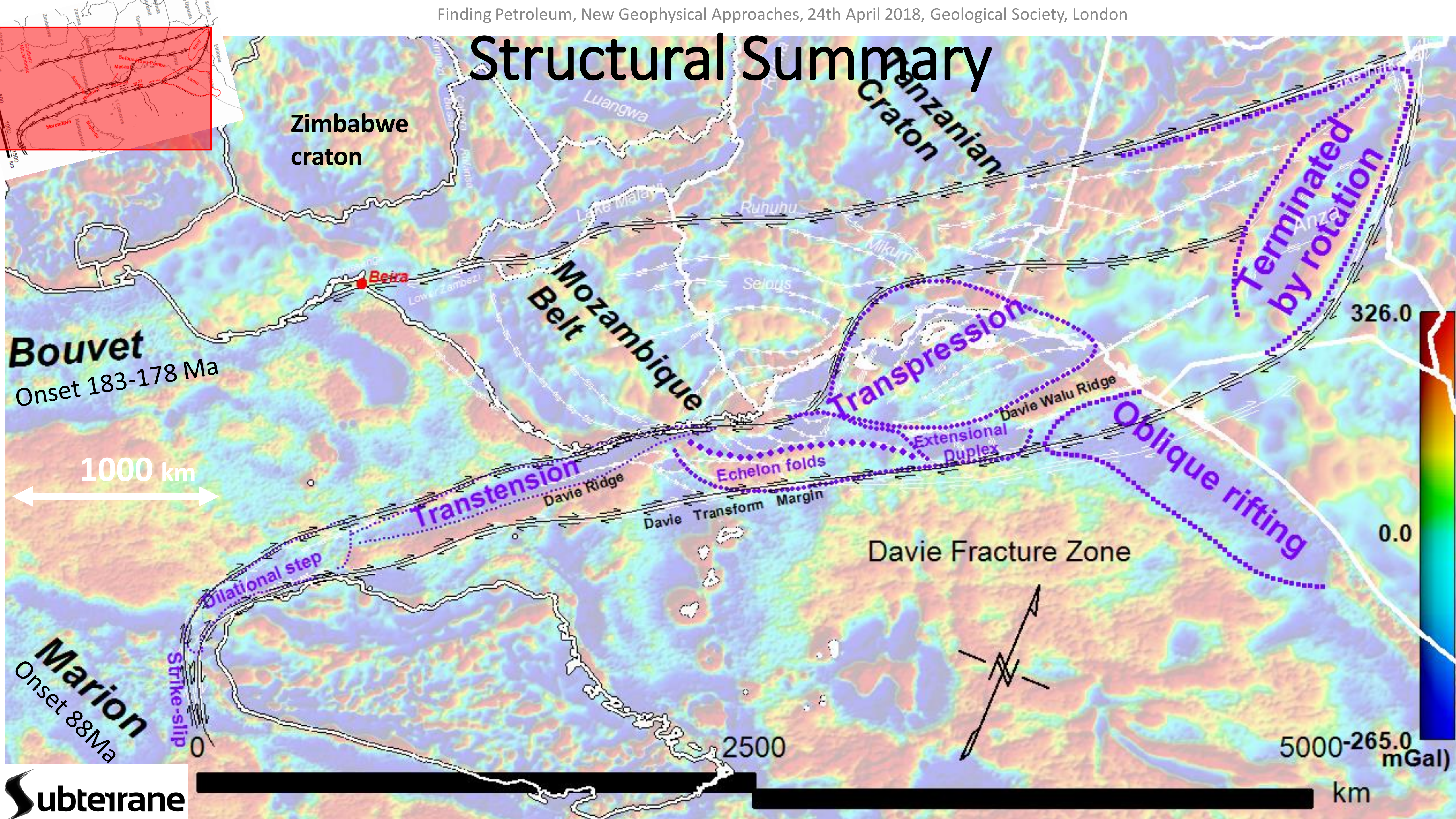




Tectonic map of Africa, CGMW, Milesi et al 2010

Subterrane

Structural Summary



Subterrane

Conclusions

Correctly processed and derived potential fields data will be:

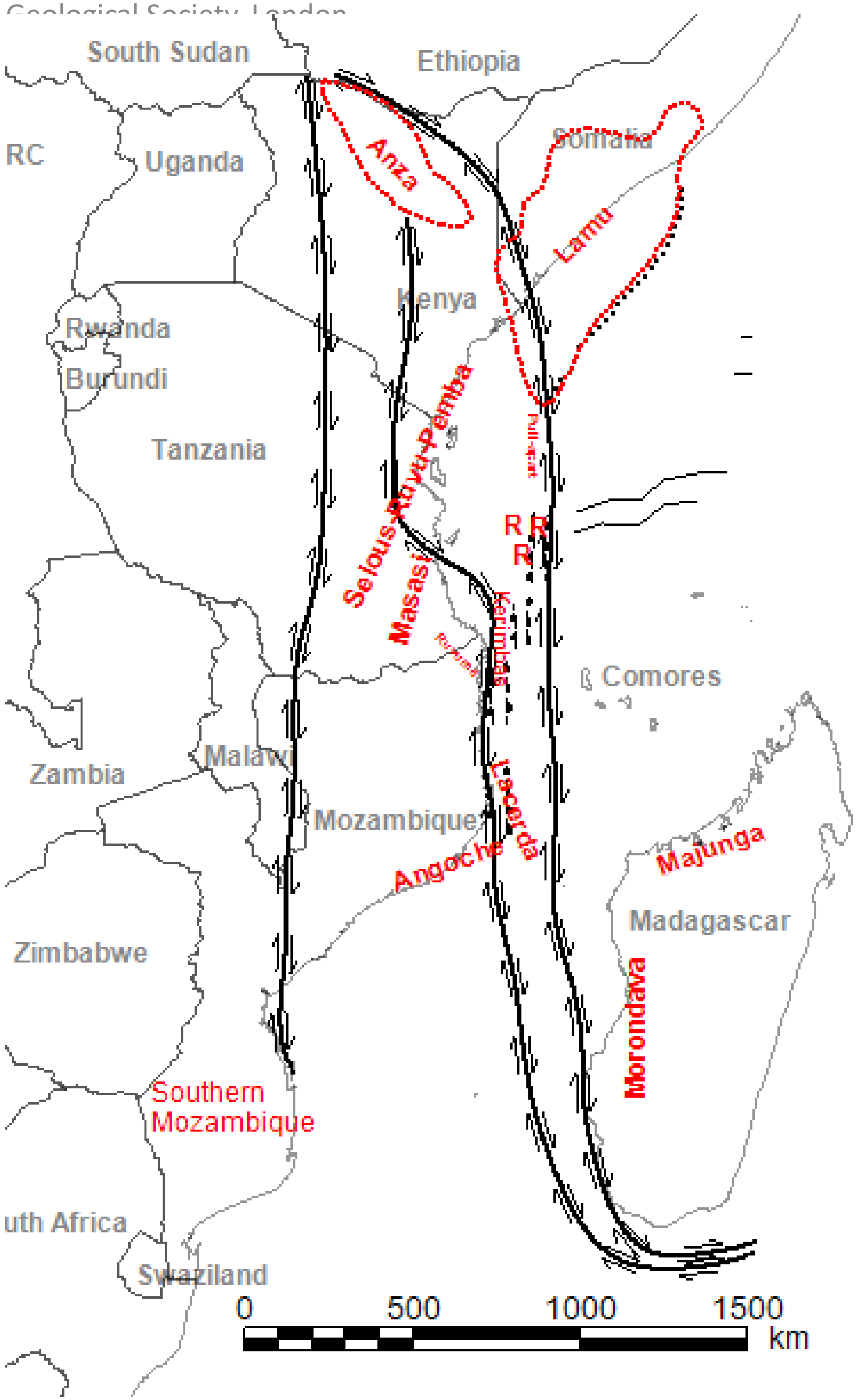
- **consistent between reliable data sources, given spatial coverage and sampling**
- **unequivocally correlative to seismic structures**
- **provide evidence of real geological structure**

