Coupled Fluid Flow, Deformation, Heat Transport & Mineral Reactions in Hydrothermal Mineralising Systems

热液成矿系统中流体流动，变形，热传递&矿物反应的耦合过程

Alison Ord

Centre for Exploration Targeting,
University of Western Australia

One Hour Presentations

1. A Systems Approach: The 5 Questions
2. Folding & Boudinage
3. Shear Zones, Fractures, Breccias and Veins.
4. The Regional Scale – Fundamentals
5. The Regional Scale – Applications
6. Synthesis – The Way Ahead

Understanding an Evolving Orogen

造山带演化的理解

Chris Wijns, Brett Davies*,
Alison Ord, Louis Moresi
CSIRO Exploration and Mining
* Normandy Mining

CSIRO

Understanding an Evolving Orogen

–Olary-Broken Hill conceptual model 概念模型

–numerical methods 数值方法

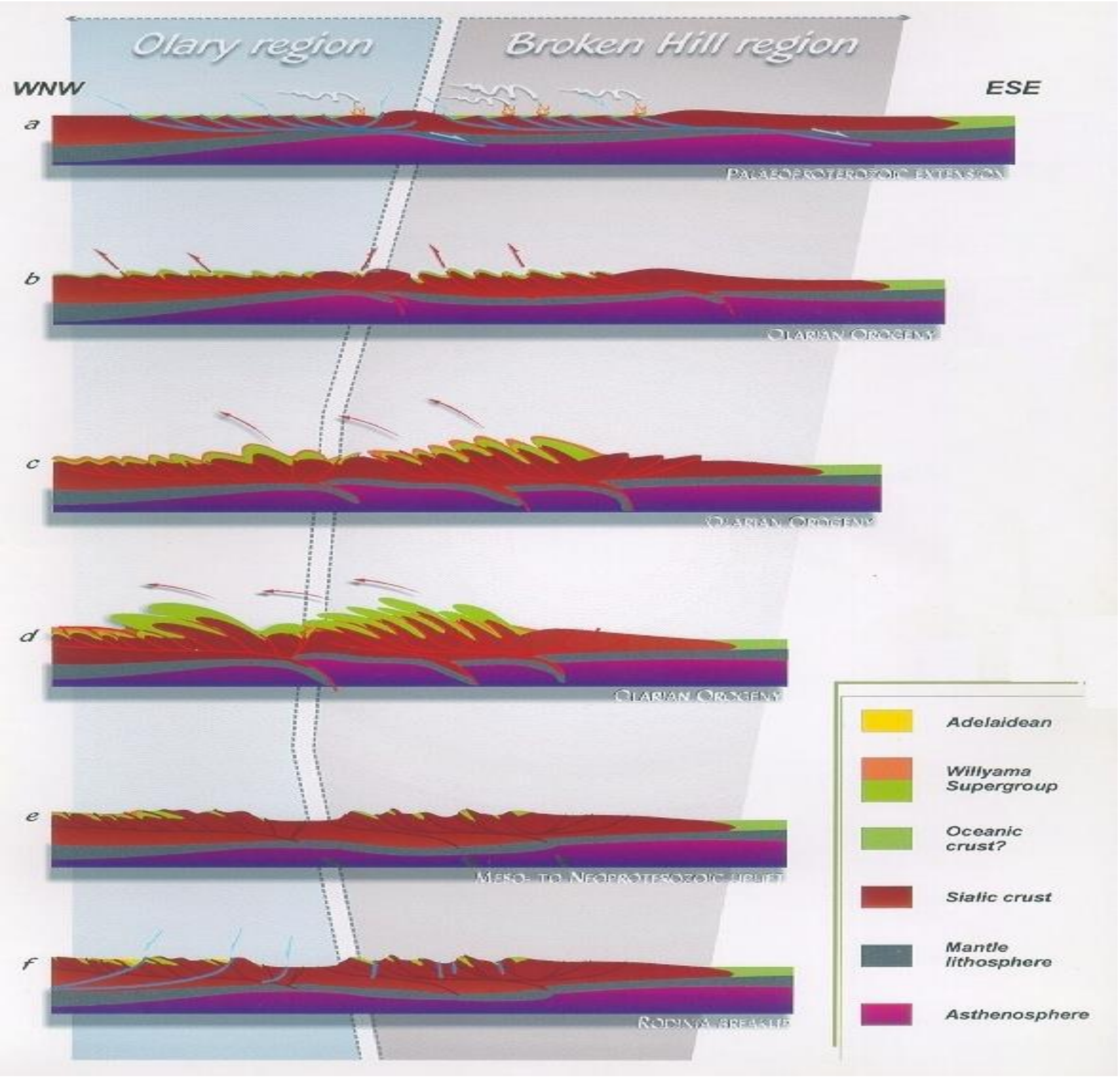
–modelling results 建模结果

Modelling Results

- dry models 干模型
- parameter experimentation 参数实验
- saturated 饱和的
- compare to conceptual model 与概念模型对比

Olary-Broken Hill Tectonic History

- **large-scale extension**
  大尺度伸展
- **regional shortening**
  区域压缩
- **propagating overthrusting**
  逆冲推覆
- **fluid generation and migration**
  产生流体并运移
- **end of orogeny → melting, end of significant fluid generation and migration**
  造山熔融终止，大规模流体产生及运移终止

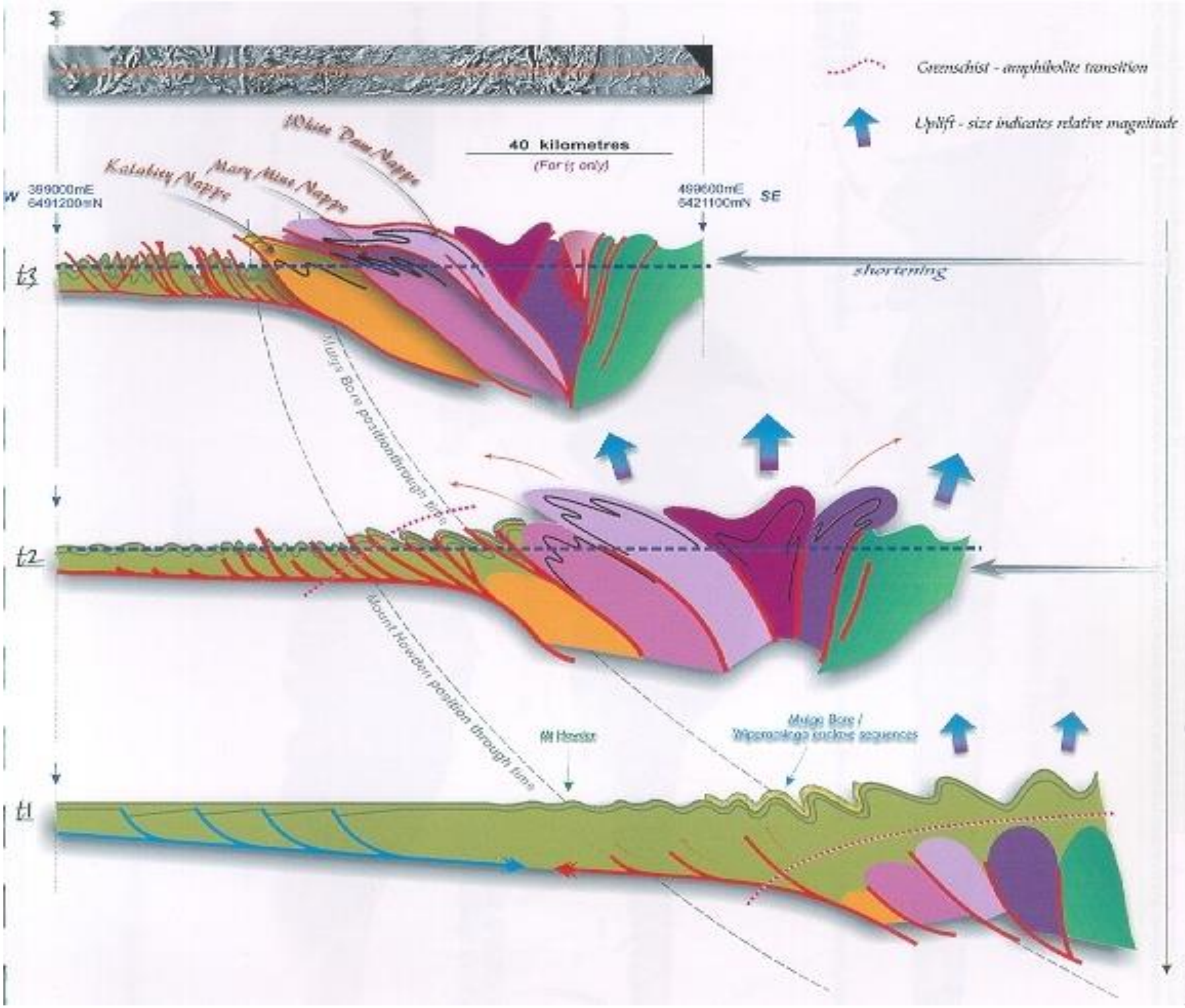


Olarian Orogeny

1570 Ma end

1600 Ma reworking

1630 Ma inversion

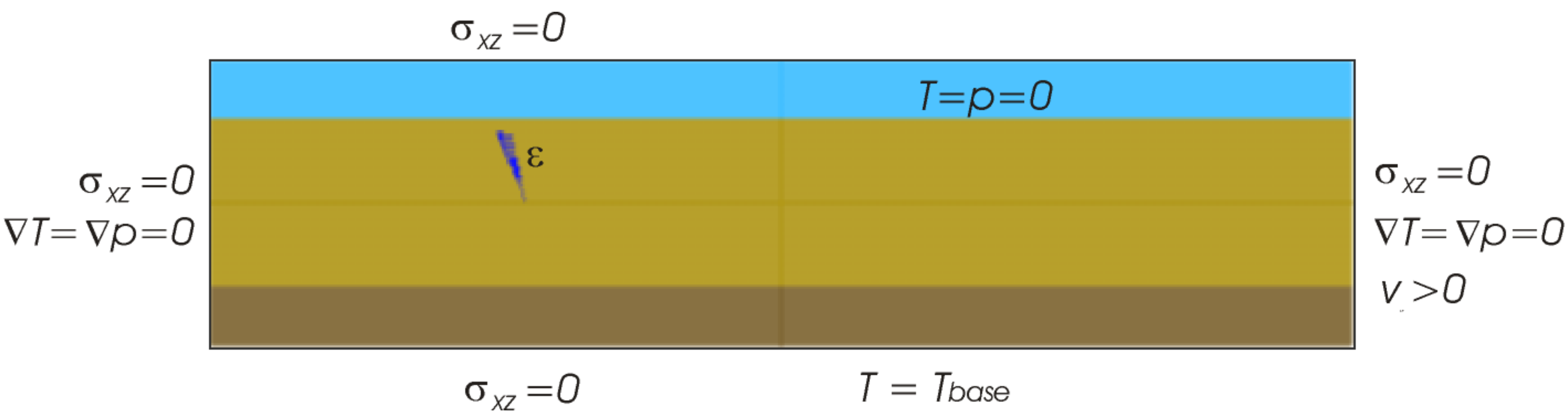


Numerical Code

- geodynamic processes (地球动力学进程)
  - **folding, thrusting, subduction （褶皱，推覆，俯冲）**
  - **partial melting of mantle （地幔部分熔融）**
  - **resultant fluid flow （流体流动）**
- large (unlimited) deformation (大/无限的变形)
  - **viscous fluid （粘性流体）**
  - **particle-in-cell-code solves finite element equations on a grid （质点网格法求解基于网格的有限元方程）**
  - **moveable integration points advect information （移动积分点传导信息）**

Experimental Box

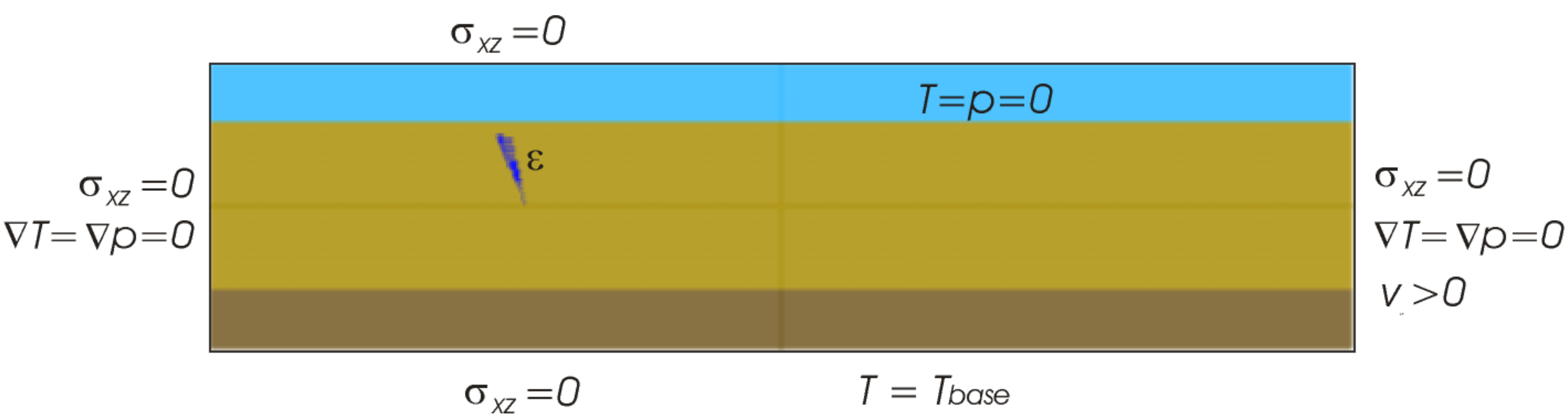
- air layer**: negligible viscosity → no interference**
  空气层：粘度可忽略，无干预
- brittle upper crust**: high viscosity, yield law to simulate brittleness**
  脆性上地壳：高粘度，基于屈服准则模拟脆性材质
- plastic lower crust**: low viscosity, some stress dependence**
  塑性下地壳：低粘度，一定的应力依赖性



Experimental Box

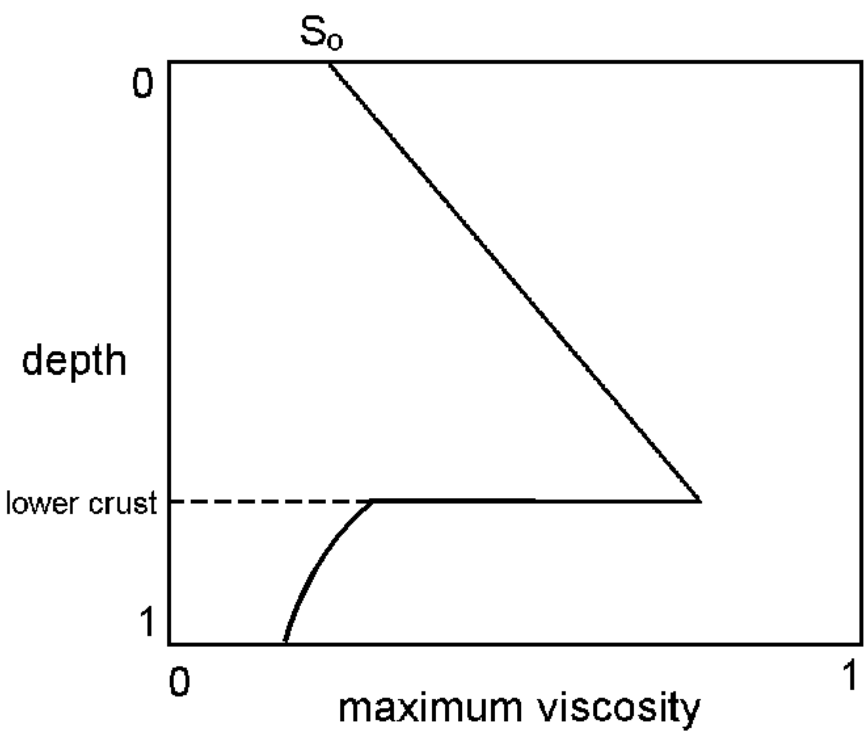
– boundary conditions **(边界条件)**：

- **-“solid” shear stress 固体剪切应力**
- **-temperature 温度**
- **-pore pressure 孔压**
- **-initial strain perturbation 初始应变扰动**



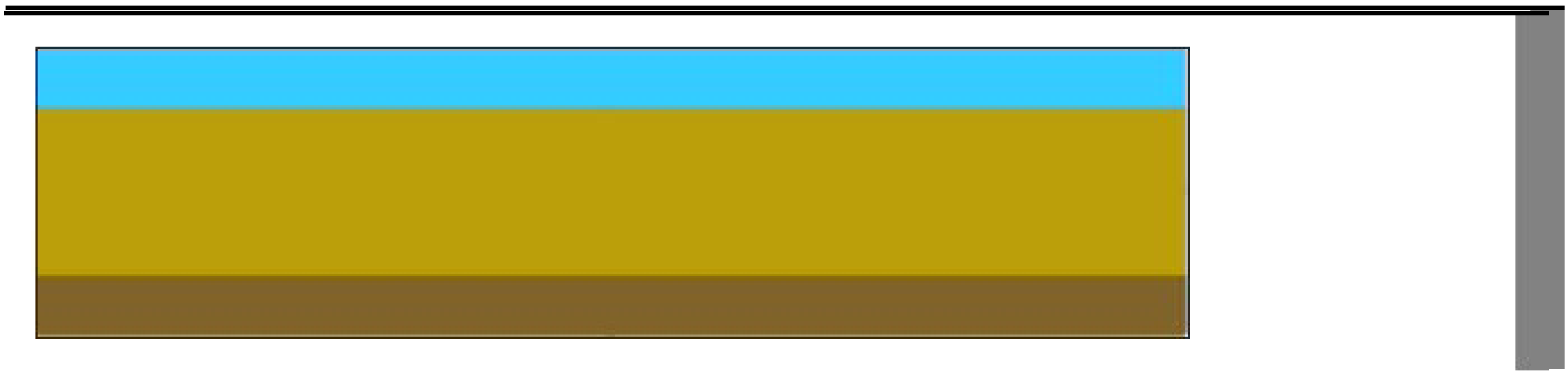
Crustal Strength

- *described by viscosity* **(粘度描述)**
  - **limited by yield curve → effective viscosity**
    受限于屈服曲线 → 有效粘度

