Foundation CMG School
Introduction to Reservoir Geomechanics

Leonardo Guimarães

http://www.lmcg.ufpe.br/chair/

Federal University of Pernambuco - UFPE

Laboratory for Computational Methods on Geomechnics - LMCG

Banff, October 1st - 2017

Recife - Brazil

UFPE

FEDERAL

UNIVERSITY

OF

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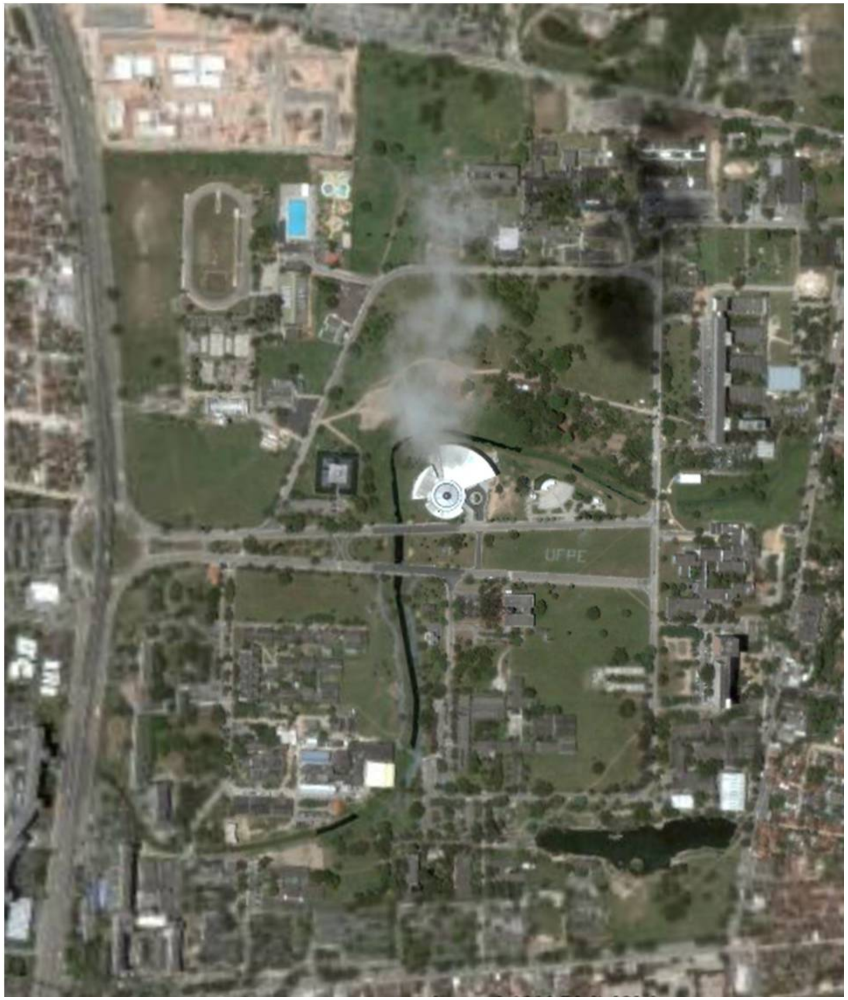
UFPE

UFPE Campus



UFPE

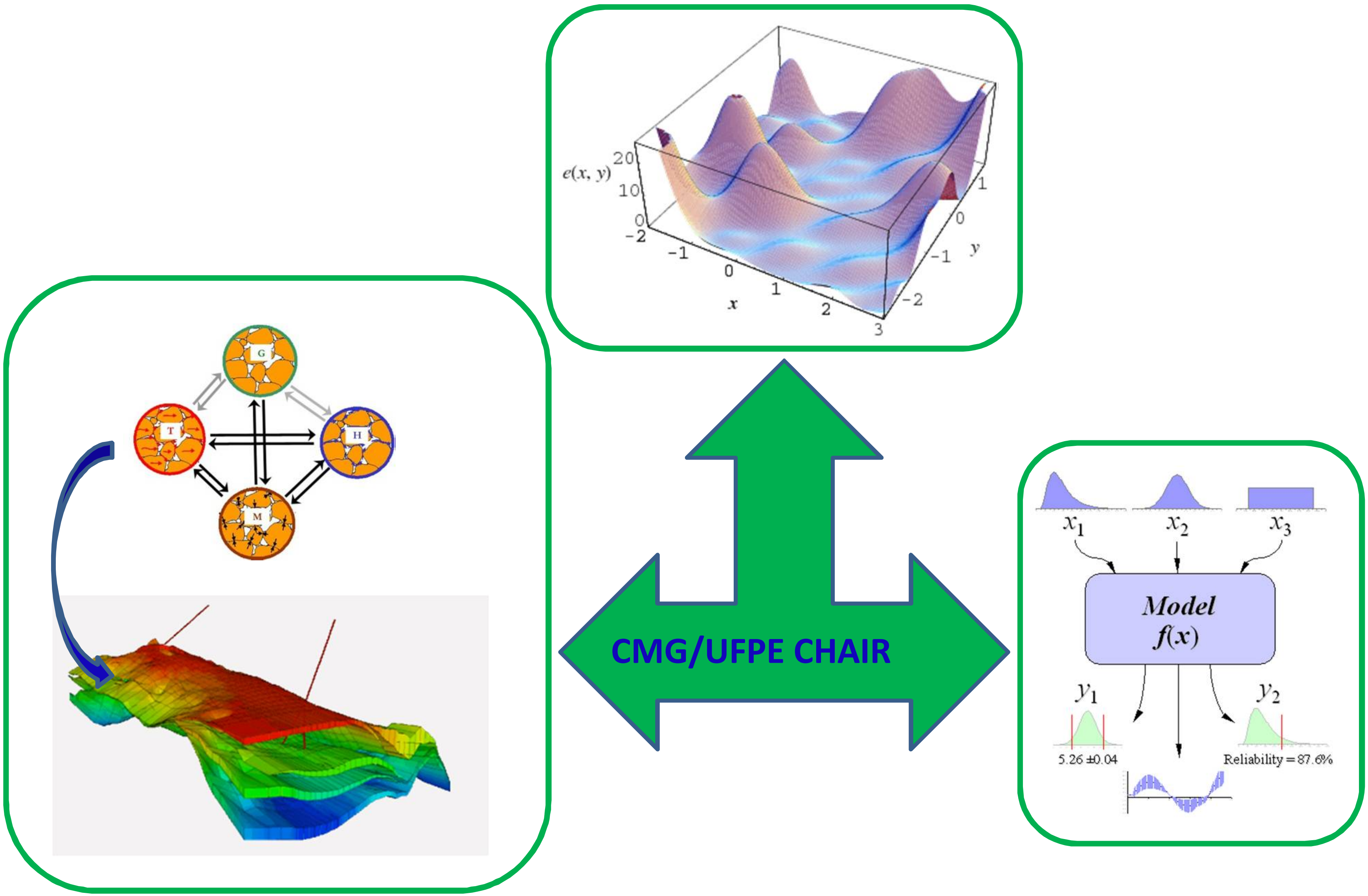
School of Engineering (120 years old):
Mines, **Chemical**, **Civil**, Electronics and Systems, Cartography, **Mechanical**, Nuclear, Production, Electrical.
Also: **Geology**, Oceanography

