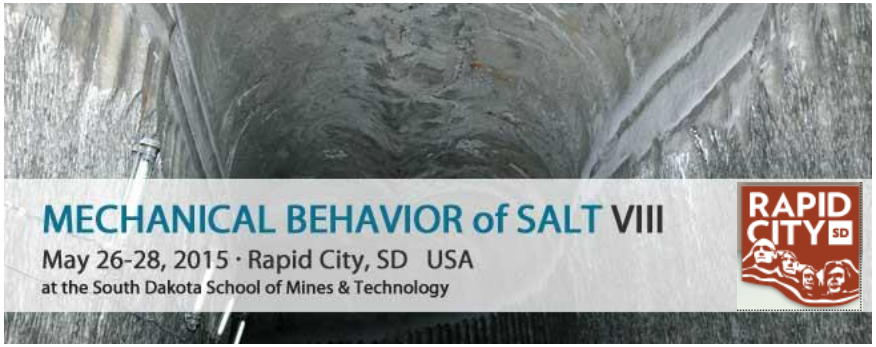

Multi-Mechanism Deformation Creep Model Applied to Brazilian Salt Rocks

Authors

Pedro A. L. P. Firme

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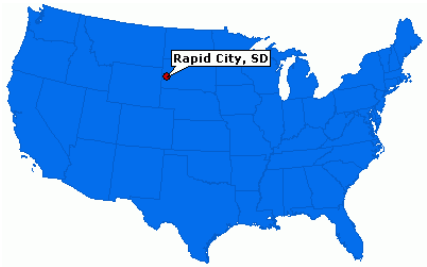
Celso Romanel

Edgard Poiate Jr.

Alvaro Maia da Costa



Rapid City, May 27th, 2015

Outline

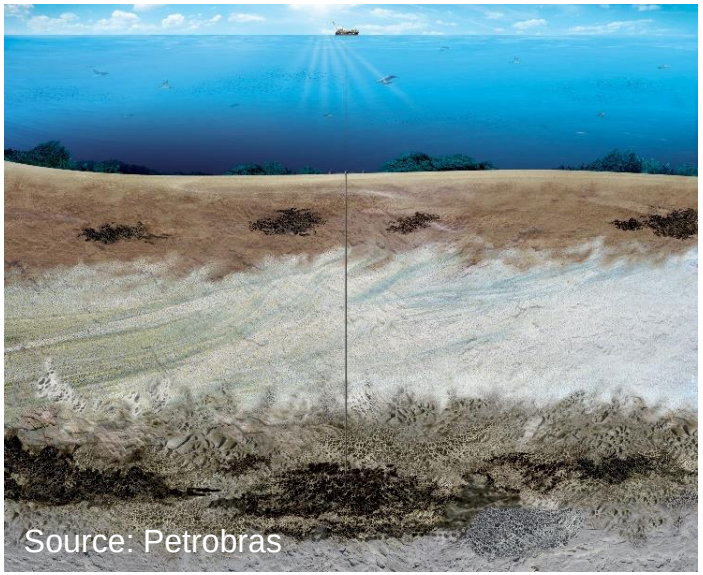
Outline

- Introduction
- Multi-Mechanism Deformation Creep Model (*MD* model)
- Calibration
- Applications
- Conclusions

Introduction

- Brazilian salt rock mechanics – experimental and numerical methodologies inherited from:
  - Taquari-Vassouras potash mine (Rosário do Catete/SE);
  - Institute for Technological Research (São Paulo/SP).
- Synergy with the industry: potash mining and Pre-salt reservoirs.

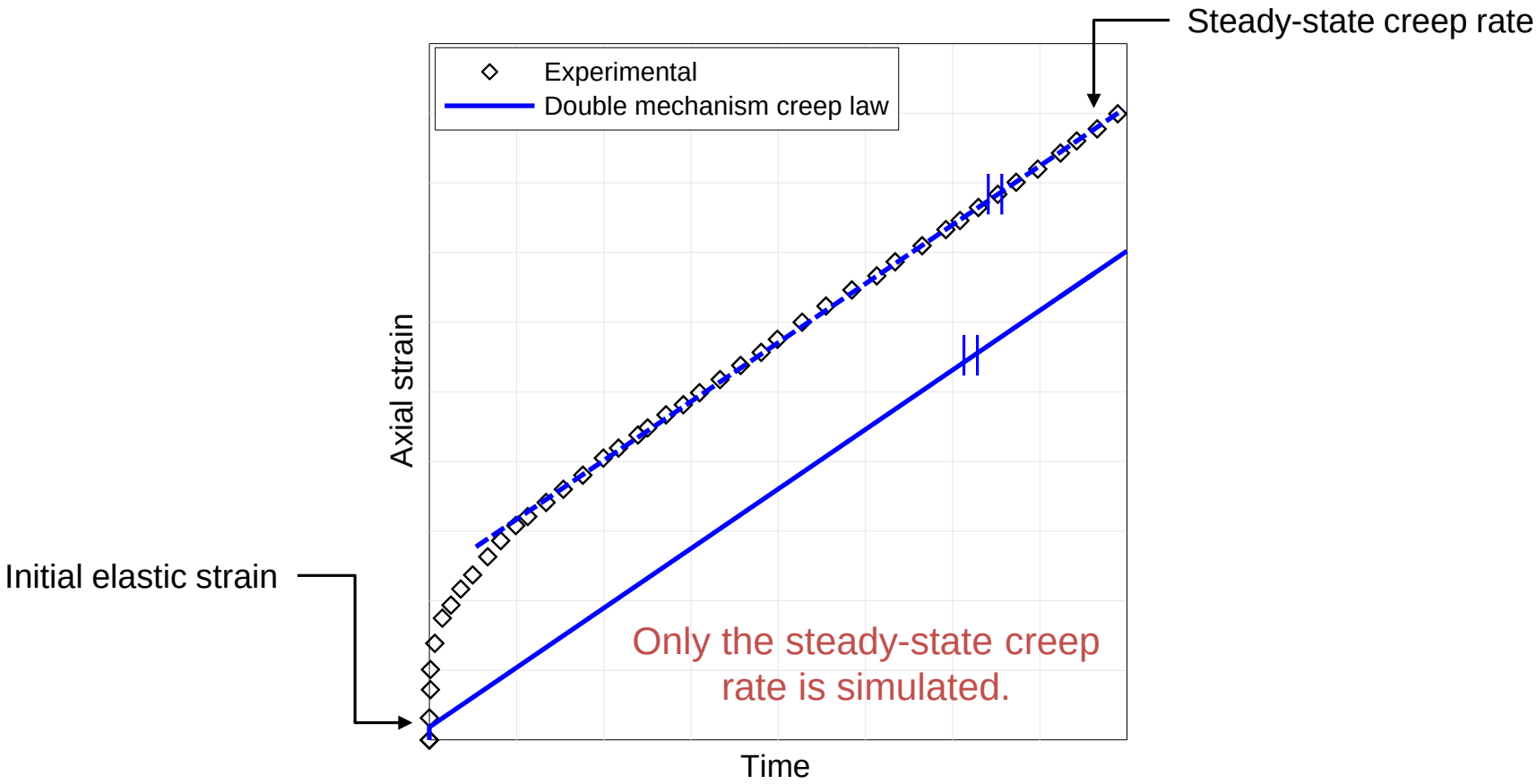
Source: Agência Vale


Source: Petrobras

Ref.: Costa (1984) and Poiate Jr. (2012)

Introduction

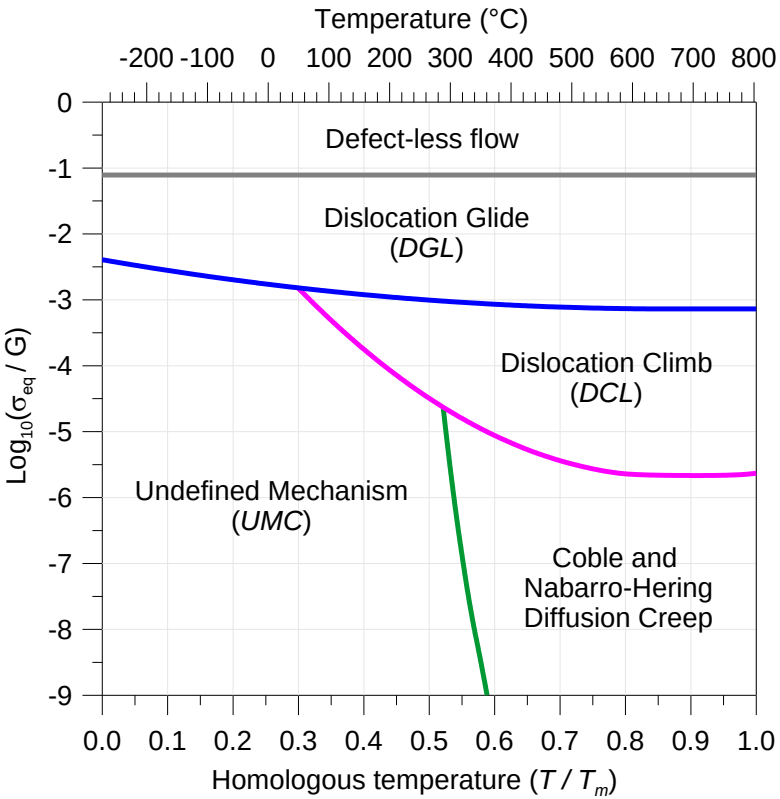
- Double mechanism creep law – widely employed model for creep in Brazilian salt rock mechanics.