…without parametric modelling, or interpolation of artificial and low signal/noise anomalies

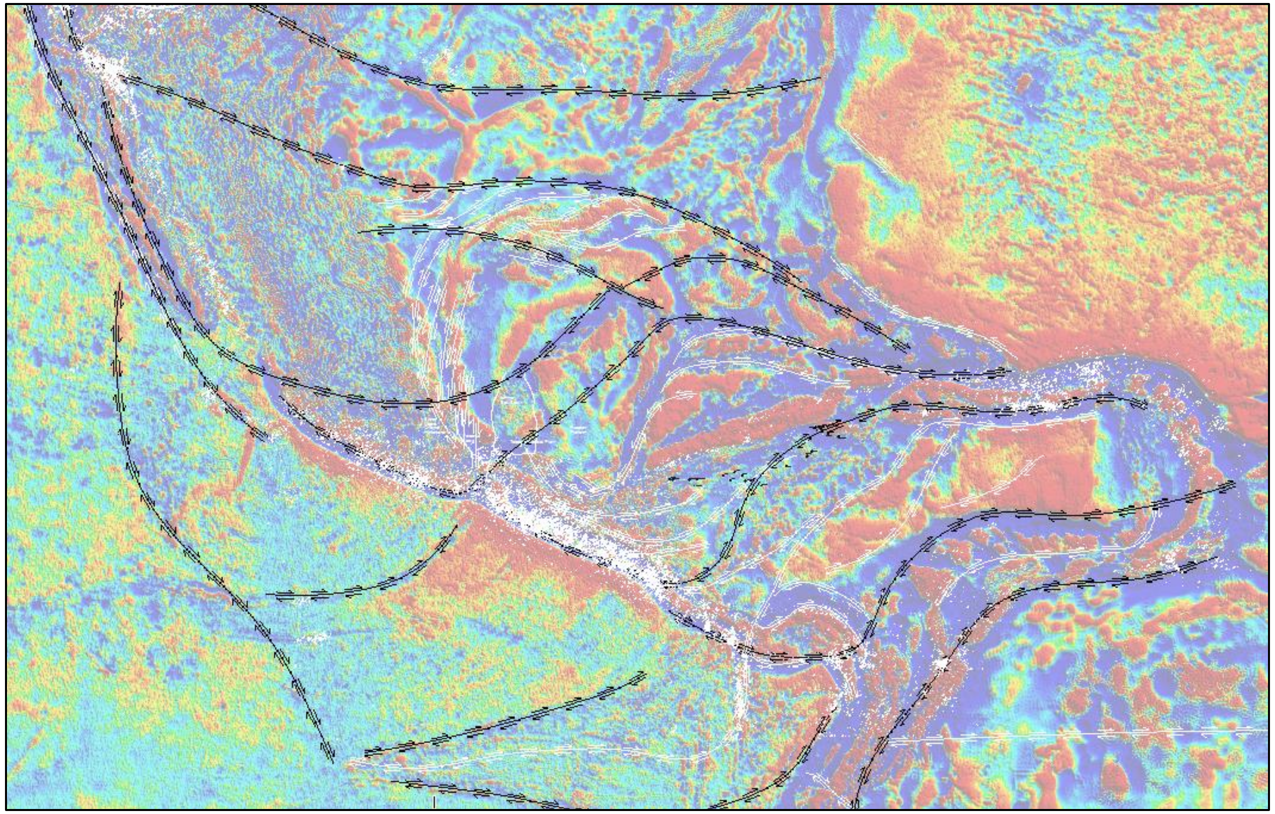
(of course 3d constrained modelling still has its purposes)