Arts and Communications (8 departments)
Biological Sciences (10 departments)
Exact and Natural Science (4 departments)
Legal Science (1 department)
Applied Social Sciences (4 departments)
Science of Health (15 departments)
Science of Education (4 departments)
Philosophy and Human Sciences (5 departments)
Computer Sciences (3 departments)
Technology and Geosciences (Geology and 10 engineering departments)

~44,000 students

UFPE/FCMG RESEARCH CHAIR IN RESERVOIR SIMULATION

Multi-physics Analysis, Optimization, and Uncertainty Propagation Applied to Reservoir Engineering



Laboratory for Computational Methods on Geomechnics

LMCG

UFPE

- **Main research area:**
  - **Numerical modeling of coupled phenomena (multi-physics) in porous media applied to oil and environmental engineering.**
- **Focus:**
  - **Finite element software to solve simultaneously thermo-hydro-mechanical and chemical problems with several levels of coupling (CODE_BRIGHT).**
  - **Constitutive modeling for the stress-strain behavior of soils and rocks (saline , brittle, clayey…), considering the effects of environmental variables such as temperature, suction and saline concentration in the material behavior.**

Introduction to Reservoir Geomechanics

1 Introduction

Definitions and some challenges of reservoir geomechanics.
Modeling of coupled phenomena.

2 Constitutive Laws: Behavior of Rocks

Fundamentals of Pore-Mechanics.

3 Constitutive Laws: Behavior of Fractures

Geomechanics of Fractured Media.

4 Reservoir Geomechanics

Elements of a geomechanical model and applications.

5 Unconventional Reservoirs

Naturally fractured reservoirs, hydraulic fracture, proppant and fracture closure model, validation (microseismicity).

6 Advanced Topics

Injection of reactive fluids and rock integrity.

UFPE

(semester course)

Introduction to Reservoir Geomechanics

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Introduction to Reservoir Geomechanics

Link to the course:

http://www.lmcg.ufpe.br/geomech/

Some important book references:

- Petroleum Related Rock Mechanics, Fjaer, E. et al. (2008).

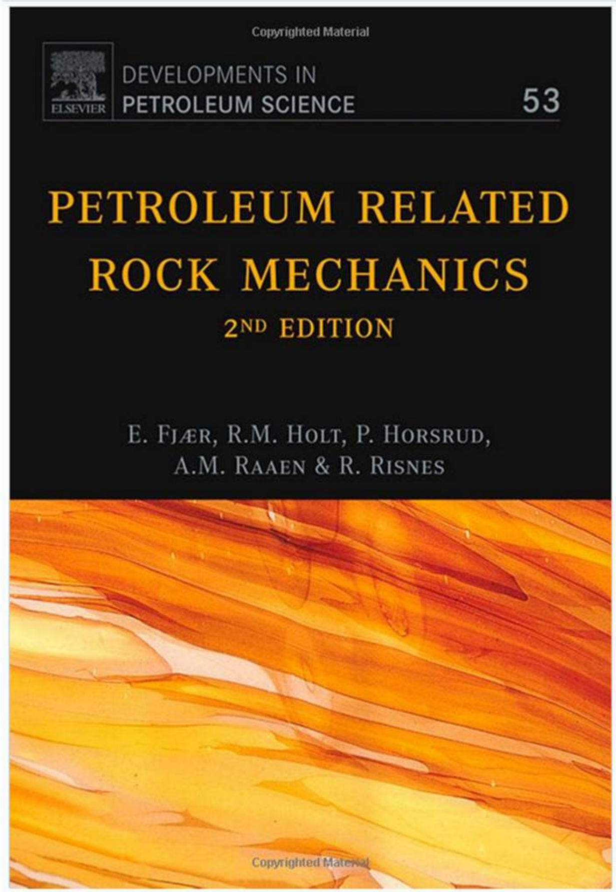
- Reservoir Geomechanic, Zoback, M. D. (2007).

-The Finite Element Method in the Static and Dynamic Deformation and Consolidation of Porous Media, Lewis & Schrefler (1998).

- Finite Element Analysis in Geotechnical Engineering: Theory (Vol 1) / Application (Vol 2), David M. Potts & Lidija Zdravkovic (2001)

Introduction to Reservoir Geomechanics

Description: engineers and geologists in the petroleum industry will find Petroleum Related Rock Mechanics, 2e, a powerful resource in providing a basis of rock mechanical knowledge - a knowledge which can greatly assist in the understanding of field behavior, design of test programs and the design of field operations. Not only does this text give an introduction to applications of rock mechanics within the petroleum industry, it has a strong focus on basics, drilling, production and reservoir engineering. Assessment of rock mechanical parameters is covered in depth, as is acoustic wave propagation in rocks, with possible link to 4D seismics as well as log interpretation.

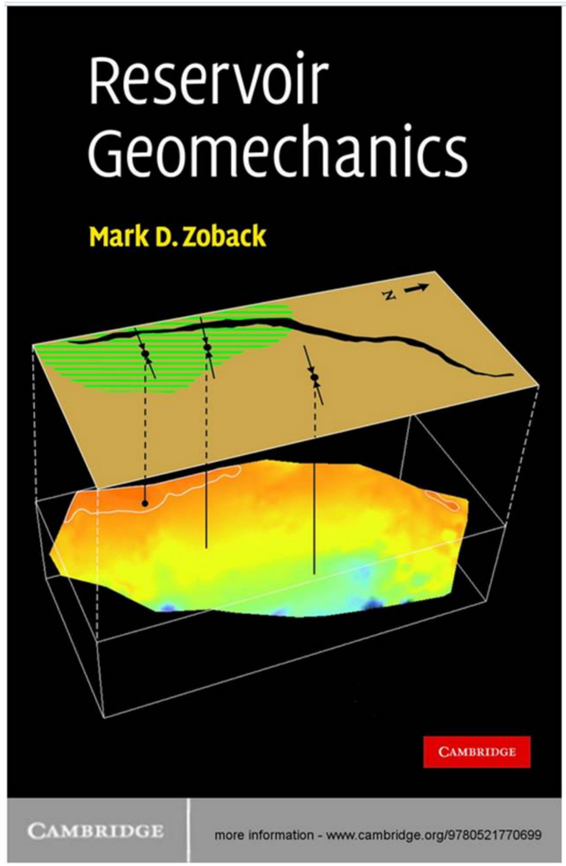


- ➔ Learn the basic principles behind rock mechanics from leading academic and industry experts
- ➔ Quick reference and guide for engineers and geologists working in the field
- ➔ Keep informed and up to date on all the latest methods and fundamental concepts

Table of Contents

Introduction to Reservoir Geomechanics

Description: this interdisciplinary book encompasses the fields of rock mechanics, **structural geology** and petroleum engineering to address a wide range of geomechanical problems that arise during the exploitation of oil and gas reservoirs. It considers key practical issues such as prediction of pore pressure, estimation of hydrocarbon column heights and fault seal potential, determination of optimally stable well trajectories, casing set points and mud weights, changes in reservoir performance during depletion, and production-induced faulting and subsidence. The book establishes the basic principles involved before introducing practical measurement and experimental techniques to improve recovery and reduce exploitation costs. It illustrates their successful application through case studies taken from oil and gas fields around the world.



