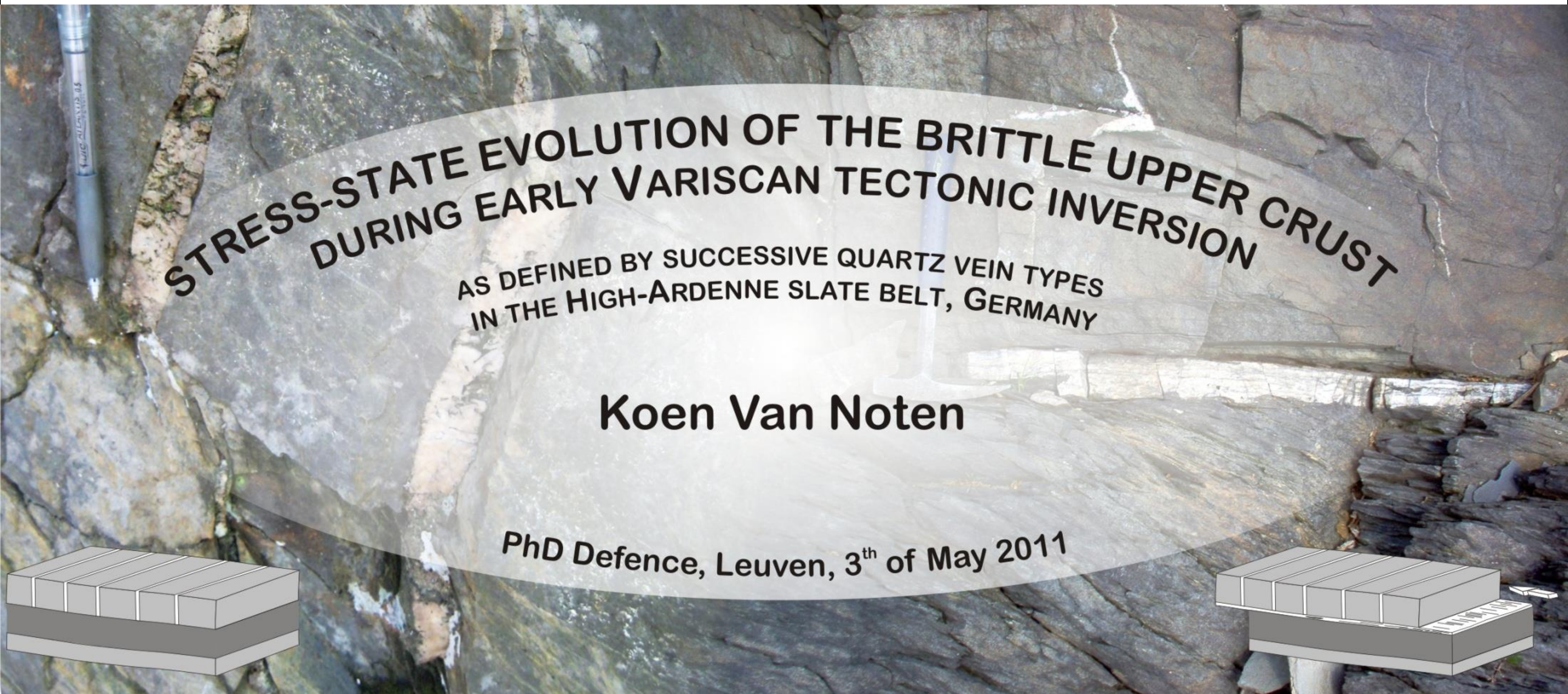
KATHOLIEKE UNIVERSITEIT LEUVEN

DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES
K.U.LEUVEN - BELGIUM

GEO fluids dynamics



STRESS-STATE EVOLUTION OF THE BRITTLE UPPER CRUST DURING EARLY VARISCAN TECTONIC INVERSION

AS DEFINED BY SUCCESSIVE QUARTZ VEIN TYPES IN THE HIGH-ARDENNE SLATE BELT, GERMANY

Koen Van Noten

PhD Defence, Leuven, 3th of May 2011

Supervisors:
prof. dr. Manuel Sintubin & prof. dr. Philippe Muchez

Members of the Examination Committee:
Universiteit Utrecht: dr. J.H.P. de Bresser   RWTH Aachen: PD. dr. C. Hilgers
K.U.Leuven: prof. dr. R. Swennen, prof. dr. N. Vandenberghe, prof. dr. J. Hertogen

Stress-state evolution

of the brittle upper crust

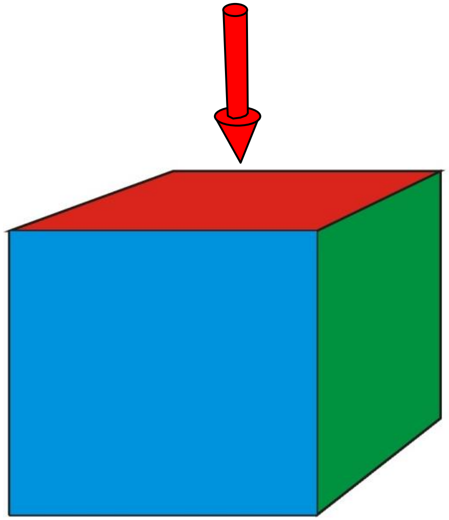
during early Variscan

tectonic inversion

as defined by successive quartz vein types

in the High-Ardenne slate belt

Germany



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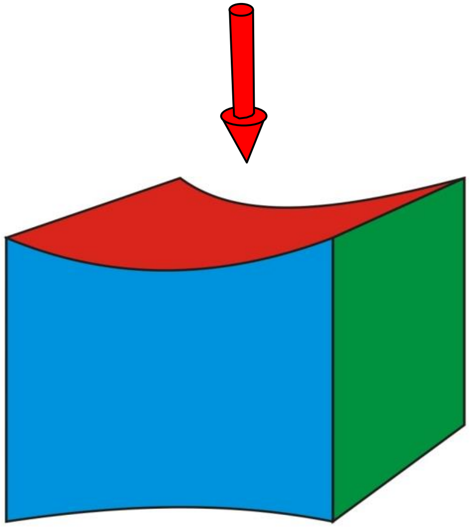

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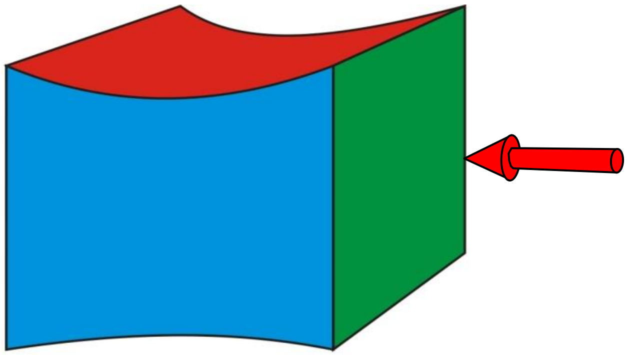

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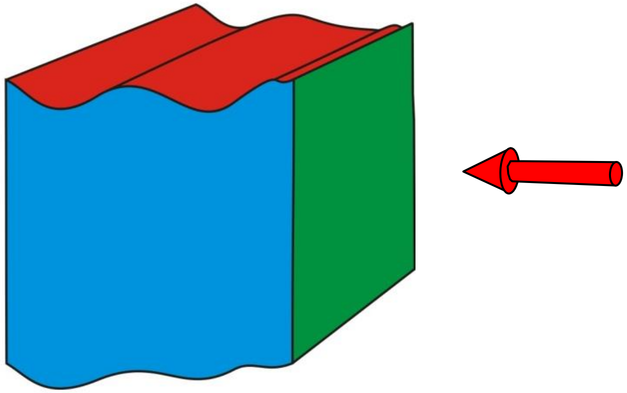
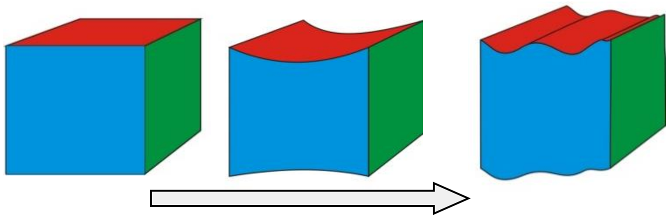


Stress-state evolution



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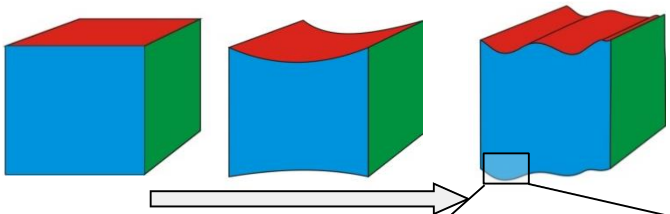

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Field observation: fold

Germany

Stress-state evolution

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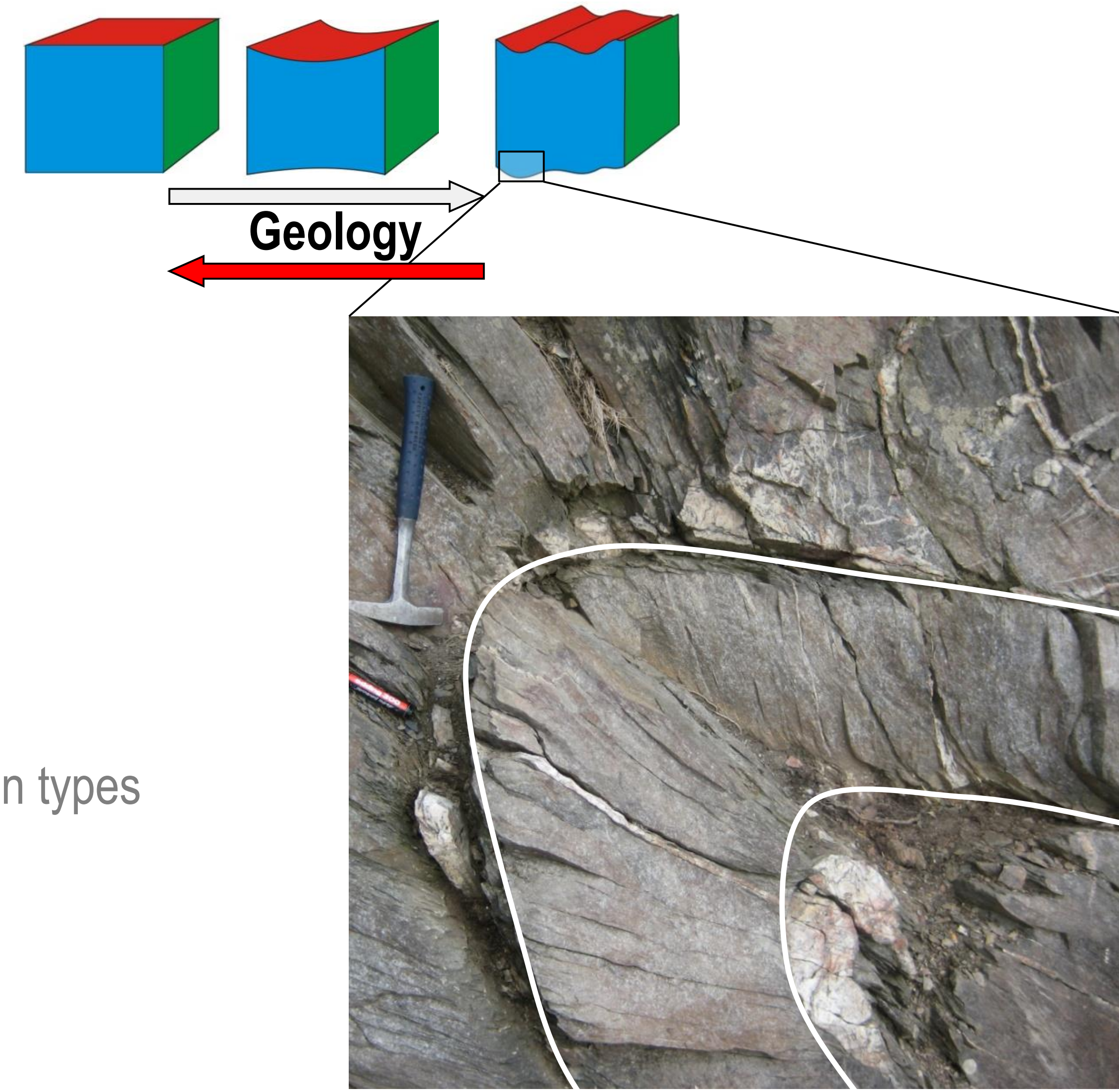
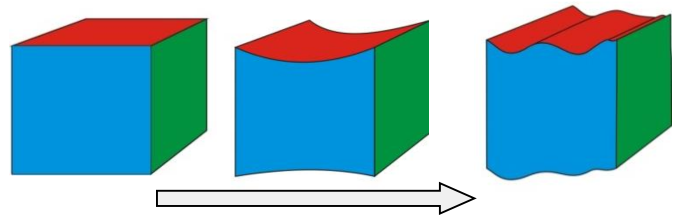
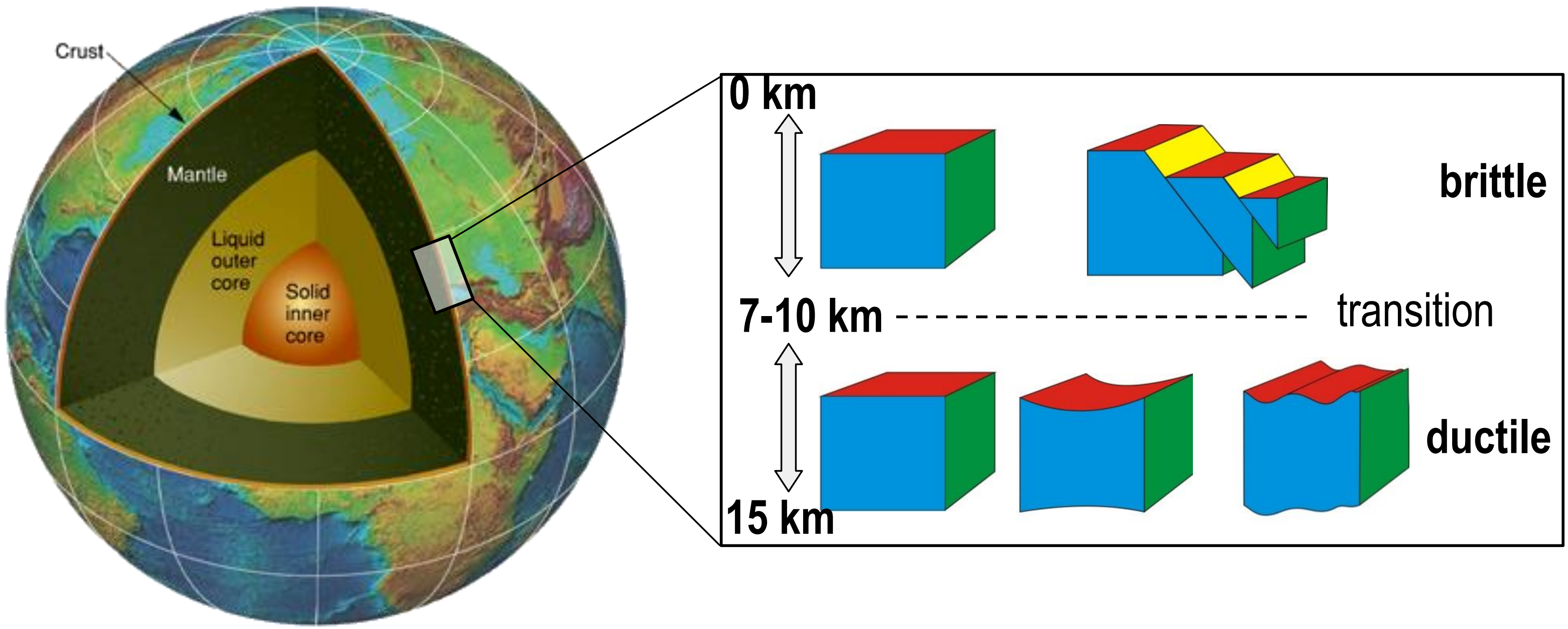


Field observation: fold

Stress-state evolution



of the **brittle upper crust**



http://startswithabang.com

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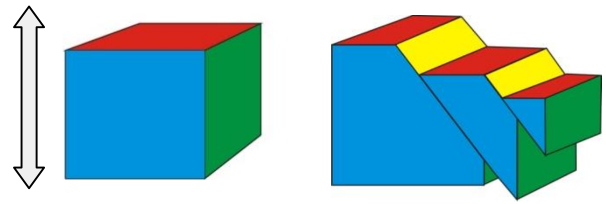


brittle

7-10 km - transition

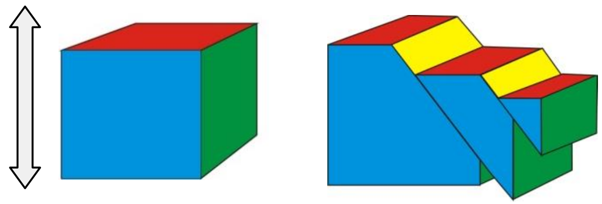
<u>Variscan orogeny</u>

Onset: **325 Million year**

Destabilisation: **300 Million year**

Title explanation

Stress-state evolution



brittle

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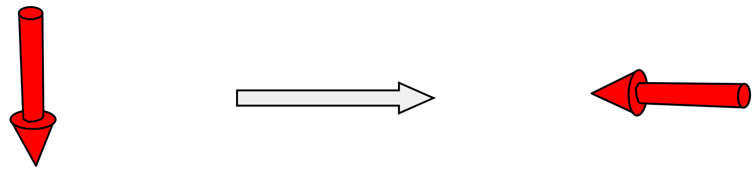

as defined by successive quartz vein types

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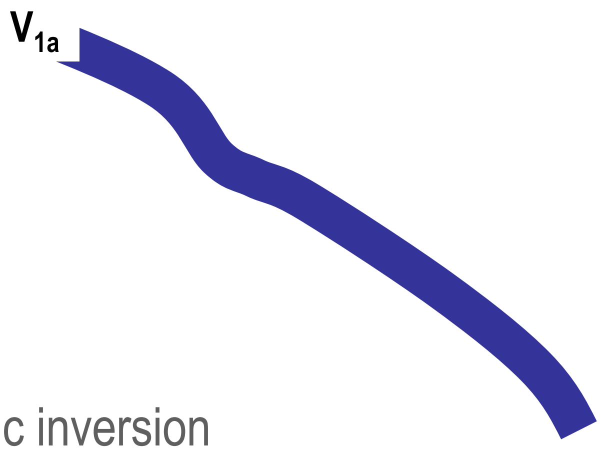

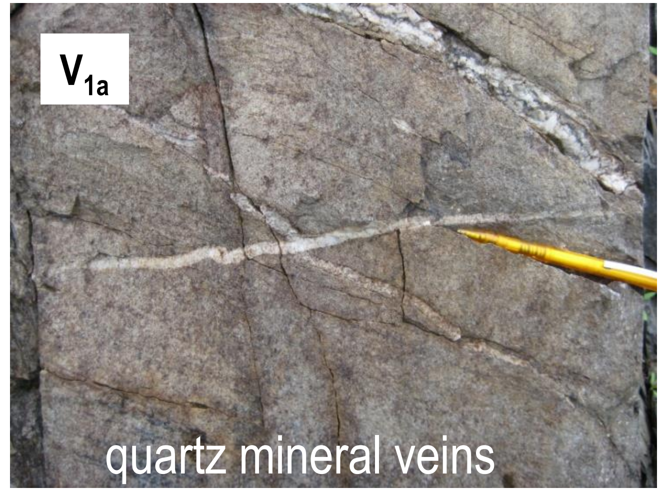

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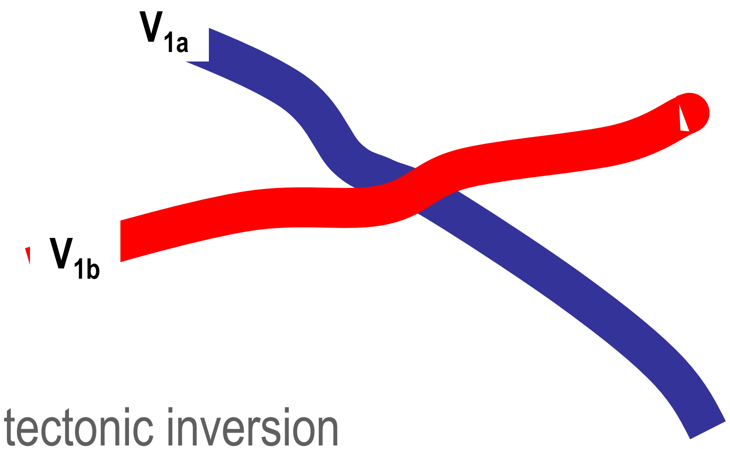

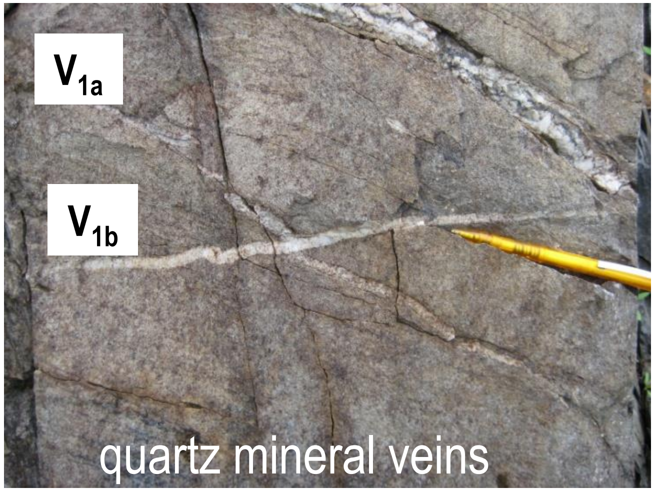

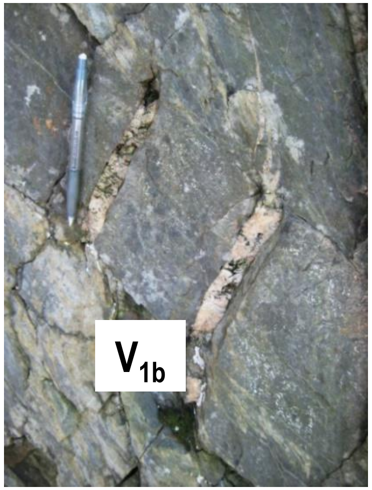

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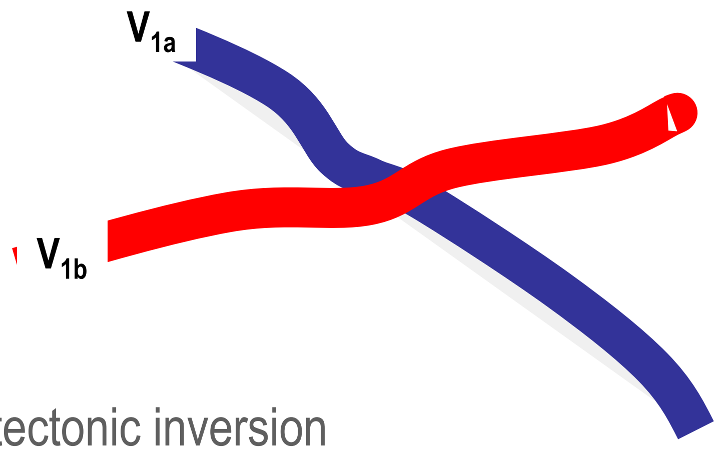

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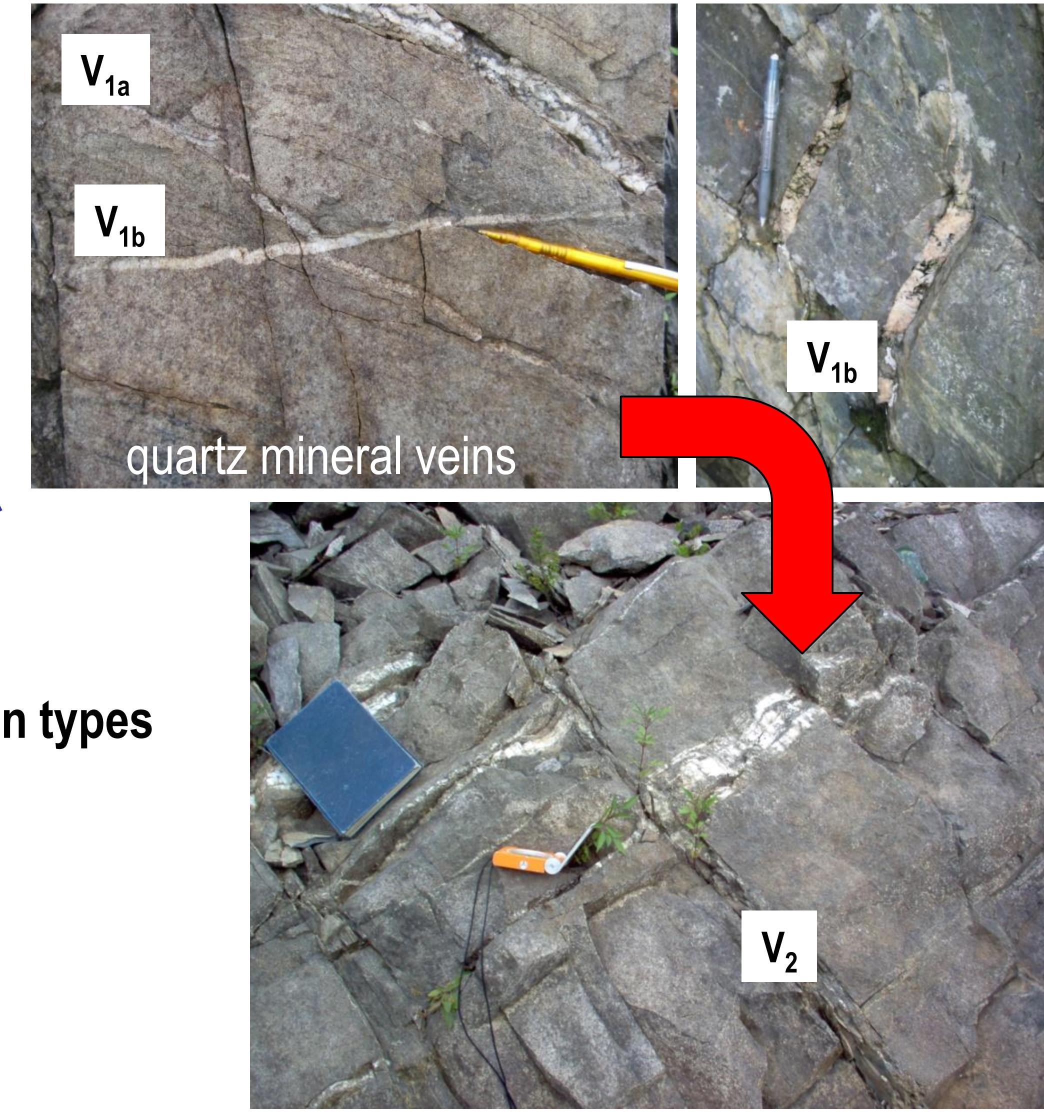

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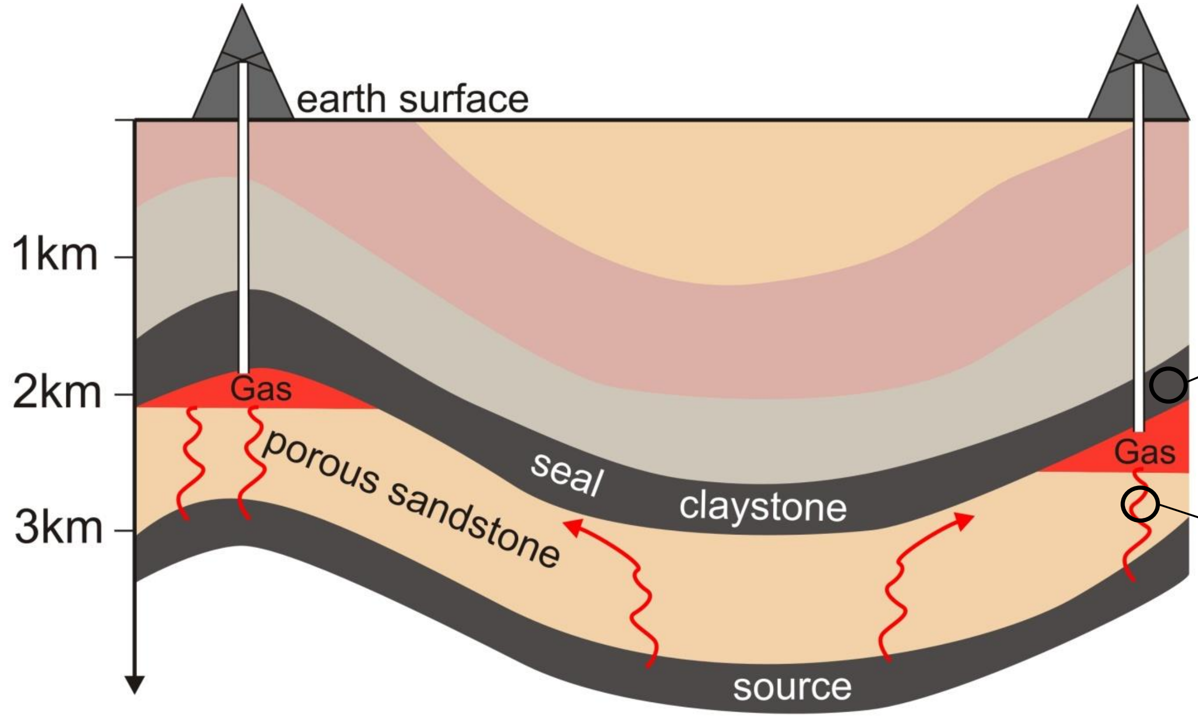
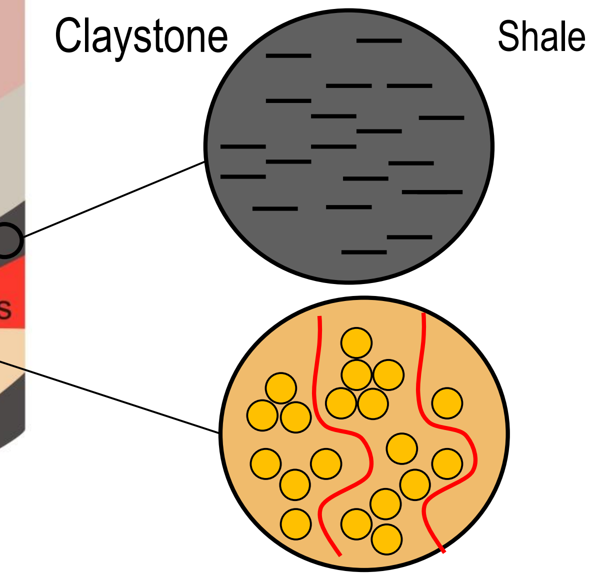
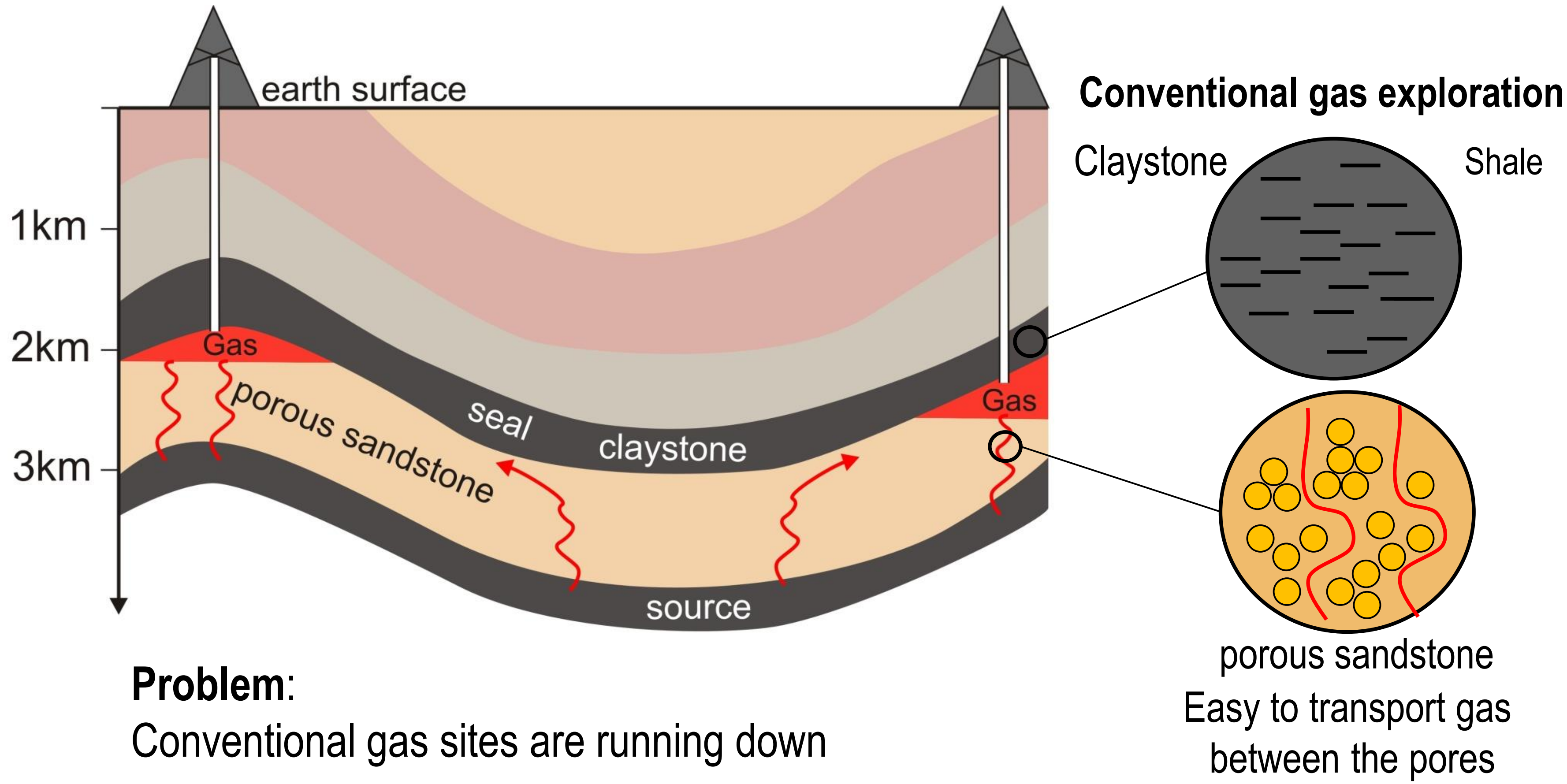
Introduction



Conventional gas exploration

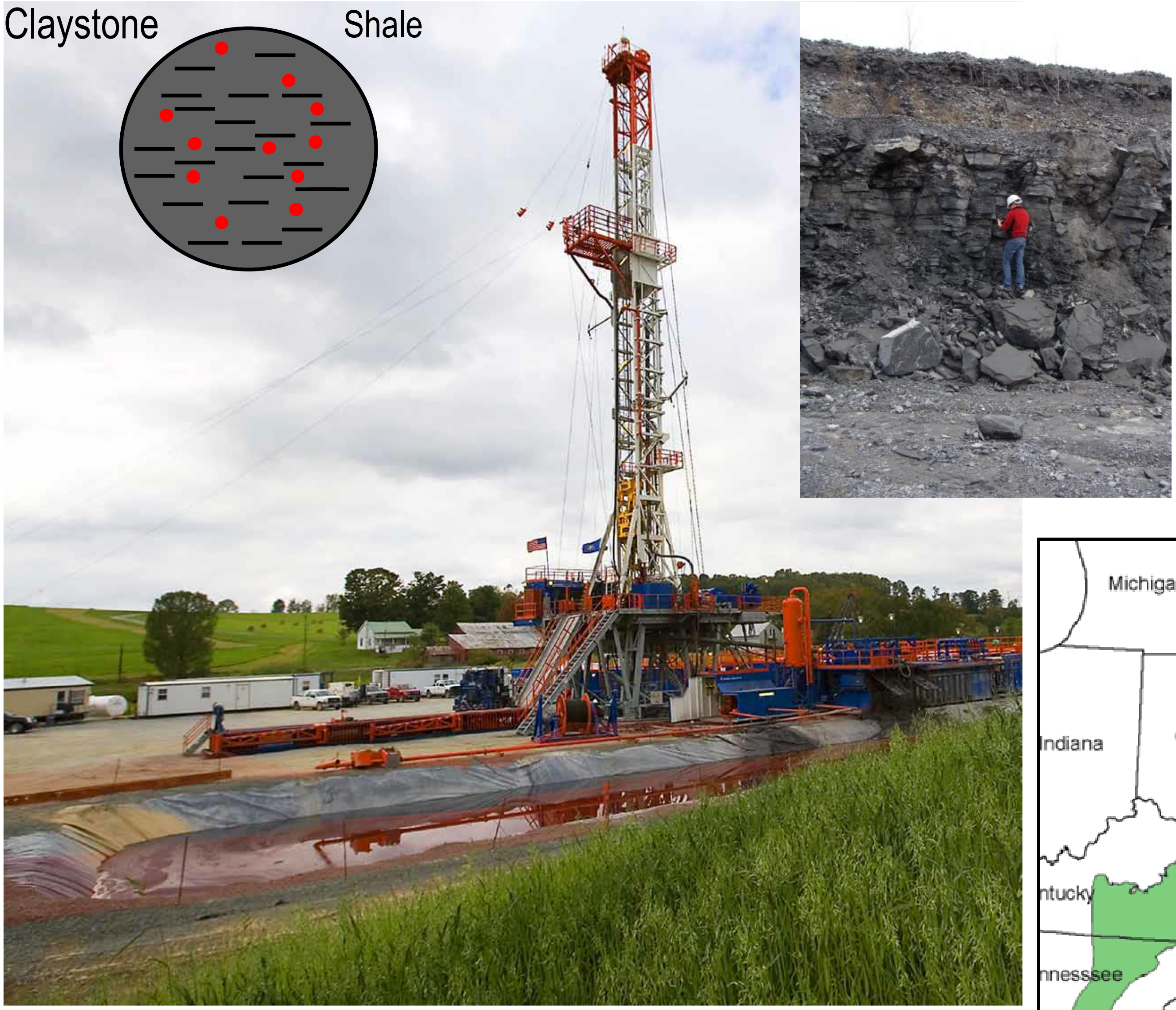




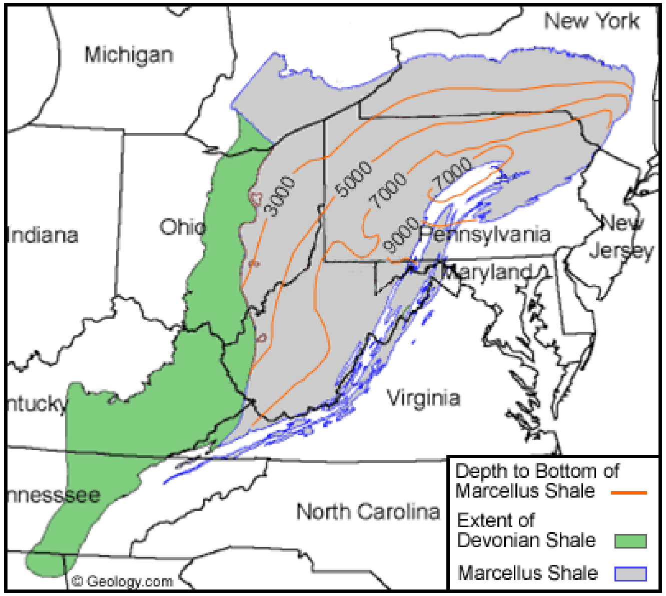
Problem:

Conventional gas sites are running down

Natural gas in Marcellus shale – Process of **hydraulic fracturing**



"Het nieuwe gas" – EOS – januari 2011



www.geology.com

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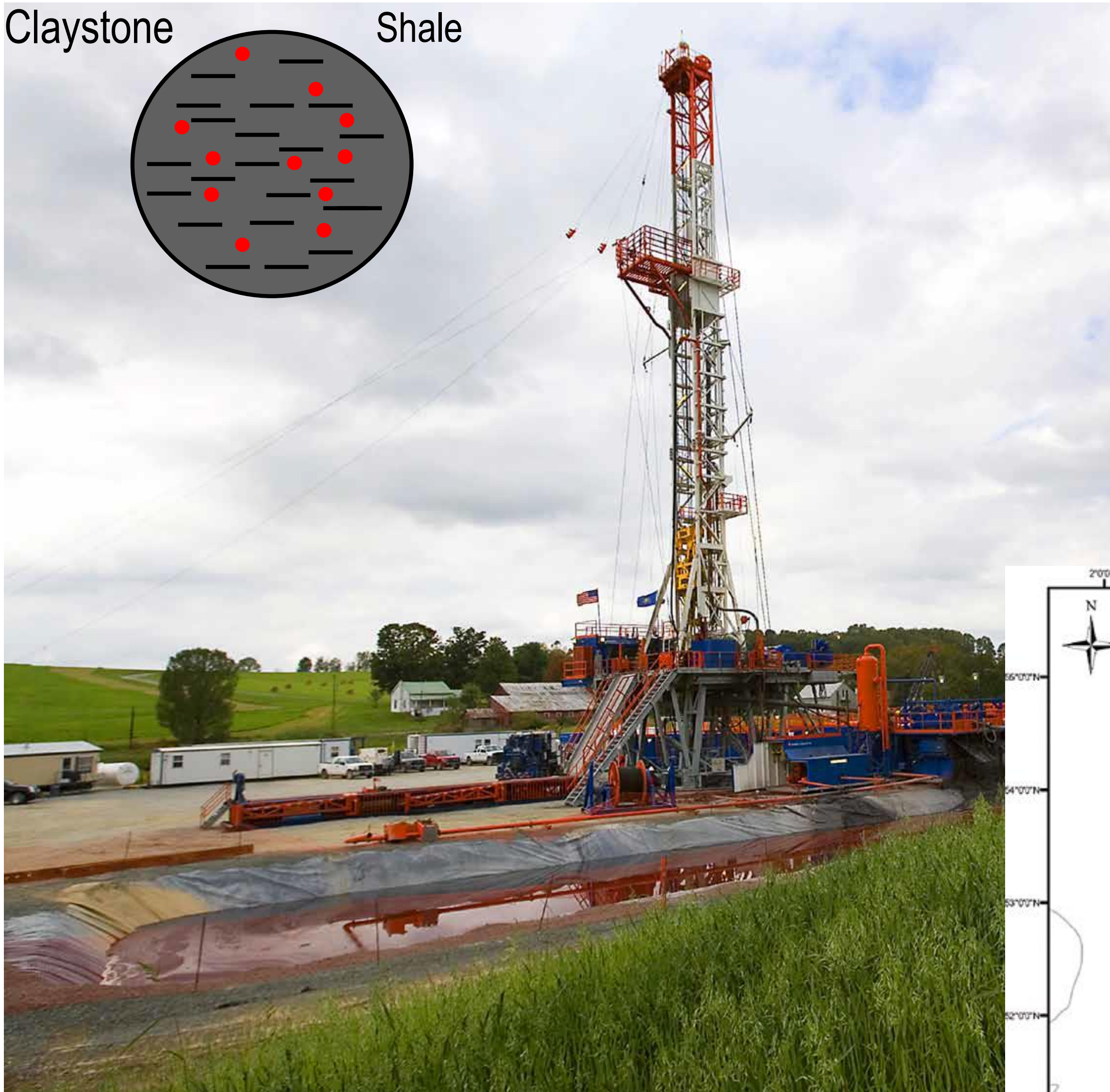

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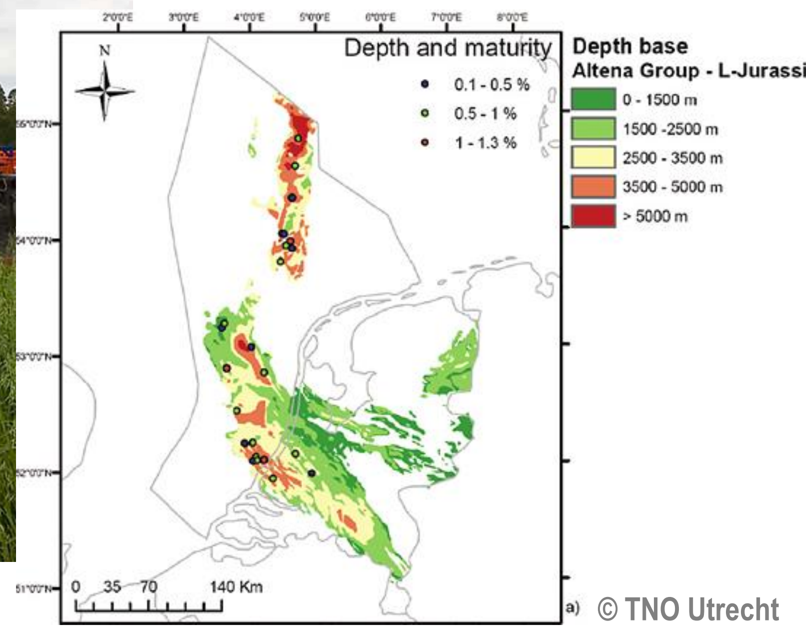
The Netherlands



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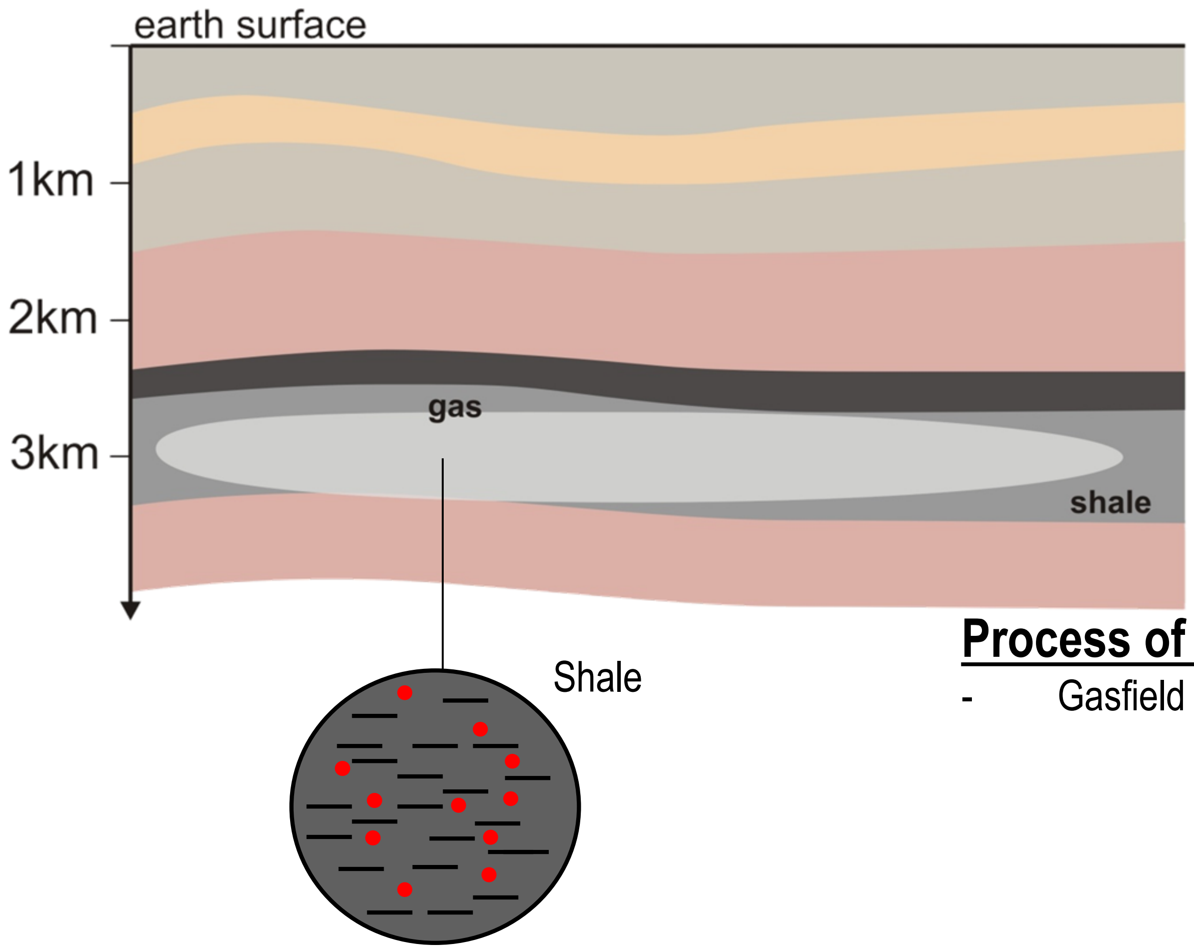
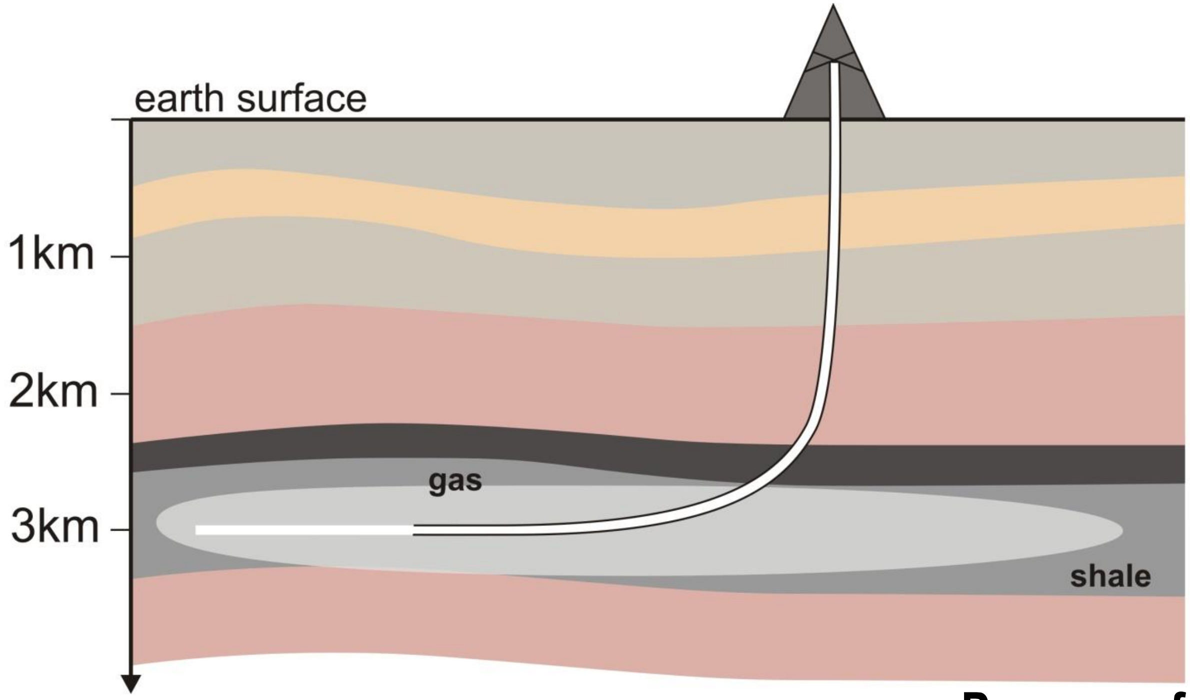
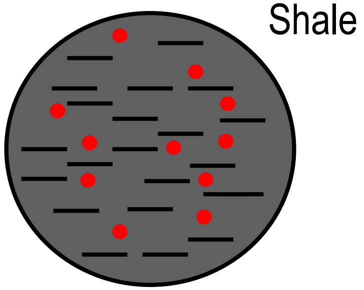


Process of hydraulic fracturing

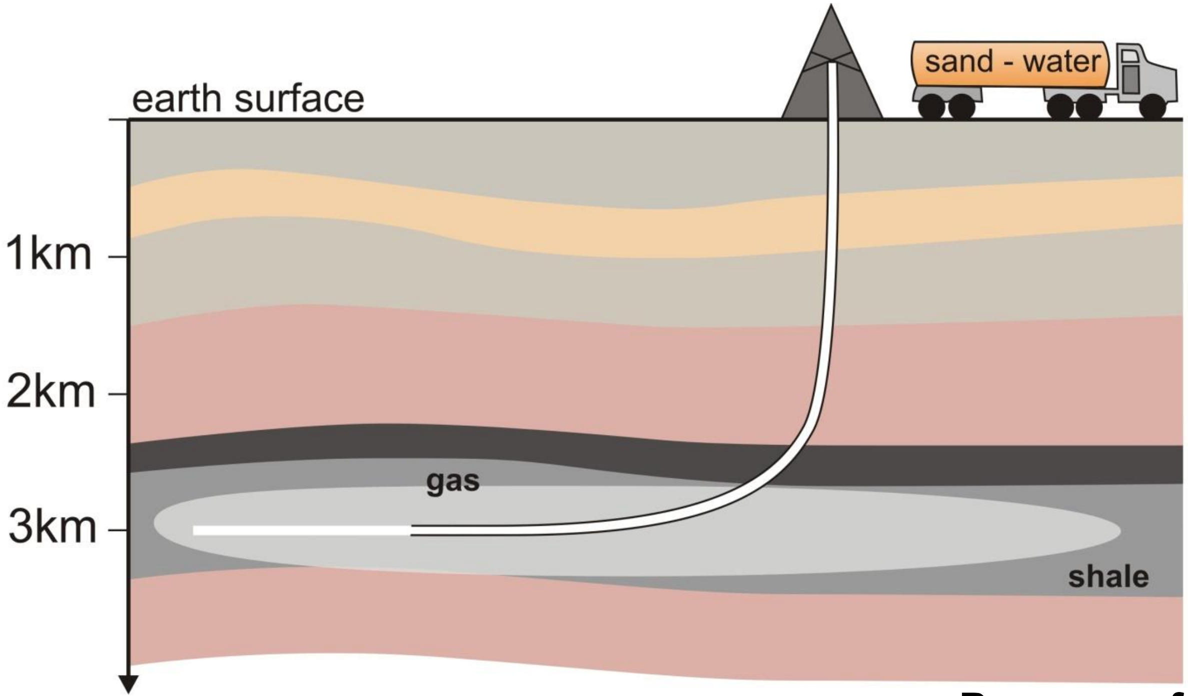
- Gasfield detection

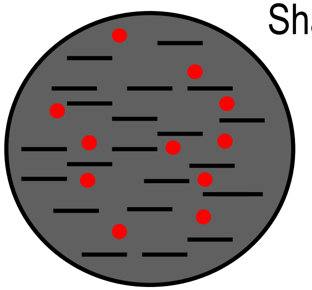




Process of hydraulic fracturing

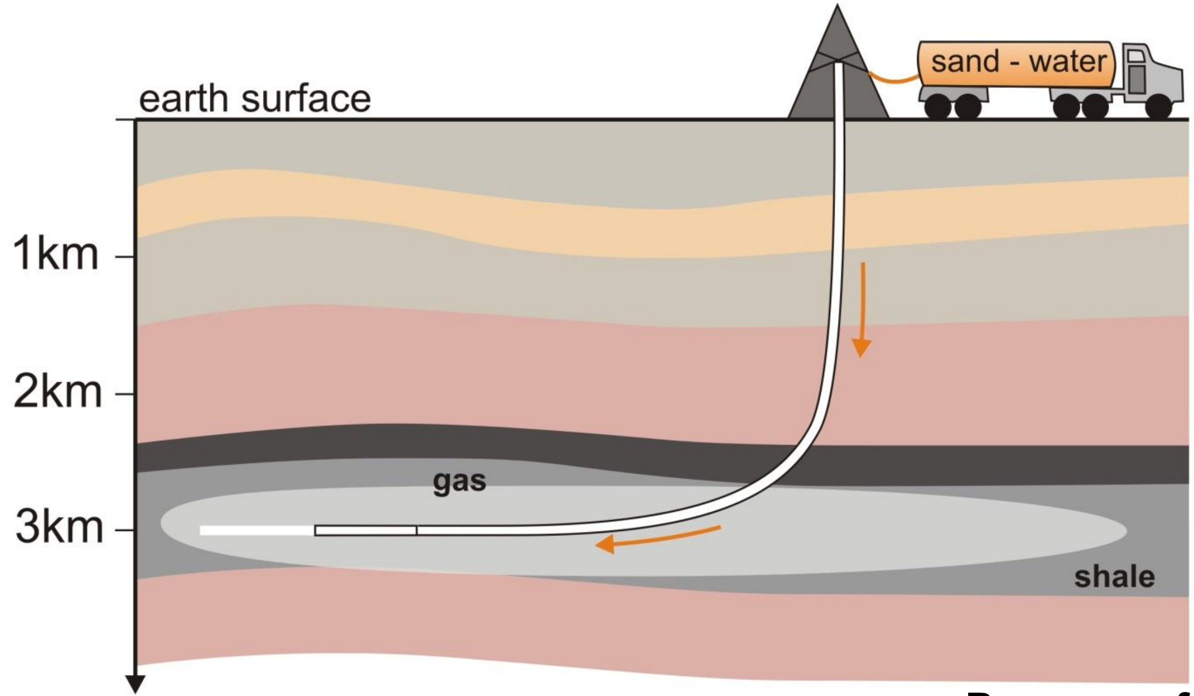
- Gasfield detection
- Drilling

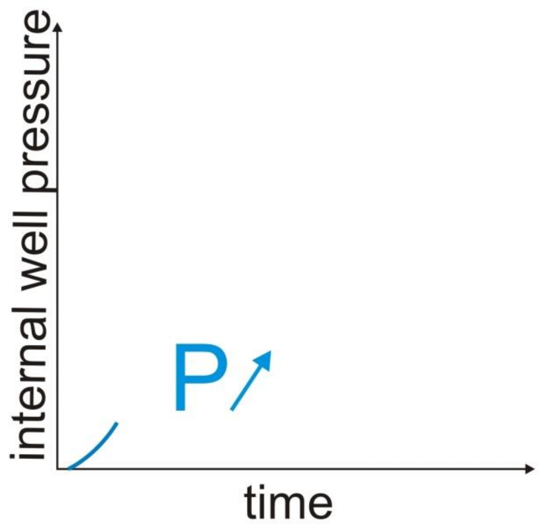


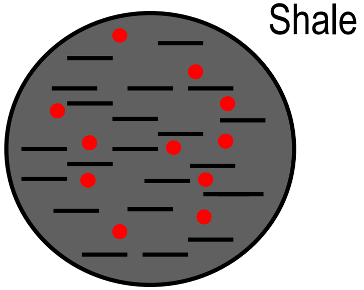


Process of hydraulic fracturing

- Gasfield detection
- Drilling
- Sand & Water input

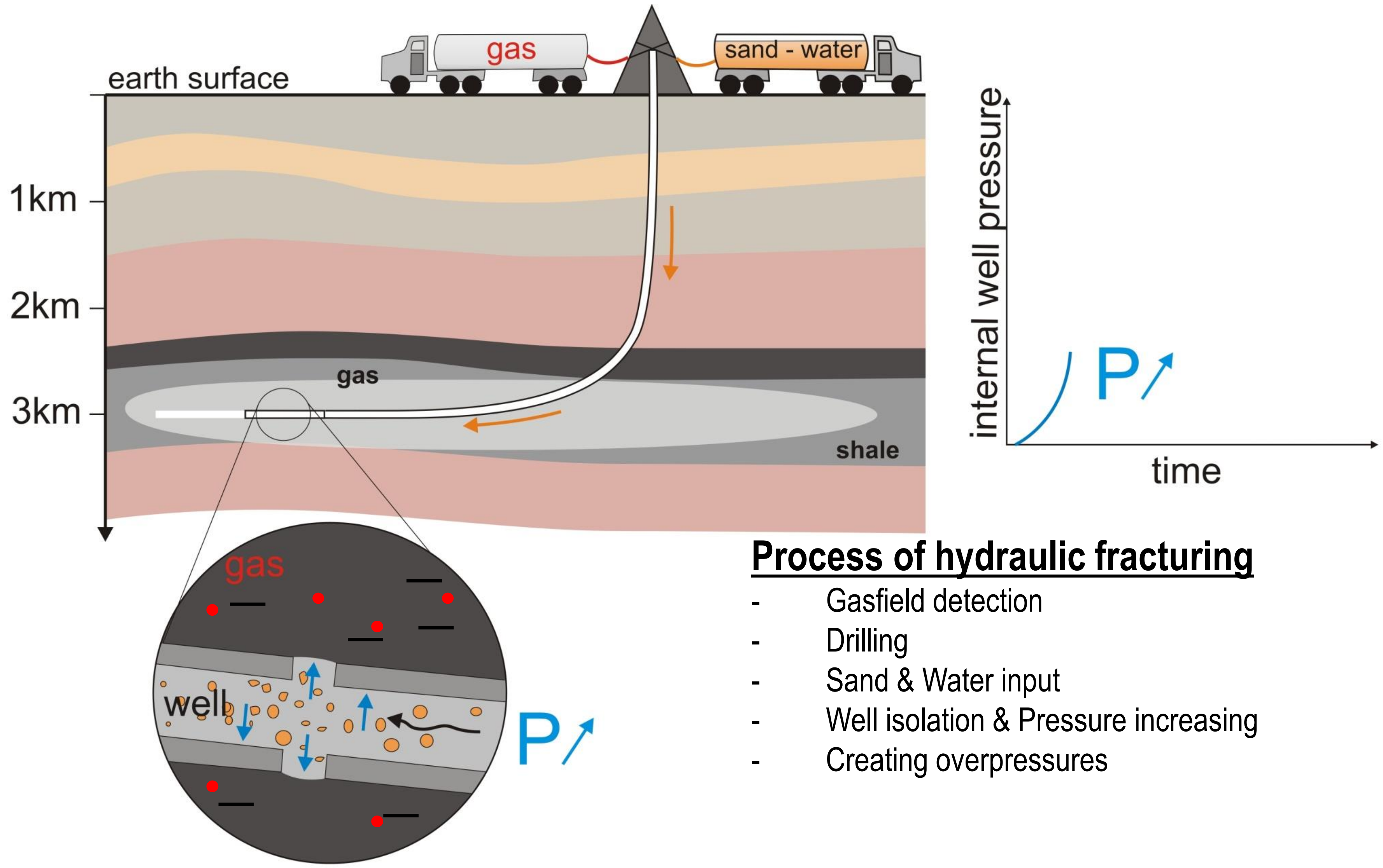






Process of hydraulic fracturing

- Gasfield detection
- Drilling
- Sand & Water input
- Well isolation & Pressure increasing