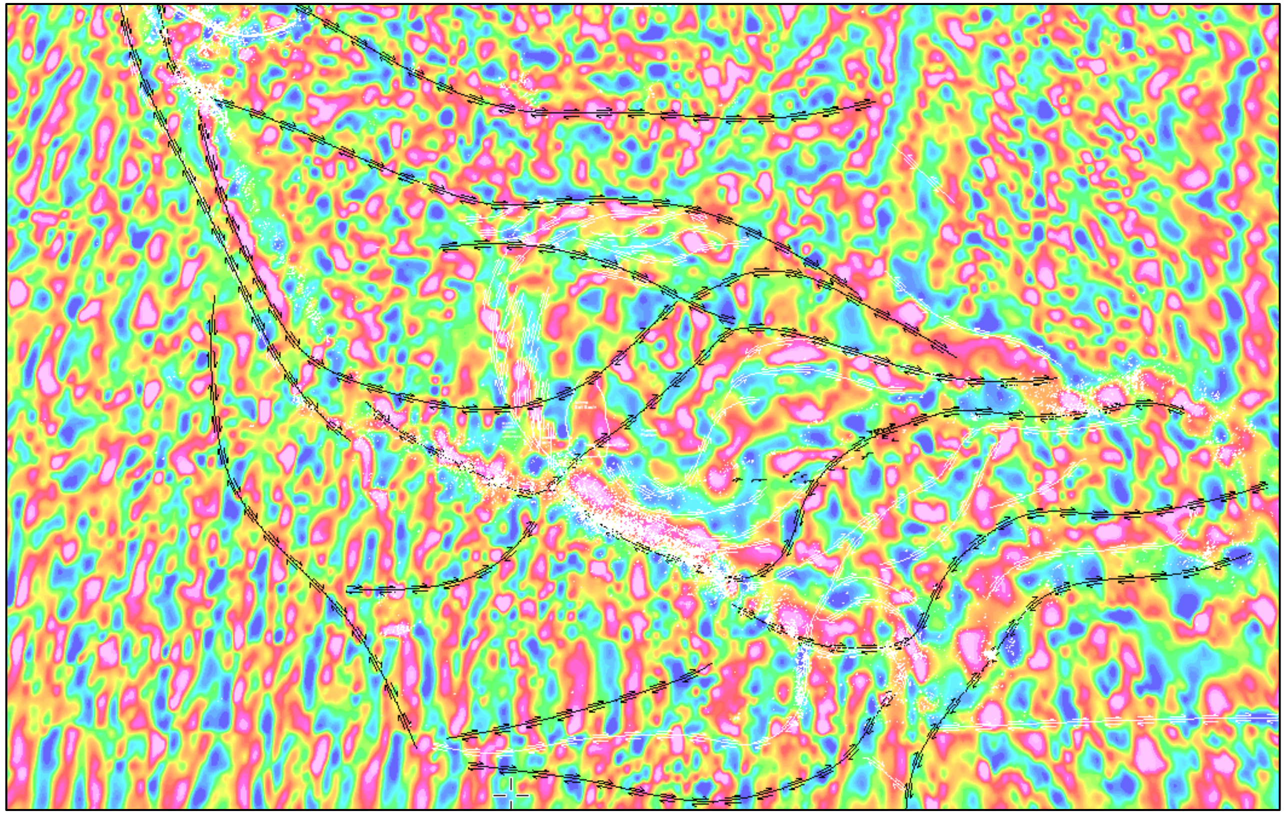
Provides a robust and regionally consistent structural framework to assess basin evolution

Further examples…



San Andreas to Panamanian subduction under Colombia – evolution of strike slip tectonics at a destructive margin





Present day structural framework attests to mobile Chortis and the tectonic evolution of the Caribbean plate (work in progress)

Storti et al, 2003 - On intraplate strike slip tectonics: ***during convergence, they help to transfer major displacements deep into the plate interiors.***

Subterrane

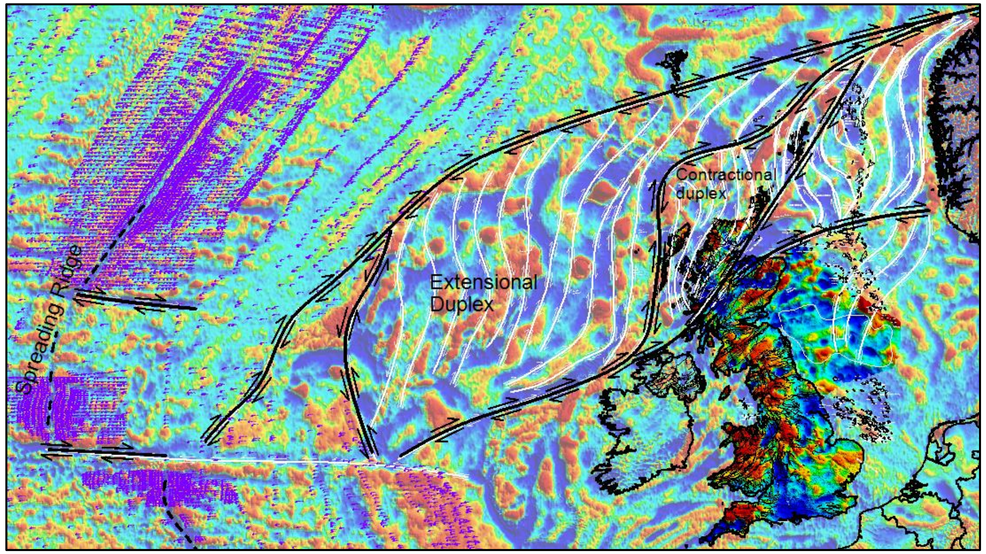
UK Continental Shelf at a constructive margin