This book is a practical reference for geoscientists and engineers in the petroleum and geothermal industries, and for research scientists interested in stress measurements and their application to problems of faulting and fluid flow in the crust.

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UFPE

Introduction to Reservoir Geomechanics

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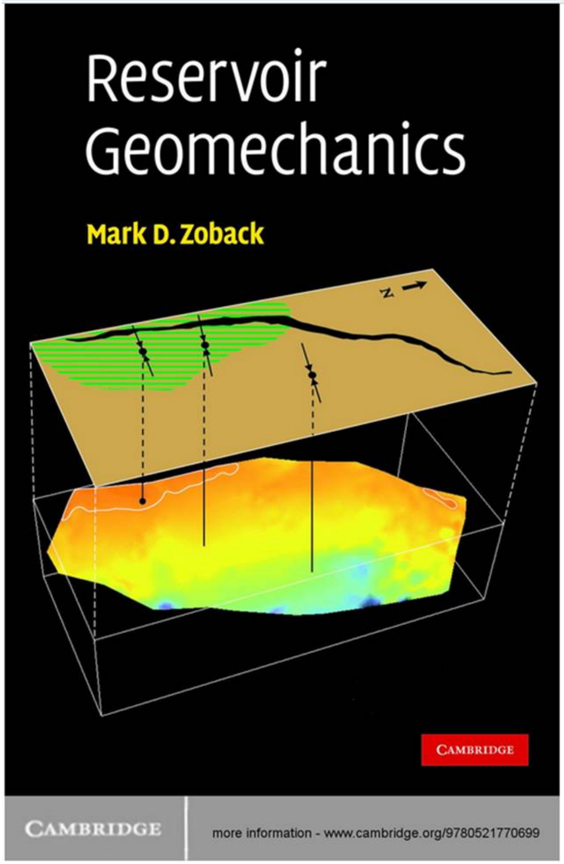
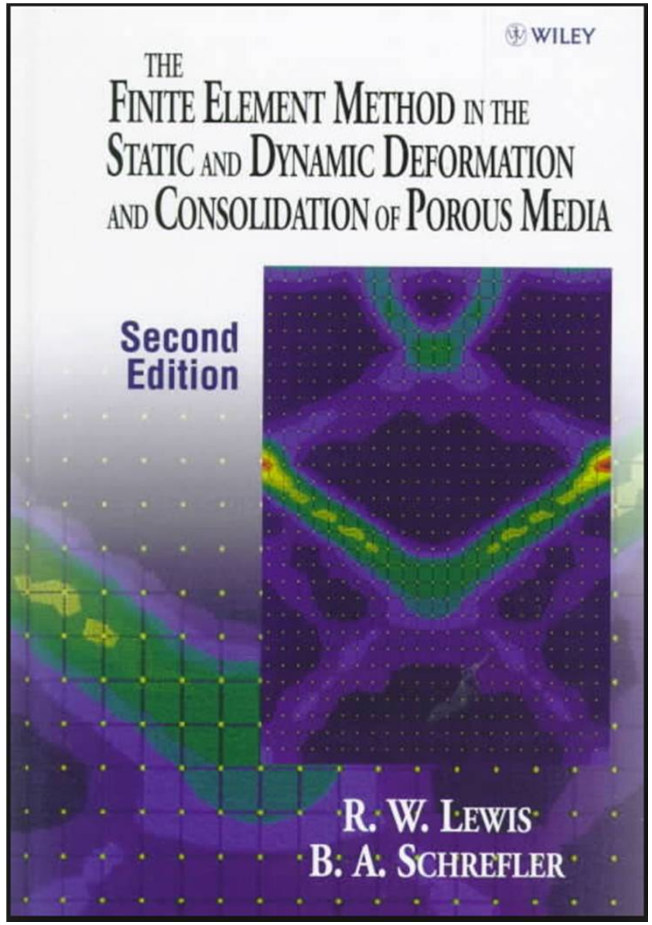


This book is a practical reference for geoscientists and engineers in the petroleum and geothermal industries, and for research scientists interested in stress measurements and their application to problems of faulting and fluid flow in the crust.

- ➔ **Introduction of elements of structural geology in the geomechanical analysis**
- ➔ **Stress polygon to determine in situ stress state**
- ➔ **Concept of critically stressed fractures in naturally fractured reservoirs**

Introduction to Reservoir Geomechanics

Description: this text deals with numerical solutions of coupled thermo-hydro-mechanical problems in porous media. Governing equations are newly derived in a general form using both averaging methods (hybrid mixture theory) and an engineering approach. Unique new features of the book include numerical solutions for fully and partially saturated consolidation, subsidence analysis including far field boundary conditions (Infinite Elements), new case studies and also petroleum reservoir simulation. Extended heat and mass transfer in partially saturated porous media, and consideration of phase change, are covered in detail. In addition, large strain, fully and partially saturated, soil dynamics problems are explained. Back analysis for consolidation problems is also included.

