Modelling the Complexity of Continental Breakup and Basin Formation Including the Role of Magmatism*

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Abstract

Continental breakup controls the origin as well as the geometric and thermal evolution of sedimentary basins, and consequently is of major importance for petroleum exploration. The architecture of basins is controlled by extensional faults formed at the onset of rifting, and the geometry of such faults governs the overall sedimentary thickness, depositional environment, fluid pathways and thermal conditions. Numerical models have to date struggled to capture the complex expression of continental extension in nature, which features a variety of structures. In addition, some extension systems have been accompanied, and possibly triggered, by voluminous magmatism; whereas others involved relatively little magma activity. Some extensional systems have been stretched for more than 100 Myr prior to breakup, whereas others ruptured to produce a passive margin after only 5–10 Myr. In an attempt to better understand the variety of continental deformation modes, we have incorporated the explicit role of magmatism and metamorphic fluids in addition to the classical brittle localization mechanism during extension of the lithosphere (Liu et al. 2014). These three different weakening mechanisms may act as triggers for localization of deformation. They represent physically distinct processes that can all occur simultaneously, i.e. with some overlap in time and space. Our new model also treats melting through the incorporation of parameterized free-energy curves generated from the

MELTS model for phase equilibria. The application of the numerical models to real case studies led to identification of a new style of tectonics, where instead of breaking plates apart through fast brittle faults that propagate into the ductile realm, the opposite mechanism is observed. The propagation of melt-rich ductile shear zones upwards into the brittle domain requires longer time scales but is extremely efficient and can potentially break cratons. We present an application to plate breakup in the Arabian Peninsula that provides new insights into extensional processes and the timing between initiation of extension and of magmatism. These models help understanding and improving thermal and depositional models of basins, and may provide an enriched geodynamic exploration toolkit for search of (un)conventional oil and gas reserves in previously unexplored domains.

Selected References

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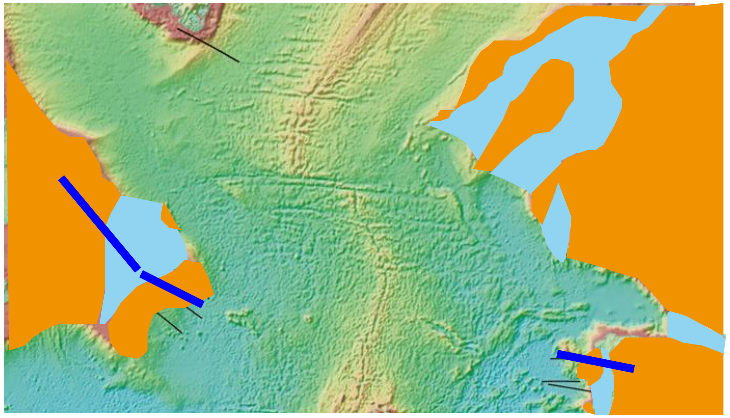
Never Stand Still

School of Petroleum Engineering

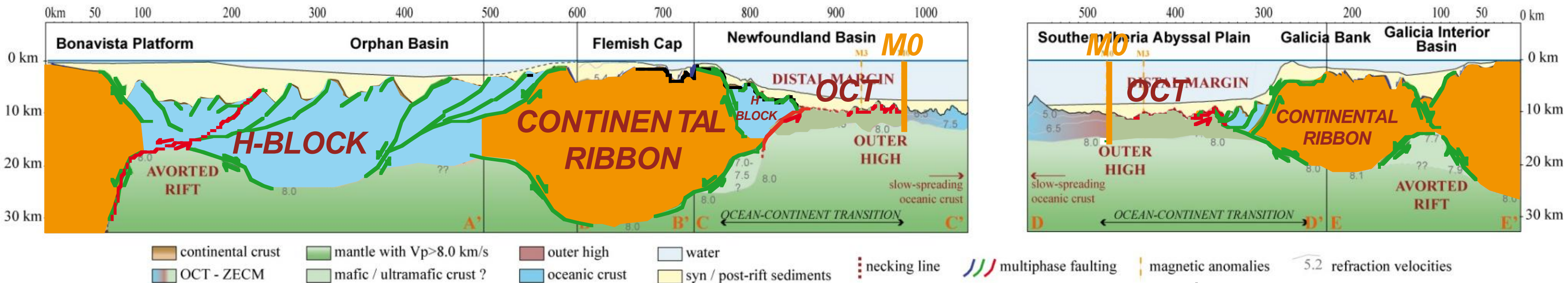
The Problem

The structure of hyper-extended rift-systems

Gianreto Manatschal



Section through the Orphan-Newfoundland-Iberia System

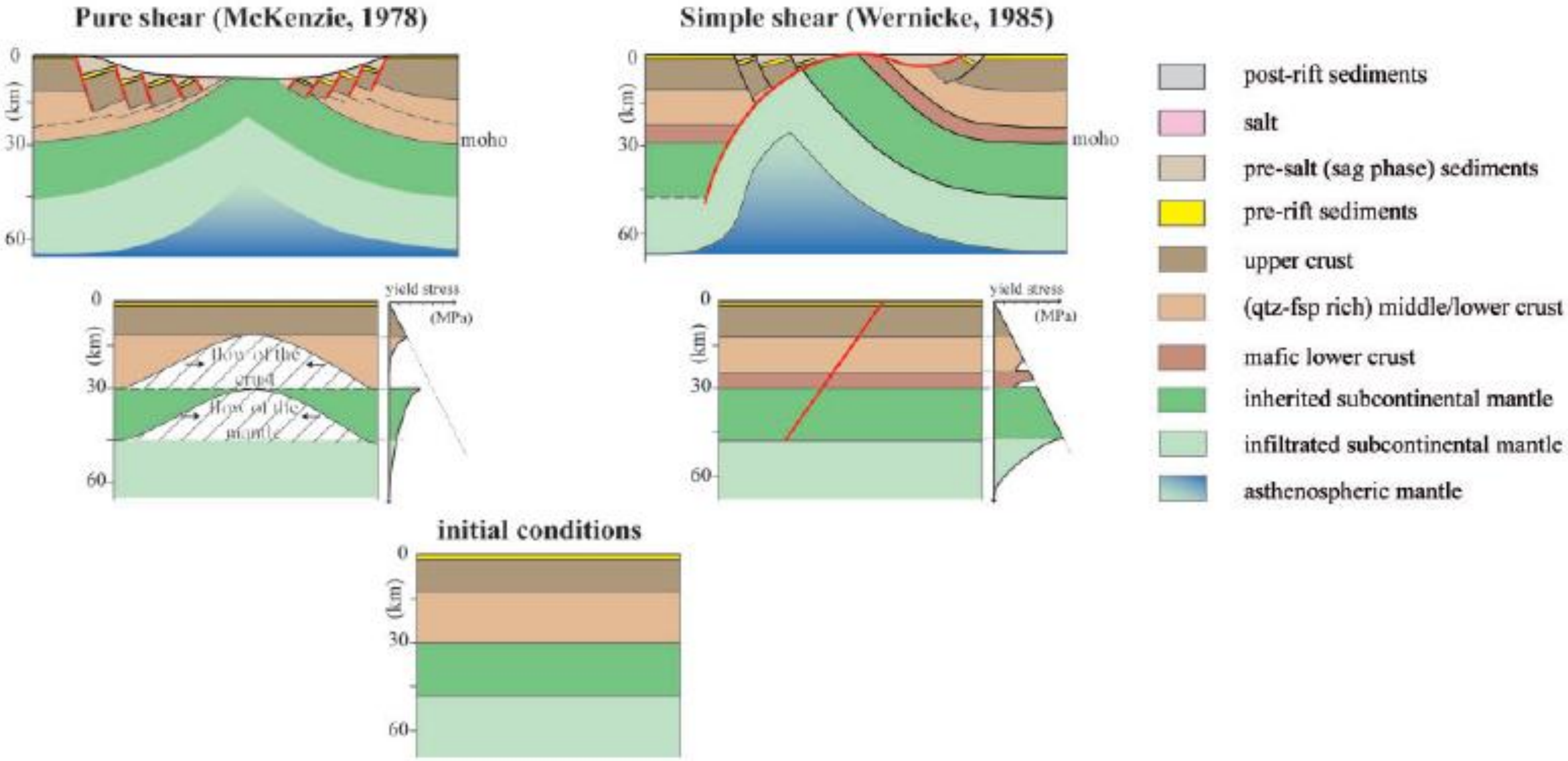


Péron-Pinvidic and Manatschal (2010)

Major observations from Gianreto Manatschal

- Structures at hyper-extended margins are complex, poly-phase and strongly 3-D
- Occurrence of continental ribbons, H-blocks, extensional allochthons and outer highs
- Ample evidence for post-breakup magmatic activity