Multi-mechanism Deformation Creep Model (*MD* model)

- Highly sophisticated physical constitutive model for salt creep
- Simulation of the transient and steady-state phases of creep
- WIPP: origin and development
- Database for *GoM* salt rocks.

Source: www.wipp.energy.gov



Ref.: Munson & Dawson (1979), Munson (1997, 2004)

Multi-mechanism Deformation Creep Model (*MD* model)

- Formulation

$$\dot{\varepsilon} = F\,\dot{\varepsilon}_{ss}$$

- $\dot{\varepsilon}_{ss}$ → Steady-state creep rate ($\dot{\varepsilon}_{ss}$)
  - Dislocation Climb (*DCL*)
  - Undefined mechanisms (*UMC*)
  - Dislocation Glide (*DGL*)
- F → Transient function (F)

Multi-mechanism Deformation Creep Model (*MD* model)

- Formulation

$$\dot{\varepsilon} = F\dot{\varepsilon}_{ss}$$

- $\dot{\varepsilon}_{ss}$: Steady-state creep rate ($\dot{\varepsilon}_{ss}$)
  - Dislocation Climb (*DCL*)
  - Undefined mechanisms (*UMC*)
  - Dislocation Glide (*DGL*)
- F: Transient function (F)

$$\dot{\varepsilon}_{ss} = \sum \begin{cases} \dot{\varepsilon}_{DCL} = A_1 \exp\left(\frac{-Q_1}{RT}\right)\left(\frac{\sigma_{eq}}{G}\right)^{n_1} \\ \dot{\varepsilon}_{UMC} = A_2 \exp\left(\frac{-Q_2}{RT}\right)\left(\frac{\sigma_{eq}}{G}\right)^{n_2} \\ \dot{\varepsilon}_{DGL} = H\left|\sigma_{eq} - \sigma_0\right|\left[B_1 \exp\left(\frac{-Q_1}{RT}\right) + B_2 \exp\left(\frac{-Q_2}{RT}\right)\right]\sinh\left[\frac{q\left(\sigma_{eq} - \sigma_0\right)}{G}\right] \end{cases}$$

Multi-mechanism Deformation Creep Model (*MD* model)

- Formulation

$$\dot{\varepsilon} = F\dot{\varepsilon}_{ss}$$

- $\dot{\varepsilon}_{ss}$ → Steady-state creep rate ($\dot{\varepsilon}_{ss}$)
  - Dislocation Climb (*DCL*)
  - Undefined mechanisms (*UMC*)
  - Dislocation Glide (*DGL*)
- F → Transient function (F)

Dislocation Climb and Undefined mechanisms - our agreement

Dislocation Climb: "*Glide with climb is often called just climb because the climb process actually controls the deformation rate even though the plastic deformation results from glide. (…)*" Fossum & Fredrich (2002).

Undefined Mechanisms: Recently, an association between this mechanism and the Dislocation Cross-Slip is suggested (Hansen, 2014).

Multi-mechanism Deformation Creep Model (*MD* model)

- Formulation

$$\dot{\varepsilon} = F\dot{\varepsilon}_{ss}$$

- $\dot{\varepsilon}_{ss}$ → Steady-state creep rate ($\dot{\varepsilon}_{ss}$)
  - Dislocation Climb (*DCL*)
  - Undefined mechanisms (*UMC*)
  - Dislocation Glide (*DGL*)
- F → Transient function (F)

Dislocation Glide - our agreement

Deviatoric stress (σ_{eq})

- $\sigma_{eq} > \sigma_0$: Energy for the dislocations to transpose the tangles of crystal grains through slip planes – the concept of Peierl's stress.

  (Individual equation is adopted)

- $\sigma_{eq} < \sigma_0$: Implicitly regarded as plastic deformations in Climb mechanism.

  (Individual equation is not adopted)

Multi-mechanism Deformation Creep Model (*MD* model)

- Formulation

$$\dot{\varepsilon} = \boldsymbol{F}\dot{\varepsilon}_{ss}$$

- $\dot{\varepsilon}_{ss}$ → Steady-state creep rate ($\dot{\varepsilon}_{ss}$)
  - Dislocation Climb (*DCL*)
  - Undefined mechanisms (*UMC*)
  - Dislocation Glide (*DGL*)
- $\boldsymbol{F}$ → Transient function (F)

$$F = \begin{cases} \exp\left[\Delta\left(1-\dfrac{\zeta}{\varepsilon_t^*}\right)^2\right] & ; \quad \zeta < \varepsilon_t^* \\ 1 & ; \quad \zeta = \varepsilon_t^* \\ \exp\left[-\delta\left(1-\dfrac{\zeta}{\varepsilon_t^*}\right)^2\right] & ; \quad \zeta > \varepsilon_t^* \end{cases}$$

Euler's Forward method

$$\dot{\zeta} = \boxed{\frac{\partial \zeta}{\partial t} \approx \frac{\Delta \zeta}{\Delta t}} = (F-1)\dot{\varepsilon}_{ss}$$

$$\varepsilon_t^* = K_0 \exp(cT)\left(\frac{\sigma_{eq}}{G}\right)^m$$

$$\Delta = \alpha_h + \beta_h \log\left(\frac{\sigma_{eq}}{G}\right)$$

Multi-mechanism Deformation Creep Model (*MD* model)

- Workflow to use the *MD* model in Brazilian halite

Calibration
Parameters for Brazilian halite

→

Implementation
MD model as subroutine

→

Validation
Methodology Parameters

Calibration

- Calibration of the material sensitive parameters for Brazilian halite

Calibration
Parameters for Brazilian halite

→

Implementation
MD model as subroutine

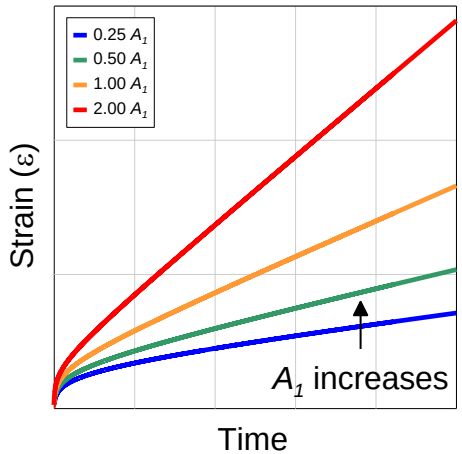
→

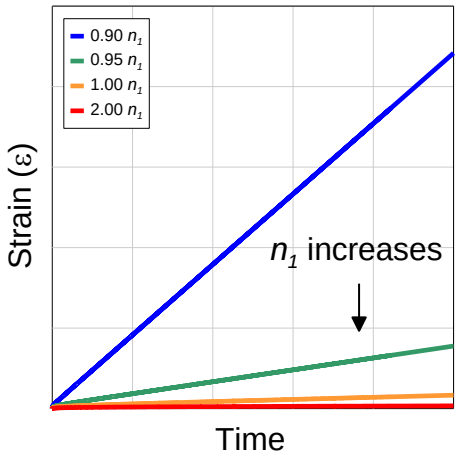
Validation
Methodology Parameters

Ref.: The methodology to the calibration was presented by Munson (1999). Analogy with the Double mechanism creep law (Costa *et al*., 2005) has also been considered.

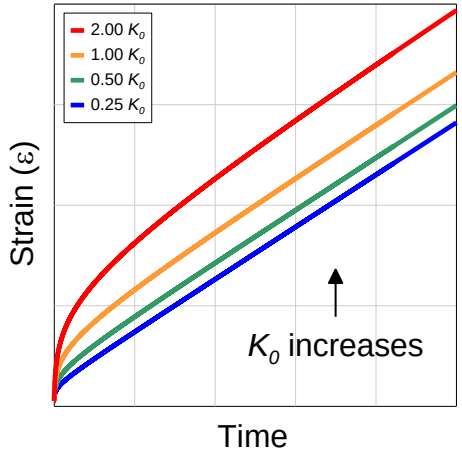
Calibration

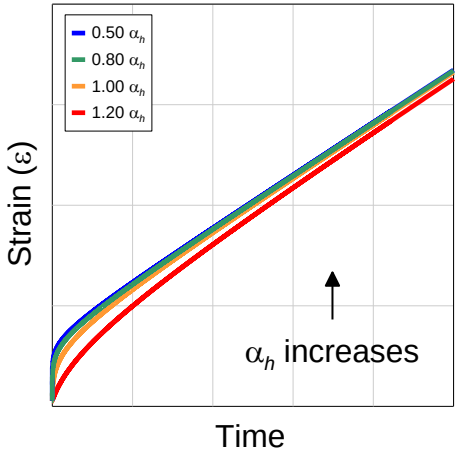
- Steady-state material sensitive parameters (*A*, *B* and *n*)