Process of hydraulic fracturing

- Gasfield detection
- Drilling
- Sand & Water input
- Well isolation & Pressure increasing
- Creating overpressures

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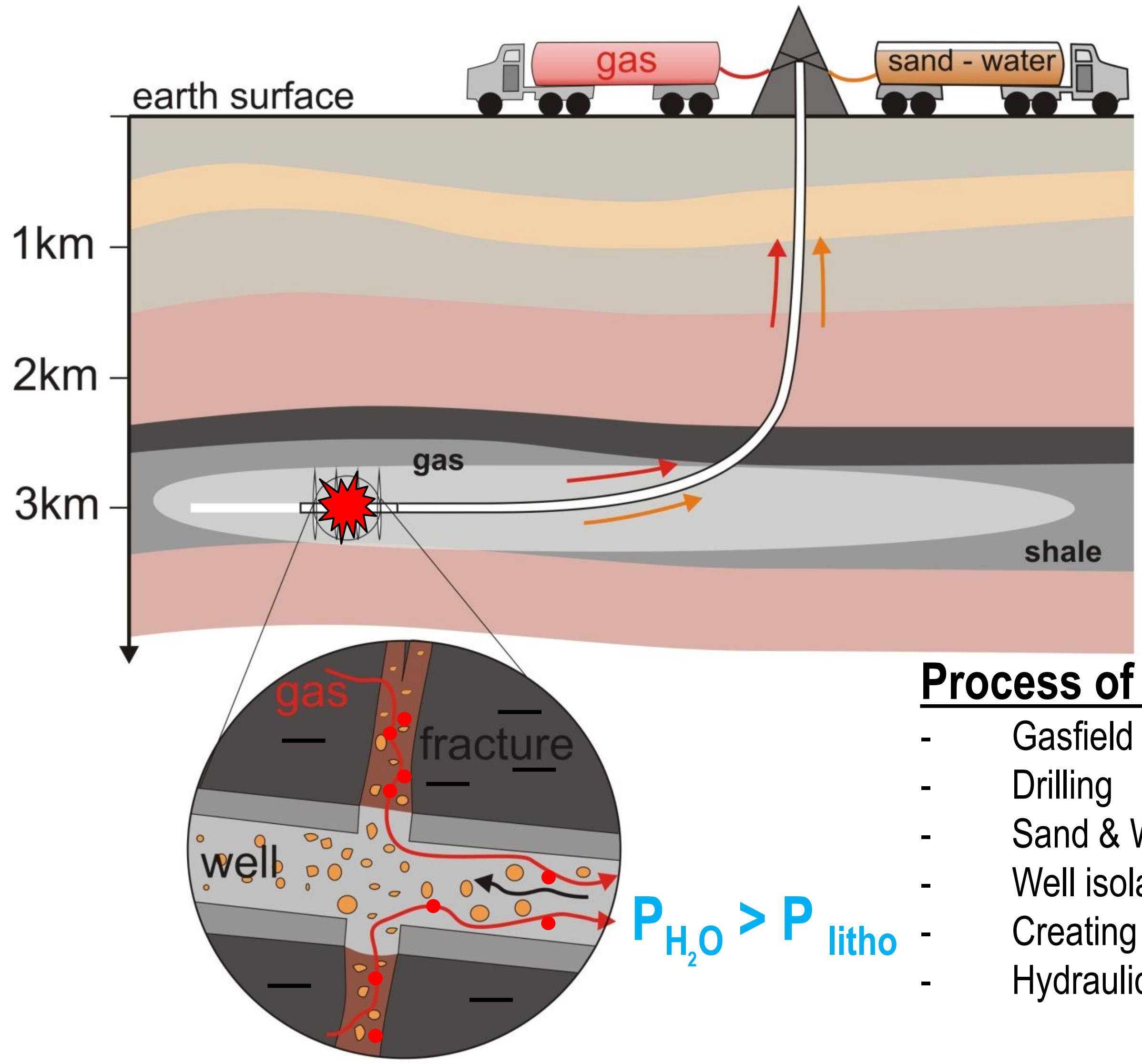
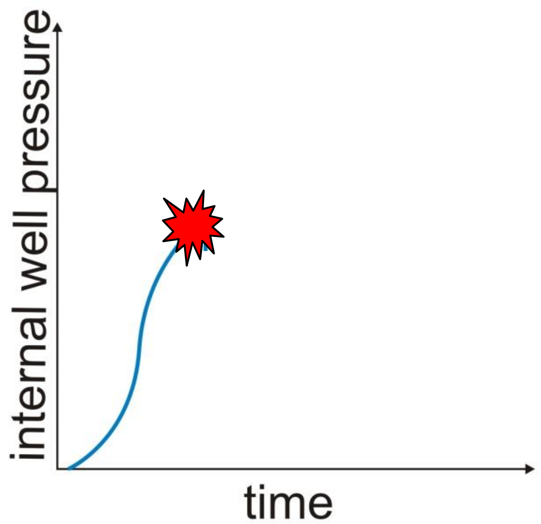
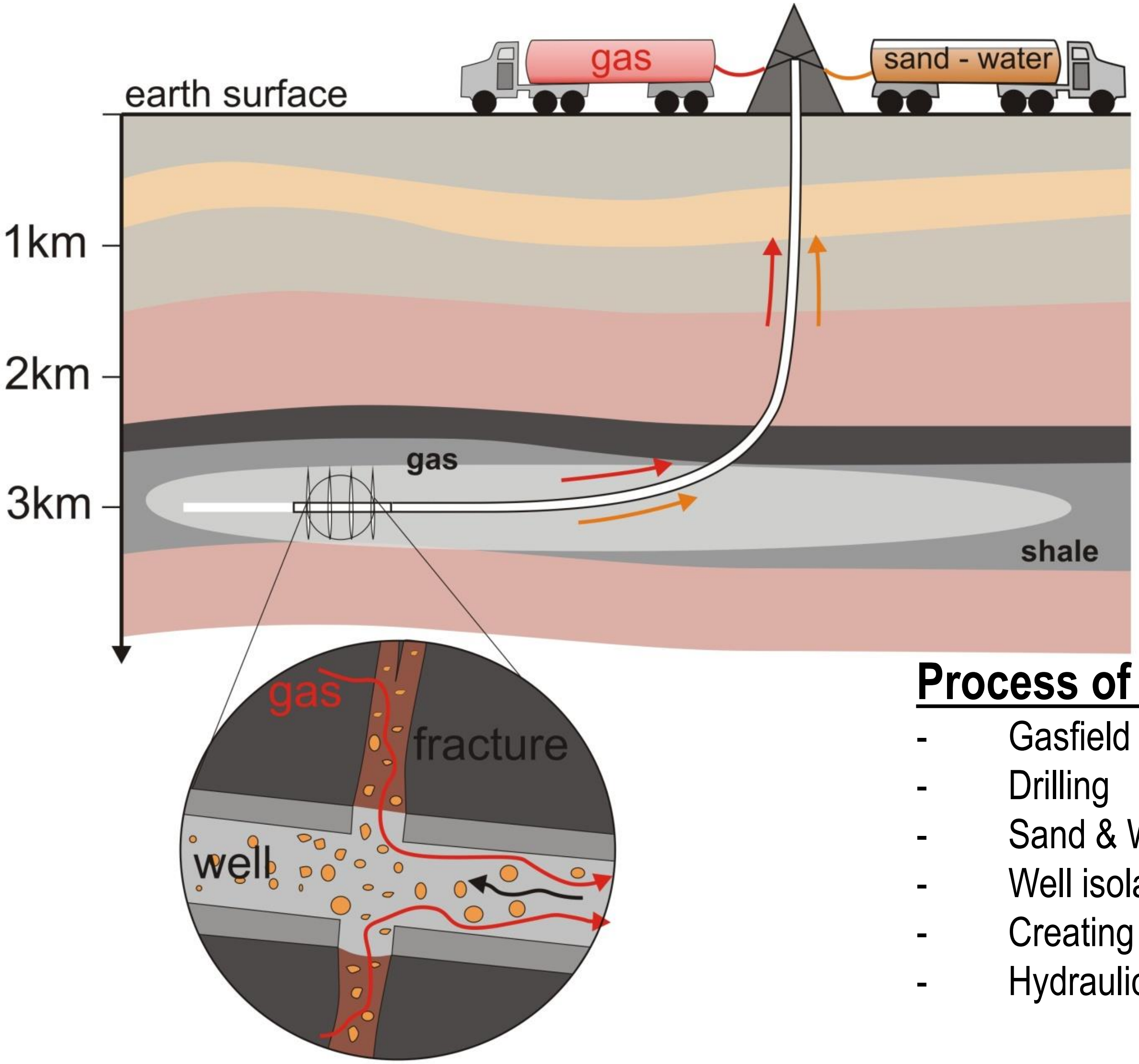
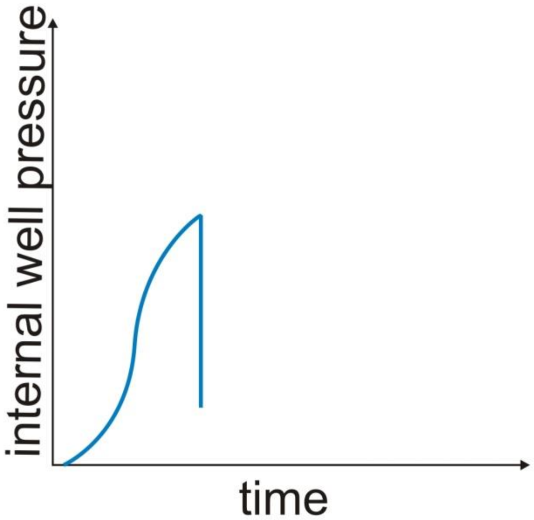




Process of hydraulic fracturing

- Gasfield detection
- Drilling
- Sand & Water input
- Well isolation & Pressure increasing
- Creating overpressures
- Hydraulic fracturing at critical rock strength





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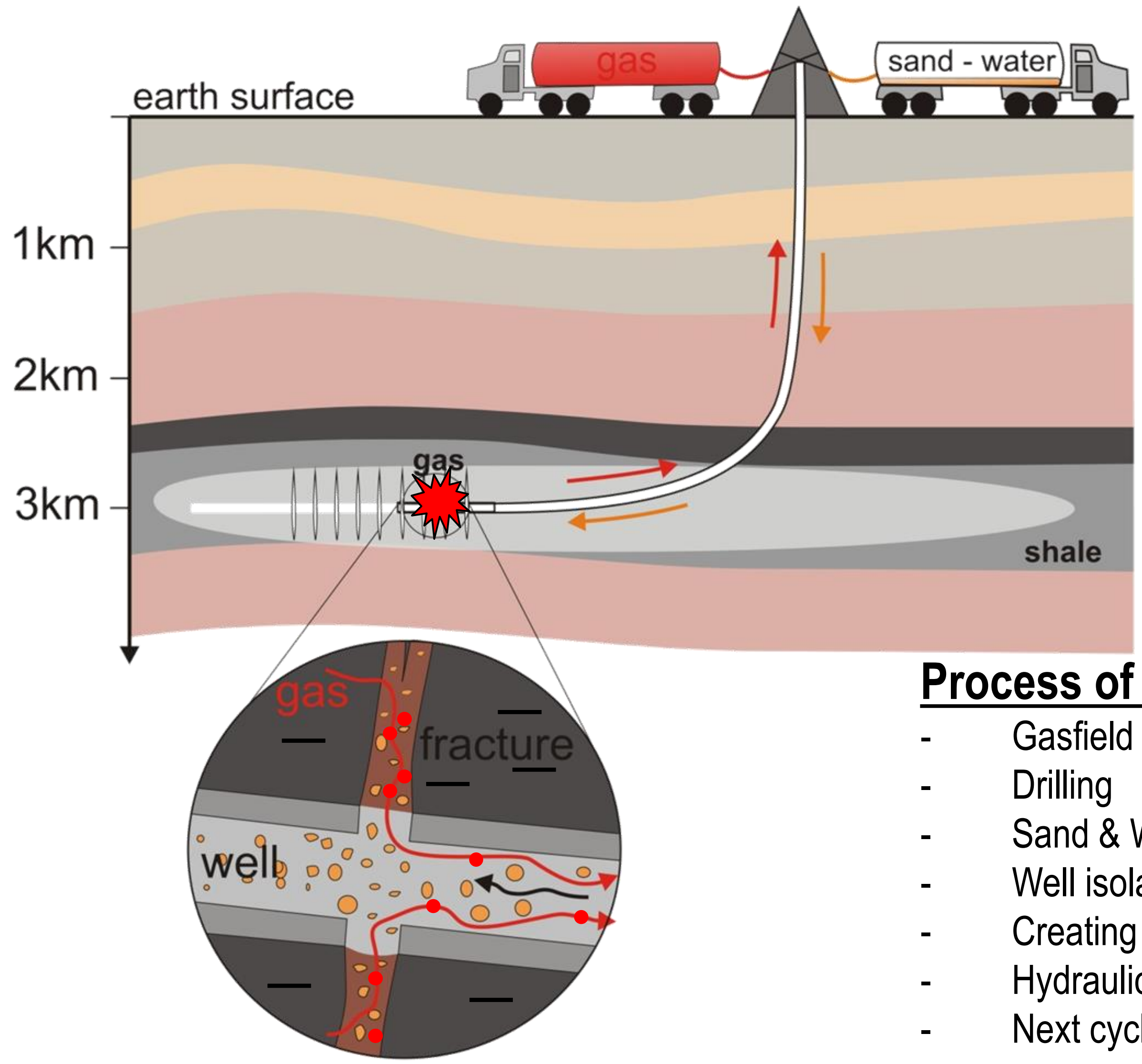

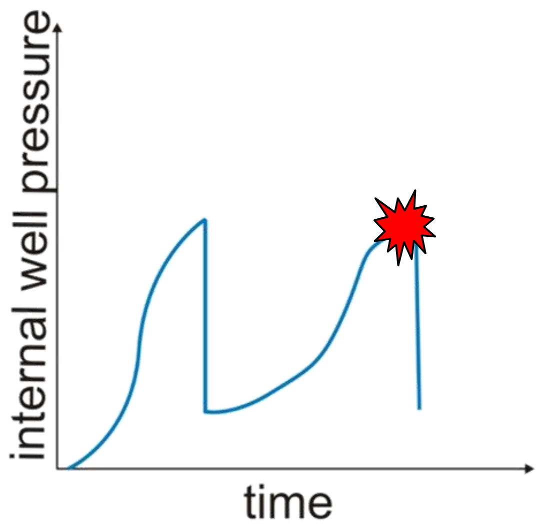

Process of hydraulic fracturing

- Gasfield detection
- Drilling
- Sand & Water input
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- Hydraulic fracturing at critical rock strength
- Next cycle at new isolated part of the borehole

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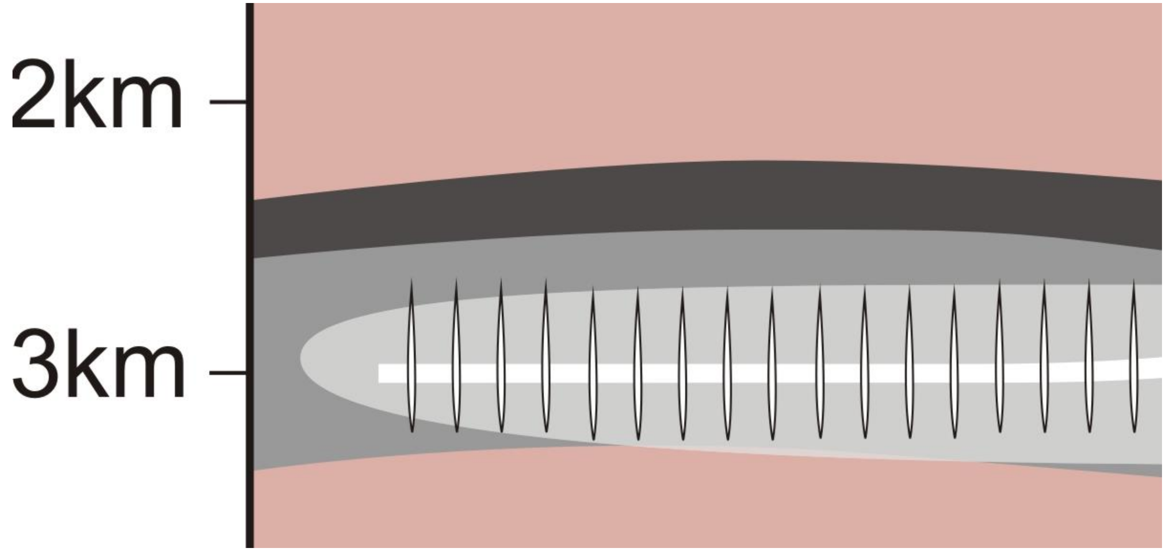

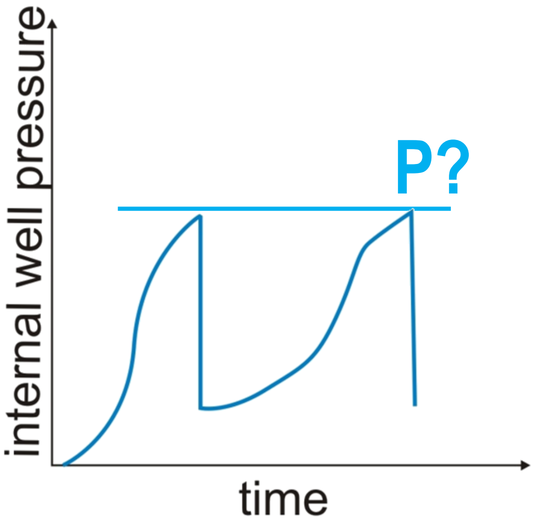

Hydraulic fracturing ?

- Degree of overpressuring ?
- Fracture orientation ?
- Vertical fractures ?
- Horizontal fractures ?
- Timing ?

Process of hydraulic fracturing

- Gasfield detection
- Drilling
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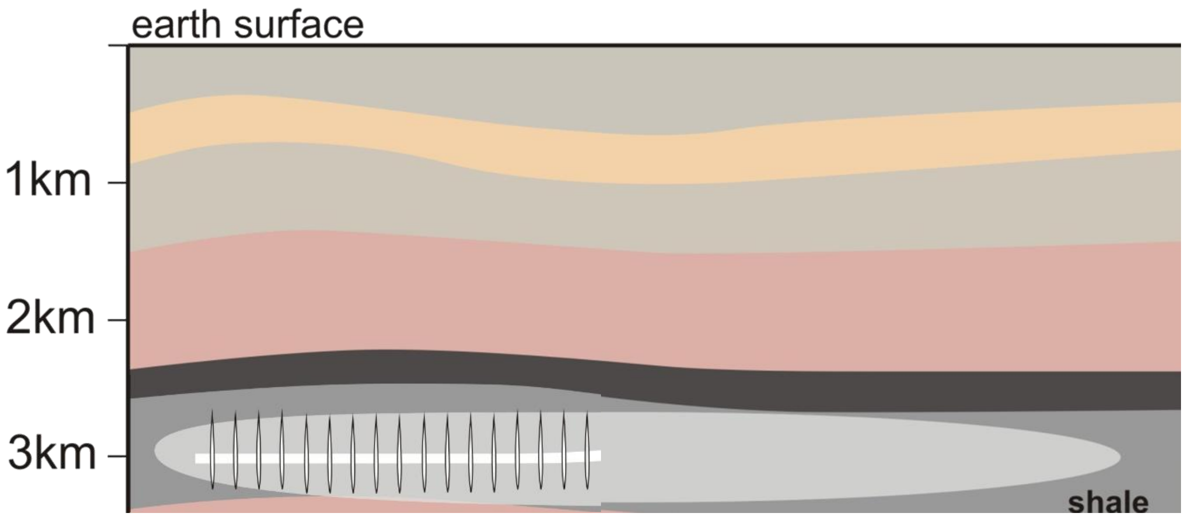
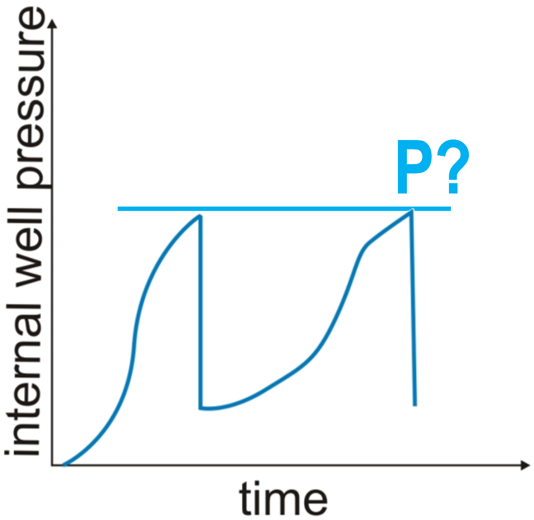
Problem outline





Hydraulic fracturing ?

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Problem:
Subsurface not accessible

Process of hydraulic fracturing

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- Hydraulic fracturing at critical rock strength
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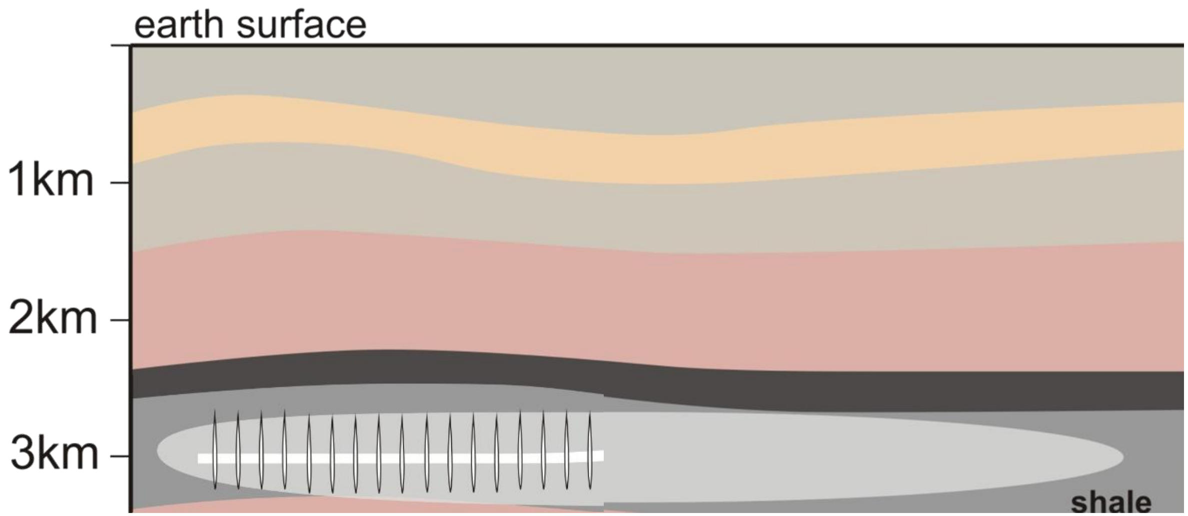

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Problem:
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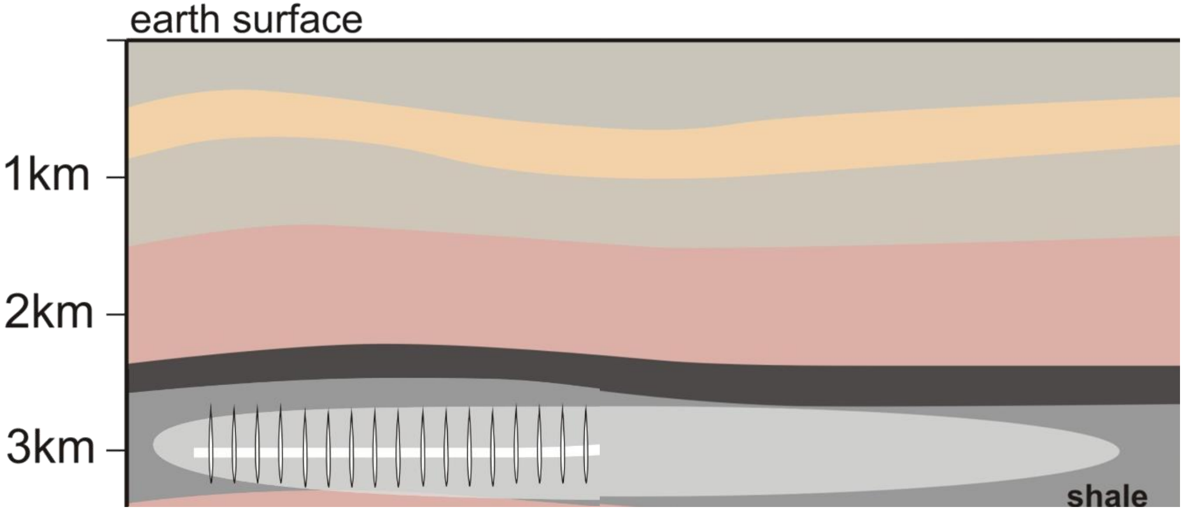
Solution:
Natural analogue: **VEINS**



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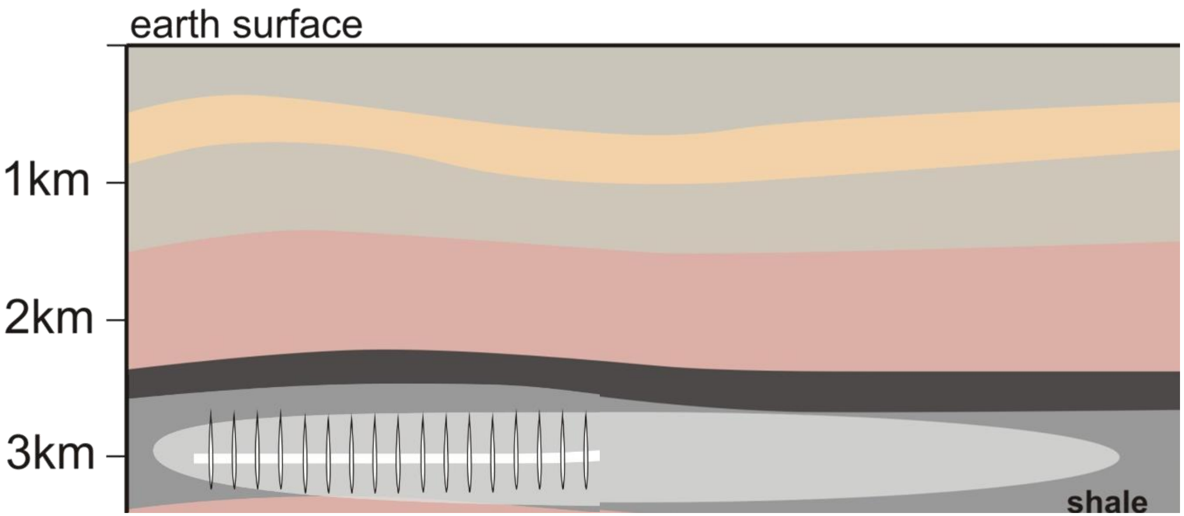

Problem:
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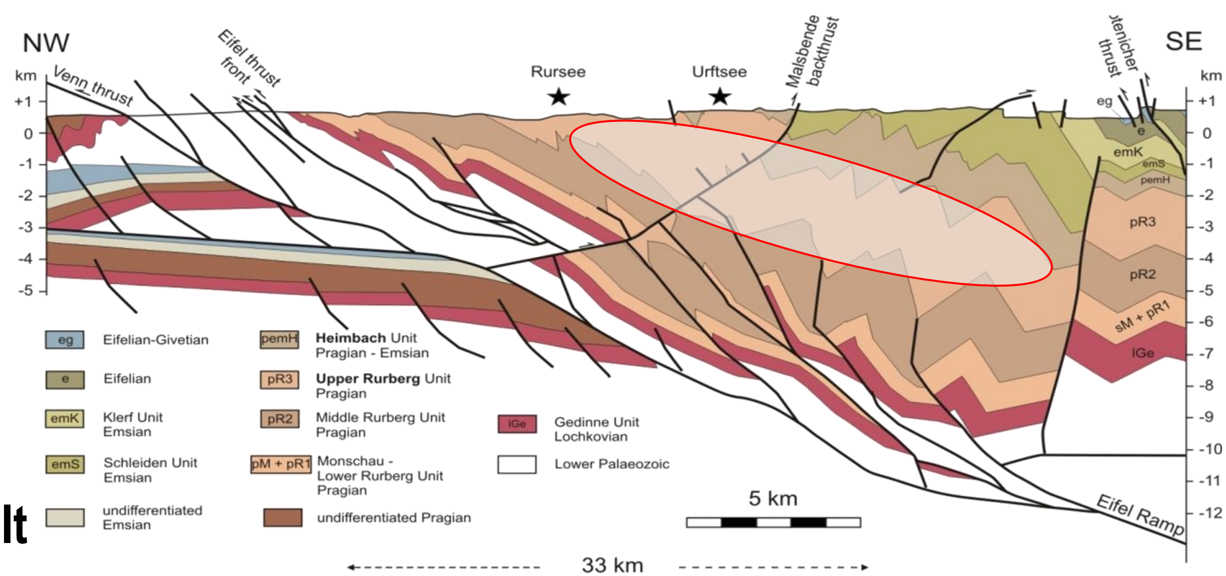


Solution:
Natural analogue: **VEINS**

High-Ardenne slate belt

1. Problem definition

2. Field area

1. Problem definition

3. Macrostructural field analysis

2. Field area

1. Problem definition

Methodology

3. Macrostructural field analysis

4. Sample preparation

2. Field area

1. Problem definition

Methodology

3. Macrostructural field analysis

4. Sample preparation

5. Microstructural analysis

5 cm

3 cm

2. Field area

1. Problem definition

3. Macrostructural field analysis

4. Sample preparation

2. Field area

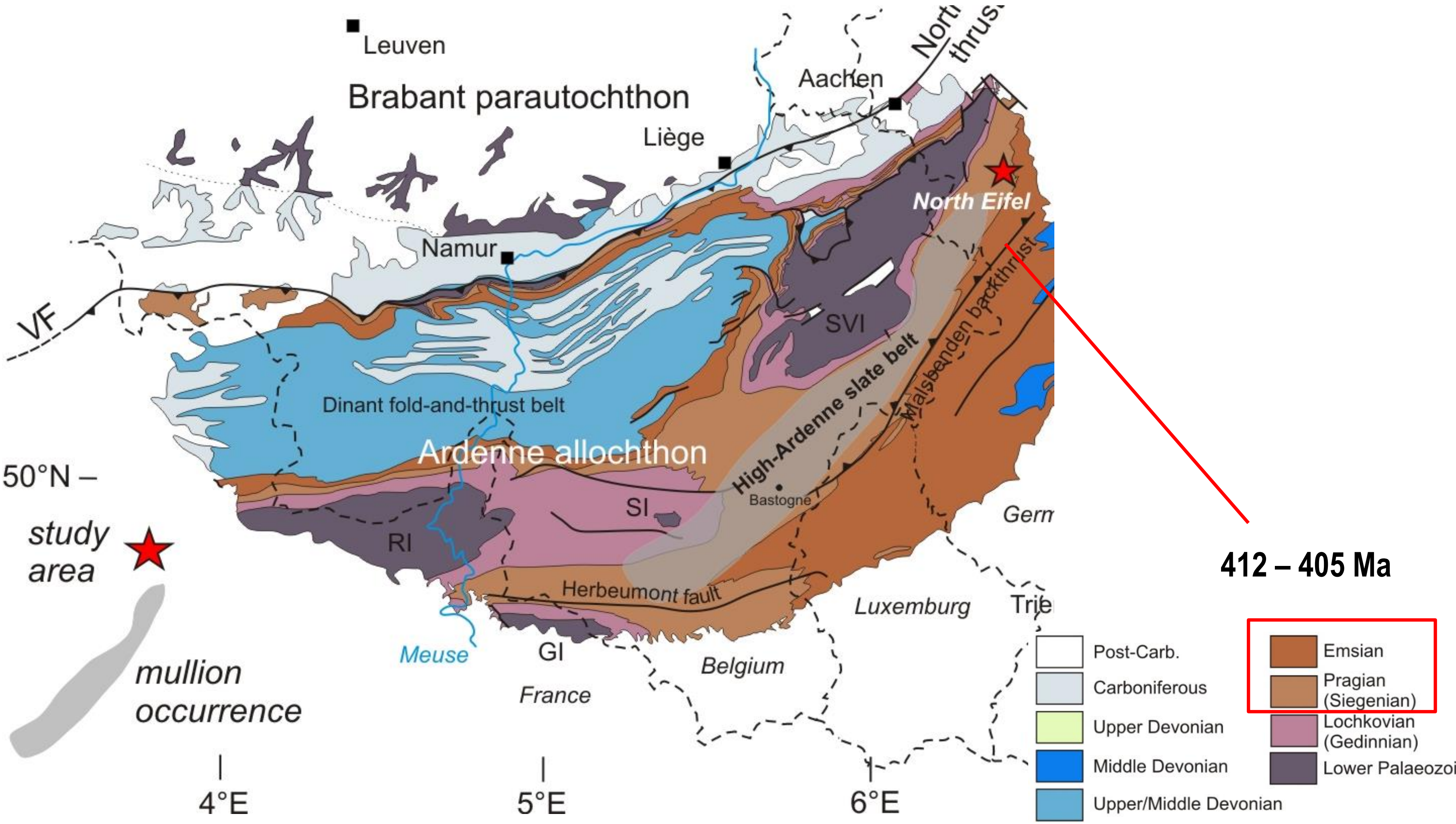
5. Microstructural analysis

1. Problem definition

7. Interpretation & Results

6. Laboratorium analysis: Pressure – Temperature conditions

Field area: Ardennes & Eifel



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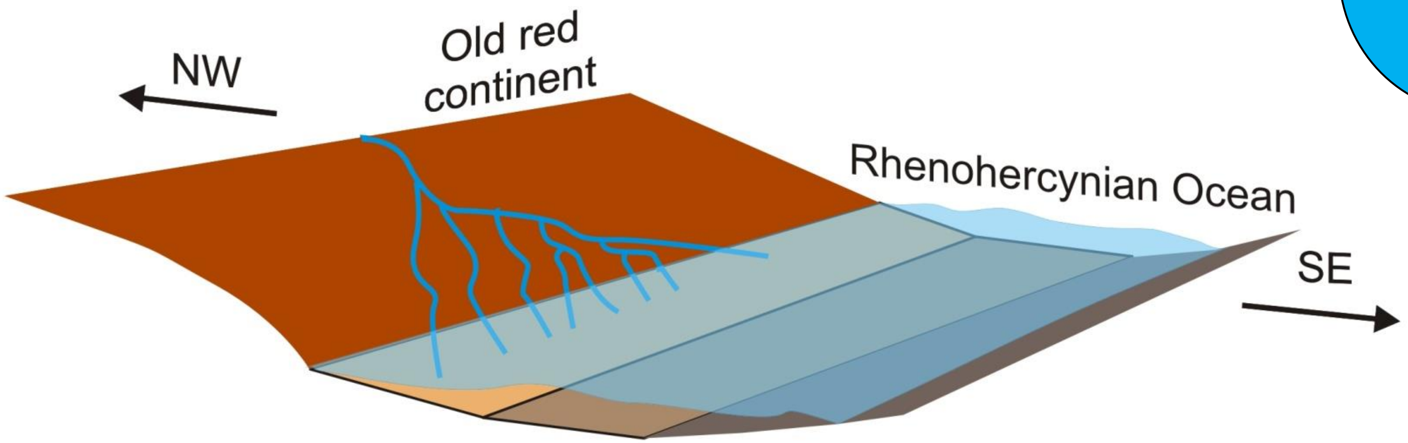

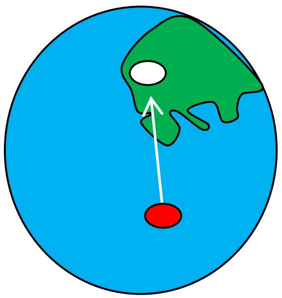

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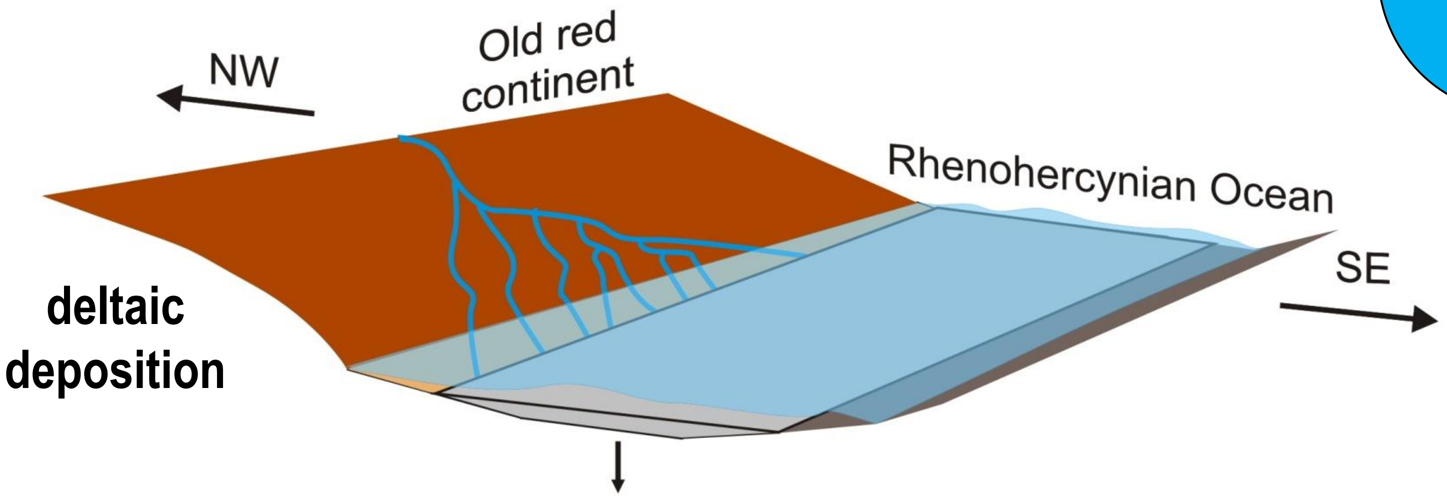

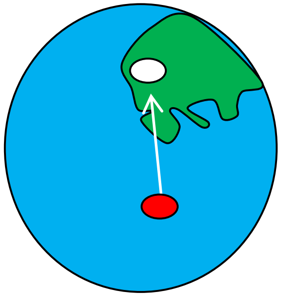

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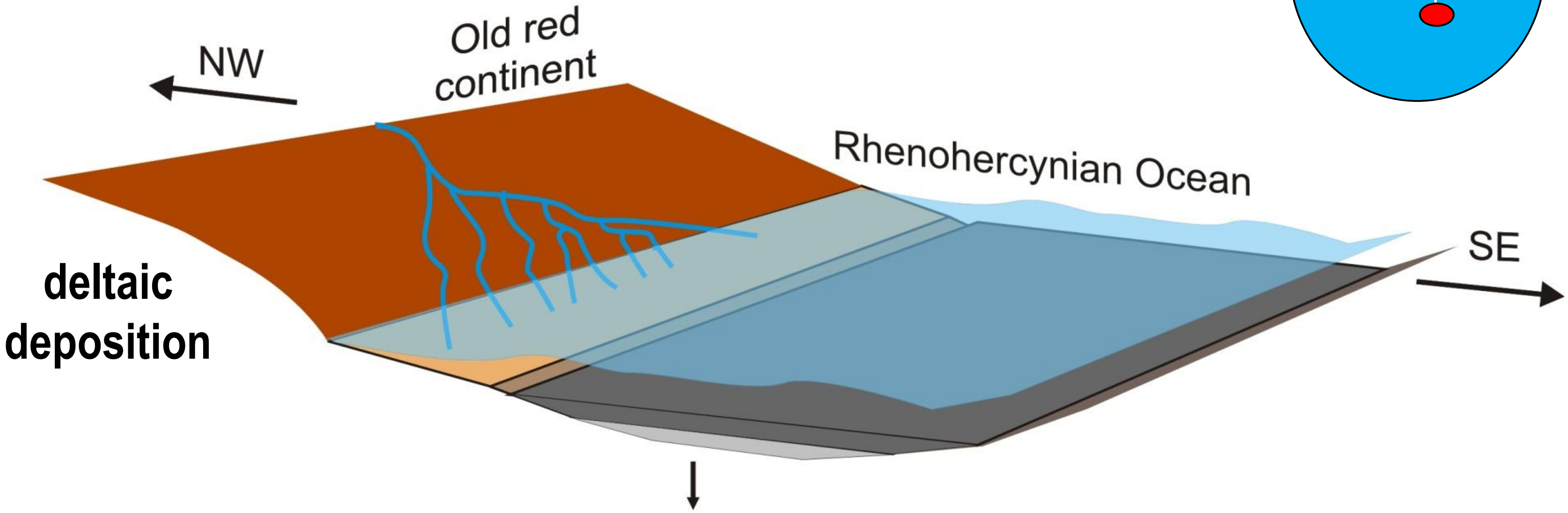
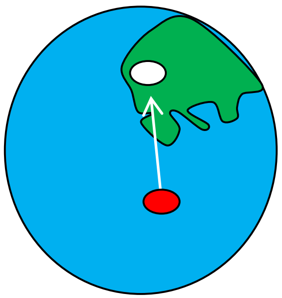
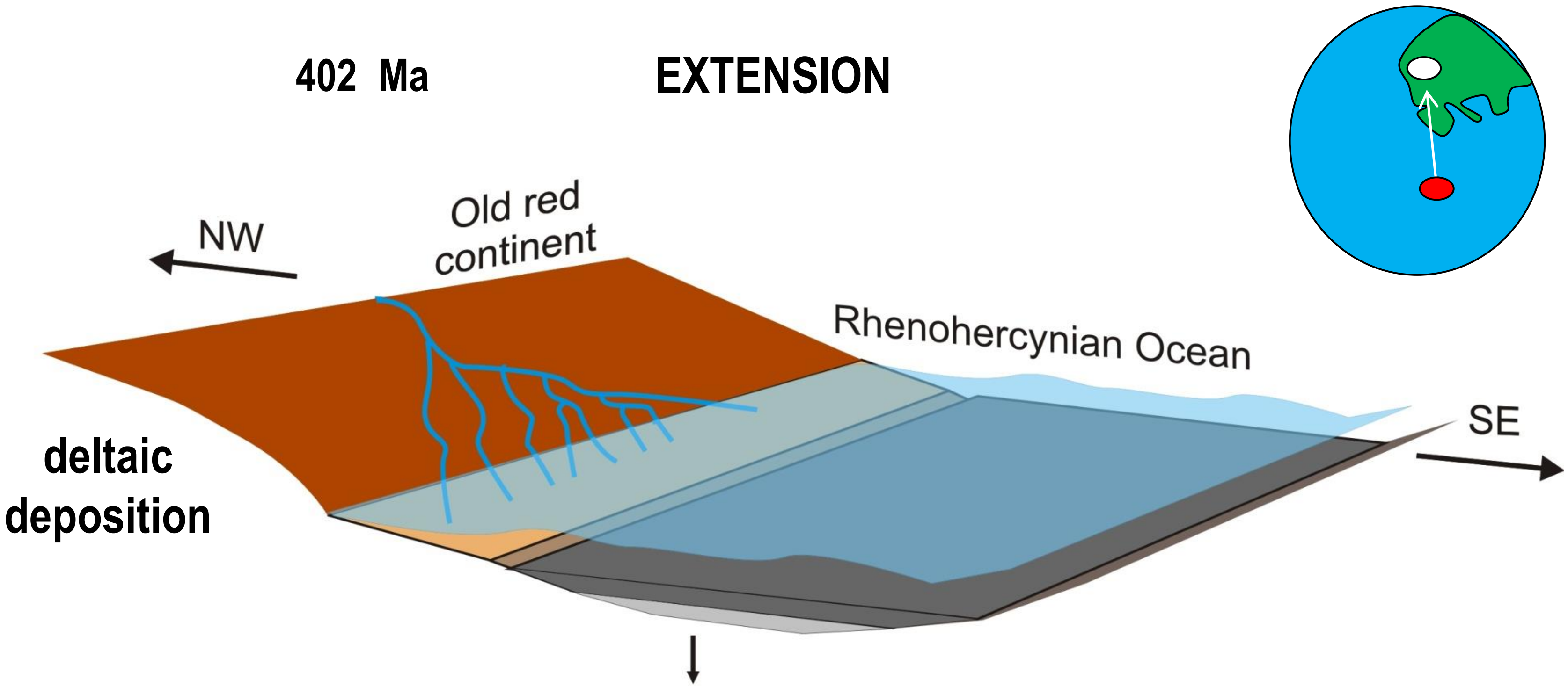
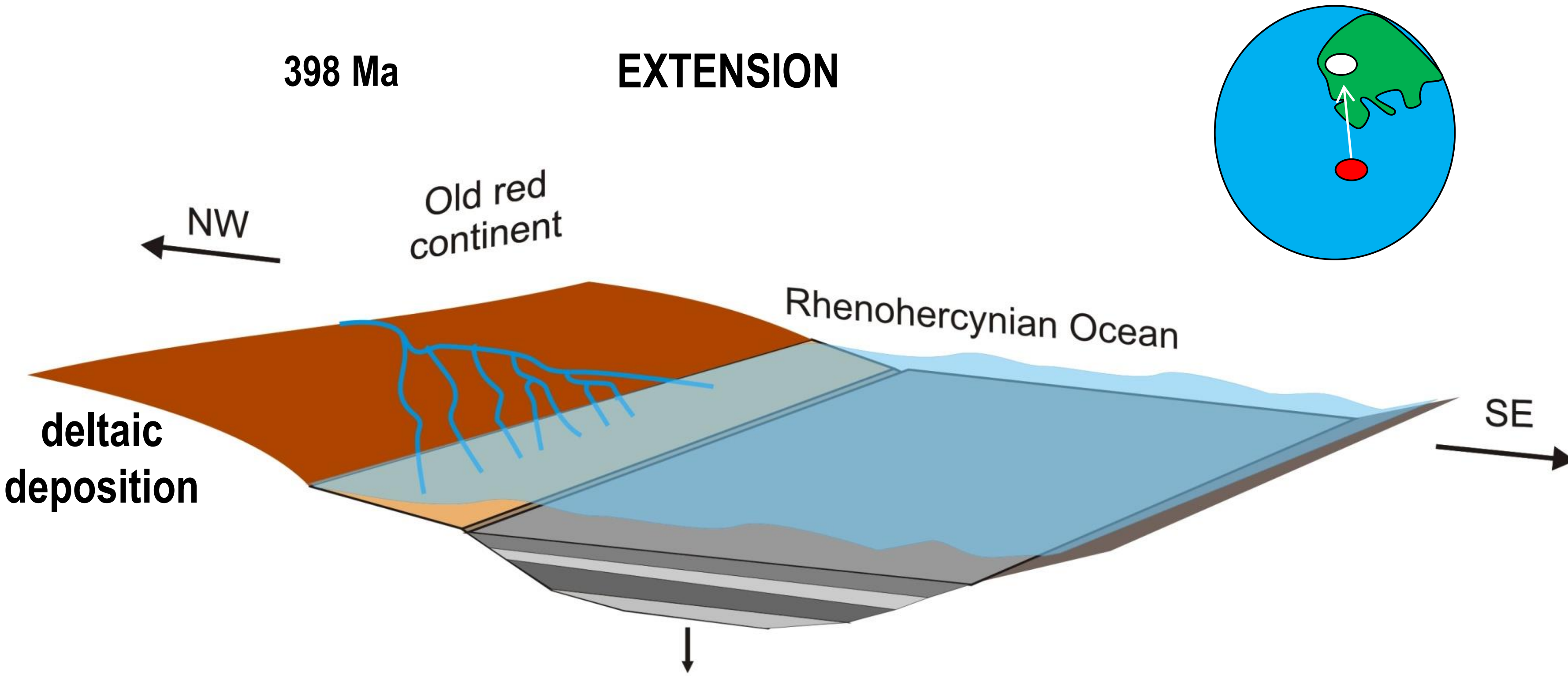


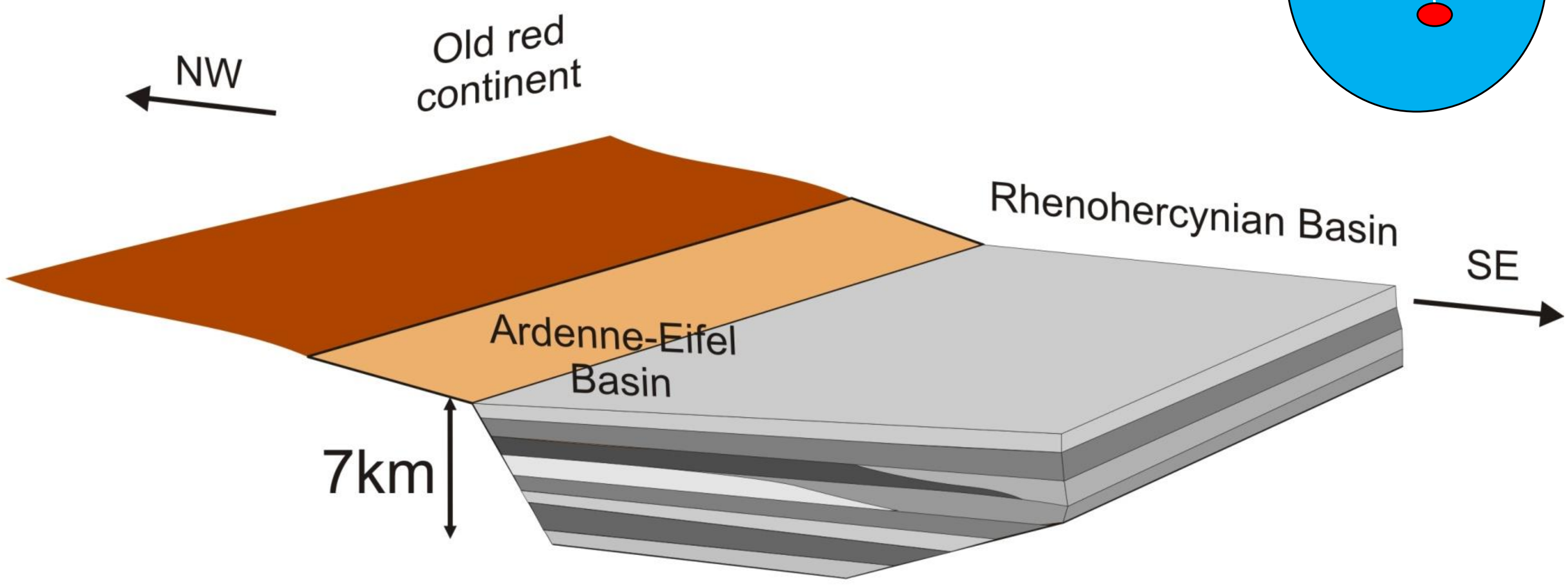


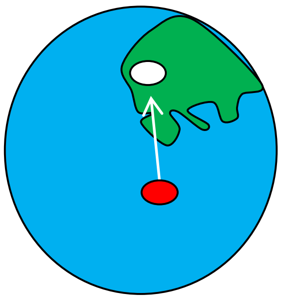
Geodynamic setting



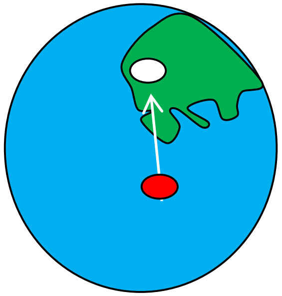

398 Ma
EXTENSION
Old red continent
NW
Rhenohercynian Ocean
deltaic deposition
SE

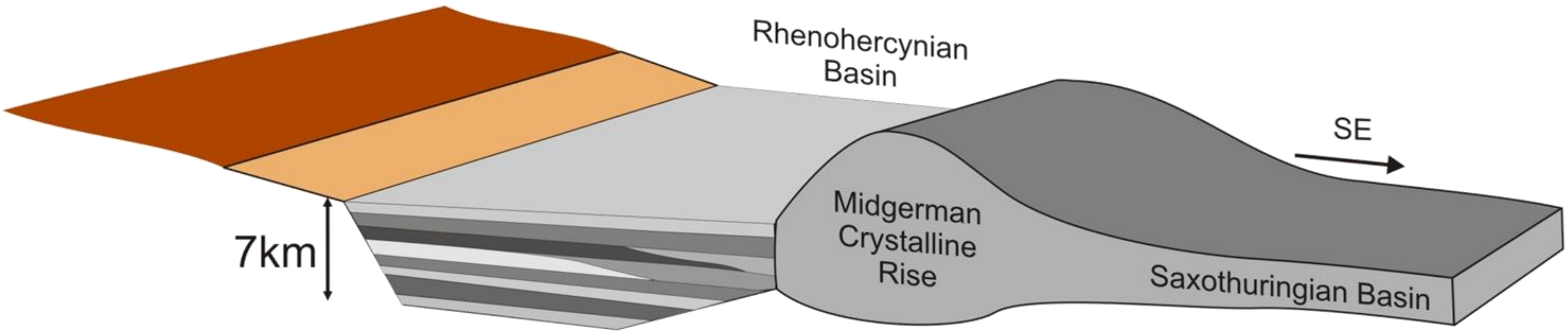
394 Ma **EXTENSION**





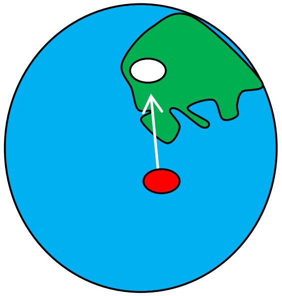
EXTENSION

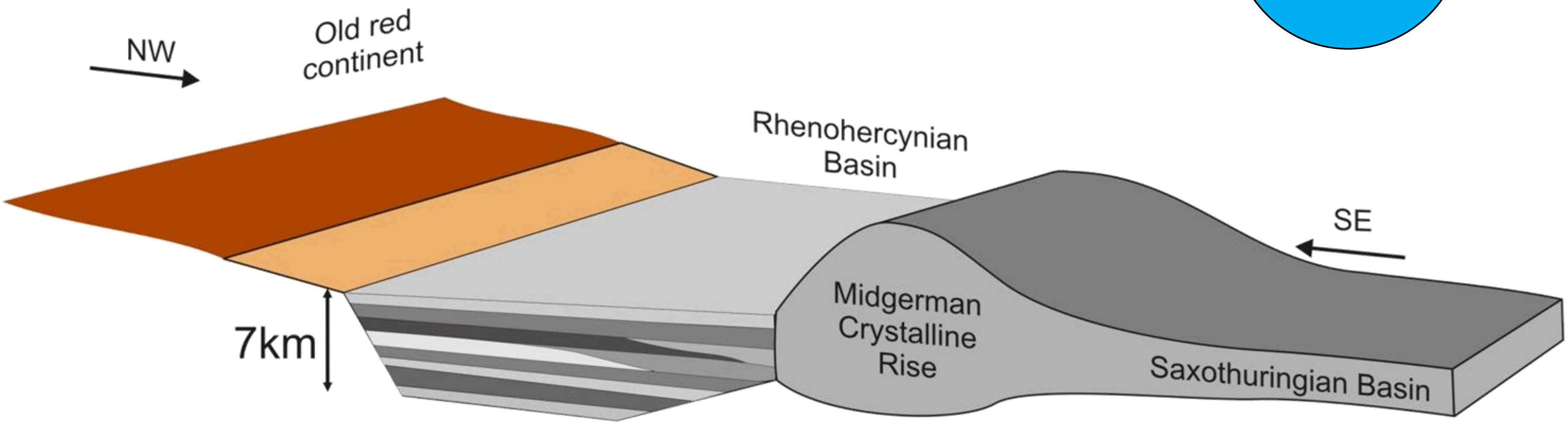



NW
Old red continent
Rhenohercynian Basin
SE
7km
Midgerman Crystalline Rise
Saxothuringian Basin