Strike slip termination at transform fault in Central Atlantic

Possibly extends significantly further east and south…

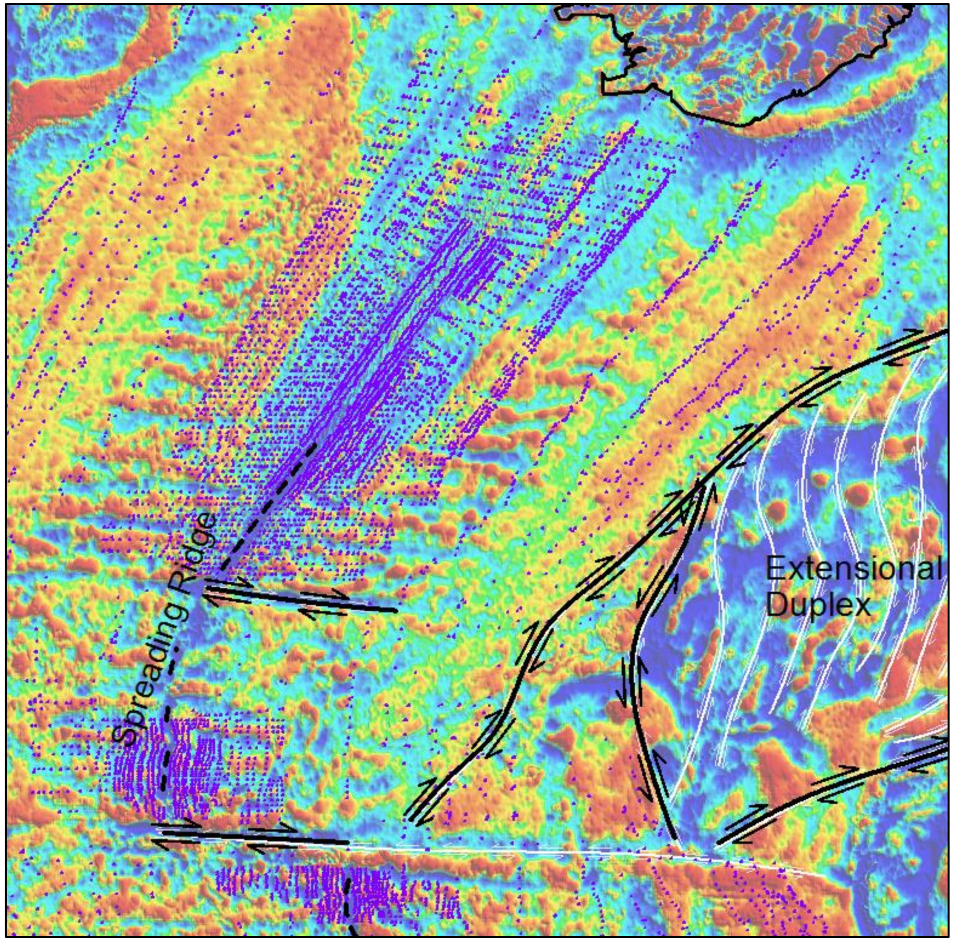
Correlative strike slip fault offsets, transform margin, crustal extension, and oceanic boundary

Storti et al, 2003 - On intraplate strike slip tectonics: *"During divergence, they act as transfer zones that segment rifts, passive continental margins and, ultimately, oceanic spreading ridges… form major persistent zones of apparent weakness whose influence may be felt over many hundreds or even thousands of million years."*



Above: (*Contains British Geological Survey materials ©NERC 2017)*

Incorporating onshore BGS and MNSH 2015 data overlying Sandwell et al 2014 satellite base (both Decompensative gravity). Magnetic chron picks from (Seton et al 2014) for Central Atlantic spreading



Above right: The Atlantic transform fault margin. The relationship between Wilson's transforms and strike slip tectonics on a sheared margin

Subterrane

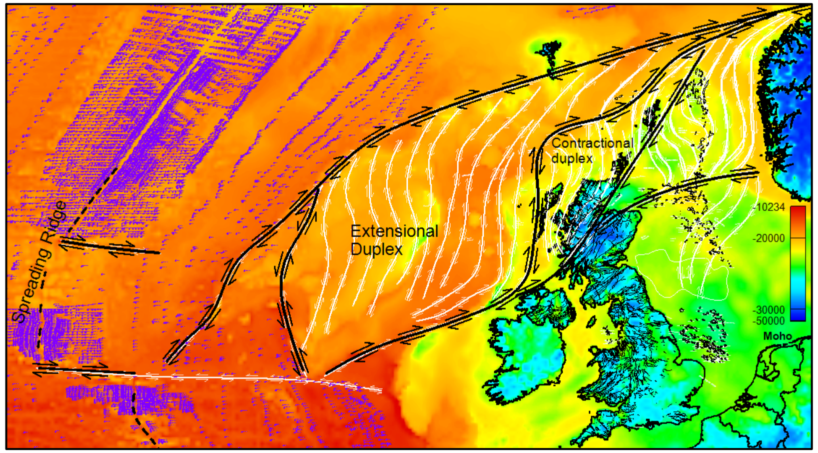
UK North Sea – dextral shear: regional strike slip tectonics

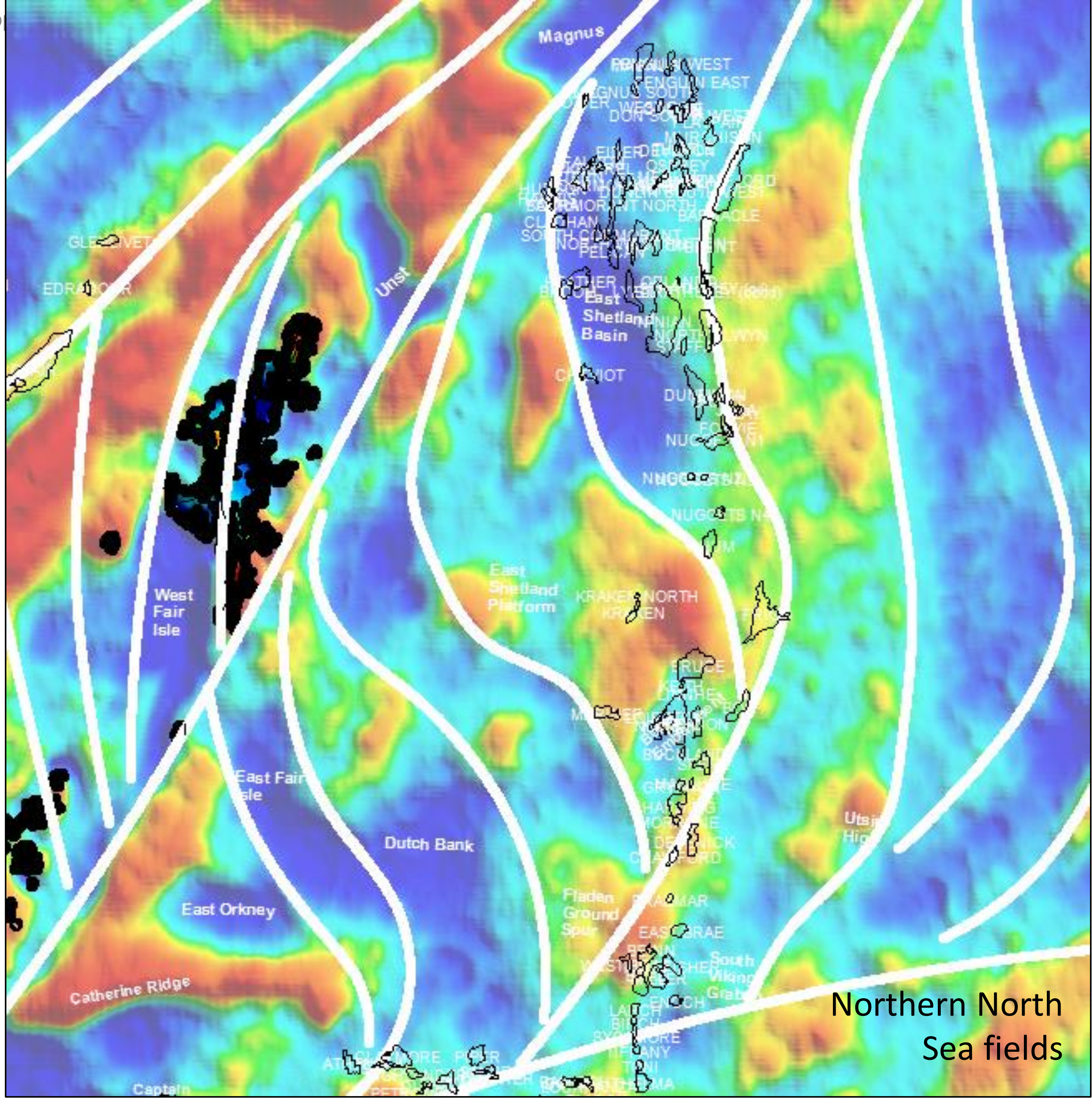
Onshore compressional to extensional transition