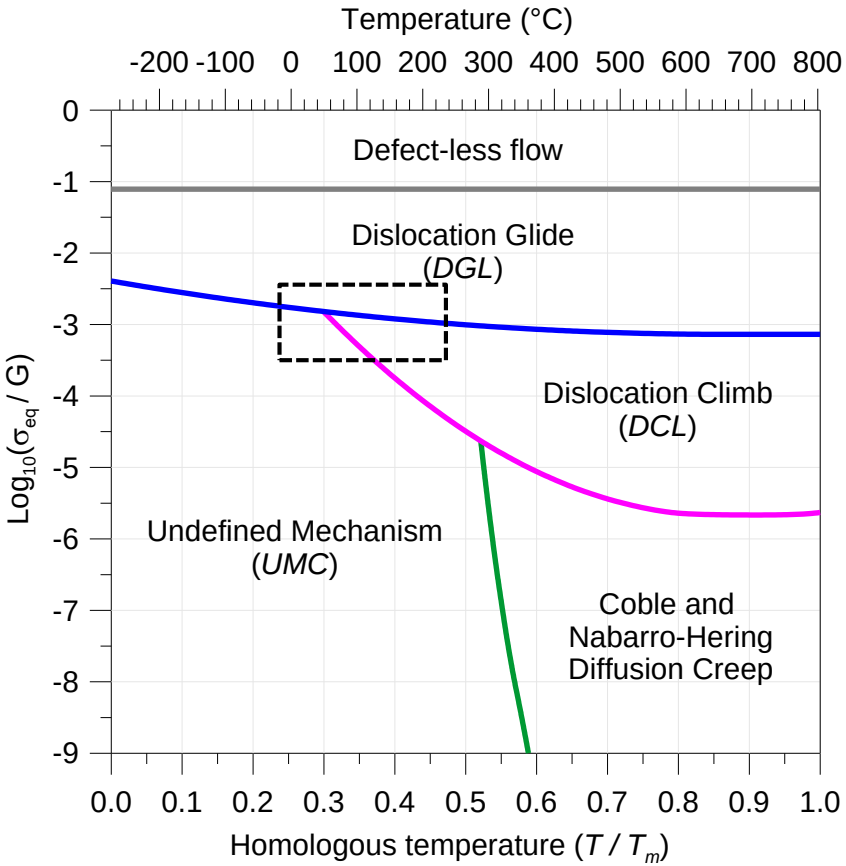
- Transient material sensitive parameters (K_0 and α_h)

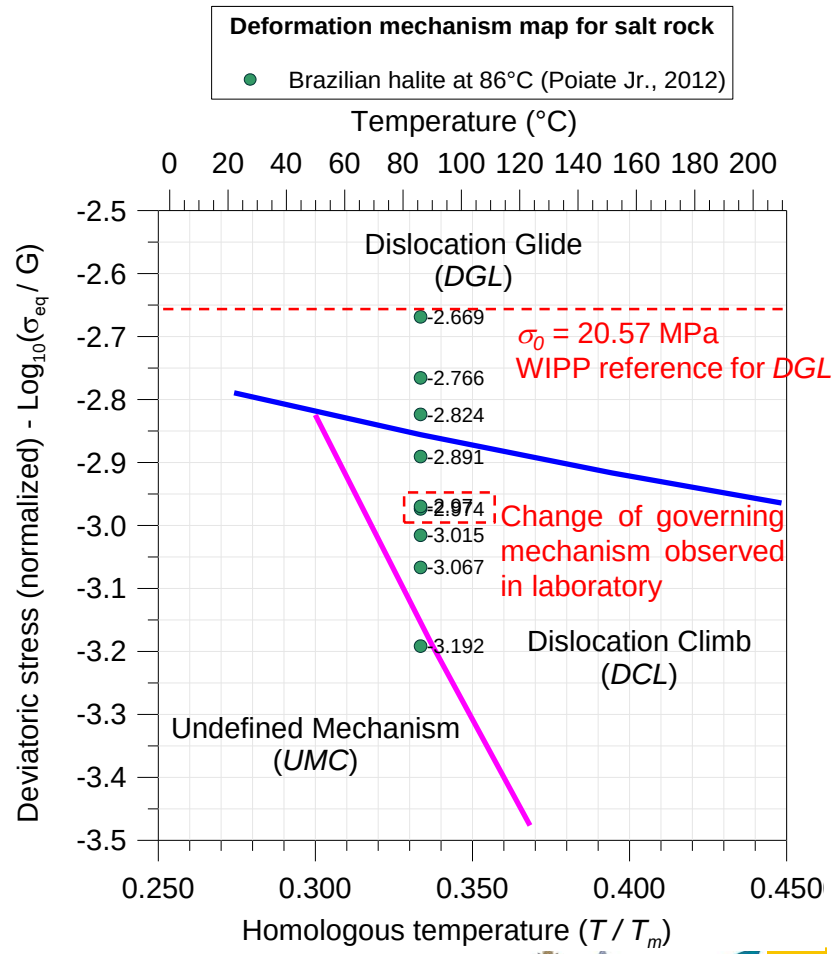




Calibration

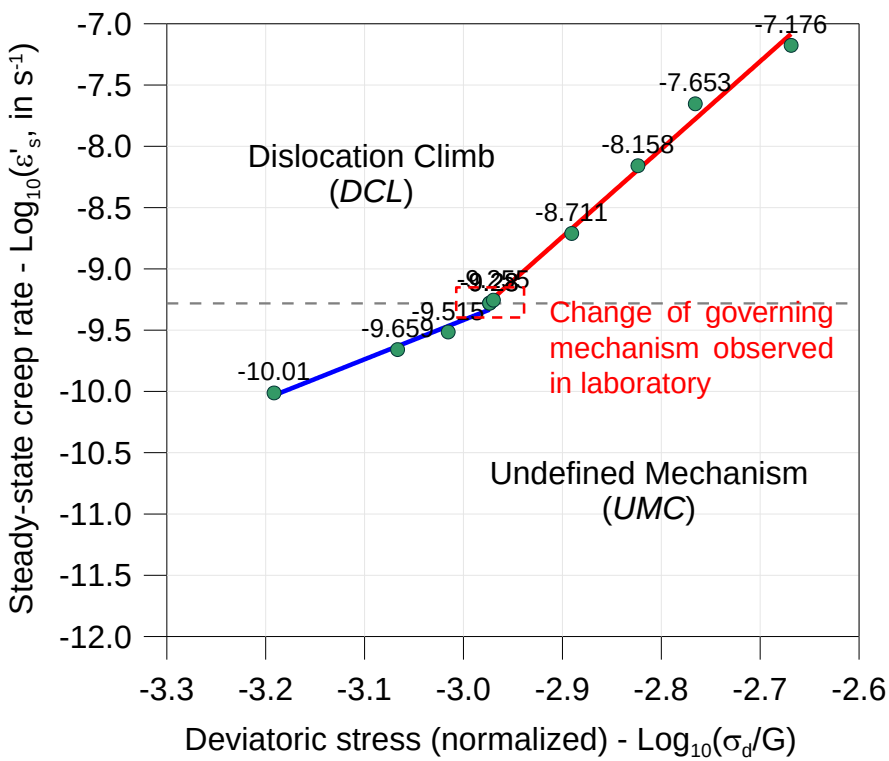
- Steady-state material sensitive parameters (*A*, *B* and *n*)