325 Ma

VARISCAN COMPRESSION



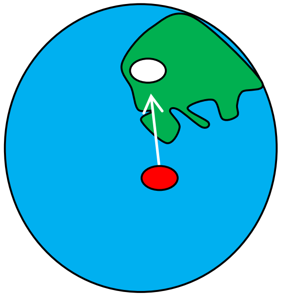


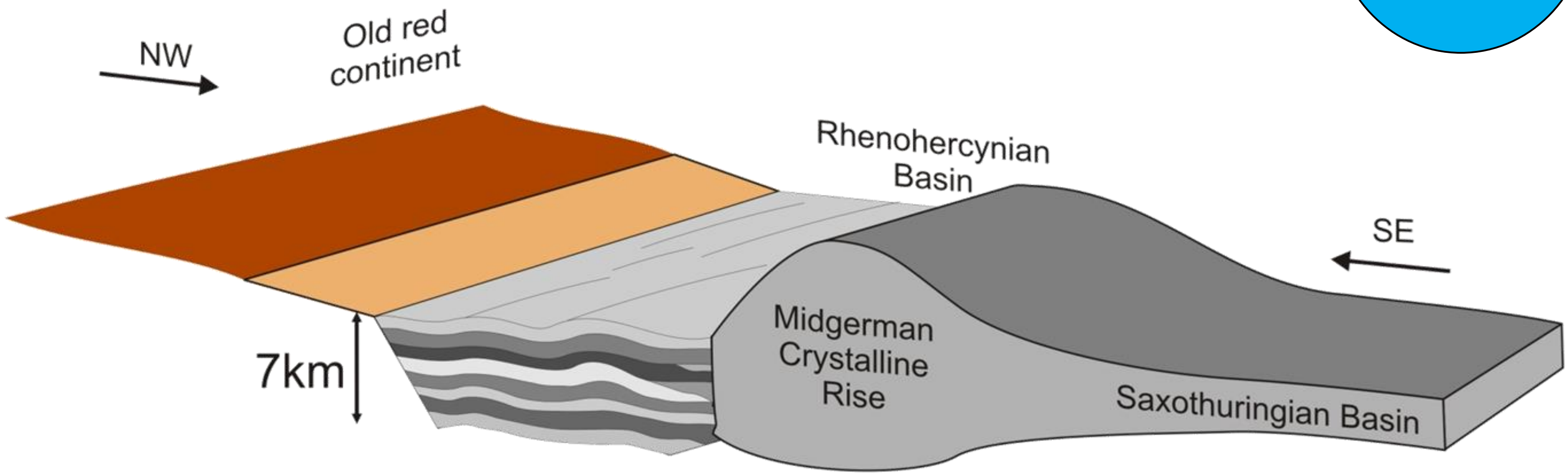
Collision of two plates

Geodynamic setting

320 Ma

VARISCAN COMPRESSION



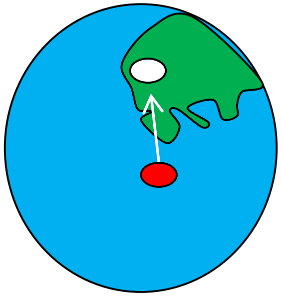


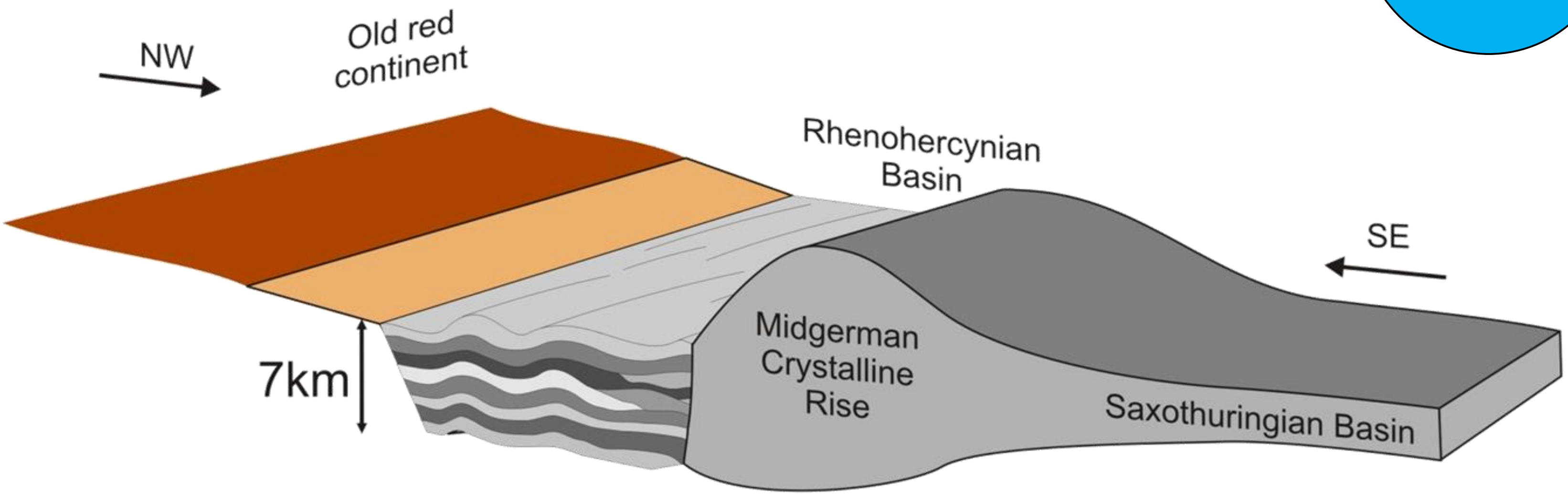
Collision of two plates

Public PhD defence Koen Van Noten, Leuven, May 3rd 2011

315 Ma

VARISCAN COMPRESSION



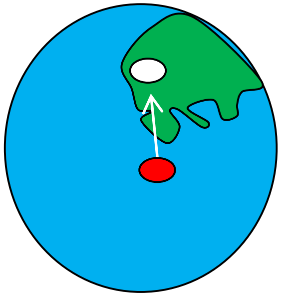


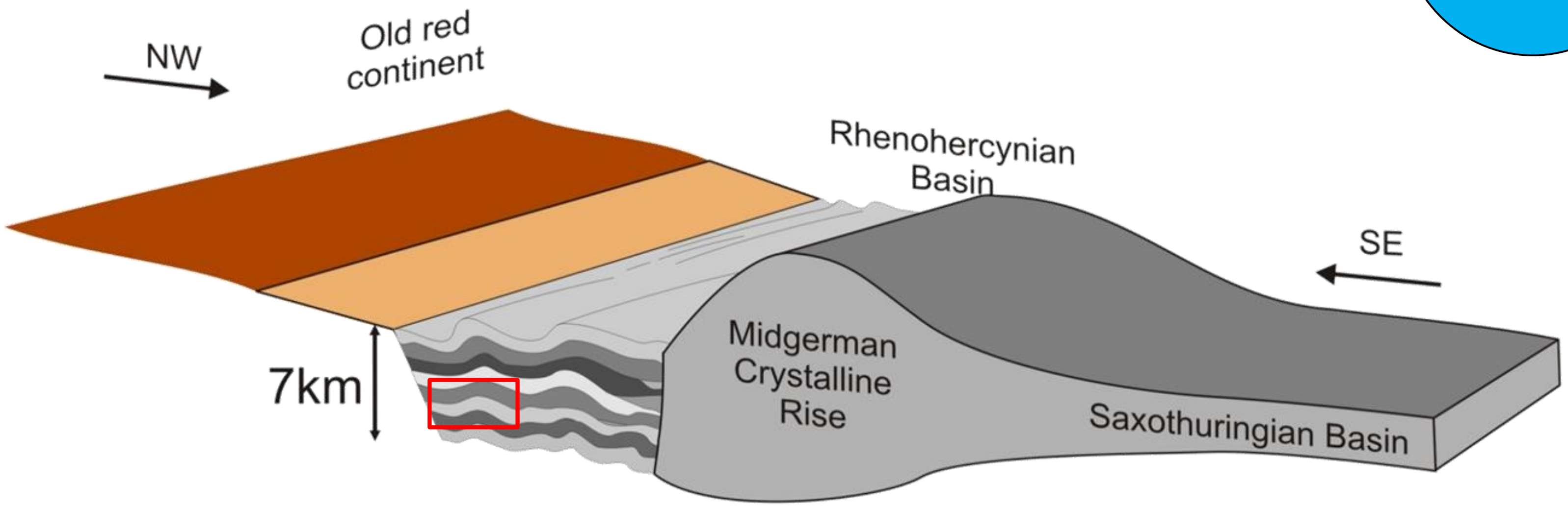
Collision of two plates

Public PhD defence Koen Van Noten, Leuven, May 3rd 2011

310 Ma

VARISCAN COMPRESSION





~40 % shortening

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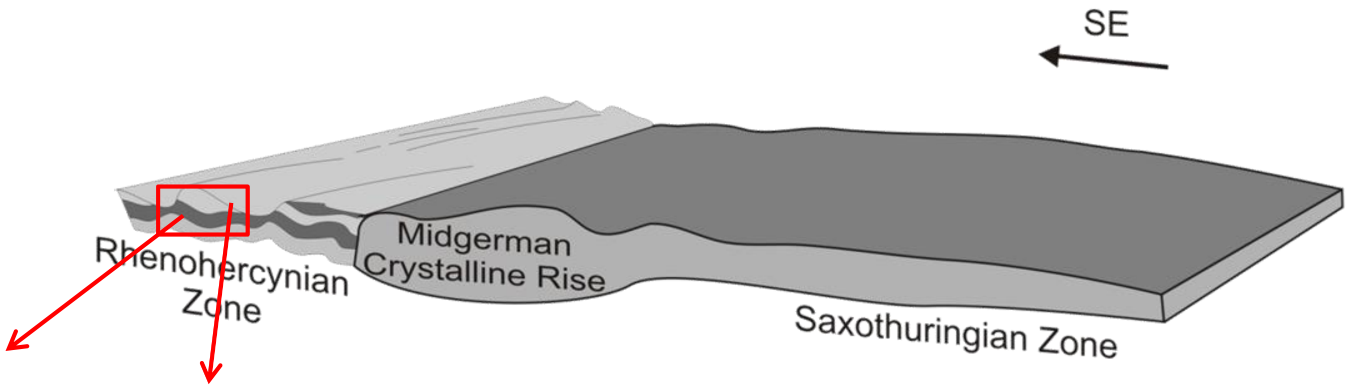
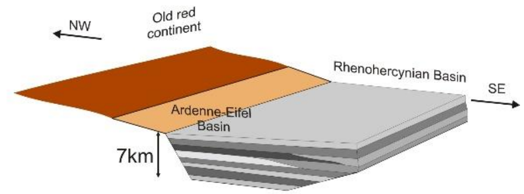
0 Ma **Present day**

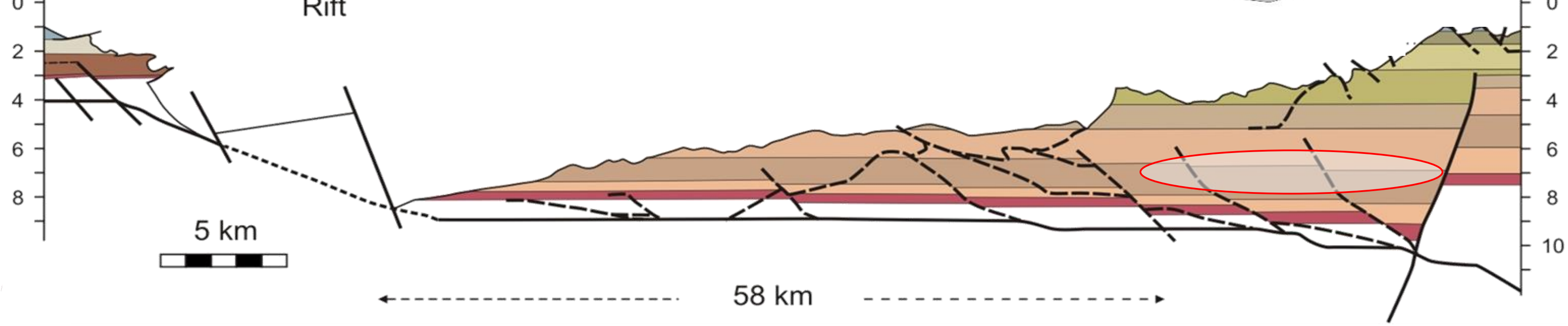


Ardennes
10 km depth

Eifel
7 km depth

Natural analogue

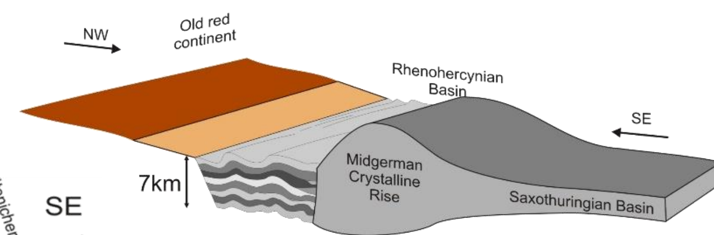


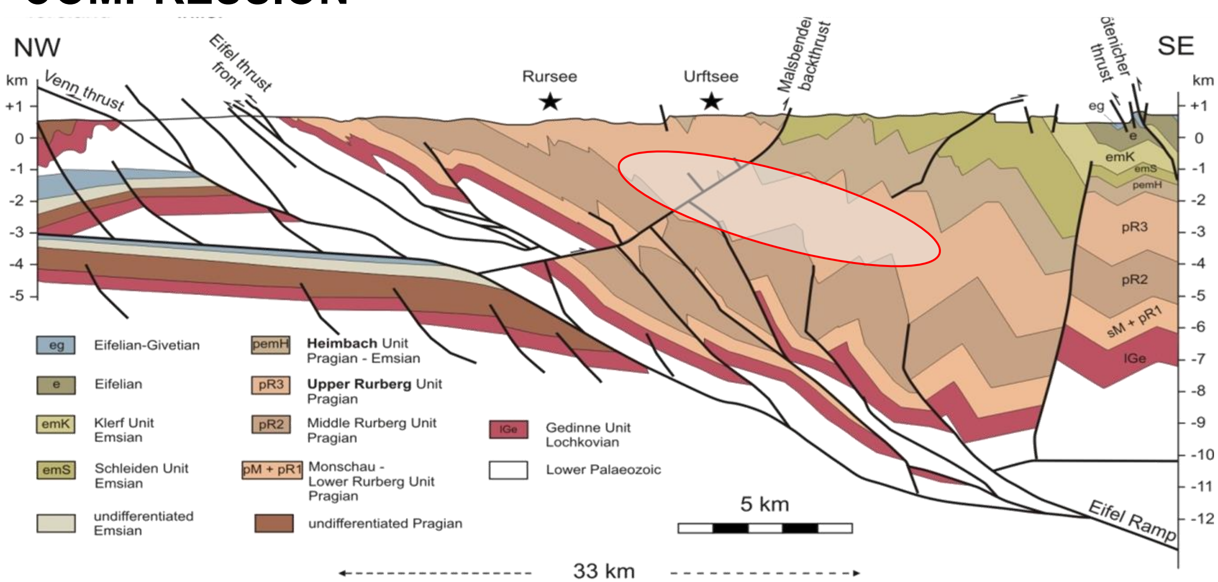


EXTENSION

COMPRESSION

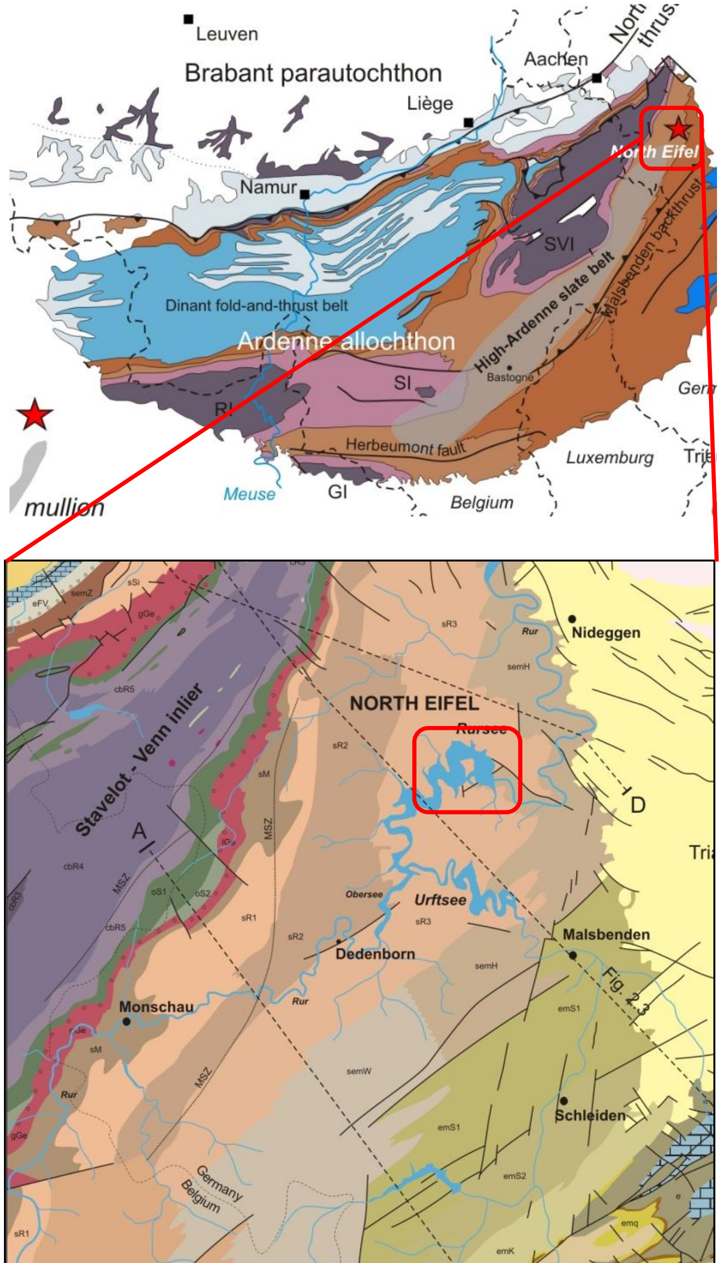
Tectonic inversion



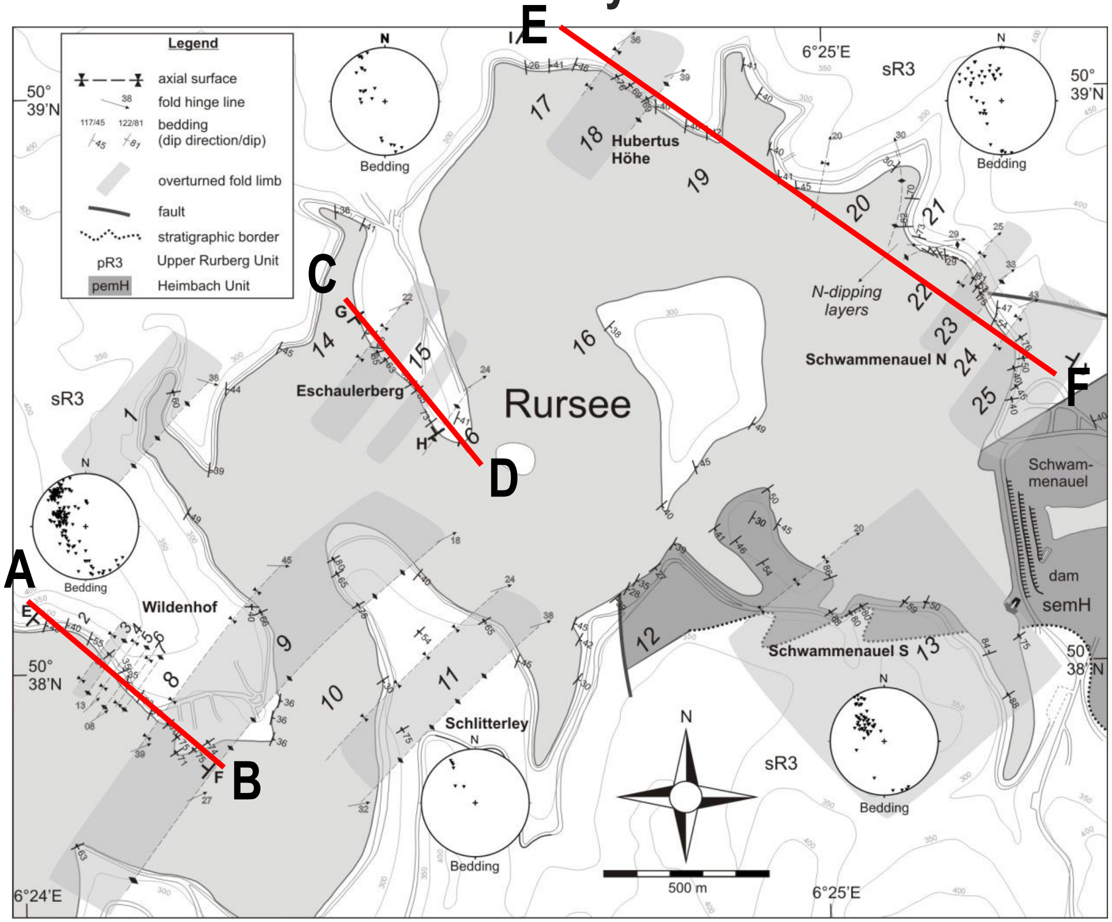


~40 % Variscan shortening

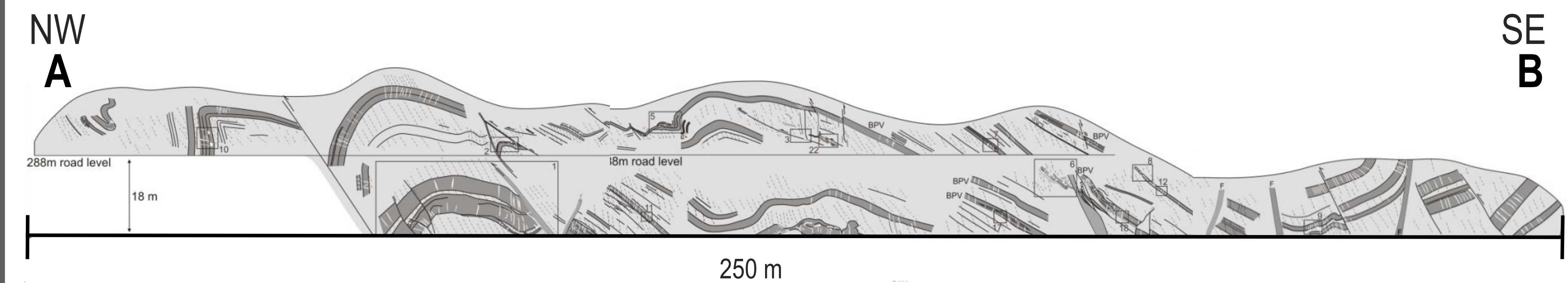
Structural analysis - Observations

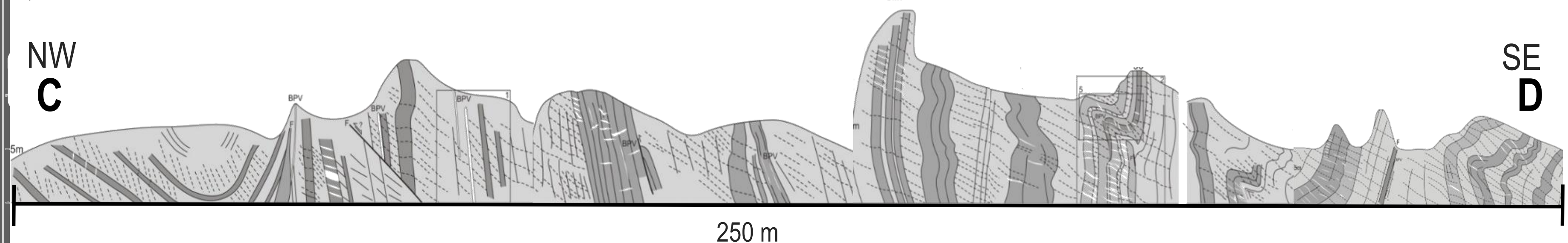


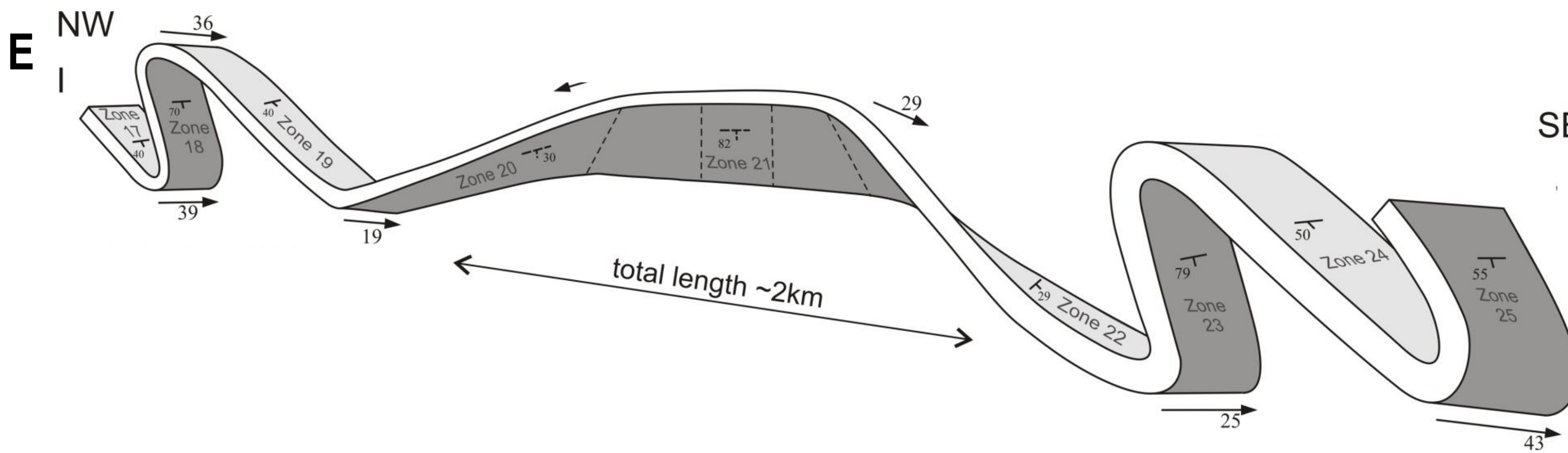
Rursee study area



Structural analysis - Observations

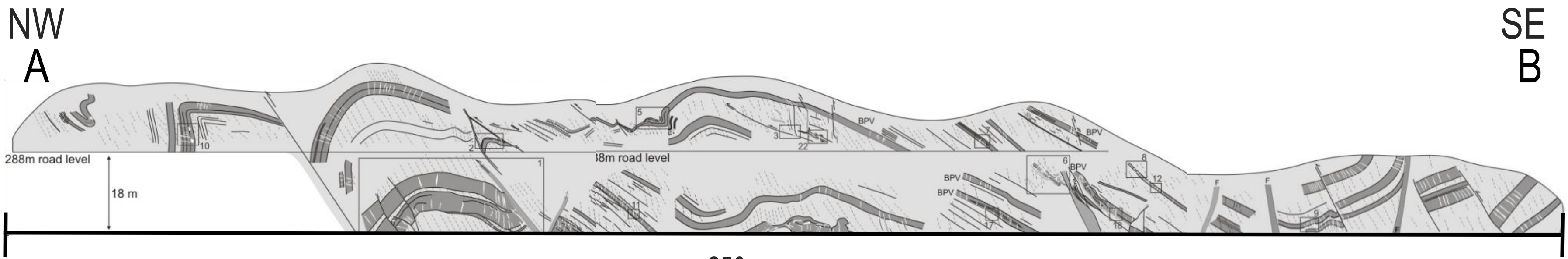




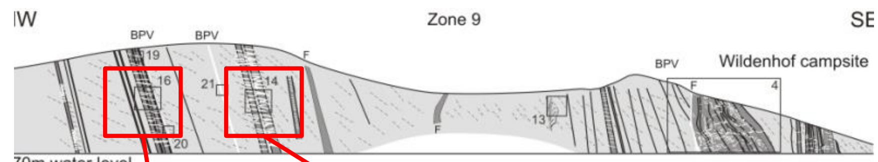


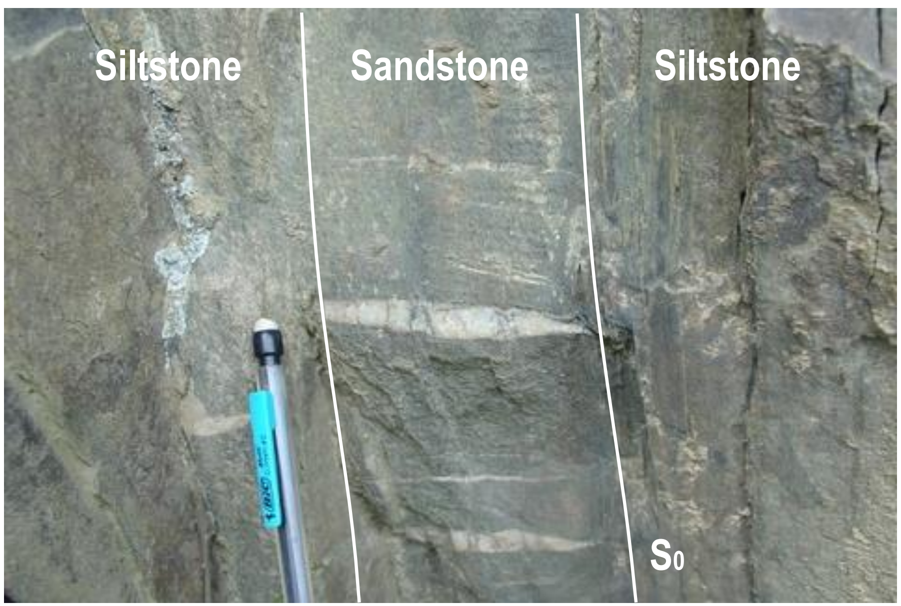
Fold geometry: consistent upright to overturned folds, NW-vergence, SE-dipping cleavage

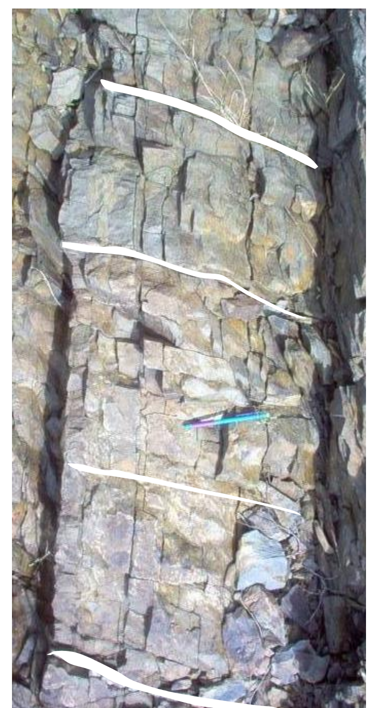
Public PhD defence Koen Van Noten, Leuven, May 3rd 2011

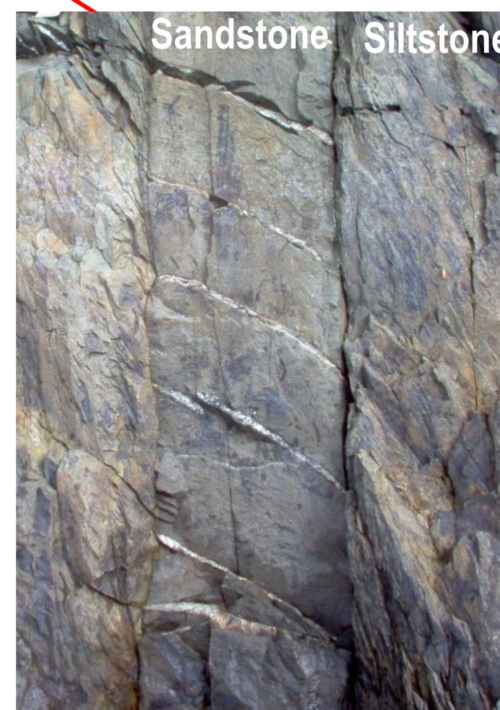


Bedding-normal veins



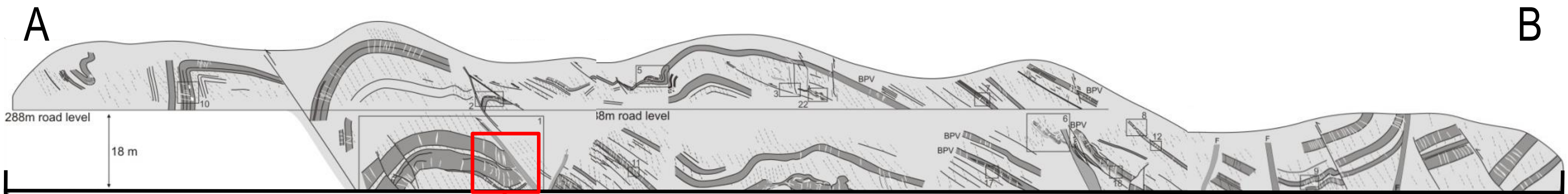




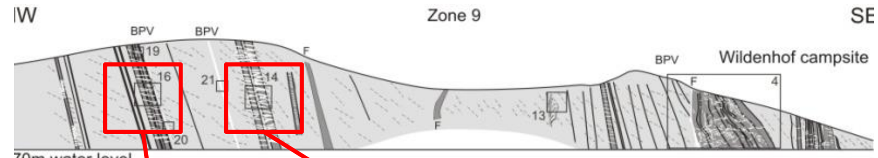


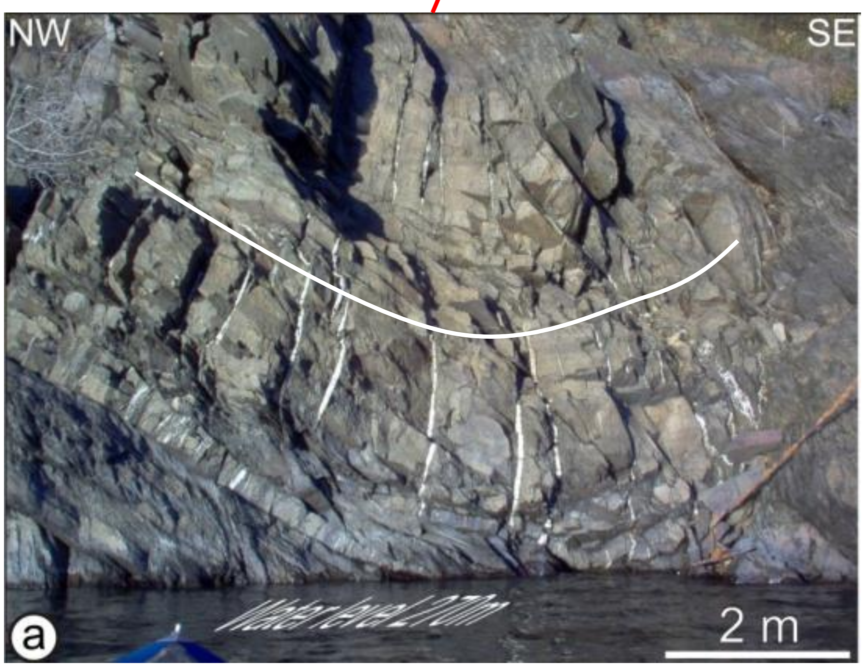
Veins perpendicular to bedding

Structural analysis - Observations

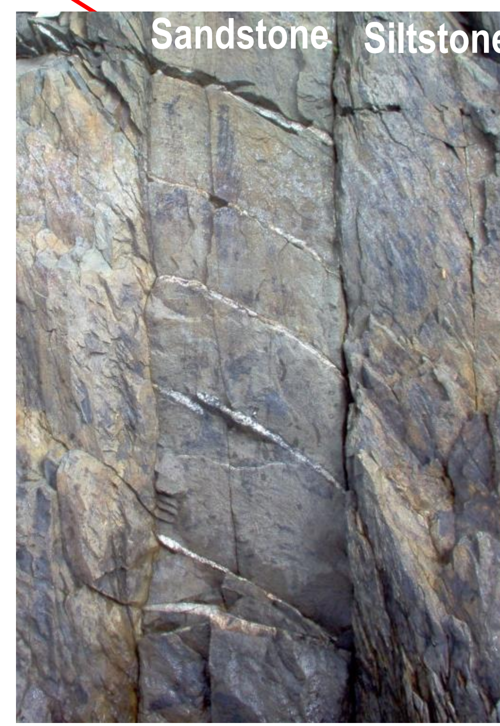


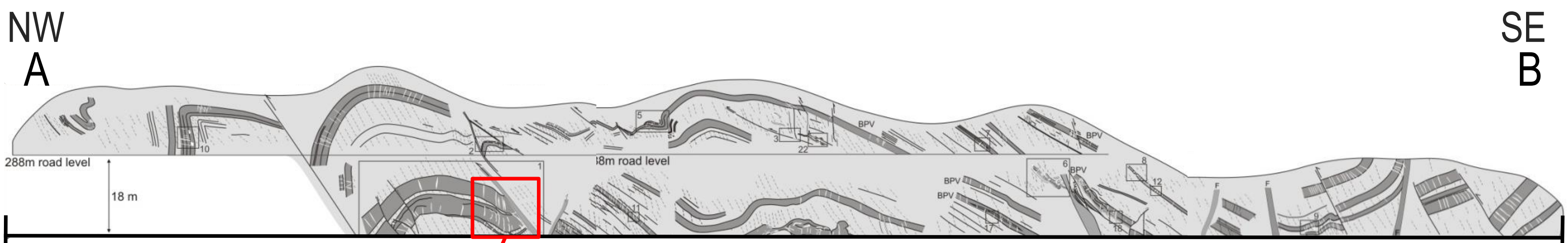
Bedding-normal veins



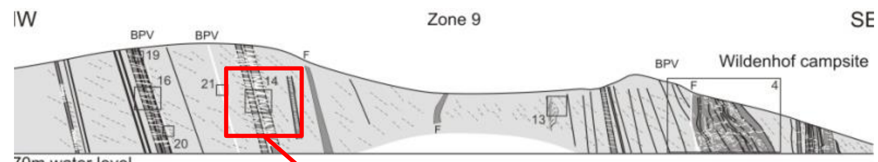


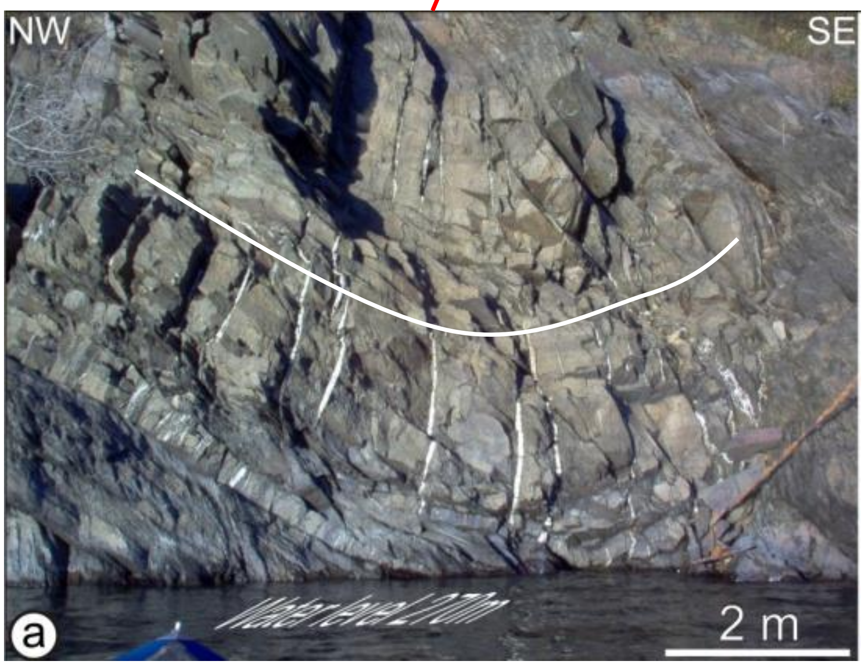
Veins continuous around the folds



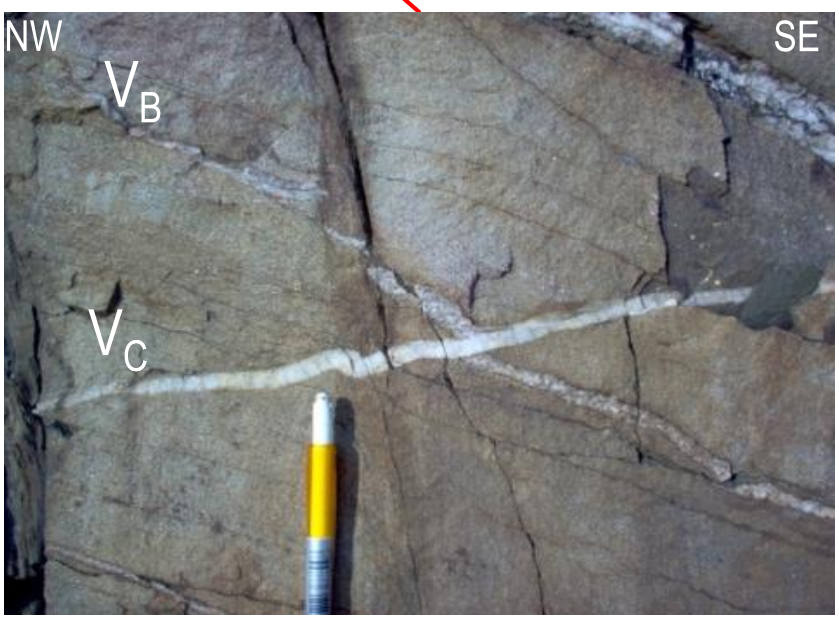


Bedding-normal veins

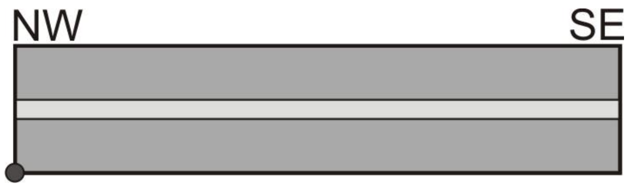




Veins continuous around the folds



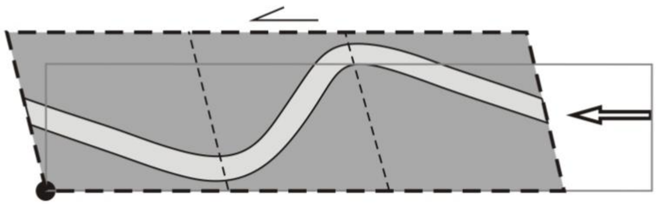
Different generations: V_B older than V_C



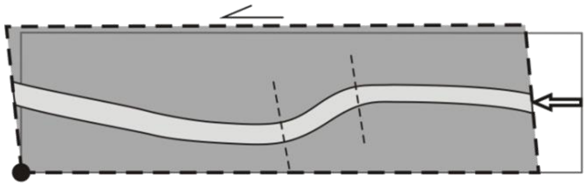
Kinematic model

Kinematic model

Structural analysis - Interpretation

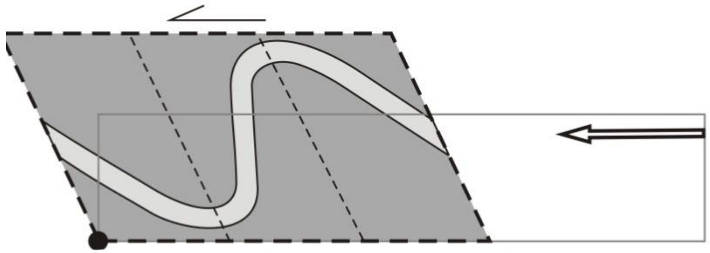


Kinematic model

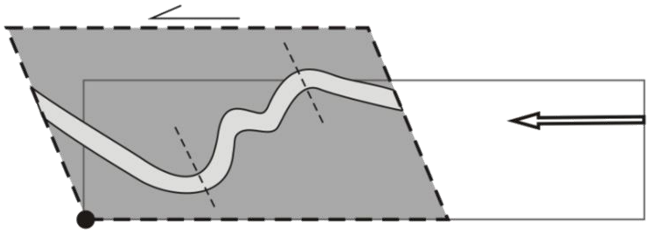


Kinematic model

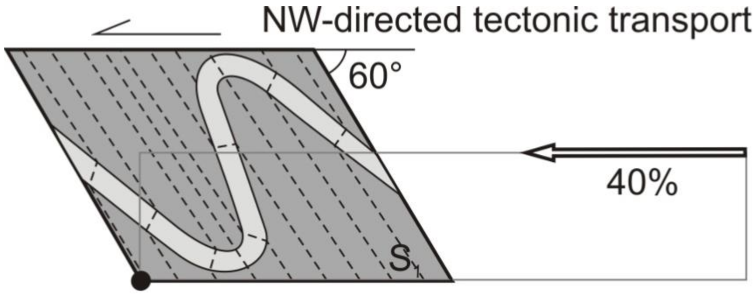
Structural analysis - Interpretation



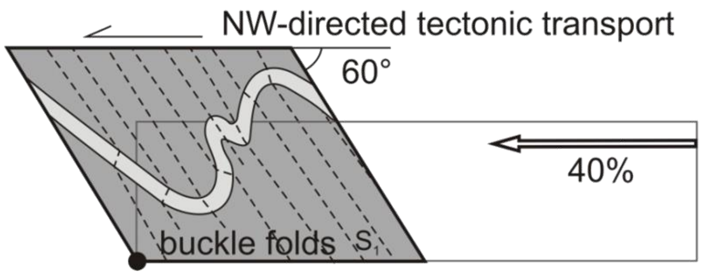
Kinematic model



Kinematic model

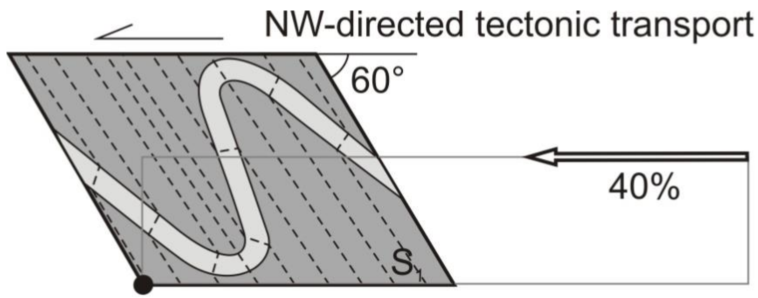


Kinematic model

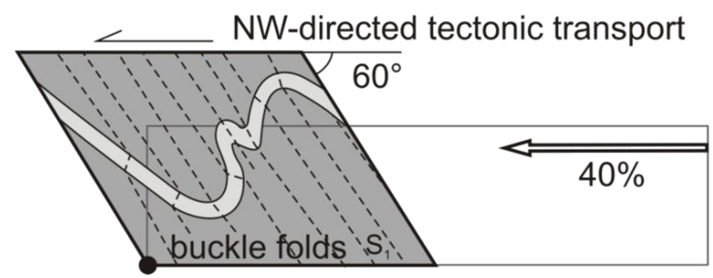


Kinematic model

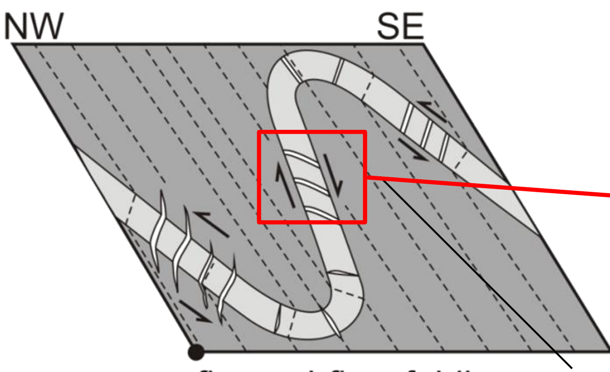
Structural analysis - Interpretation



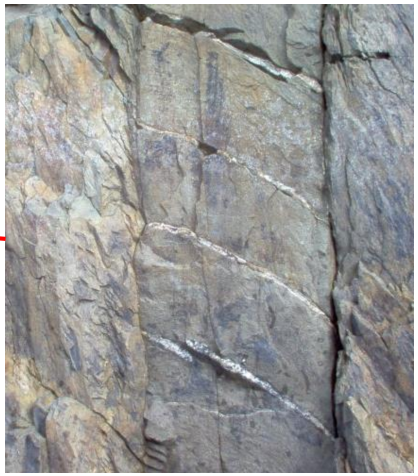
Kinematic model

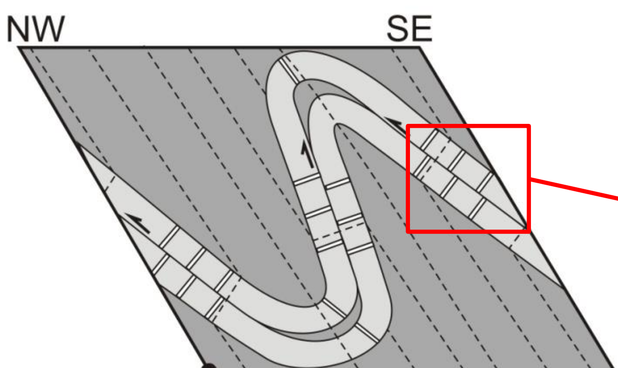


Kinematic model

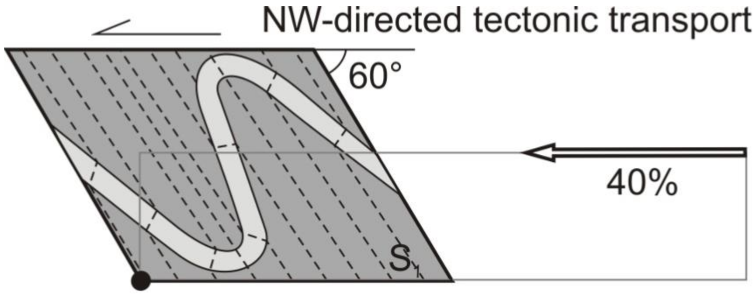


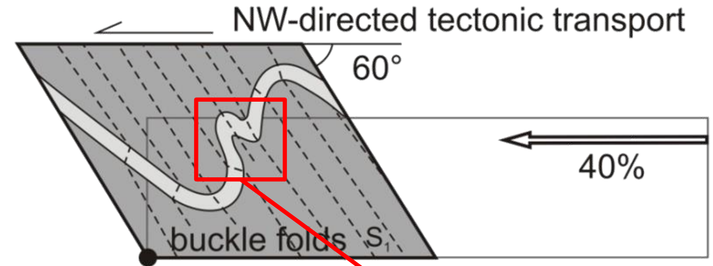
flexural-flow folding





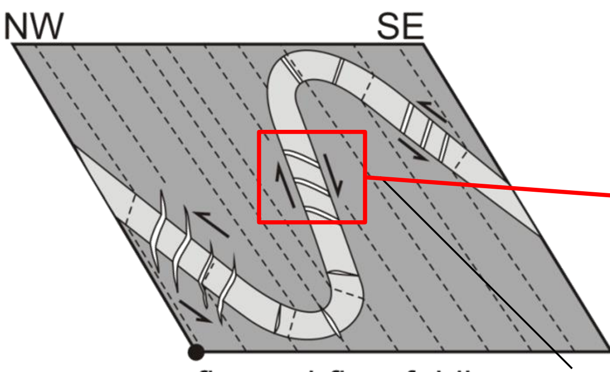
flexural-slip folding



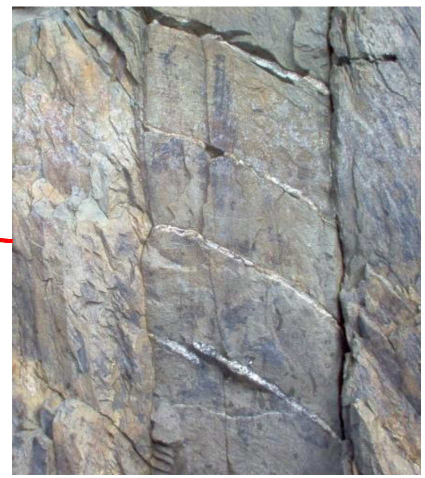


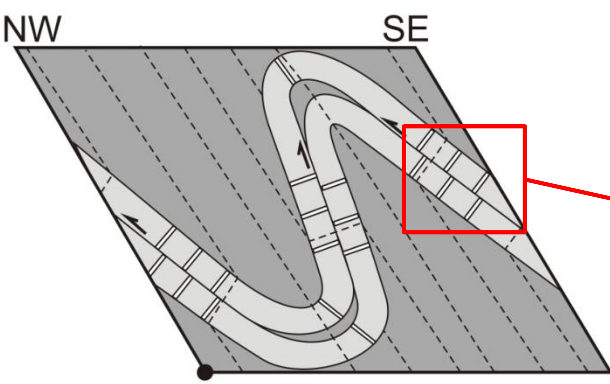
Kinematic model

Kinematic model

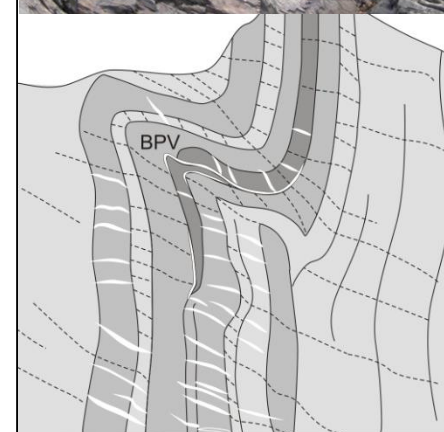


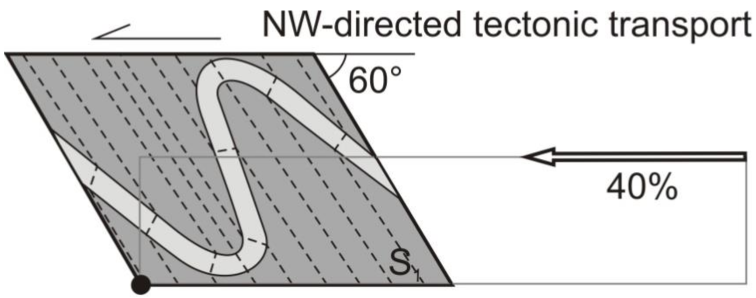
flexural-flow folding



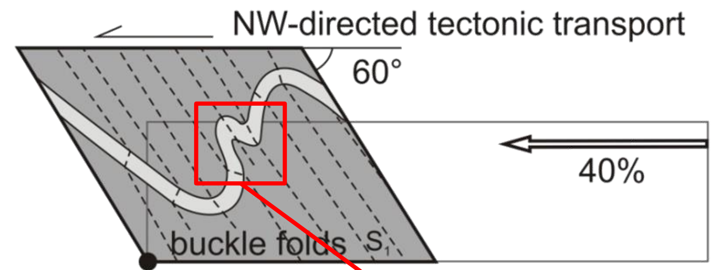


flexural-slip folding

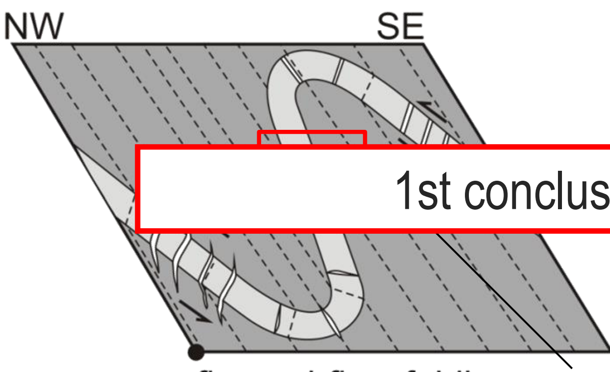




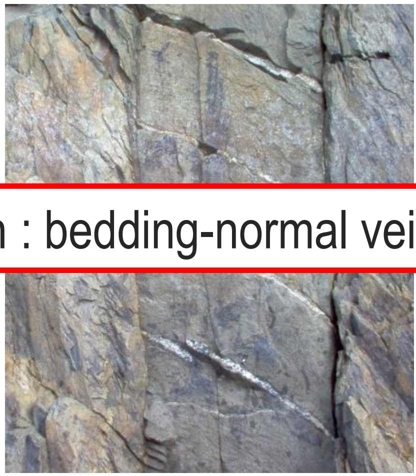
Kinematic model



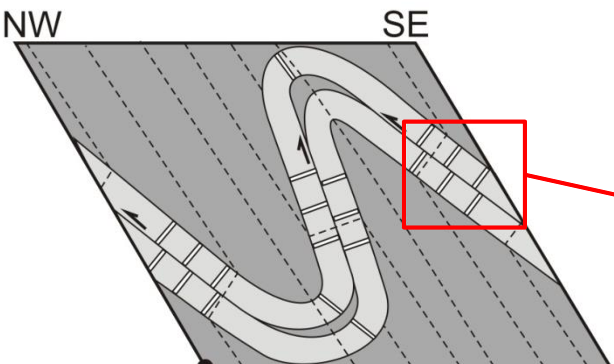
Kinematic model



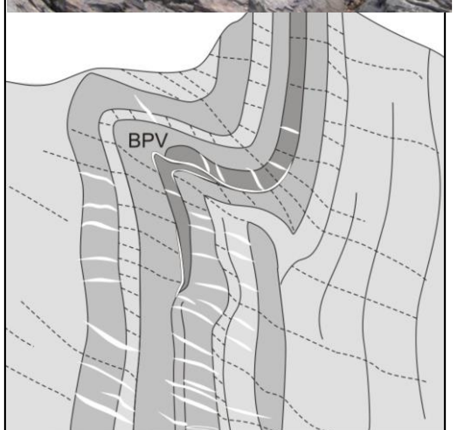
flexural-flow folding



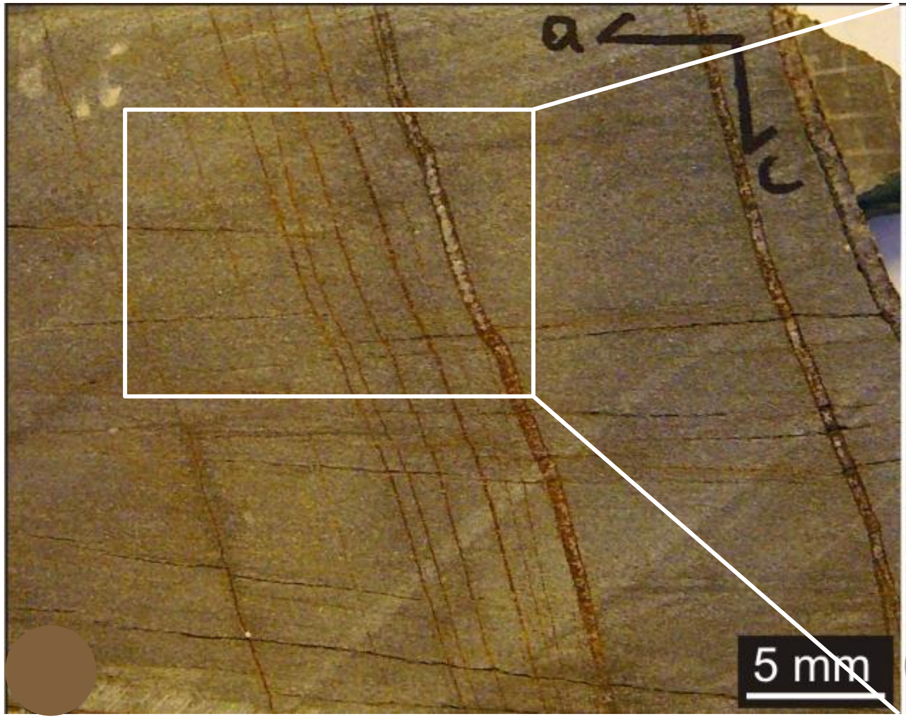
1st conclusion : bedding-normal veins are prefolding !!