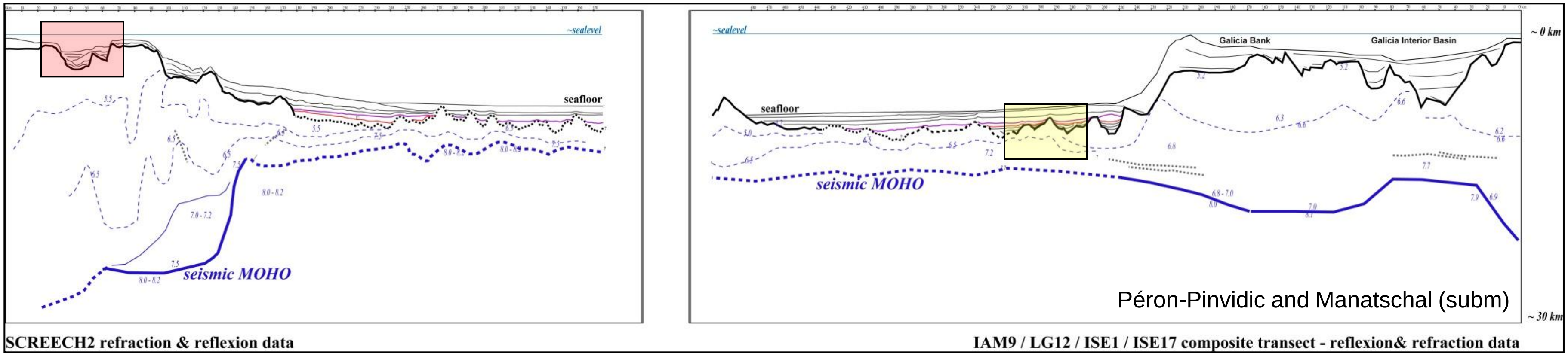
Extending the lithosphere
proposed conceptual geological models



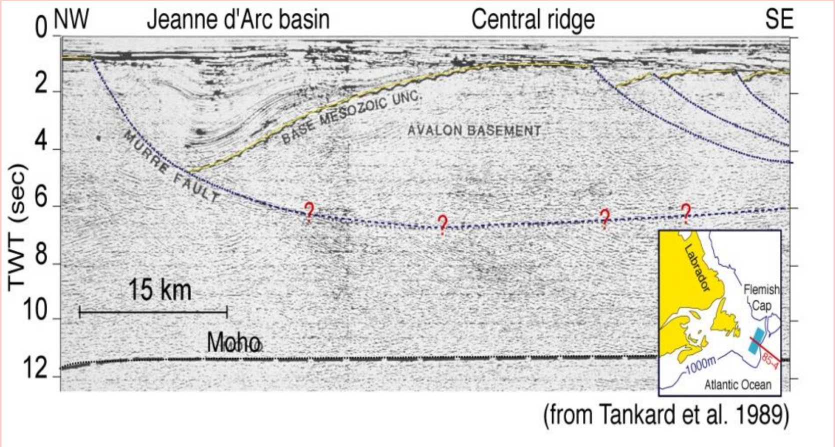
Reflection seismic data

(SCREECH2, IAM9, LG12, ISE17)

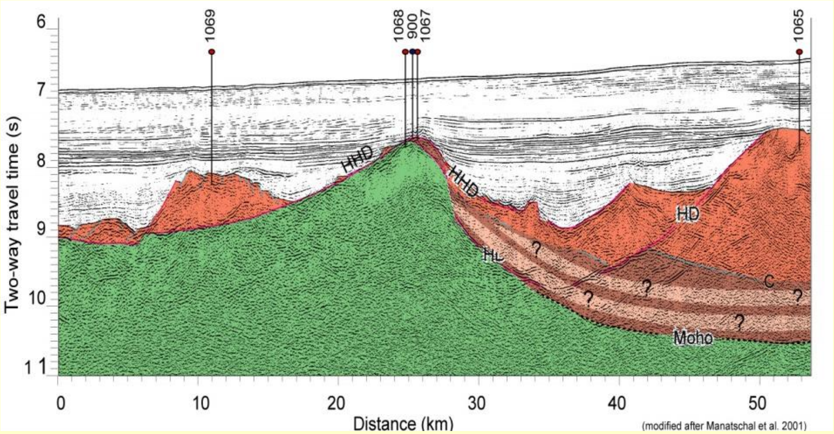
Newfoundland **Iberia**



Jeanne d'Arc Basin



Iberia Abyssal Plain (LG12)

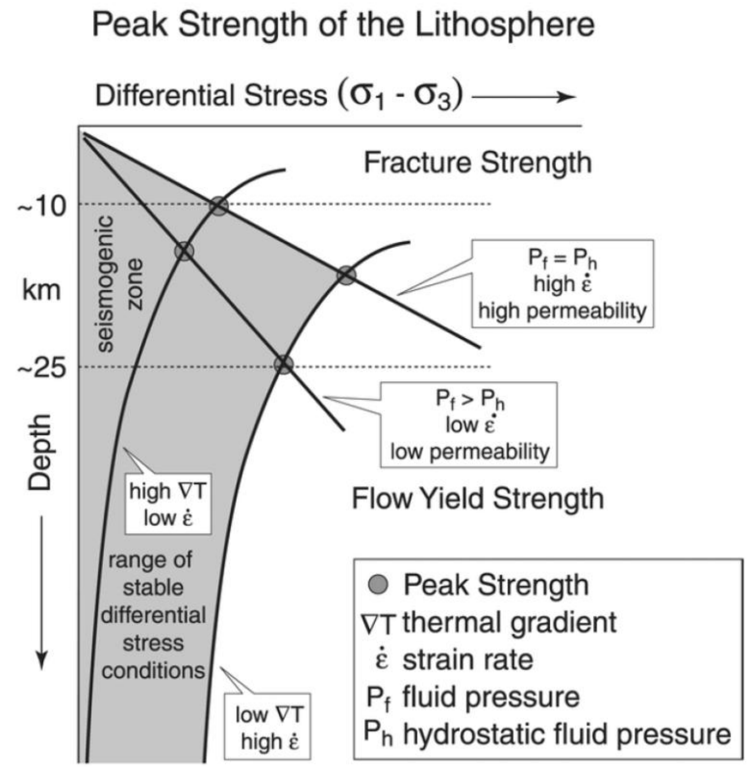


Architecture of rift basins is different in the proximal and distal margins

(coupling vs. decoupling / high- vs. low-angle faulting)