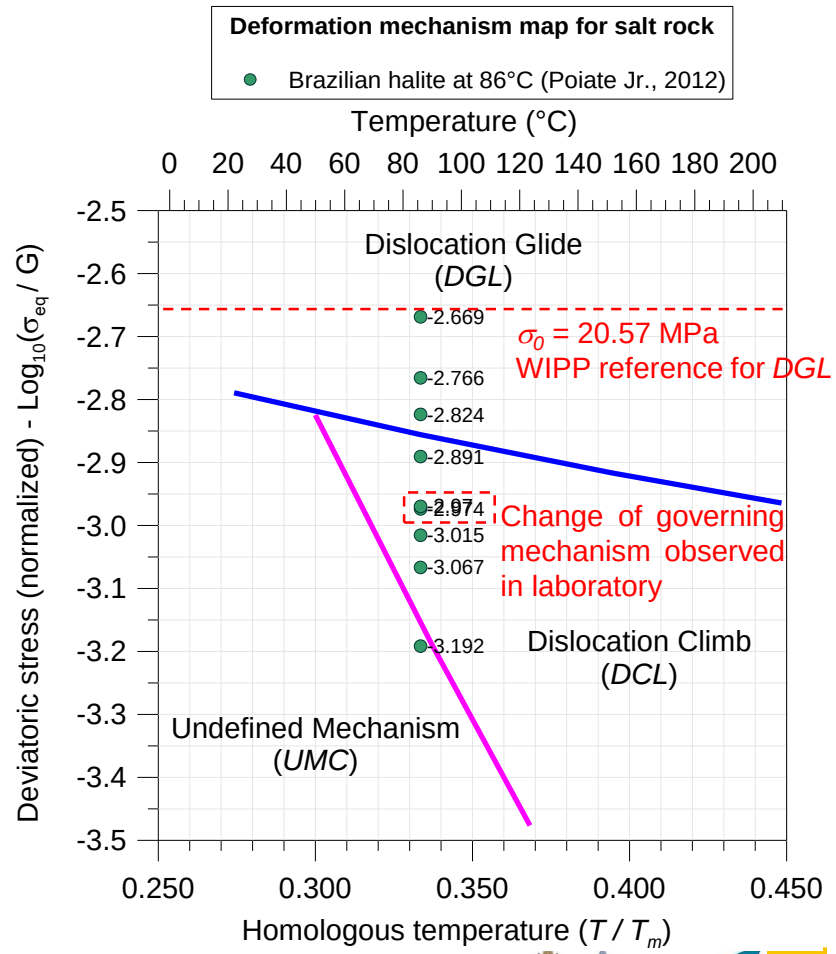




Calibration

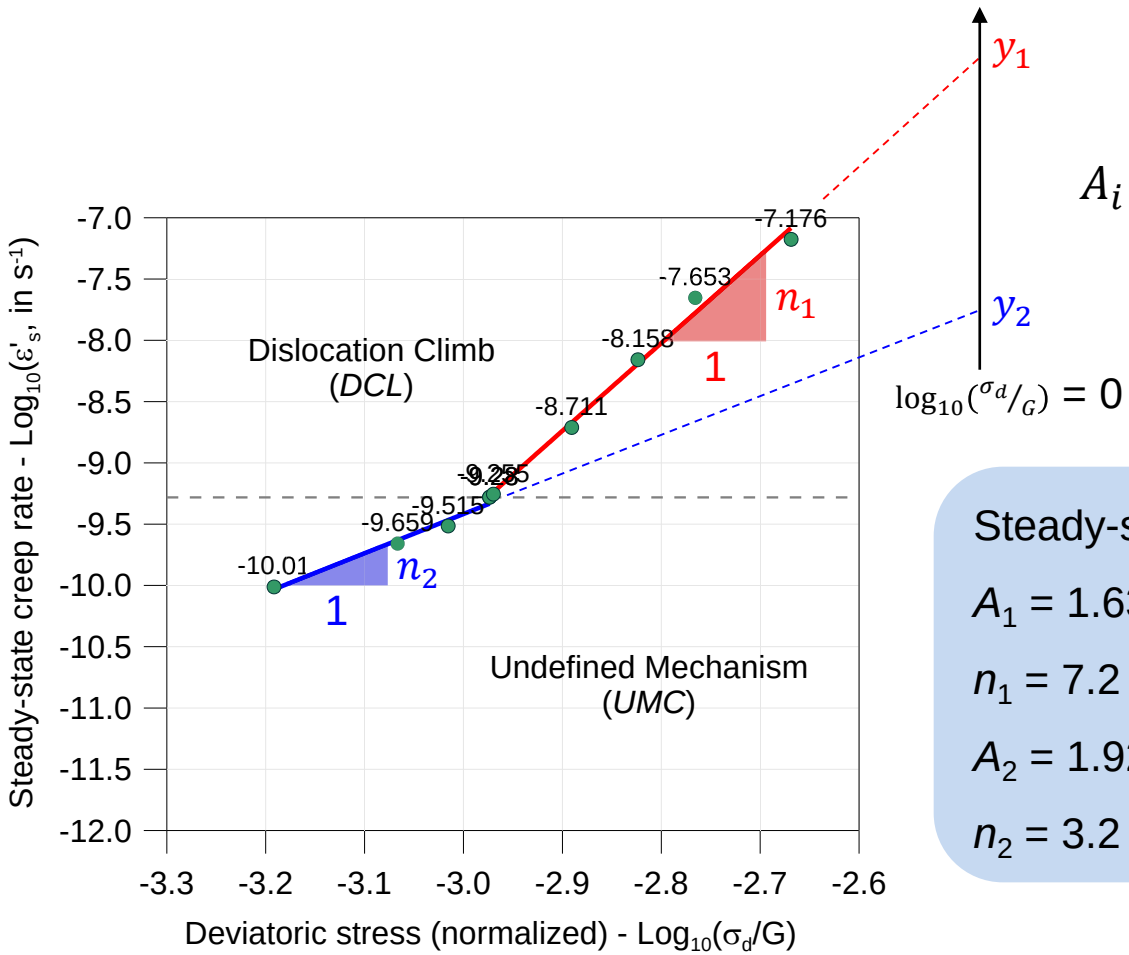
- Steady-state material sensitive parameters (*A*, *B* and *n*)





Calibration

- Steady-state material sensitive parameters (*A*, *B* and *n*)



$$A_i = (10^{y_i}) \exp\left(\frac{Q}{RT_0}\right)$$

Steady-state creep parameters

A_1 = 1.638 (10^{27}) s^{-1}

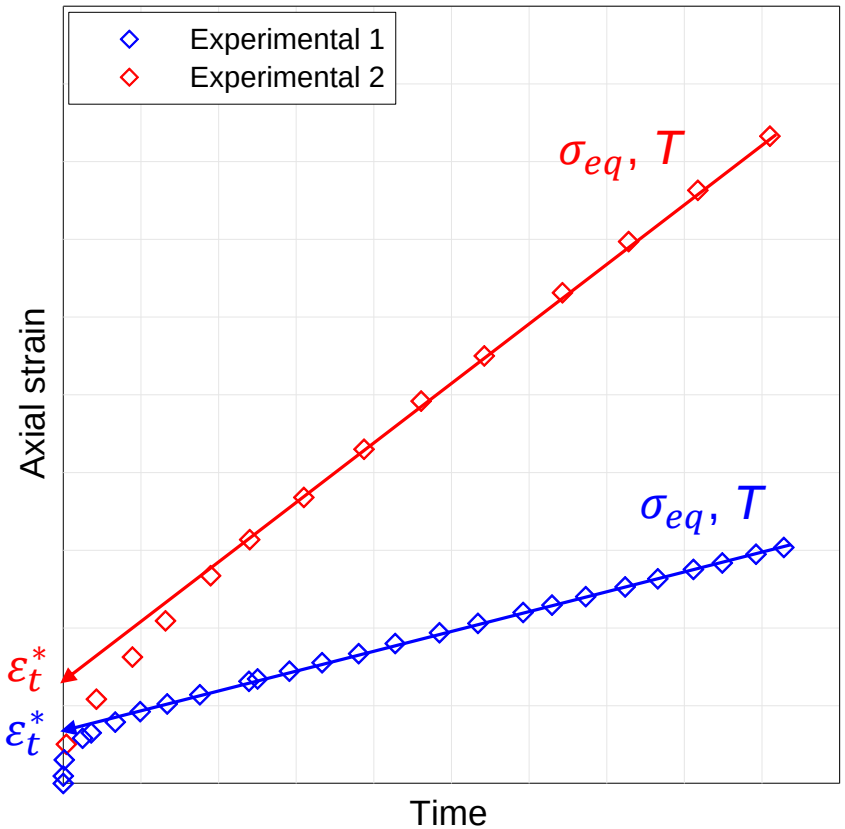
n_1 = 7.2

A_2 = 1.924 (10^{6}) s^{-1}

n_2 = 3.2

Calibration

- Transient material sensitive parameters (K_0 and α_h)



$$\varepsilon_t^* = K_0 \exp(cT) \left(\frac{\sigma_{eq}}{G}\right)^m$$

Transient creep parameters

K_0 = 7.750 (10^4)

α_h = -17.37 (trial and error, WIPP)

Calibration

- Set of parameters for Brazilian halite

Steady-state parameters		
A_1 (s^{-1})	Structural factor for DCL	1.638 (10^{27})
Q_1 (J/mol)	Thermal activation for DCL	104500.0 ***
n_1	Stress power for DCL	7.2
A_2 (s^{-1})	Structural factor for UMC	1.924 (10^{6})
Q_2 (J/mol)	Thermal activation for UMC	41800.0 ***
n_2	Stress power for UMC	3.2
σ_0 (MPa)	Reference stress for DGL	20.57 ***
q	Stress constant	5335.0 ***
B_1 (s^{-1})	Structural factor for DGL	9.981 (10^{6}) **
B_2 (s^{-1})	Structural factor for DGL	4.976 (10^{-2}) **

Transient function parameters		
m	Theoretical constant	3.0 ***
K_0	Limit factor of transient creep	7.750 (10^{4})
c (K^{-1})	Constant - activation process	9.198 (10^{-3}) ***
α_h	Hardening parameter	-17.37 ***
β_h	Hardening parameter	-7.738 ***
δ	Softening parameter	0.58 ***

Dynamic elastic parameters		
E (GPa)	Young's modulus	25.37
ν	Poisson's ratio	0.36 ****

Ref.: **Big Hill Salt and ***WIPP standard from Fossum & Fredrich (2002), ****Costa et al. (2005).

Calibration

➢ Set of parameters for Brazilian halite

Steady-state parameters		
A_1 (s^{-1})	Structural factor for DCL	**1.638 (10^{27})**
Q_1 (J/mol)	Thermal activation for DCL	104500.0 ***
n_1	Stress power for DCL	**7.2**
A_2 (s^{-1})	Structural factor for UMC	**1.924 (10^{6})**
Q_2 (J/mol)	Thermal activation for UMC	41800.0 ***
n_2	Stress power for UMC	**3.2**
σ_0 (MPa)	Reference stress for DGL	20.57 ***
q	Stress constant	5335.0 ***
B_1 (s^{-1})	Structural factor for DGL	9.981 (10^{6}) **
B_2 (s^{-1})	Structural factor for DGL	4.976 (10^{-2}) **

Transient function parameters		
m	Theoretical constant	3.0 ***
K_0	Limit factor of transient creep	**7.750 (10^{4})**
c (K^{-1})	Constant - activation process	9.198 (10^{-3}) ***
α_h	Hardening parameter	-17.37 ***
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Dynamic elastic parameters		
E (GPa)	Young's modulus	**25.37**
ν	Poisson's ratio	0.36 ****

Our contribution

Ref.: **Big Hill Salt and ***WIPP standard from Fossum & Fredrich (2002), ****Costa et al. (2005).