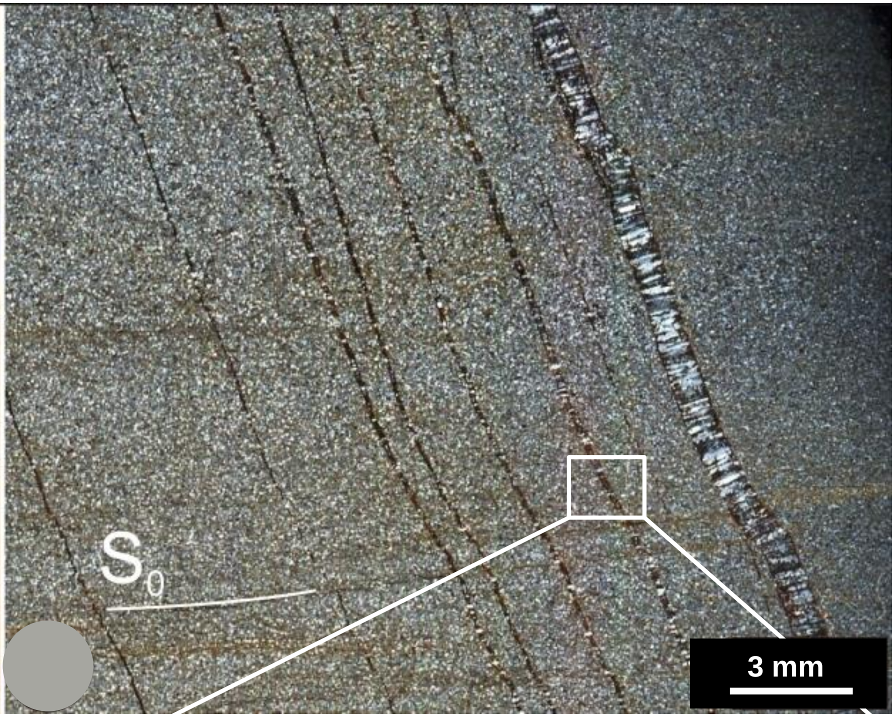


flexural-slip folding

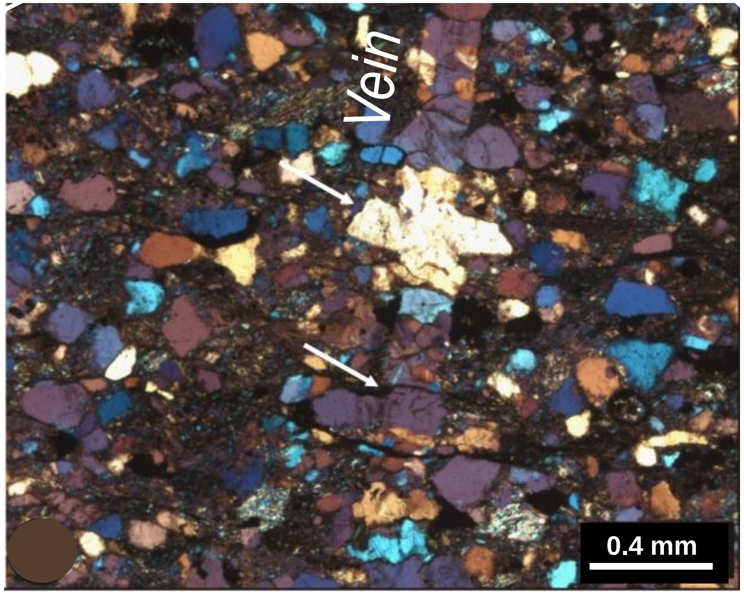


Microstructural analysis - Observation

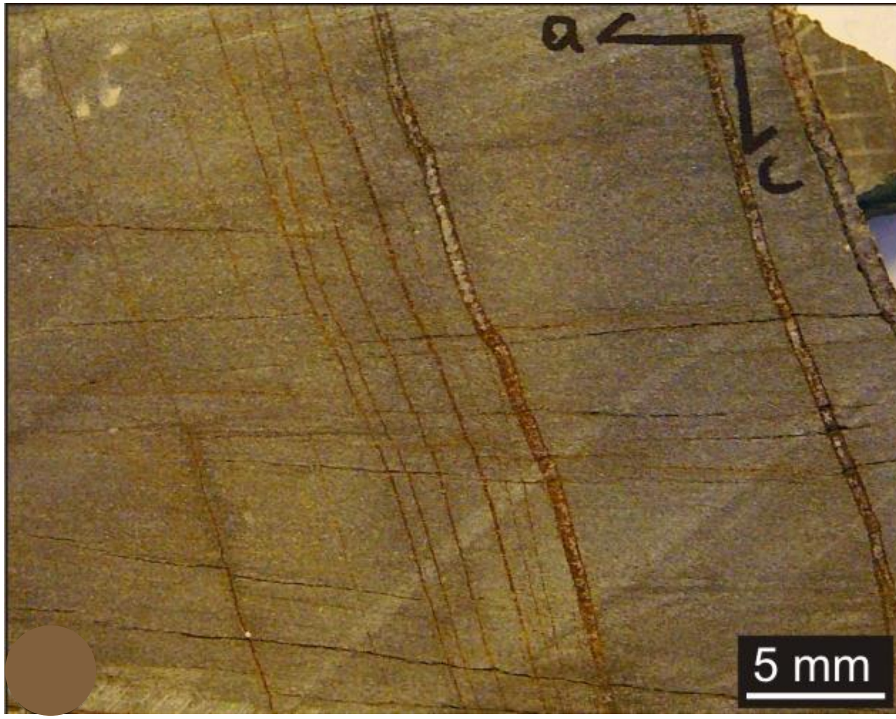


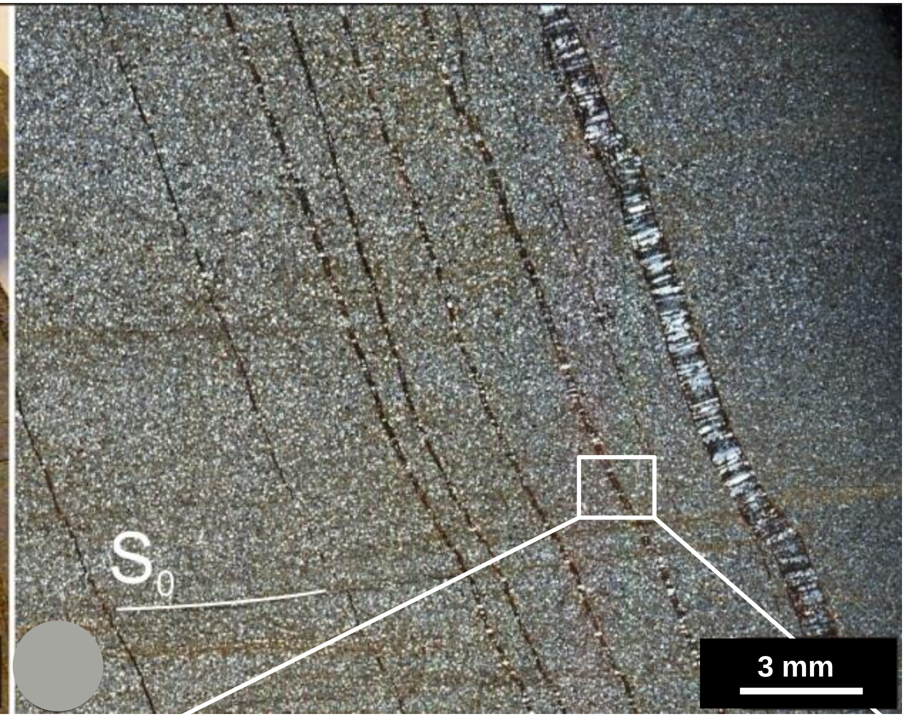


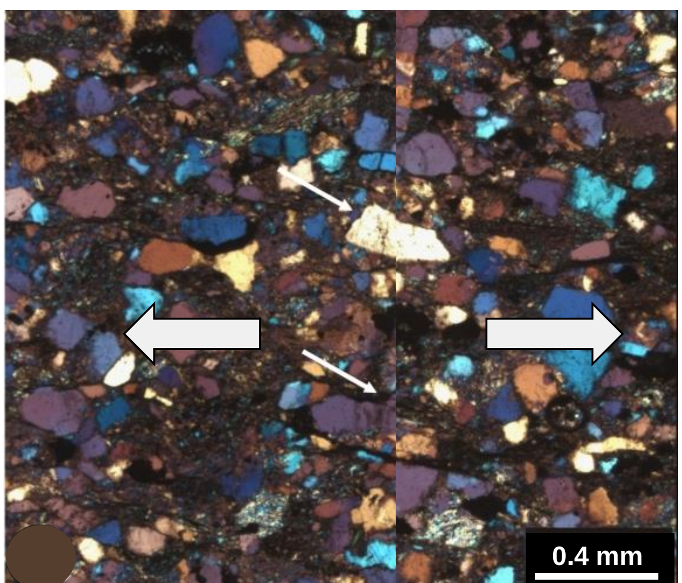
Hairline bedding normal Veins



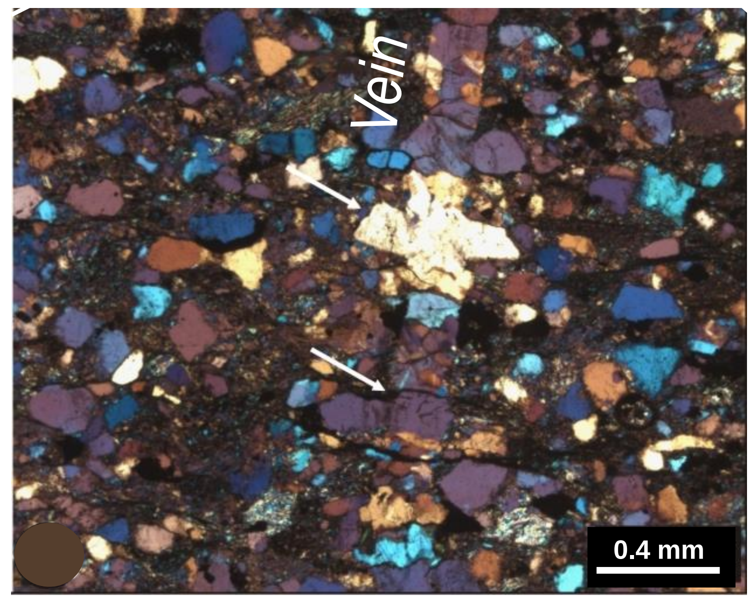
Microstructural analysis

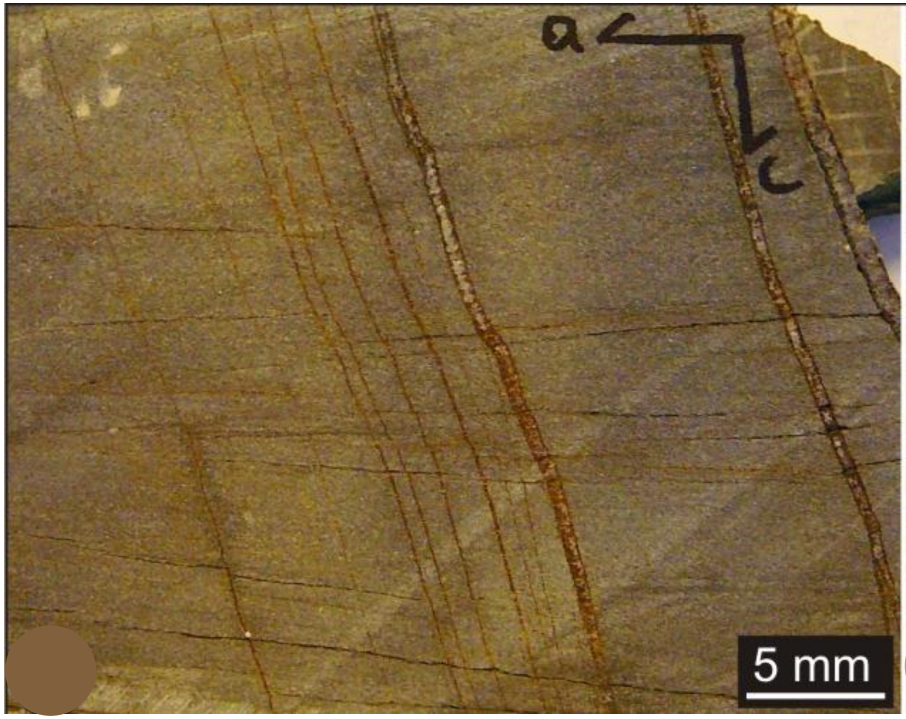


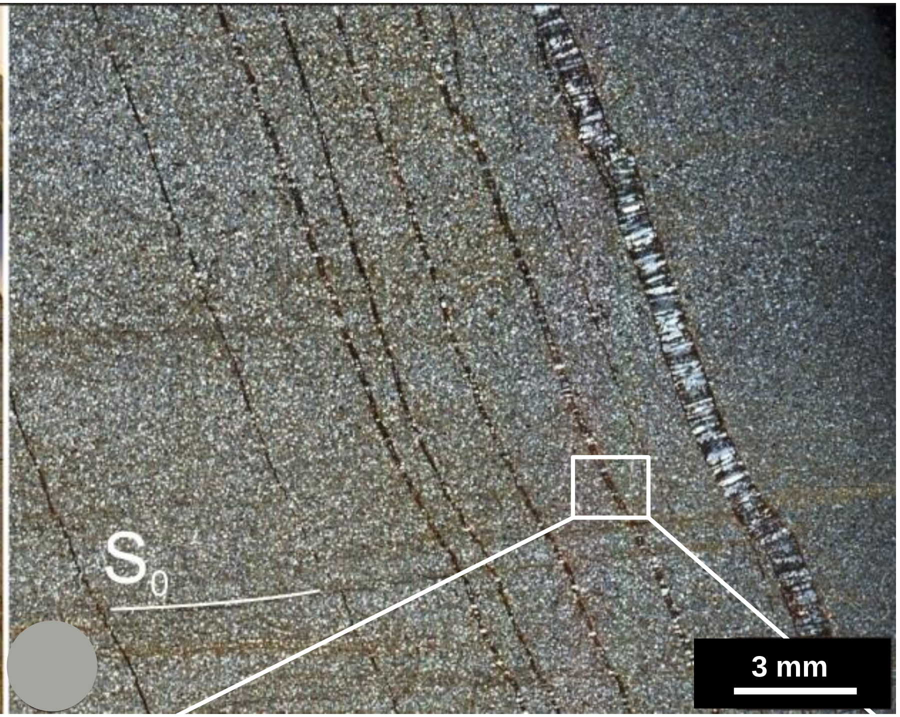


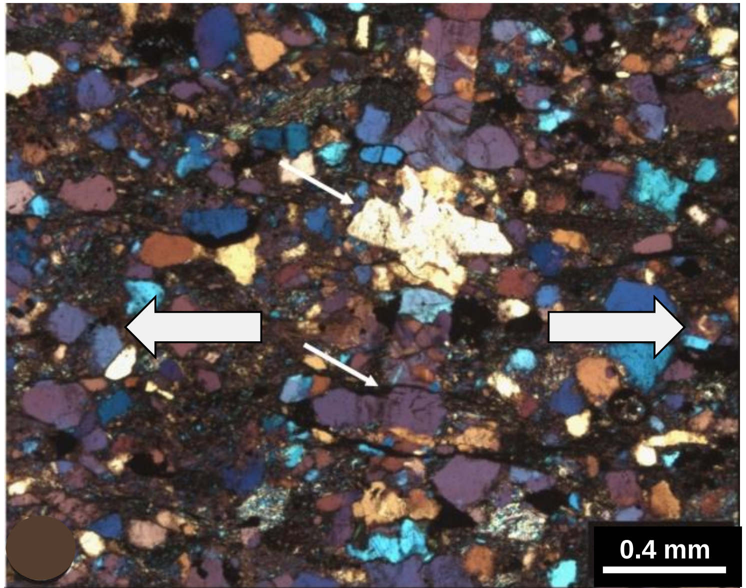


Hairline bedding normal Veins





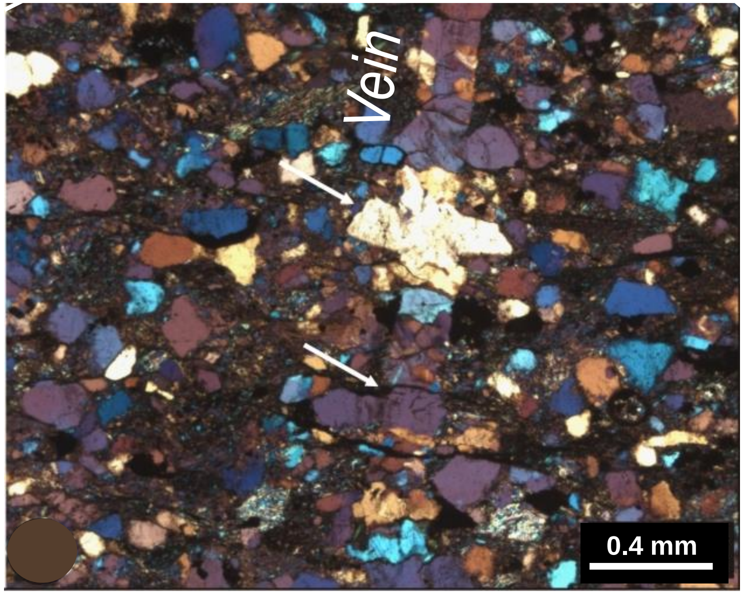




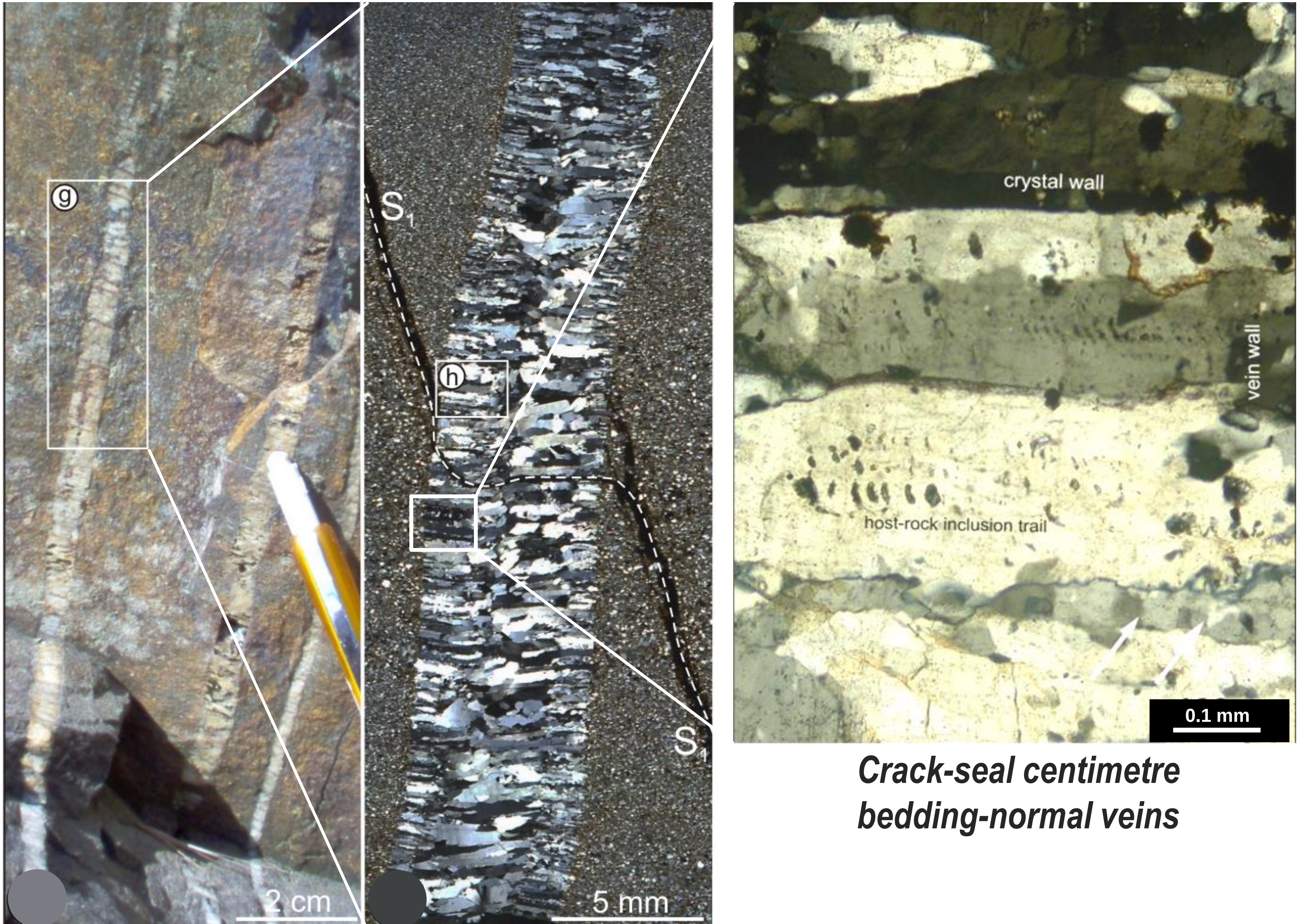
Hairline bedding normal Veins

=

EXTENSION VEINS

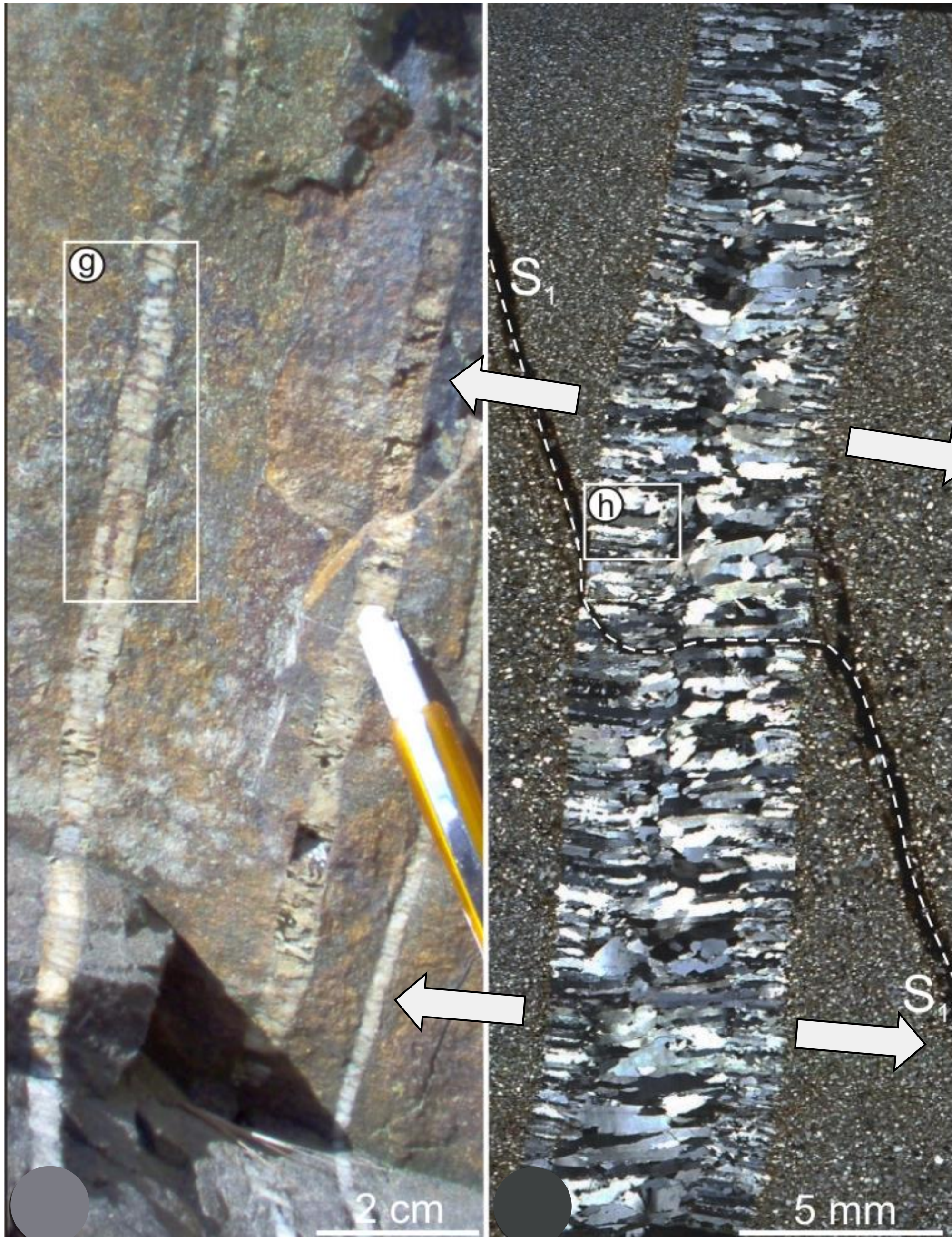


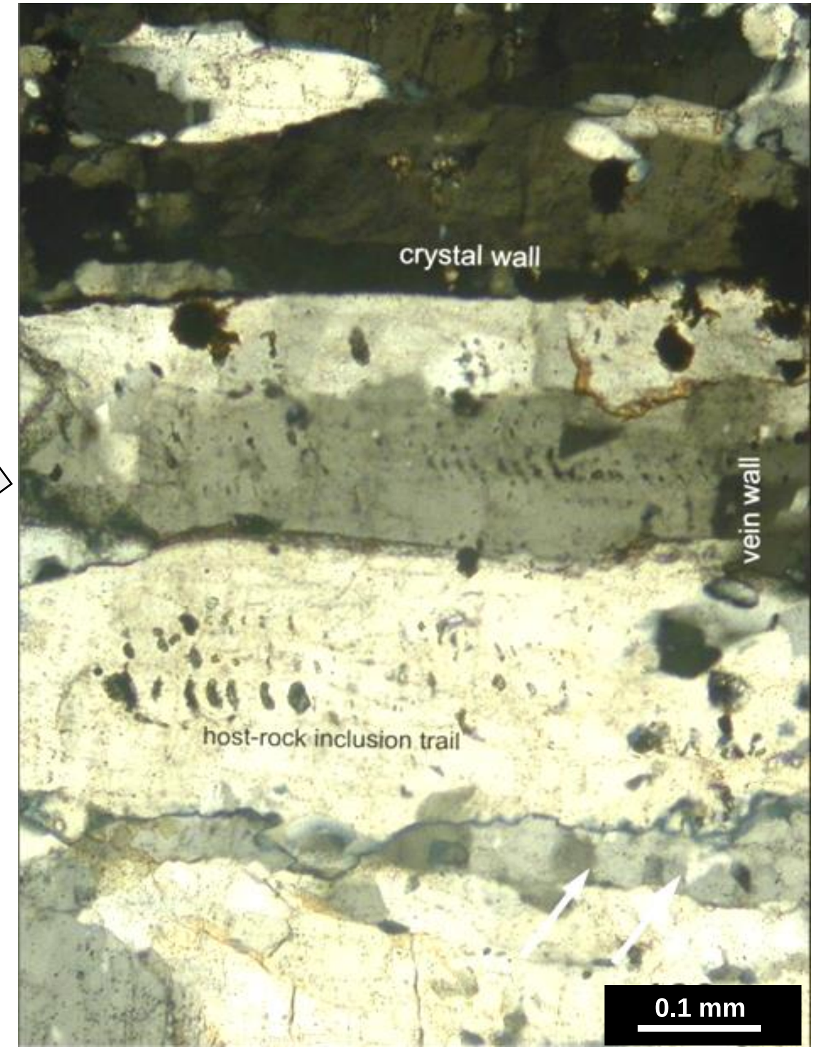
Microstructural analysis - Observation



Crack-seal centimetre bedding-normal veins

Microstructural analysis - Interpretation





Crack-seal centimetre bedding-normal veins
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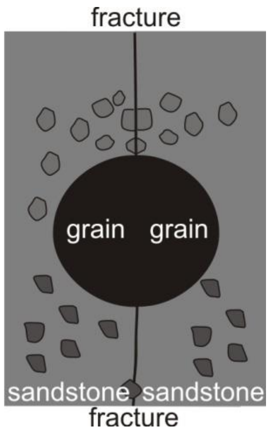
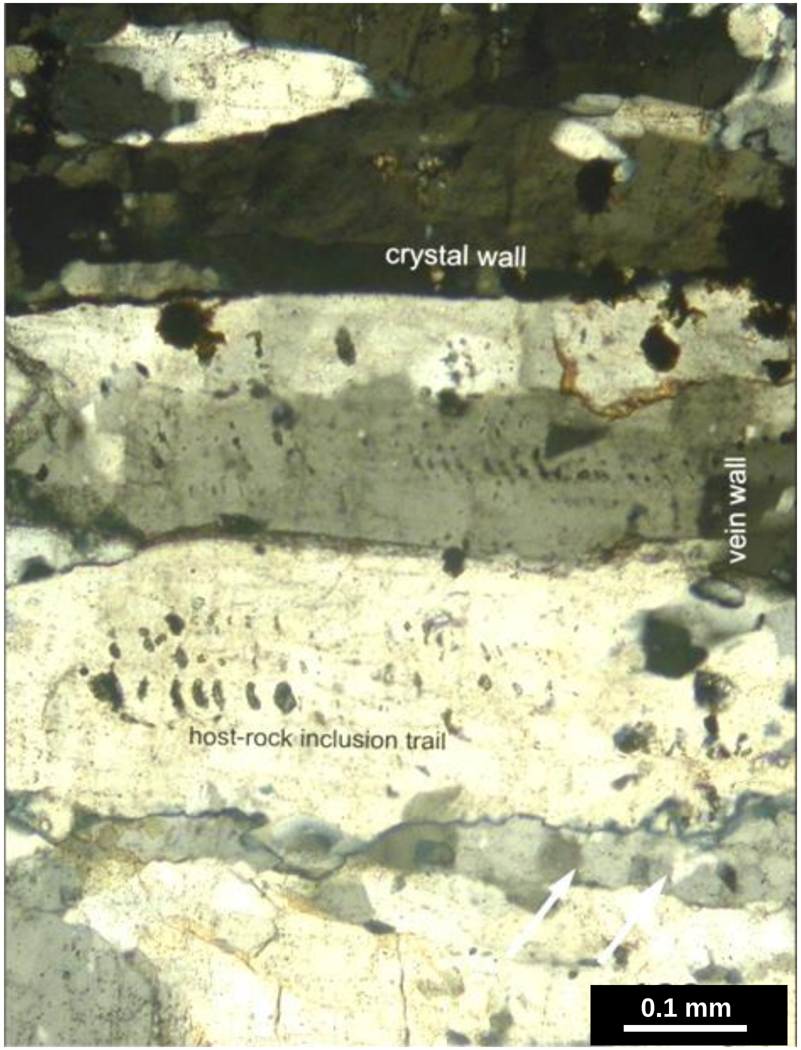
EXTENSION VEINS



rate of crystal growth > fracture growth



Crack-seal centimetre bedding-normal veins

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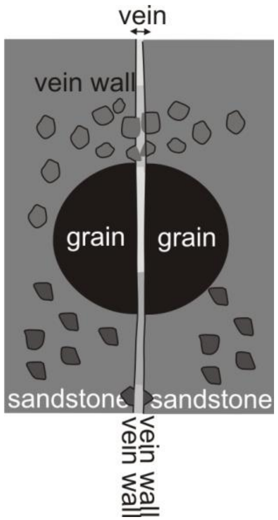
EXTENSION VEINS



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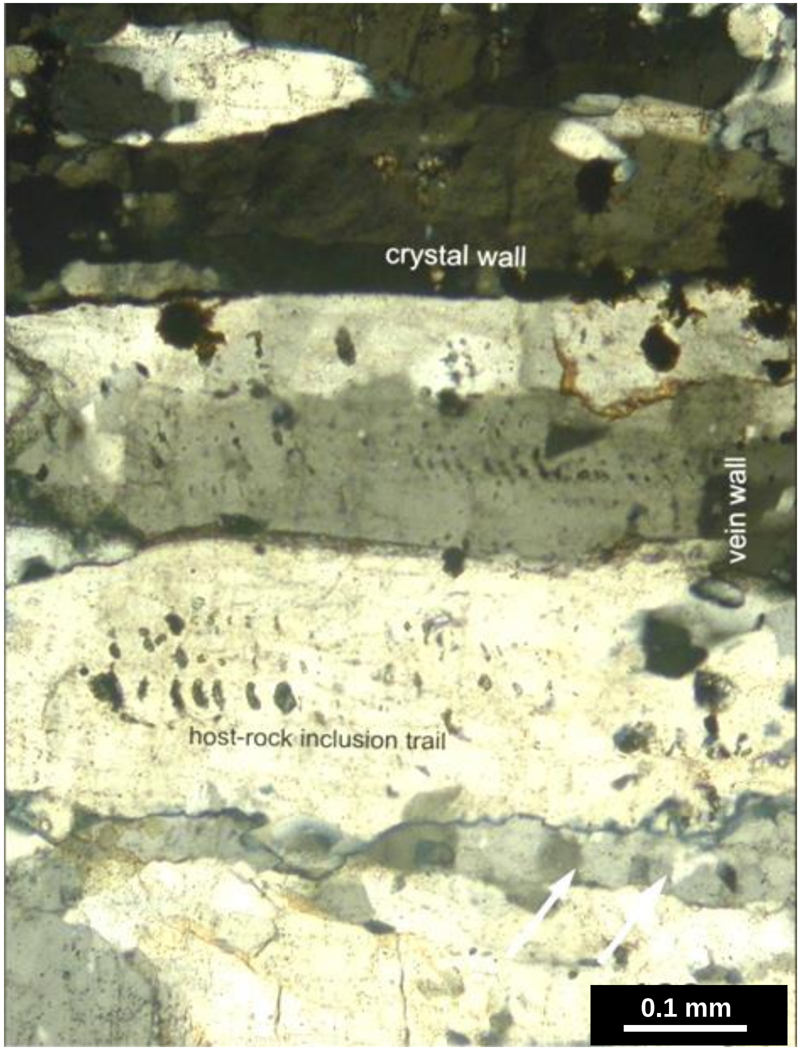

Crack-seal centimetre bedding-normal veins

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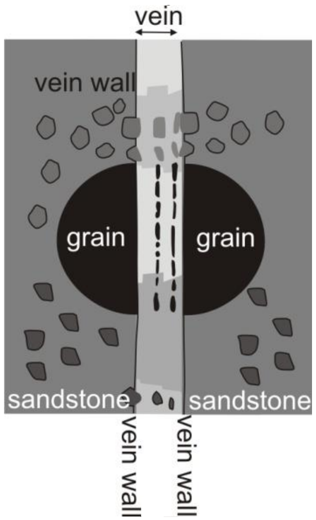
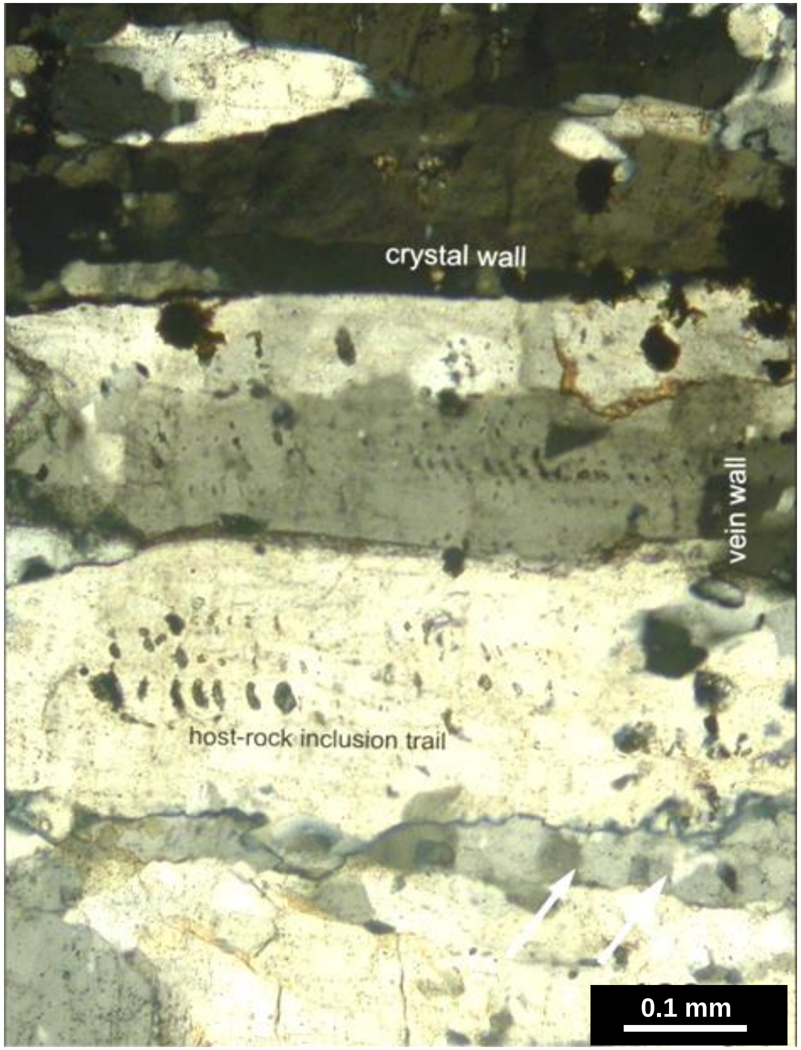
EXTENSION VEINS

Microstructural analysis - Interpretation



rate of crystal growth > fracture growth



Crack-seal centimetre bedding-normal veins

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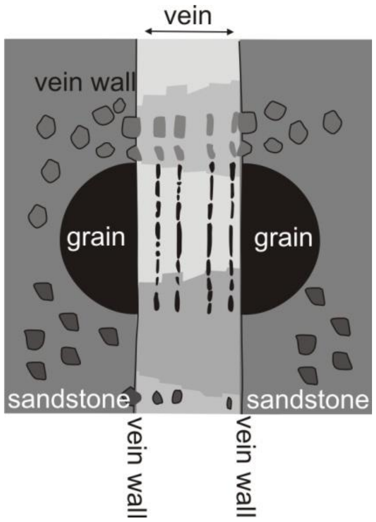
EXTENSION VEINS

Microstructural analysis - Interpretation



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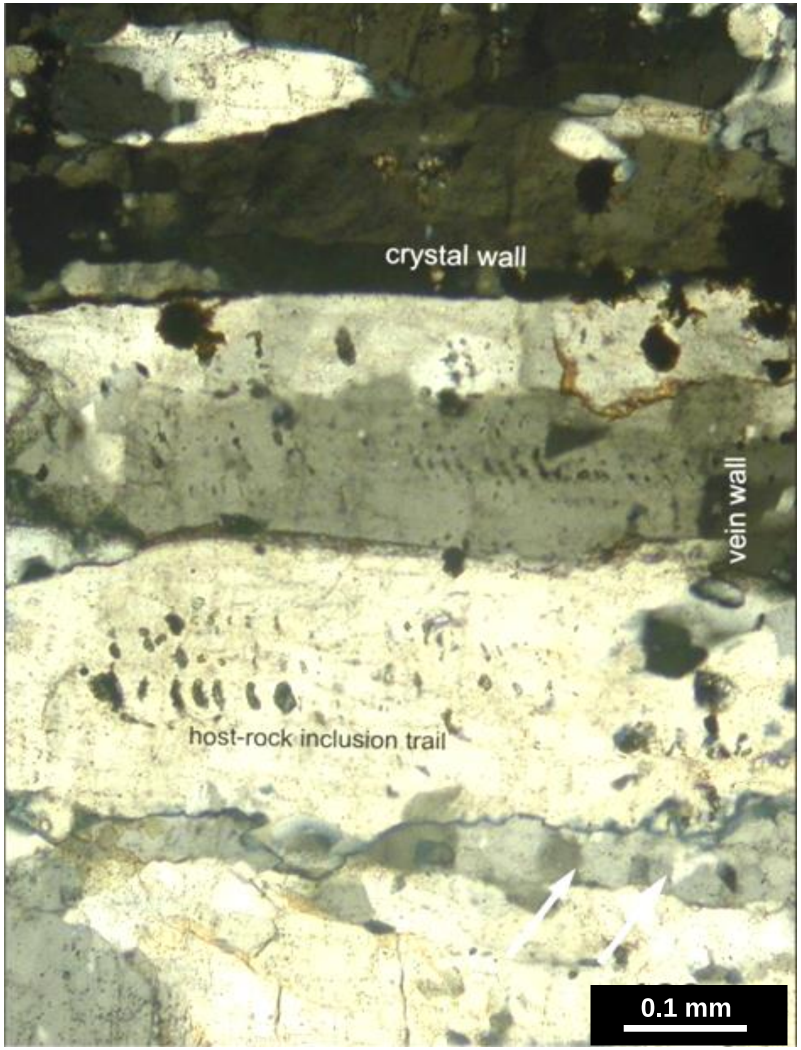

Crack-seal centimetre bedding-normal veins

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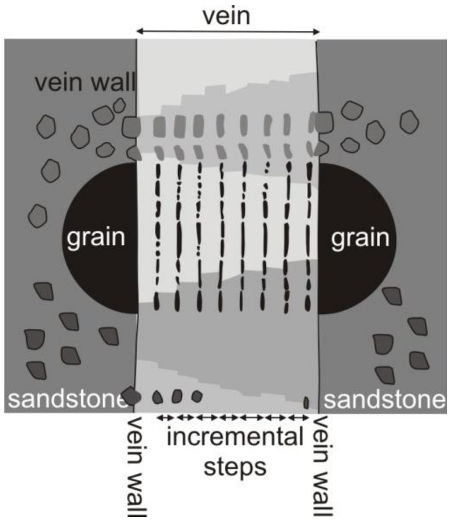
EXTENSION VEINS

Microstructural analysis - Interpretation



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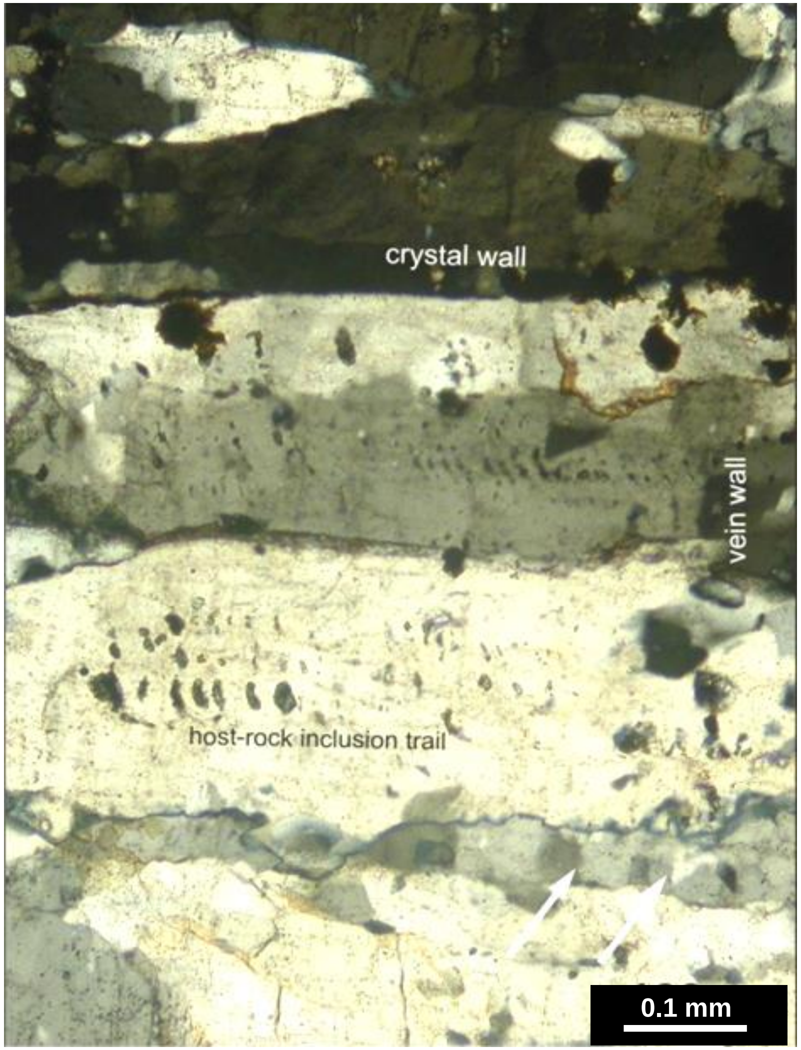

Crack-seal centimetre bedding-normal veins

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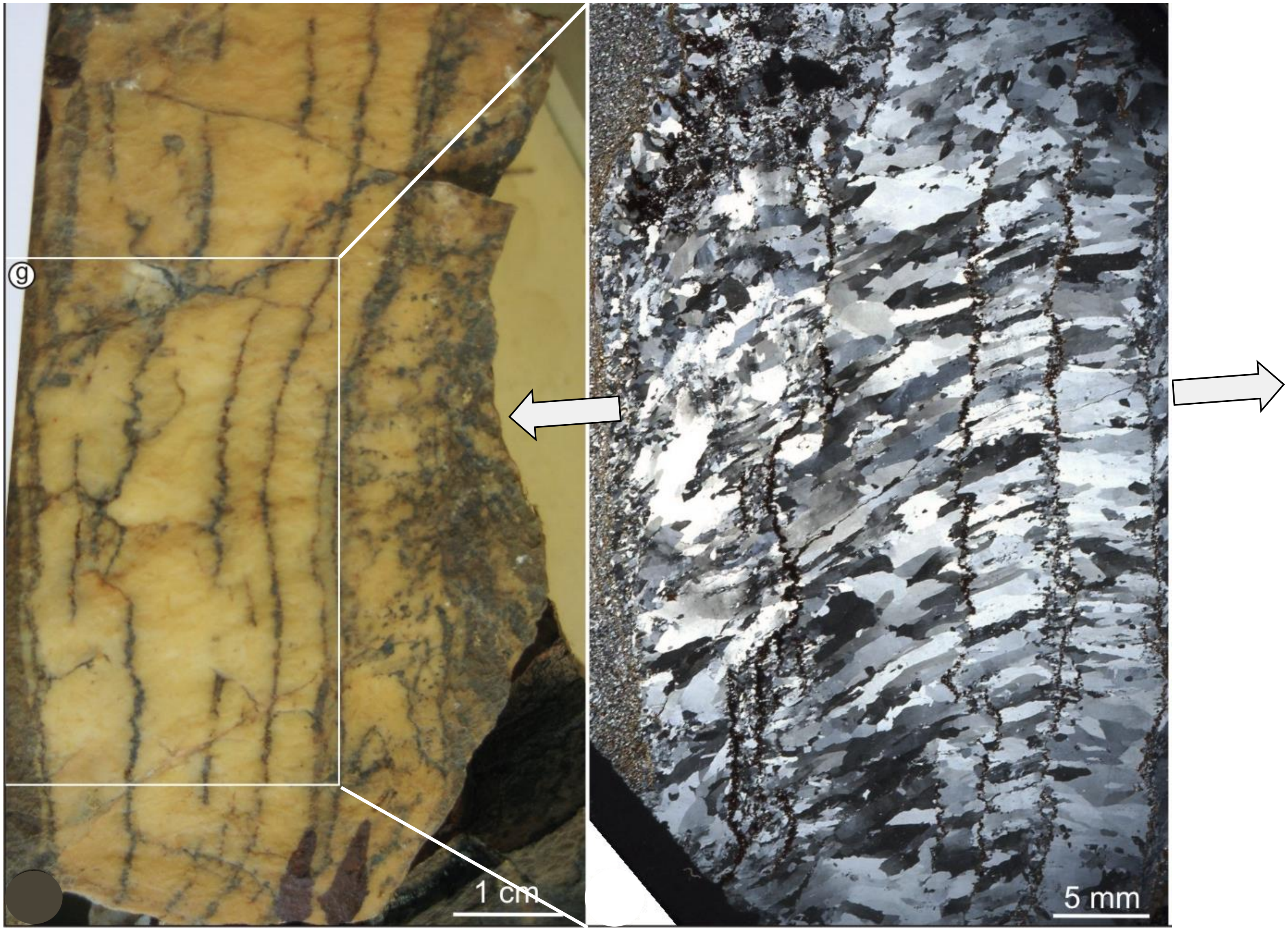
EXTENSION VEINS

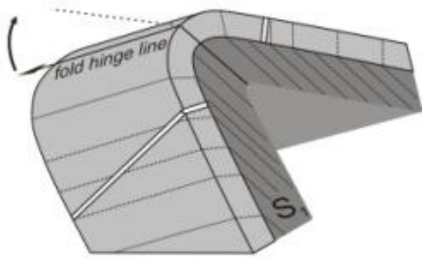
Microstructural analysis – Observation/Interpretation

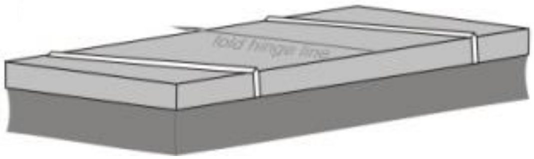


Fibrous composite bedding-normal veins **=** ***EXTENSION VEINS***

1st conclusion : bedding-normal veins are prefolding !!

current orientation → original prefolding orientation





EXTENSION VEINS

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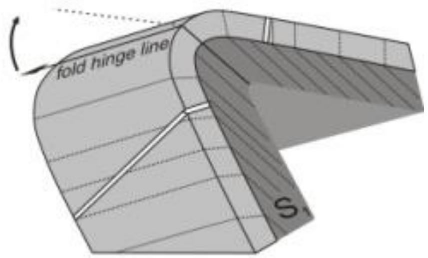
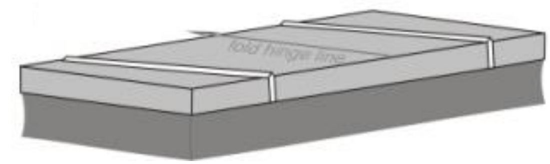
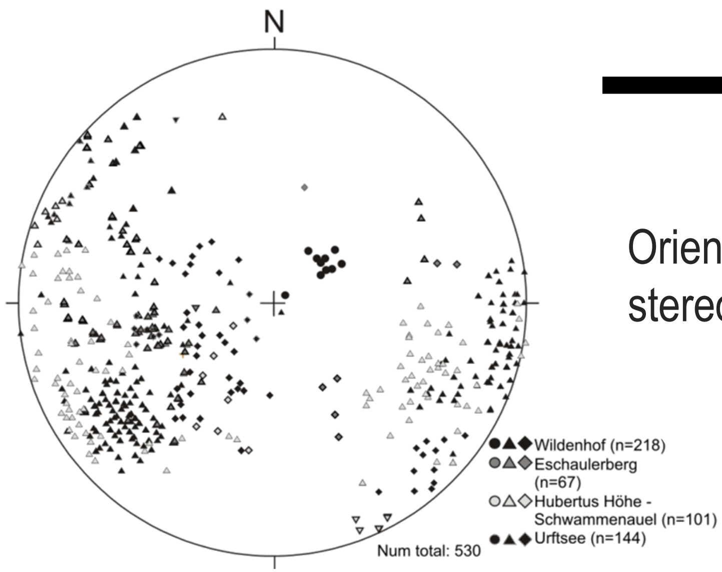




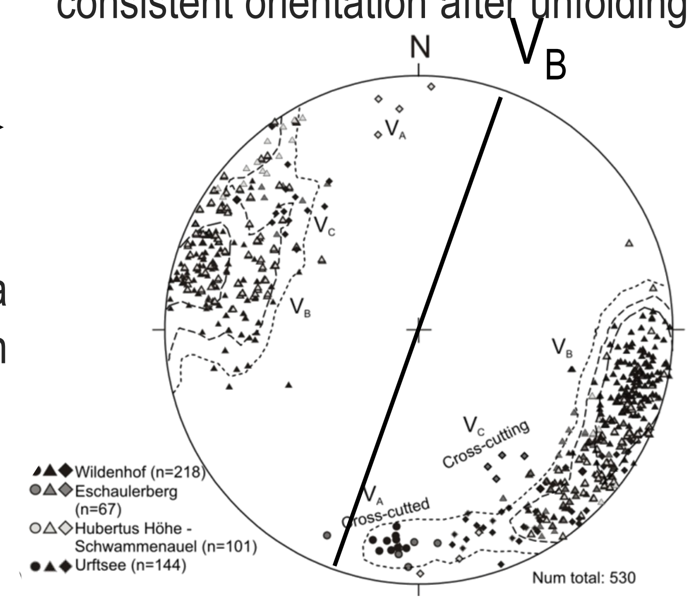
Eifel area



Unfolding exercise

Orientation analysis in a stereographic projection

consistent orientation after unfolding



EXTENSION VEINS

1st conclusion : bedding-normal veins are prefolding !!