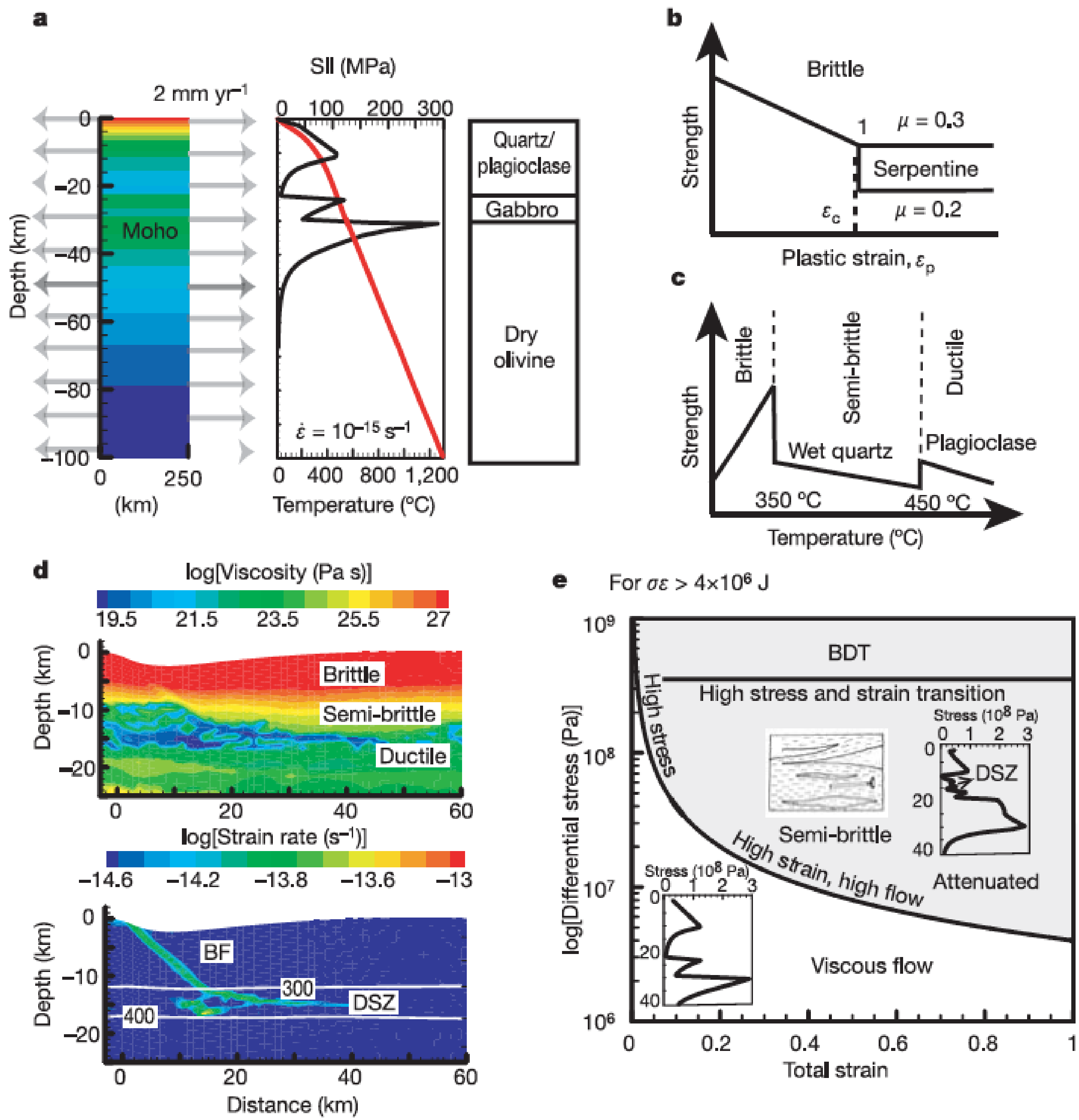
1. Conventional Geomechanics Approach

(Descriptive) numerical models



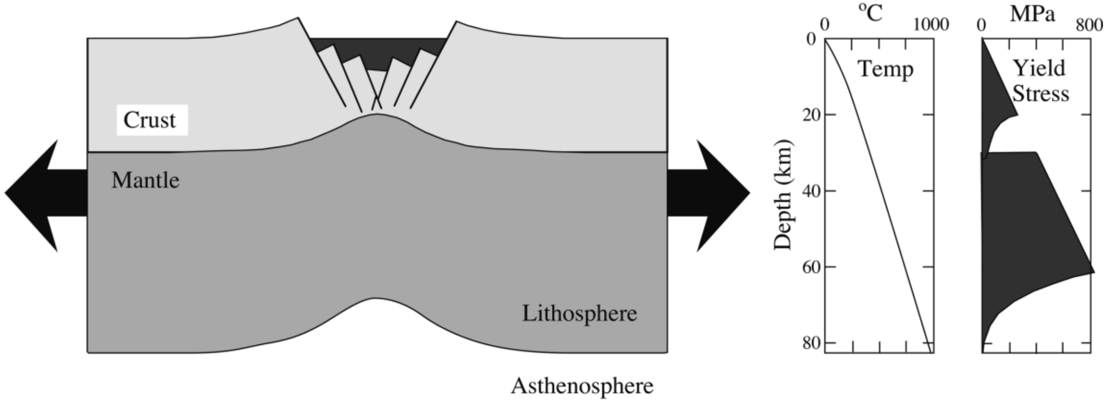
Presenter's notes: Mechanical damage models have quite maturely developed. Generally, two fundamentally different processes are considered. The first process is a classical brittle damage (dilatancy). The second process is a creep damage caused by the slow creep deformation of the solid rock matrix and the associated growth/shrinkage of micropores.

Lavier and Manatschal NATURE 2006



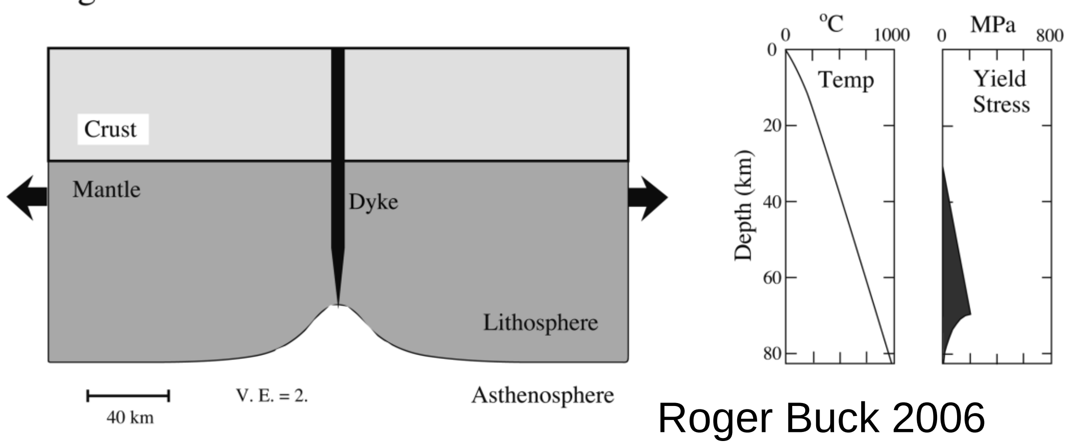
Descriptive Models put the model results into the assumptions; each model needs new assumptions

(a) Tectonic Stretching



How do you turn this

(b) Magmatic Extension



Into this?

Roger Buck 2006

AAPG SEG International Conference & Exhibition 2015
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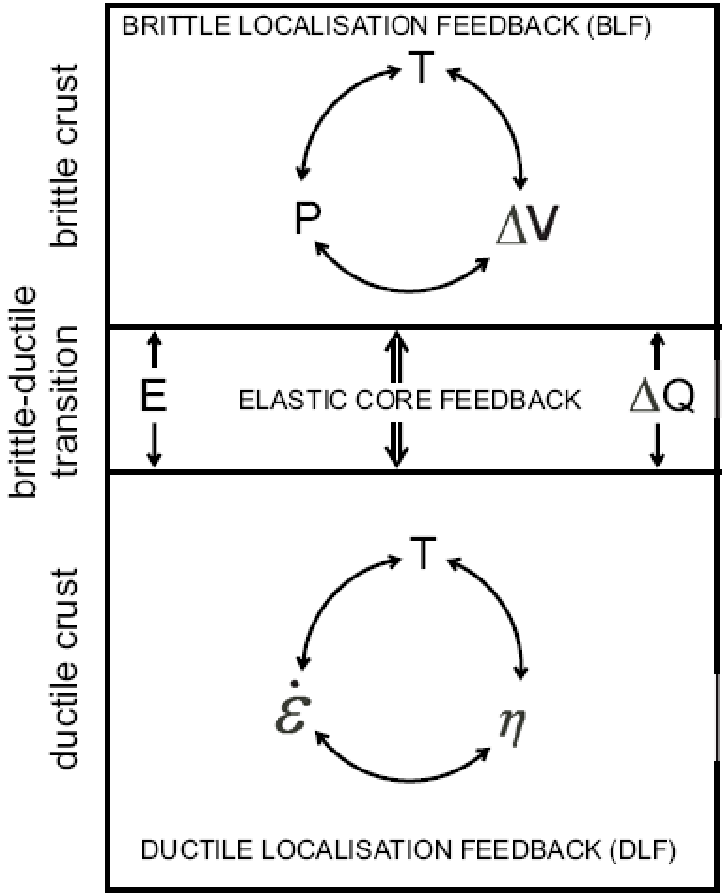
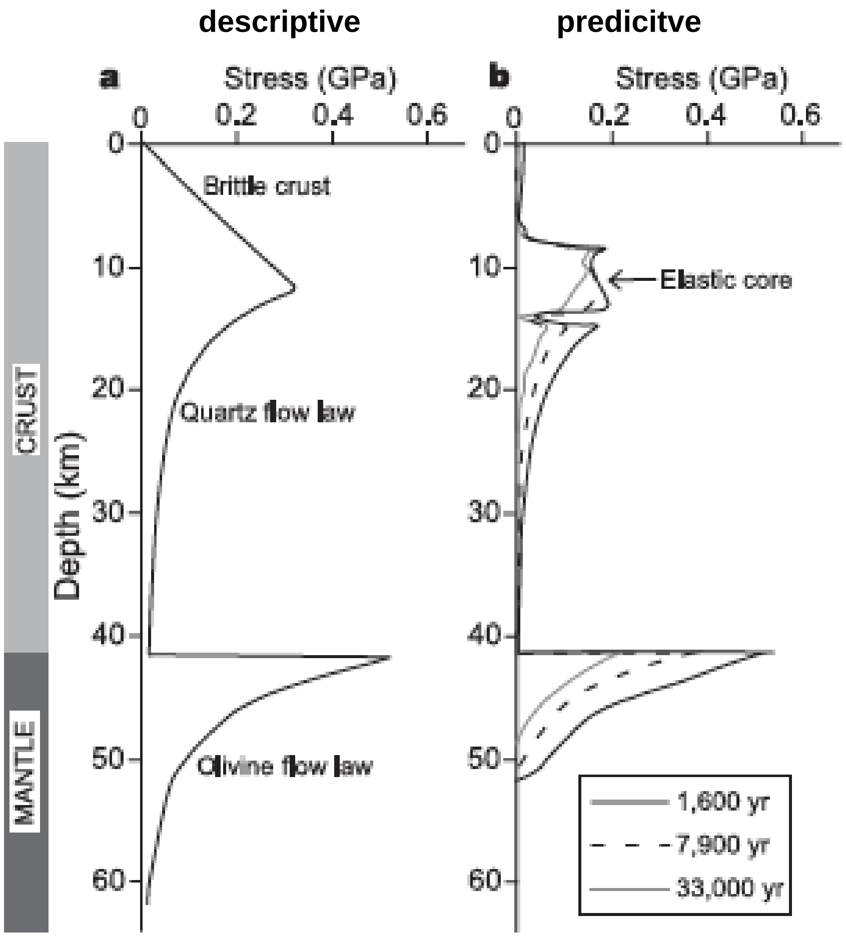
PESA Incorporating PESA's Eastern Australasian Basins Symposium