Applications

- *MD* model as subroutine for a commercial *FE* code

Calibration
Parameters for Brazilian halite

→

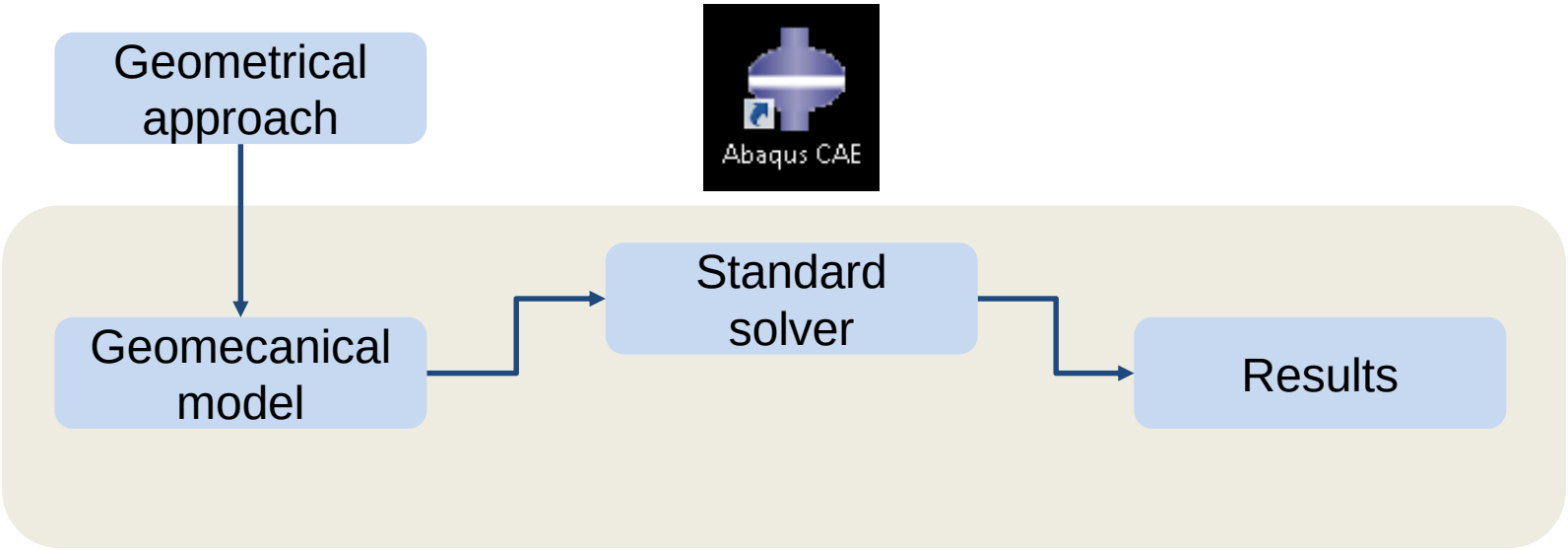
Implementation
MD model as subroutine

→

Validation
Methodology Parameters

Applications

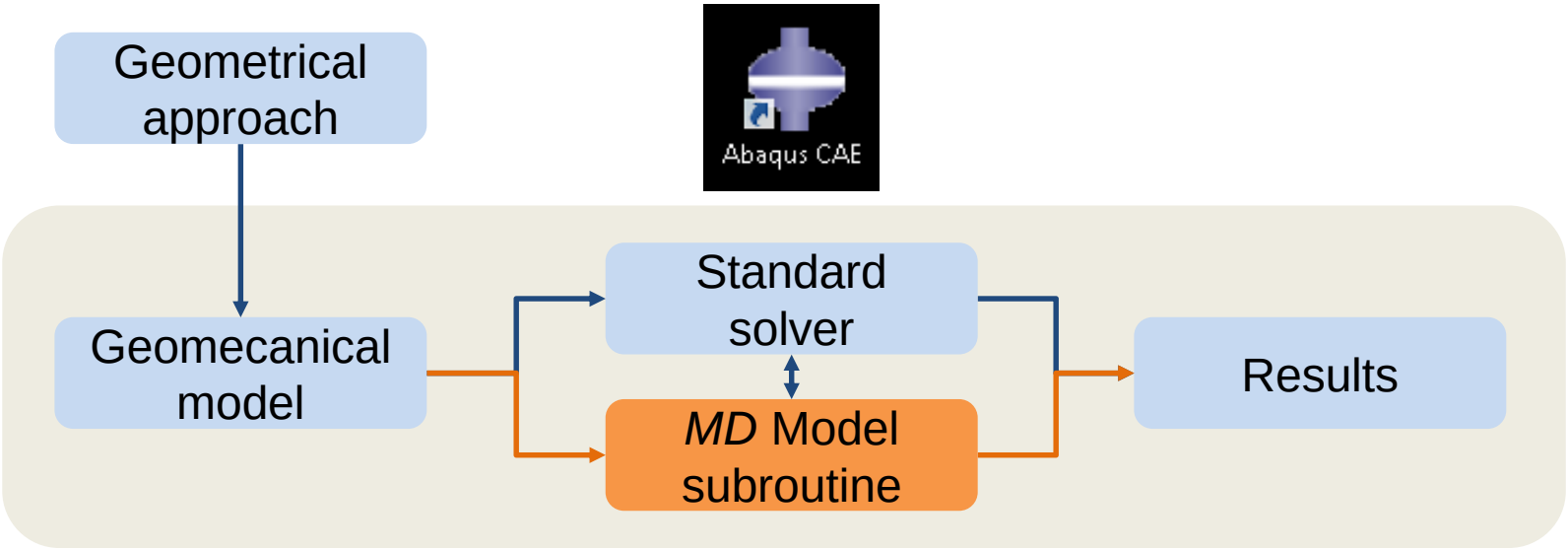
- *MD* model as subroutine for a commercial *FE* code



Application itself

Applications

- *MD* model as subroutine for a commercial *FE* code




```
C ---------------------------------------------------------------------
C
C --------- MODELO DE MULTIMECANISMO (Munson e Dawson, 1979) ---------
C
C ---------------------------------------------------------------------
C
C
C $*CREEP, LAW=USER
      SUBROUTINE CREEP(DECRA,DESWA,STATEV,SERD,EC,ESW,P,QTILD,
     1 TEMP,DTEMP,PREDEF,DPRED,TIME,DTIME,CMNAME,LEXIMP,LEND,
     2 COORDS,NSTATV,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)
      INCLUDE 'ABA_PARAM.INC'
      CHARACTER*80 CMNAME,ROTULO
      DIMENSION DECRA(5),DESWA(5),STATEV(*),PREDEF(*),DPRED(*),
     1 TIME(2),COORDS(*),EC(2),ESW(2)
      REAL*8 A1,Q1,n1,A2,Q2,n2,B1,B2,q,SIG0,c,m,K0,alphaH,betaH,alphaR,
     1 betaR,E,ni,G,WD,ds,TFM,GTSed,GTSalt
C ---------------------------------------------------------------------
C
C ---------------------------------------------------------------------
C     R = Constante Universal dos Gases
      R = 8.3143
      zeta = STATEV(1)
C
C ---------------------------------------------------------------------
```

```
C ---------------------------------------------------------------------
C
C     CÁLCULO DAS PARCELAS DA TAXA DE FLUÊNCIA SECUNDÁRIA
C
C ---------------------------------------------------------------------
C
      CREEP_DISLOCATION_CLIMB = A1*EXP(-Q1/(R*T))*((QTILD/G)**n1)
      CREEP_UNDEFINED_MECHANISM = A2*EXP(-Q2/(R*T))*((QTILD/G)**n2)
      CREEP_DISLOCATION_GLIDE = H*(B1*EXP(-Q1/(R*T))+B2*EXP(-Q2/(R*T)))
     1 *SINH((q*(QTILD-SIG0))/G)
C
      CREEP_STEADY_STATE_RATE =
     1 CREEP_DISLOCATION_CLIMB +
     2 CREEP_UNDEFINED_MECHANISM +
     3 CREEP_DISLOCATION_GLIDE
C
C
C
      CREEP_STEADY_STATE_RATE_FIRST_DIFF =
     1 (A1*EXP(-Q1/(R*T))*(n1/QTILD)*((QTILD/G)**n1))/QTILD +
     2 (A2*EXP(-Q2/(R*T))*(n2/QTILD)*((QTILD/G)**n2))/QTILD +
     3 (H*(B1*EXP(-Q1/(R*T))+B2*EXP(-Q2/(R*T)))
     4 *COSH((q*(QTILD-SIG0))/G)*q)/G
C
```