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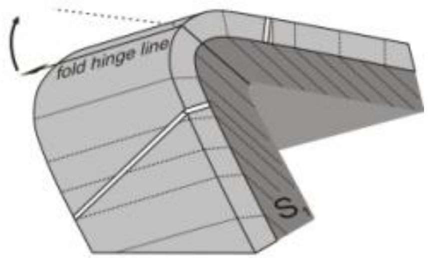
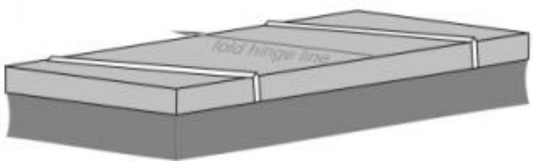
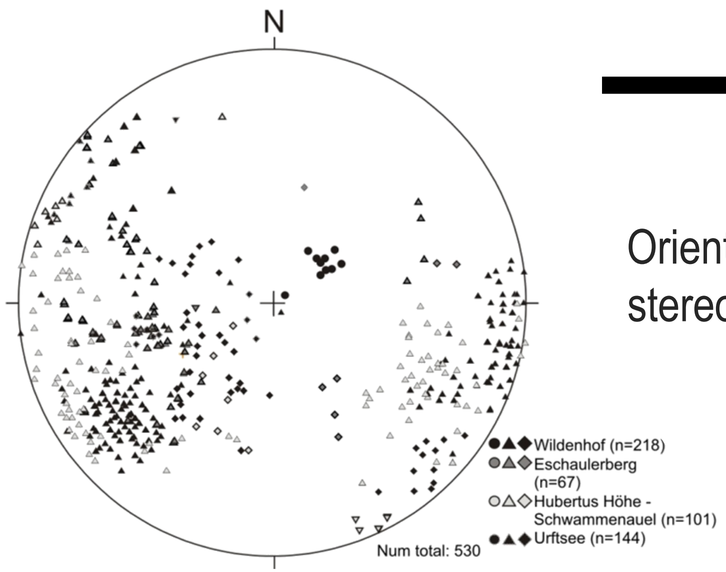




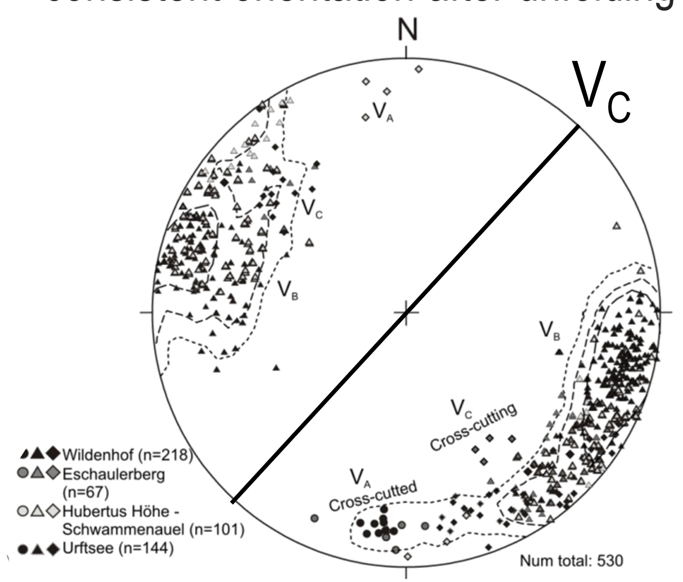
Eifel area



Unfolding exercise →

Orientation analysis in a stereographic projection

consistent orientation after unfolding

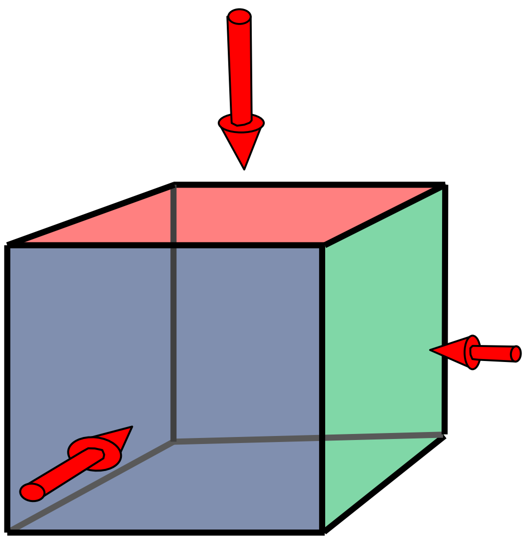


EXTENSION VEINS

Bedding-normal veins - Interpretation

σ_1 Maximum vertical principal stress

σ_V Burial stress ~ load of the overburden

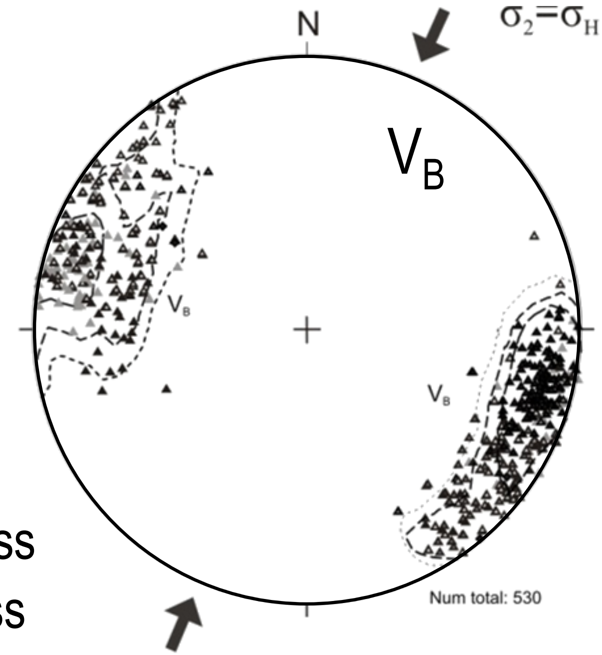


σ_3 Minimum principal stress

σ_h Min. hor. principal stress

σ_2 Intermediate principal stress

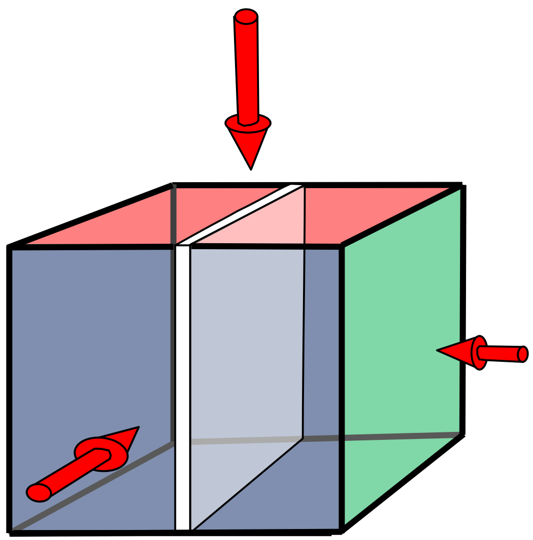
σ_H Max. hor. principal stress



Bedding-normal veins - Interpretation

σ_1 Maximum vertical principal stress

σ_V Burial stress ~ load of the overburden



σ_3 Minimum principal stress

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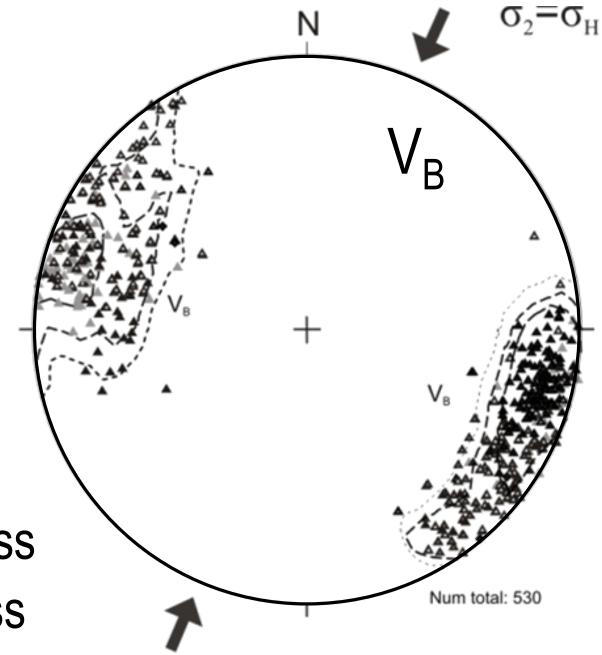

Extension veins

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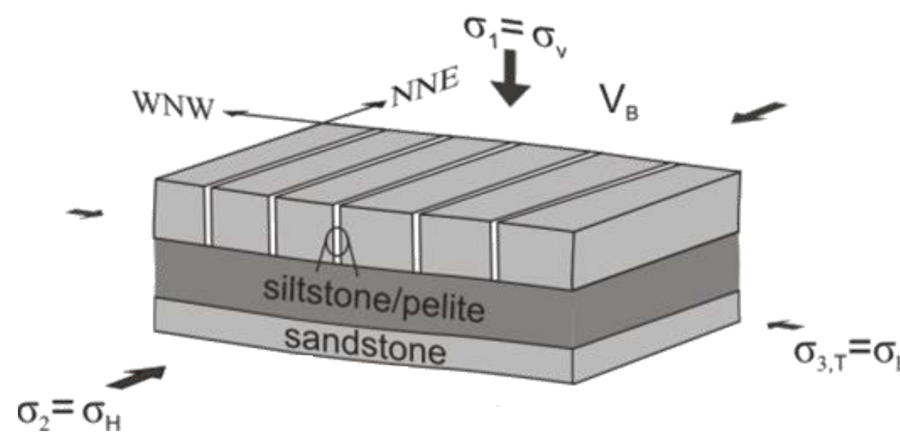
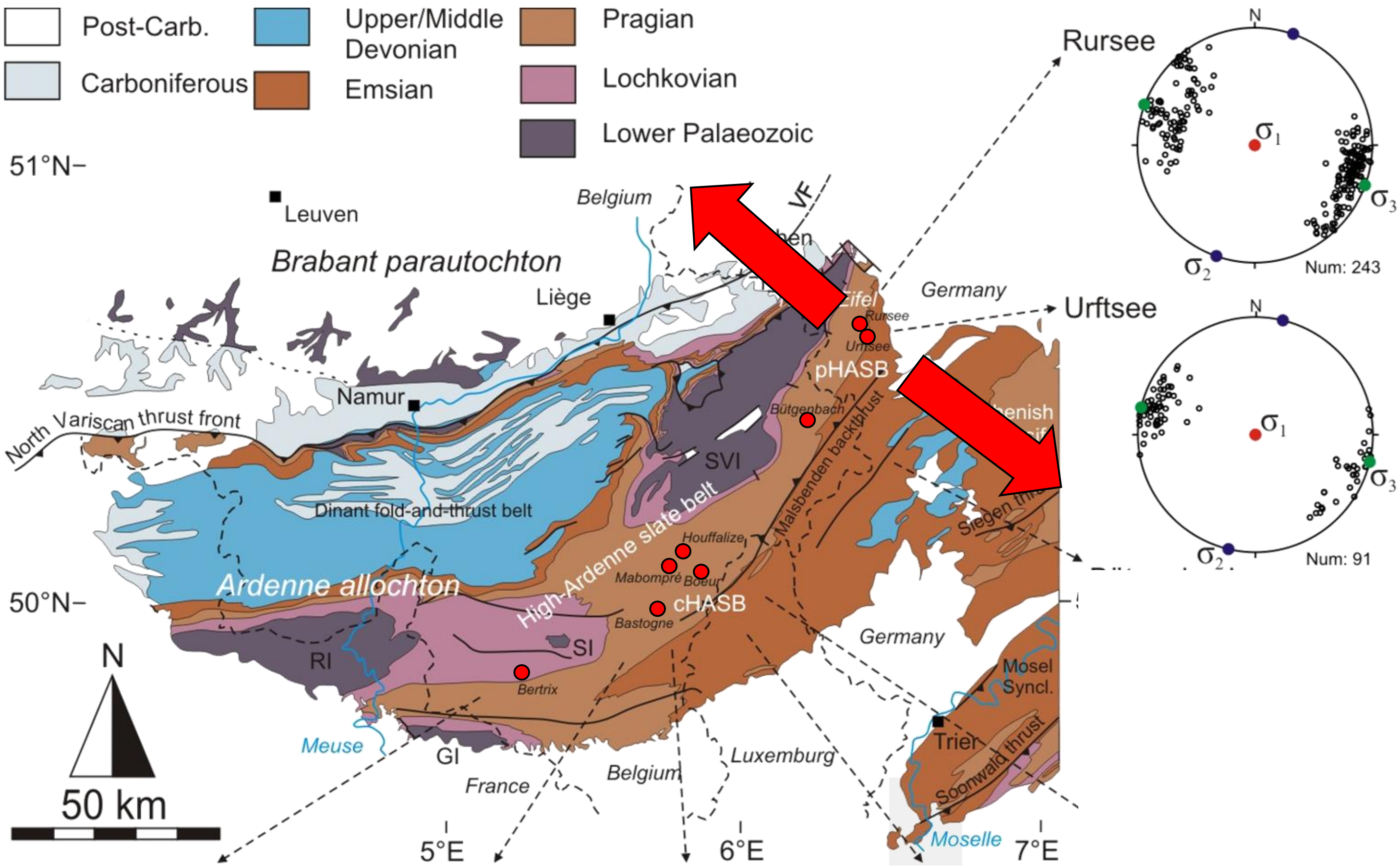
Low differential stresses

Secor 1965 $\sigma_1 - \sigma_3 < 4T$



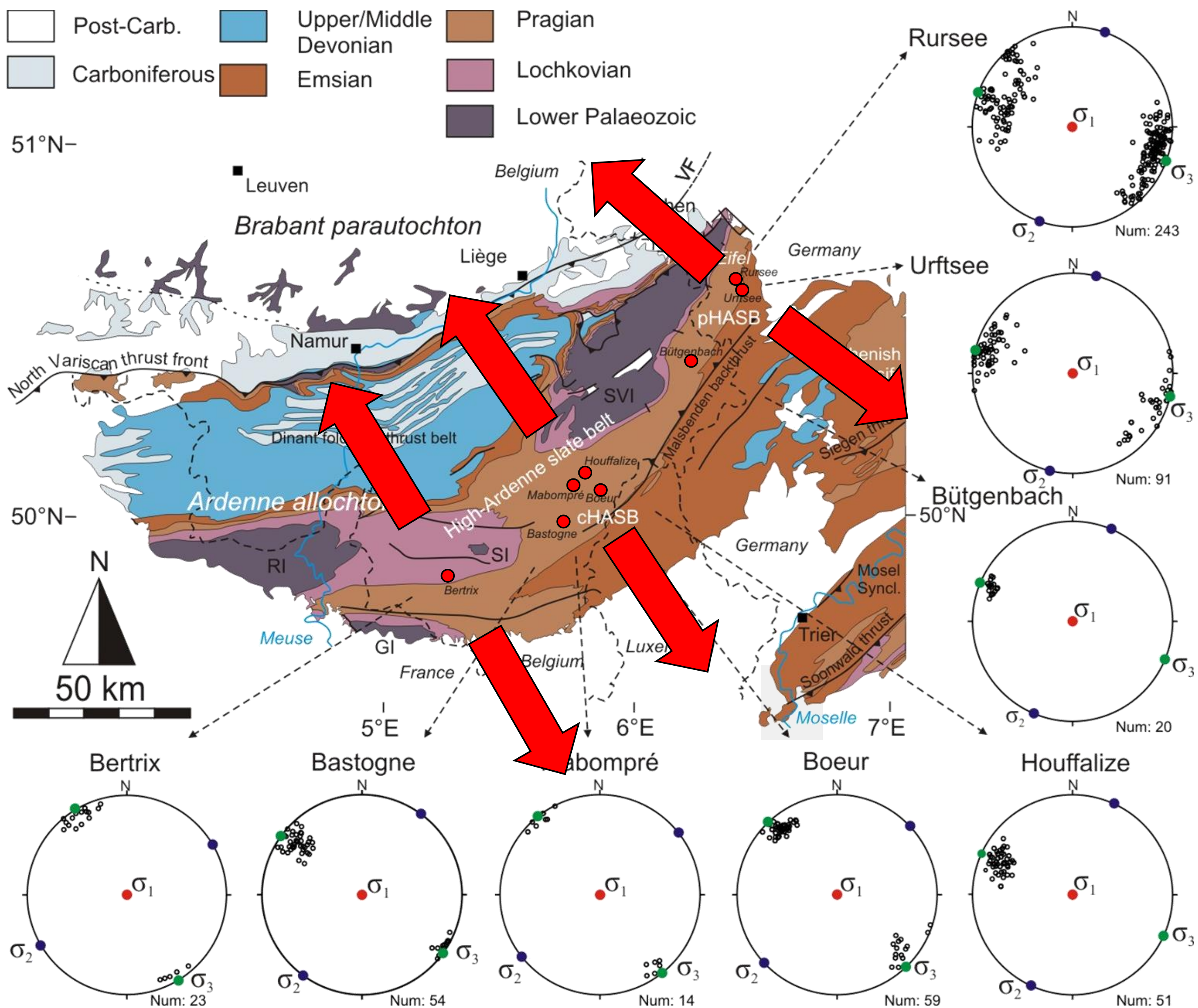
Stress state of the basin



Prefolding vein orientation reflects stress orientation

Orientations from Van Noten *et al.* 2012

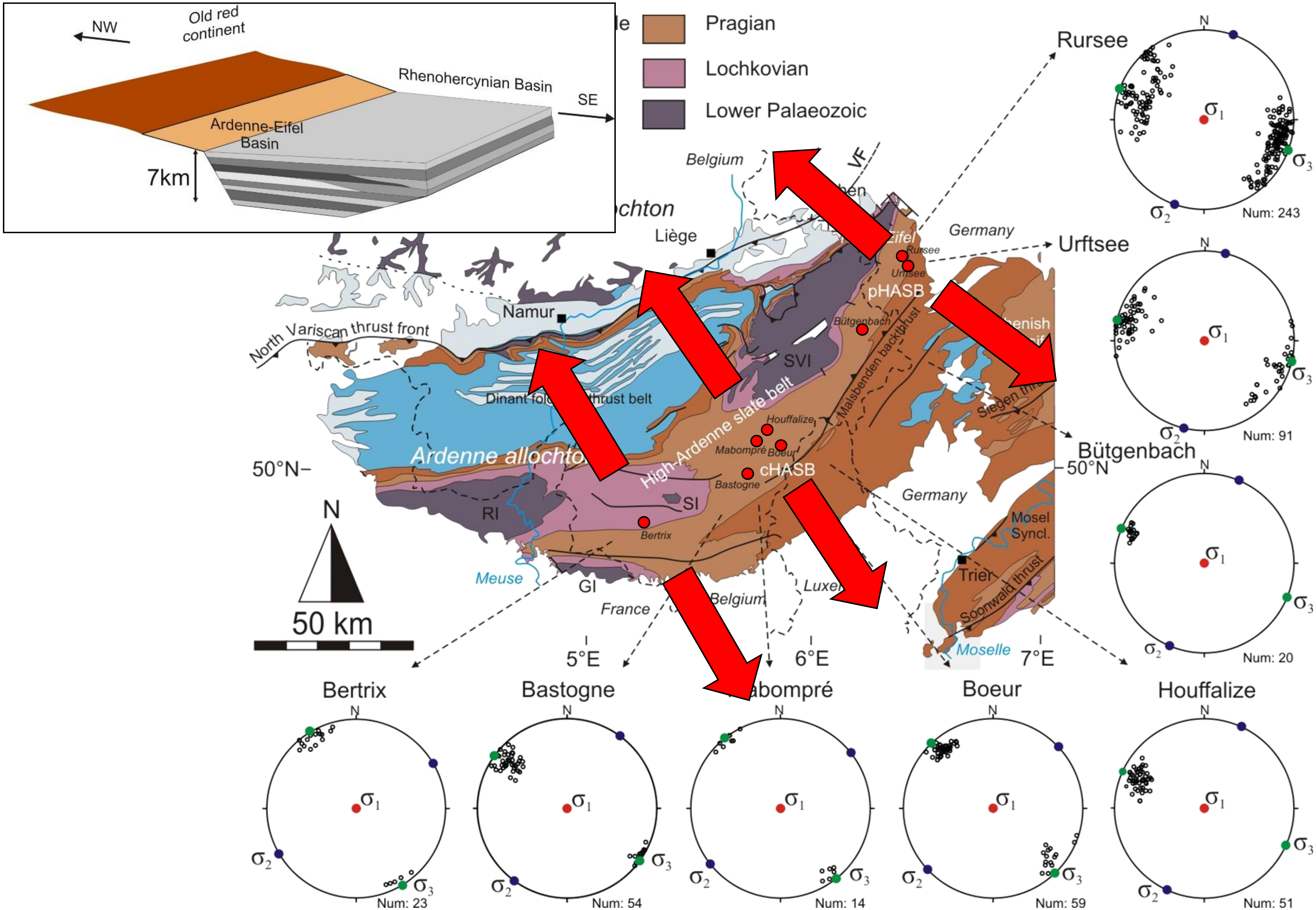
Stress state of the basin



Prefolding vein orientation reflects stress orientation

Orientations from Kenis 2004 & Van Noten *et al.* 2012

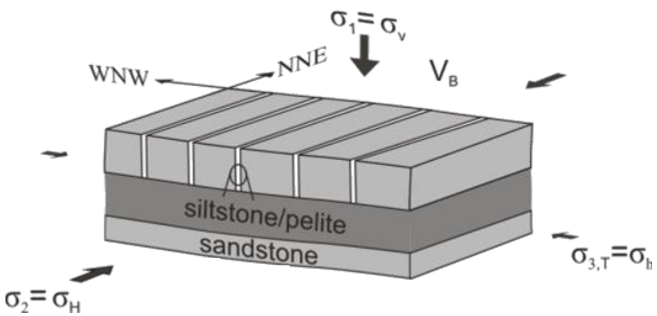
Stress state of the basin



Prefolding vein orientation reflects stress orientation

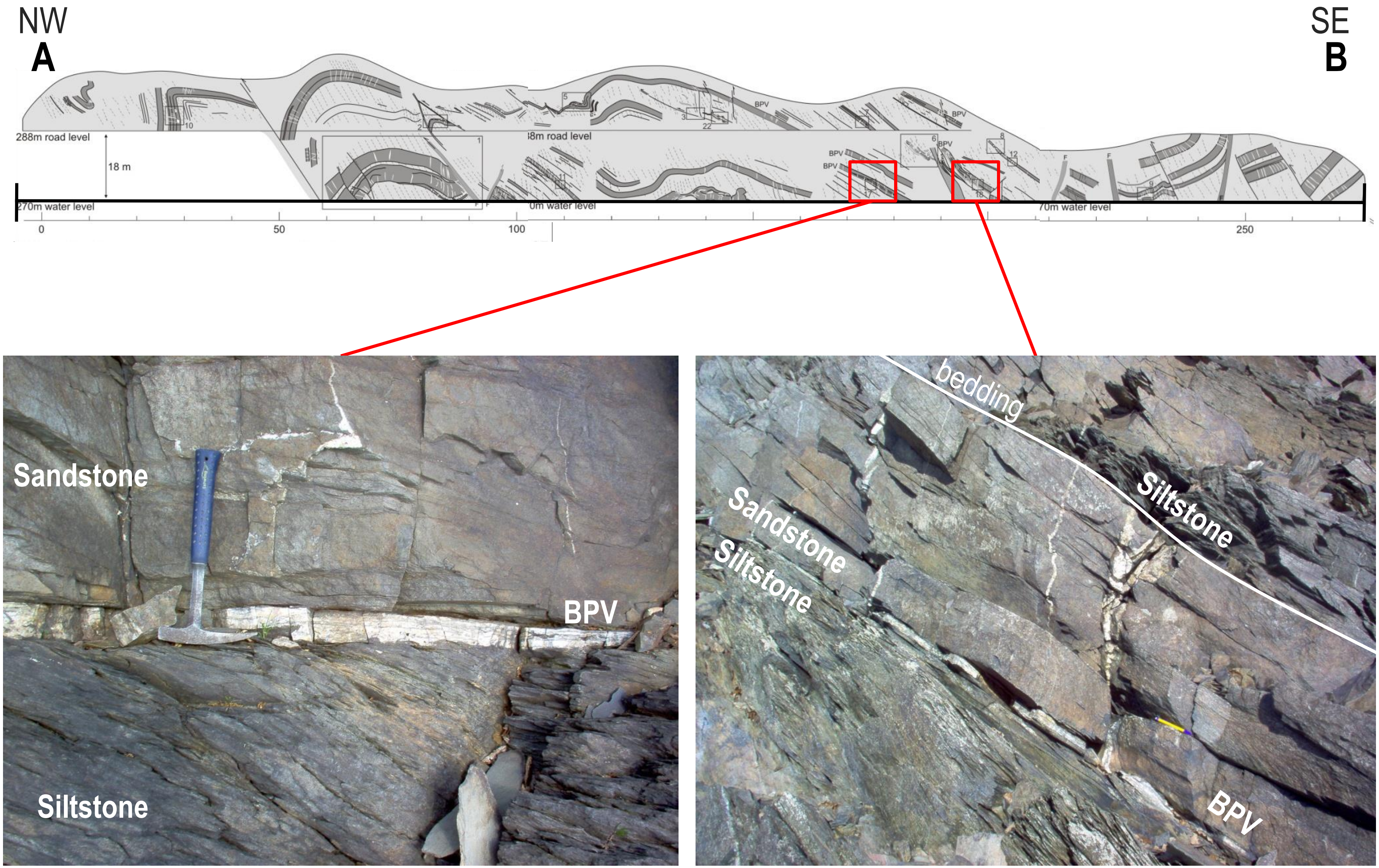
Orientations from Kenis 2004 & Van Noten *et al.* 2012

Bedding-parallel veins



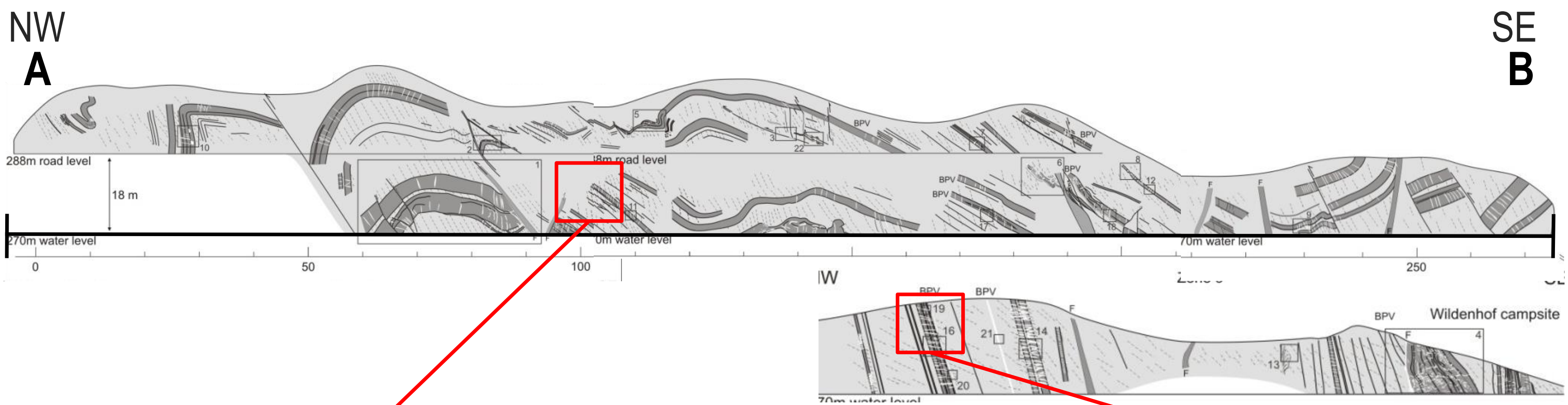
?

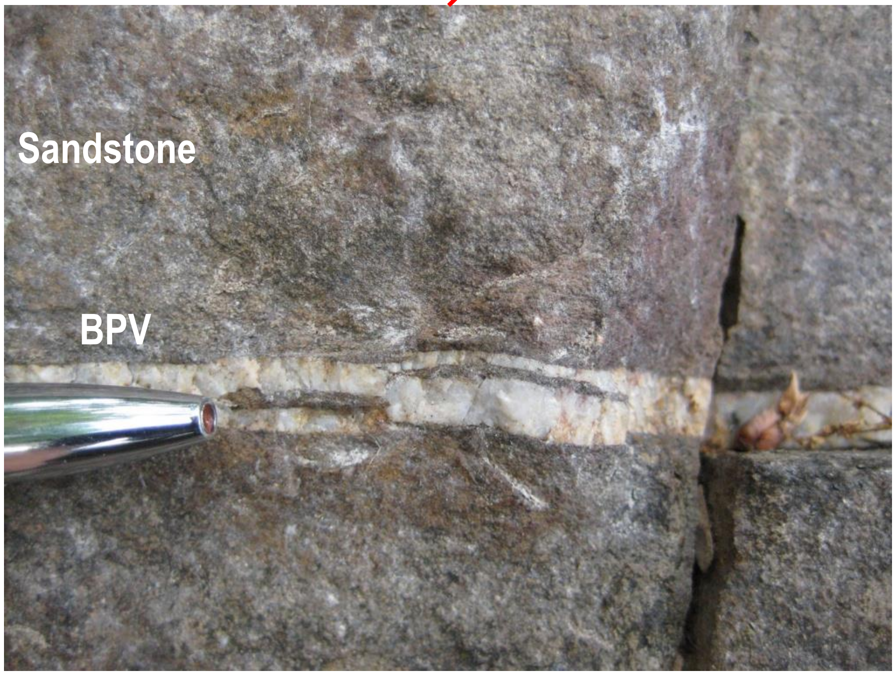
Structural analysis - Observations

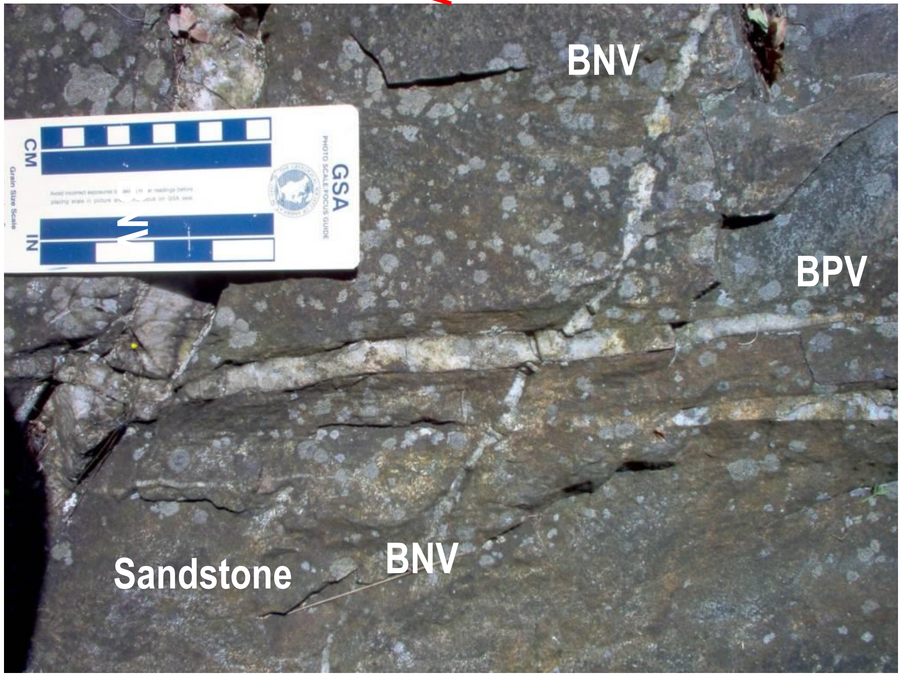


Interbedded bedding-parallel quartz veins (BPV)

Structural analysis - Observations

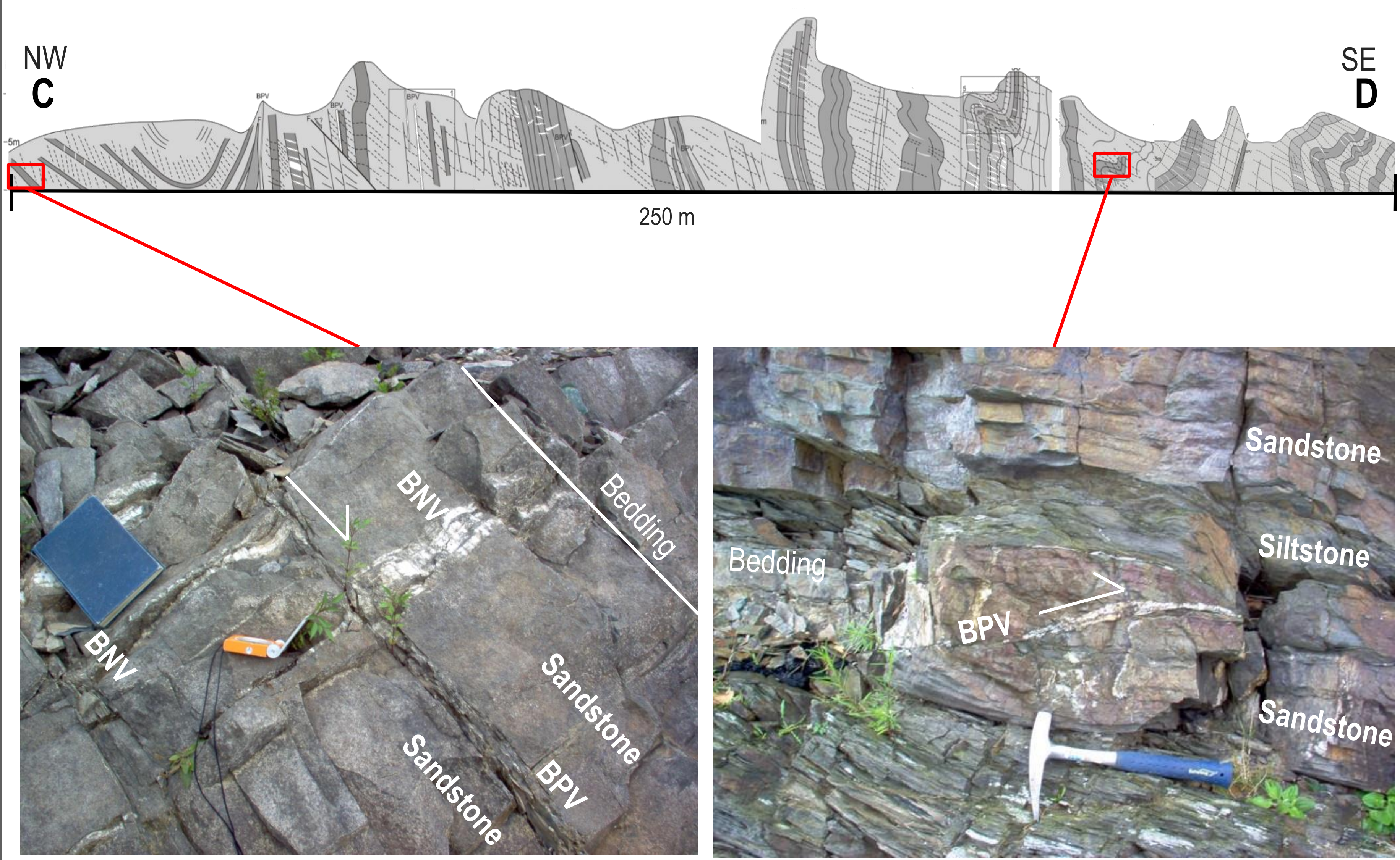






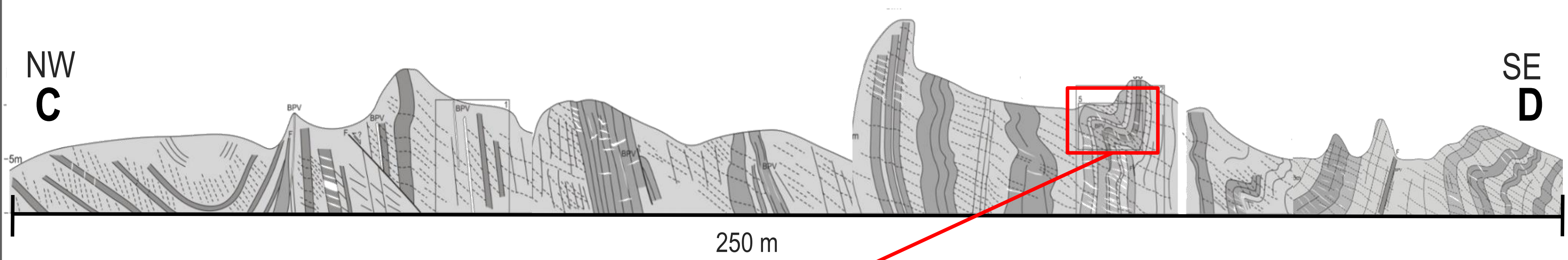
Intrabedded bedding-parallel quartz vein (BPV): cross-cutting bedding-normal veins

Structural analysis - Observations



Interbedded BPVs – cross-cutting and displacement of bedding-normal veins

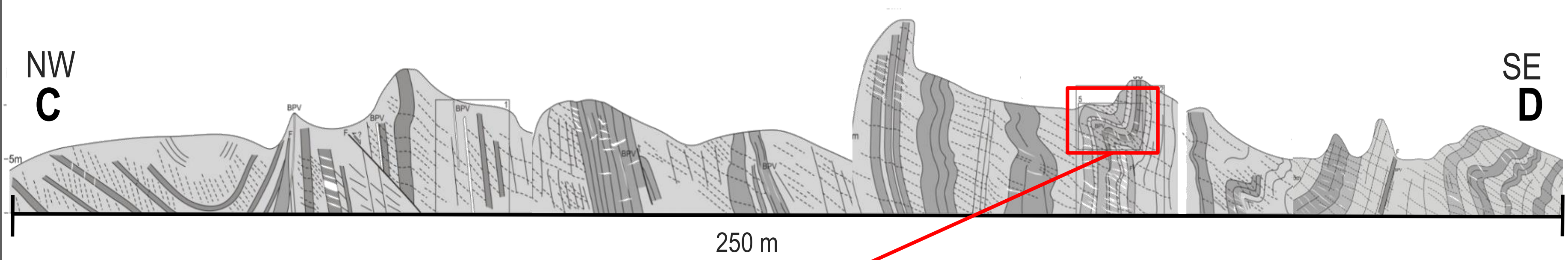
Structural analysis - Observations

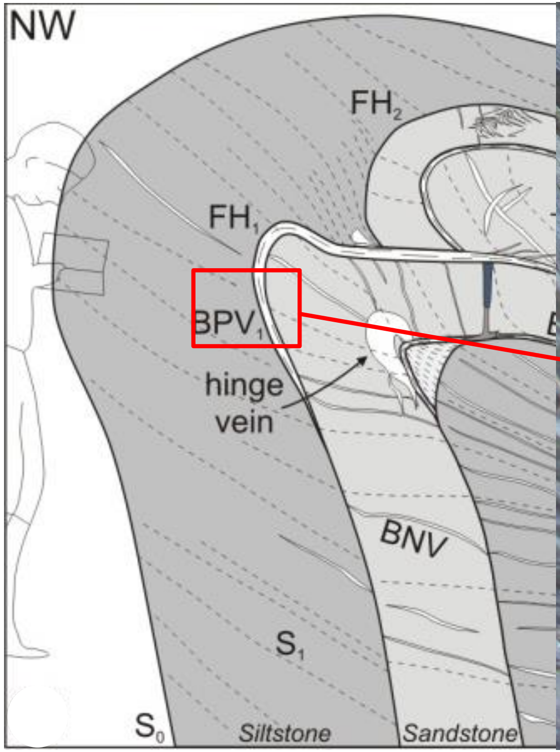


Interbedded BPVs – continuous present around fold hinge

Structural analysis - Observations

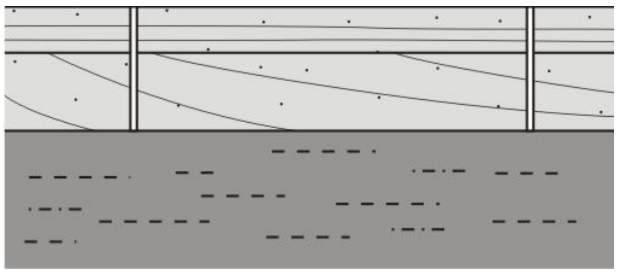
Interbedded BPVs – continuous present around fold hinge



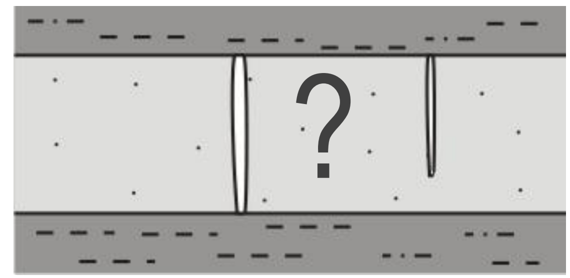


Interbedded BPVs – related with bedding-parallel thrusting

Structural analysis – Interpretation?

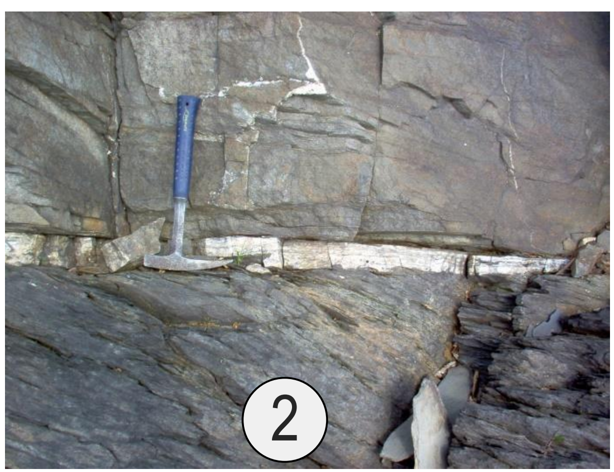


Kinematic model

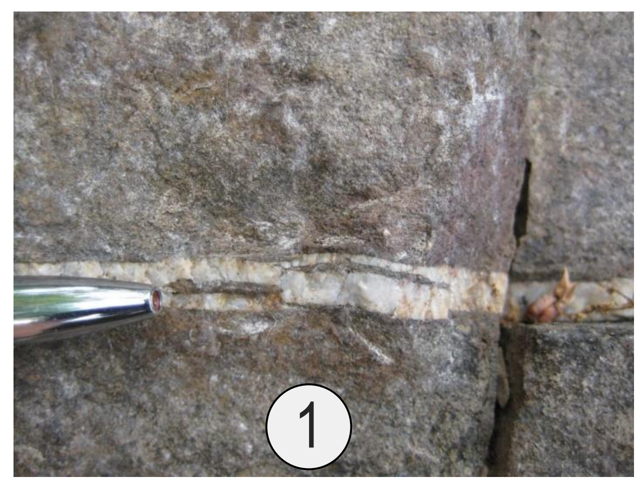


Kinematic model

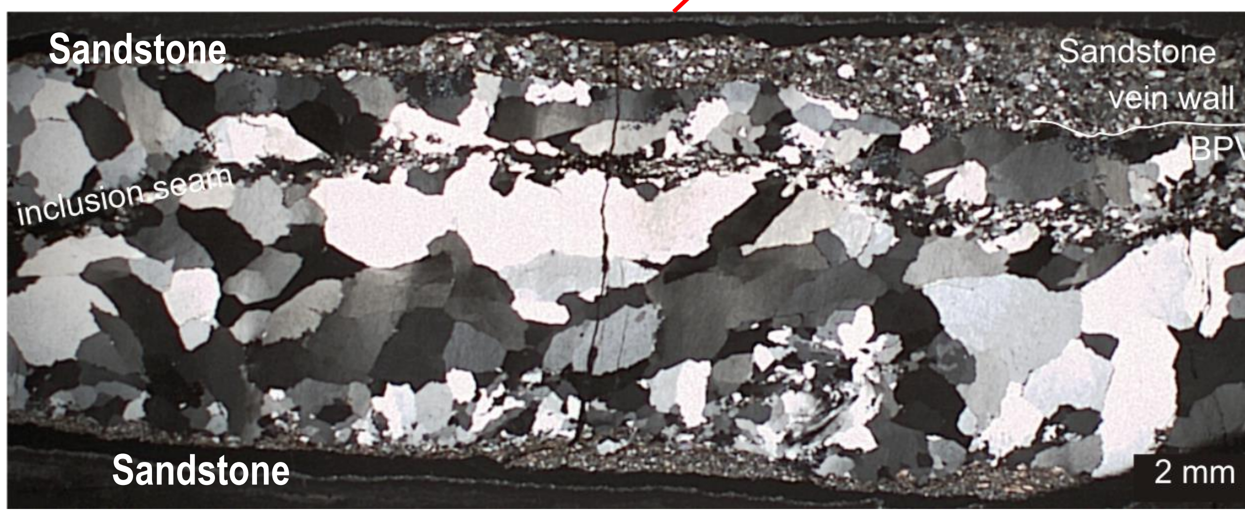
Interbedded BPVs



Intrabedded BPVs

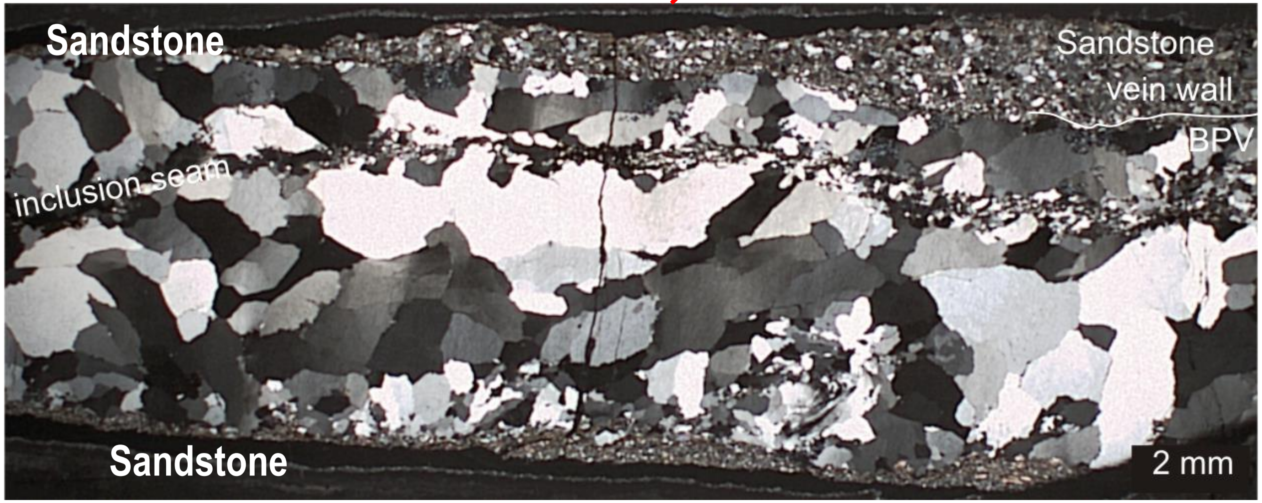


1 Intrabedded BPVs



1 Intrabedded BPVs

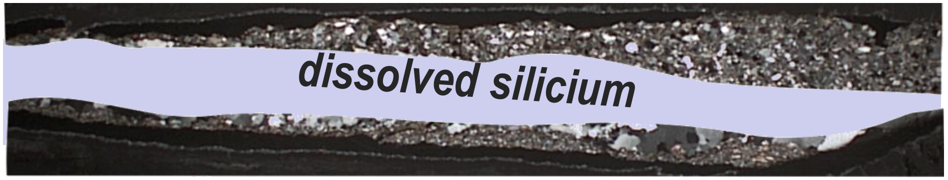
Fracture rate > rate of crystal growth



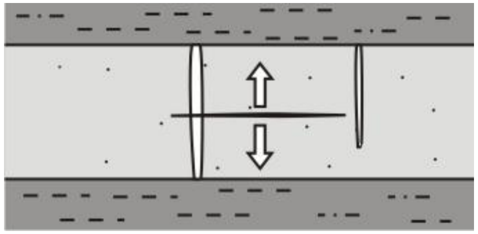
Microstructural analysis

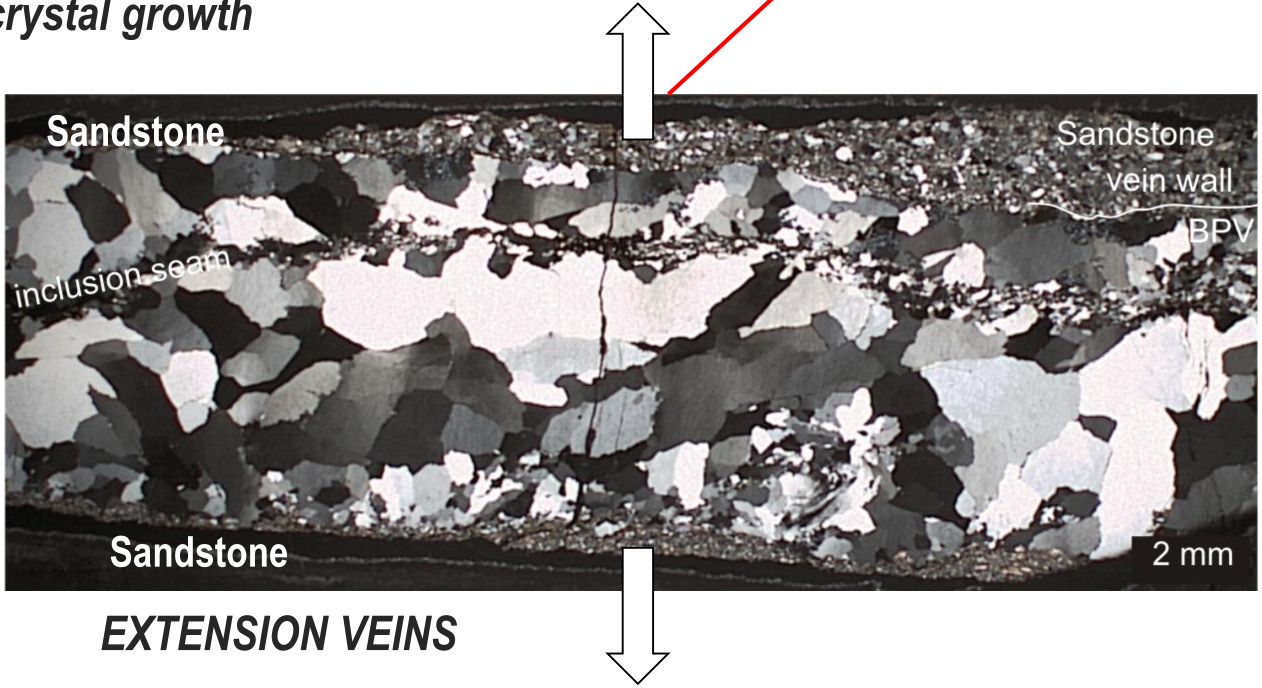
Public PhD defence Koen Van Noten, Leuven, May 3rd 2011

① Intrabedded BPVs



Fracture rate > rate of crystal growth

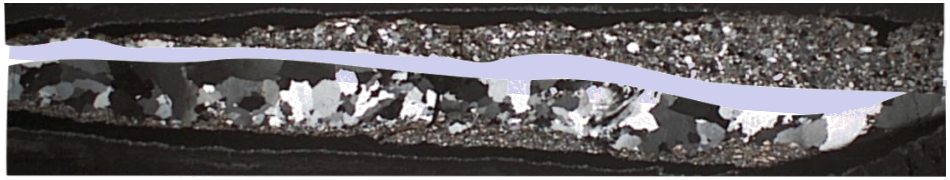




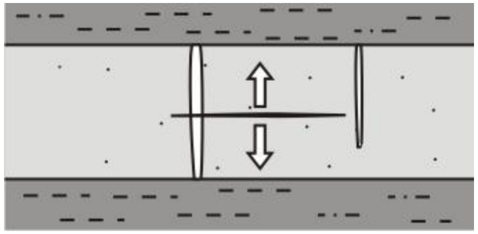
EXTENSION VEINS

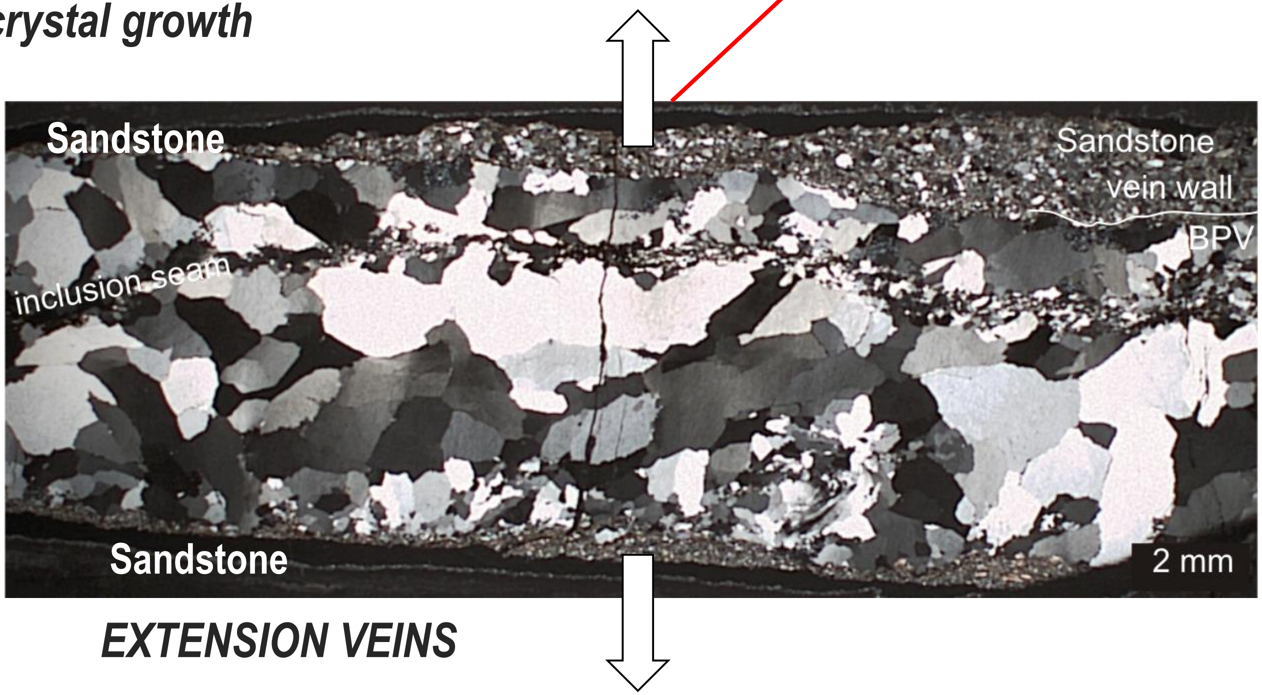
Microstructural analysis

1 Intrabedded BPVs



Fracture rate > rate of crystal growth

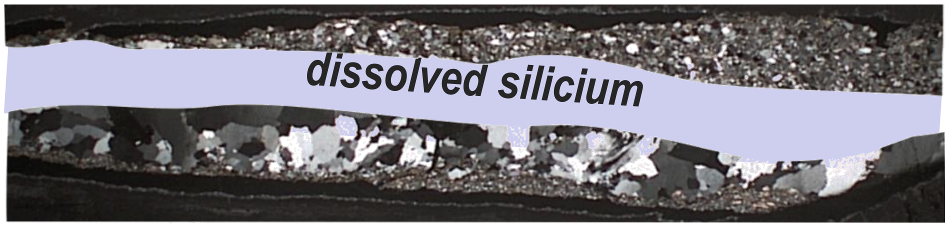




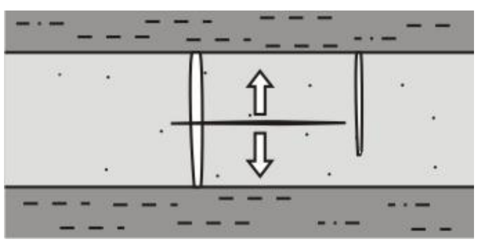
EXTENSION VEINS

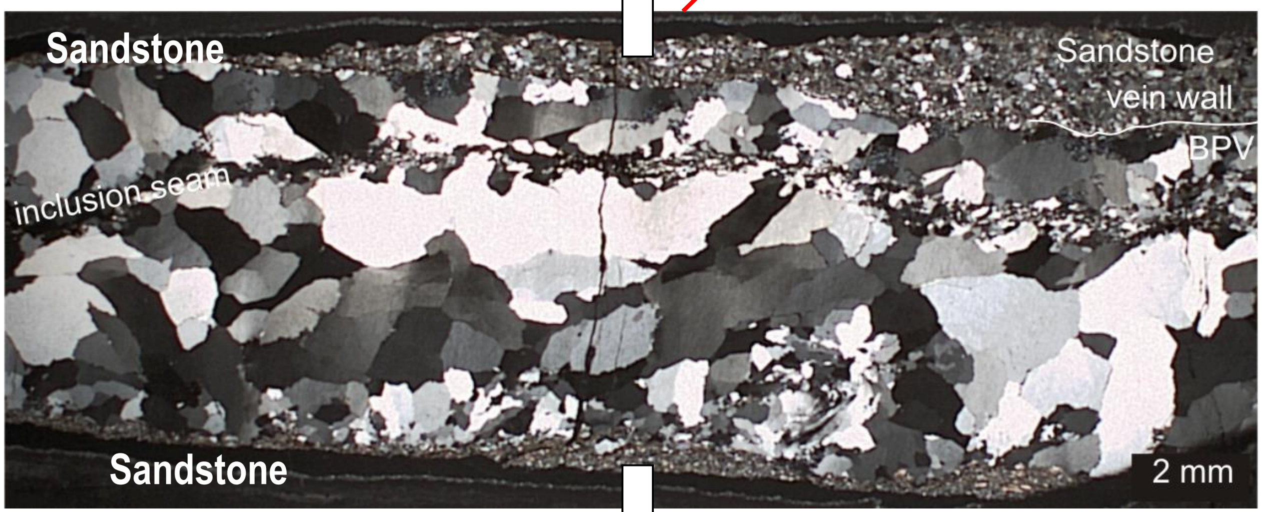
Microstructural analysis

1 Intrabedded BPVs



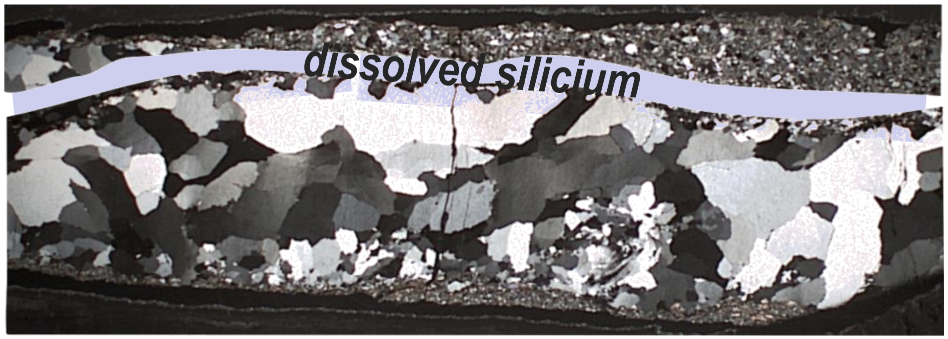
Fracture rate > rate of crystal growth





EXTENSION VEINS

1 Intrabedded BPVs



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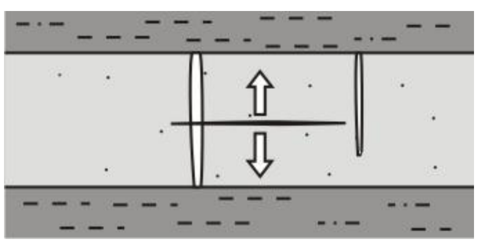
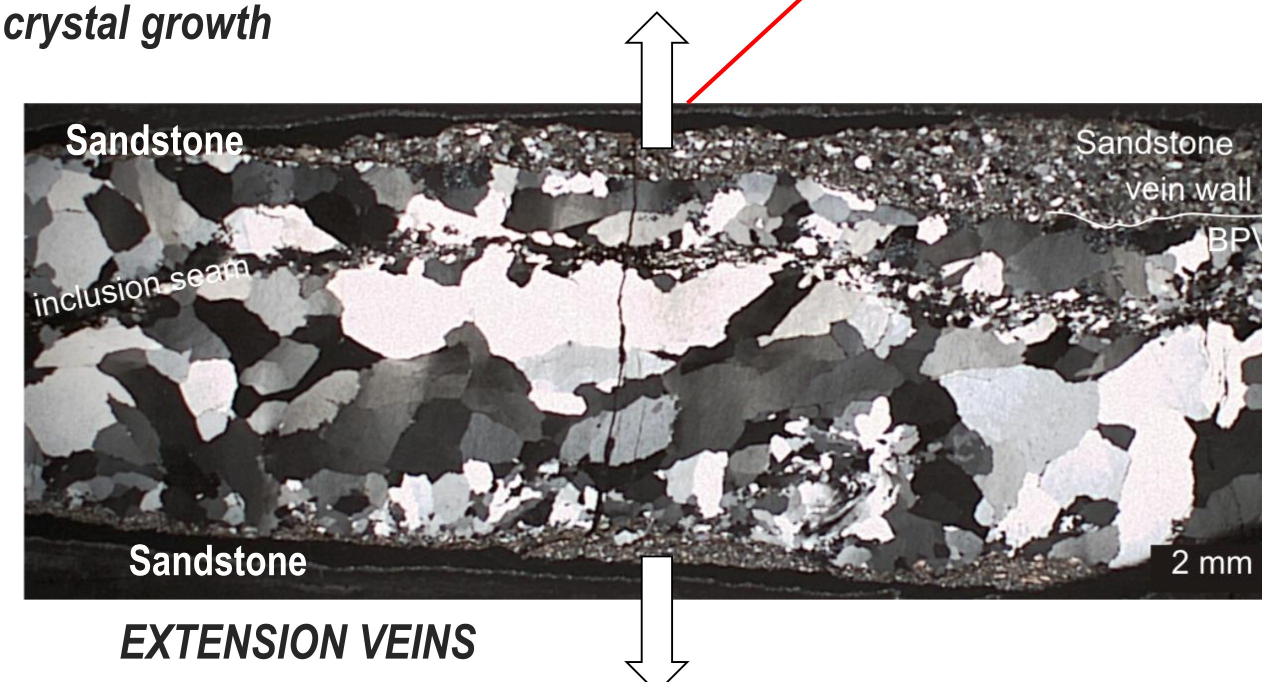