2. Unconventional Geomechanics Approach

Predictive Models: Complexity arises out of physics

If the right physics is found one material model can explain all observation



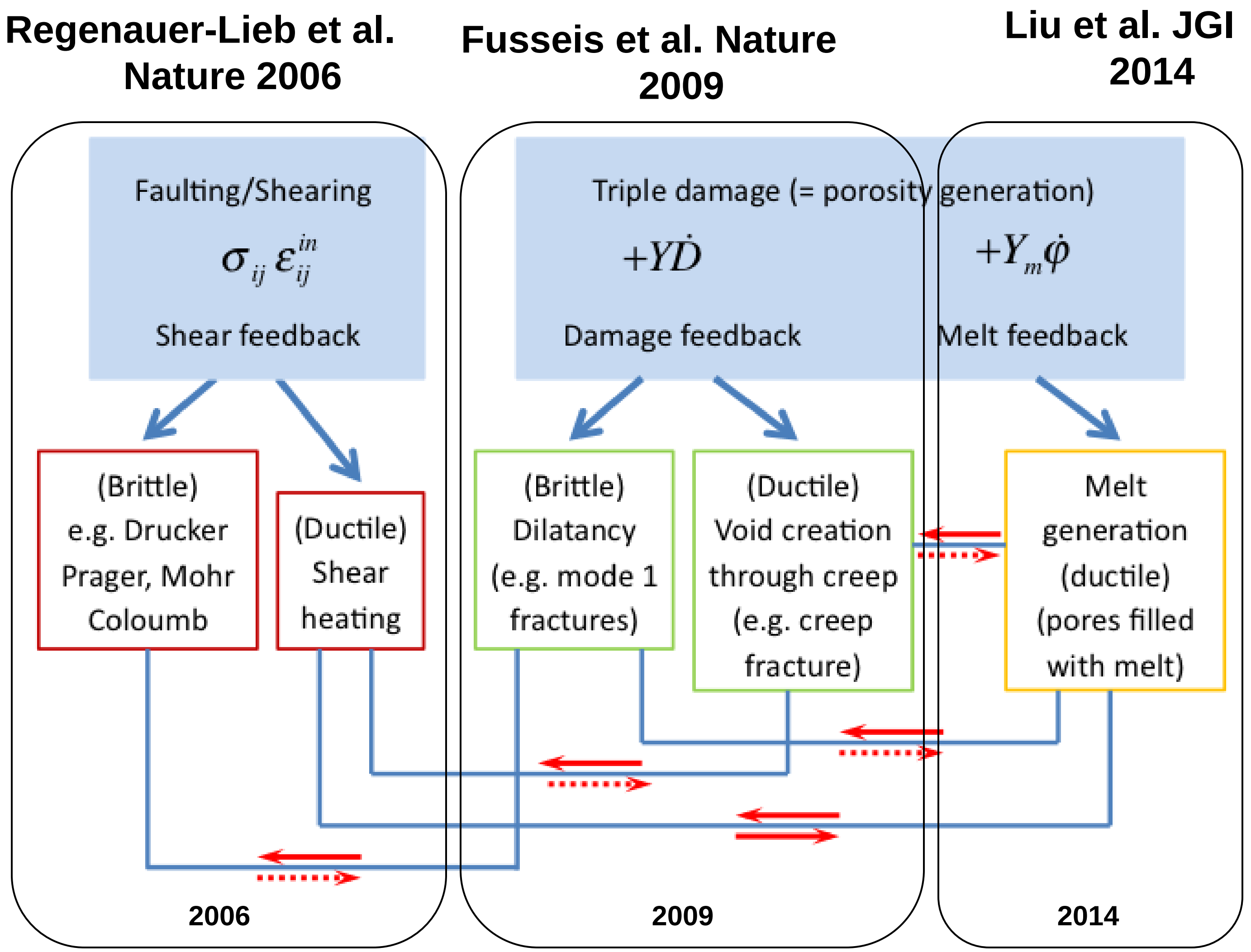


Regenauer-Lieb et al. Nature 2006

Energy Feedback

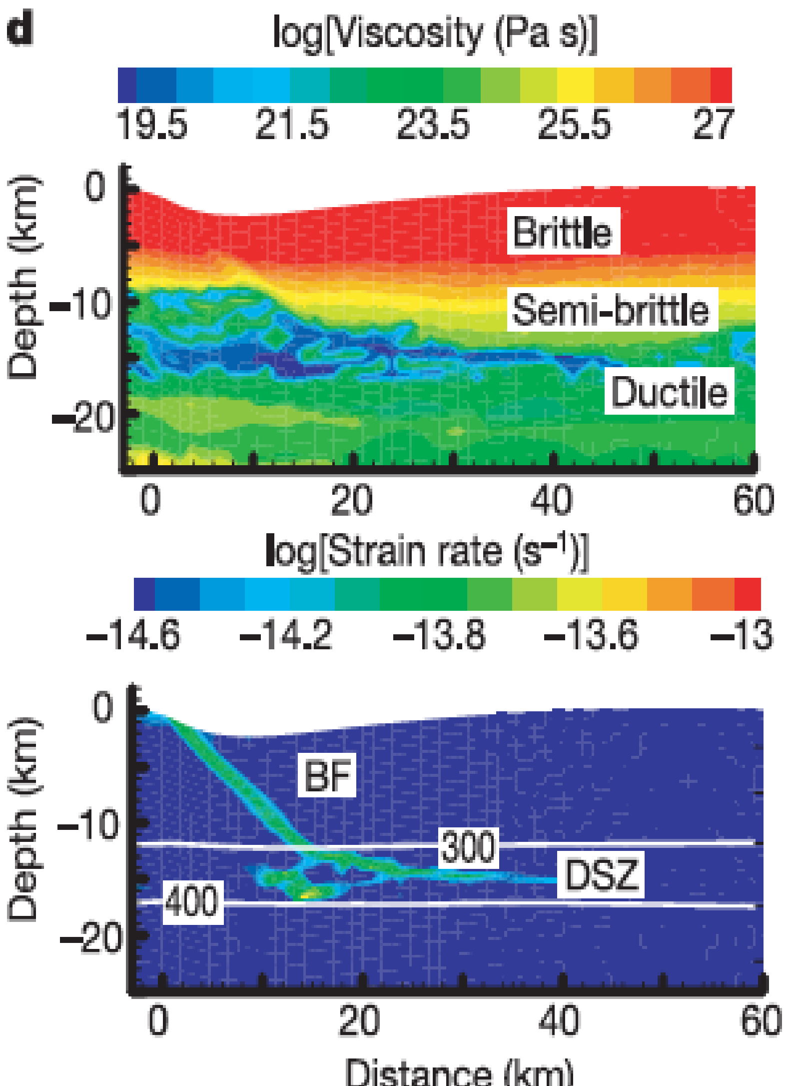
2006 "Only shear heating feedback"

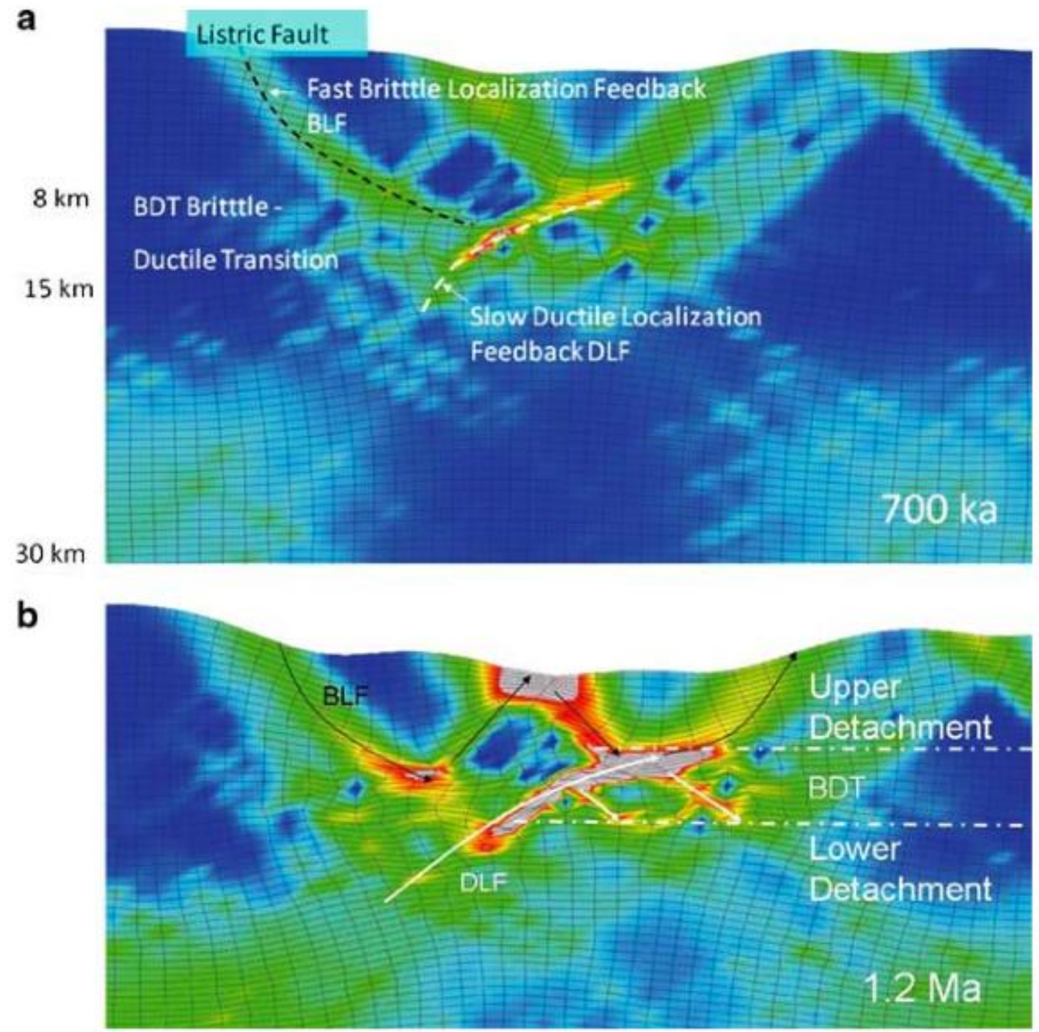
2009 -2014 "Addition of fluids, first dissolution-precipitation then melts"