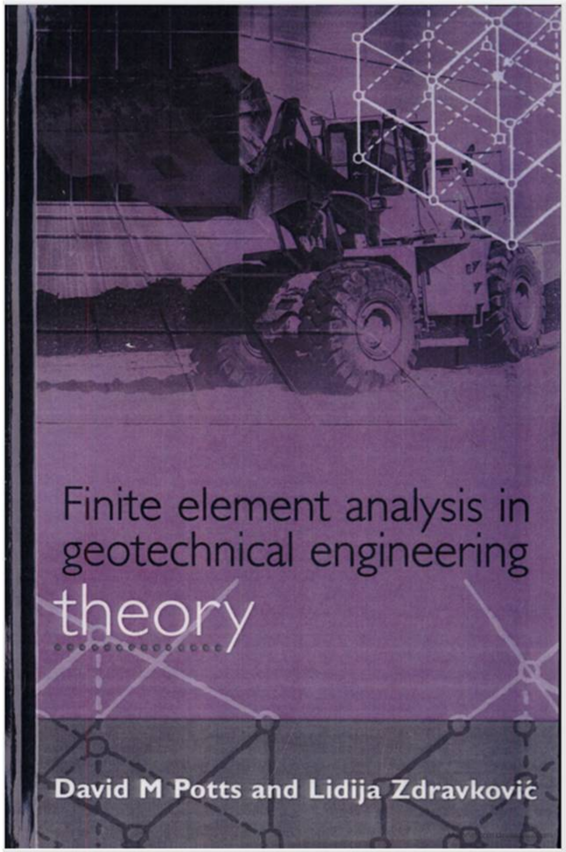


- **Detailed mathematical formulation of coupled thermo-hydro-mechanical problems in deformable porous media**
- **Detailed implementation in finite element codes (fully coupled scheme)**

important to correctly implement/use other coupling schemes

Significantly, the reader is provided with access to a Finite Element code for coupled thermo-hydro-mechanical problems in partially saturated porous media with full two phase flow and phase change, written according to the theory outlined in the book and obtainable via the Network of the Italian Research Council (COMES). With a range of engineering applications from geotechnical and petroleum engineering through to bioengineering and materials science, this book represents an important resource for students, researchers and practising engineers in all these and related fields.

Introduction to Reservoir Geomechanics



- **Numerical aspects related to geotechnical modeling using Finite Element Method** (initial stress state, excavation, interface elements...)

- **Constitutive modeling** (classical and advanced constitutive models, formulation of constitutive models using stress invariants, critical state models)

Description: this comprehensive new two-volume work provides the reader with a detailed insight into the use of the finite element method in geotechnical engineering. As specialist knowledge required to perform geotechnical finite element analysis is not normally part of a single engineering degree course, this lucid work will prove invaluable. It brings together essential information presented in a manner understandable to most engineers.Volume 1 presents the theory, assumptions and approximations involved in finite element analysis while Volume 2 concentrates on its practical applications.

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INTRODUCTION

Current state of Reservoir Simulation (Settari, 2003):

- Simulation models are now considered tools with widespread use
- Trend to increasing complexity
- Emphasis on user friendliness, robustness
- Understanding of the inner workings (and therefore limitations) is disappearing
- Expectations on the part of users are high
- Consolidation in the software industry left only a few players of mainstream software

INTRODUCTION

Sources of complexity in simulation (Settari, 2003):

- Explosion in the sophistication of 3-D seismic, geological and petrophysical modeling
- Use of stochastic methods for generation of reservoir properties
- Ever increasing computing power and data handling capacity
- Increasing understanding of complex, coupled processes in reservoir engineering

RESERVOIR GEOMECHANICS

Geomechanical coupling should only be performed when one believes in the quality of the simulation model

INTRODUCTION

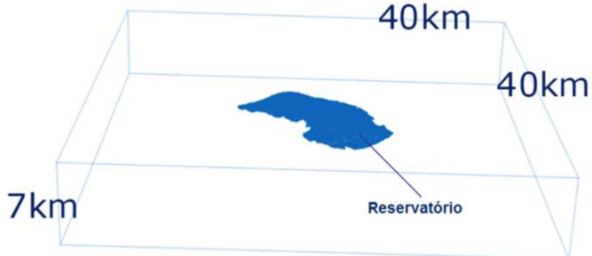
Complexity of physical processes (Settari, 2003):

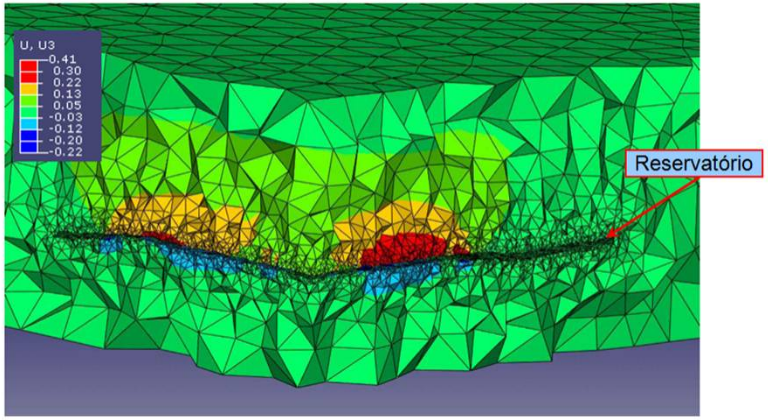
- Complexities related to fluid flow and heat transfer (in the reservoir and surface networks) have been extensively studied and still evolving
- Rock/soil behavior (**geomechanics**) is just as complex, but has been simplified in modeling
- Other processes (**geochemistry**, solids transport,…) may be important in special cases
- **Geomechanical** aspects have been traditionally consider by drilling, completion and production engineers in isolation from reservoir engineering

Coupled geomechanical modeling (Settari, 2003):

- Simultaneous modeling of fluid flow and heat transfer (conventional simulation) and stresses and strains in the reservoir AND its surroundings
- Fracture mechanics modeling can be also considered
- The physical coupling between all processes is accounted for