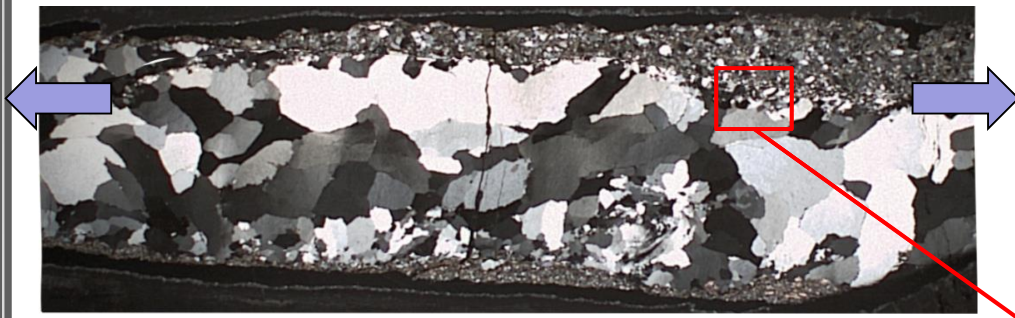


EXTENSION VEINS

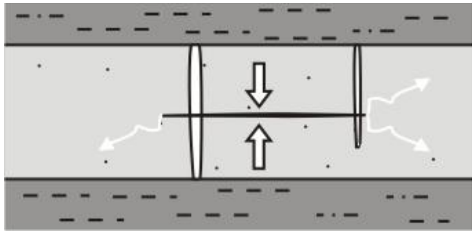
Microstructural analysis

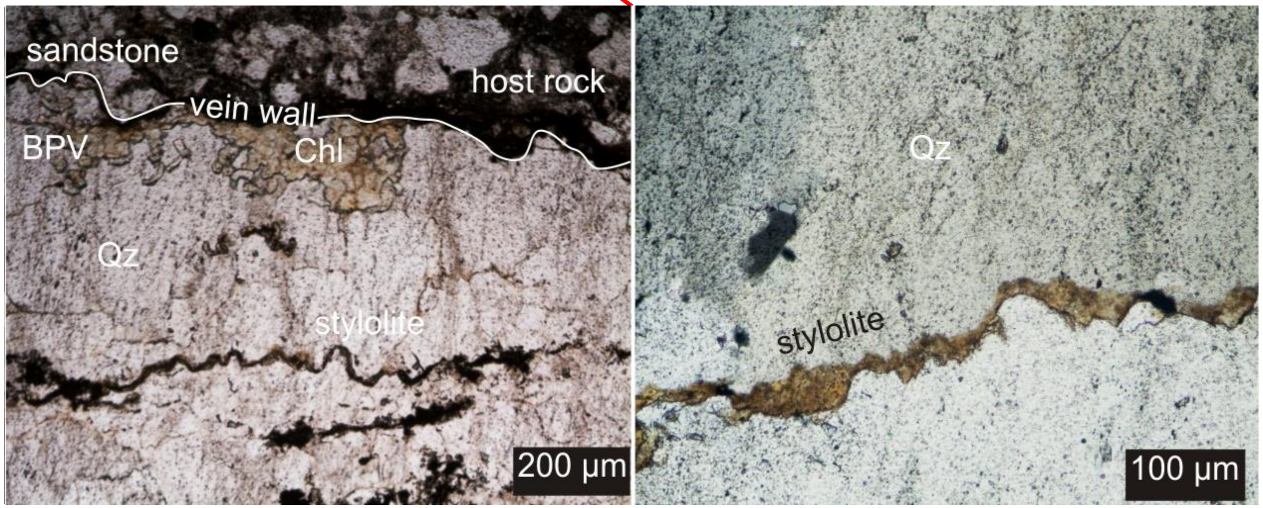
1 Intrabedded BPVs

Bedding-normal collapse



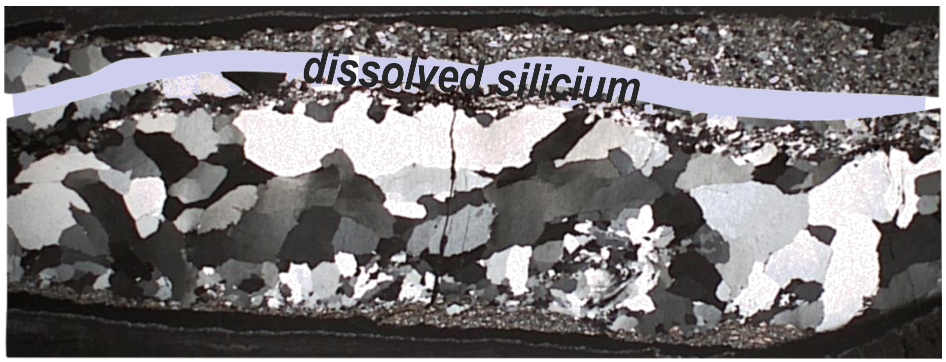
Fracture rate > rate of crystal growth



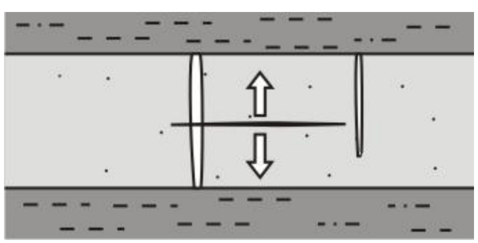


Stylolites : bedding-parallel dissolutions

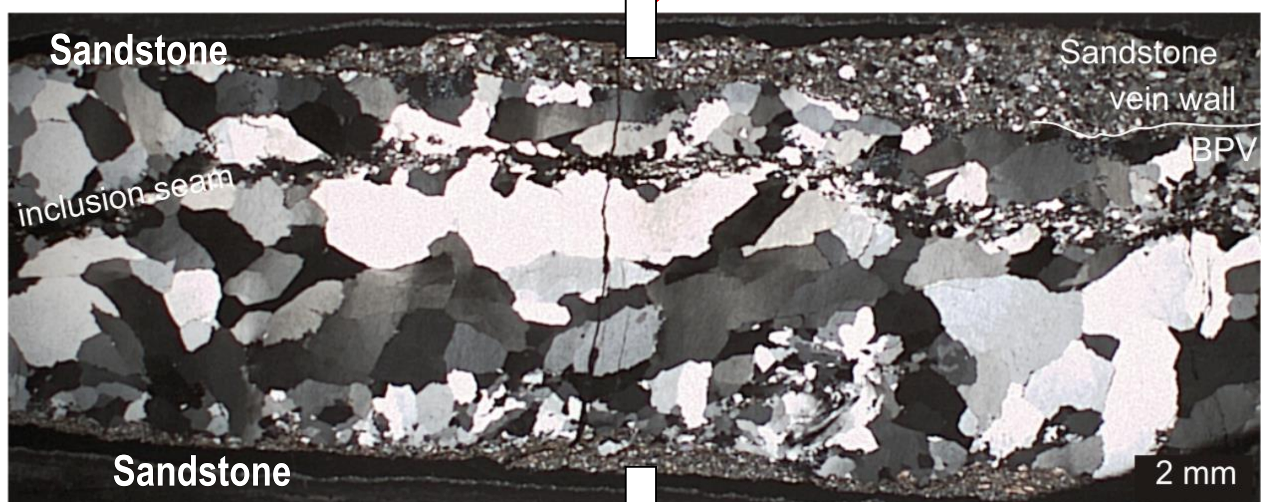
Microstructural analysis



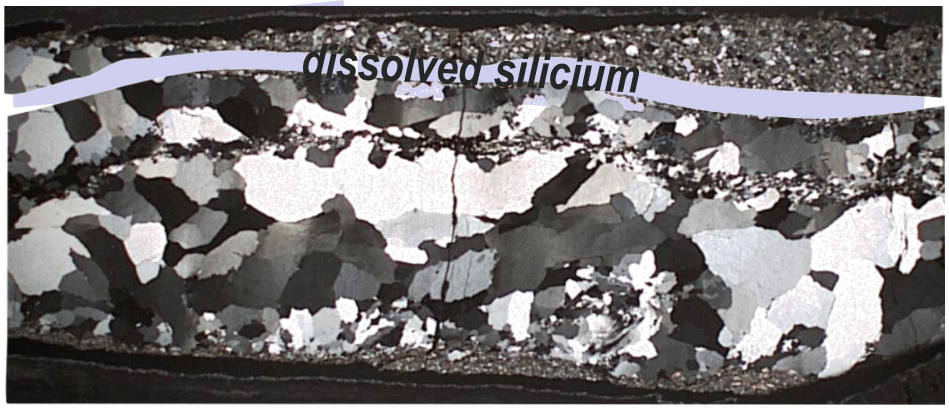
Fracture rate > rate of crystal growth



1 Intrabedded BPVs

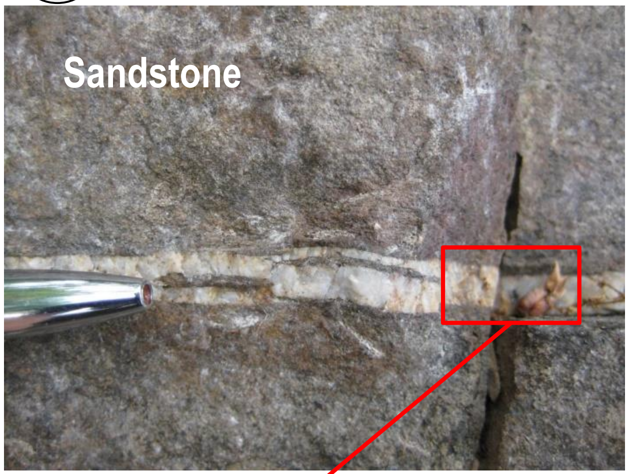


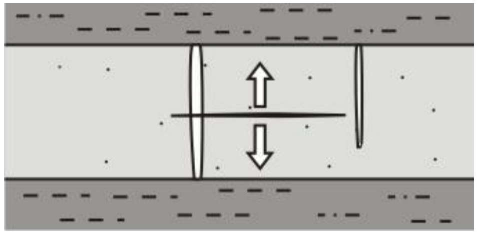
EXTENSION VEINS

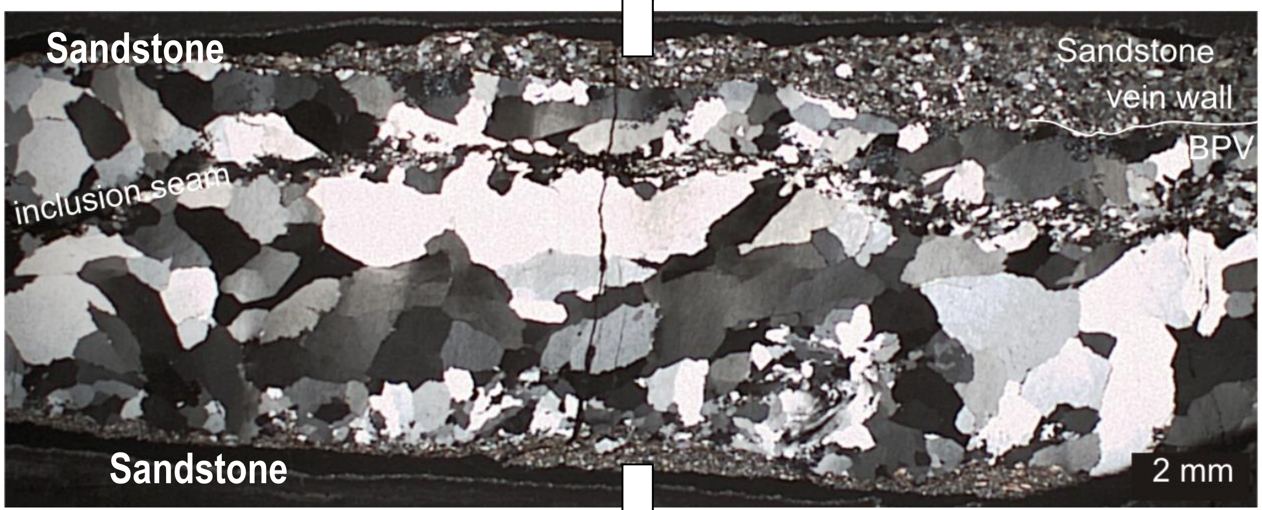


Fracture rate > rate of crystal growth

① Intrabedded BPVs





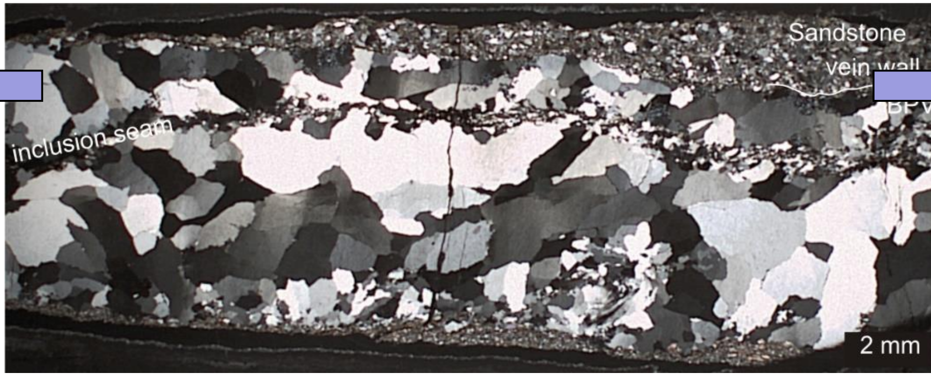


EXTENSION VEINS

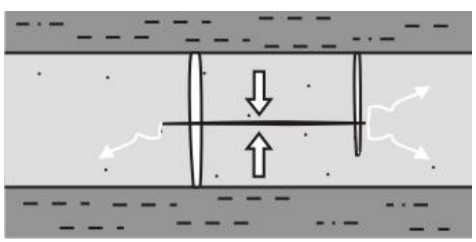
Microstructural analysis

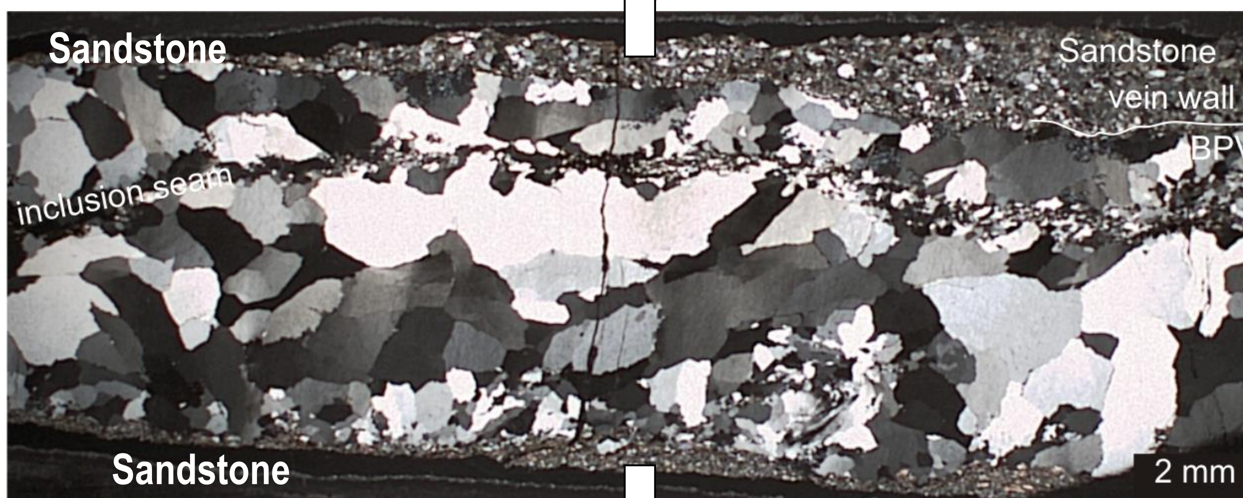
1 Intrabedded BPVs

Bedding-normal collapse



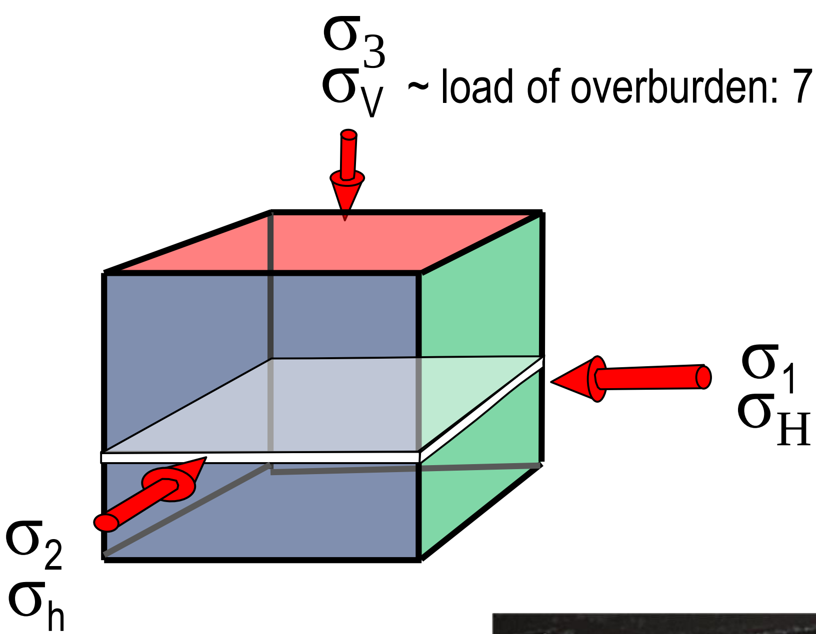
Fracture rate > rate of crystal growth

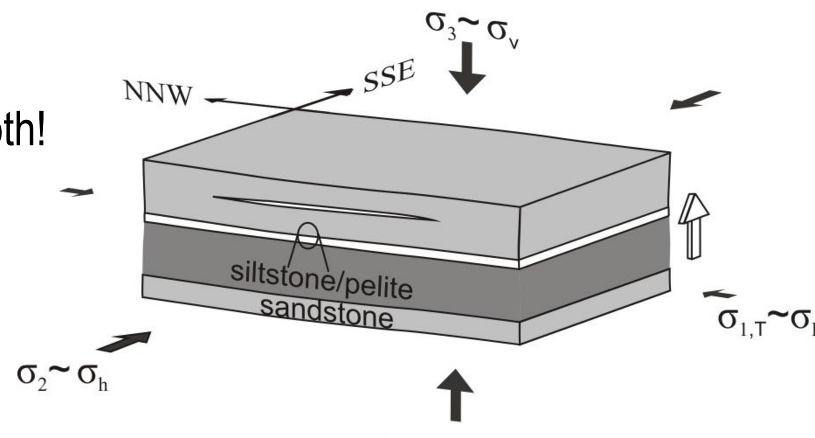




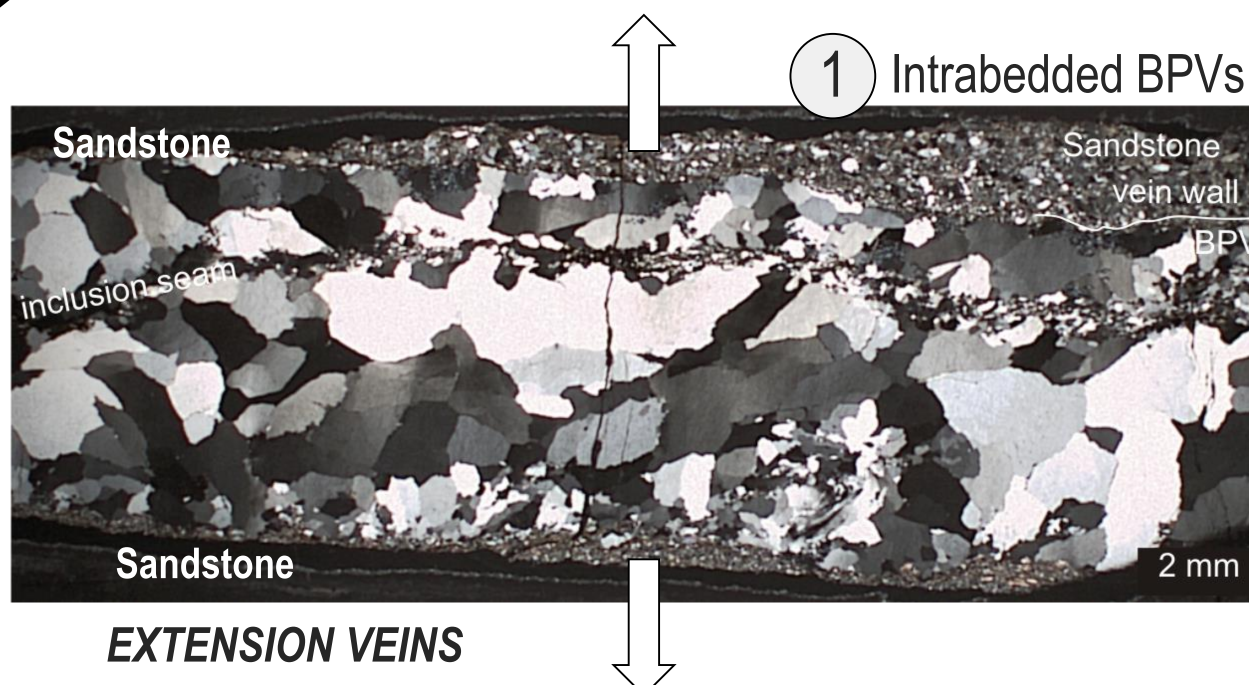
EXTENSION VEINS

Public PhD defence Koen Van Noten, Leuven, May 3rd 2011



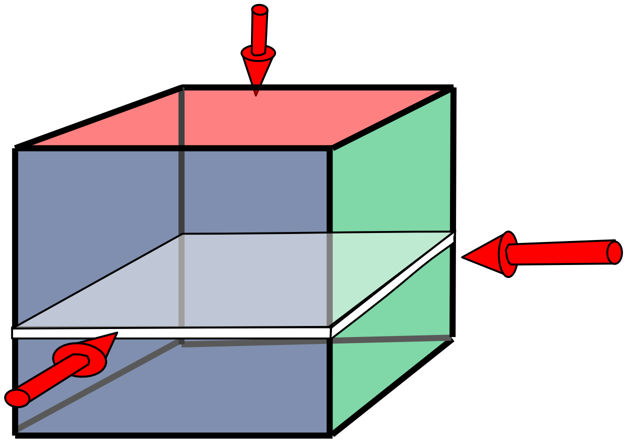


1 Intrabedded BPVs



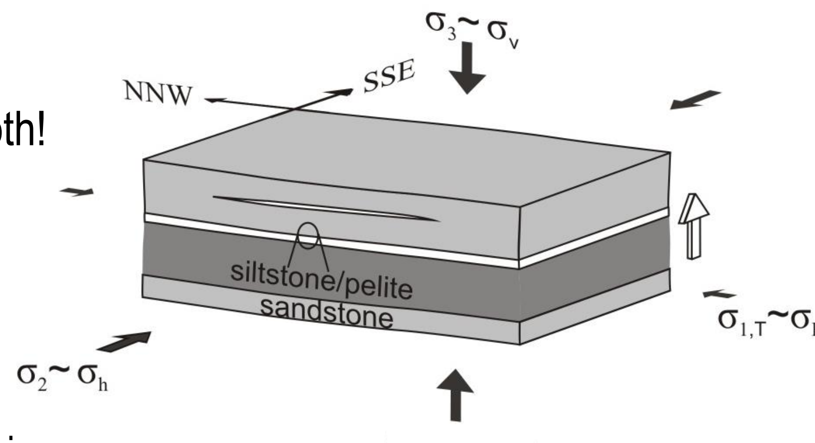
EXTENSION VEINS

σ_3
σ_V ~ load of overburden: 7 km depth!

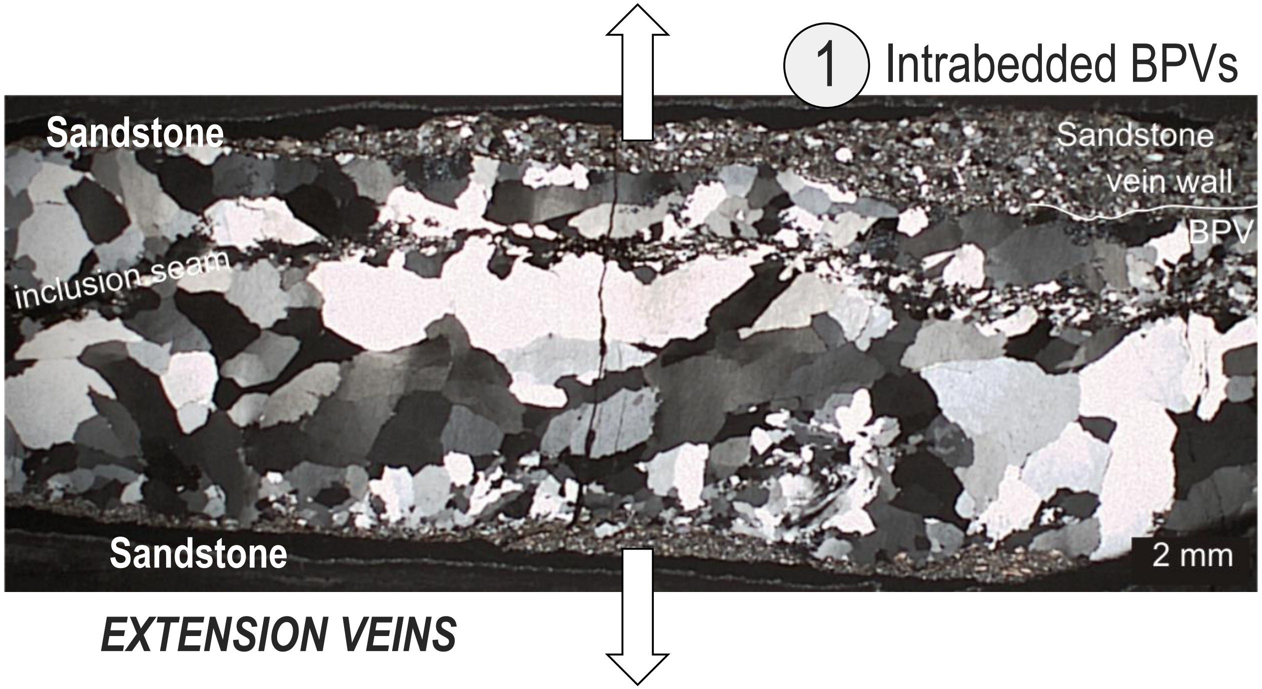


σ_1
σ_H $\sigma_{Tectonic}$

σ_2
σ_h

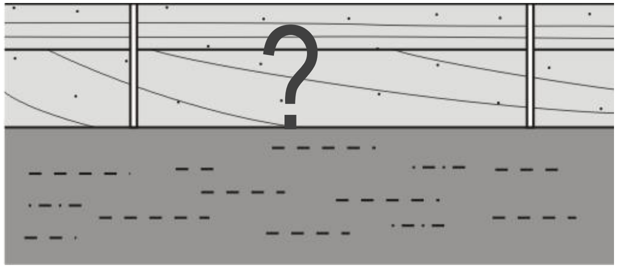


1 Intrabedded BPVs

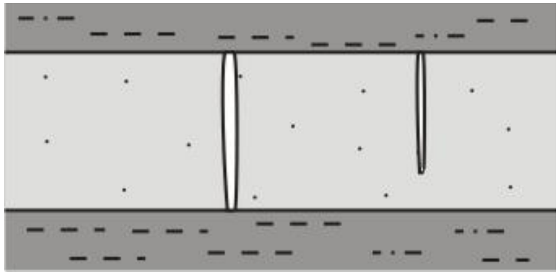


COMPRESSION – RELATED

EXTENSION VEINS

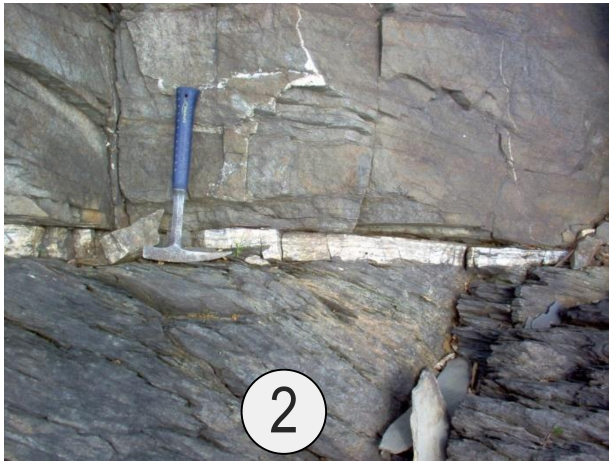


Kinematic model

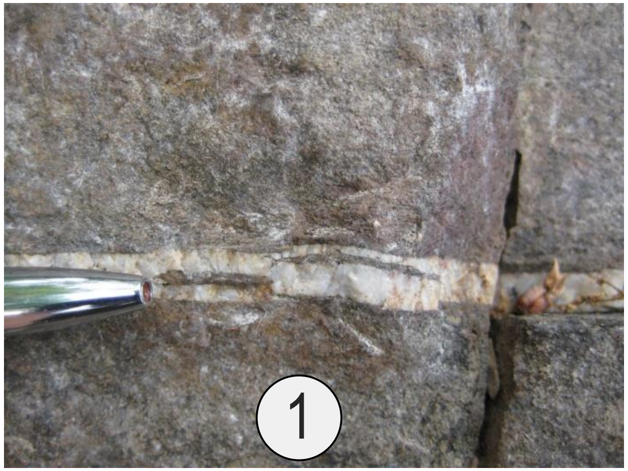


Kinematic model

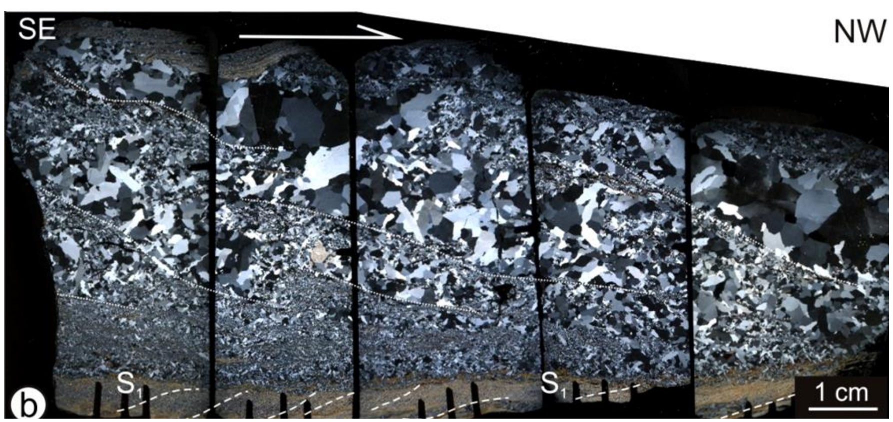
Interbedded BPVs



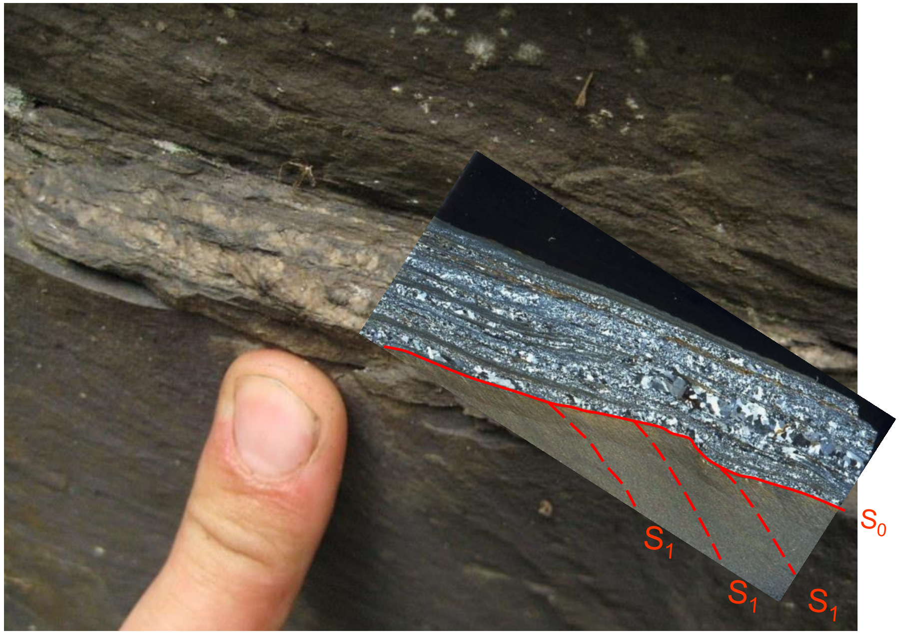
Intrabedded BPVs

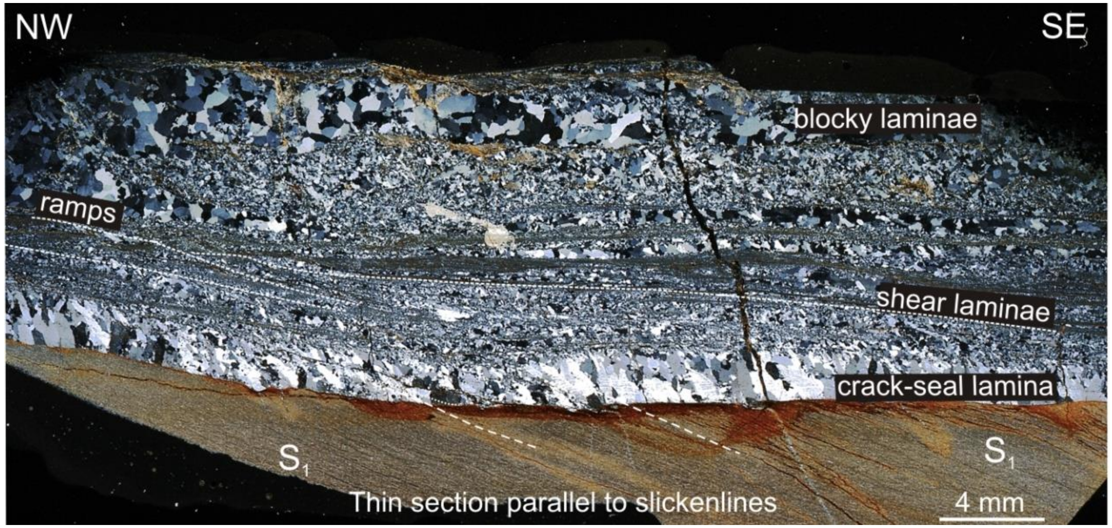


2 Interbedded BPVs



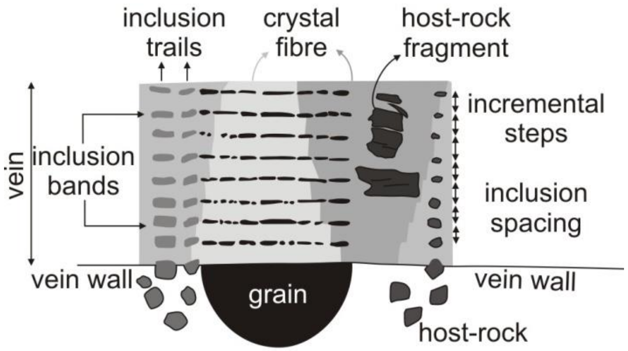
2 Interbedded BPVs

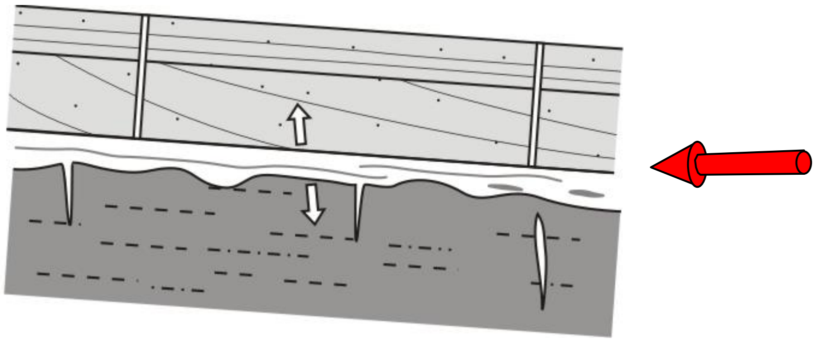




2 Interbedded BPVs

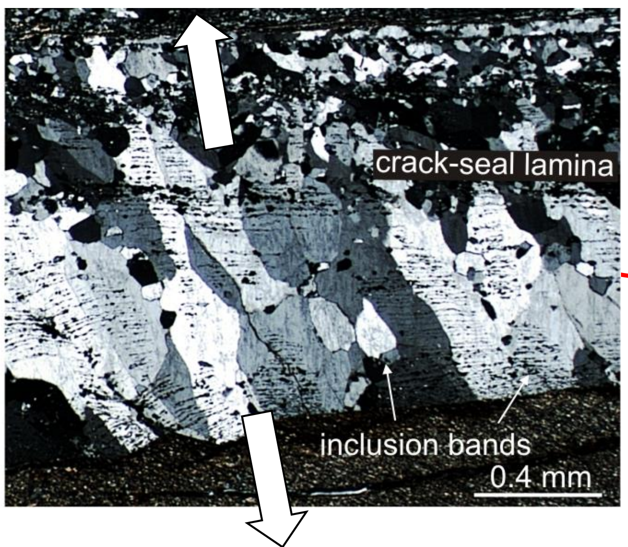
crack-seal laminae:
rate of crystal growth > fracture rate

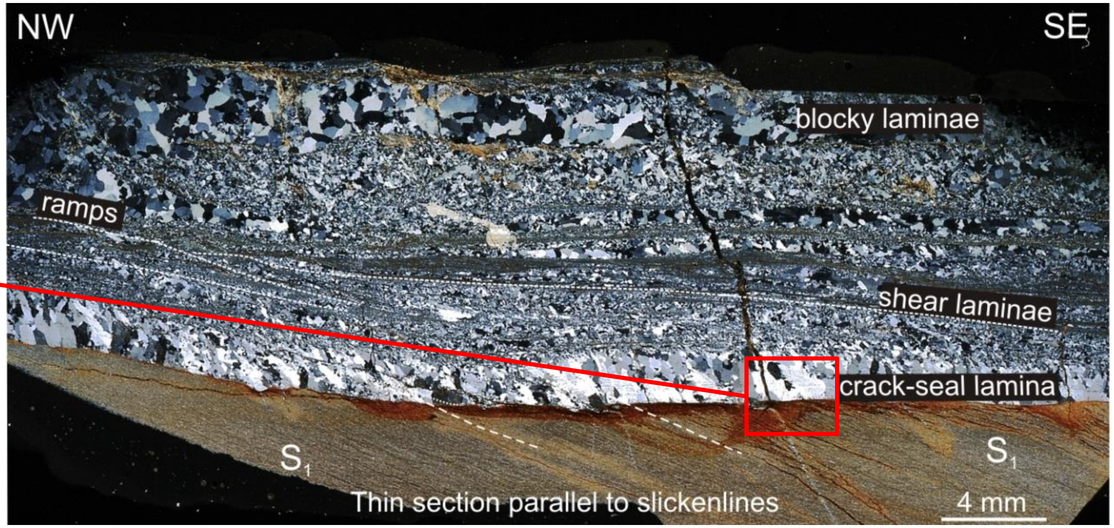




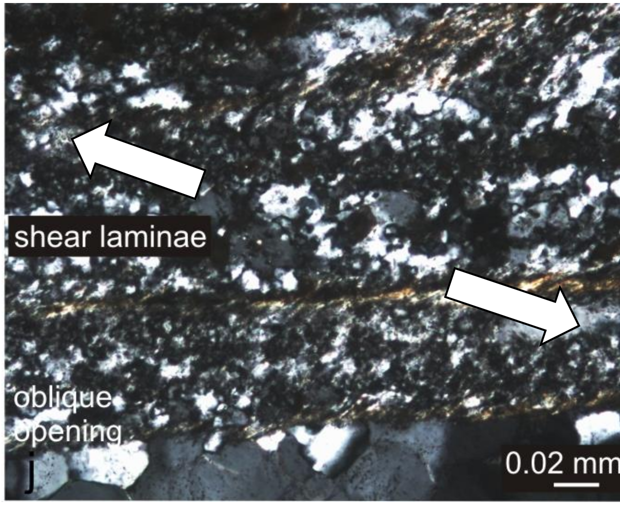
Extension veins

crack-seal laminae: oblique opening

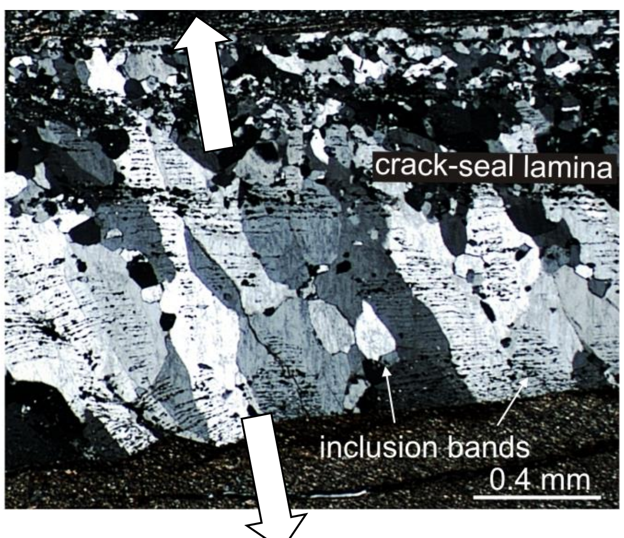




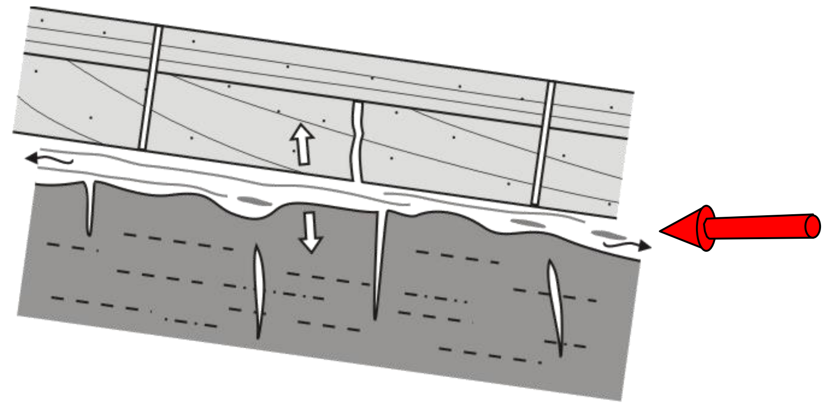
shear laminae:
Small crystal sizes & strong recrystallisation