Conventional Geomechanics

Unconventional Geomechanics



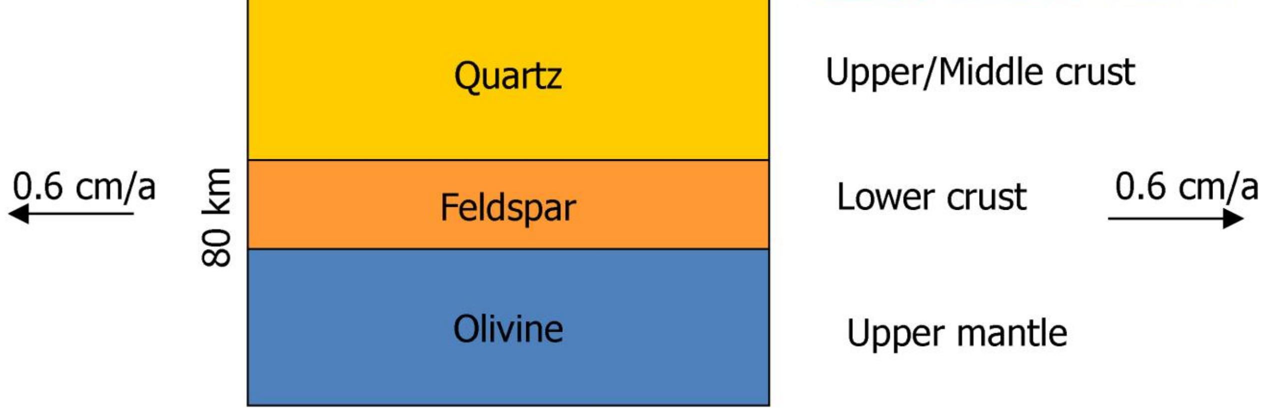


Lavier & Manatschal 2006

Regenauer-Lieb et al 2006

Unconventional Geomechanics

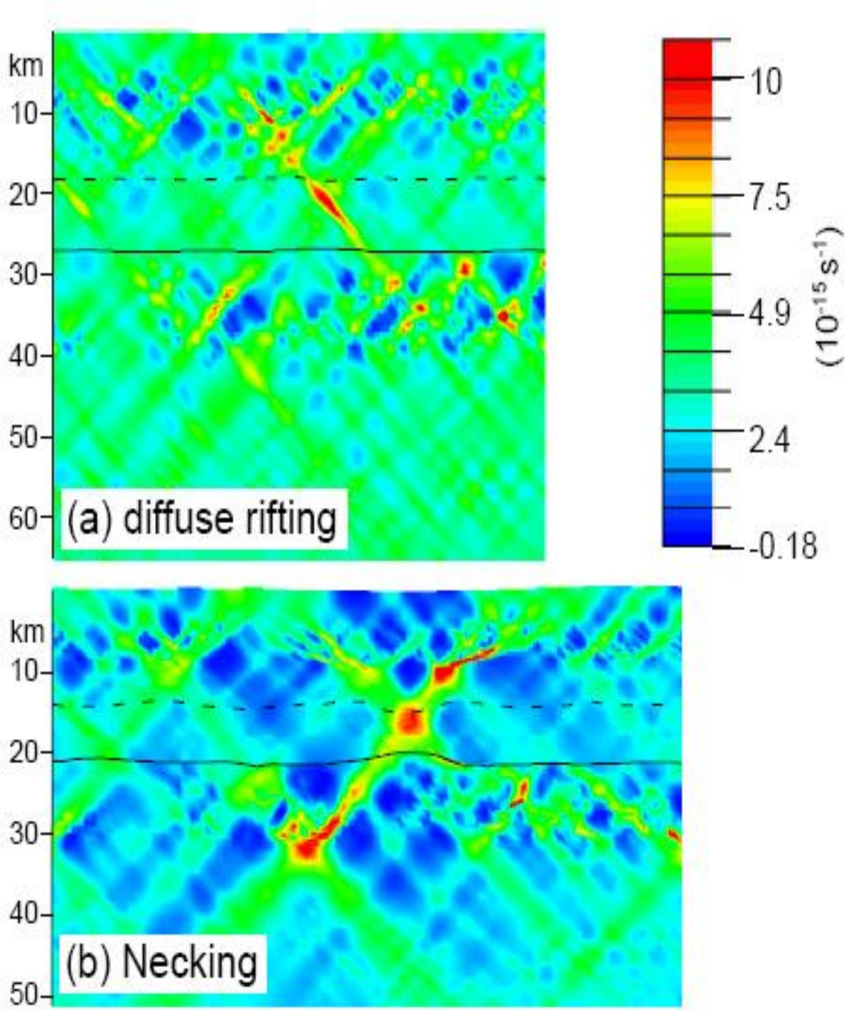
a) No Melting considered



- Elasto-Visco-Plastic rheology
- Extension velocity 0.6 cm/a at each side over a period of 13.7 Myr (β = 2.6)
- Crustal thickness – 30, 40, 50, 60 km
- Crustal heat flow – 50, 60, 70, 80 mW/m^2

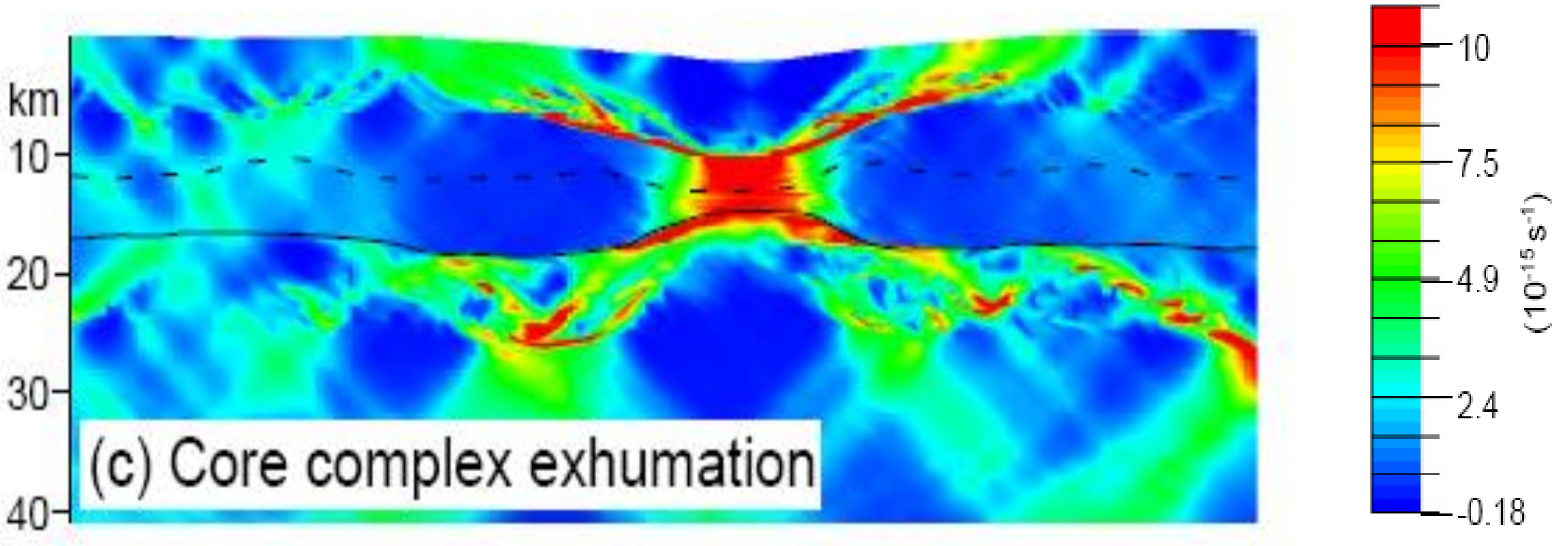
Presenter's notes: We try to understand to resolve some of these questions by insights from numerical modelling. We use a three-layer elasto-visco-plastic model made of olivine lithospheric mantle, feldspar lower crust and quartz upper crust.