Application itself

Our contribution

Applications

- Simulations for validation

Calibration
Parameters for Brazilian halite

→

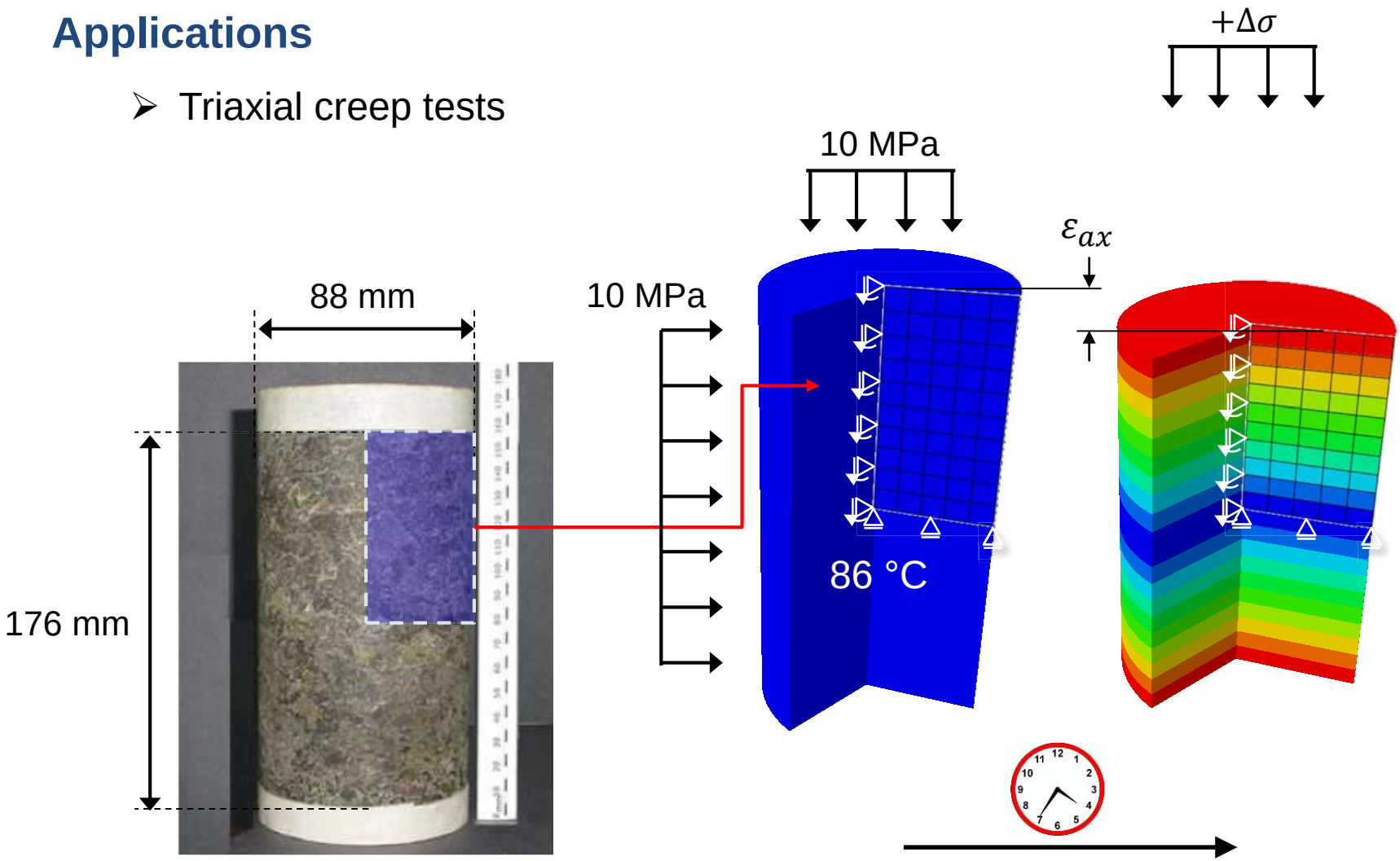
Implementation
MD model as subroutine

→

Validation
Methodology
Parameters

Applications

- Triaxial creep tests

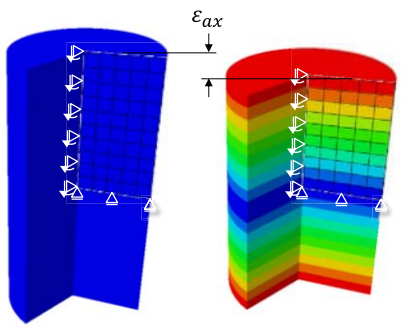


Sample of Brazilian halite
(Poiate Jr., 2012)

Time domain analyses

Applications

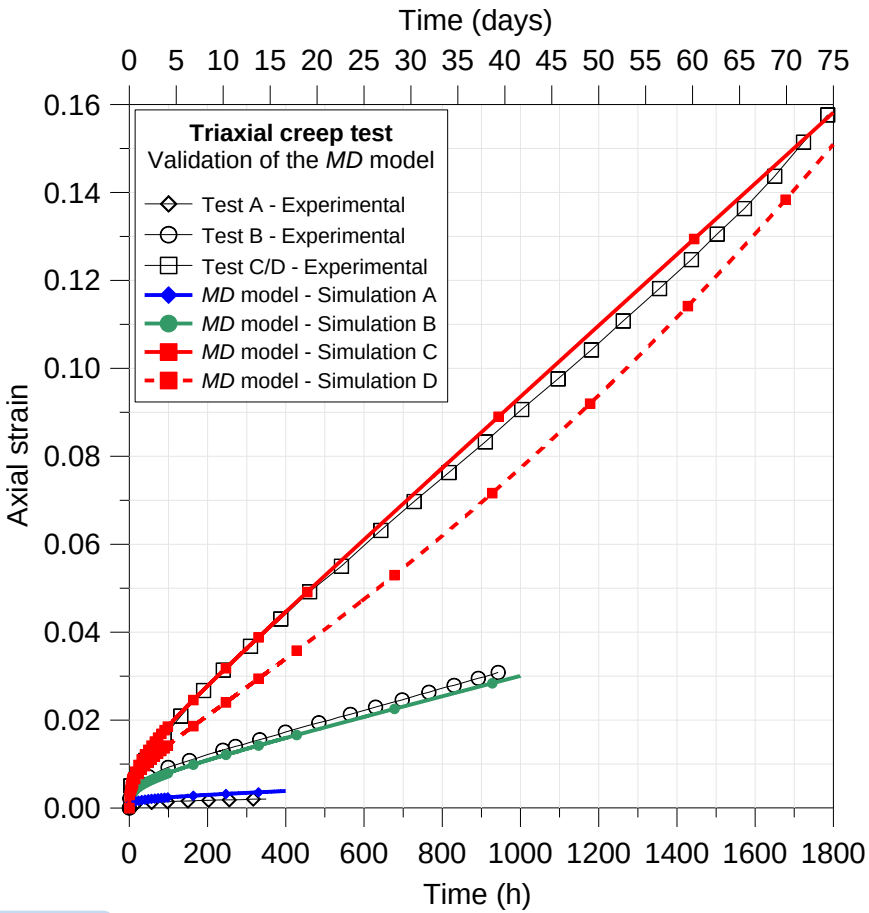
- Triaxial creep tests



Simulation	Dev. stress (MPa)	Duration (h)
A	10.0 *	350
B	14.0 *	1000
C	17.0 *	2200
D	16.0 – 18.0 **	2200

*Instantaneous deviatoric stress application

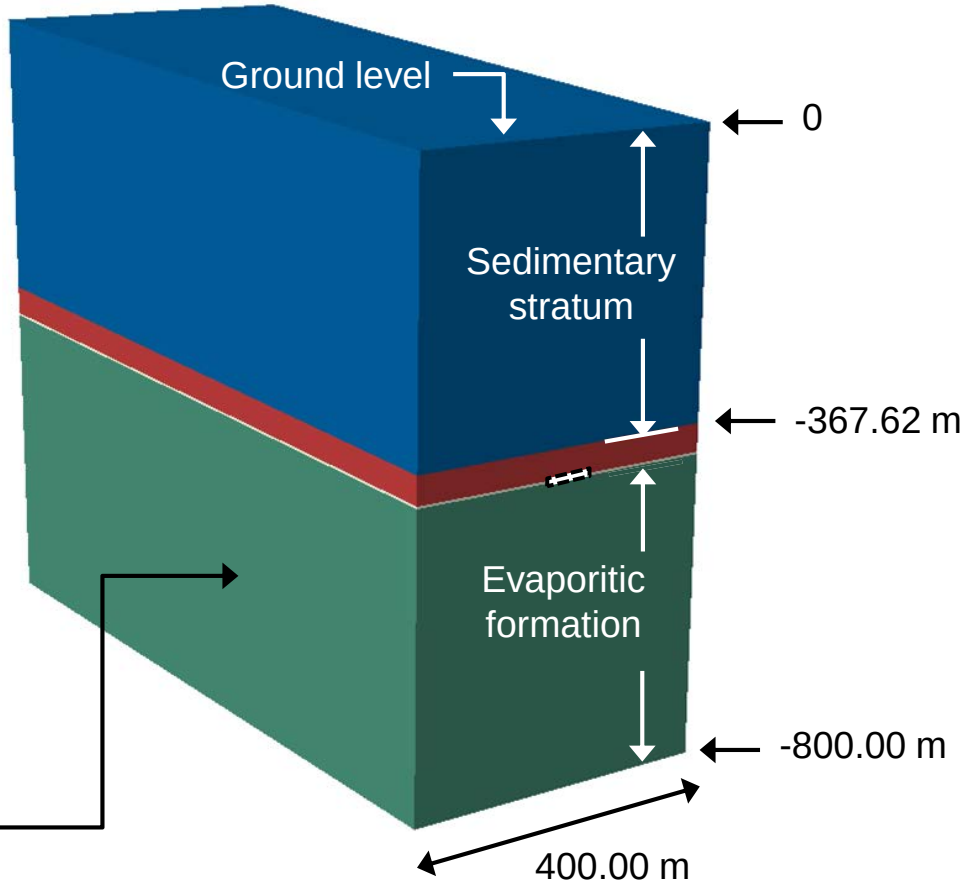
**Linear load increase



Ref.: Experimental results from Costa et al. (2005) and Poiate Jr. (2012)