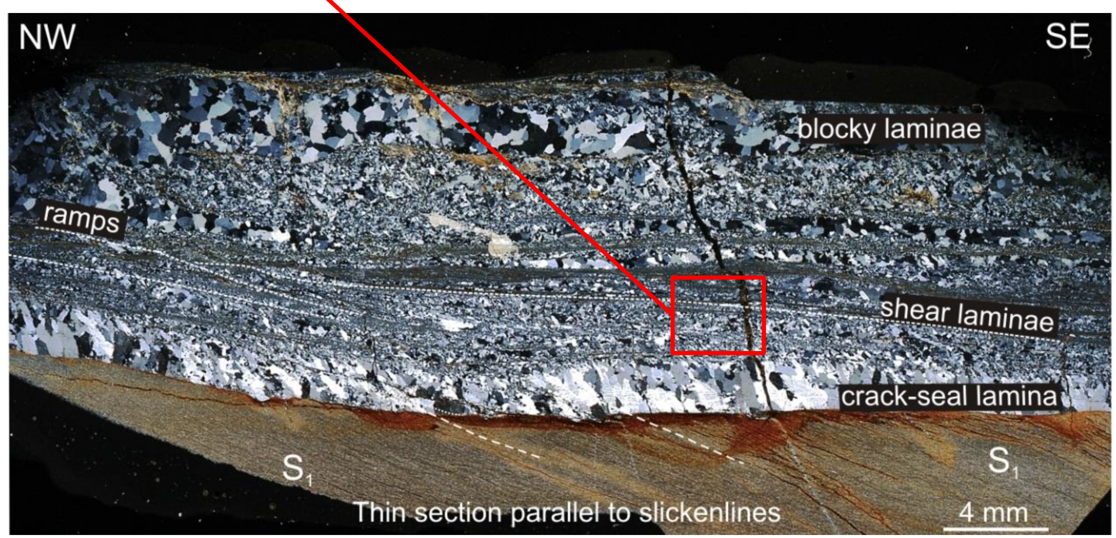
crack-seal laminae: oblique opening



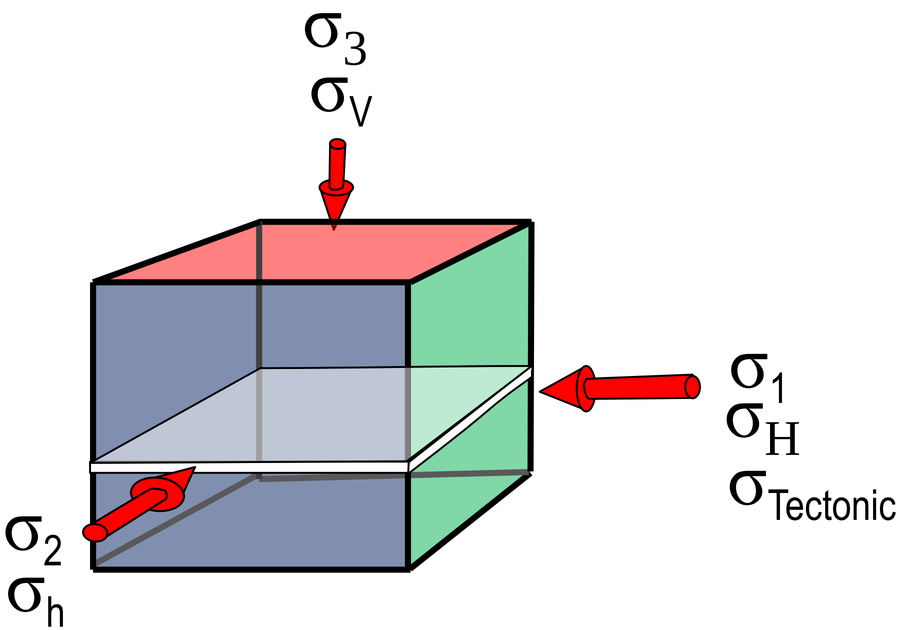
② Interbedded BPVs



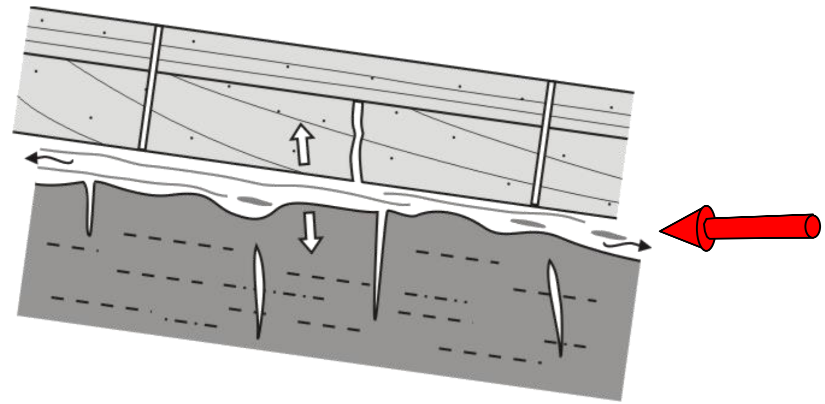
Extension to extensional-shear veins



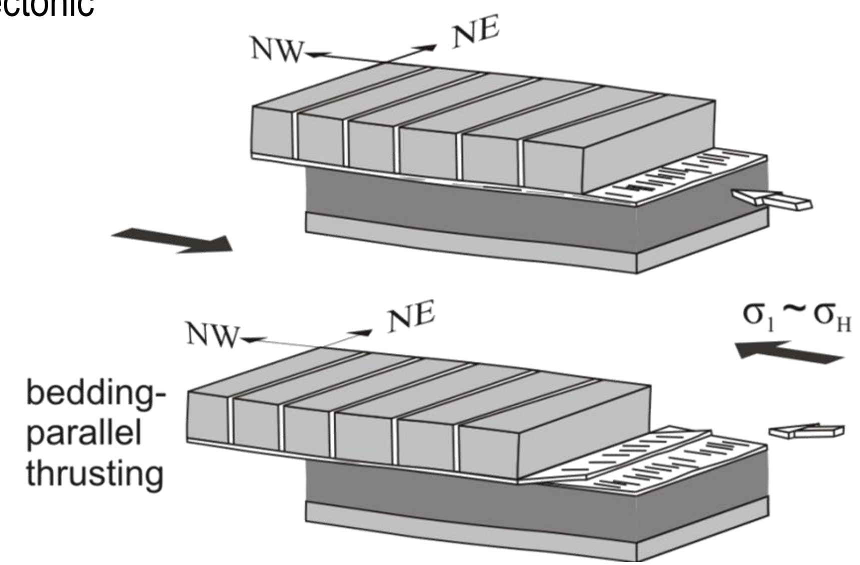
② Interbedded BPVs



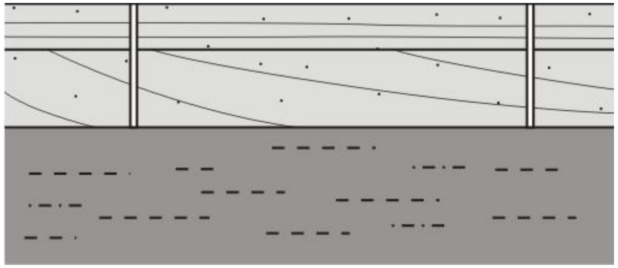
COMPRESSION – RELATED



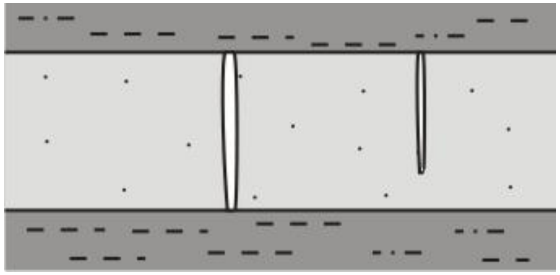
Extension to extensional-shear veins



Structural analysis - Interpretation

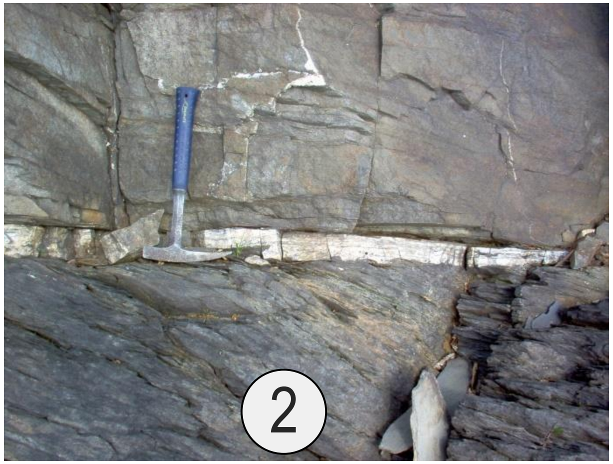


Kinematic model

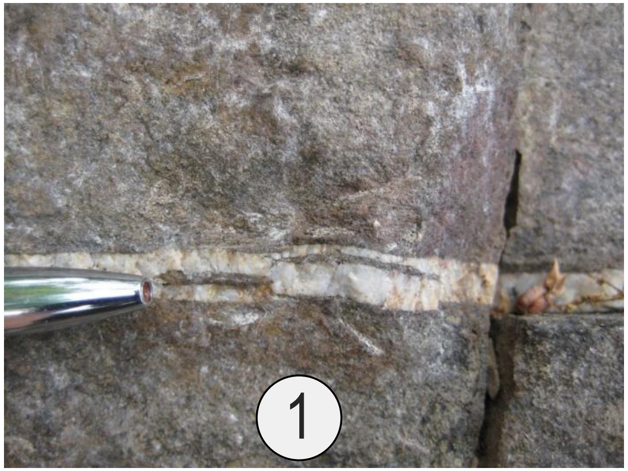


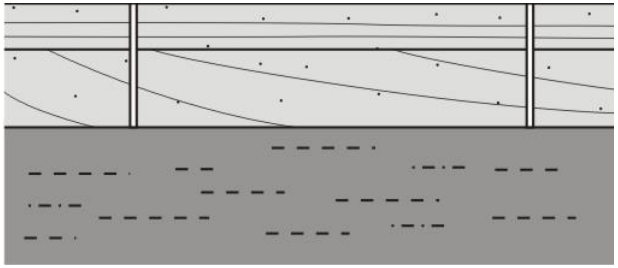
Kinematic model

Interbedded BPVs



Intrabedded BPVs

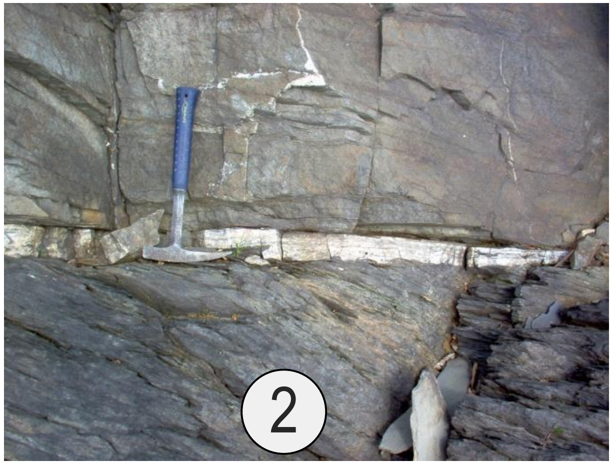


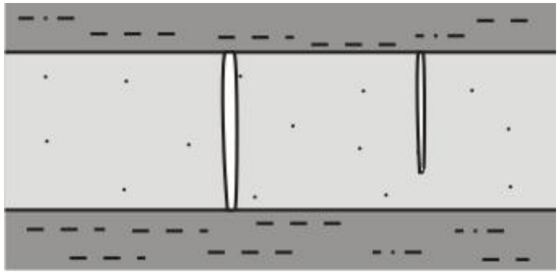


Kinematic model

bedding-normal veining

Interbedded BPVs

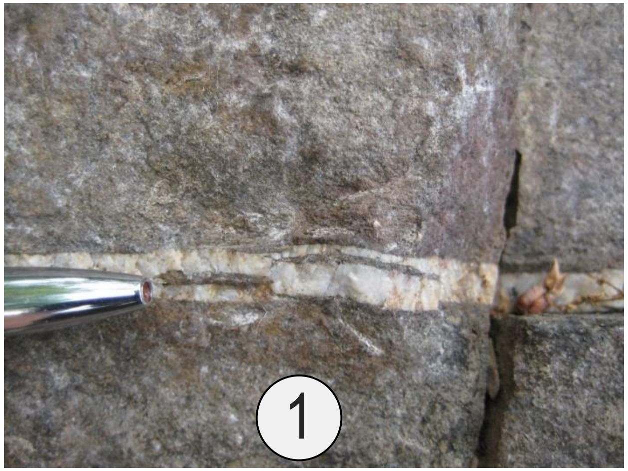




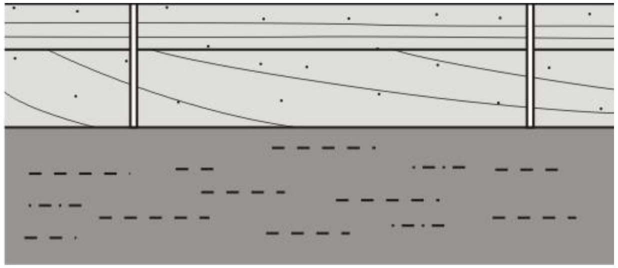
Kinematic model

bedding-normal veining

Intrabedded BPVs



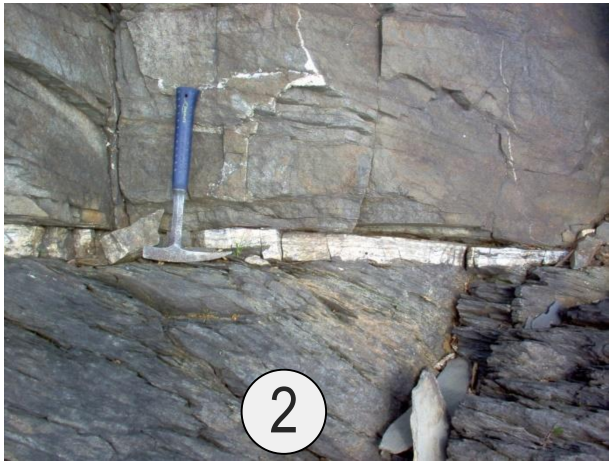
Structural analysis - Interpretation

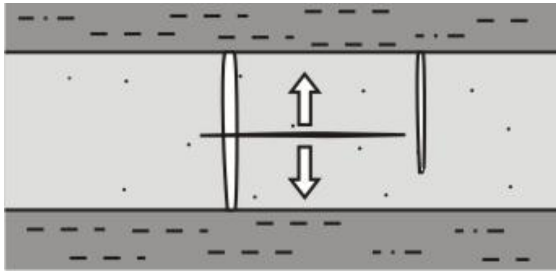


Kinematic model

bedding-normal veining

Interbedded BPVs

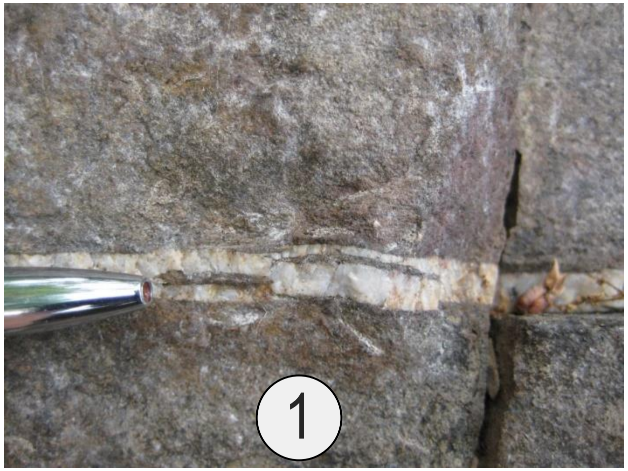




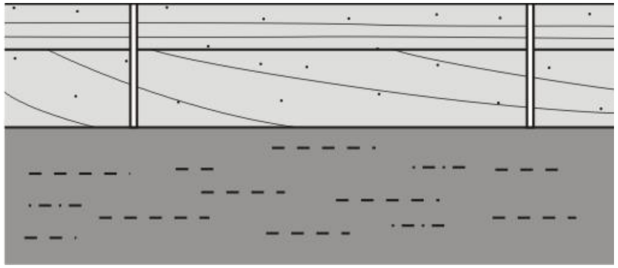
Kinematic model

bedding-normal uplift

Intrabedded BPVs



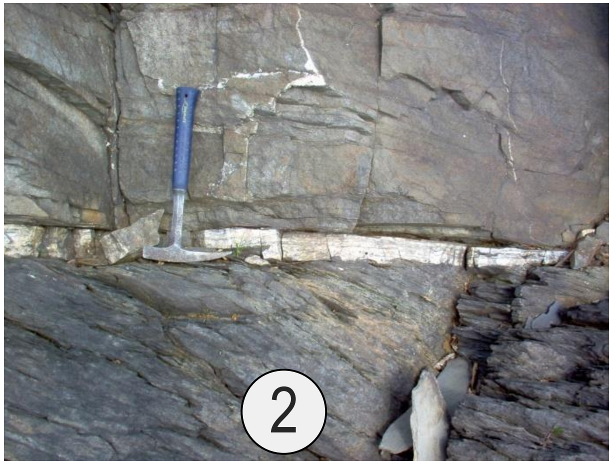
Structural analysis - Interpretation

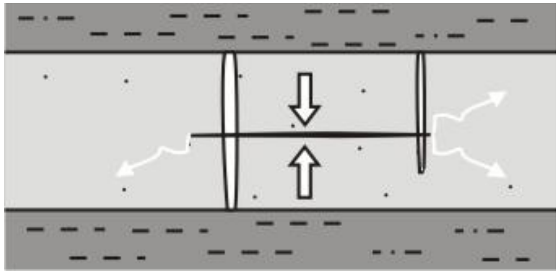


Kinematic model

bedding-normal veining

Interbedded BPVs

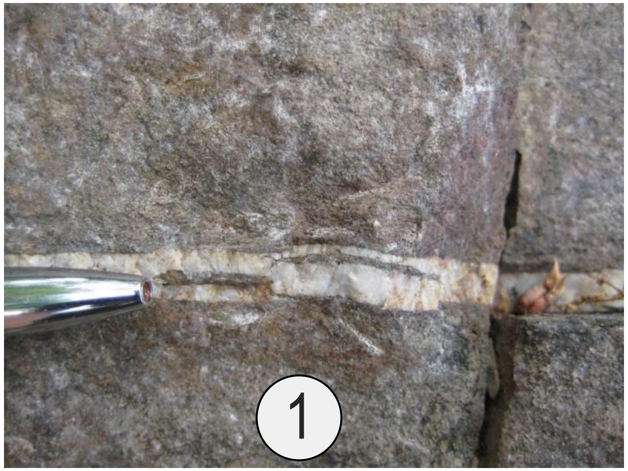


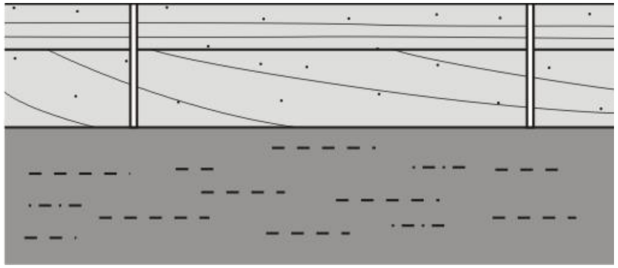


Kinematic model

bedding-normal collapse

Intrabedded BPVs

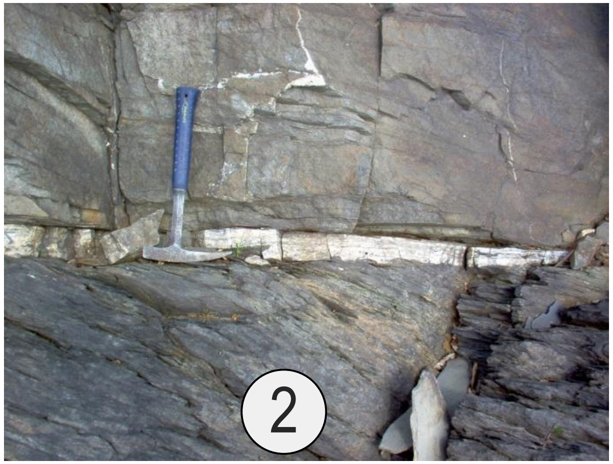


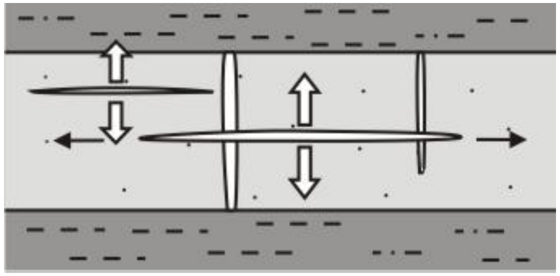


Kinematic model

bedding-normal veining

Interbedded BPVs

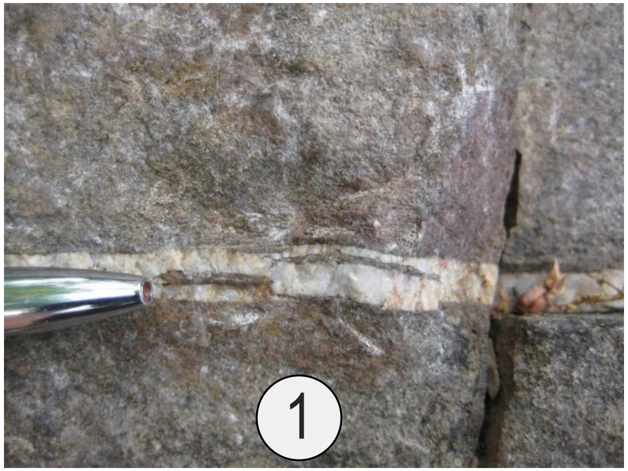




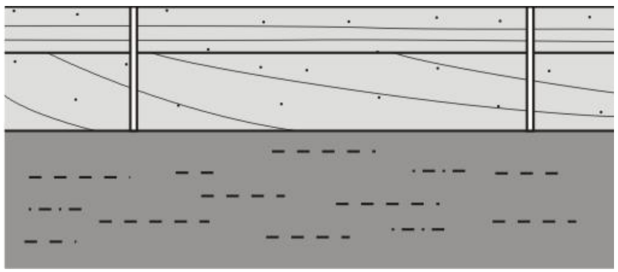
Kinematic model

bedding-normal uplift

Intrabedded BPVs



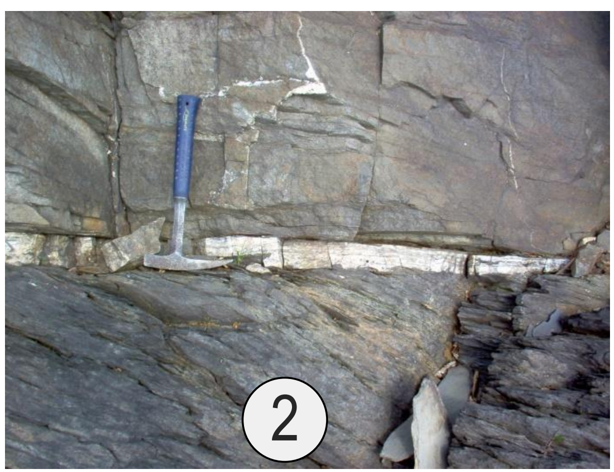
Structural analysis - Interpretation

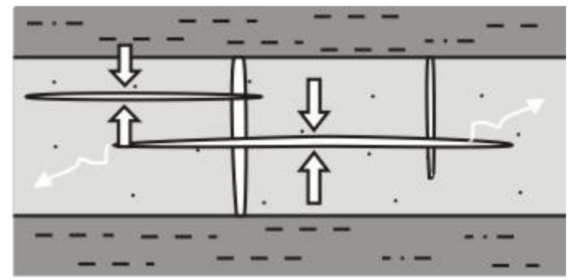


Kinematic model

bedding-normal veining

Interbedded BPVs

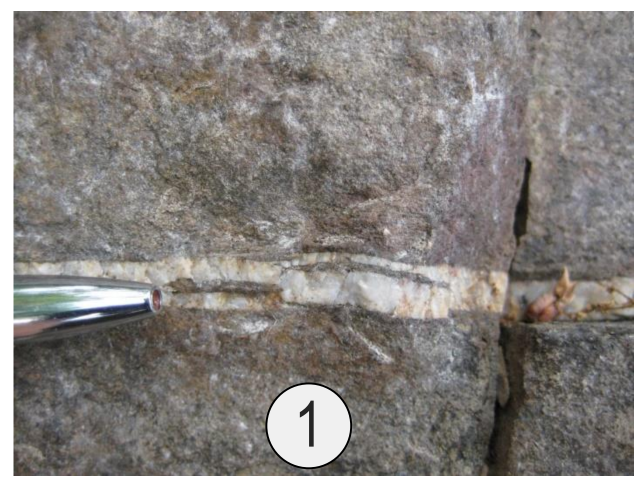




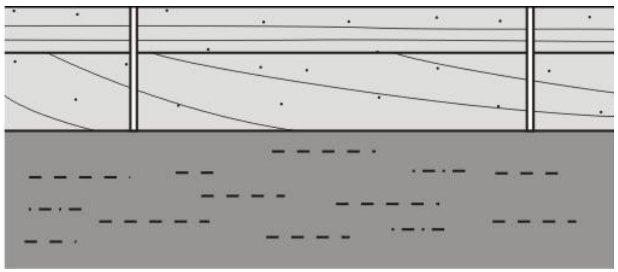
Kinematic model

bedding-normal collapse

Intrabedded BPVs



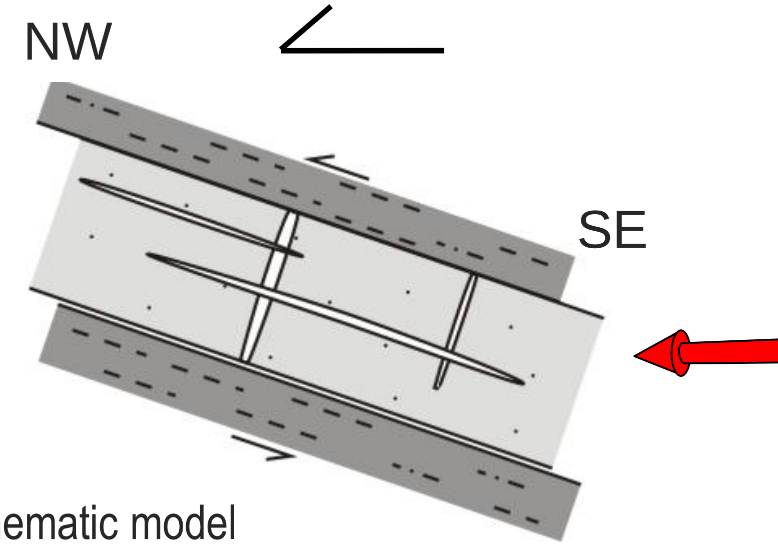
Structural analysis - Interpretation



Kinematic model

bedding-normal veining

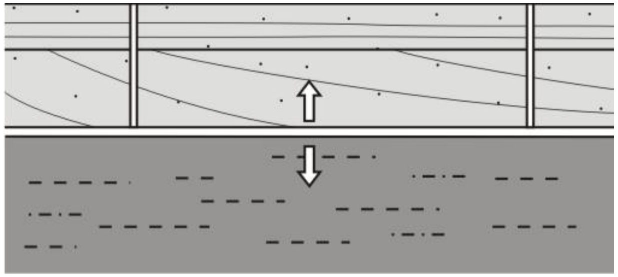
Interbedded BPVs



Kinematic model

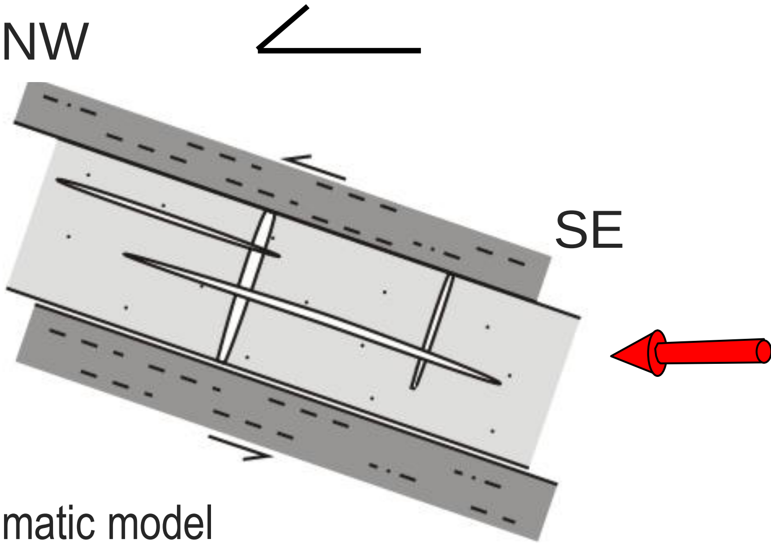
overall fold-and-cleavage development

Intrabedded BPVs



Kinematic model

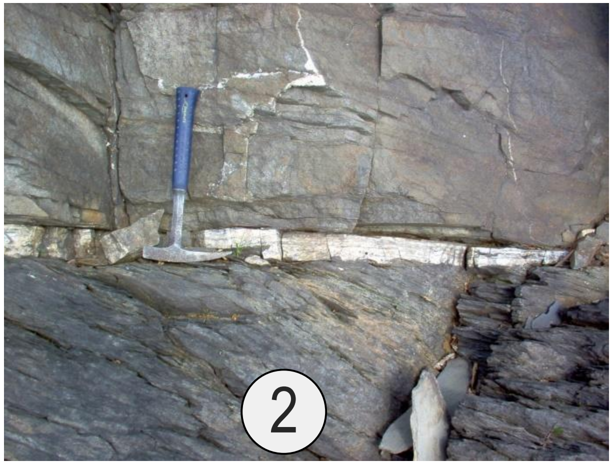
bedding-normal uplift



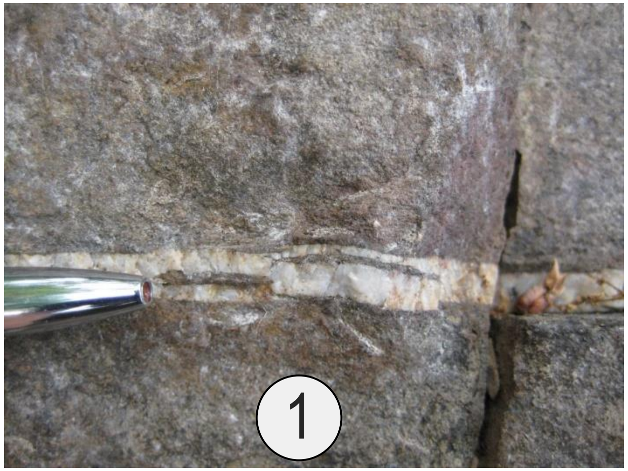
Kinematic model

overall fold-and-cleavage development

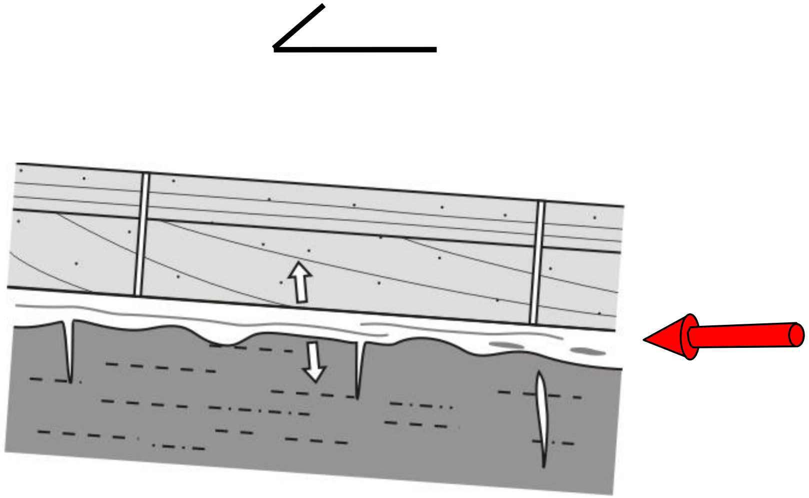
Interbedded BPVs



Intrabedded BPVs

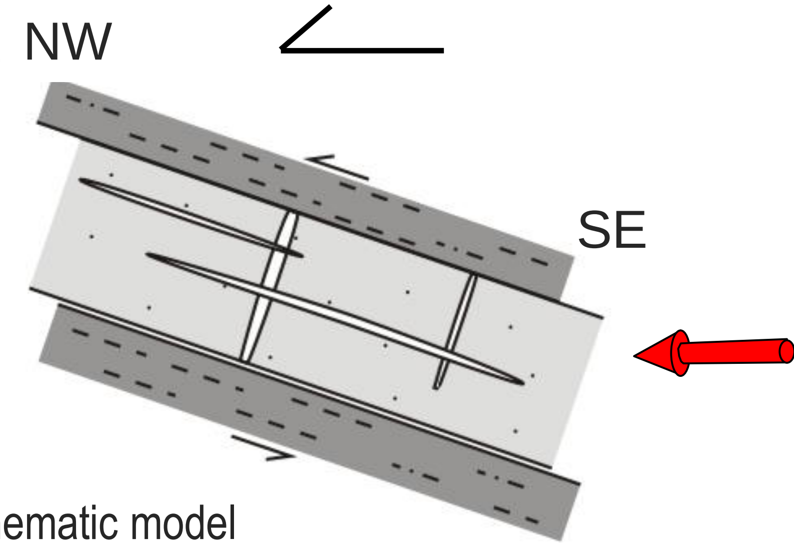


Structural analysis - Interpretation



Kinematic model

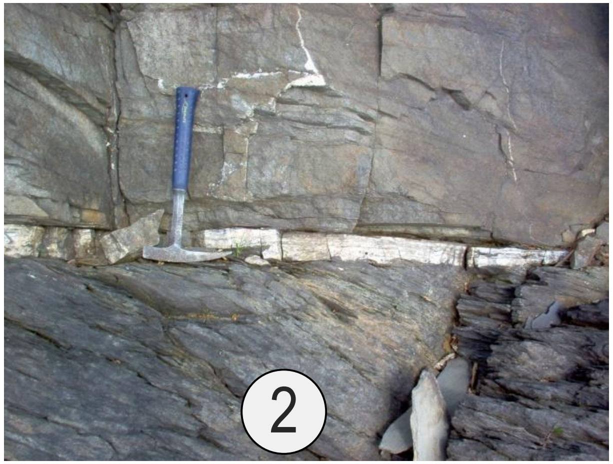
bedding-normal uplift + bedding-parallel thrusting



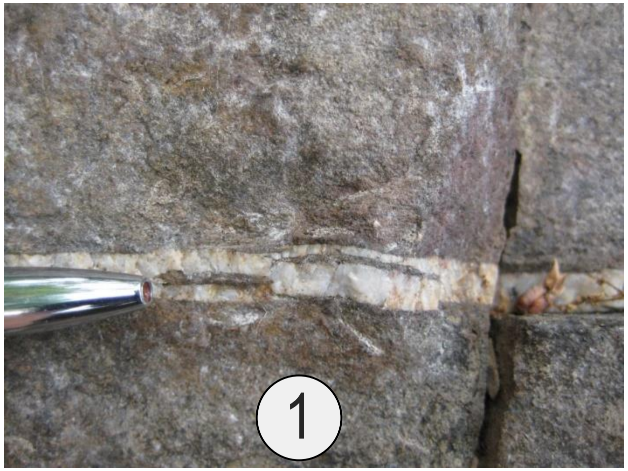
Kinematic model

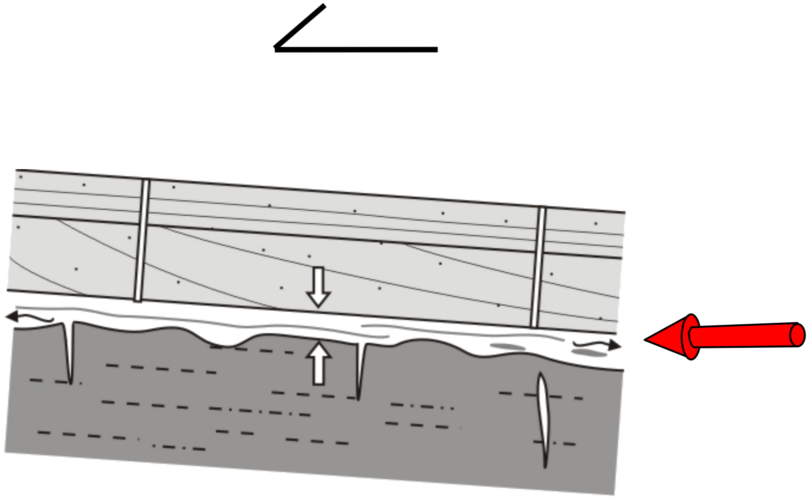
overall fold-and-cleavage development

Interbedded BPVs



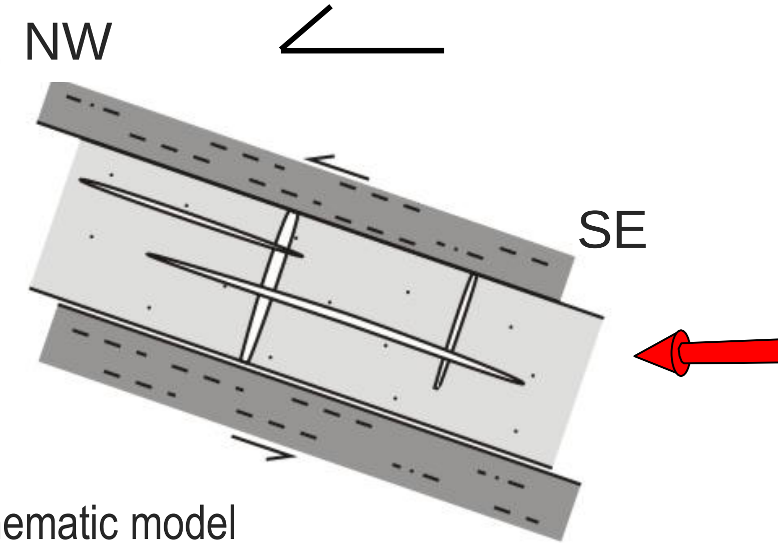
Intrabedded BPVs





Kinematic model

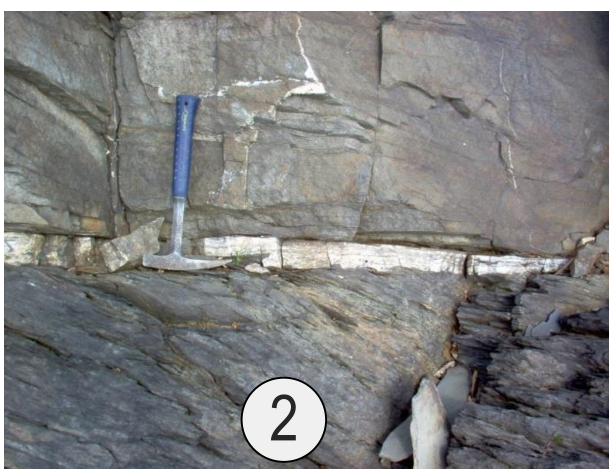
bedding-normal collapse



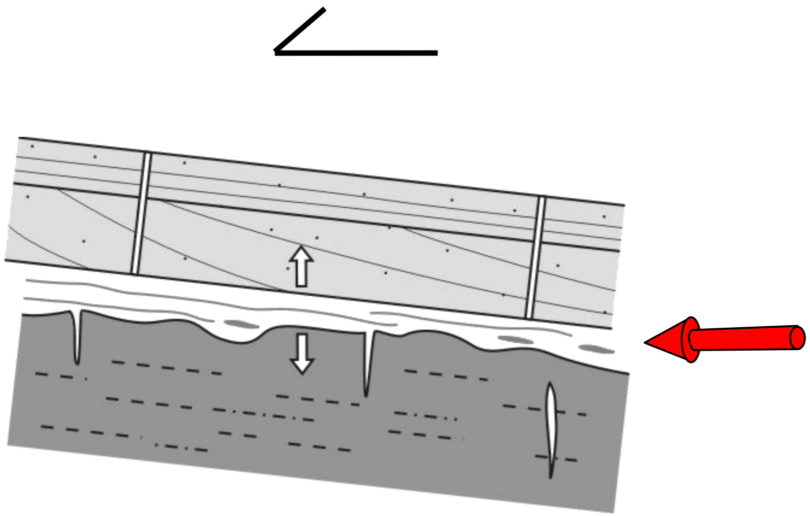
Kinematic model

overall fold-and-cleavage development

Interbedded BPVs



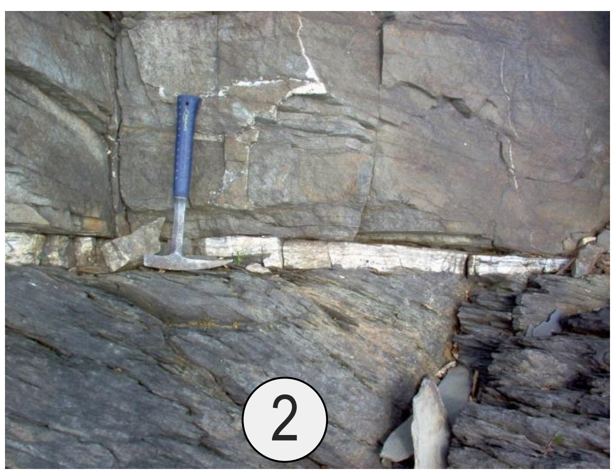
Intrabedded BPVs

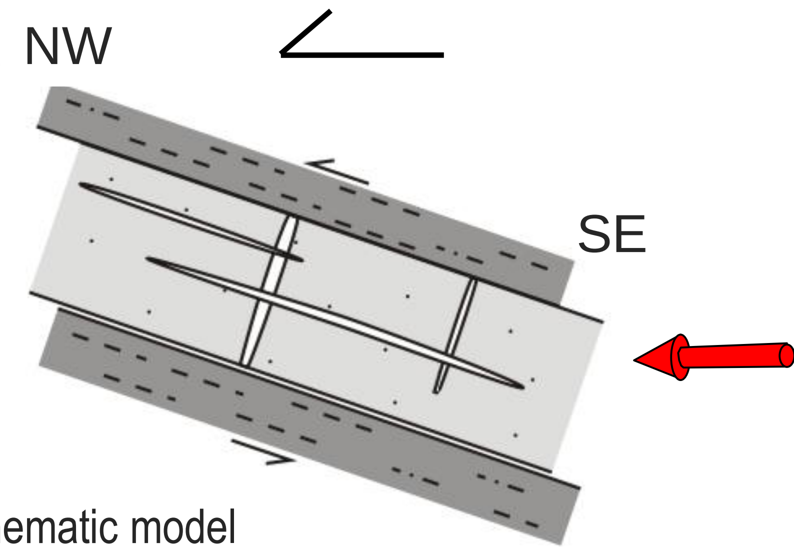


Kinematic model

bedding-normal uplift & bedding-parallel thrusting

Interbedded BPVs



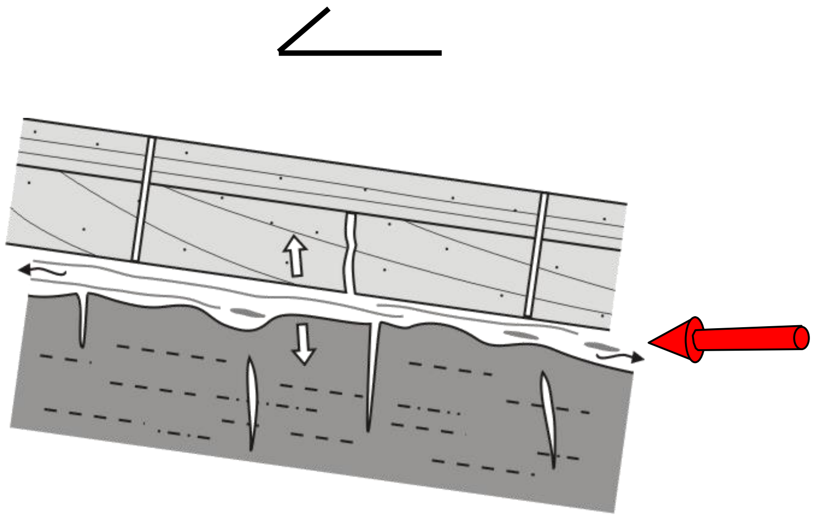


Kinematic model

overall fold-and-cleavage development

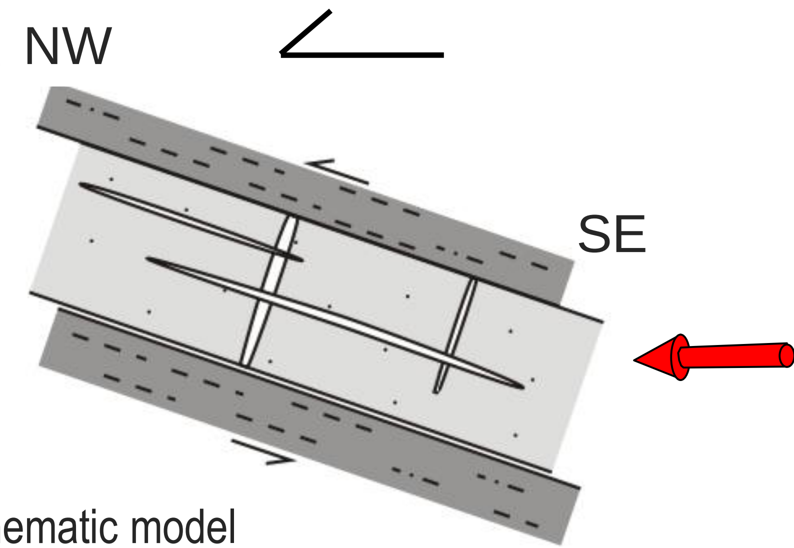
Intrabedded BPVs

Structural analysis - Interpretation



Kinematic model

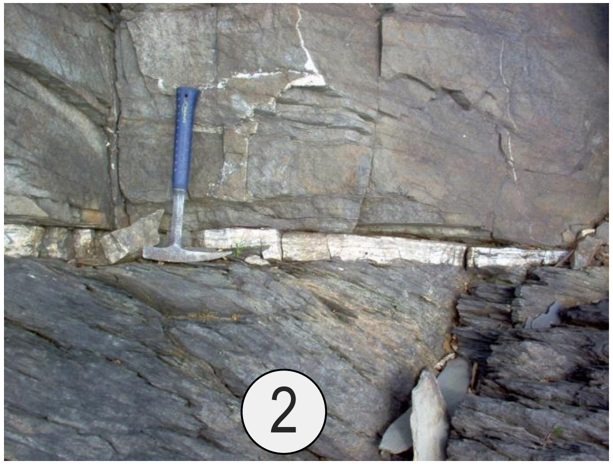
bedding-normal uplift & bedding-parallel thrusting



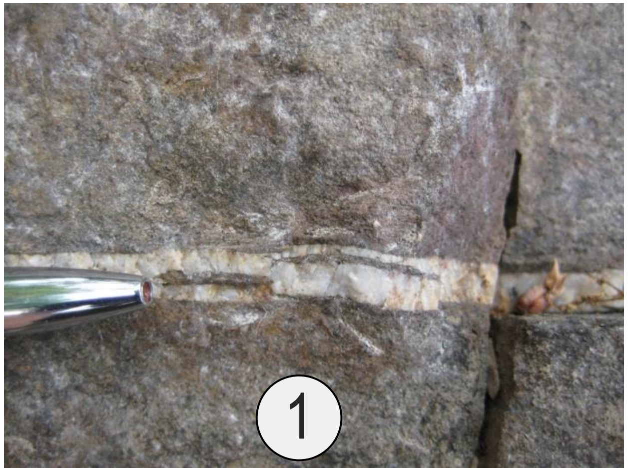
Kinematic model

overall fold-and-cleavage development

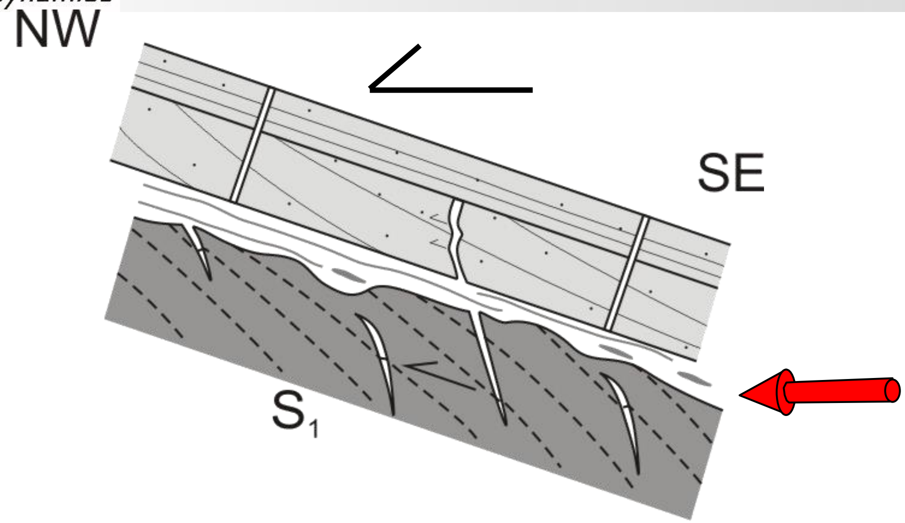
Interbedded BPVs



Intrabedded BPVs



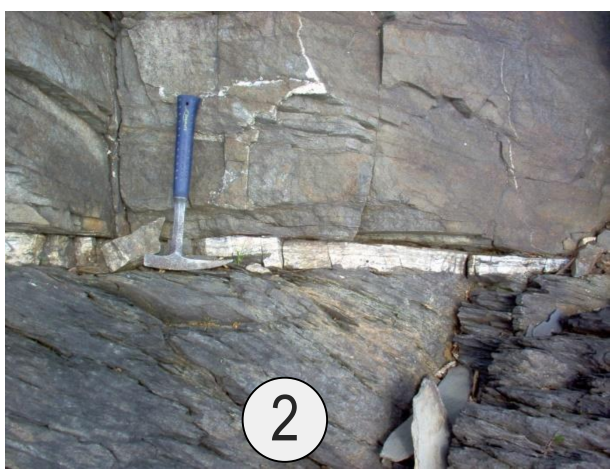
Structural analysis - Interpretation

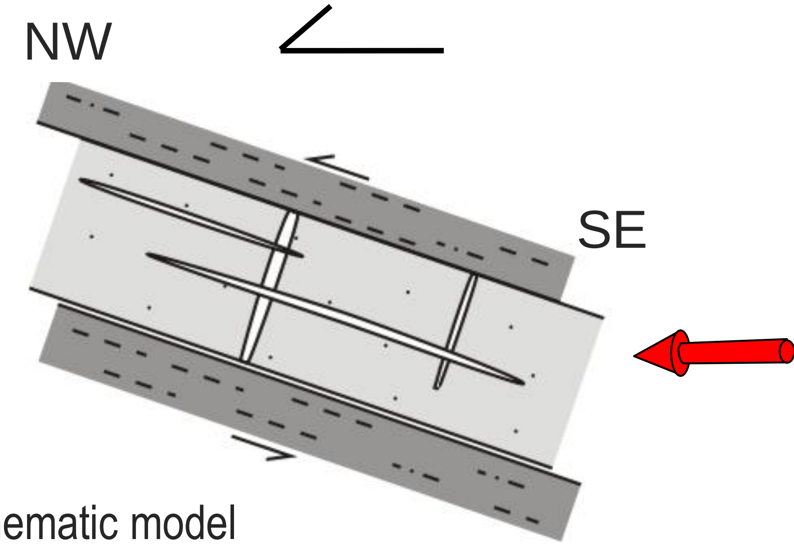


Kinematic model

overall fold-and-cleavage development

Interbedded BPVs



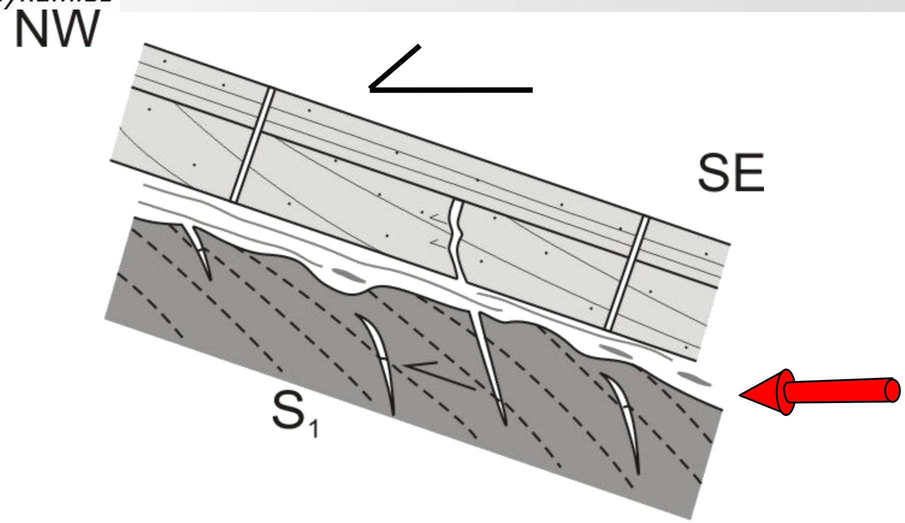


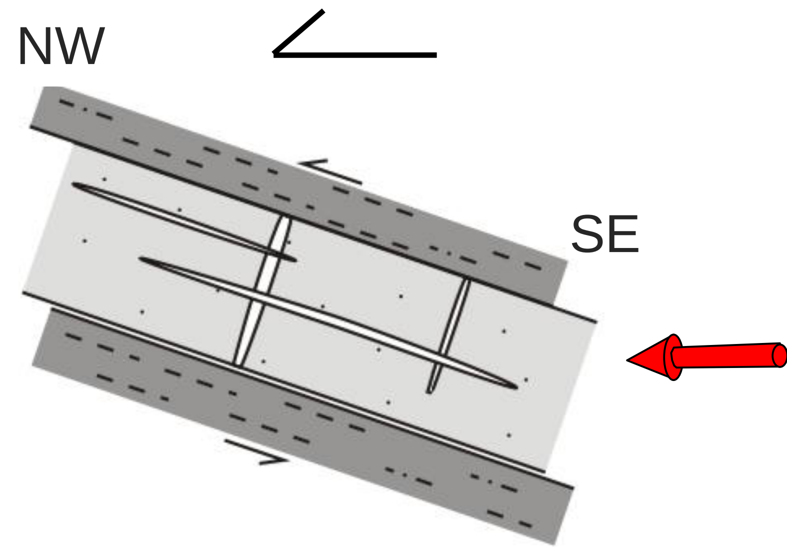
Kinematic model

overall fold-and-cleavage development

Intrabedded BPVs

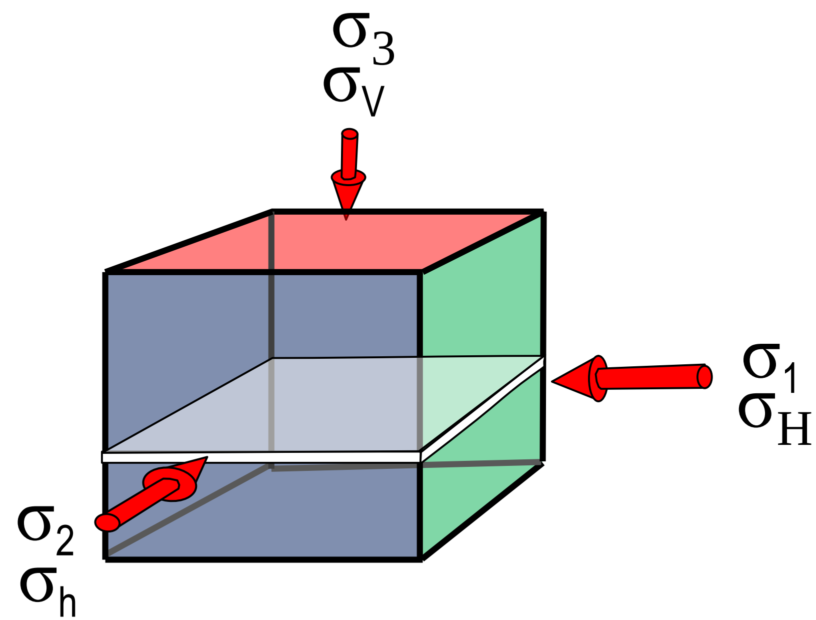
Structural analysis - Interpretation





Interbedded BPVs formed at the onset of folding

Intrabedded BPVs formed prior to folding or at the onset of folding



Extension to extensional-shear veins

σ_1-$\sigma_3 < 5.66T$

Low differential stresses

Extension veins

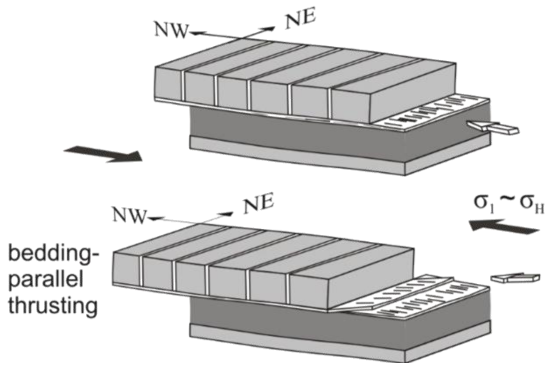
σ_1-$\sigma_3 < 4T$

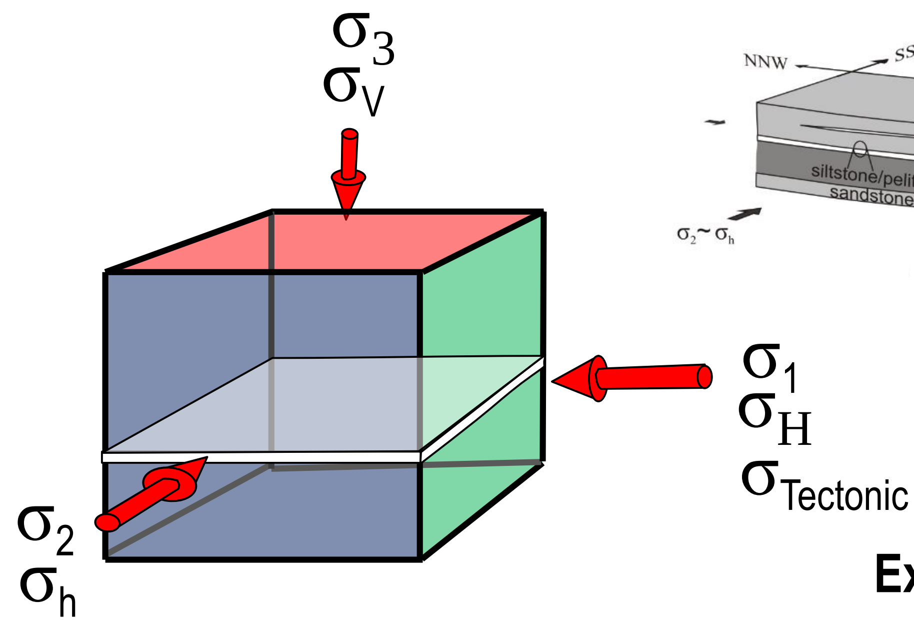
Low differential stresses

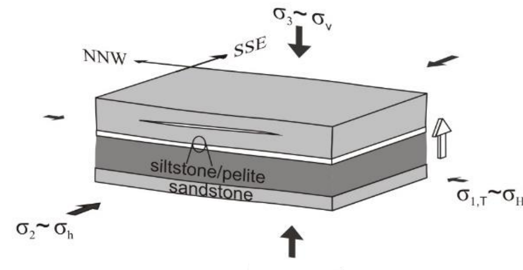
Interbedded BPVs formed at the onset of folding

Intrabedded BPVs formed prior to folding or at the onset of folding

Bedding-parallel veins - synthesis







Extension to extensional-shear veins

$\sigma_1 - \sigma_3 < 5.66T$

Low differential stresses

Extension veins

$\sigma_1 - \sigma_3 < 4T$

Low differential stresses

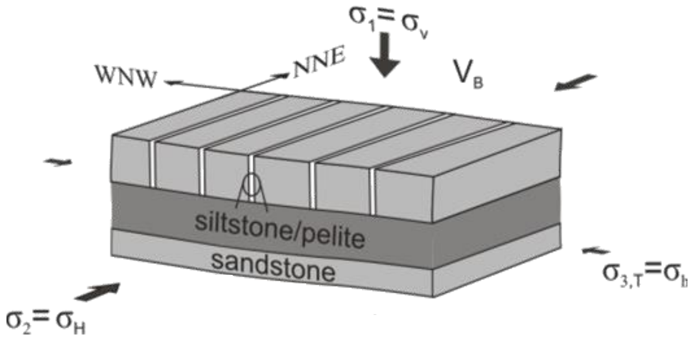
COMPRESSION – RELATED

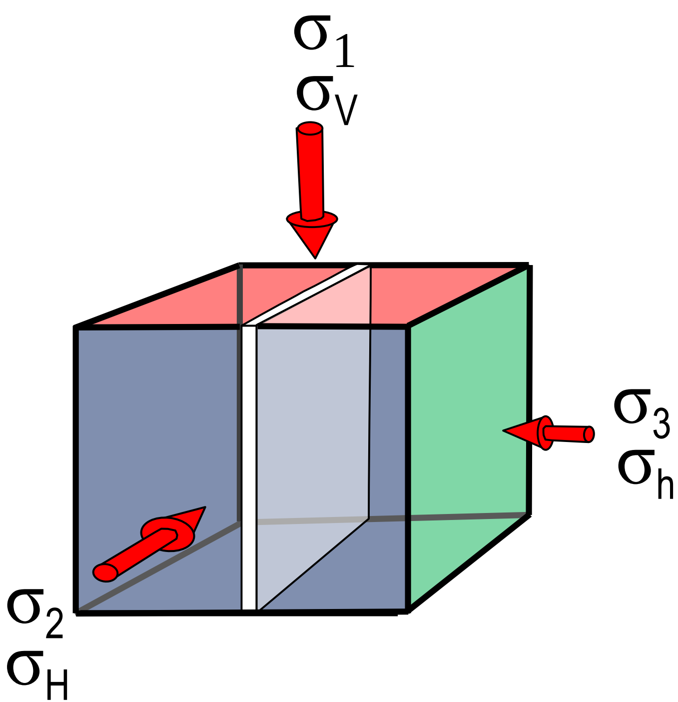
Interbedded BPVs formed at the onset of folding

Intrabedded BPVs formed prior to folding or at the onset of folding

EXTENSION

Bedding-normal veins





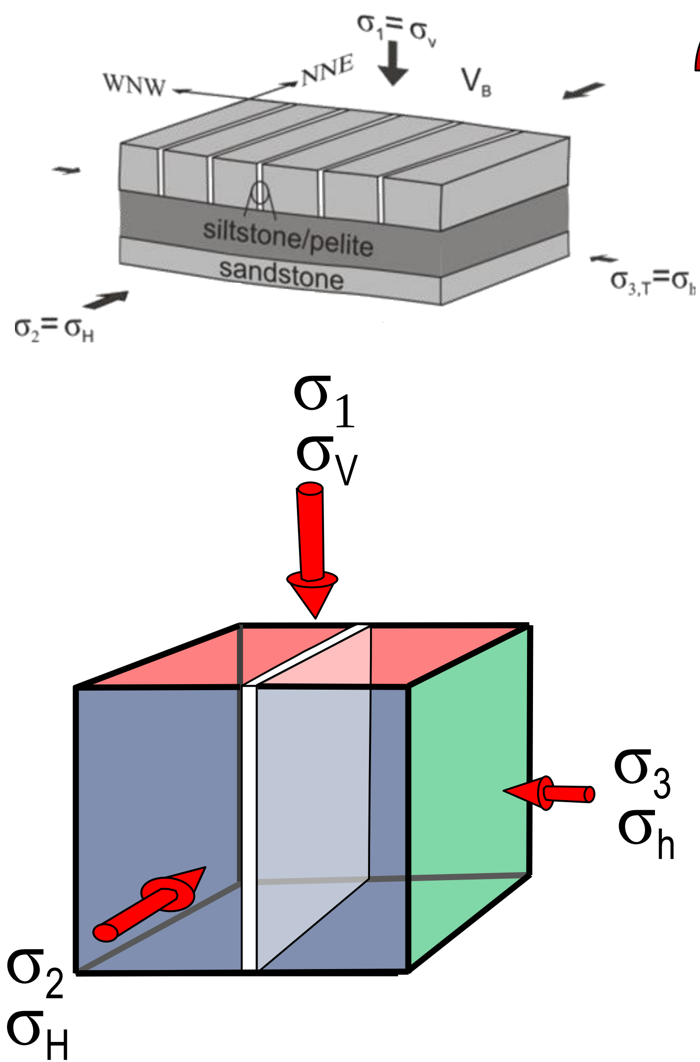
EXTENSION

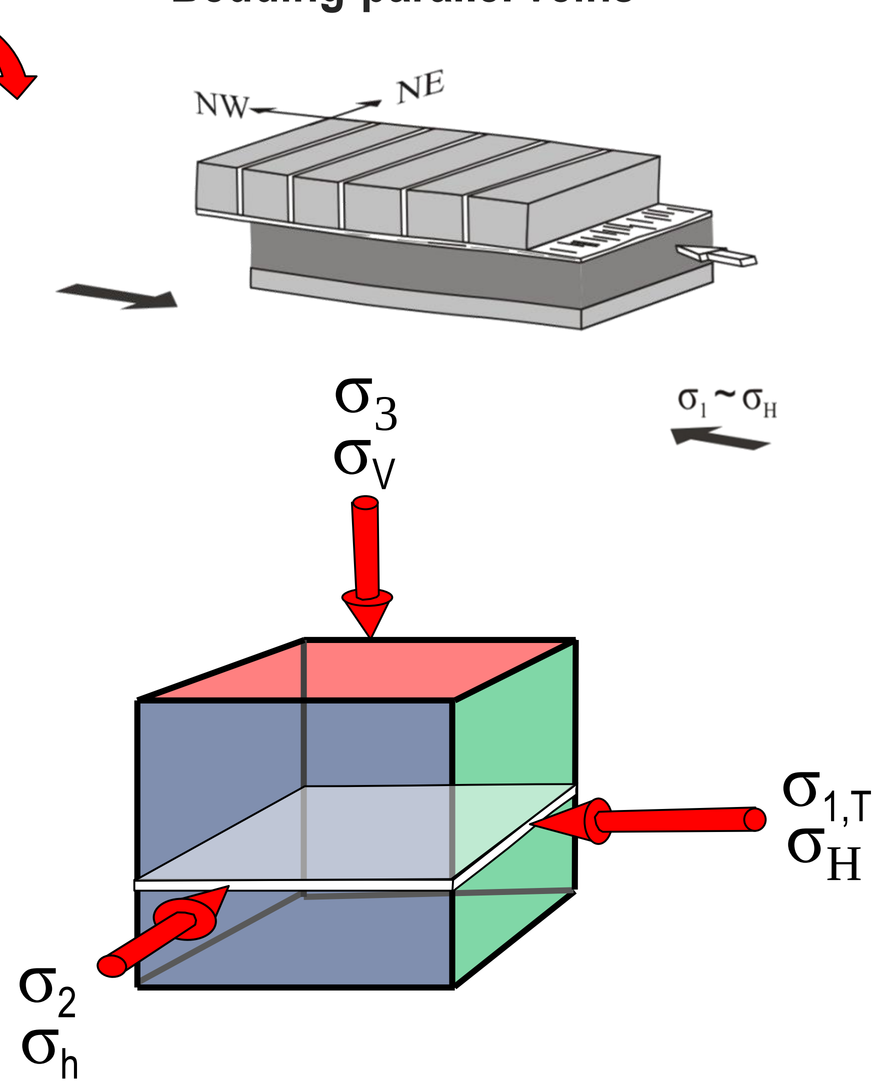
Bedding-normal veins

Tectonic inversion

COMPRESSION

Bedding-parallel veins



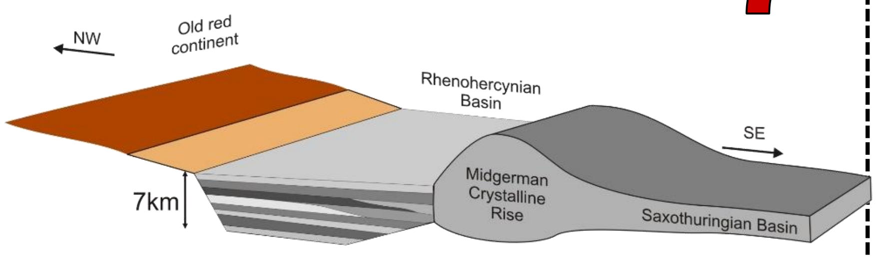


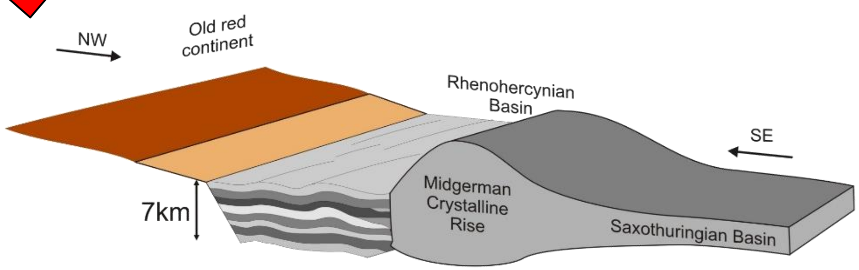
Stress-state evolution of the brittle upper crust