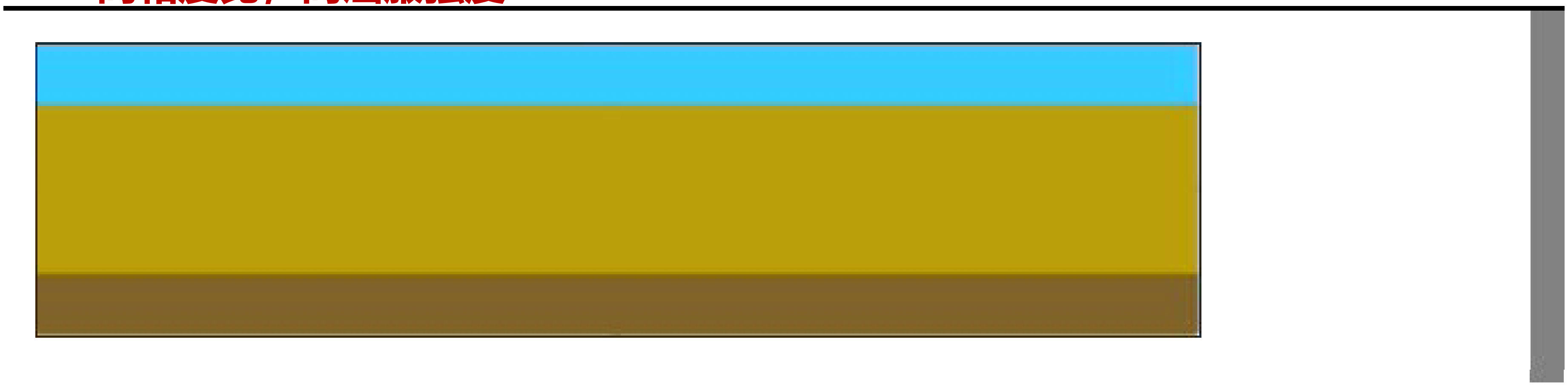


Dry Model Experiments

- **Low viscosity contrast between layers**
  层间低粘度比

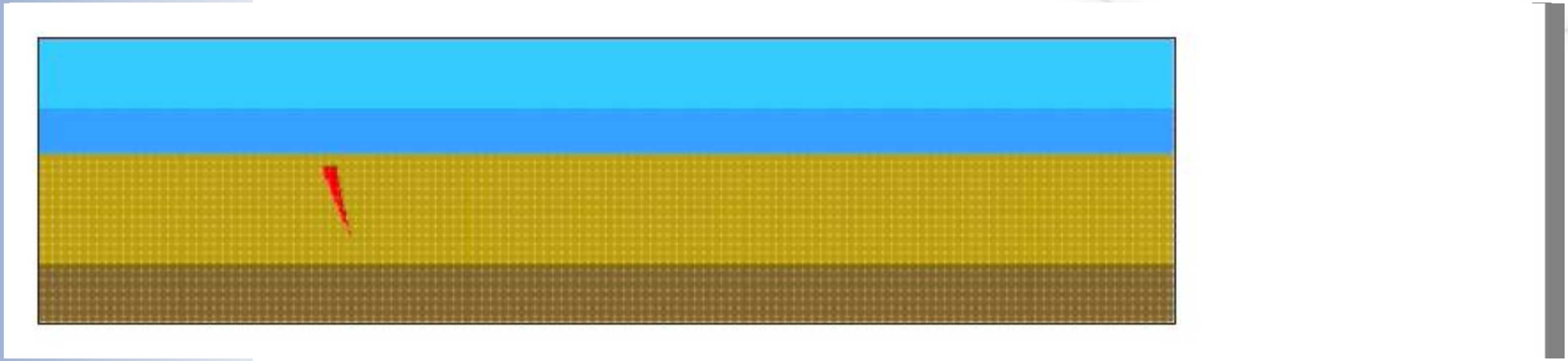


- **High viscosity contrast, high yield strength**
  高粘度比，高屈服强度



Dry Model Experiments

- **large viscosity contrast between crustal layers, lower yield viscosity (blue = shear zones)**
  地壳层间粘度比很高，低屈服粘度（蓝色 = 剪切带）



Addition of Pore Fluid

- effective stress 有效压力

solid stress + fluid stress

= solid stress + pore pressure

固体压力+流体压力

= 固体压力+孔隙压力

Addition of Pore Fluid

- porosity evolution   孔隙度演变

Porosity ϕ depends upon bulk solid volume changes

孔隙度Φ取决于固体体积变化

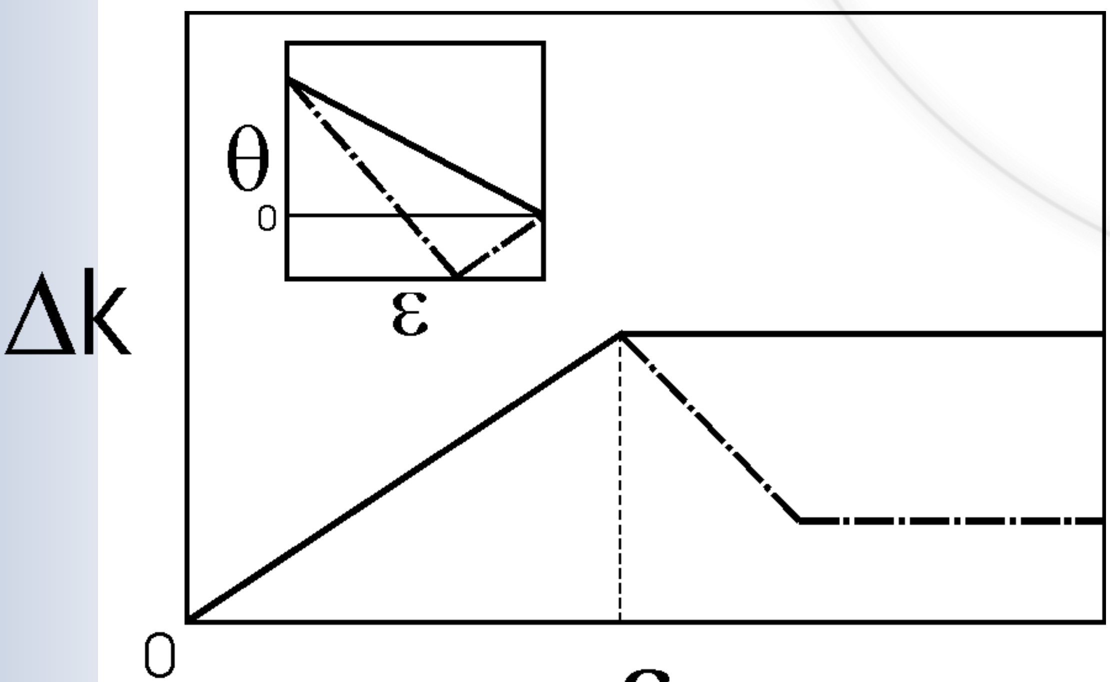
Addition of Pore Fluid

- permeability evolution **(渗透率演变)**

permeability k = k(ϕ , ε_p)

(plastic strain dependence → dilation angle)

(塑性应变依赖→ 膨胀角)

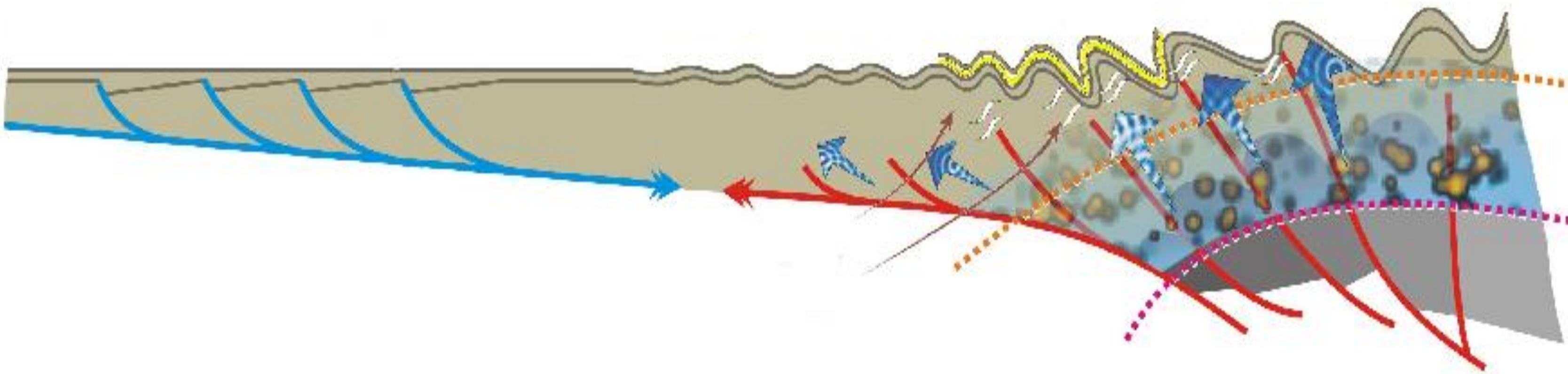


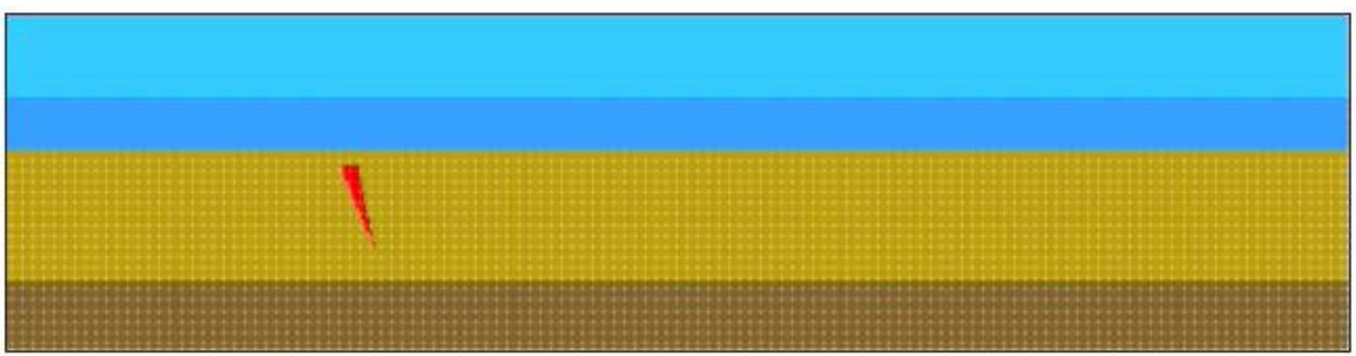
Physical Assumptions

- connected pore network 孔隙网骆相连
- saturated medium 饱和媒介
- fluid flows according to Darcy's Law 流体流动遵循达西定律
- ignore capillary pressures 忽略毛细管压
- neglect gain compression(i.e. incompressible solid)
  忽视压缩增益（例如：固体不可压缩）
- no thermal strains in the solid 固体中无热应变

Pore Flow

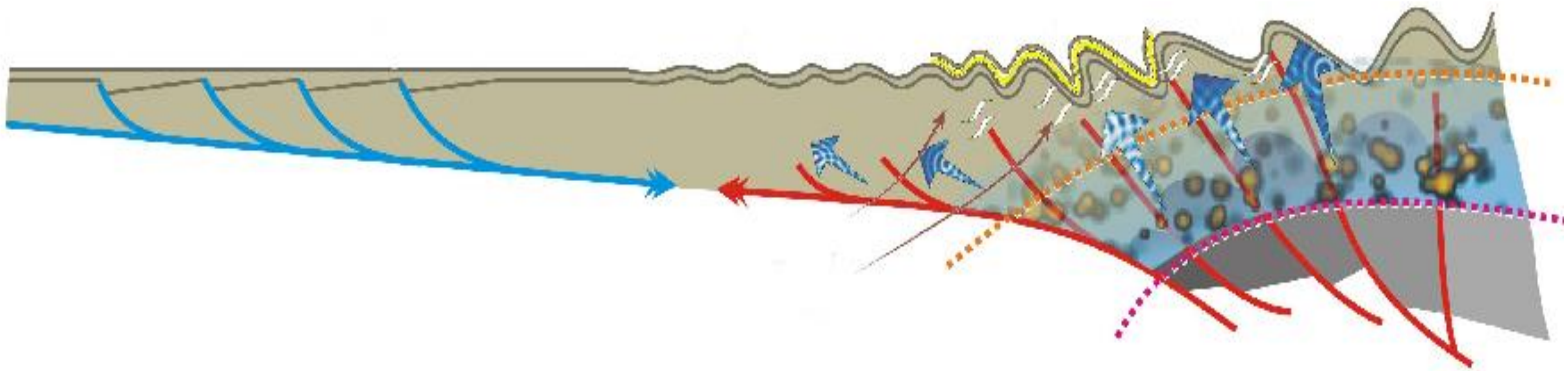
- **extension + compression** 伸展+挤压

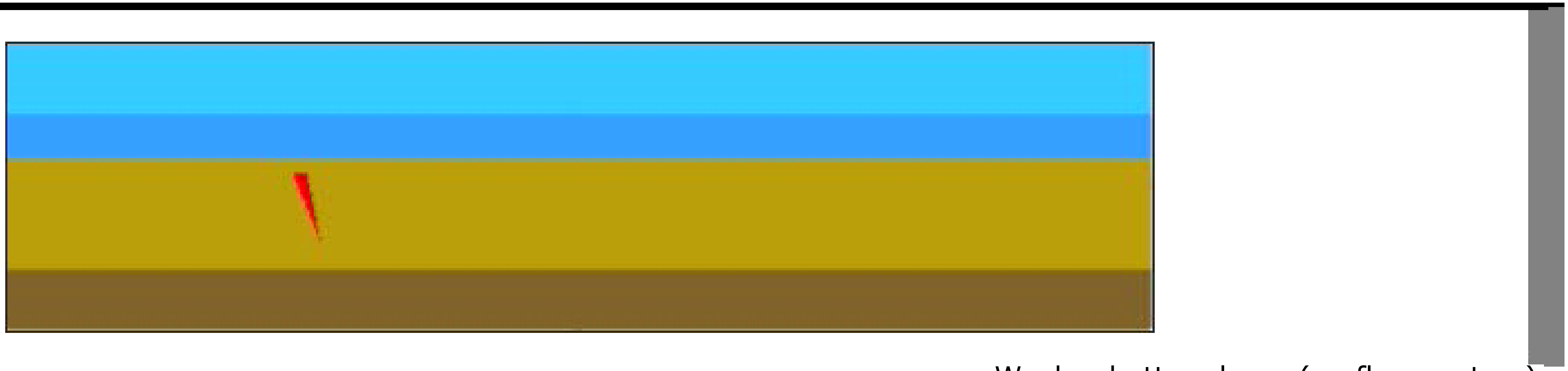




Pore Flow

- extension + compression 伸展+挤压

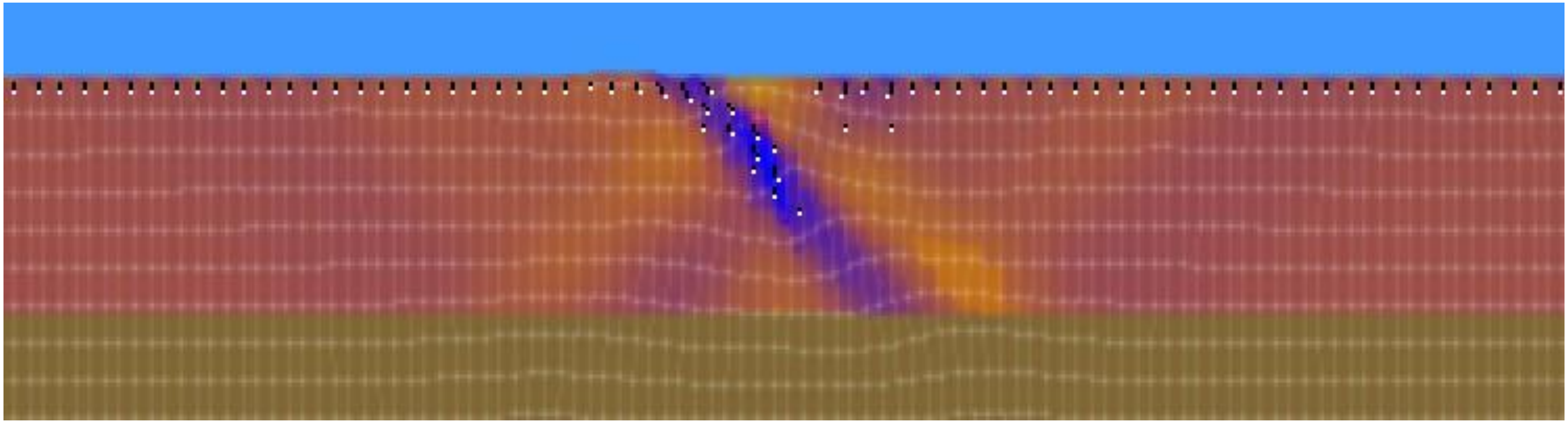




Weaker bottom layer (no flow vectors)

Pore Flow

- initial drawdown during extension
  - 伸展过程中，初始为向下流动



Pore Flow

- flow down faults （blue）during extension
  - 伸展过程中，向下流经断层

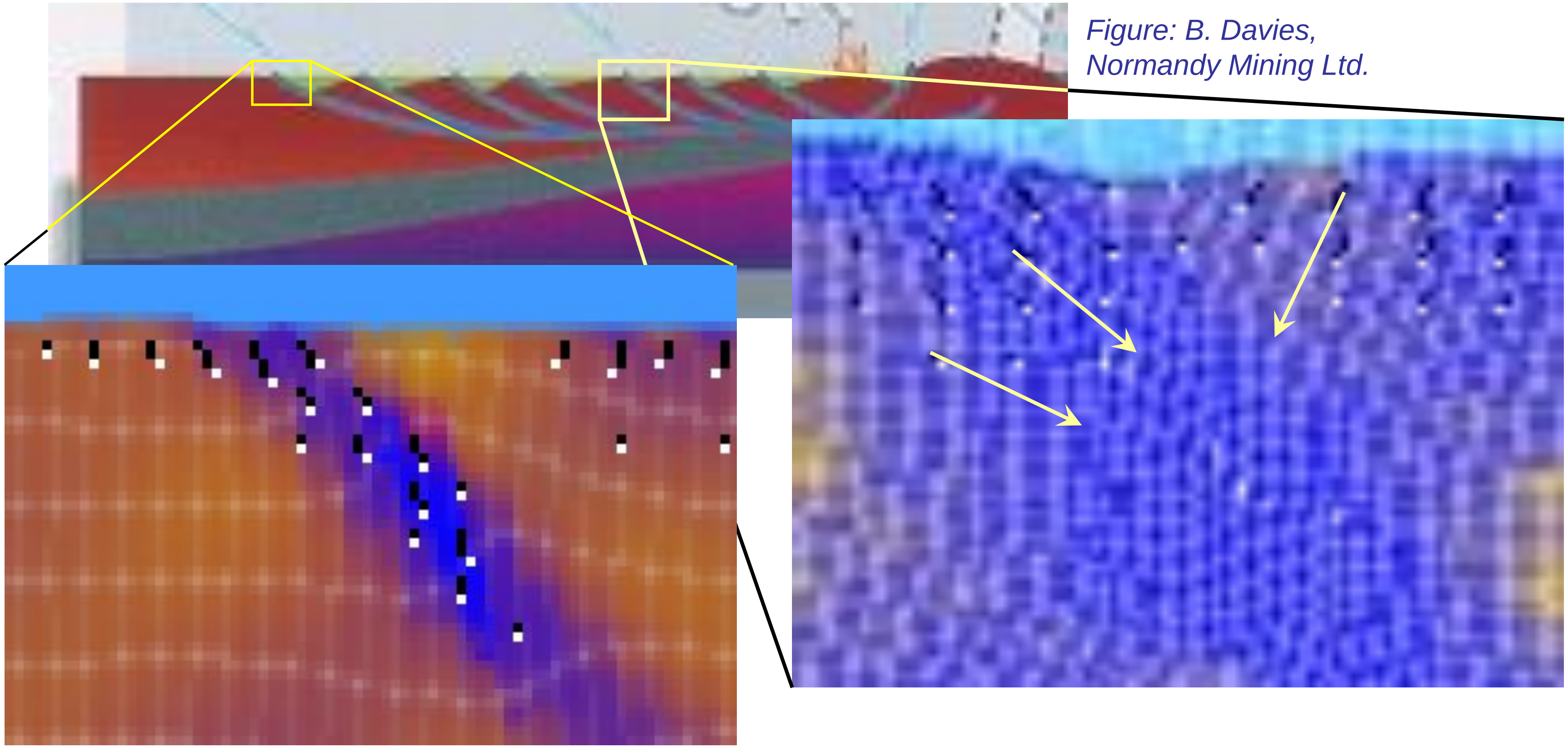


Figure: B. Davies, Normandy Mining Ltd.