Terminates at the Central Atlantic oceanic crust boundary

Work in progress

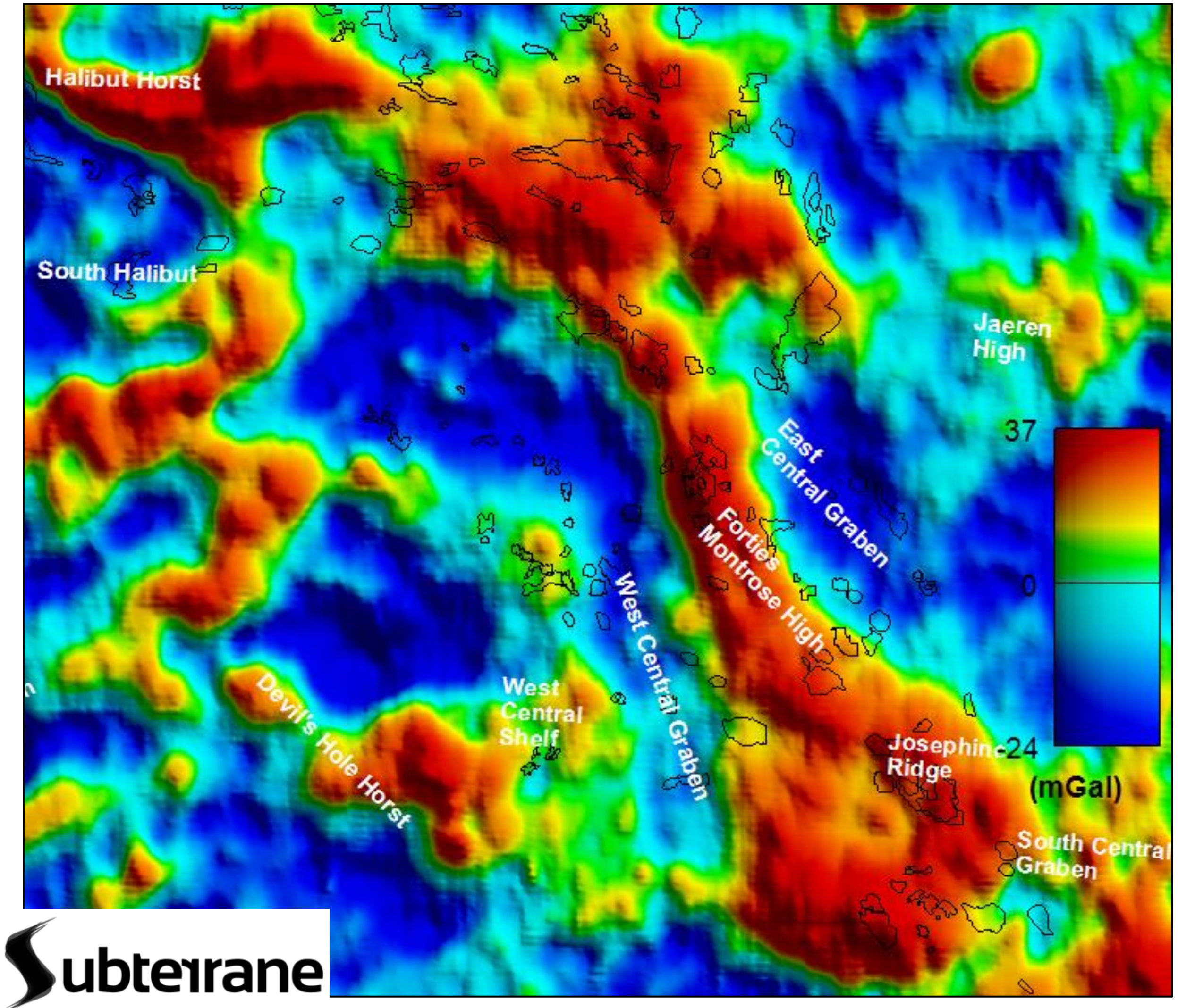
Below: Gravity derived Moho and magnetic chron picks