INTRODUCTION





Reservoir into geomechanical model: huge volume of rock is considered

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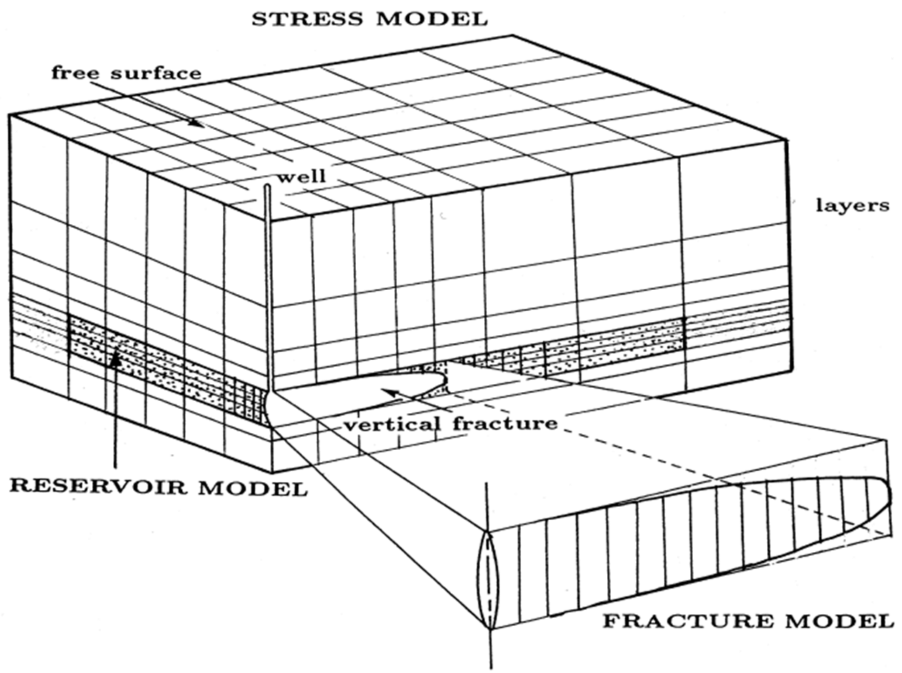
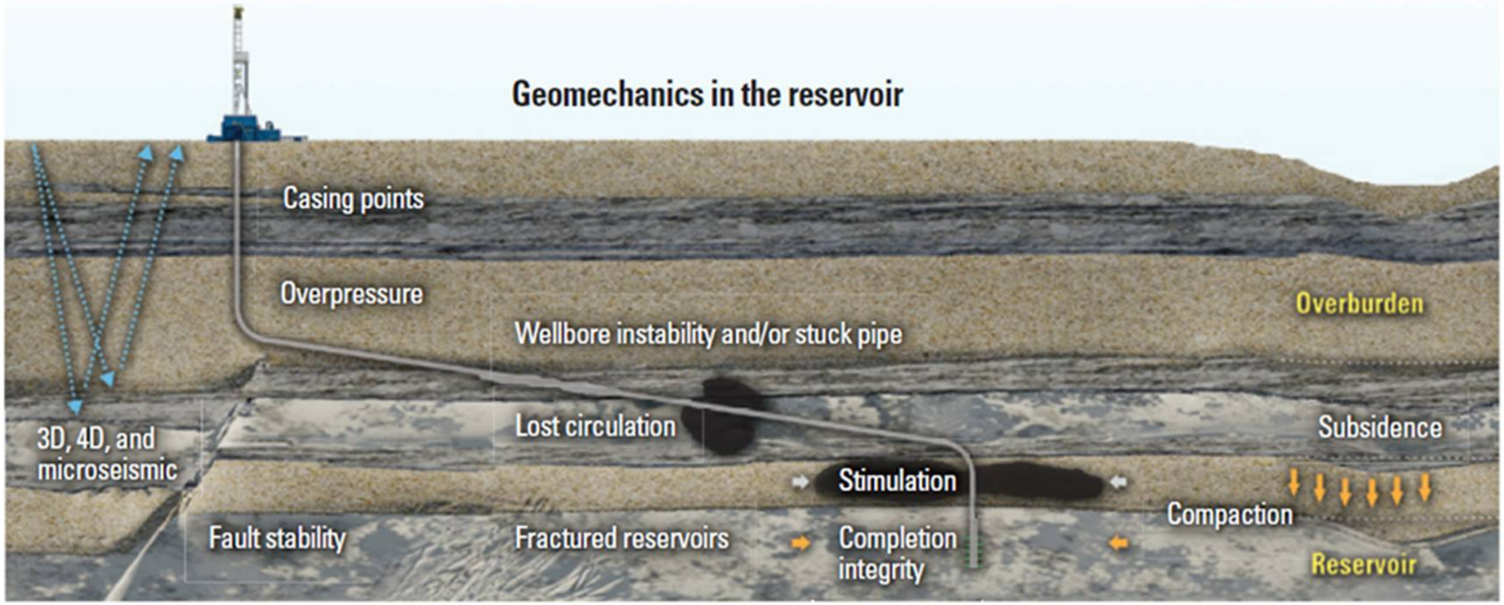
INTRODUCTION

Why consider Geomechanics in reservoir simulation? (Settari, 2003)

- Majority of the reservoir material is rock or soil (skeleton), not fluids!
- Rock/soil deformation can have a large effect on recovery - coupling exists between solid and fluid mechanics
- Conventional (uncoupled) modeling which ignores the complexity of the skeleton behavior can be inadequate or misleading
- Coupled modeling can answer questions beyond classical reservoir engineering (opportunity for integrated reservoir management)

Coupled Reservoir, Stress and Fracture Mechanical Model





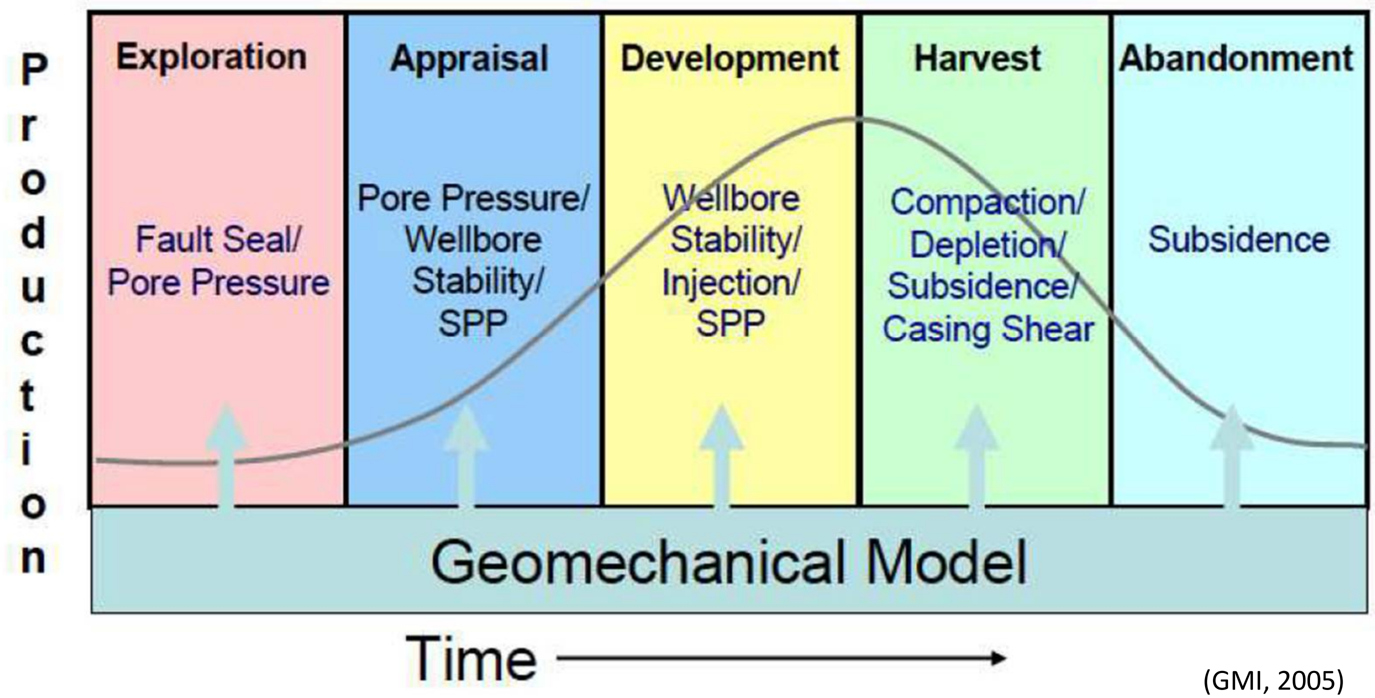
Effects occur in the reservoir and the over- and under-burden, not only in weak compacting rocks. Geomechanics can affect depletion, hot/cold injection, disposal, CO_2, and underground storage.