Pore Flow

- **flow up (blue) faults during compression**

挤压过程中，流体经断层向上流动

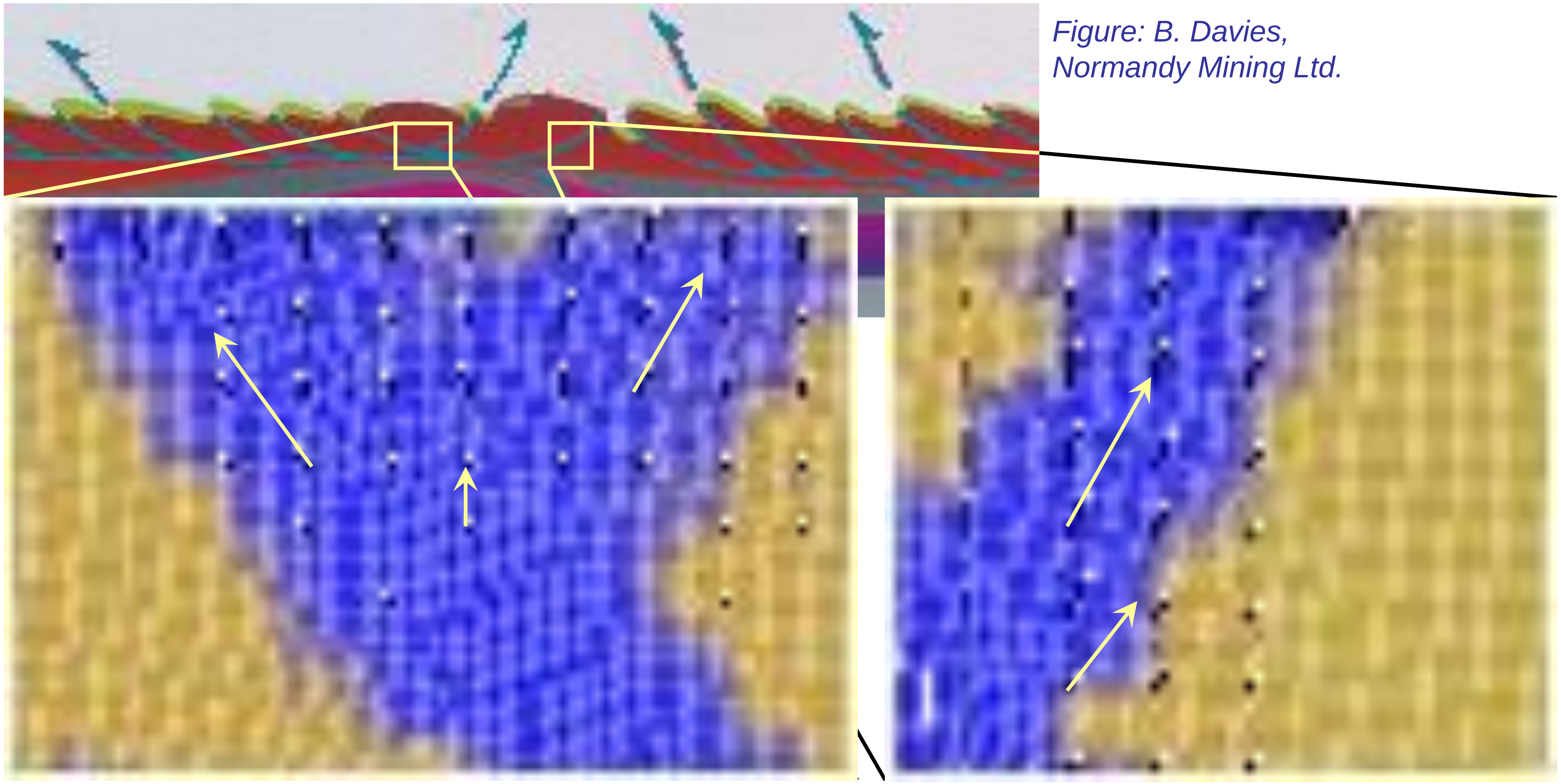
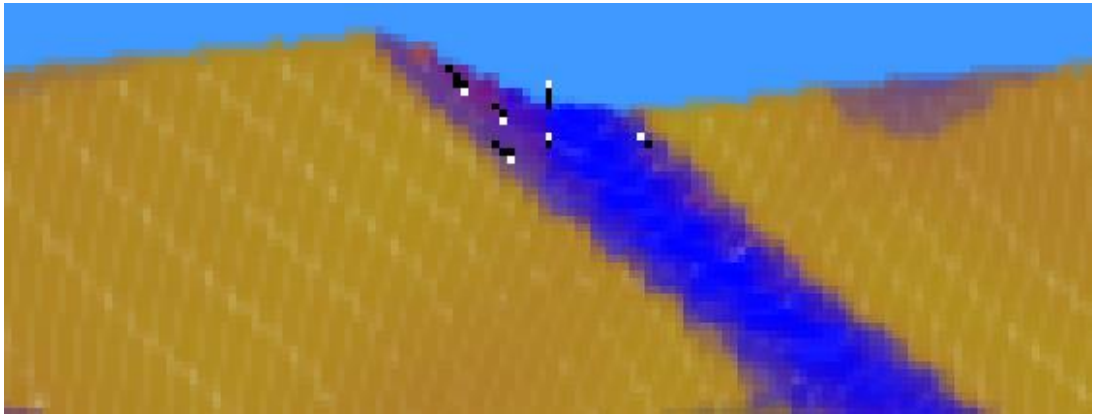


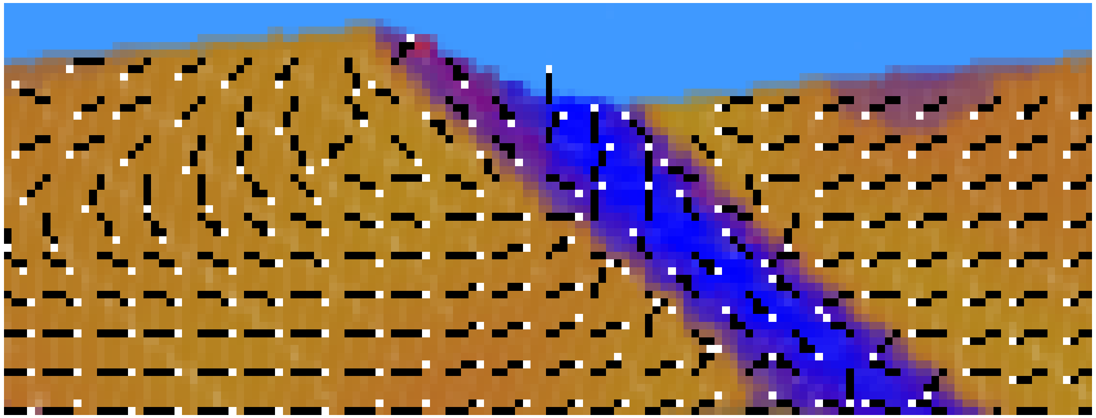
Figure: B. Davies, Normandy Mining Ltd.

Pore Flow

- **influence of topography**

受地势影响





Competing effects of upward flow from compression and topographically driven downward flow

挤压导致的向上运动的流体与地势引起的向下运动的流体出现竞争效应

Next Steps

- anisotropic dilation angle effect

  各向异性膨胀角影响

- anisotropic permeability development in shear zones

  剪切带中的渗透率各向异性

  → fluid flow seal across perpendicular

  → 垂向流体流动封闭

- fluid boundary conditions need to be carefully considered

  细致考虑流体边界条件

Conclusions

- code is a tool
  代码是工具
- reproduces qualitative features of conceptual model
  重建概念模型中的定性特征
- extension - fluid channelled towards and down faults
  伸展 - 流体在断层中上下运移
- compression - fluid channelled up faults during reworking of domains
  挤压 -流体在断层中向上运移

Future

- fully coupled deformation, fluid flow, thermal, and chemical effects

  完全耦合的变形、流体、热和化学反应
- predictive mineral discovery

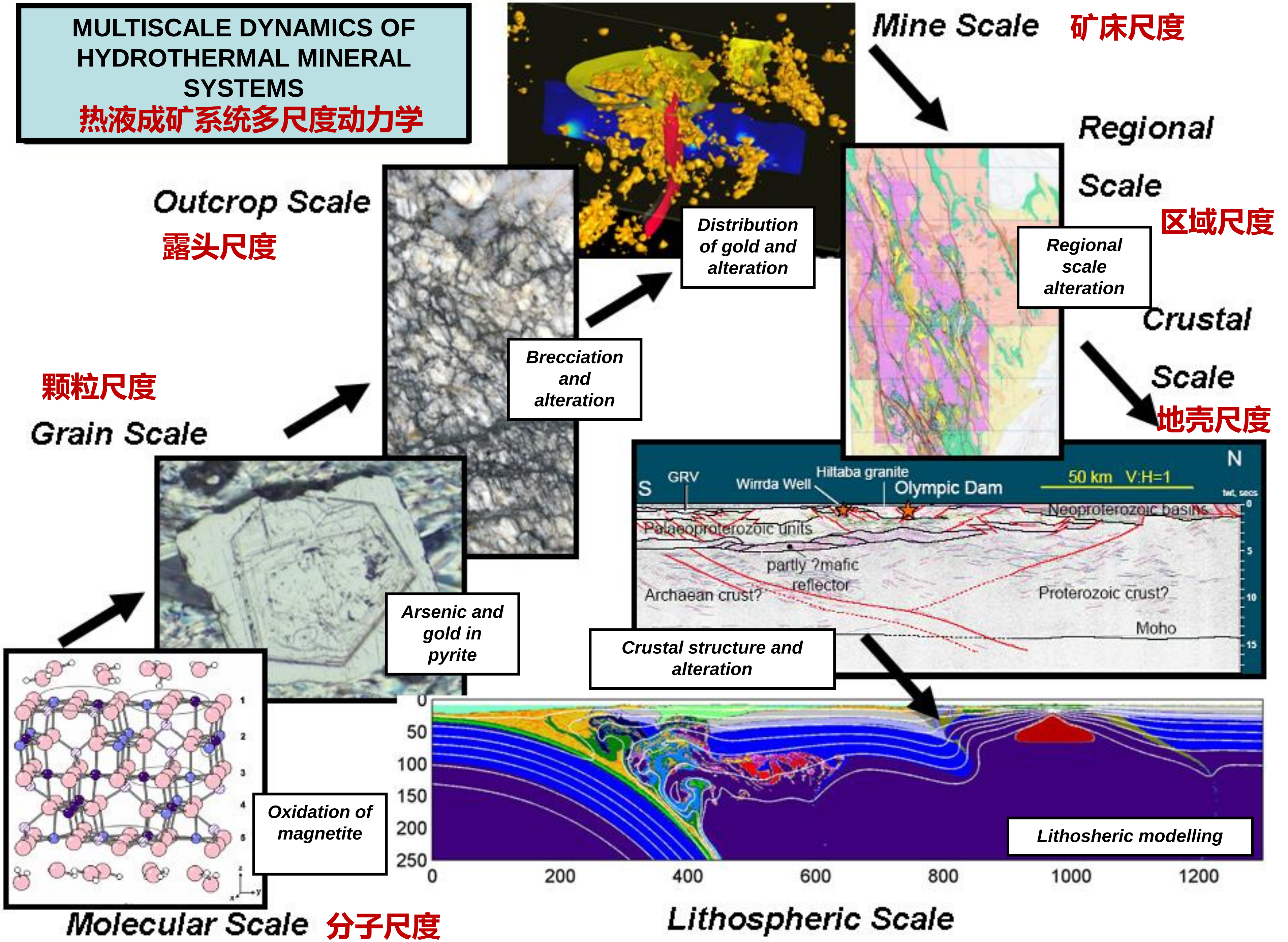
  辅助找矿预测

MULTISCALE DYNAMICS OF ORE BODY FORMATION

Bruce Hobbs, Weronika Gorczyk, Alison Ord and Klaus Gessner

成矿多尺度动力学

Thanks to Ian Tyler, Catherine Spaggiari and Hugh Smithies



MULTISCALE DYNAMICS OF HYDROTHERMAL MINERAL SYSTEMS
热液成矿系统多尺度动力学
Mine Scale 矿床尺度
Distribution of gold and alteration
Regional Scale 区域尺度
Regional scale alteration
Crustal Scale 地壳尺度
Outcrop Scale 露头尺度
Brecciation and alteration
颗粒尺度 Grain Scale
Arsenic and gold in pyrite
Molecular Scale 分子尺度
Oxidation of magnetite
S
GRV
Wirrda Well
Hiltaba granite
Olympic Dam
50 km V:H=1
N
Neoproterozoic basins
Palaeoproterozoic units
partly ?mafic reflector
Archaean crust?
Proterozoic crust?
Moho
Crustal structure and alteration
0
50
100
150
200
250
0
200
400
600
800
1000
1200
Lithosheric modelling
Lithospheric Scale

Our messages for today:

1. Deformation and metamorphism originating from lithospheric drips are common.

   源于岩石圈下降流变形和变质作用非常普遍

2. This setting may have little to do with nearby subduction.

   这种地质背景与靠近俯冲带可能不存在关系

3. Mineralisation is common in these areas [Olympic Dam,Yilgarn, Carlin, Yangste, Mt. Isa, Albany-Fraser(?)].

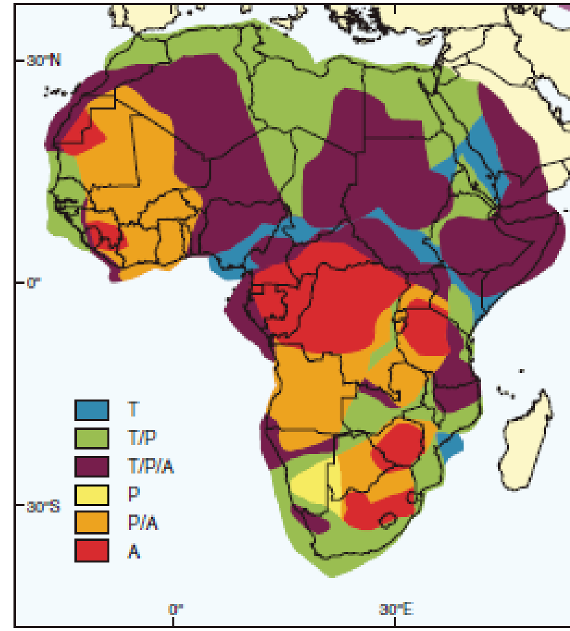
   在这些区域矿化普遍

4. There are clear signatures in the geological record waiting to be read.

   在地质记录里这里有许多特征需要解读

Background: Lithospheric architecture

背景： 岩石圈结构



Old continents are composed of an amalgamated mosaic of micro-continents that are characterized by different:

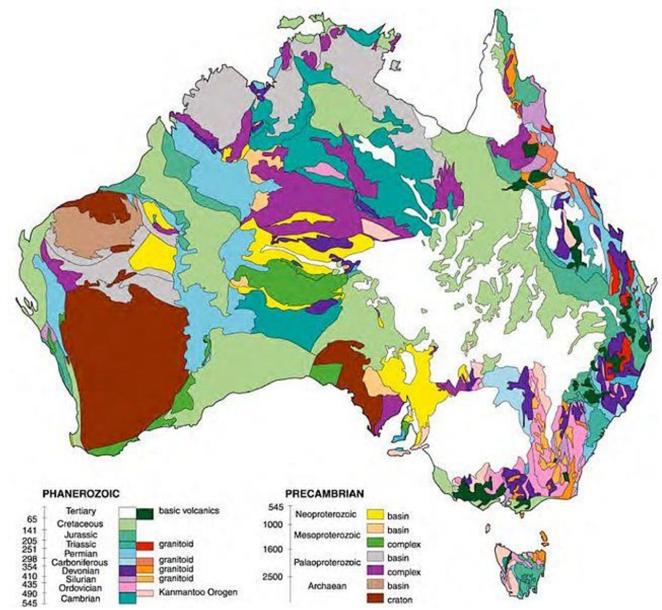
古陆由许多具有不同特点的微大陆组成

- thermal structure 热结构
- composition of SCLM 次大陆岩石圈地幔
  (subcontinental mantle lithosphere)
- geometries 几何形态
- rheological characteristics 流变学特征

⇩

Laterally heterogeneous structure of continental lithosphere

大陆岩石圈横向非均匀

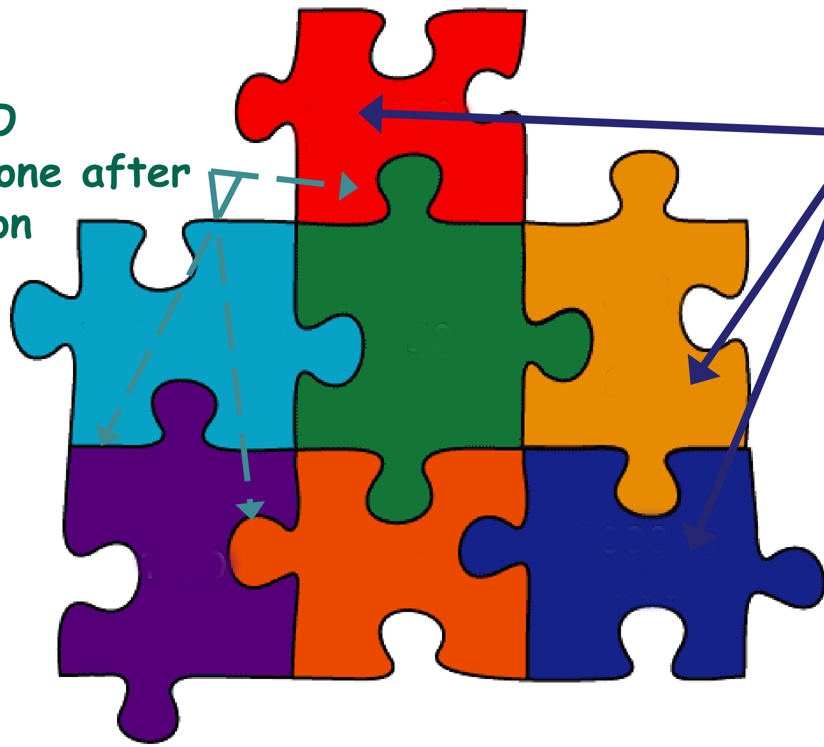


Old continents can be characterized as puzzles of strong and solid blocks with the weakest places at the boundaries of the blocks