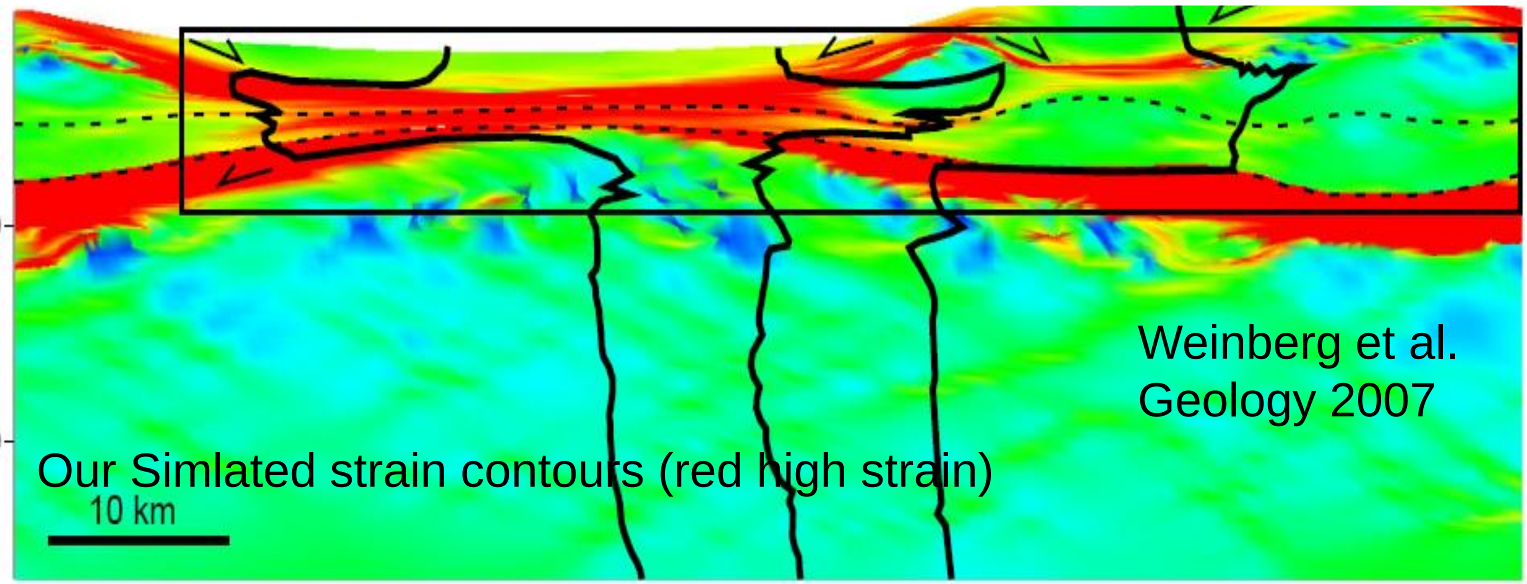
Three stages of rifting

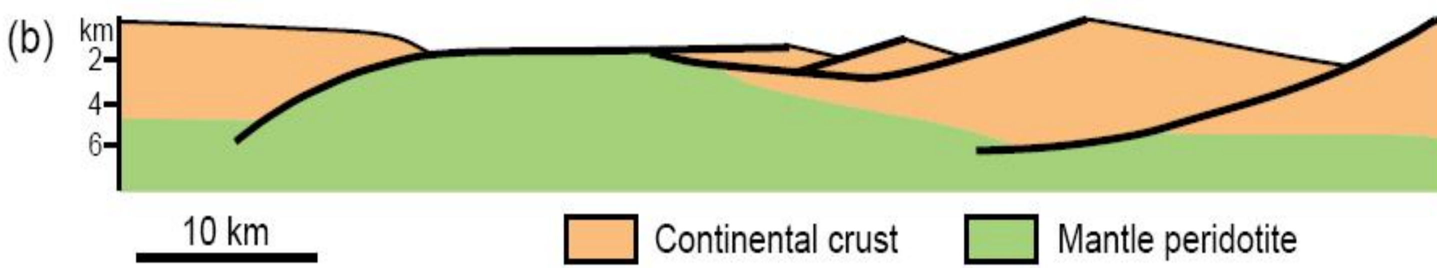


Mantle core complex phase

Roberto Weinberg

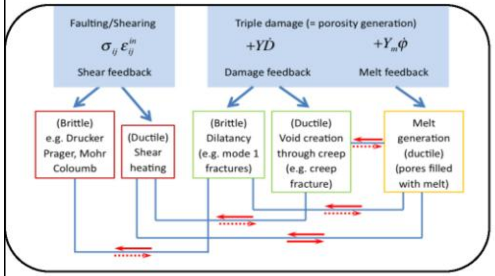


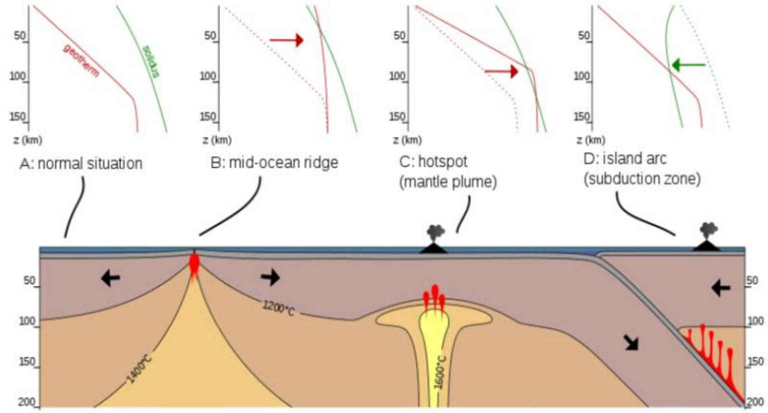




Whitmarsh 2001 Nature

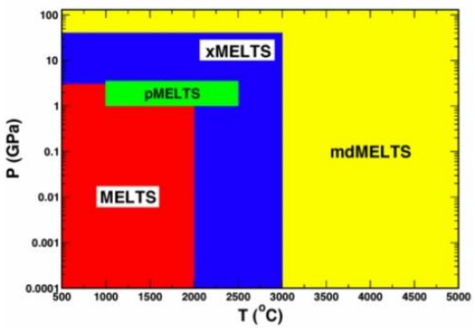
Unconventional Geomechanics Approach
b) Partial melting considered



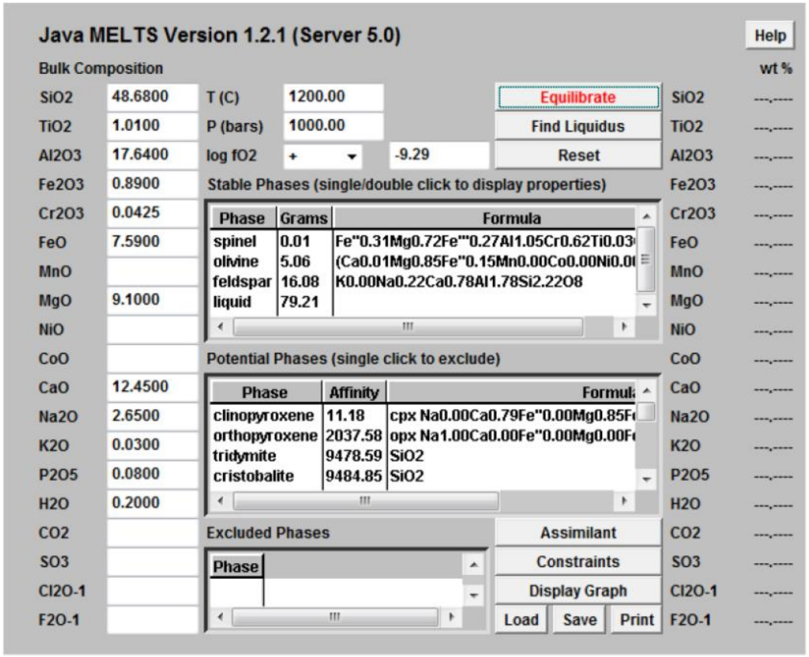


Presenter's notes: Partial melting of rocks occurs when temperature is higher than the liquids of at least one mineral. When conditions for melting are first met, melt accumulates on the grain boundaries and softens the rock matrix. Thus, partial melting can be recognised as the third type of damage.

MELTS Package



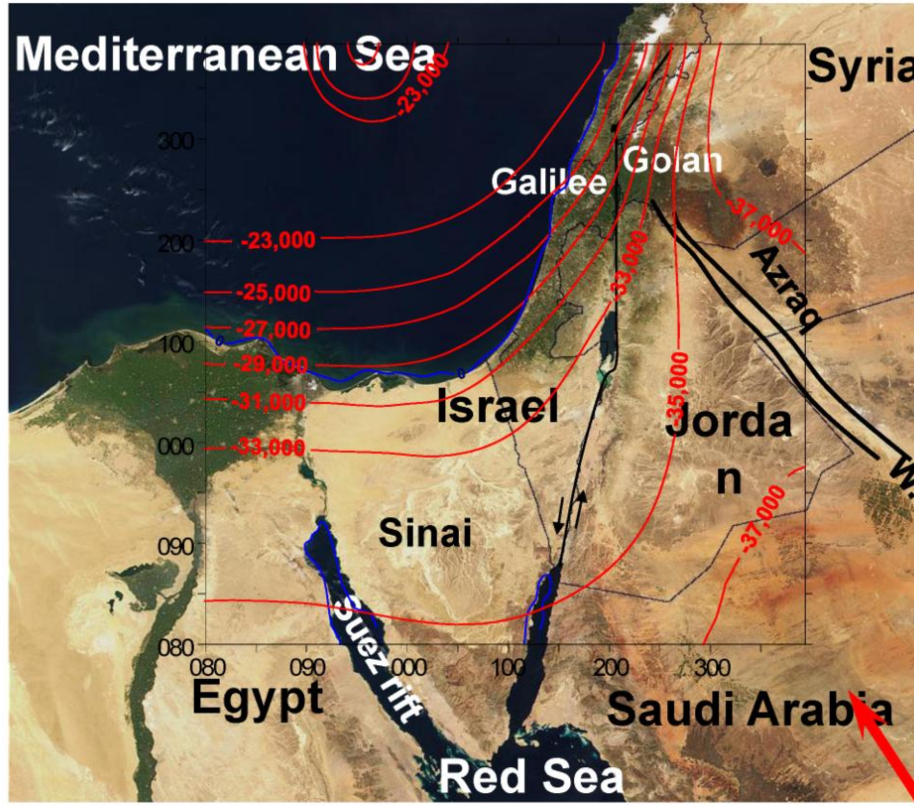
Ranges of T and p can be analysed by MELTS family



Presenter's notes: For different ranges of temperature and pressure, we should use proper package of MELTS family to perform the thermodynamic calculations. Generally, we specify the composition of the rock, temperature and pressure. Then we obtain thermodynamic outputs, including melt fraction.