RESERVOIR GEOMECHANICS

Understand and predict phenomena such as:

- **Fault reactivation (cap rock integrity)**
- **Fracturing of cap rock (cap rock integrity)**
- **Reservoir compaction and subsidence (reservoir performance)**
- **Naturally fractured reservoirs (reservoir performance)**
- **Geomechanical damage (well performance)**
- **etc**

The role of **Geomechanics** in field development:



(GMI, 2005)

- **Exploration**: makes it easier to predict the pore pressure, hydrocarbon column height and the sealing potential of faults

- **Development**: well stability due to the determination of optimal stress path; determining the critical or optimum mud weight and predict anisotropic permeability in fractured reservoirs.

- **Harvest**: completion methods used on wells, prediction of changes in reservoir performance during depletion and increase the recovery factor of reservoir.

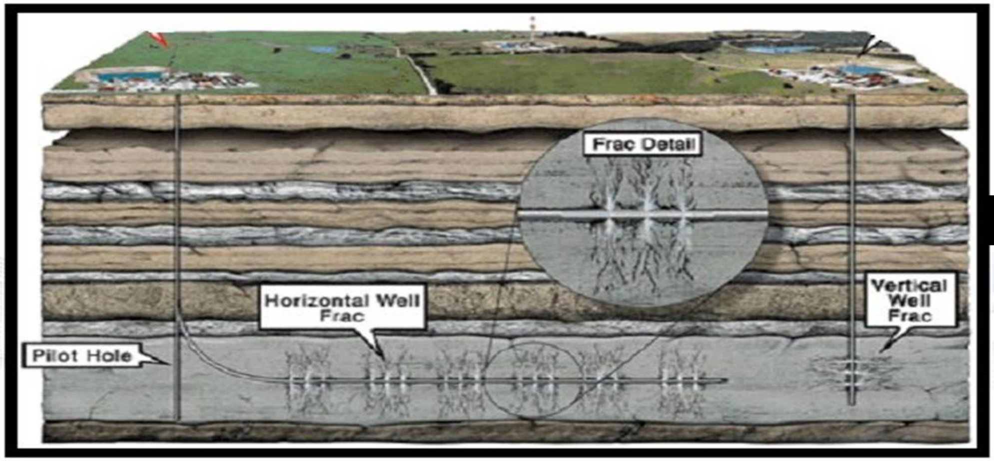
- **Secondary and Enhanced oil recovery**: better schemes of water/CO_2/steam flooding

INTRODUCTION

Stress Sensitive Reservoirs – candidates for geomechanical engineering (Settari, 2003):

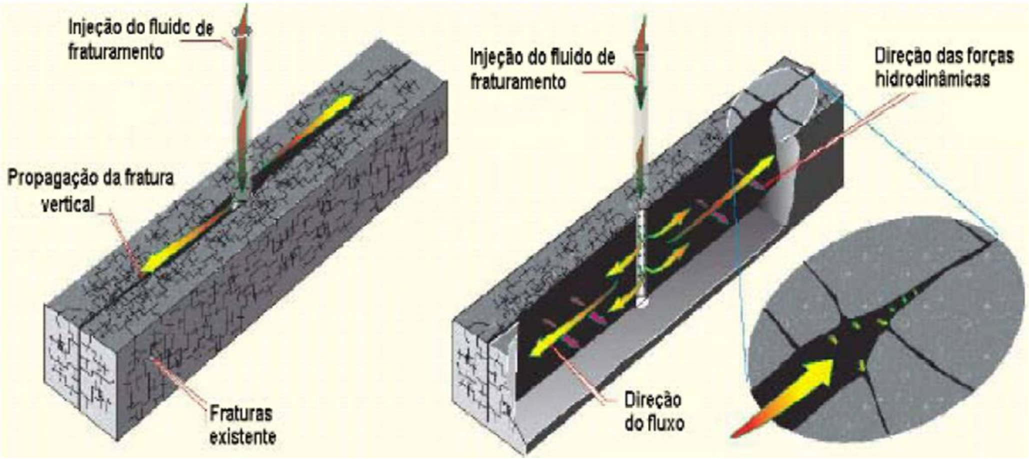
- Unconsolidated sands (oil sands, aquifer zones for disposal,...)
- Loose sands (Diatomite, Gulf of Mexico, compacting reservoirs ...)
- Chalk reservoirs (often naturally fractured)
- Low permeability rock (in particular microfractured)
- Coal seams (cleat systems are stress sensitive)
- Shales

Other candidates:
-Very shalow or very deep reservoirs
- Sand production or fine migration
-HP/HT injection
- Highly depleted reservoirs
- Reservoir crossed by faults