古陆可以看作是一些强大坚韧而边部软弱的块体

Weak:
- residue H2O
- weakened zone after amalgamation

残留水
混染后的软弱区



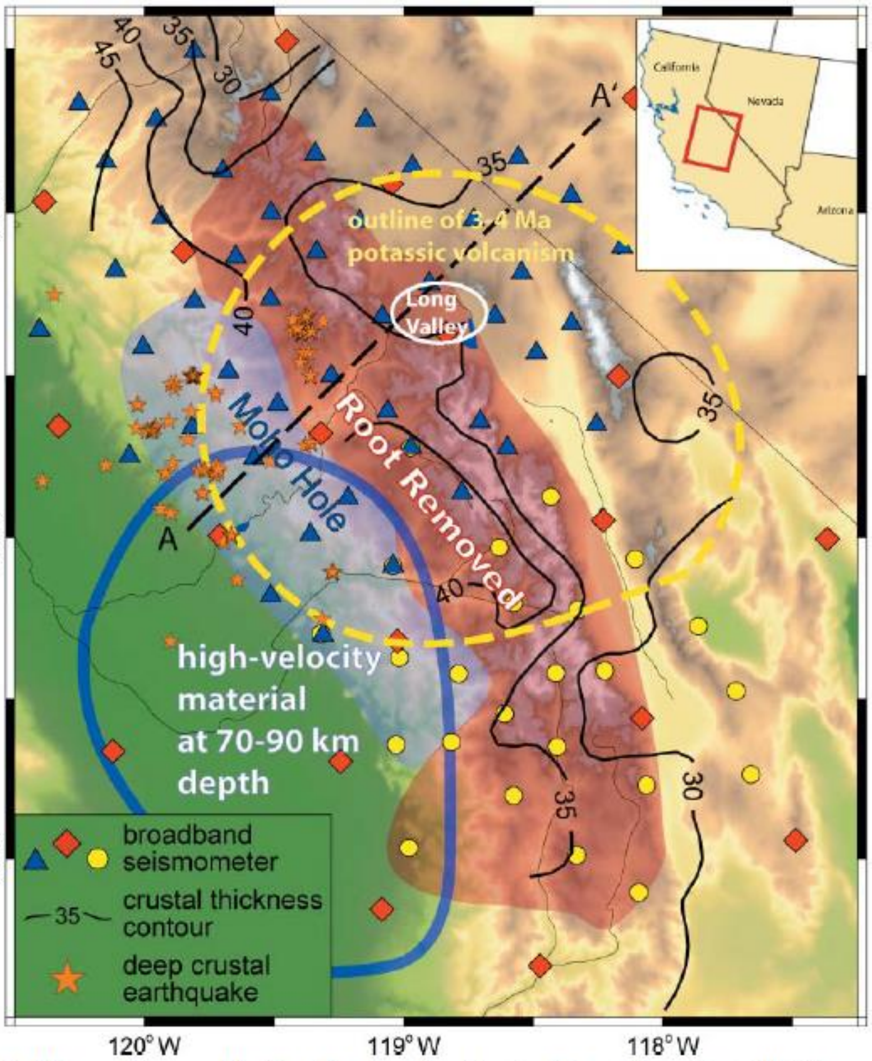
Strong:
- depleted mantle lithosphere
- dry
- stiff

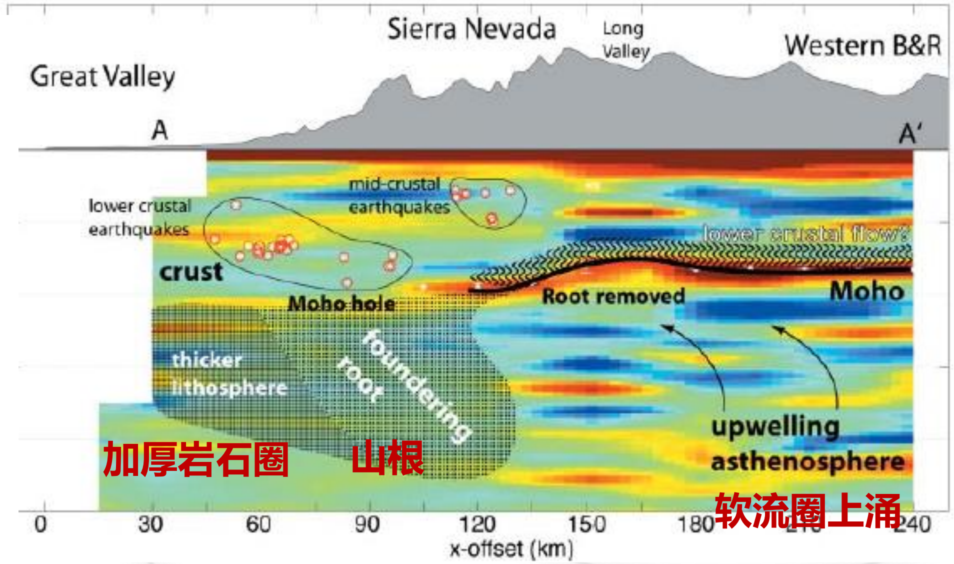
亏损岩石圈地幔
干
僵硬

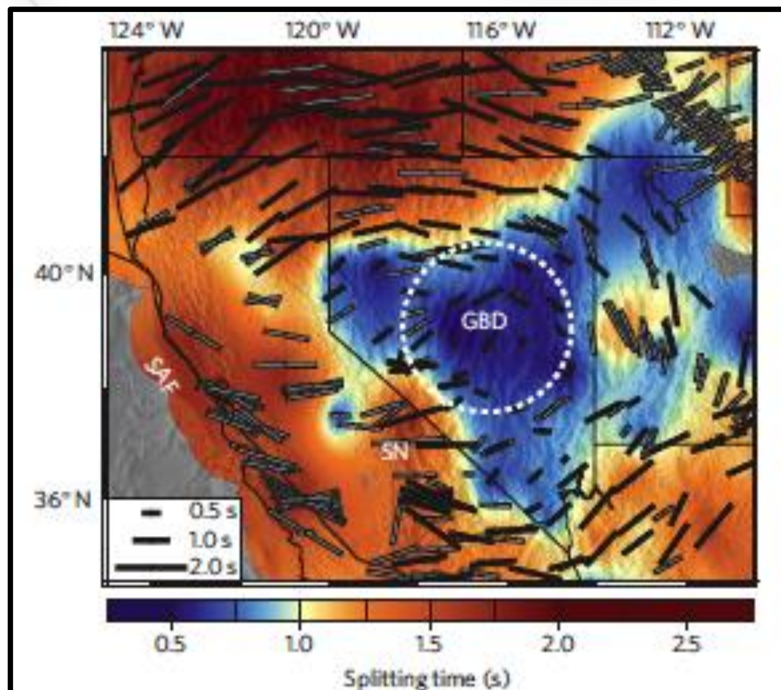
The evidence indicates that these boundaries are channel-ways for CO_2 + other juices during later reactivation leading to alkaline magmatism and mineralisation

证据表明这些边界是后期活化过程中CO2和其他流体的通道，导致了碱性岩浆及成矿作用

Eos, Vol. 88, No. 21, 22 May 2007



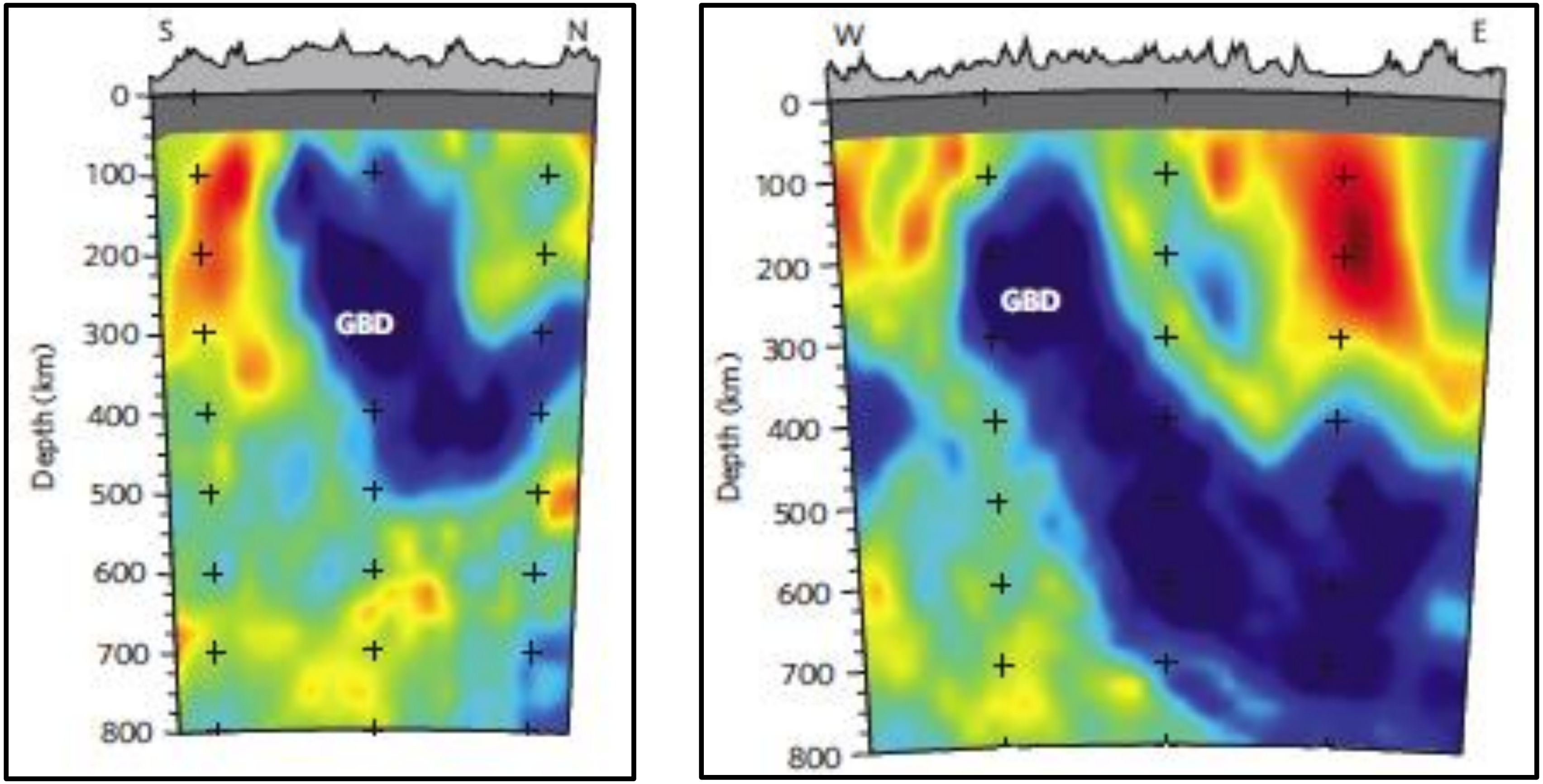




From West et al. (2009)

LITHOSPHERIC DRIP UNDER NEVADA

内华达深部岩石圈滴落



From West et al. (2009)

岩石圈滴落方向

Orientation of Lithospheric Drip

- Mantle flow is northeast relative to North American plate motion? 地漫流相对北东向美洲板块运动?

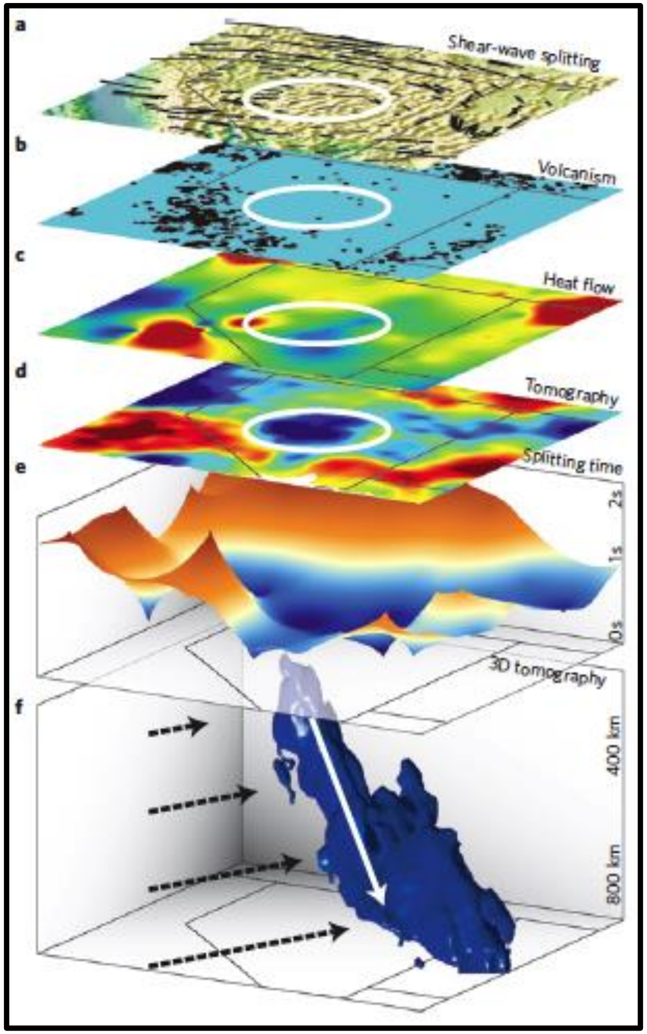


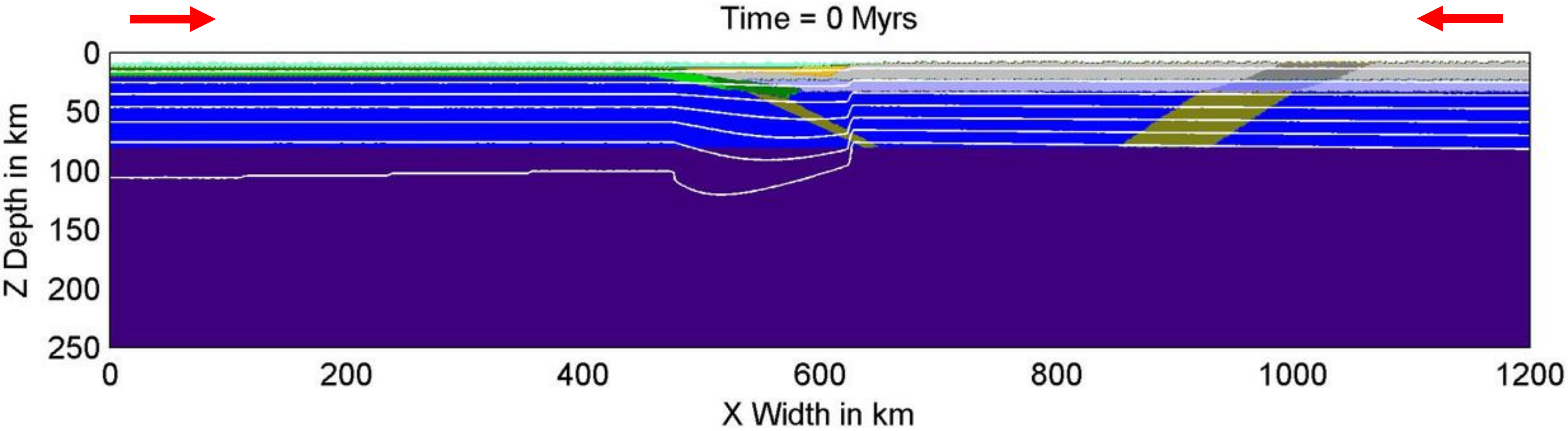
Figure 4 | Summary of geological and geophysical constraints for the central Great Basin. a, Shear-wave splitting with the topography background for reference. **b**, Post-10-Myr volcanism (black circles)[29] shows a regional dearth of volcanic activity. **c**, Heat flow[14] showing reduced values (~50 mW m^{-2}, blue) in the regional high (>100 mW m^{-2}; yellow and red). **d**, Seismic tomography horizontal slice at 200 km depth, as in Fig. 2a. **e**, Shear-wave splitting times surface showing the strong drop in the central Great Basin. The colour range is as in Fig. 1. **f**, Isosurface at +0.95% velocity perturbation for NWUS08-P2 showing the morphology of the drip, which merges with a larger structure at ~500 km depth. The black arrows denote the inferred mantle flow direction; the white arrow denotes the flow direction of the Great Basin drip.

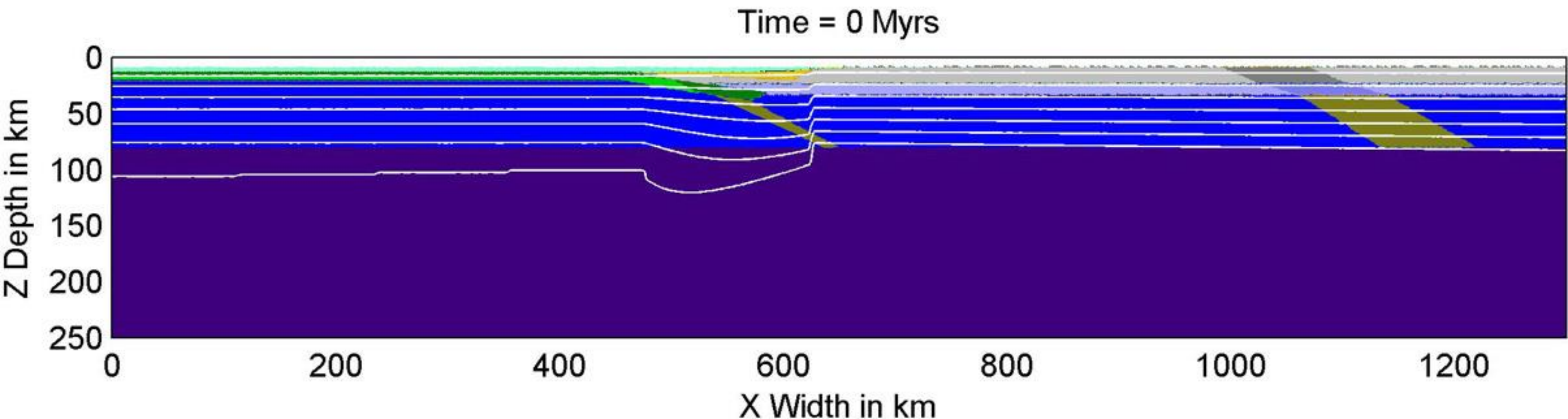
From West et al. (2009)

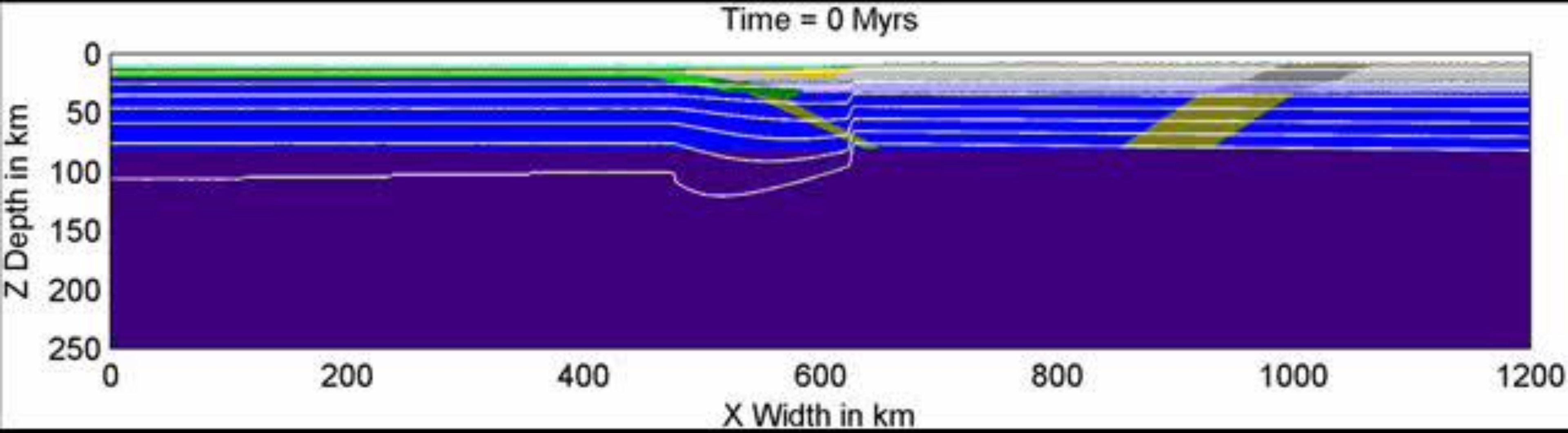
The following movies have the same strength for the weak zones but the strength of the lower crust is lower in the second and fourth movies.