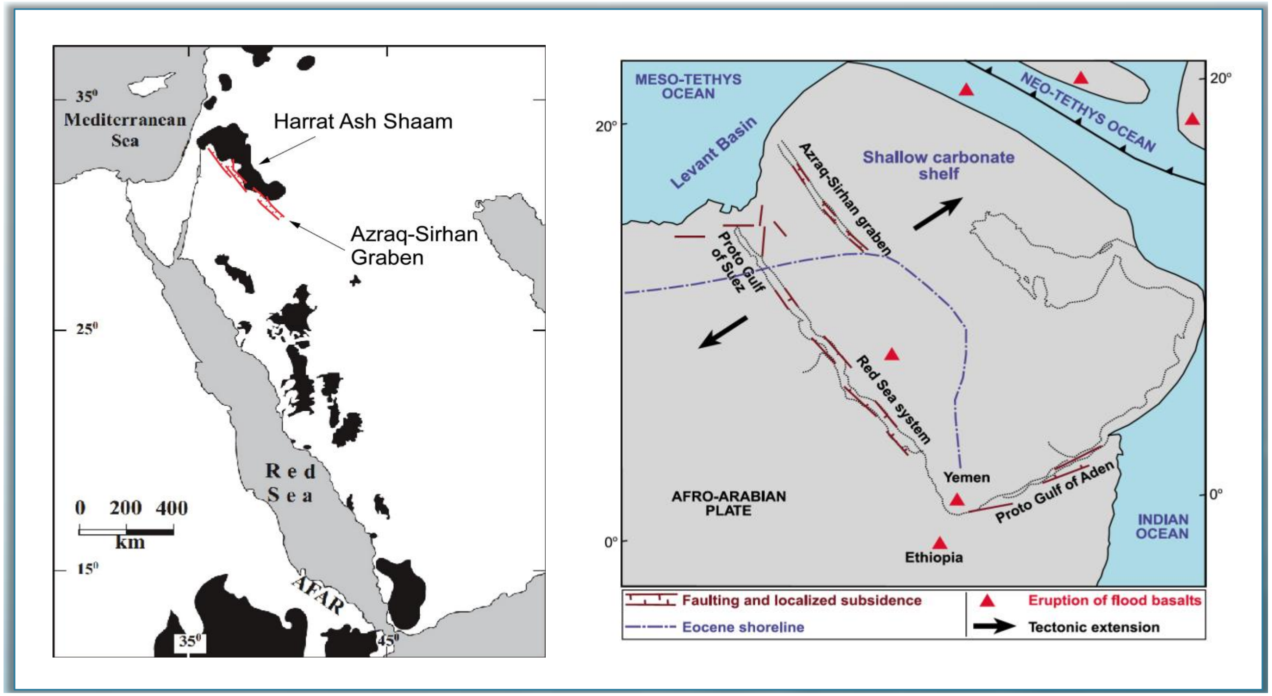
An application

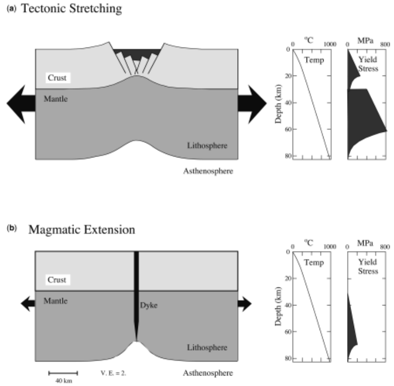
- Initially magma-absent activity
- Later magma-rich activity (~ 30 Ma)
- Slow extension
- Arabian Shield is with low heat flow (cold)
- Why is melting localised and maintained here?



Presenter's notes: The first geological application of this method is to the area of Azraq Sirhan, which is a rift parallel to Suez rift. The geodynamical features include: initially magma-absent activity, later magma-rich activity (~ 30 Ma), slow extension, and developed in relatively cold continent. So the question is: Why is melting localised and maintained here?

Harrat Ash-Shaam Volcanic Province

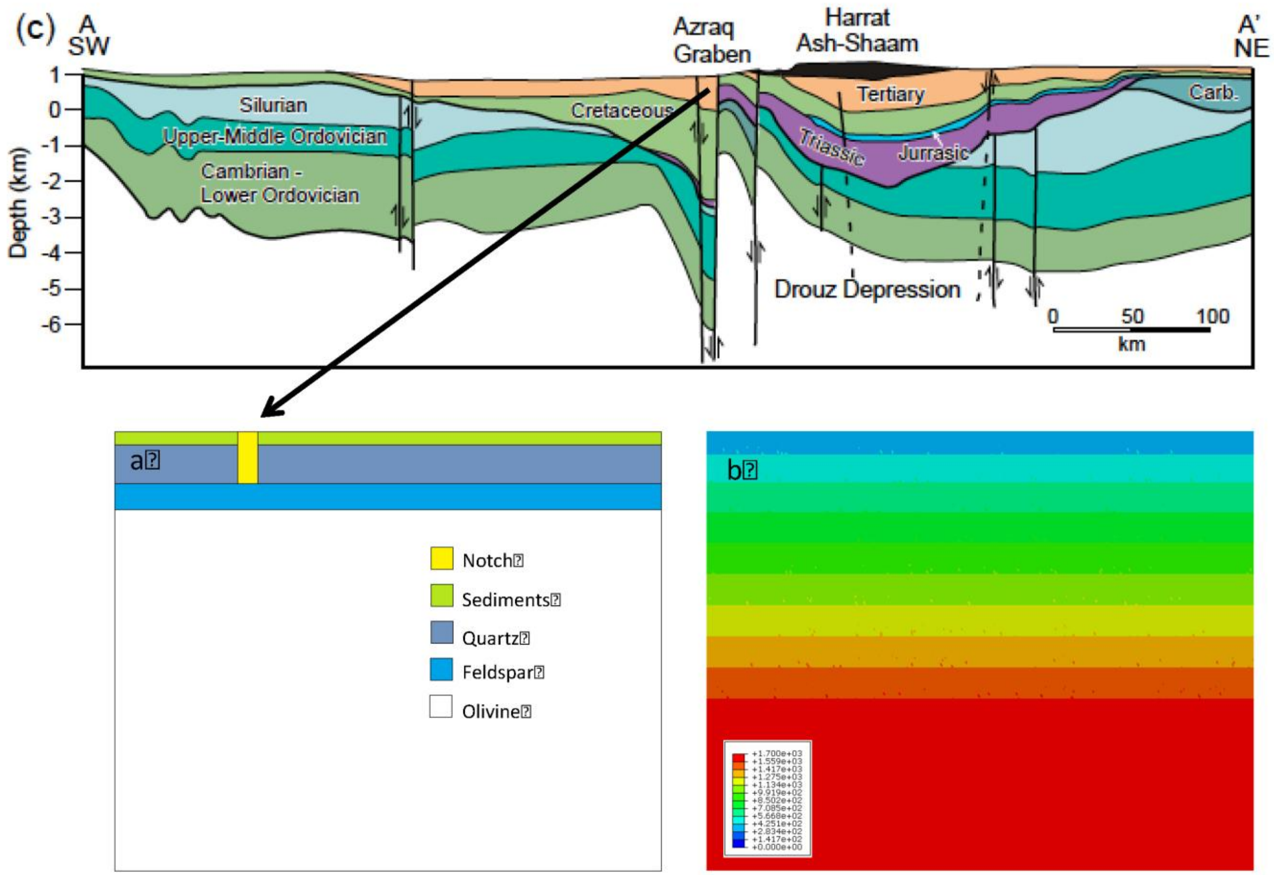




How do you turn this

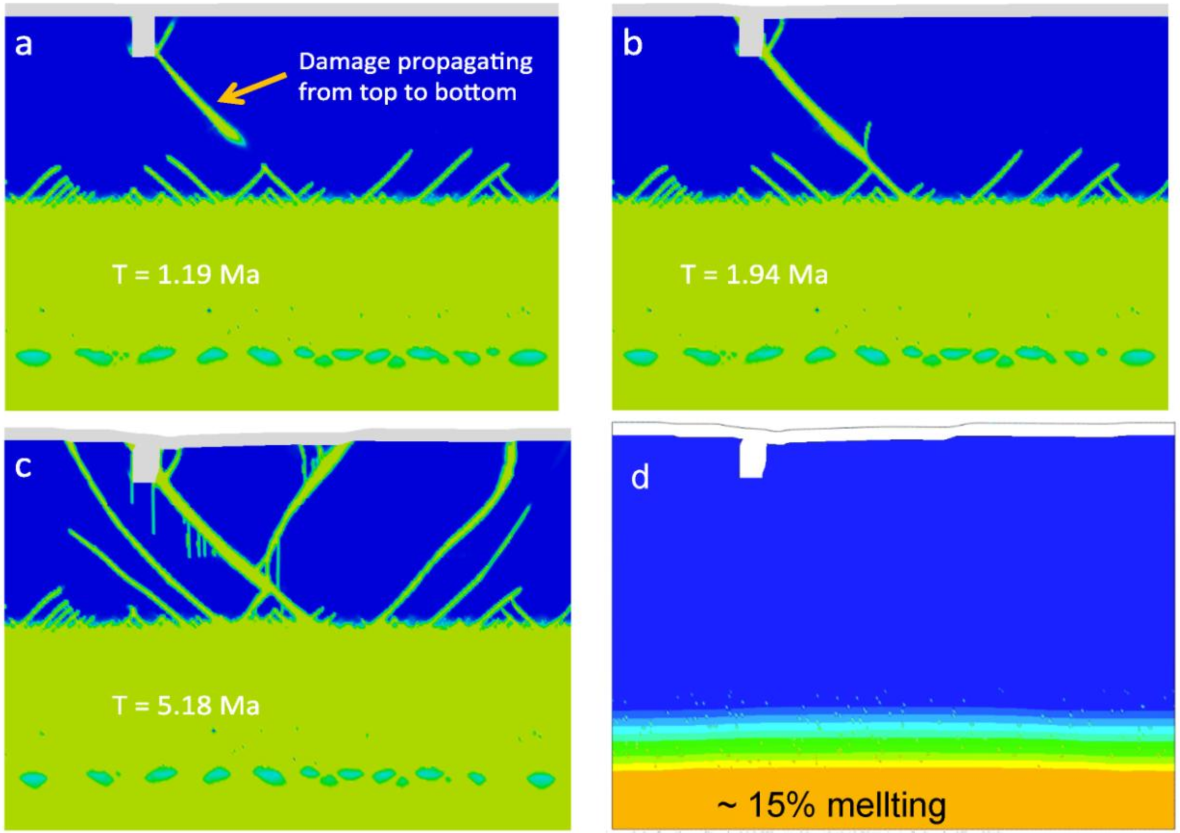
Into this?