EXTENSION

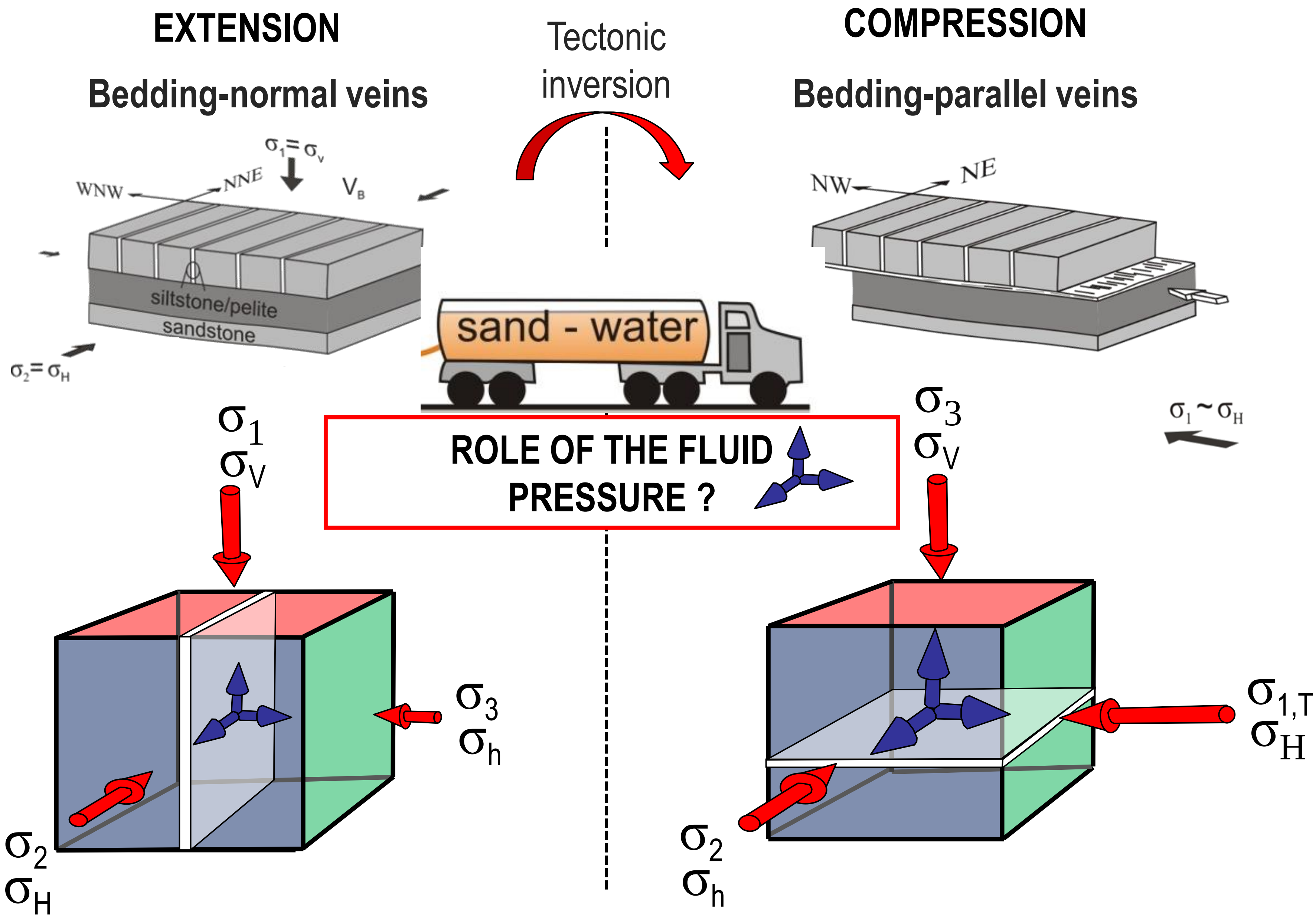
Variscan tectonic inversion

COMPRESSION

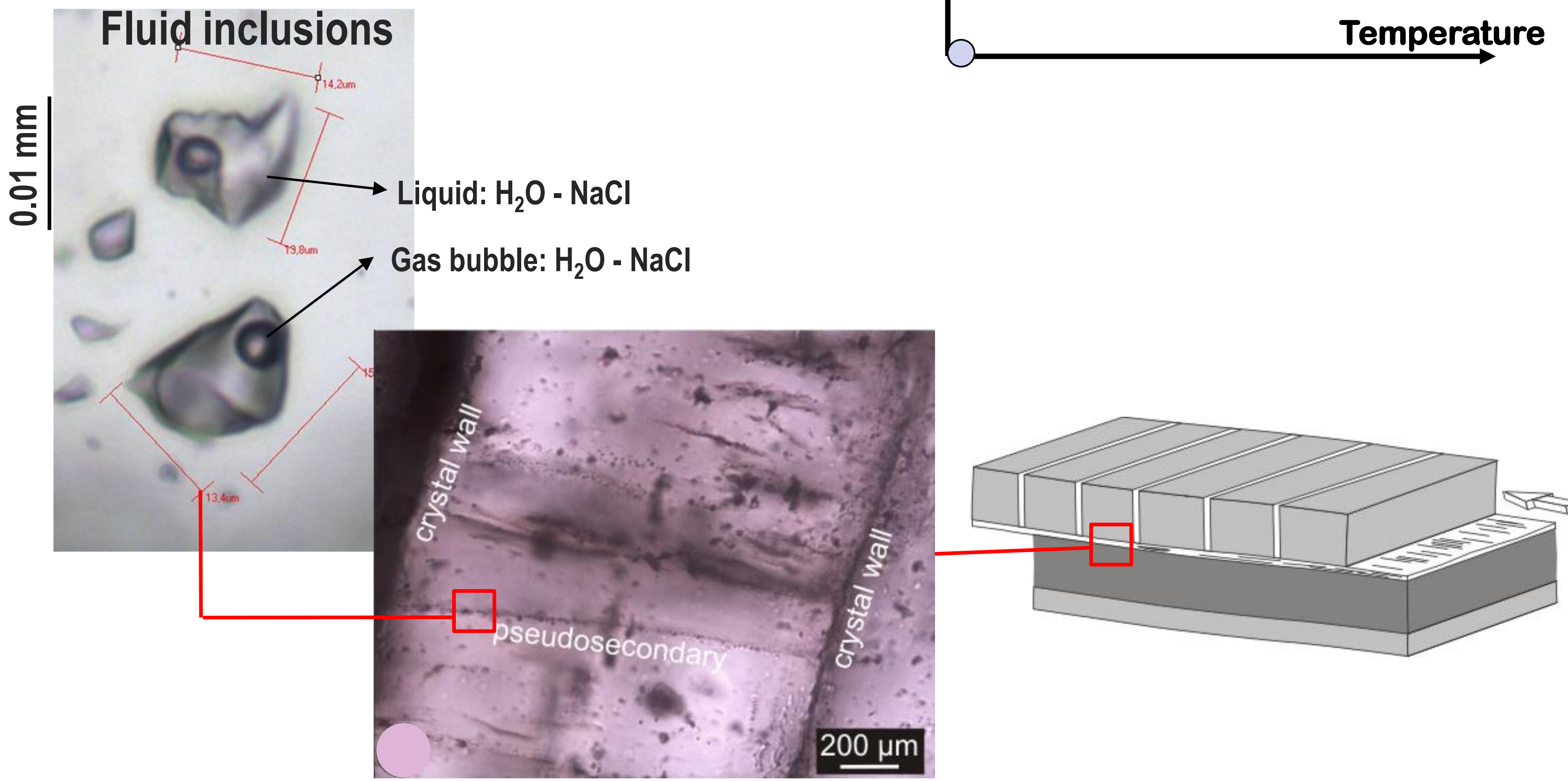


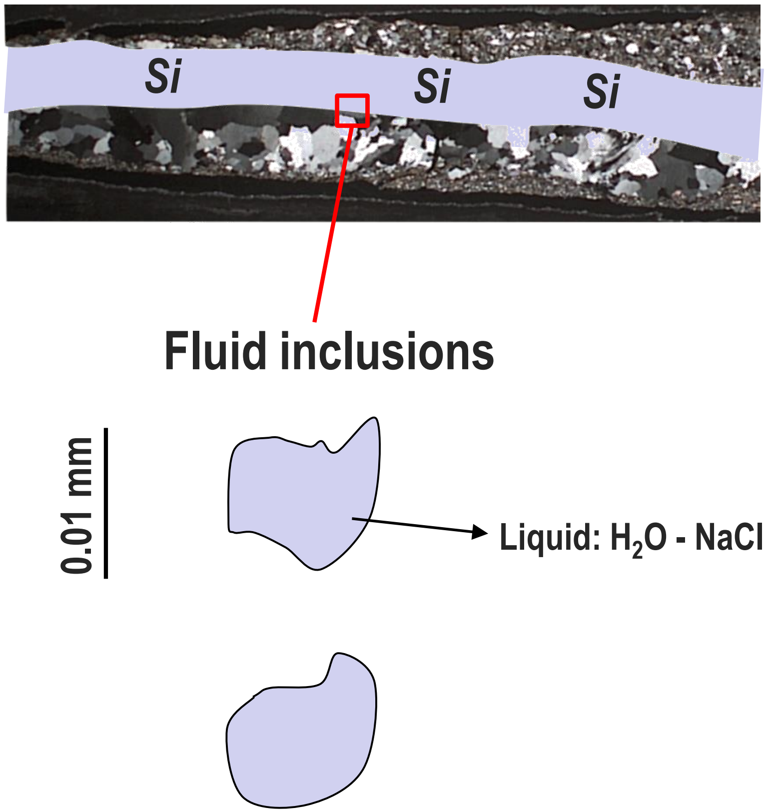


P-T conditions of vein formation

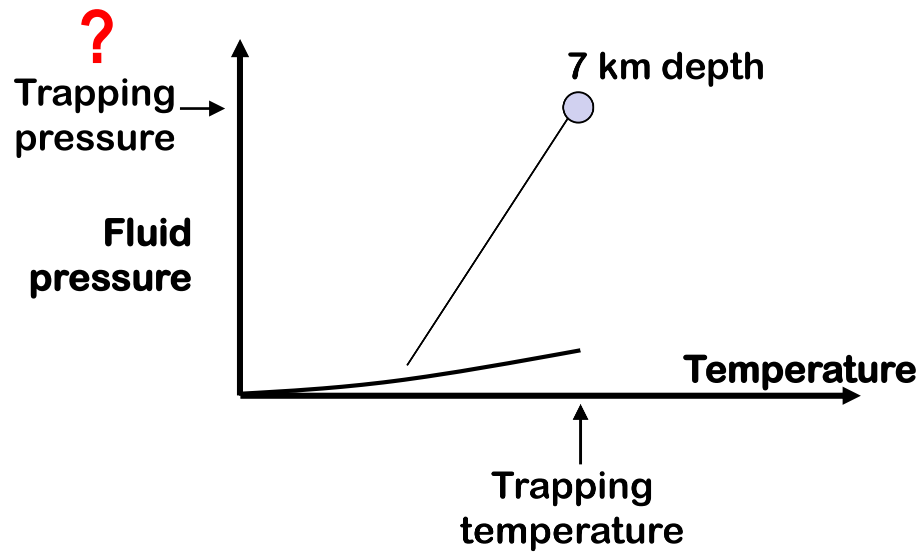


P-T conditions of vein formation

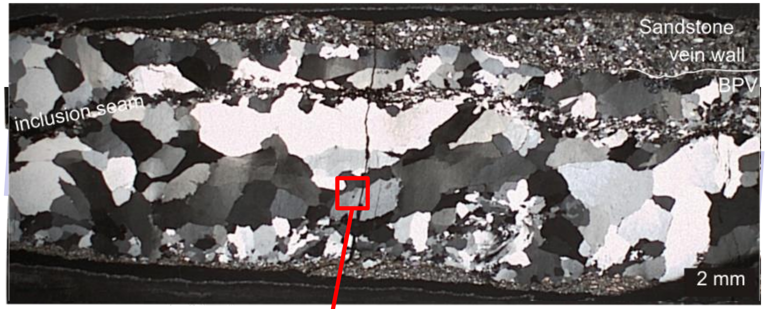




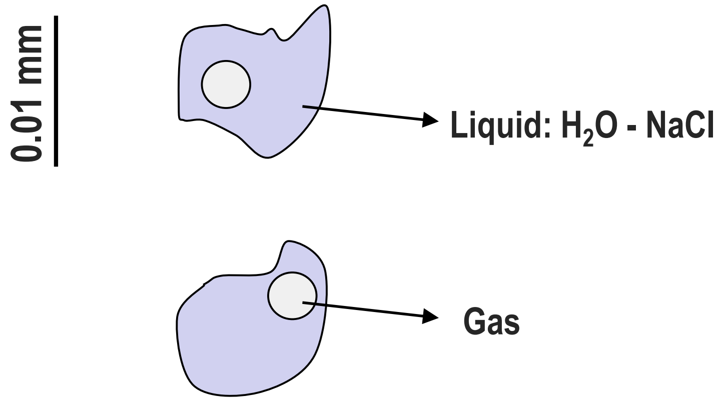
Constant volume of fluid inclusion



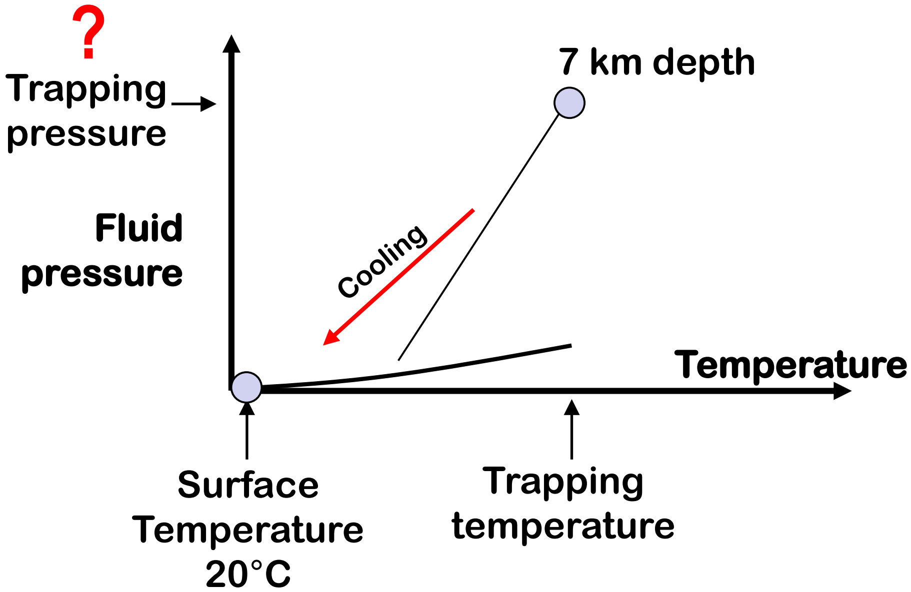
P-T conditions of vein formation



Fluid inclusions

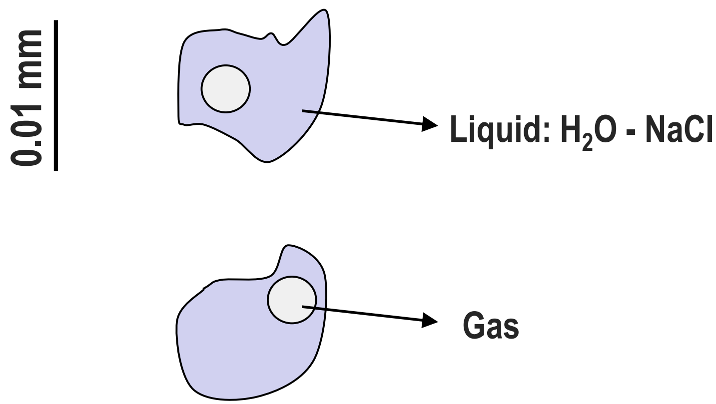


Constant volume of fluid inclusion

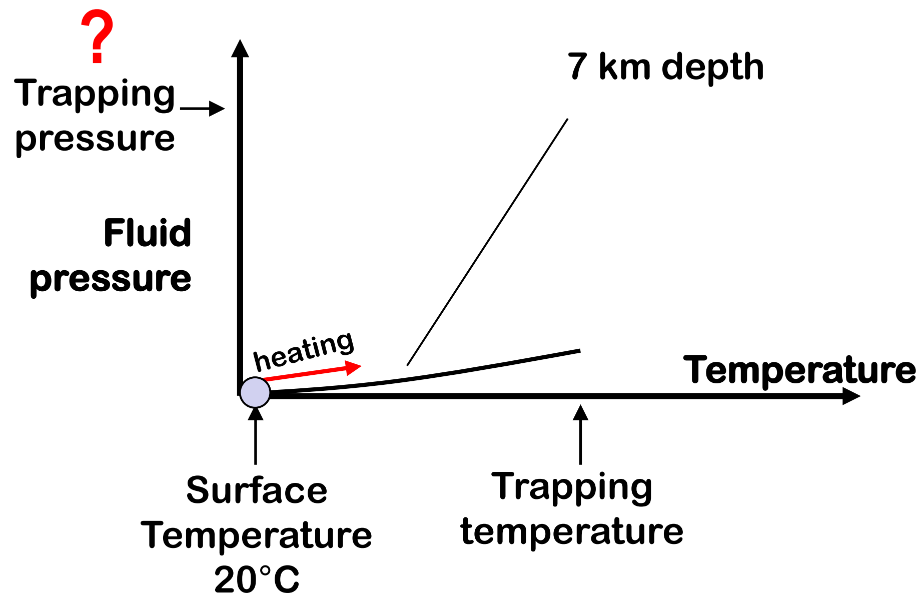


P-T conditions of vein formation

Fluid inclusions



Constant volume of fluid inclusion

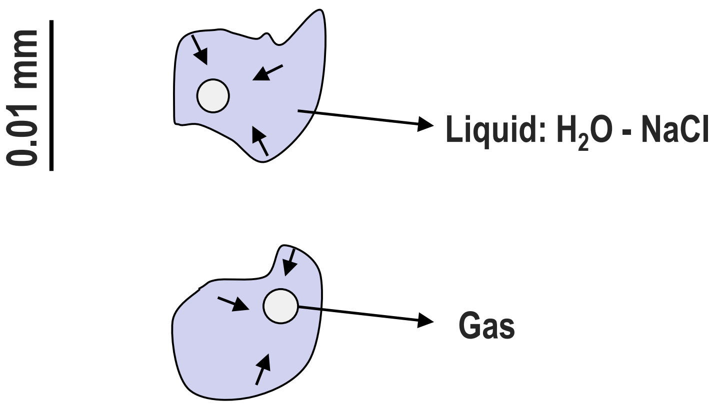


Microthermometry

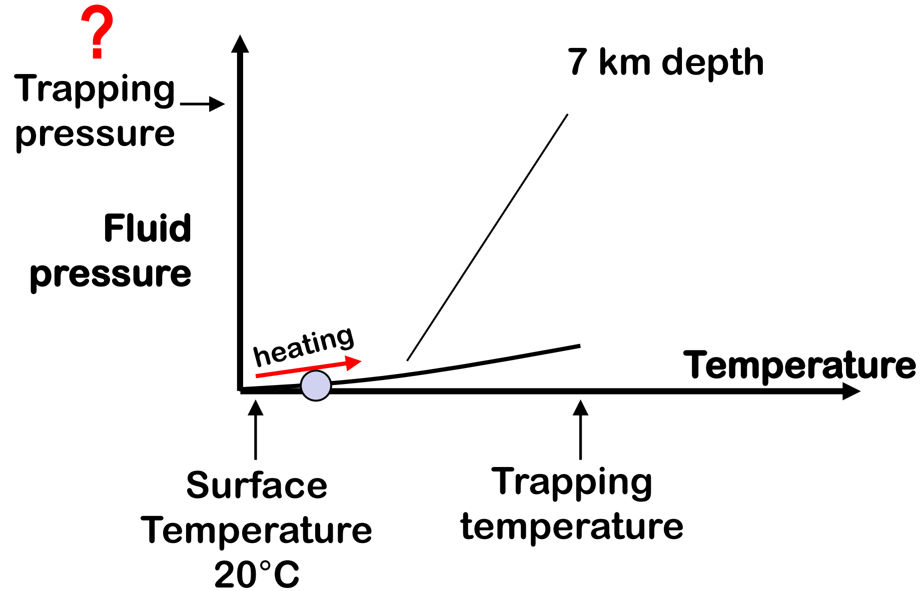
Laboratory 200C K.U.Leuven – dark room

P-T conditions of vein formation

Fluid inclusions



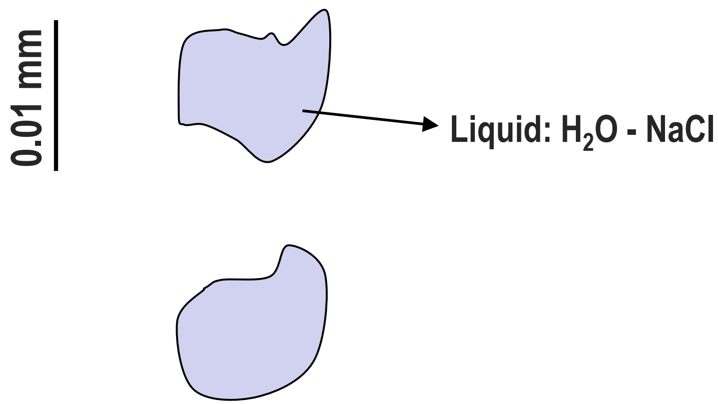
Constant volume of fluid inclusion



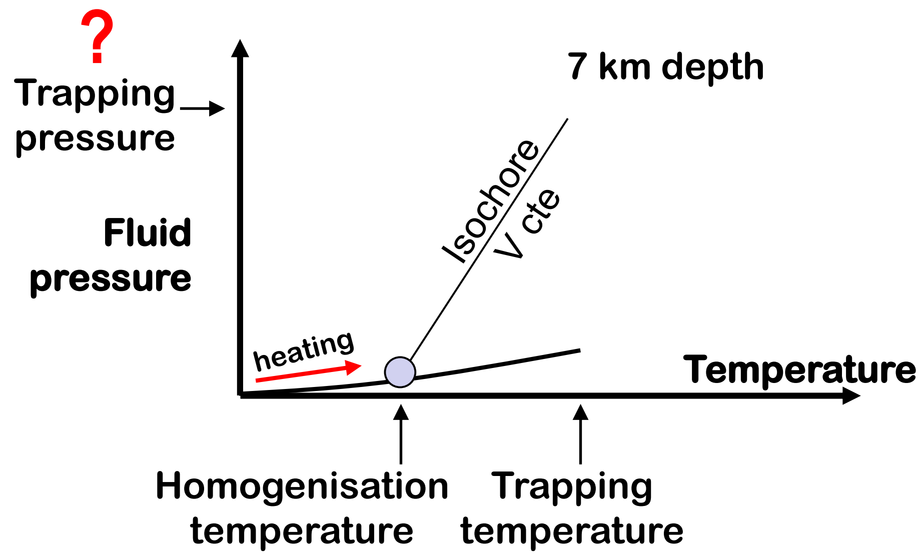
Microthermometry

P-T conditions of vein formation

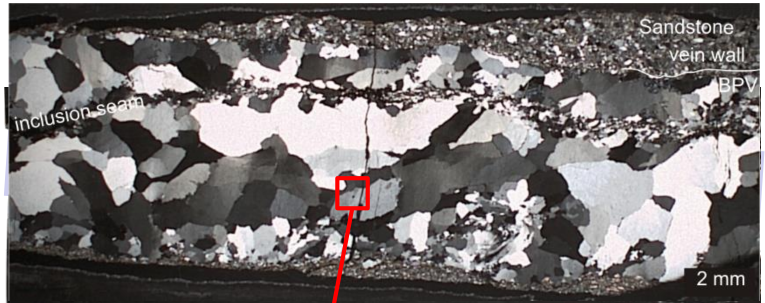
Fluid inclusions



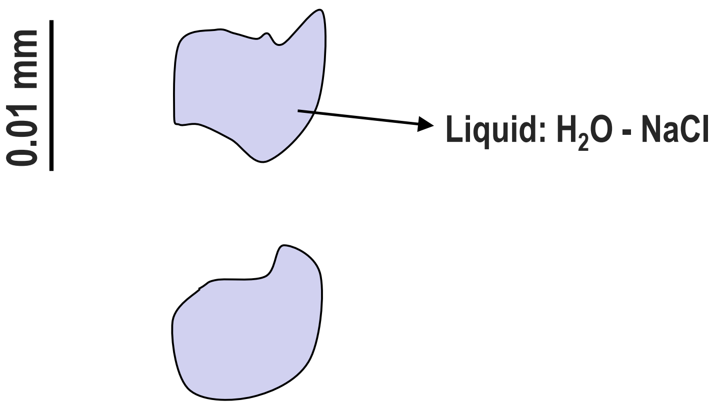
Constant volume of fluid inclusion



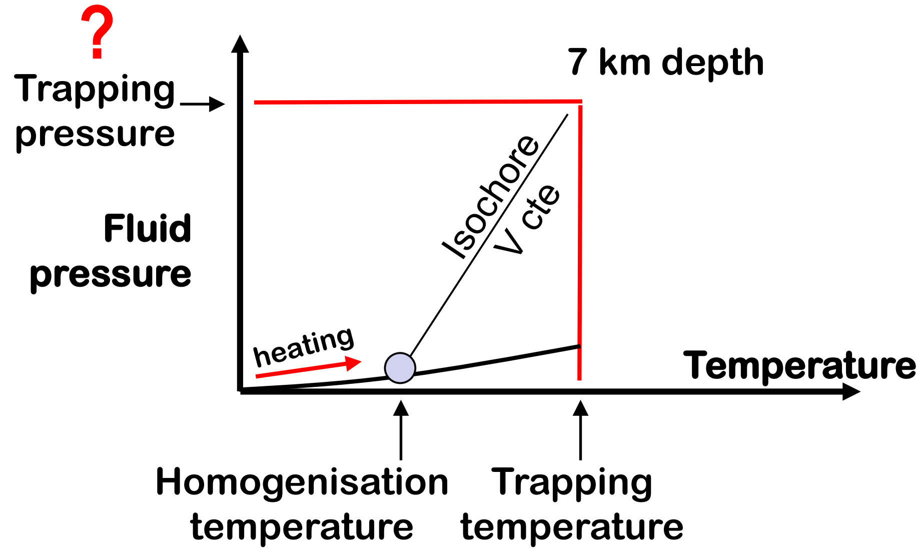
Microthermometry



Fluid inclusions



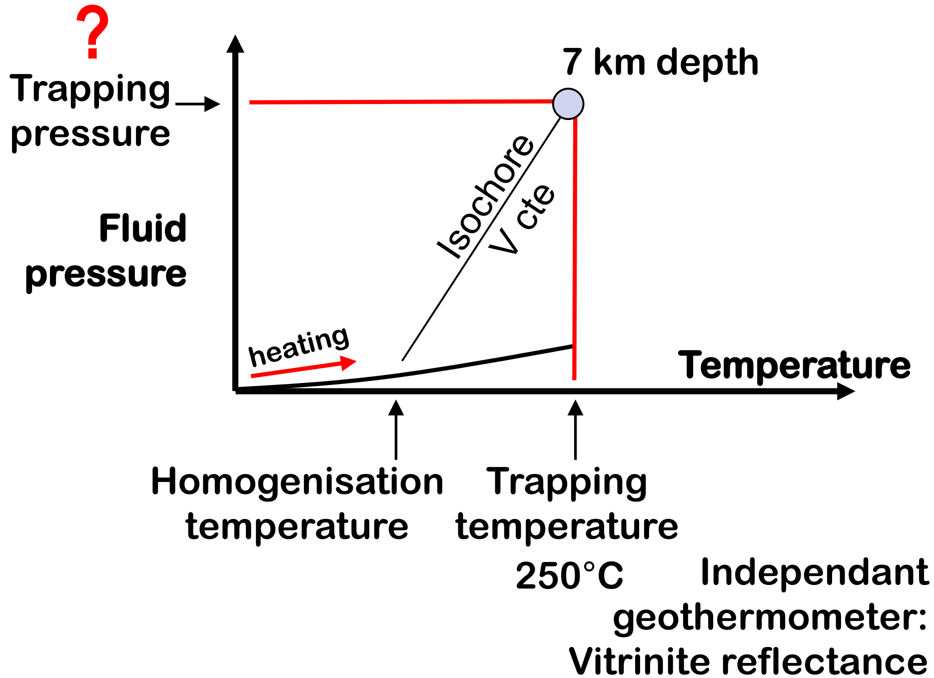
Constant volume of fluid inclusion



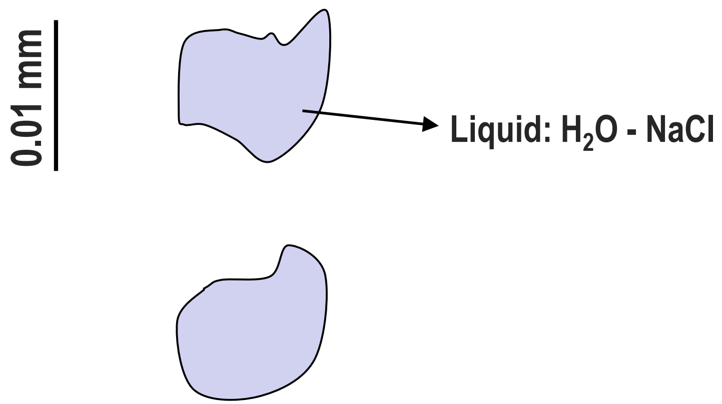
Independant geothermometer: Vitrinite reflectance

Microthermometry

P-T conditions of vein formation



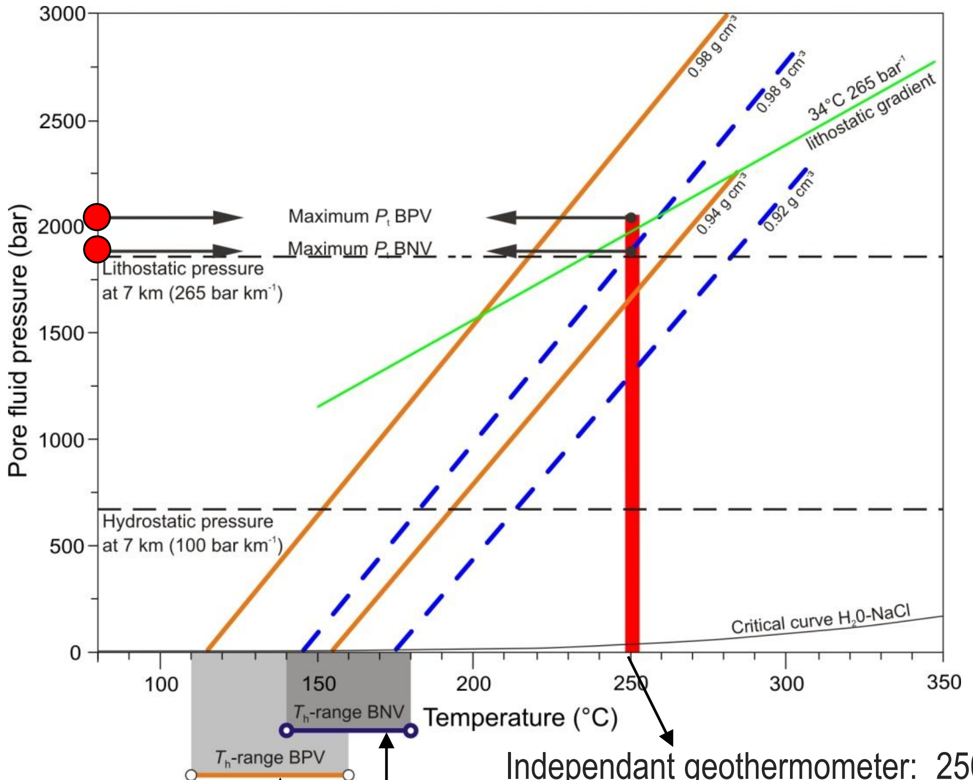
Fluid inclusions



Constant volume of fluid inclusion

Microthermometry

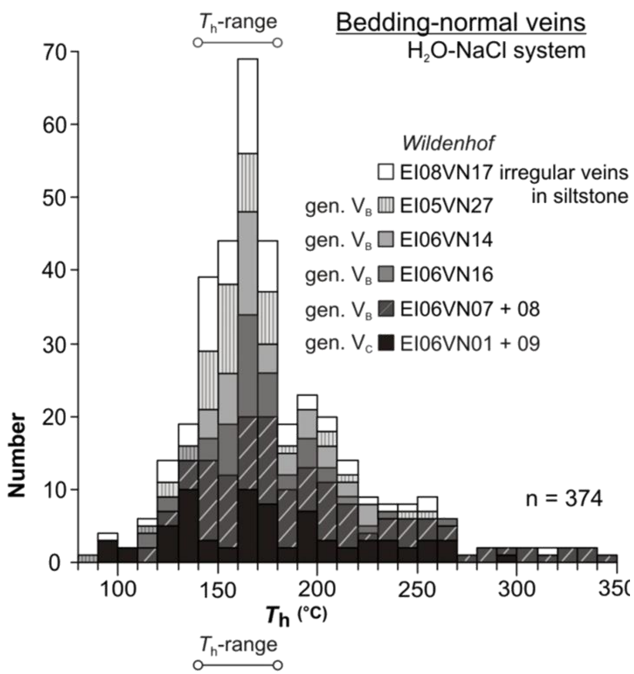
P-T conditions of vein formation

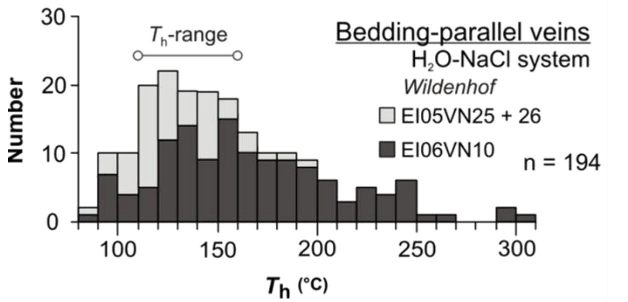


Independant geothermometer: 250°C vitrinite reflectance

Bedding-normal veins
$P_{f\ max}$ 1900 bar

Bedding-parallel veins
$P_{f\ max}$ 2050 bar

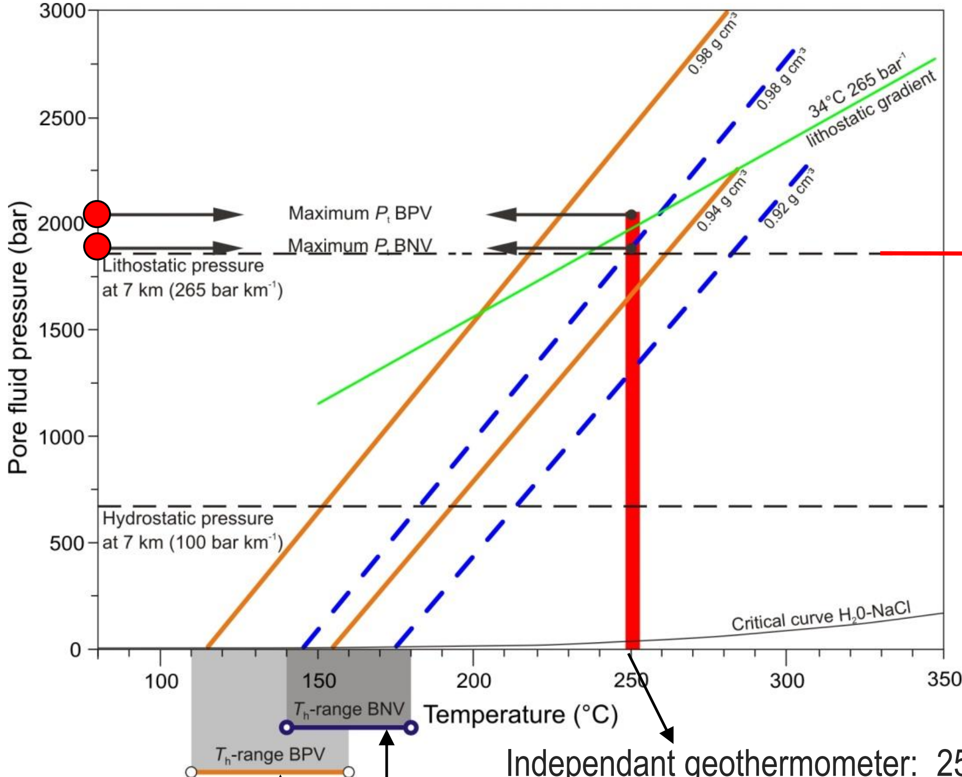




Homogenisation temperatures

Van Noten *et al.* 2011, Geol. Soc. London 168

P-T conditions of vein formation



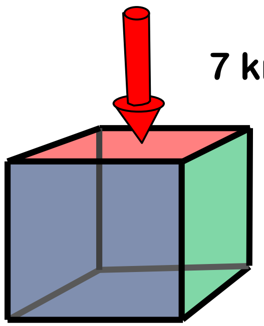
Independant geothermometer: 250°C
vitrinite reflectance

Bedding-normal veins
$P_{f\ max}$ 1900 bar = lithostatic fluid pressure

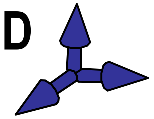
Bedding-parallel veins
$P_{f\ max}$ 2050 bar = supralithostatic fluid pressure

Lithostatic fluid pressure =
Load of overlying rock column

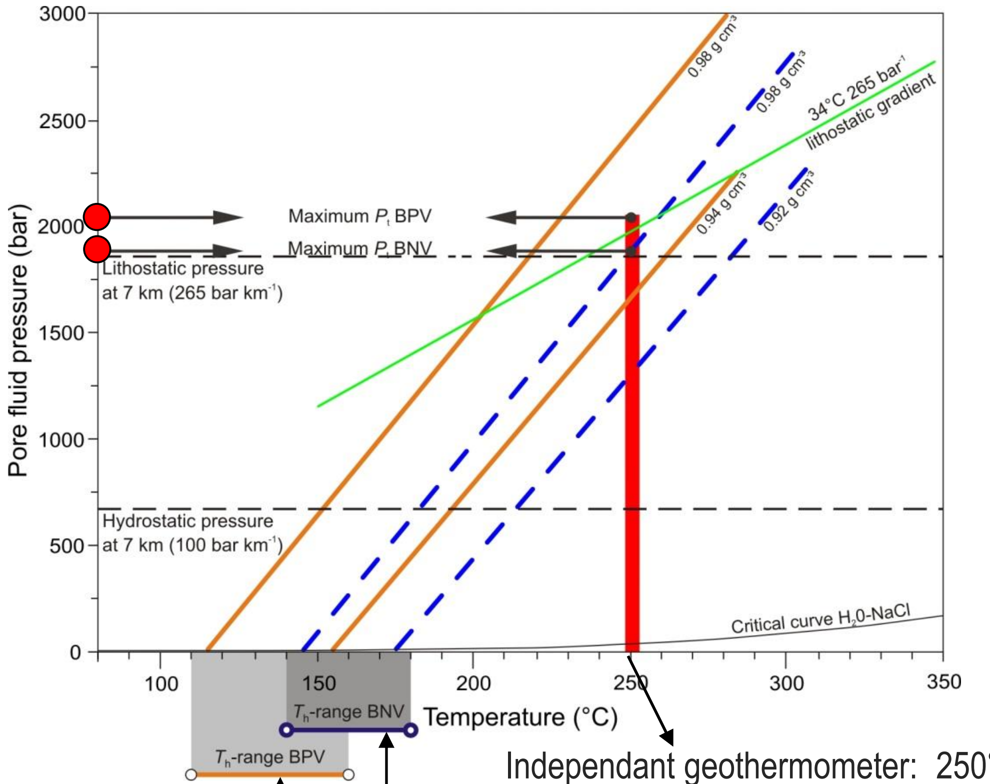
Lithostatic fluid pressure =
7 km * 265 bar /km = 1855 bar



ROLE OF THE FLUID PRESSURE ?



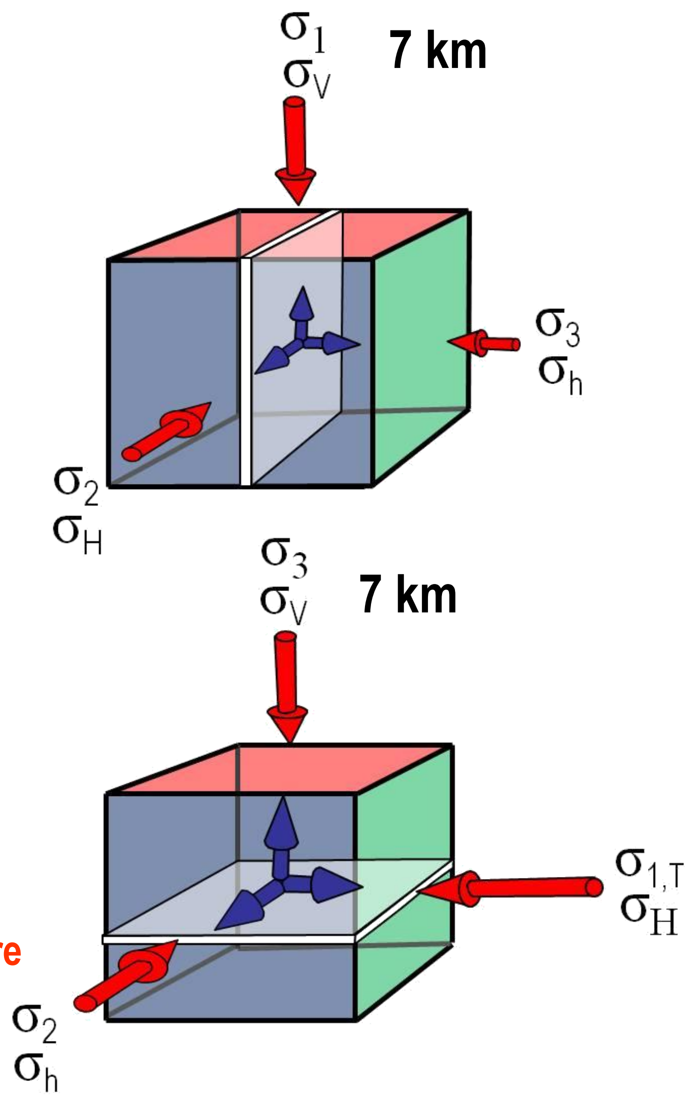
P-T conditions of vein formation



Independant geothermometer: 250°C
vitrinite reflectance

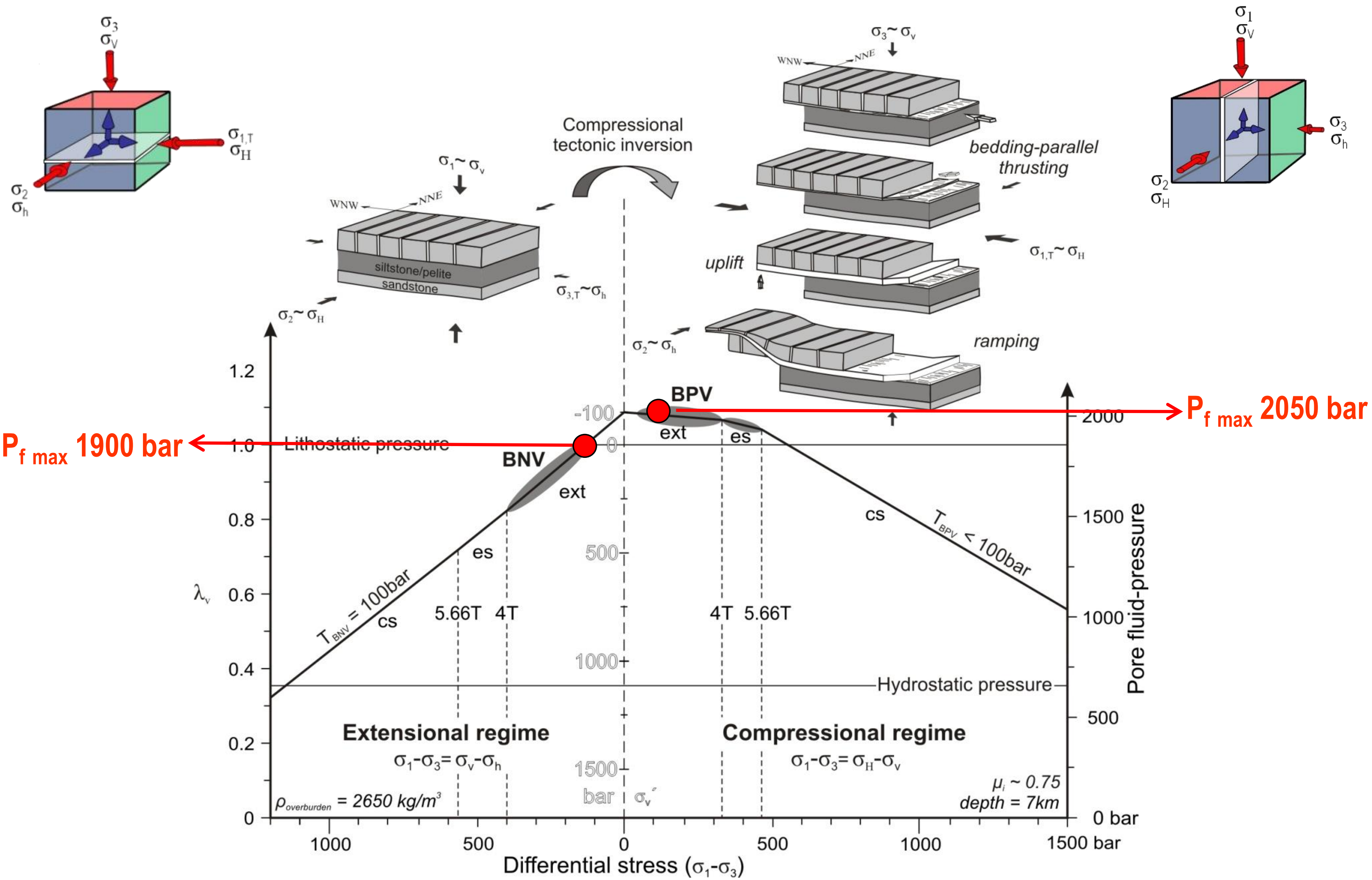
Bedding-normal veins
$P_{f\ max}$ 1900 bar = lithostatic fluid pressure

Bedding-parallel veins
$P_{f\ max}$ 2050 bar = supralithostatic fluid pressure



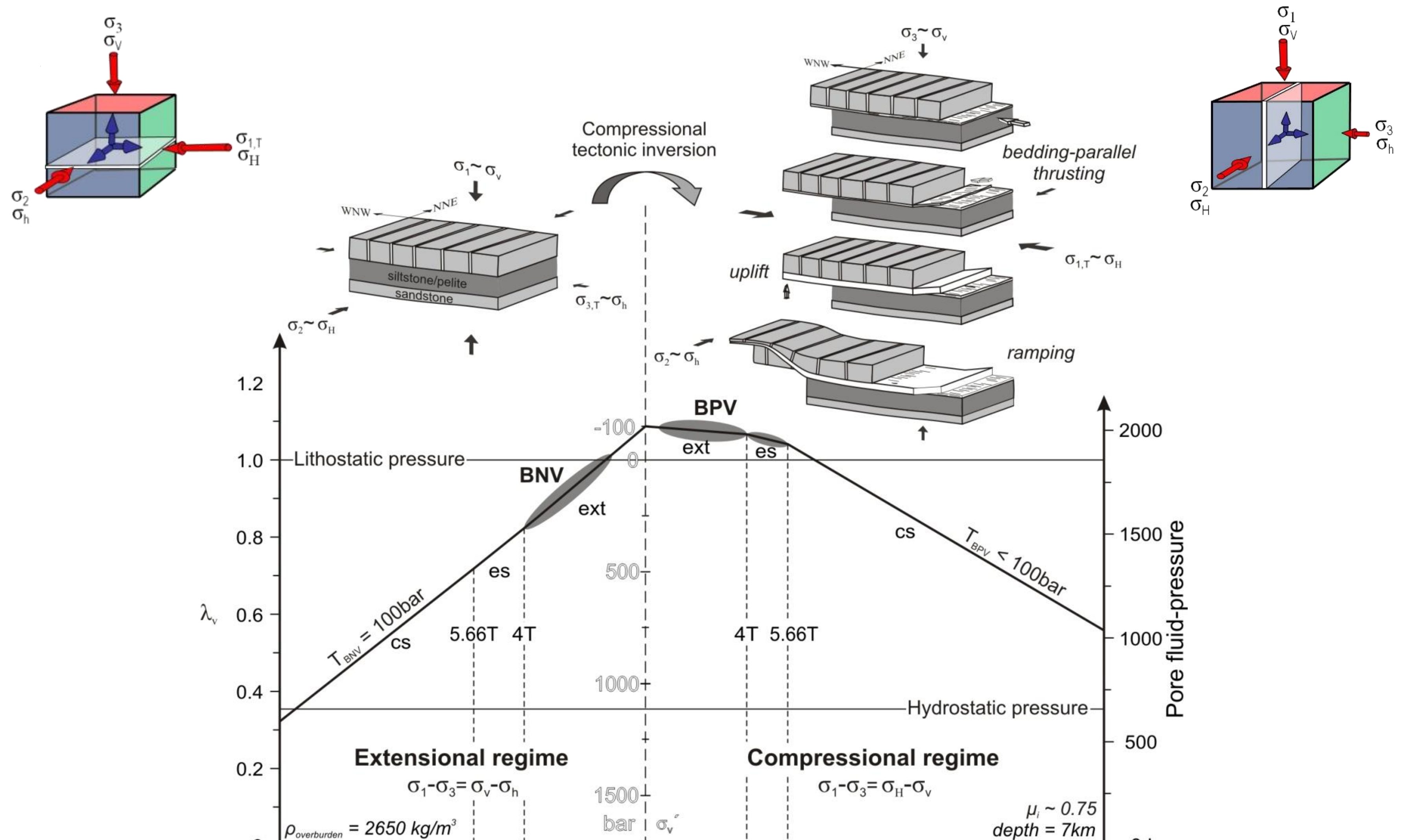
ROLE OF THE FLUID PRESSURE ?

Conclusions



Brittle failure mode plots
e.g. Sibson 1998, 2004
Cox 2010

Van Noten *et al.* 2011, Geol. Soc. London 168
Van Noten *et al.* 2012, Spec. Pub. Geol. Soc. London 367



Final conclusion : Tectonic inversion are crucial timing to sustain lithostatic fluid pressures and to allow hydraulic fracturing !!

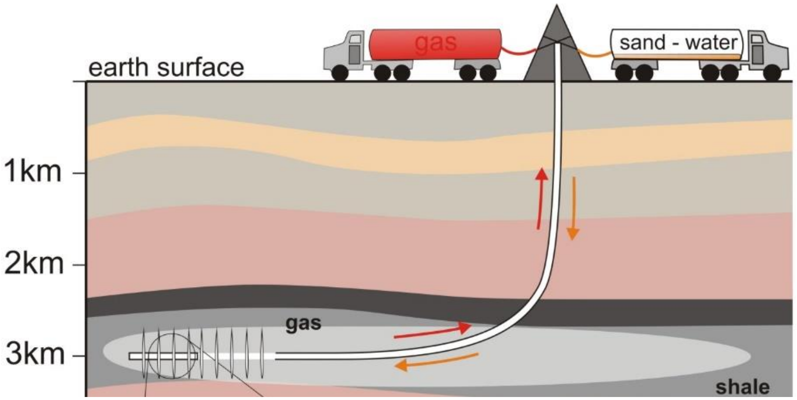
→ important for the prediction of ore deposits.

Conclusions

1. The naturally fractured Ardenne-Eifel basin at the onset of Variscan orogeny can serve as possible analogue to present reservoirs by its extent of overpressuring, both in time as in thickness of sequences that are affected by overpressures.

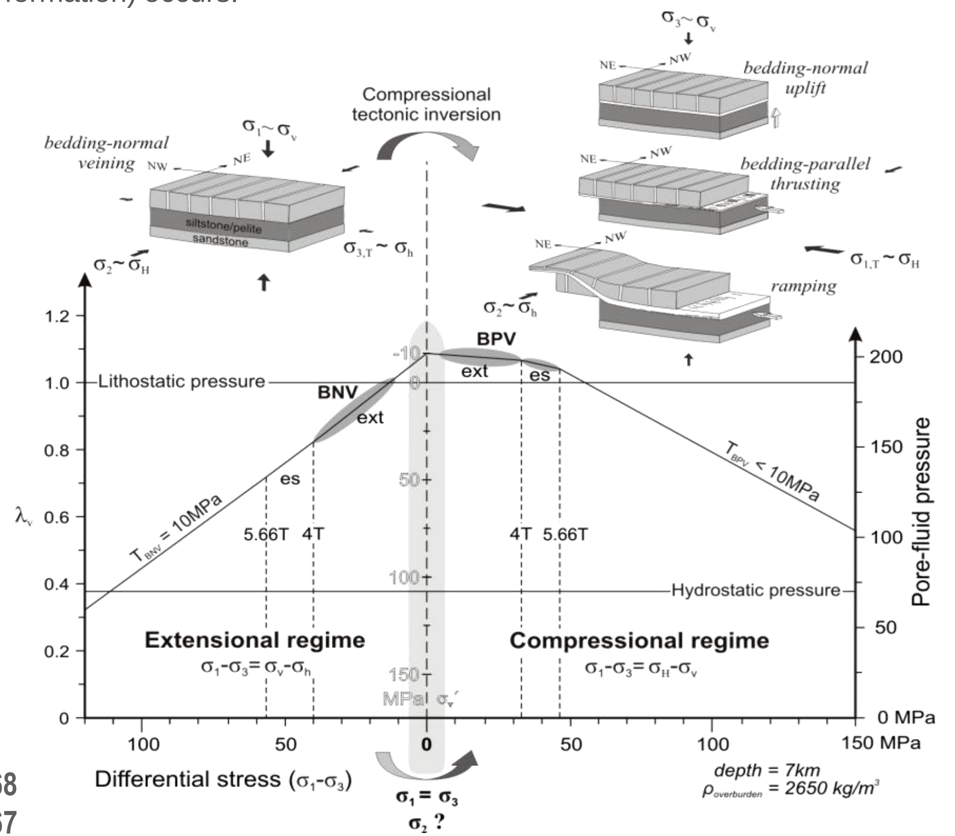
2. More importantly, this research has shown that a tectonic inversion from extension to compression is the crucial timing during which overpressures can be sustained, which was, up to date, only demonstrated by theoretical studies.

3. As result, tectonic inversions turn out to be promising periods in the orogenic cycle during which important fluid enhancement (vein formation) occurs.



Hydraulic fracturing ?

Degree of overpressuring?	Lithostatic
Fracture orientation ?	Vertical before inversion
Fracture orientation ?	Horizontal after inversion
Timing ?	TECTONIC INVERSIONS!



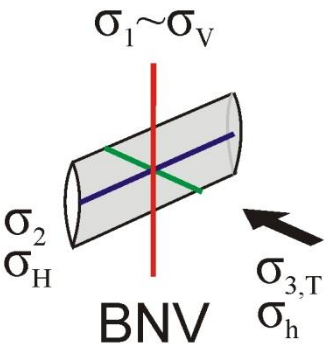
4. Owing to this intimate relationship between fluid redistribution and changes in stress regimes, these tectonic inversions might be important for the genesis of ore deposits.

Perspectives: Tectonic inversions are **more complex** than classically represented. Although structures related to the transitional wrench tectonic regime have not been reported during inversion, this stage contributes to the fluid enhancement during inversion.

Van Noten *et al.* 2011, Geol. Soc. London 168
Van Noten *et al.* 2012, Spec. Pub. Geol. Soc. London 367

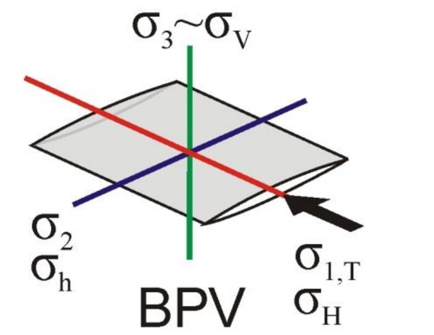
Extensional regime

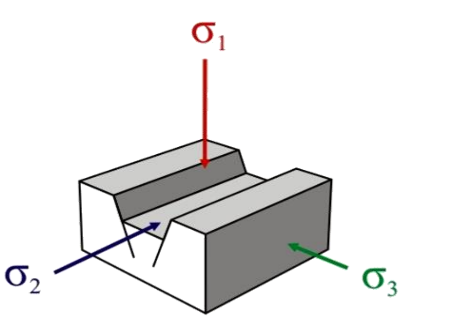
$\sigma_1 - \sigma_3 = \sigma_v - \sigma_h$



Compressional regime

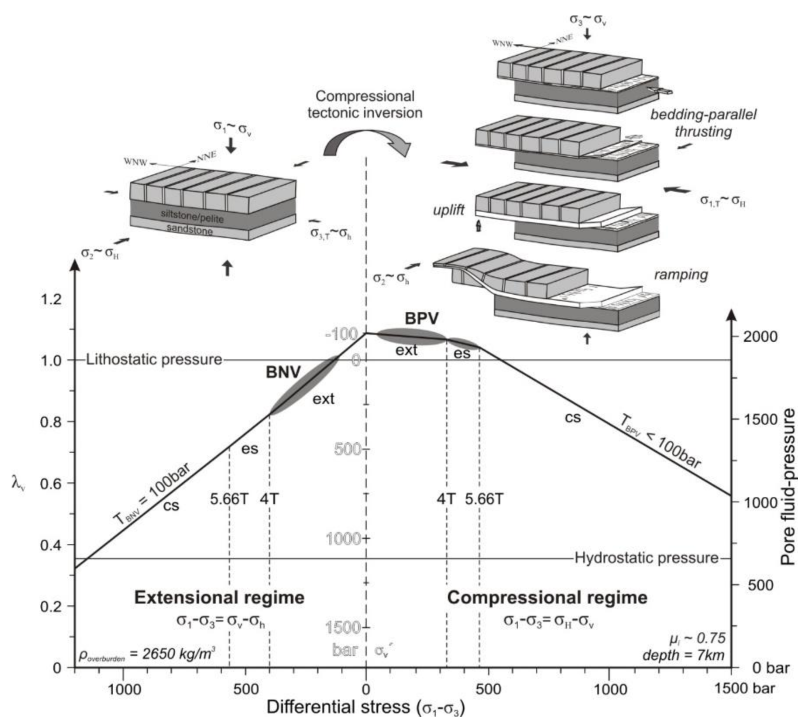
$\sigma_1 - \sigma_3 = \sigma_H - \sigma_v$

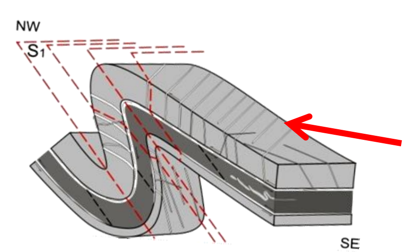


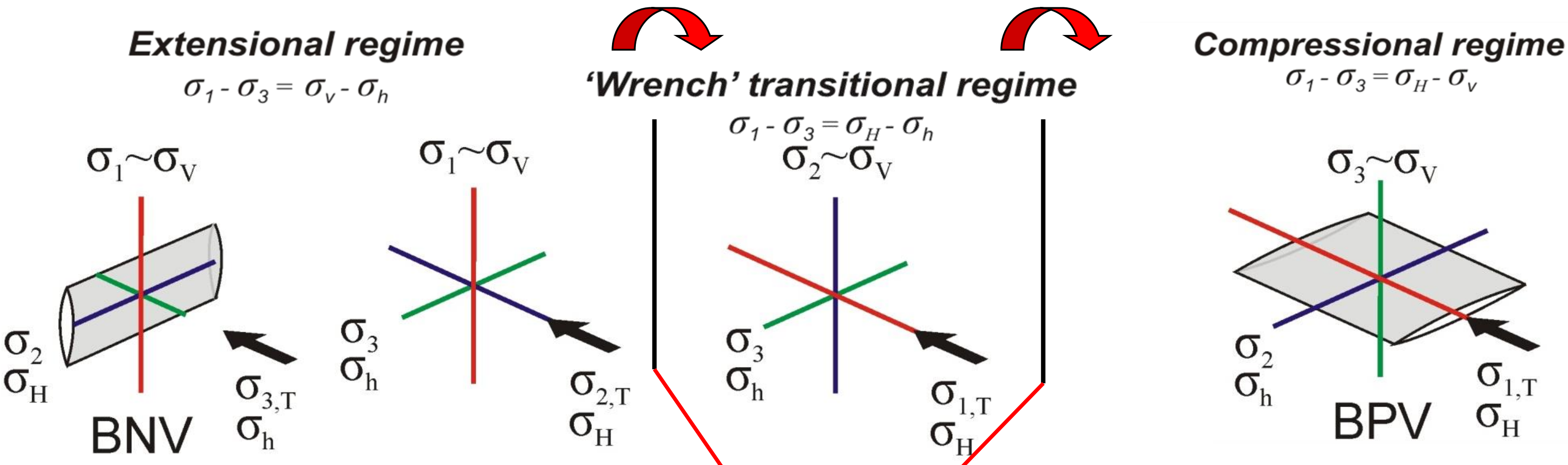


$\sigma_1 = \sigma_V$ $\sigma_1 > \sigma_2 > \sigma_3$

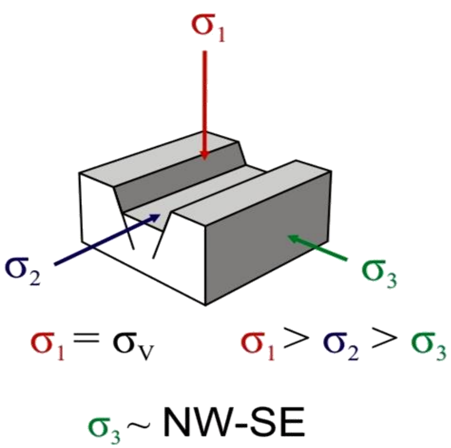
$\sigma_3 \sim$ NW-SE



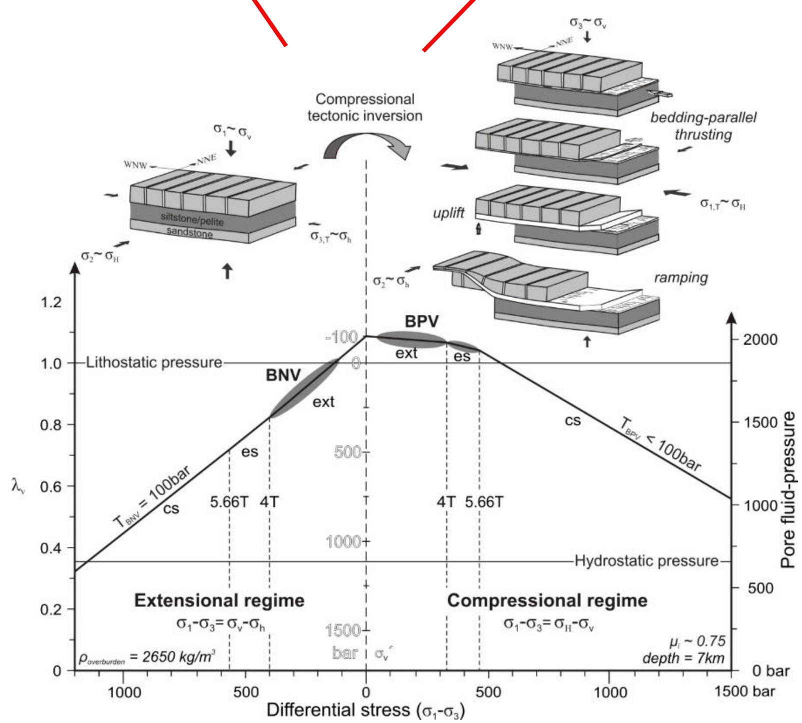




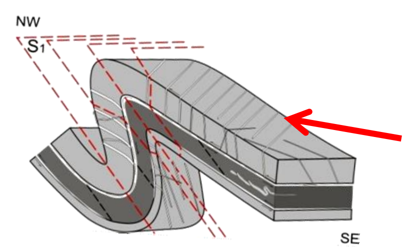
Extensional regime
σ1 - σ3 = σv - σh
'Wrench' transitional regime
σ1 - σ3 = σH - σh
Compressional regime
σ1 - σ3 = σH - σv
σ1~σV
σ2 σH
σ3,T σh
BNV
σ1~σV
σ3 σh
σ2,T σH
σ2~σV
σ3 σh
σ1,T σH
σ3~σV
σ2 σh
σ1,T σH
BPV



σ1
σ2
σ3
σ1 = σV
σ1 > σ2 > σ3
σ3 ~ NW-SE



Compressional tectonic inversion
bedding-parallel thrusting
uplift
ramping
siltstone/pelite
sandstone
BPV
BNV
Lithostatic pressure
Hydrostatic pressure
ext
es
cs
5.66T
4T
Extensional regime
σ1-σ3=σv-σh
Compressional regime
σ1-σ3=σH-σv
Differential stress (σ1-σ3)
Pore fluid-pressure
λv
ρoverburden = 2650 kg/m³
μi ~ 0.75
depth = 7km
1000
500
0
1500 bar
2000
0 bar



NW
S1
SE


THANKS !!!!
Rursee sunset, North Eifel, Germany
PhD citation
Van Noten, K. 2011. Stress-state evolution of the brittle upper crust during early Variscan tectonic inversion as defined by successive quartz vein types in the High-Ardenne slate belt, Germany. Aardkundige mededelingen 28. 241 p.
ISBN 978-90-8649-408-8
Papers
Van Noten et al. 2008. Geologica Belgica 11, 179-198
Van Noten & Sintubin 2010. Journal of Structural Geology 32, 377-391
Van Noten et al. 2011. Geol. Soc. London 168, 407-422
Van Noten et al. 2012. Spec. Pub. Geol. Soc. London 367, 51-69