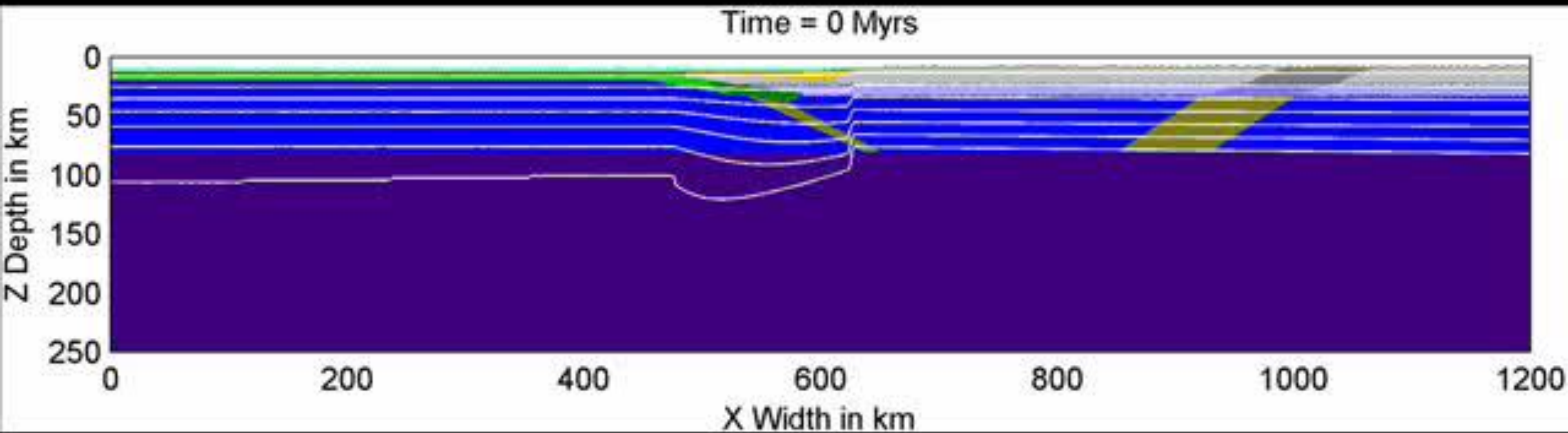
下面的影片中具有相同强度的软弱区，但在第二个和第四个影片中，上地壳强度较小

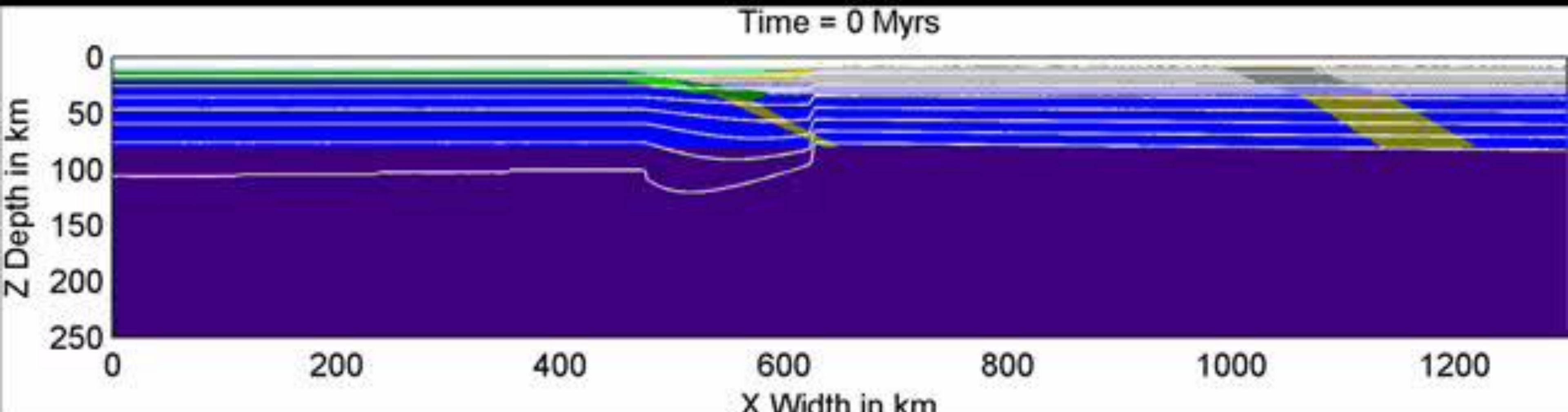
Initial condition

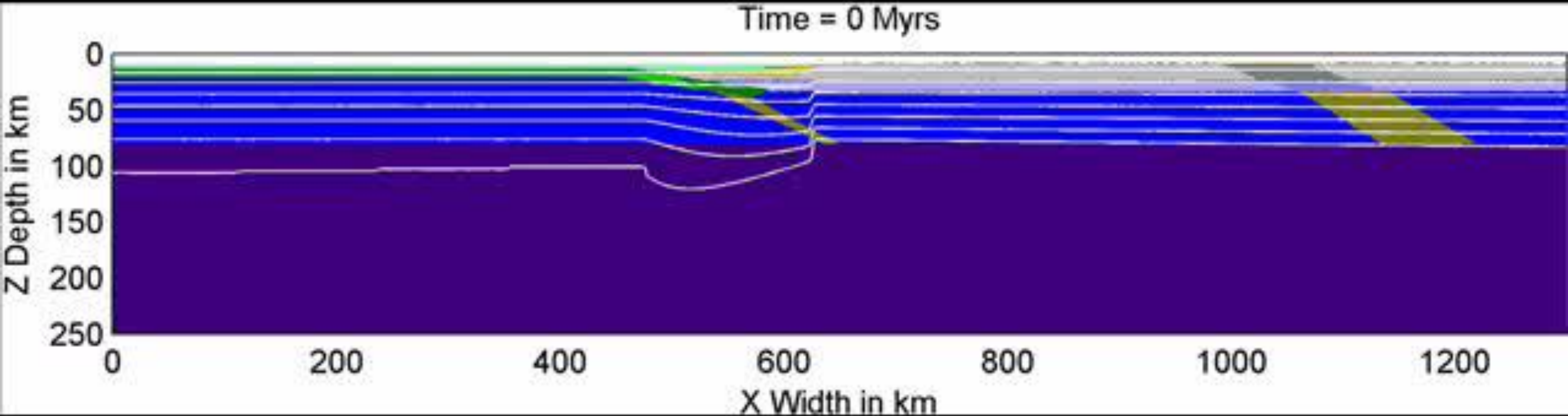




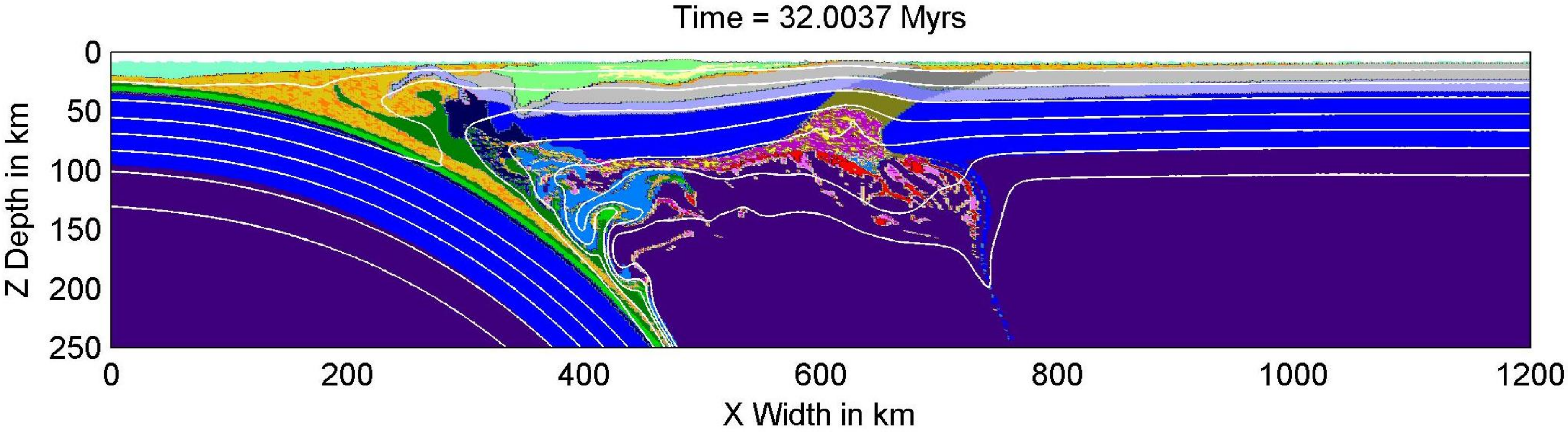

Time = 0 Myrs
0
50
100
150
200
250
Z Depth in km
0
200
400
600
800
1000
1200
X Width in km


Time = 0 Myrs
0
50
100
150
200
250
Z Depth in km
0
200
400
600
800
1000
1200
X Width in km

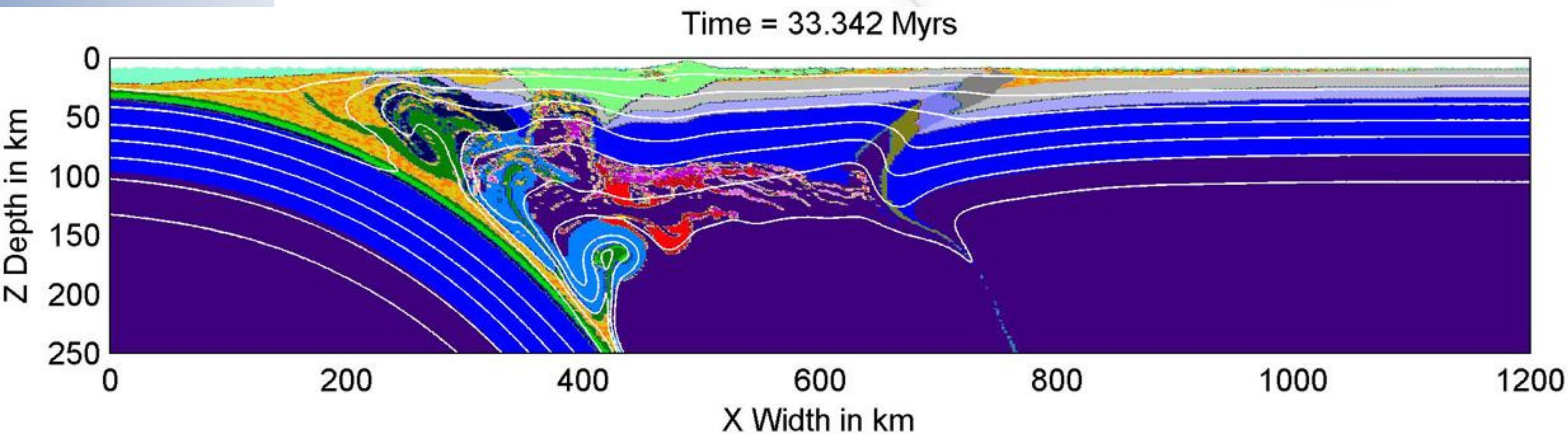

Time = 0 Myrs
Z Depth in km
0
50
100
150
200
250
0
200
400
600
800
1000
1200
X Width in km



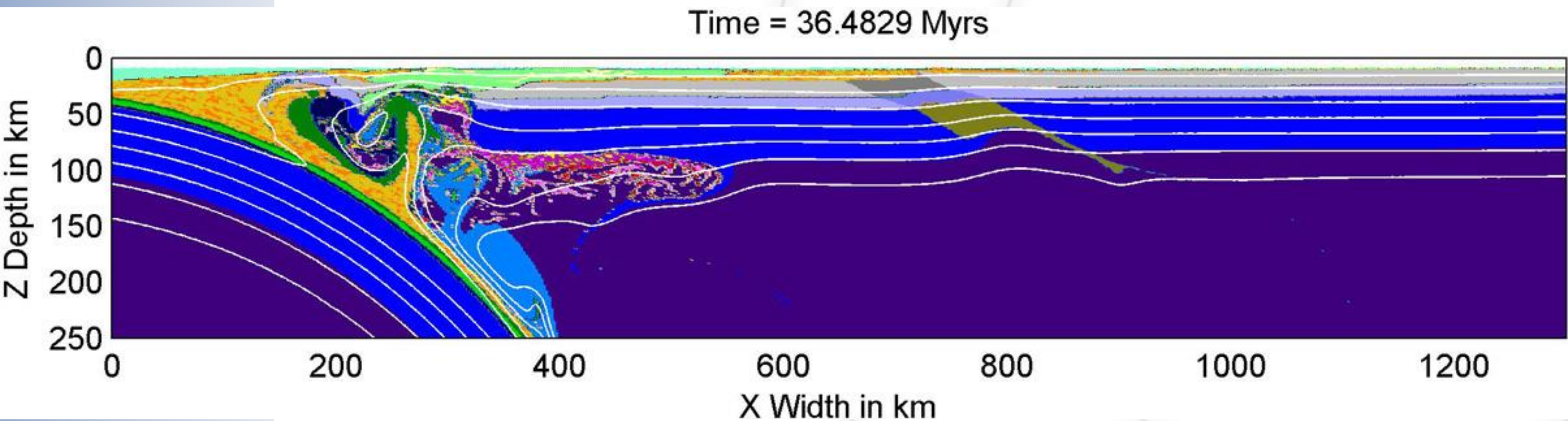
Time = 0 Myrs
Z Depth in km
0
50
100
150
200
250
0
200
400
600
800
1000
1200
X Width in km

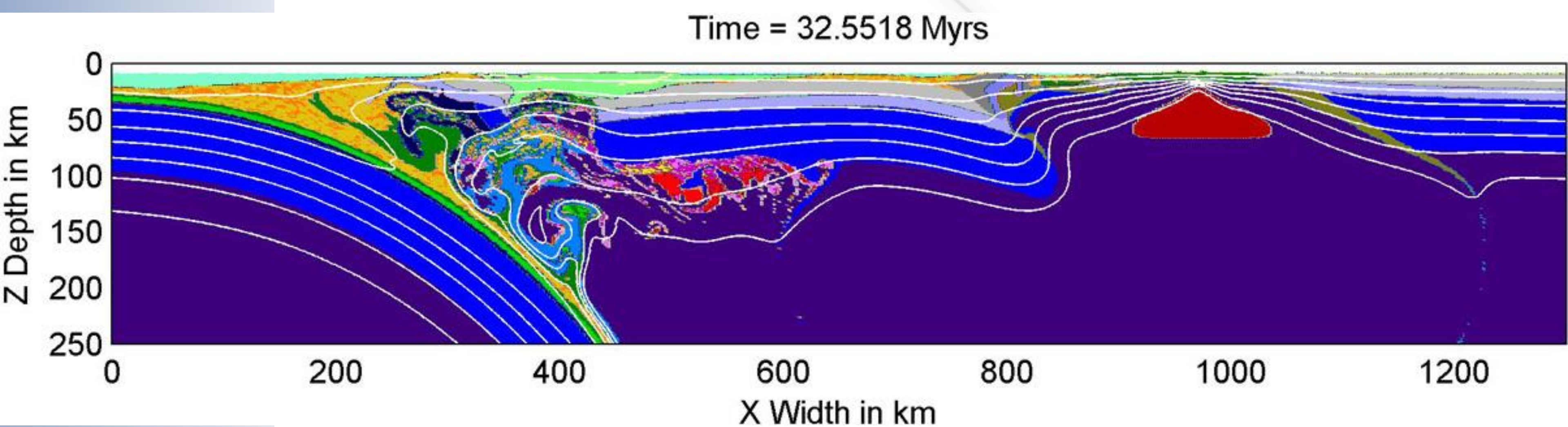


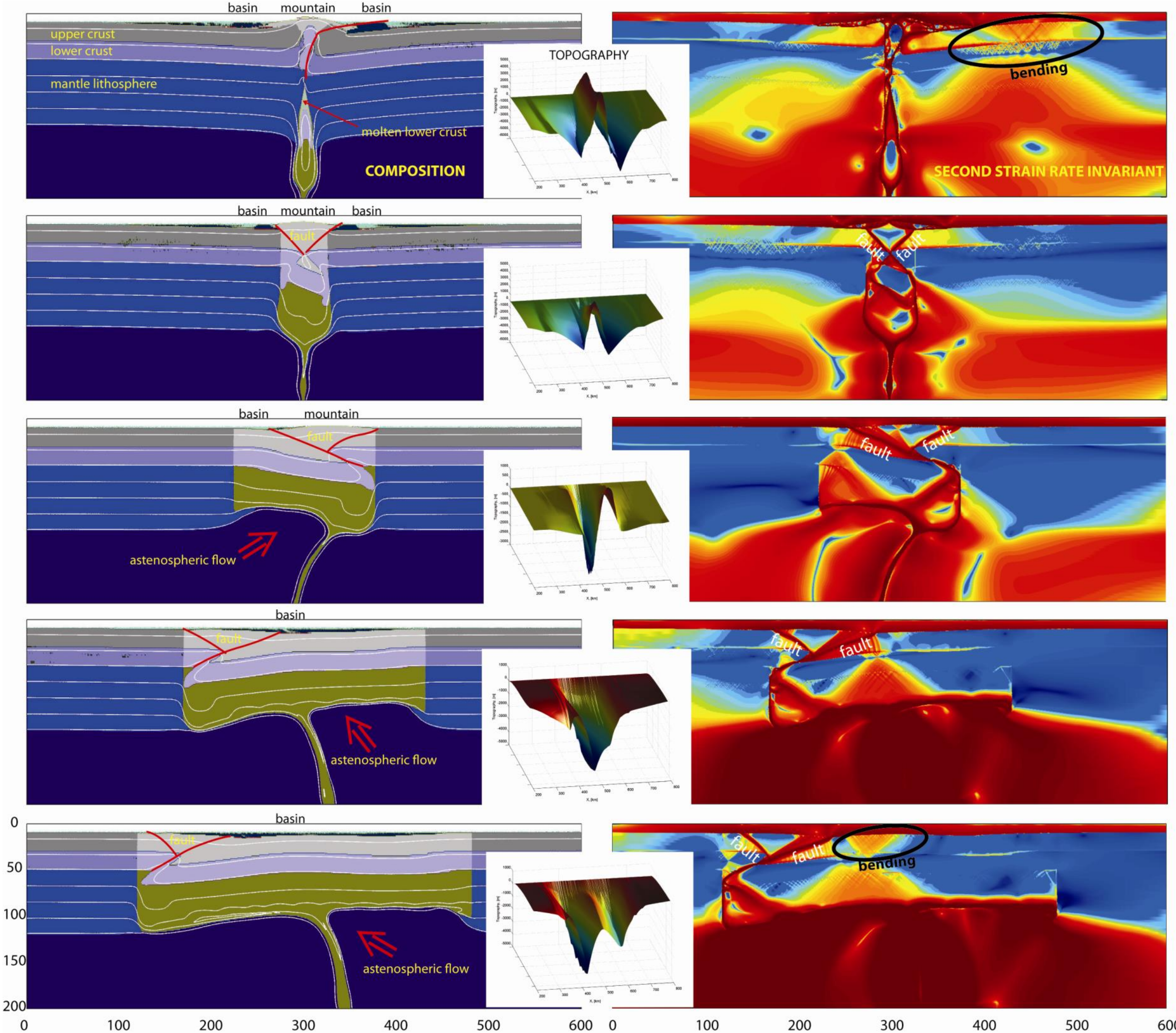
Time = 32.0037 Myrs
Z Depth in km
X Width in km