Initial model: Like previous model but higher temperature



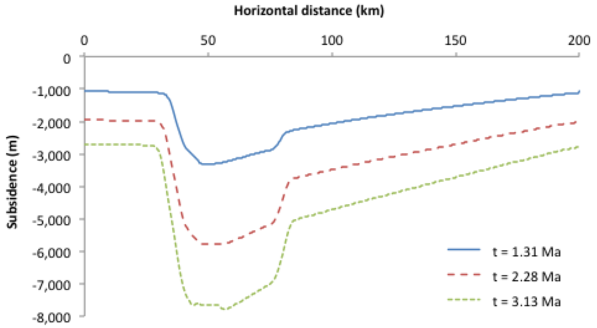
Presenter's notes: We analysed a series of models matching the geological settings. One initial model here. Some models without a notch, some with a notch, and the depth of the notch may different from model to to model. And the temperature distribution at depth may slightly different as well.

> 20 km deep Graben required to have effect

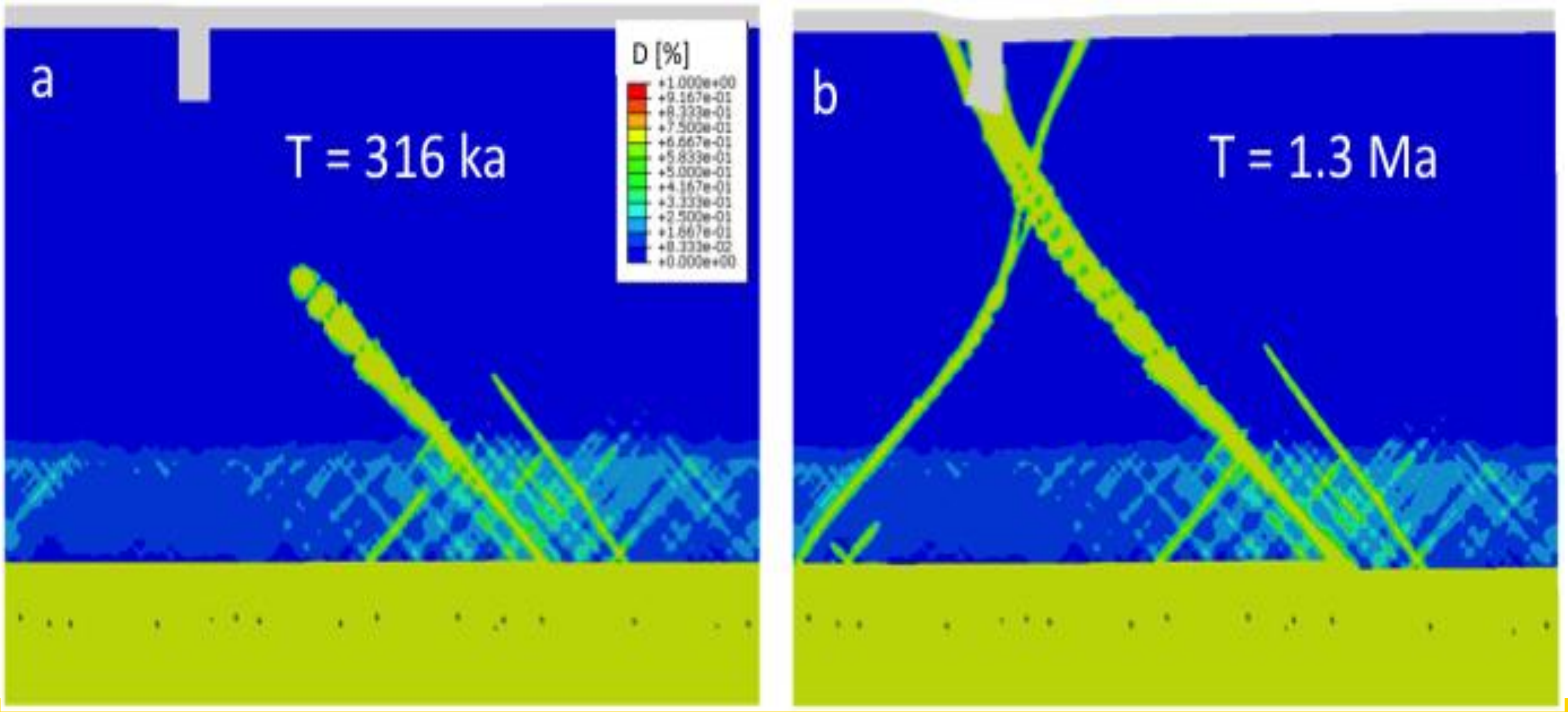


Presenter's notes: For models with a notch the propagation of mechanical damage are similar, from bottom to top. Only when the notch is quite deep, such as this one, it affects the propagation of the mechanical damage. These models show us that melt localization and efficient melt transfer can be explained by coupling melt damage to mechanical damage in the lithosphere. This may explain the fast transition from magma-absent to magma rich extension even in slow deforming and relatively cold continental settings.

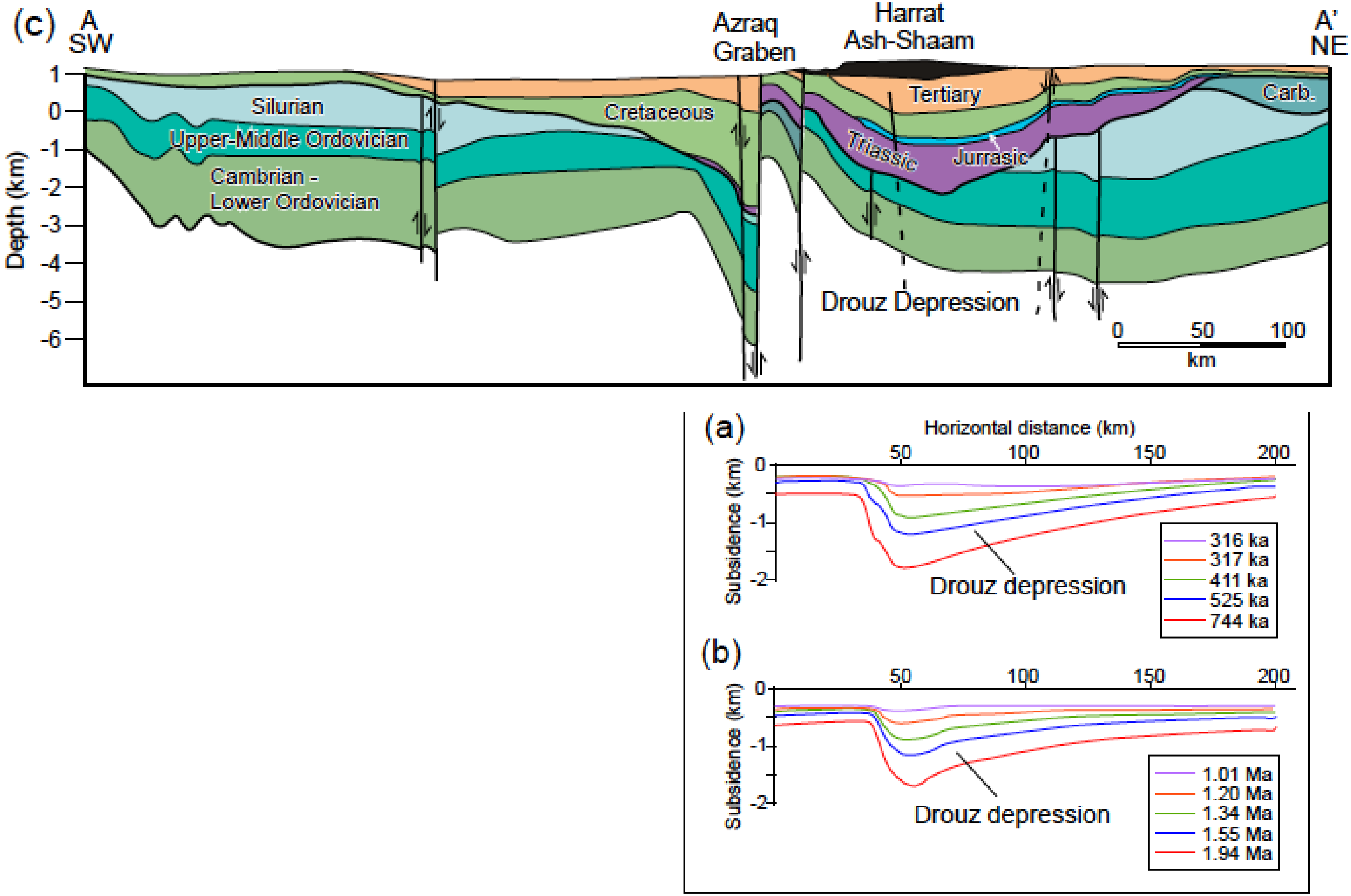
Adding sublithospheric melts can solve the transition from magma-poor to magma rich breakup



Azraq-Sirhan Graben Model: Regenauer-Lieb et al. 2014



Observed vs predicted subsidence



Summary

The time has come to lift numerical modeling of basins up from a descriptive **conventional geomechanics approach** to a predictive **unconventional geomechanics approach**

Rich complexity of rifted margins can be reproduced by numerical modeling by just considering fundamental energy feedbacks

The model has been applied to three case studies but needs further testing

We have developed a new MOOSE* application for **Unconventional Geomechanics and Reservoir Engineering**

REDBACK*

https://github.com/pou036/redback

an Open-Source Highly Scalable Simulation Tool for Rock Mechanics with Dissipative Feedbacks

* a MOOSE application (http://mooseframework.org)

Thank you!