Applications

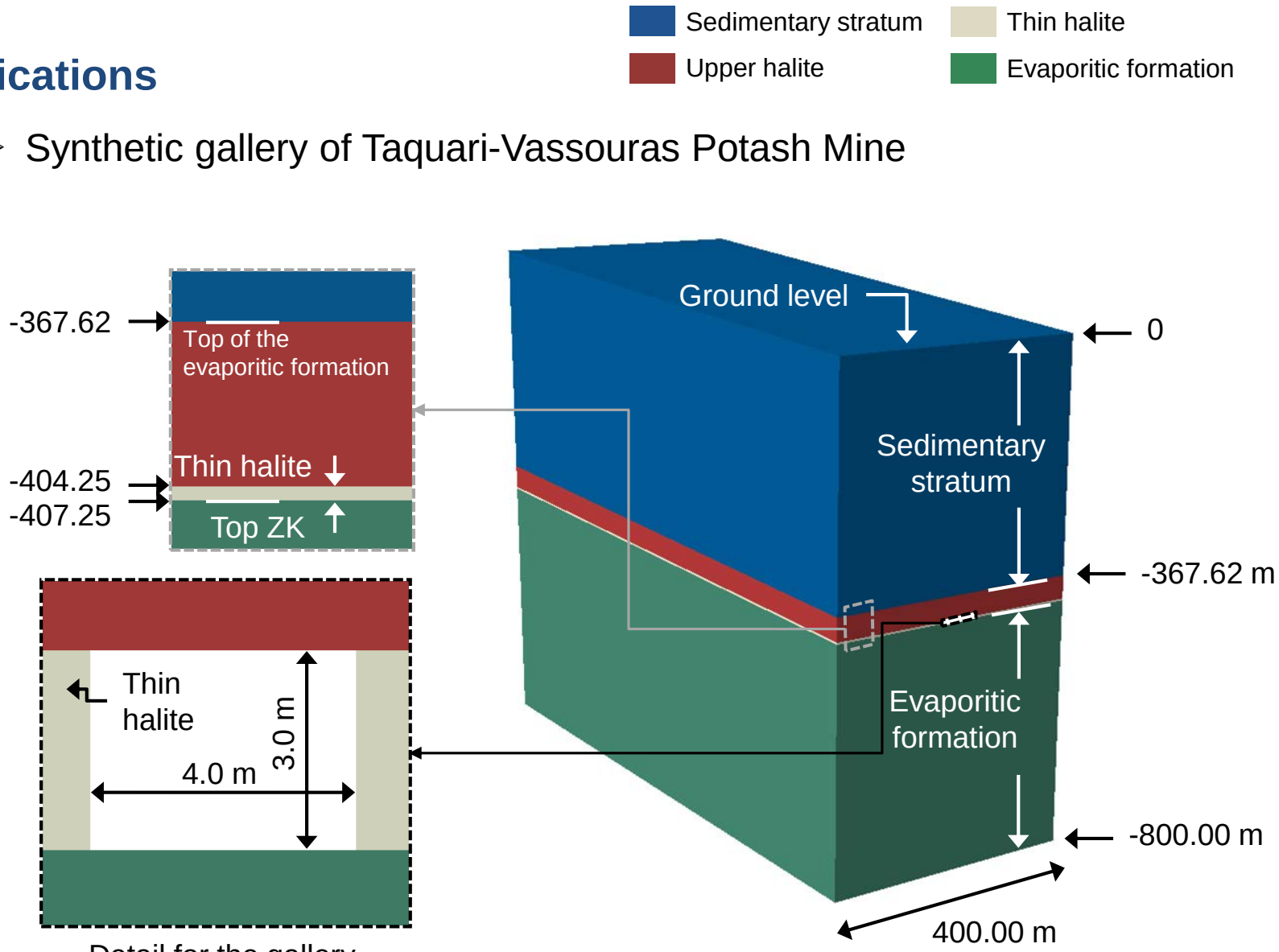
- Synthetic gallery of Taquari-Vassouras Potash Mine