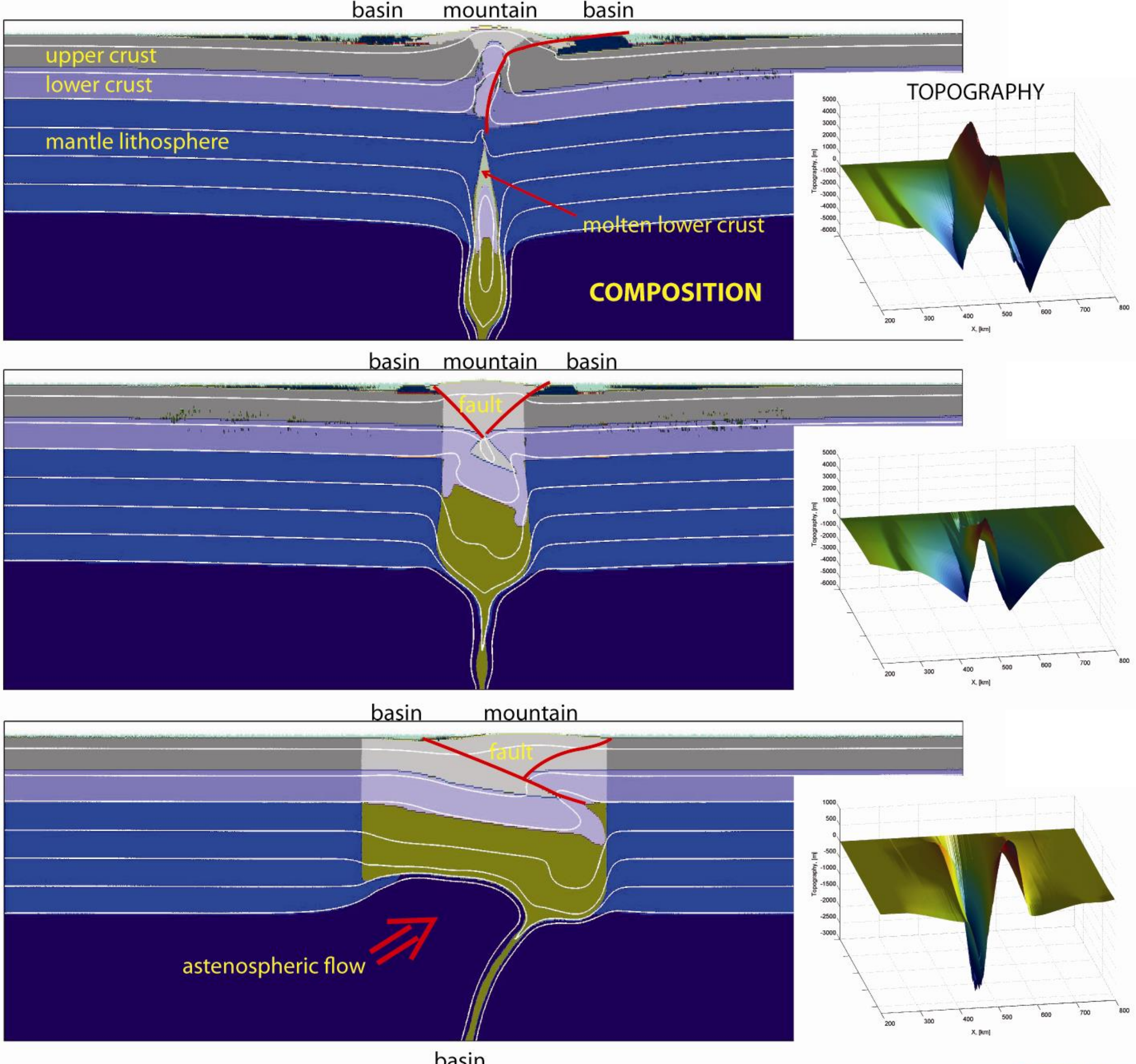
Time = 33.342 Myrs
Z Depth in km
X Width in km

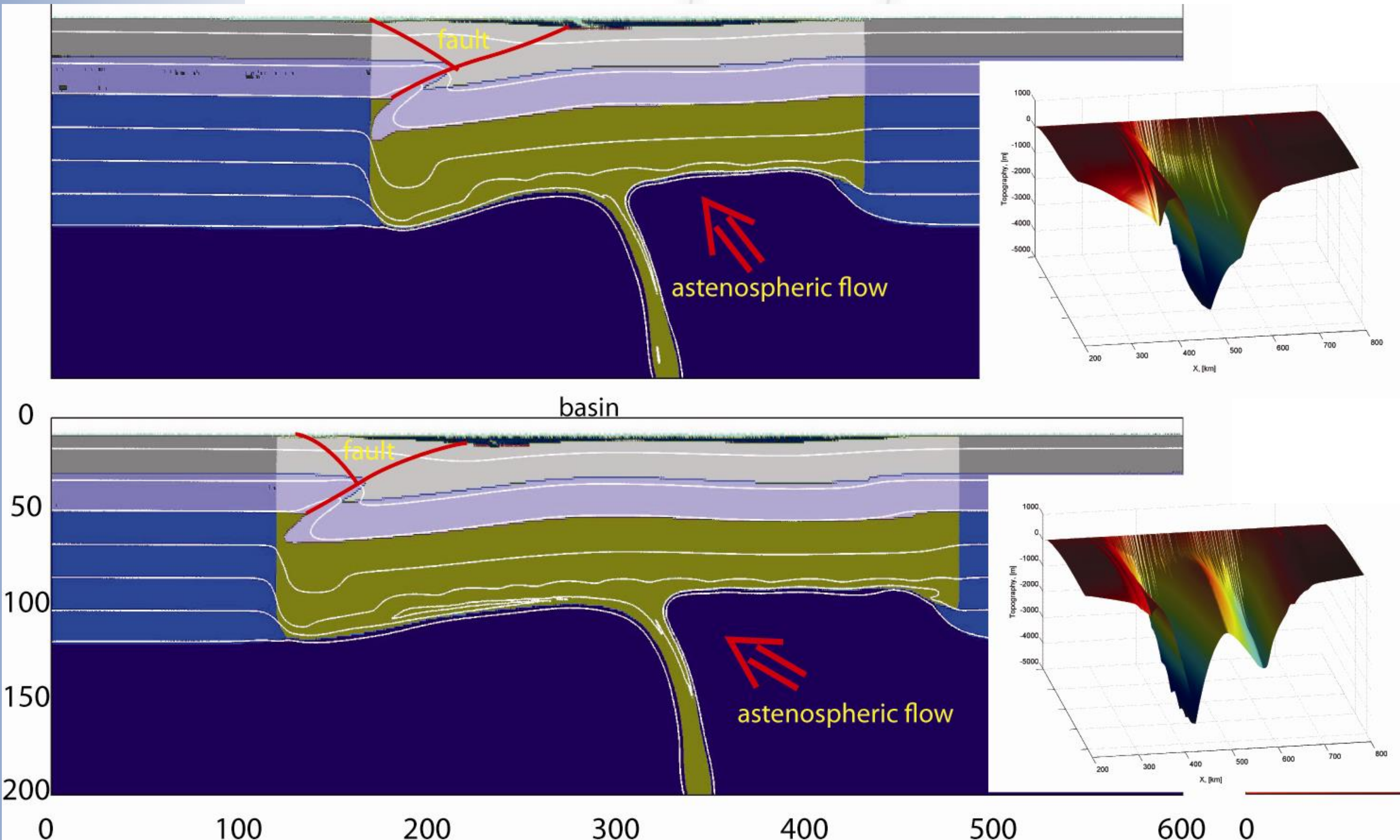

Time = 36.4829 Myrs
Z Depth in km
0
50
100
150
200
250
0
200
400
600
800
1000
1200
X Width in km


Time = 32.5518 Myrs
Z Depth in km
0
50
100
150
200
250
0
200
400
600
800
1000
1200
X Width in km



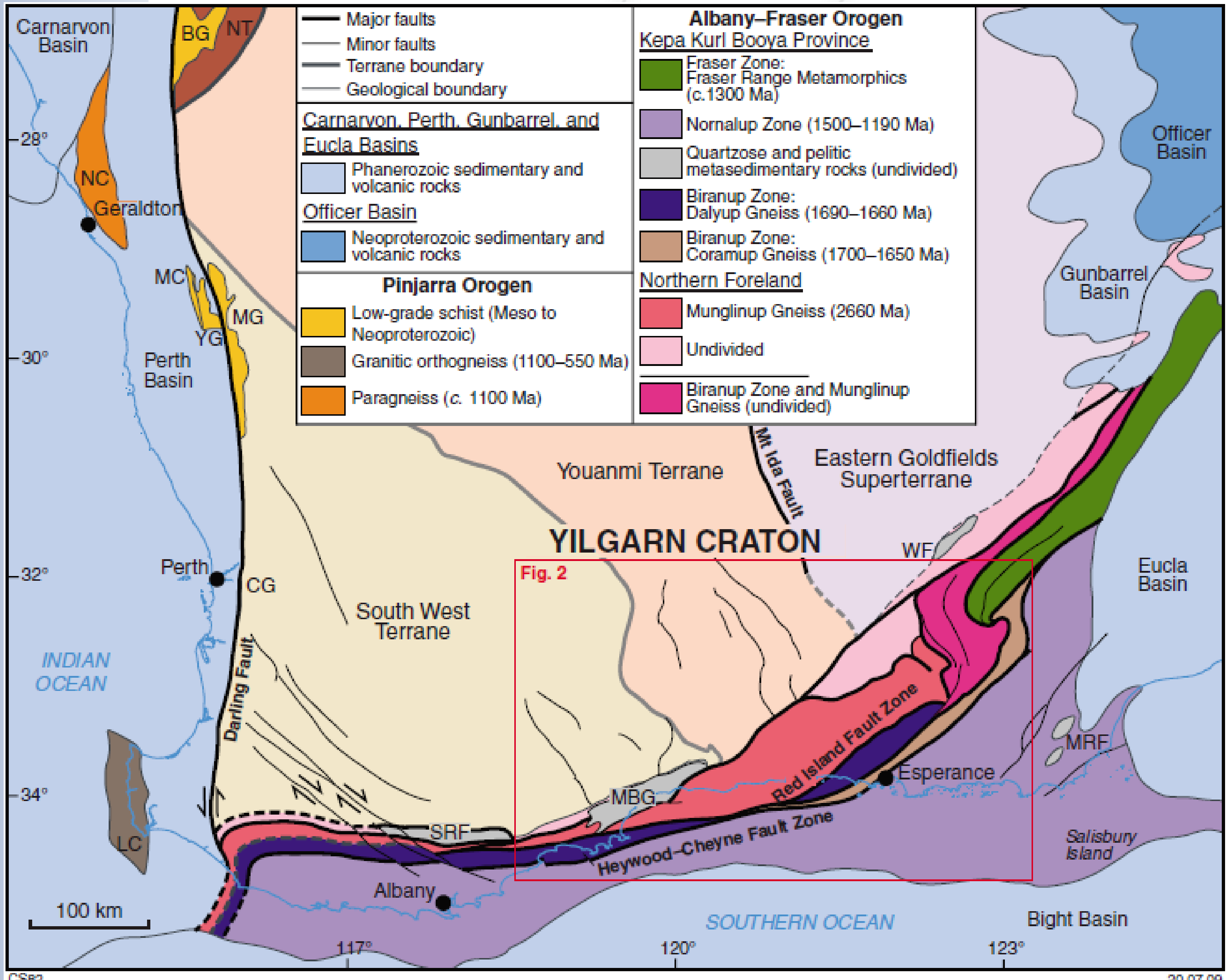
basin
mountain
basin
upper crust
lower crust
mantle lithosphere
molten lower crust
COMPOSITION
TOPOGRAPHY
bending
SECOND STRAIN RATE INVARIANT
fault
astenospheric flow
0
50
100
150
200
0
100
200
300
400
500
600


basin
mountain
basin
upper crust
lower crust
mantle lithosphere
molten lower crust
COMPOSITION
TOPOGRAPHY
basin
mountain
basin
fault
basin
mountain
fault
astenospheric flow
basin

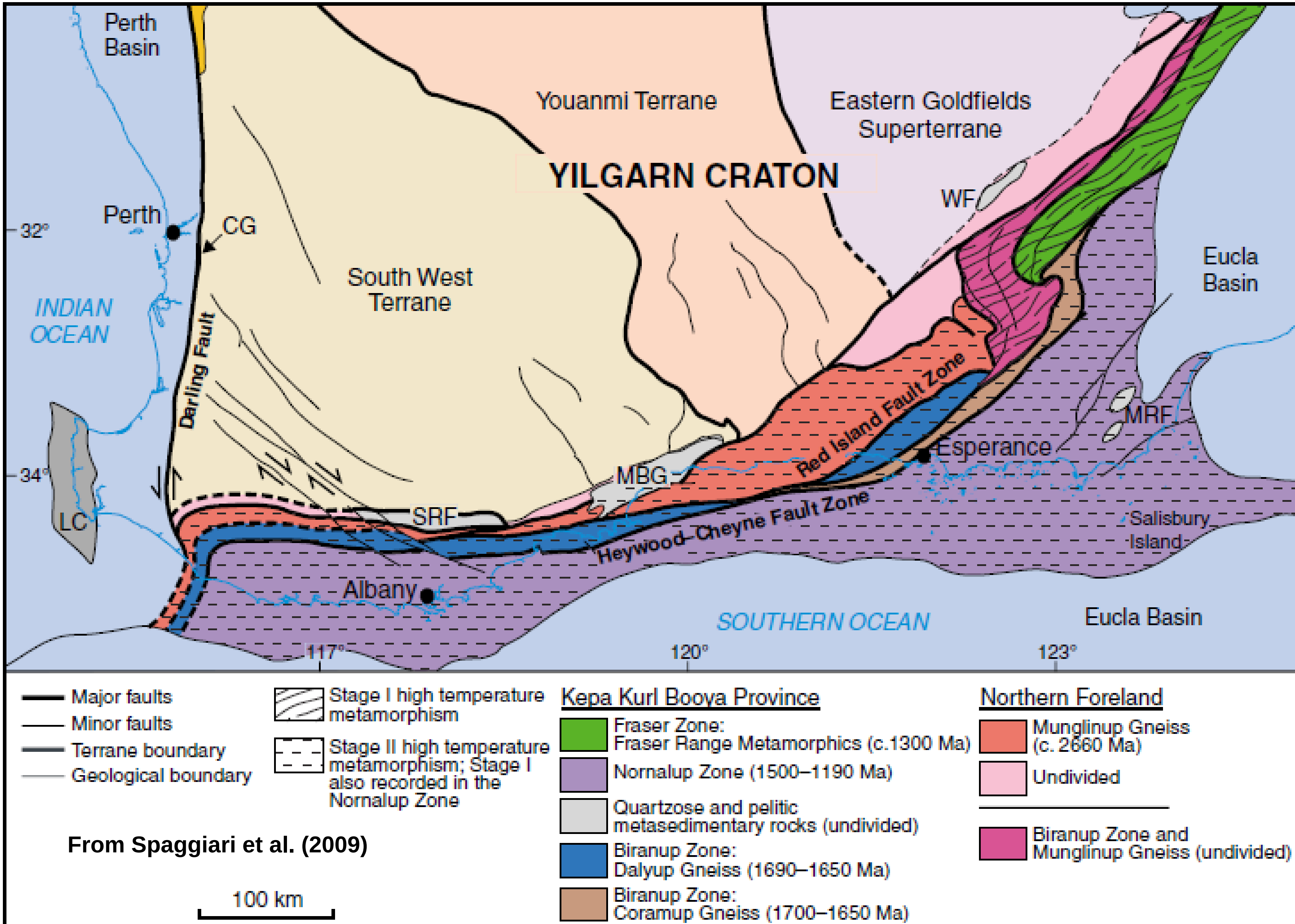


fault
astenospheric flow
basin
fault
astenospheric flow
0
50
100
150
200
0
100
200
300
400
500
600
0
Topography, [m]
X, [km]

TARGETING



From Spaggiari et al. (2009)



From Spaggiari et al. (2009)

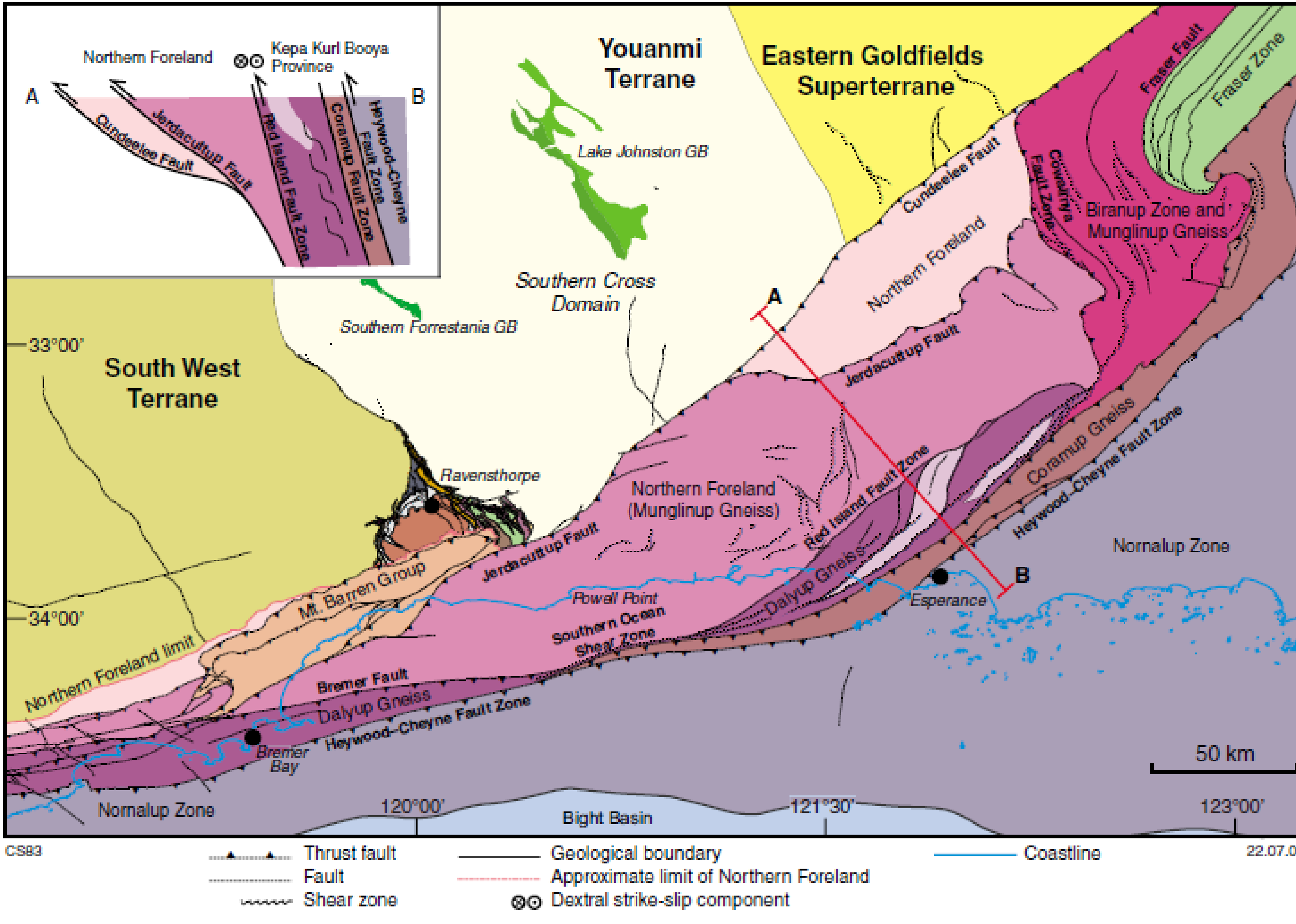


Figure 2. Simplified geological map of the Albany–Fraser Orogen and southern Yilgarn Craton extracted from the interpreted bedrock geology map (Geological Survey of Western Australia, 2007).