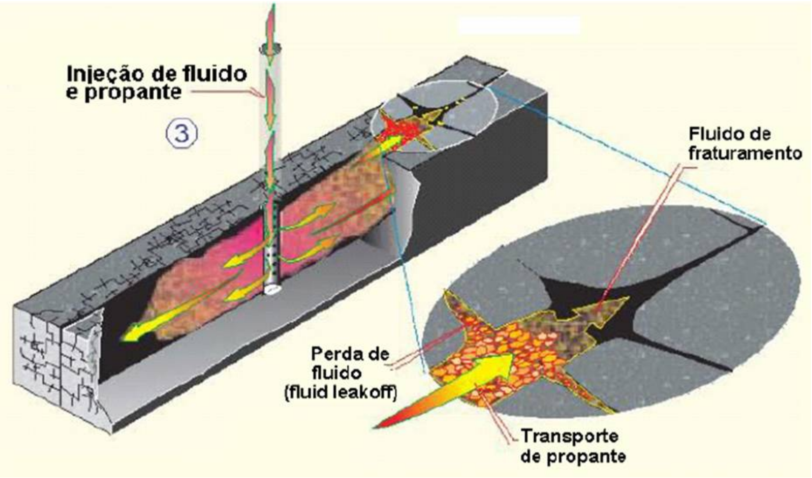
Hydraulic fracturing in shale gas

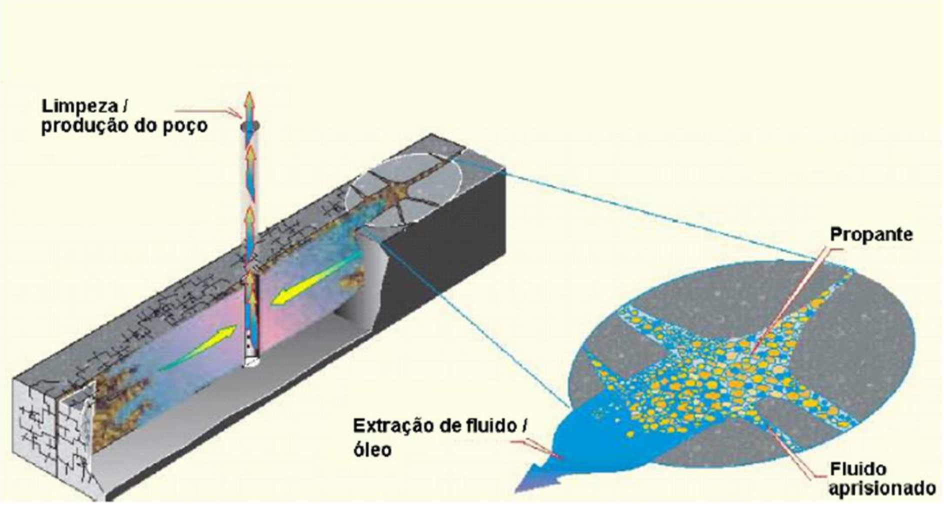
Example: shale gas



1) Bombeamento a altas pressões de um líquido (fluido de fraturamento), através de um poço em uma formação subterrânea para causar a propagação de fraturas na rocha e permitir a extração de petróleo e gás natural. O líquido mais comum é a água, que é misturada com alguns produtos químicos, para que tenha sua consistência aumentada.

(Cachay, 2004)



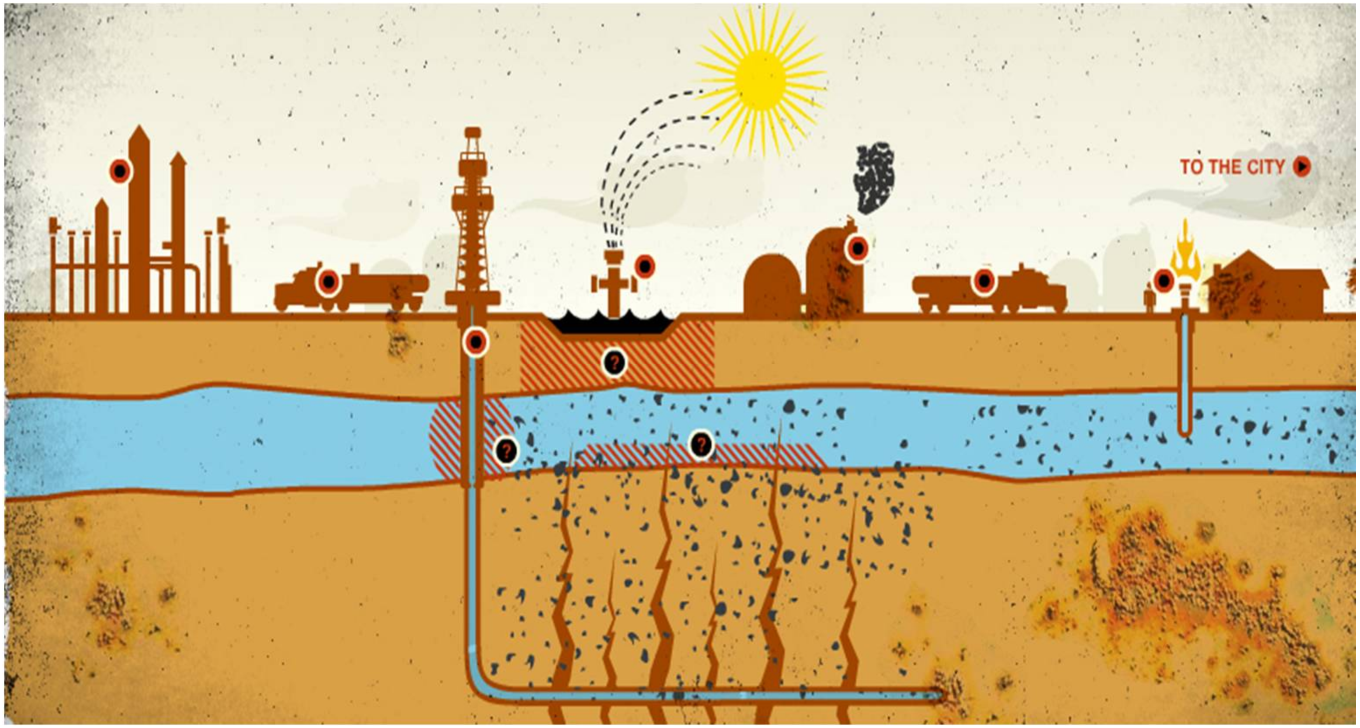


2) Uma fratura induzida hidraulicamente é mantida aberta pela pressão aplicada pelo fluido e para mantê-la aberta após a interrupção do bombeamento, introduz-se um material granular conhecido como material de sustentação ou propante, criando um canal de fluxo de alta permeabilidade estável no interior da formação e conectado ao poço.

3) A última etapa consiste na limpeza do poço, onde normalmente ocorre uma baixa produção de material de sustentação (proppant flowback) devido à presença de propante no poço logo após o tratamento da fratura.

Example: shale gas

(Source: The Old Speak Journal, 2011)



Contamination of an aquifer caused by hydraulic fracturing

***Enviromental Geomechanics*:**

Geomechnics is often dealing with enviromental problems

INTRODUCTION

Coupling between reservoir flow and rock or soil mechanics (Settari, 2003):

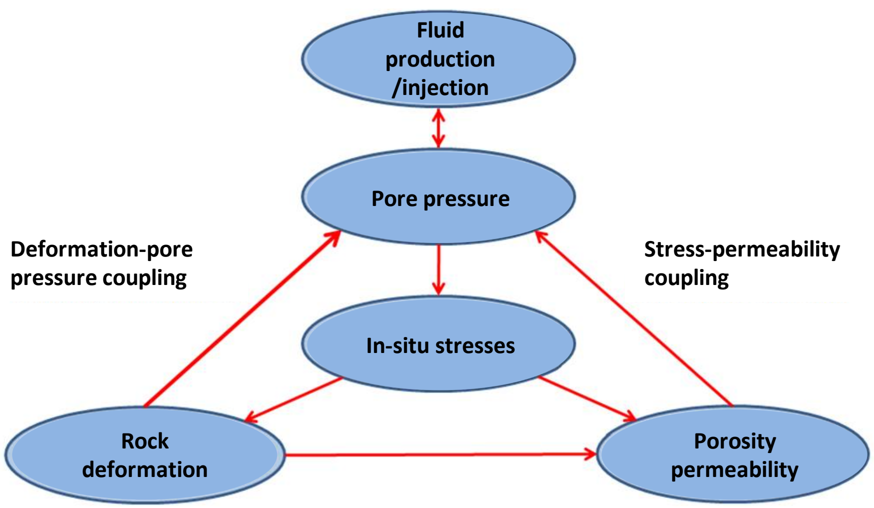
- Volume Coupling
  - Rock matrix (skeleton) elastic moduli and volume changes are functions of stress state and temperature
  - Pore volumes changes in the reservoir mode must be the same as those computed in the solid modeling by volumetric strain and bulk volume changes
- Flow Properties Coupling
  - Permeability function of stress state
  - Larger changes after failure, develops anisotropy
  - Creation of dual porosity system in-situ – affects k_{rl}
  - Induced fractures