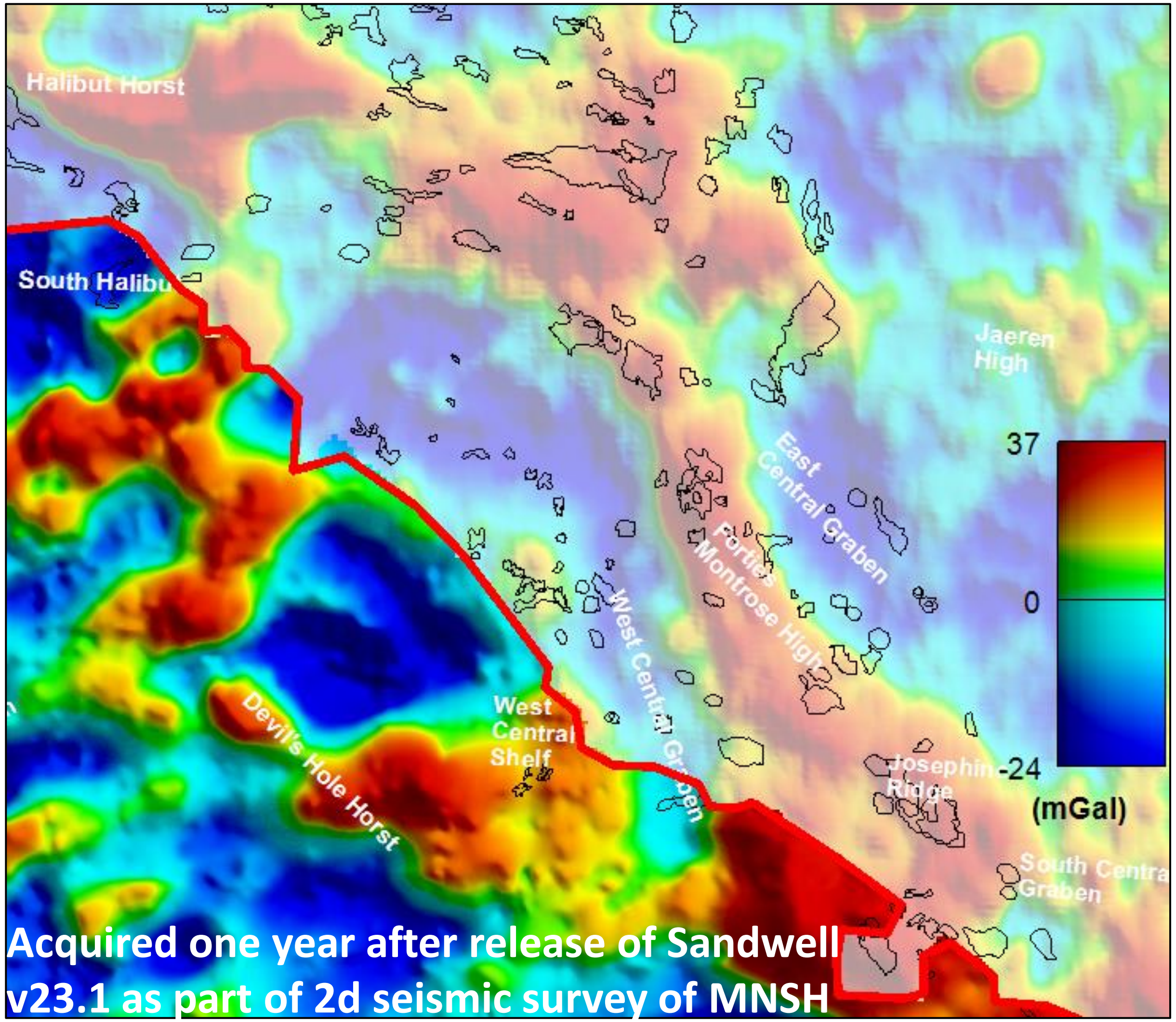


Consistent – satellite and marine shiptrack gravity – Central Graben North sea

Sandwell processed for decompensative gravity residual



Marine acquired, processed for decompensative gravity residual, 2015 (red outline) *Contains British Geological Survey materials ©NERC 2017*