Table 1: ALBANY-FRASER TECTONIC REGIME

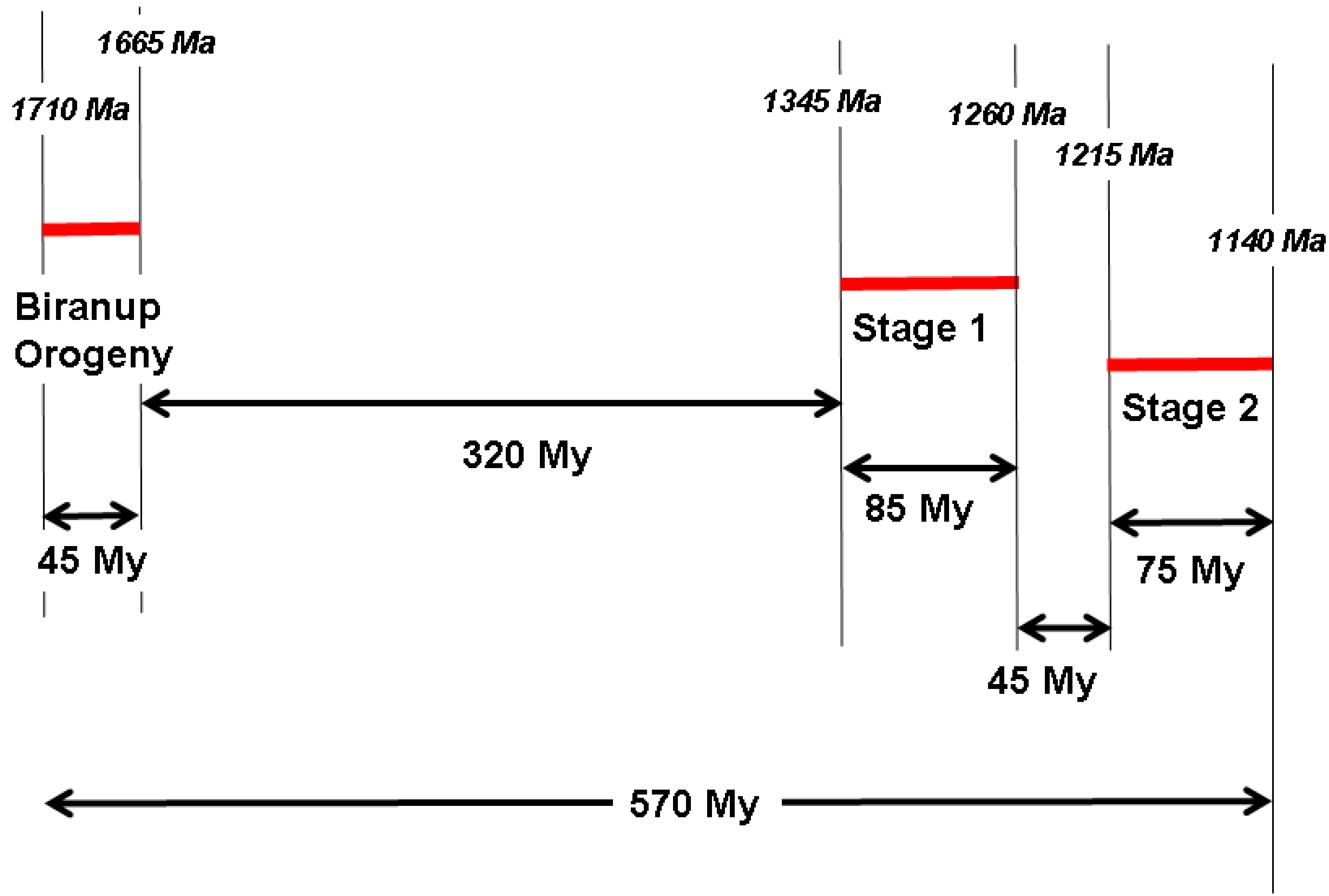
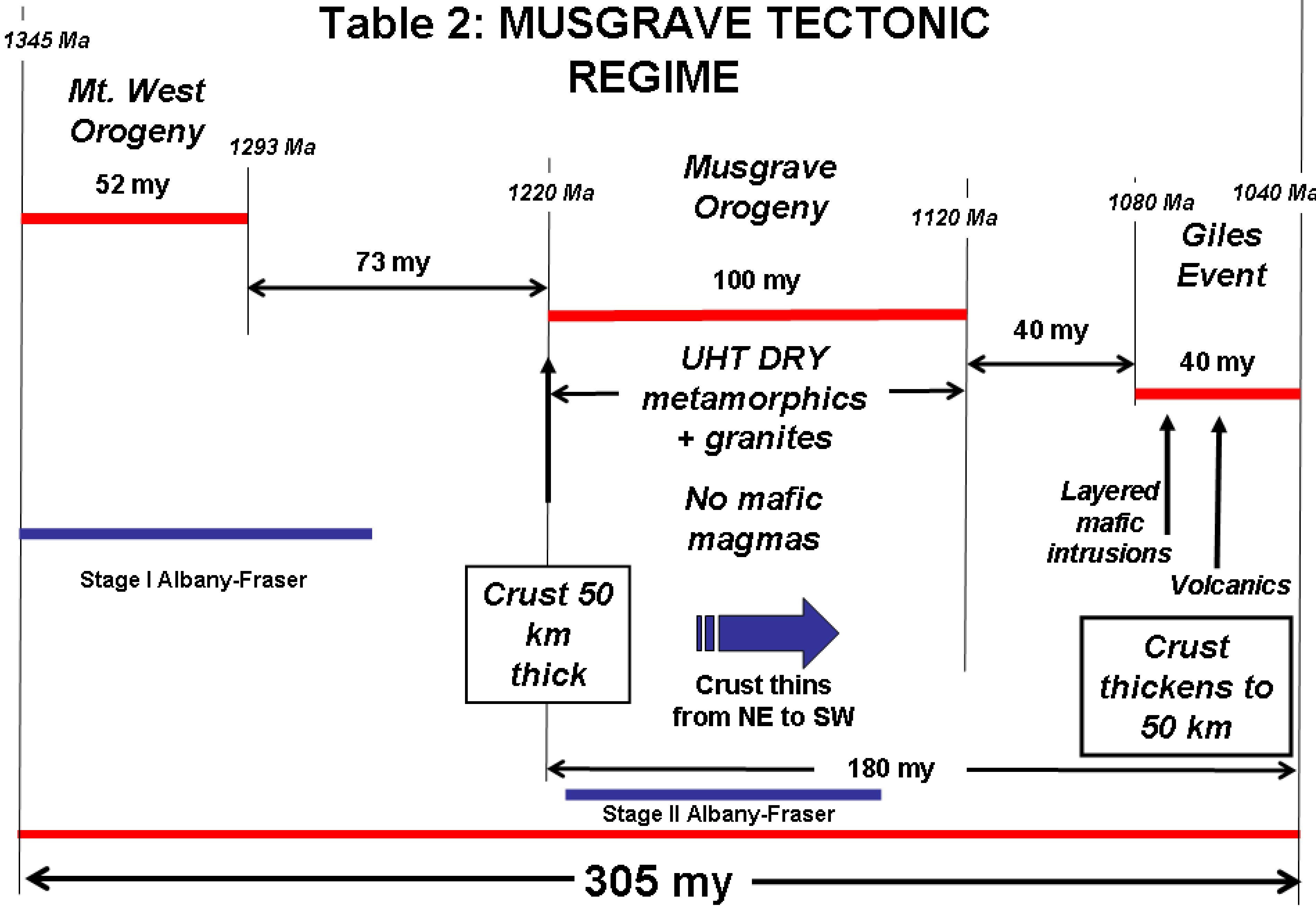
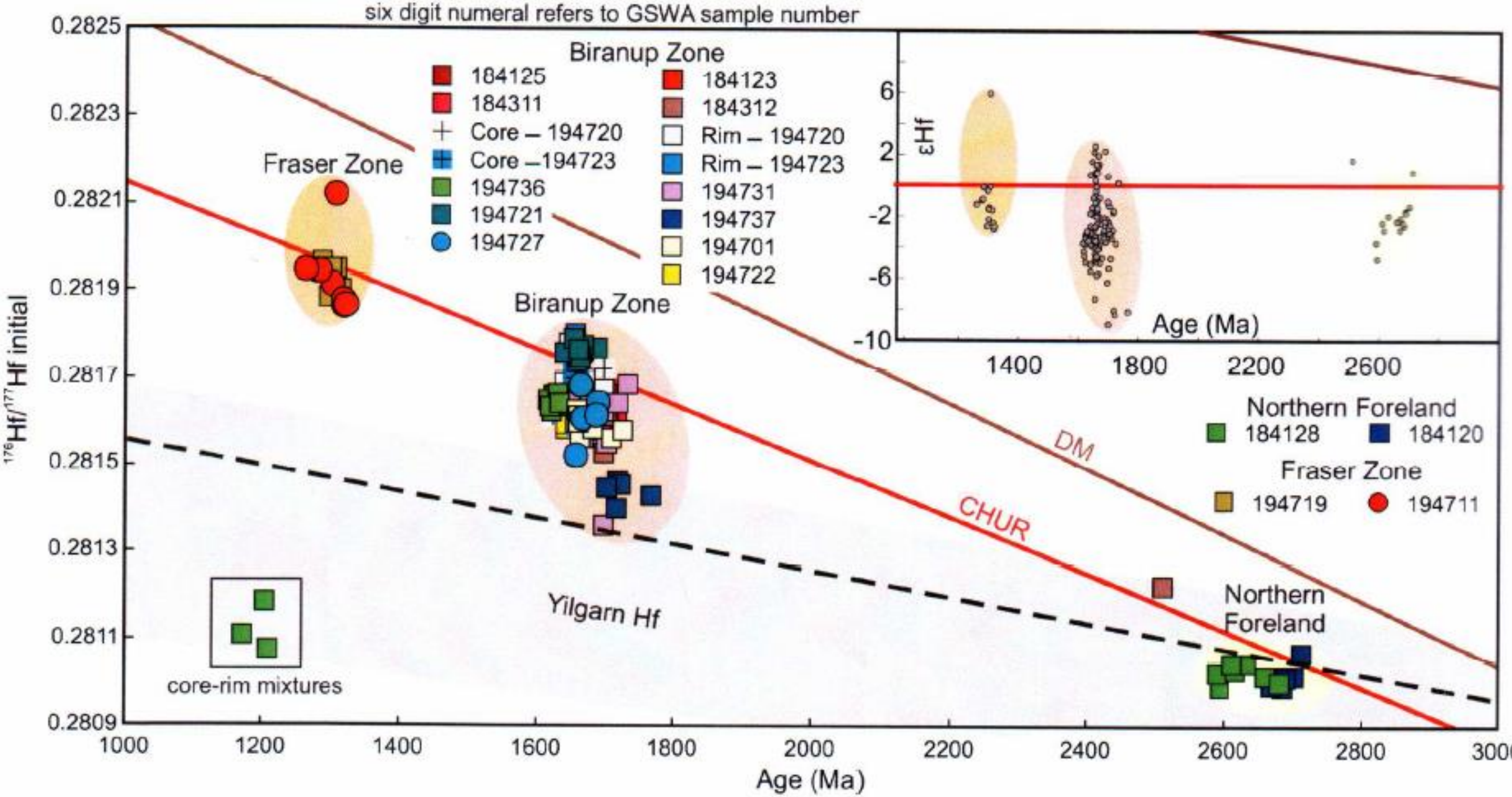
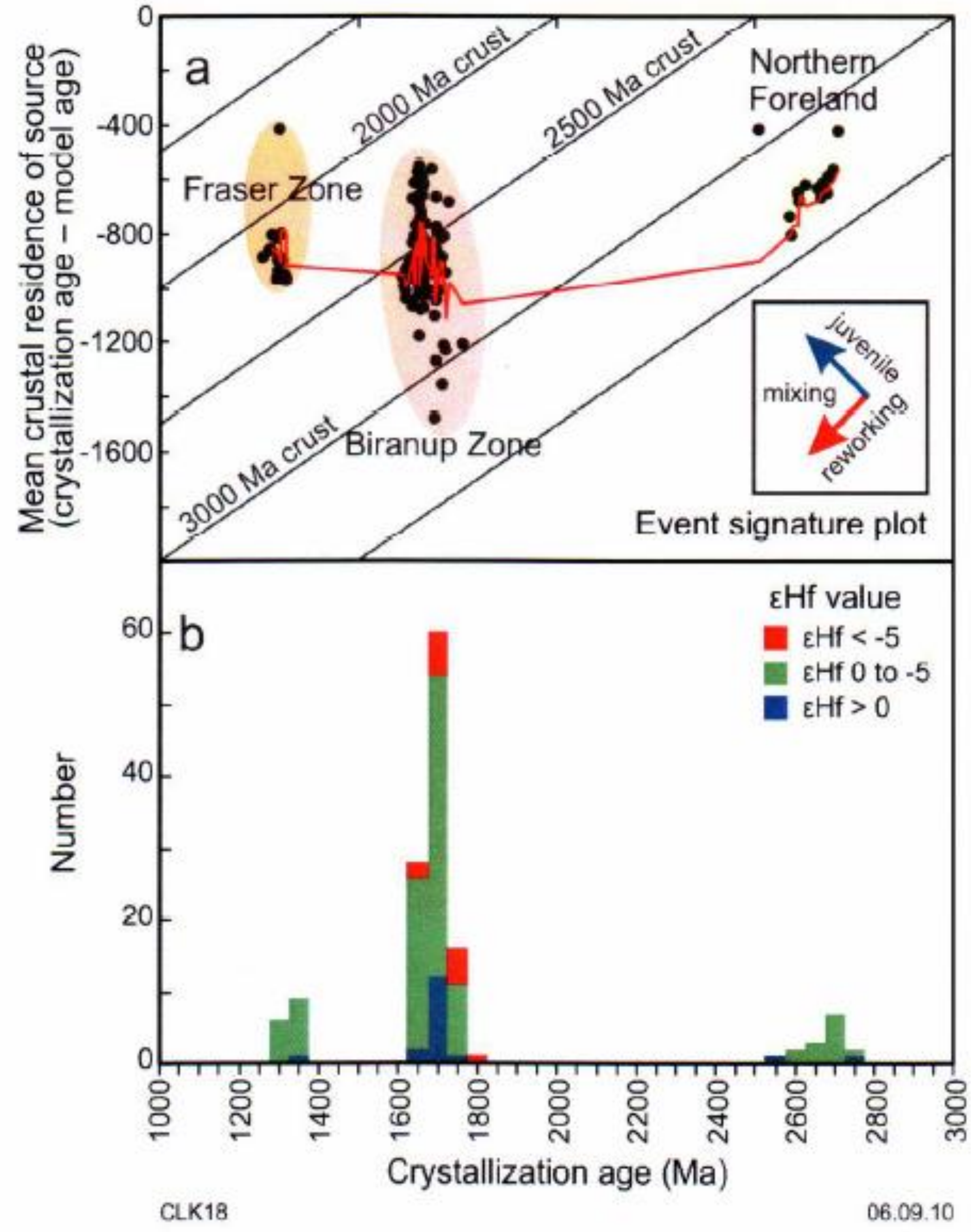