Halite-dominant rock mass

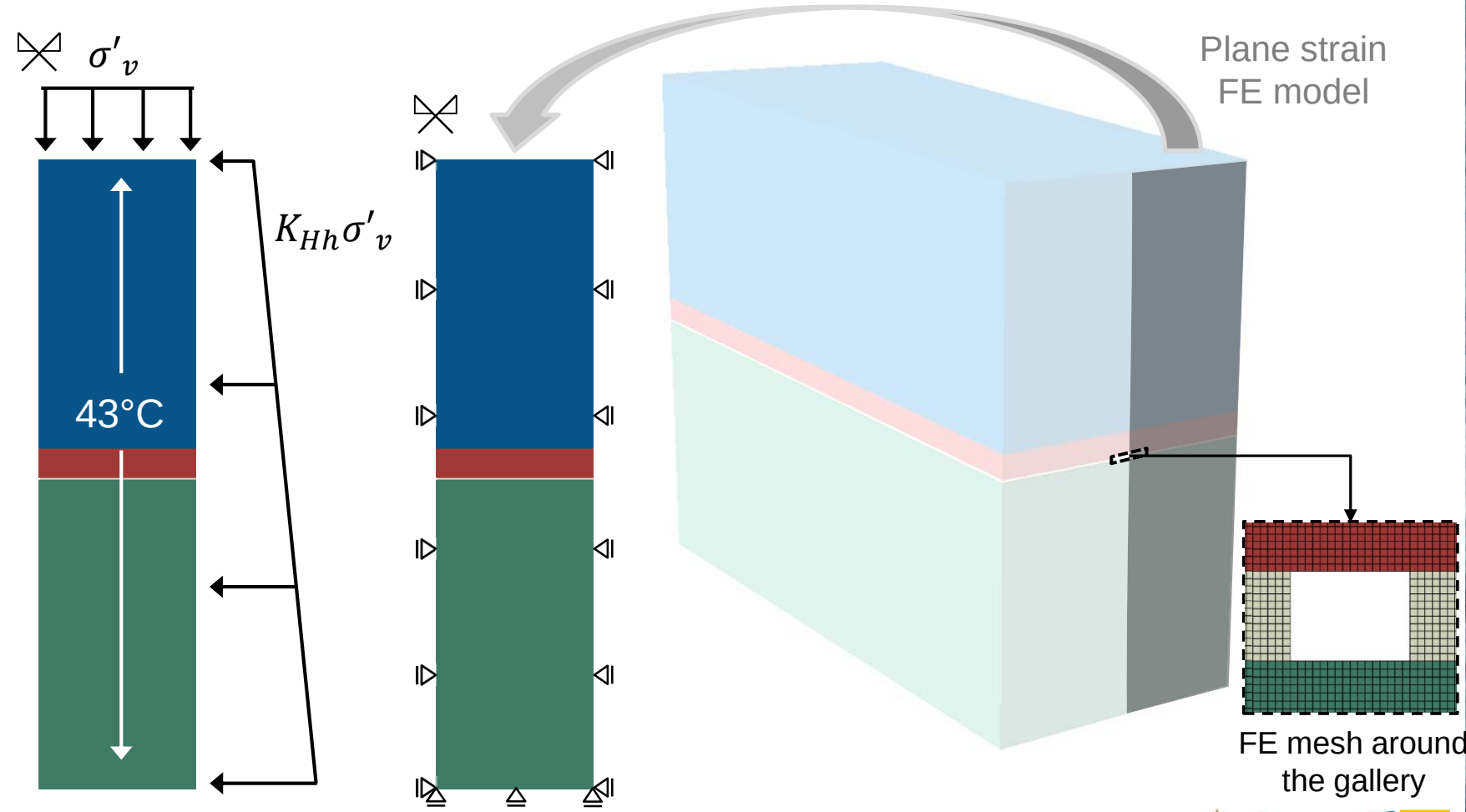
Applications

- Synthetic gallery of Taquari-Vassouras Potash Mine



Applications

- Synthetic gallery of Taquari-Vassouras Potash Mine

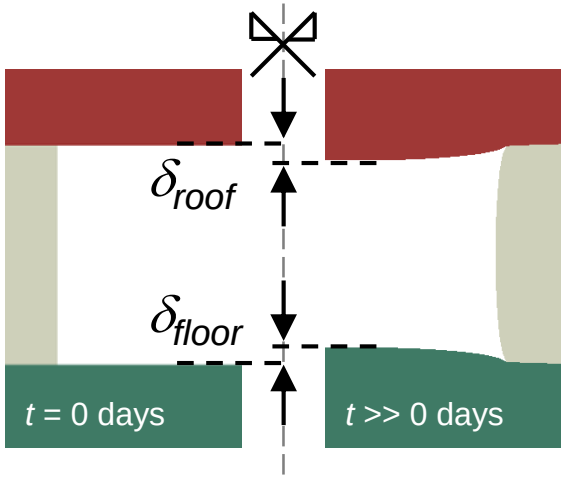


Initial stress state

Boundary conditions

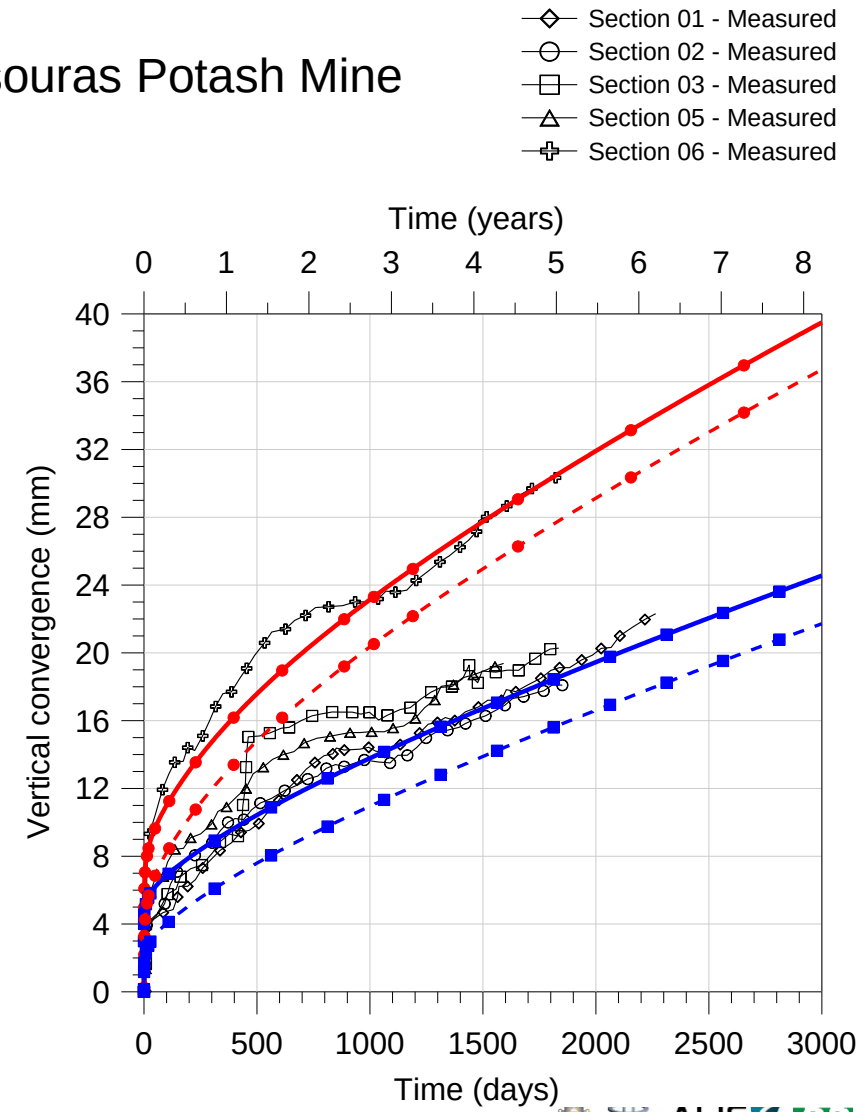
Applications

- Synthetic gallery of Taquari-Vassouras Potash Mine



Vertical convergence (δ_v) = $\delta_{floor} - \delta_{roof}$

Simulation	Vertical convergence
K_{Hh} = 1.0	Total
K_{Hh} = 1.0	Only by creep
K_{Hh} = 1.5	Total
K_{Hh} = 1.5	Only by creep

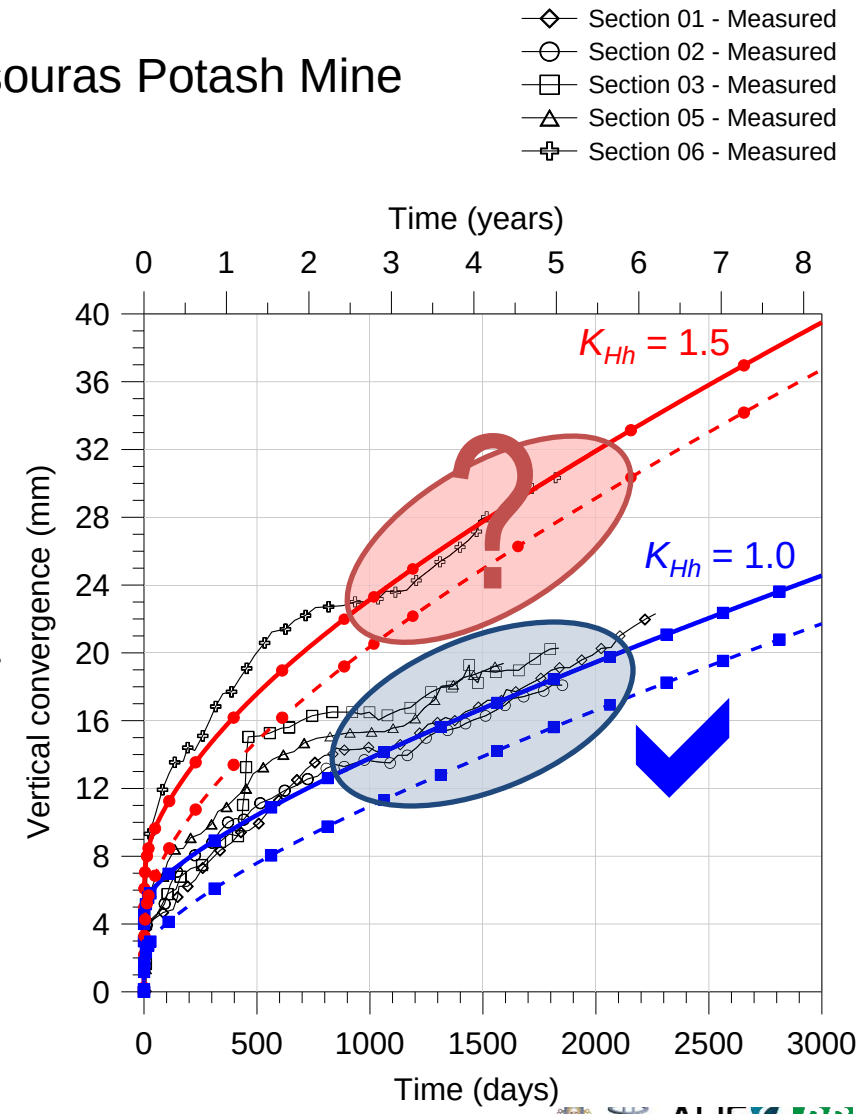


Ref.: Experimental results from D'Ellia (1991)

Applications

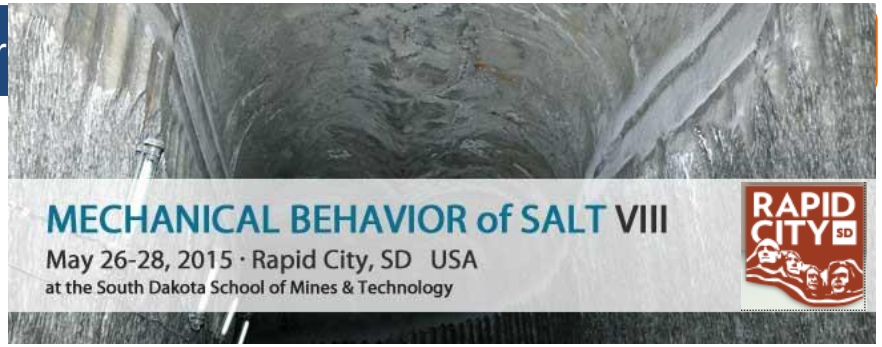
- Synthetic gallery of Taquari-Vassouras Potash Mine

- Excellent agreement between numerical solutions and field measurements.
- Most measurements seem related to an isotropic stress state (K_{Hh} = 1.0).
- Section 06 has adequately been simulated considering K_{Hh} = 1.5, but other geological aspects might be responsible for this (rather than K_{Hh}).
- In-situ stresses in the region of the TV mine are likely to be hydrostatic (Fairhurst *et al*., 1979).



Conclusions

- The calibration of the Brazilian halite sensitive parameters has led to structure factors and stress powers quite distinct from the typical range observed for *WIPP* and *GoM* salts.
- Transient and steady-state creep phases have been successfully simulated with the *MD* model and with this set of parameters.
- Further investigation should continue in order to consolidate this set of parameters and identify its possible limitations.
- Extension to other salt rocks: sylvinite, carnallite and tachyhydrite.



We appreciate your attention!

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