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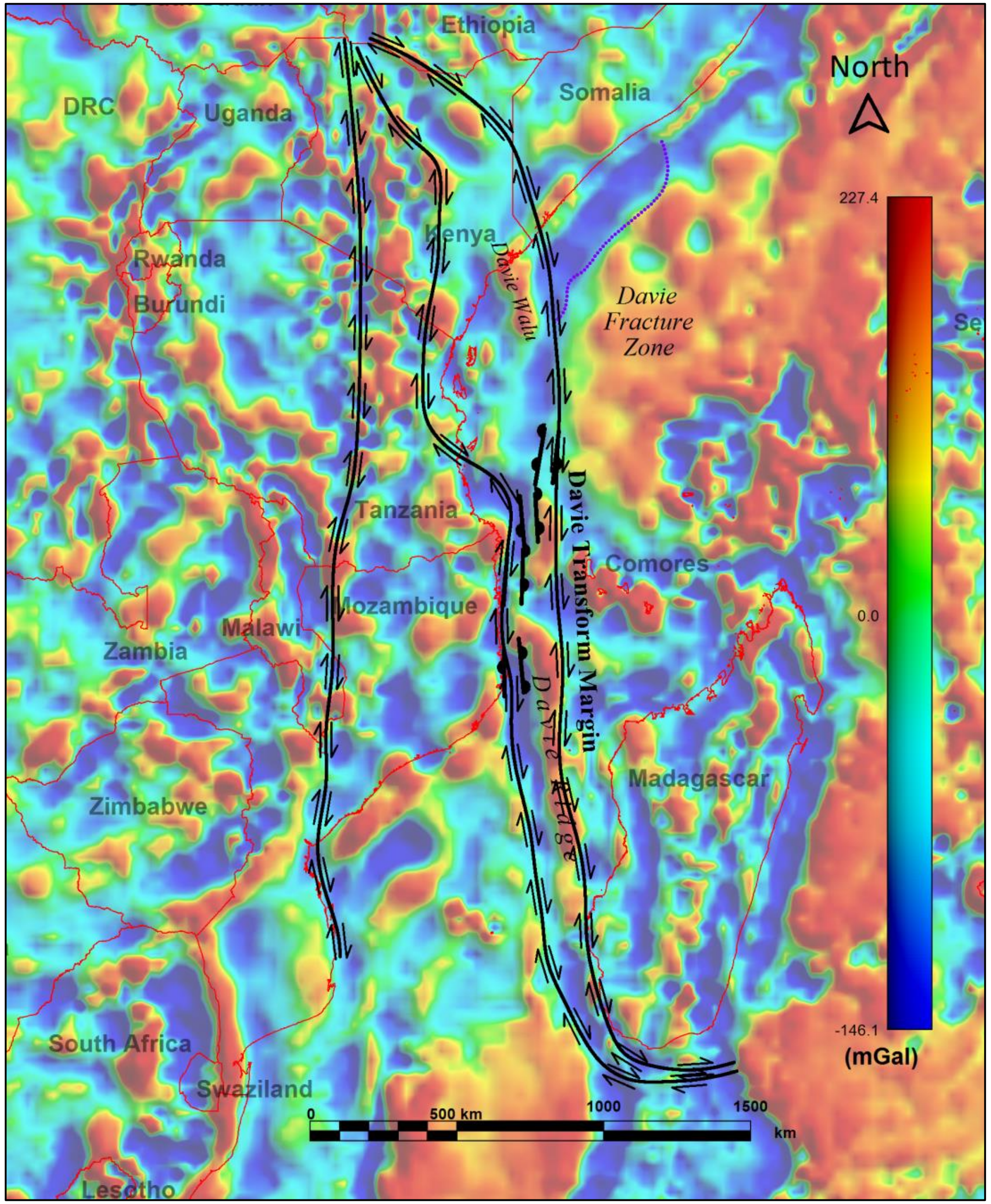
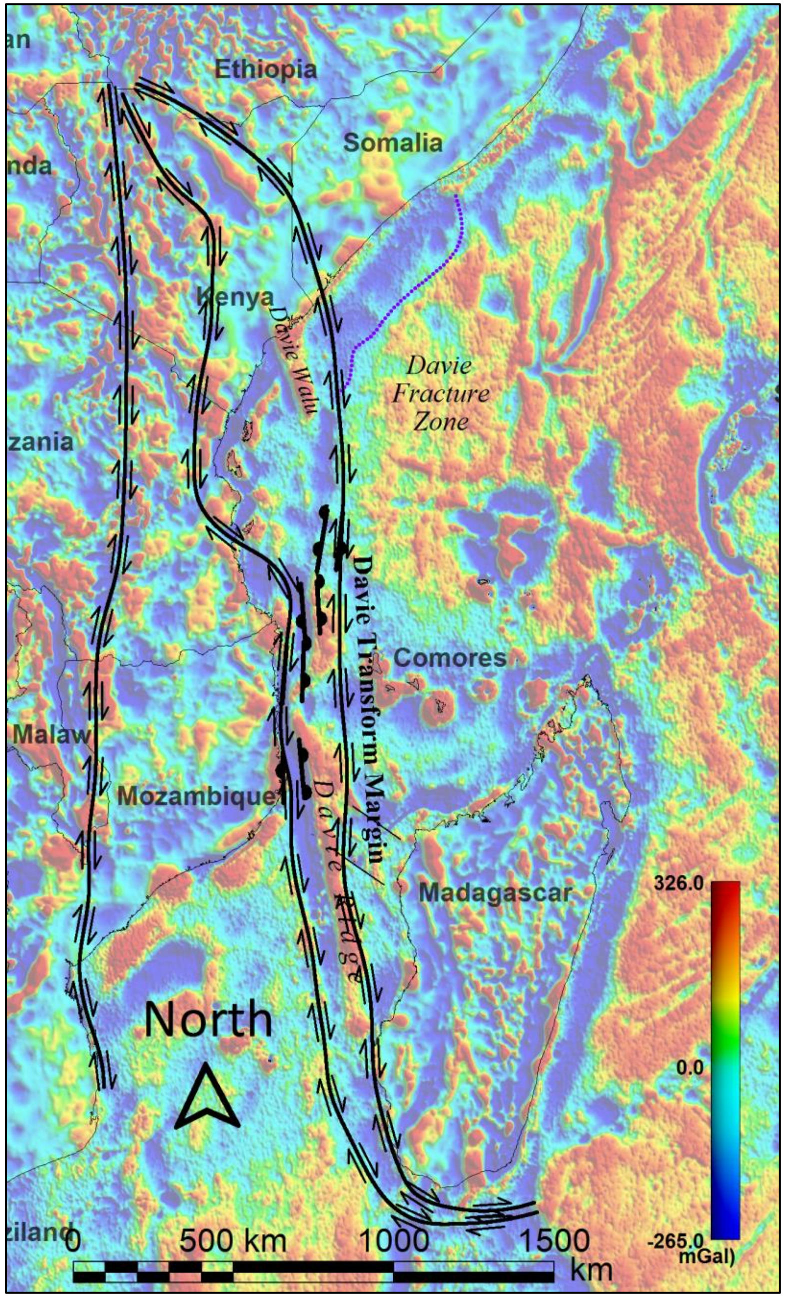
subterrane

Subterrane

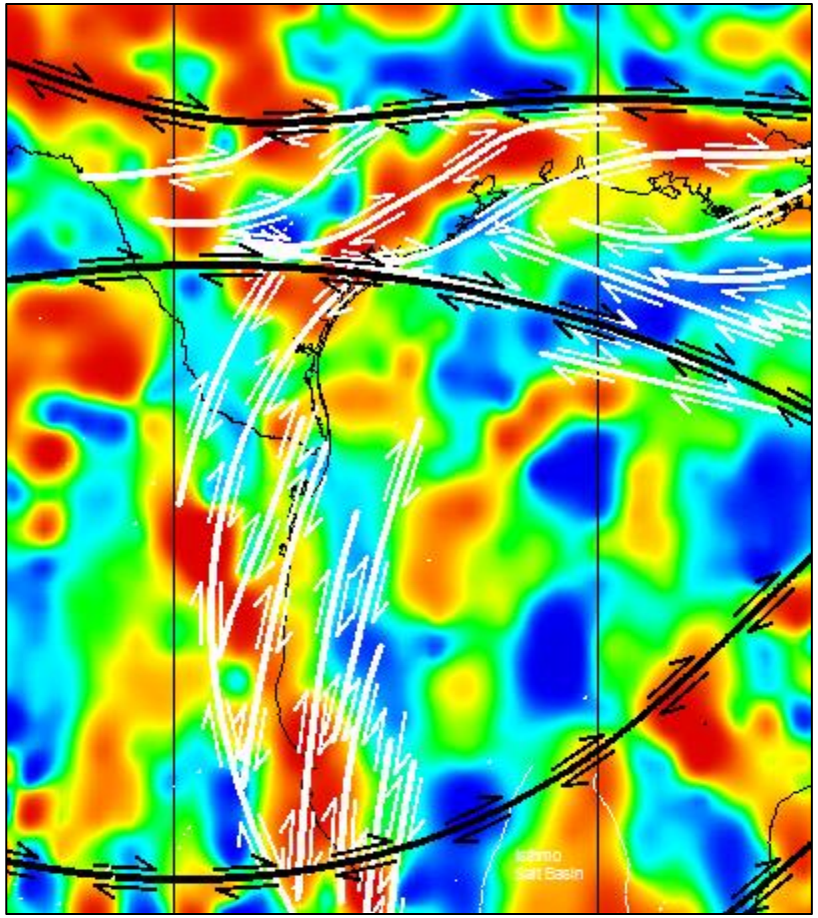


Sandwell decompensative gravity (GRS80 ellipsoid)