Table 2: MUSGRAVE TECTONIC REGIME



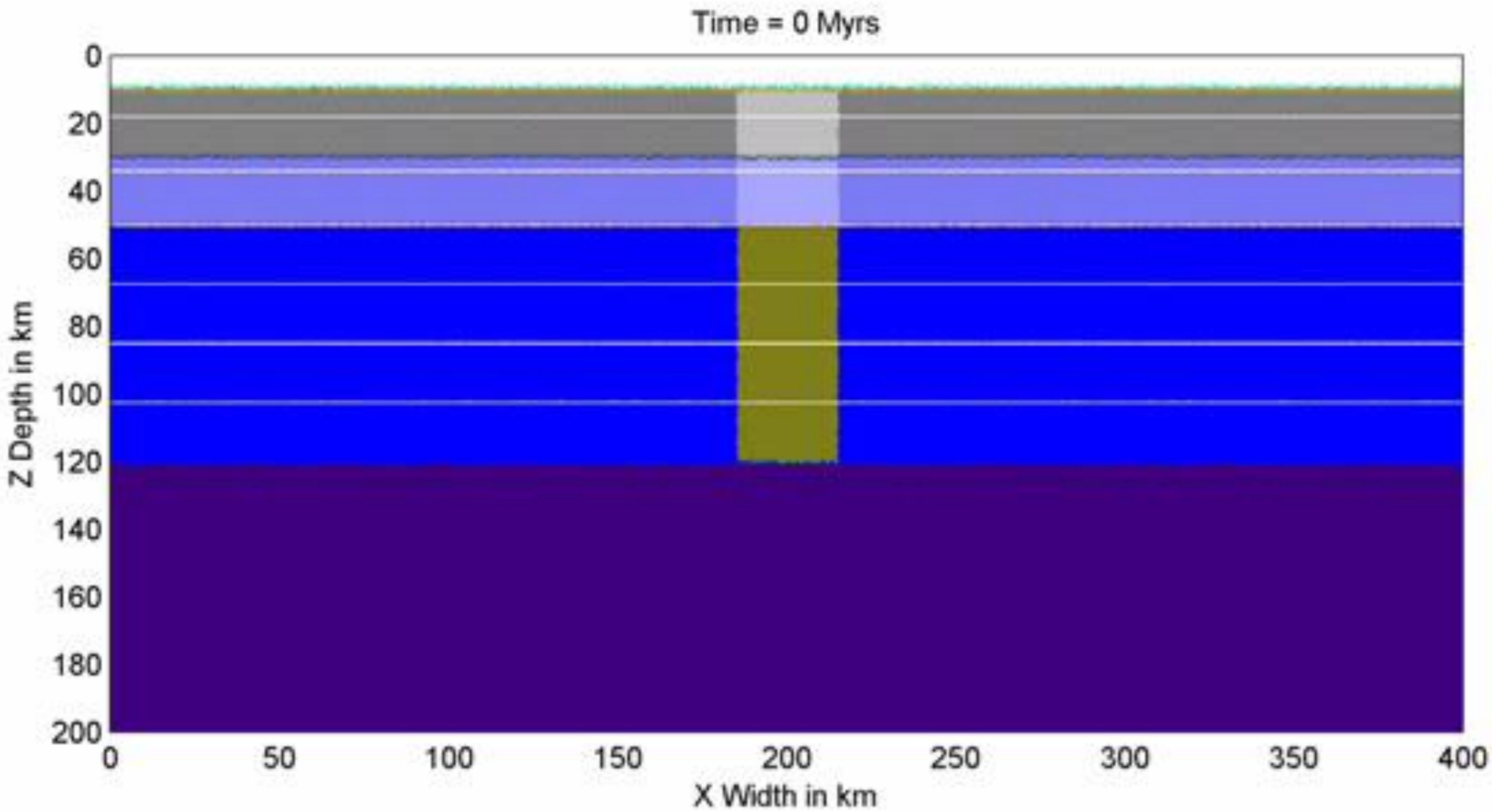


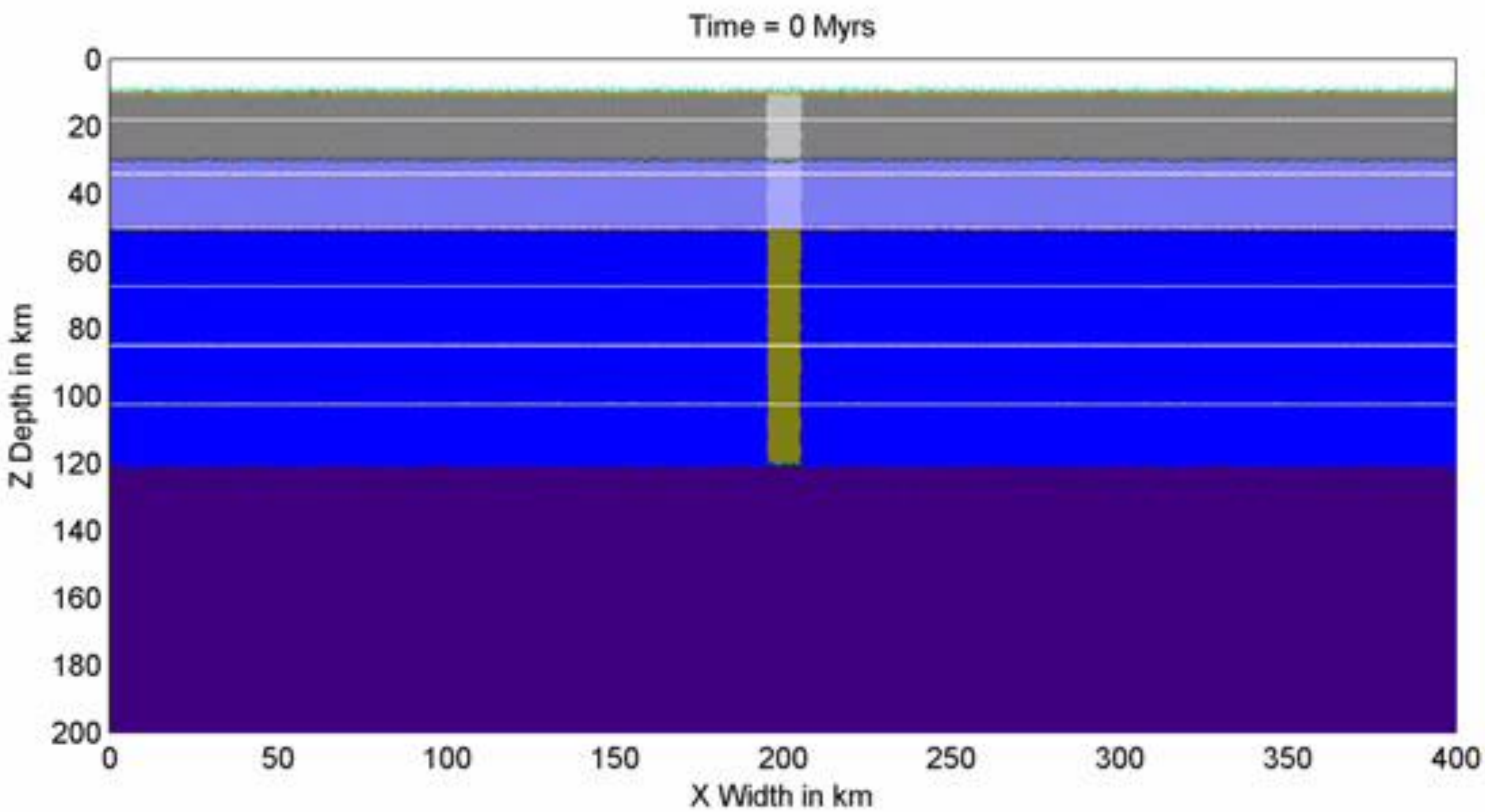
From Kirkland et al., 2011

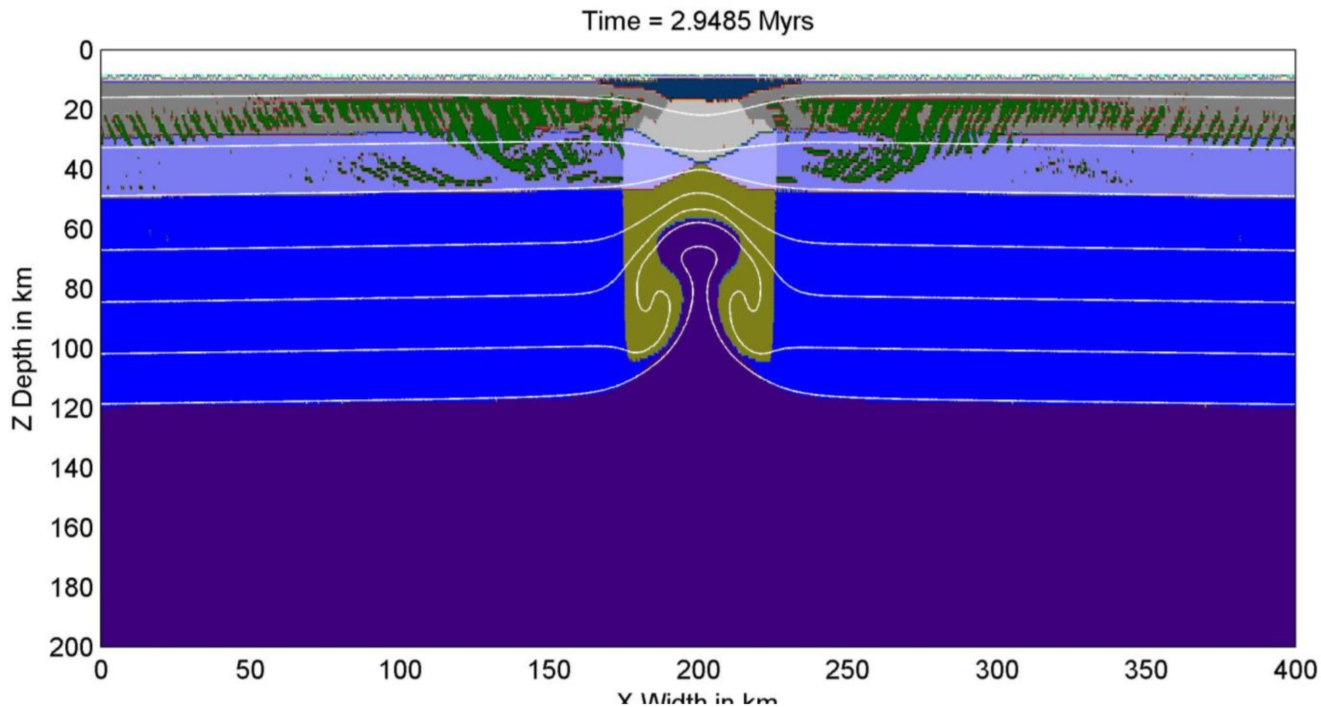


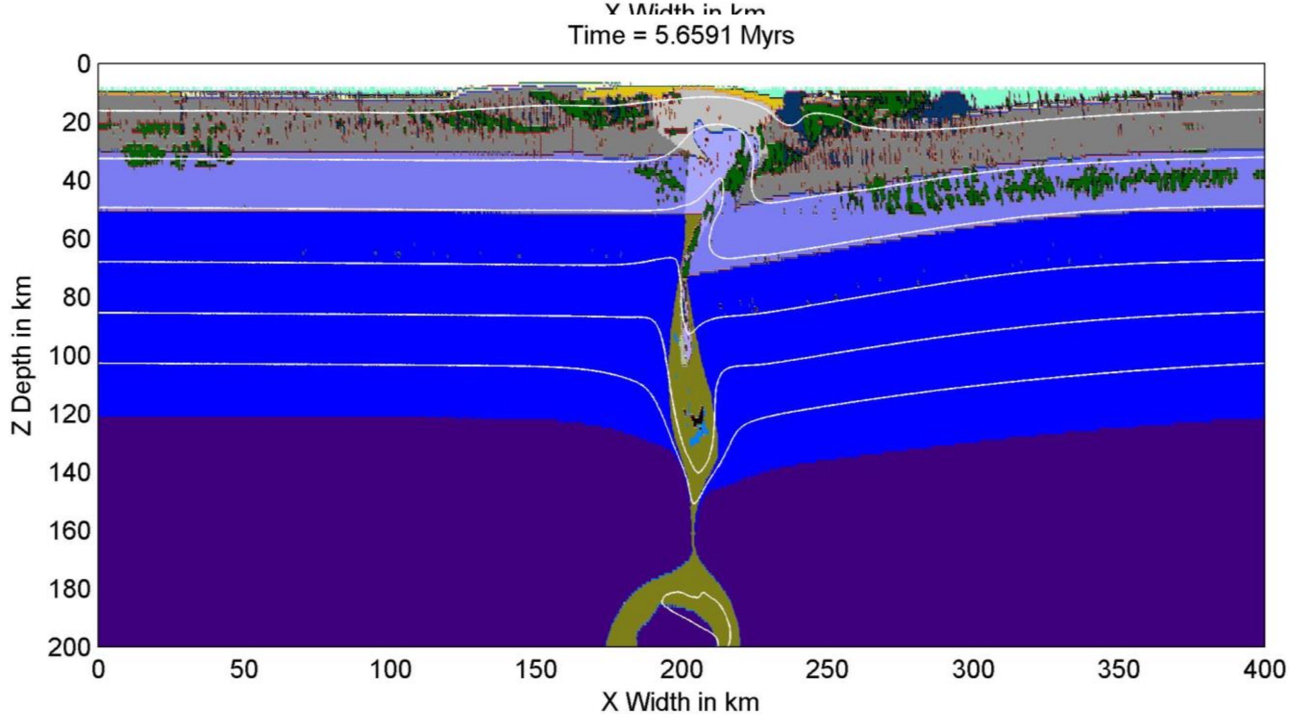
Event Signature Diagram

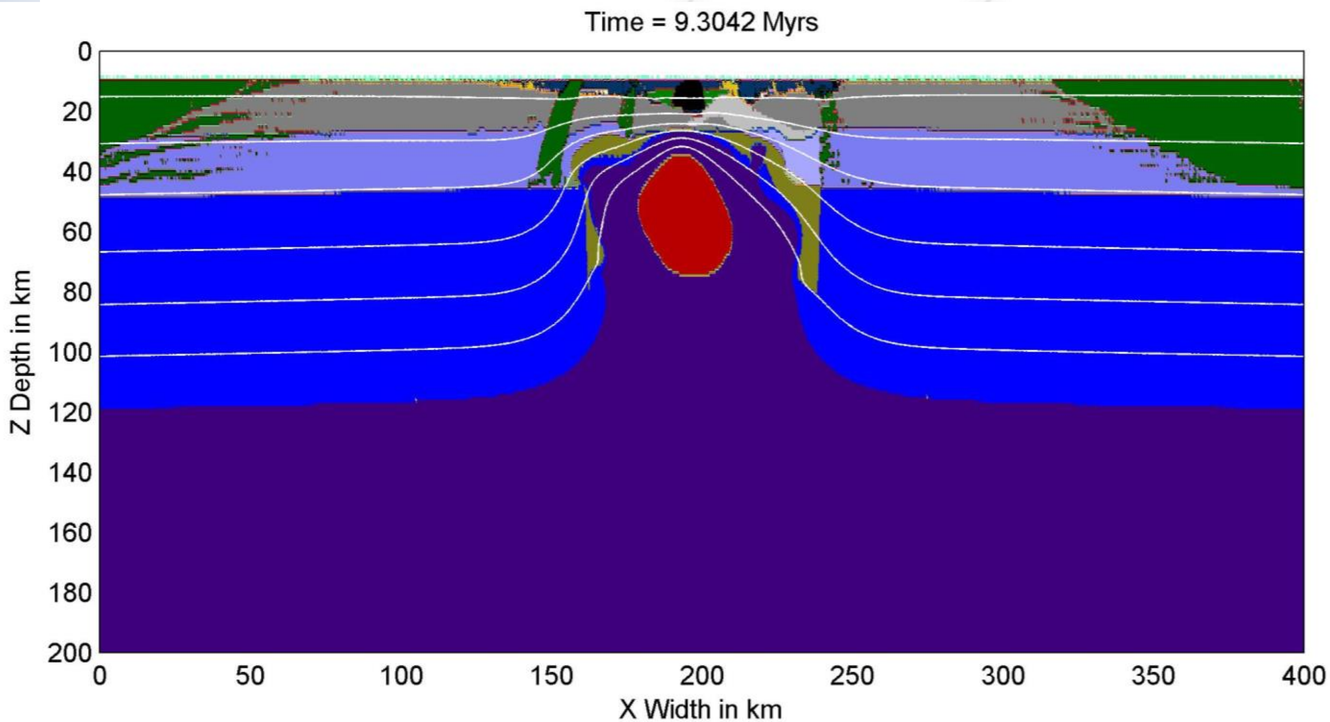
From Kirkland et al., 2011

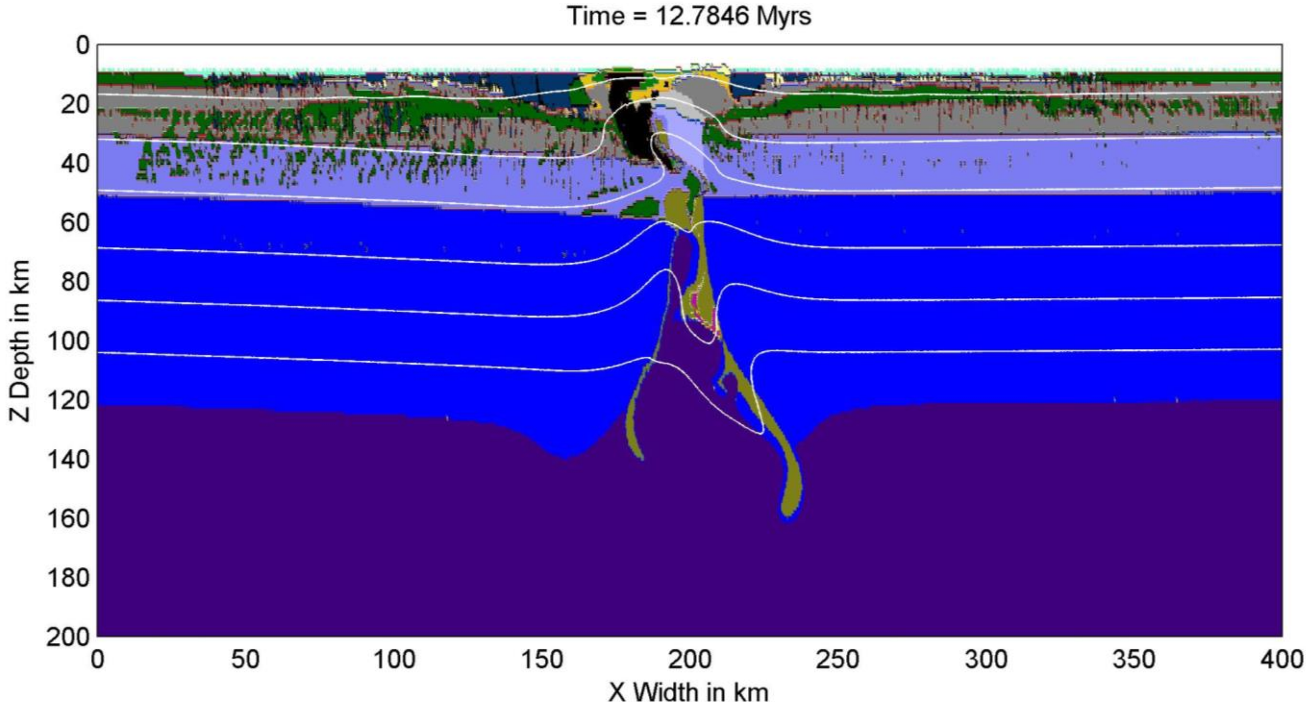

Time = 0 Myrs
Z Depth in km
X Width in km
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400


Time = 0 Myrs
Z Depth in km
0
20
40
60
80
100
120
140
160
180
200
X Width in km
0
50
100
150
200
250
300
350
400


Time = 2.9485 Myrs
Z Depth in km
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
X Width in km


Time = 5.6591 Myrs
Z Depth in km
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
X Width in km


Time = 9.3042 Myrs
Z Depth in km
X Width in km
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400


Time = 12.7846 Myrs
Z Depth in km
X Width in km
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400

What are the geological signatures of intracontinental events originating as lithospheric drips?

起源于岩石圈滴落的陆内事件的地质特征是什么?

1. No or little evidence of subduction (perhaps early).
   没有或基本没有俯冲证据
2. Asymmetrical orogens.
   非对称的造山带
3. High temperature, high pressure metamorphism (can last for 100 my).
   高温，高压变质
4. Perhaps slabs of mantle in the crust.
   可能地壳中存在地幔残片
5. Relatively late sedimentary basins (symmetrical or asymmetrical).
   相对晚的沉积盆地（对称或非对称）
6. Alkaline magmatism.
   碱性岩浆作用
7. Mineralisation.
   矿化作用

Centre for EXPLORATION TARGETING

Our messages for today:

1. Deformation and metamorphism originating from lithospheric drips are common.

   源于岩石圈滴落的变形和变质作用非常普遍

2. This setting may have little to do with nearby subduction.

   这种地质背景与靠近俯冲带可能不存在关系

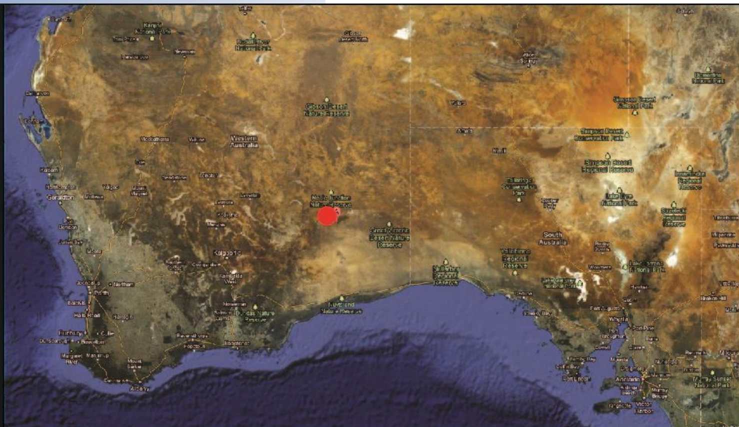
3. Mineralisation is common in these areas [Olympic Dam,Yilgarn, Carlin, Yangste, Mt. Isa, Albany-Fraser(?)].

   在这些区域矿化普遍

4. There are clear signatures in the geological record waiting to be read.

   在地质记录里这里有许多信号需要解读

Centre for EXPLORATION TARGETING



Delivering numerical modelling to wild field geologists in their natural habitat.