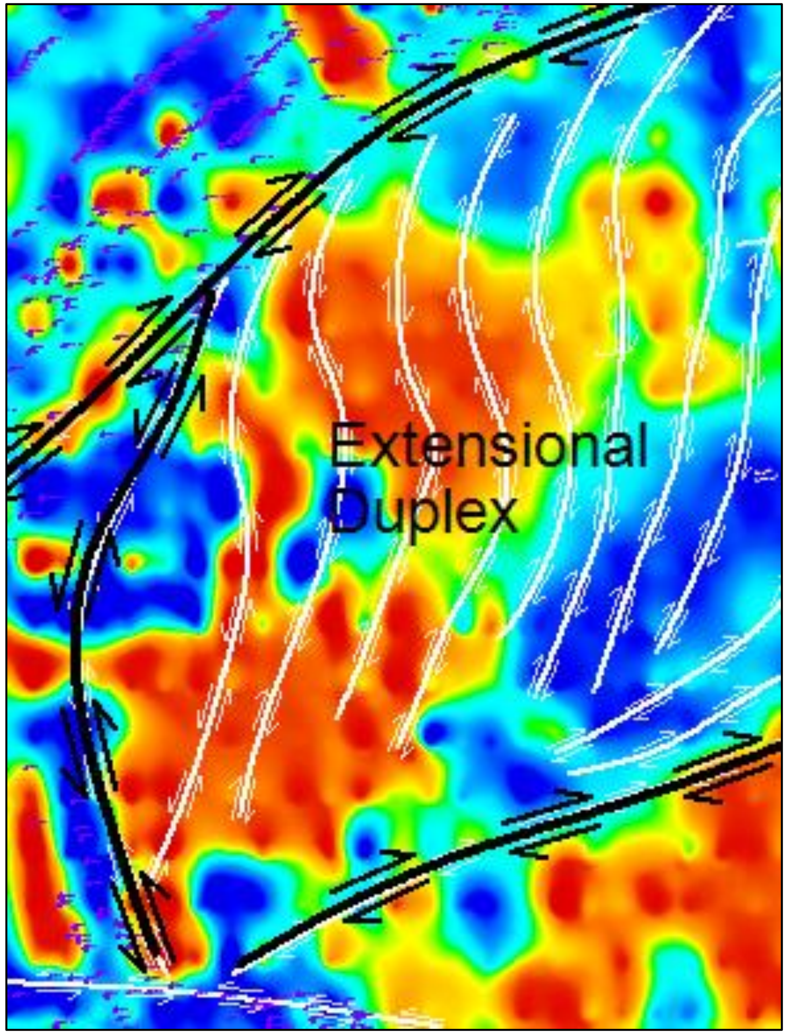


Grace decompensative gravity EGM96 adjusted to GRS80 ellipsoid elevation

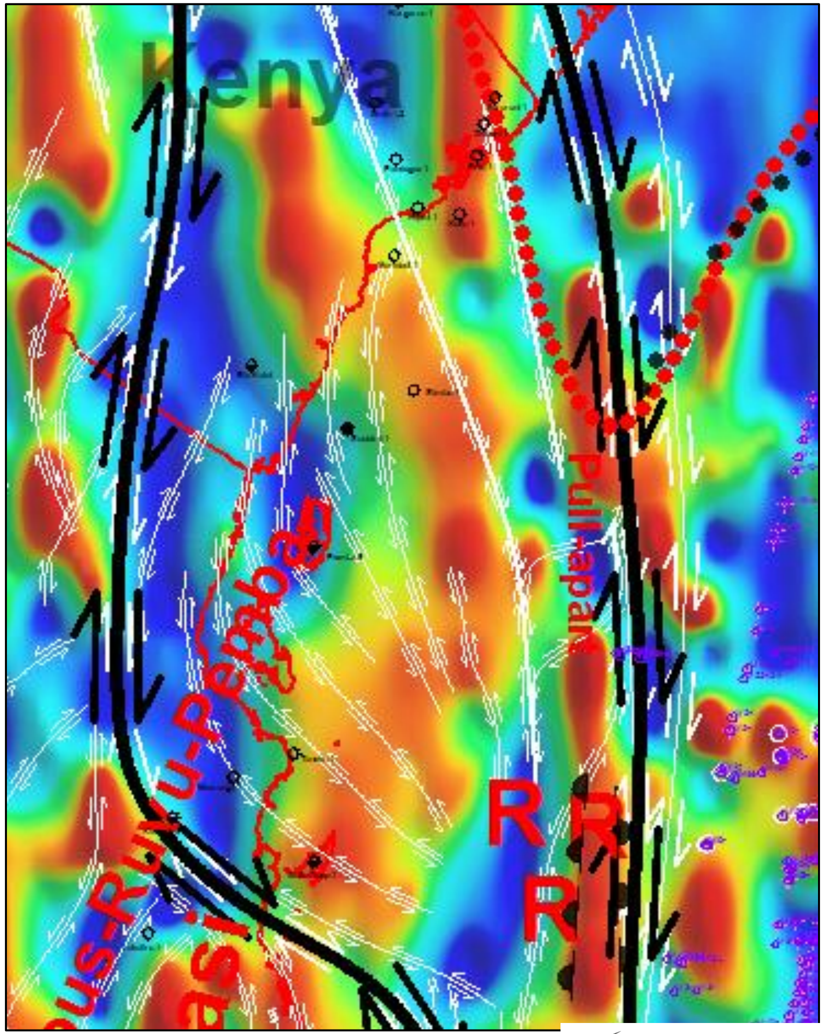
Supplementary: Indicative of strike slip structural deformation



Pacific margin



North Sea



East Africa