INTRODUCTION

Coupling between reservoir flow and rock or soil mechanics:

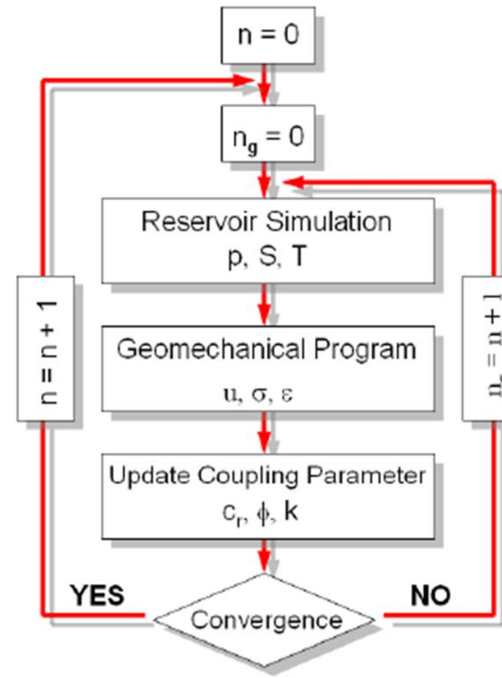
PHYSICAL COUPLING

(Gutierrez, M. and Lewis, R. W., 1998)



NUMERICAL COUPLING

(Fleming, P. D., 2004)

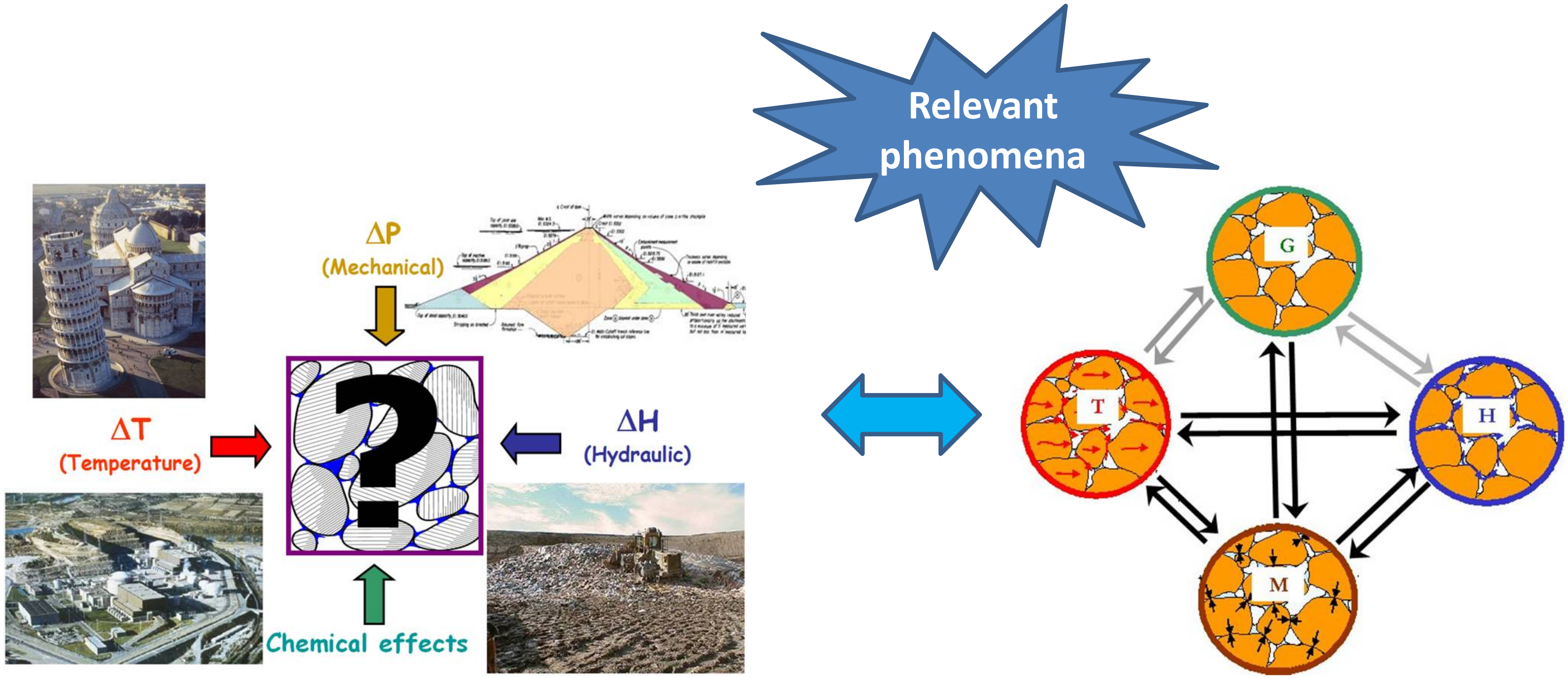


Multiphysical Approach!!

Multiphysical Approach

In the development of numerical tools to analyze engineering problems involving geomaterials there has been a strong trend towards coupled formulations incorporating an increasing number of phenomena.

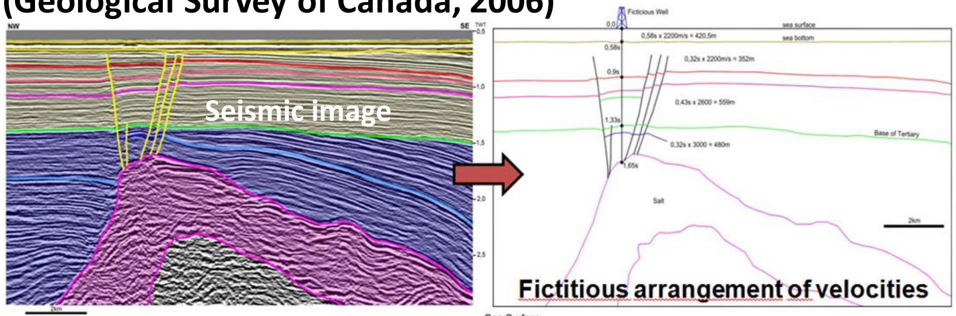
The aim is to account for the full range of interactions between the various processes occurring simultaneously in the same problem.

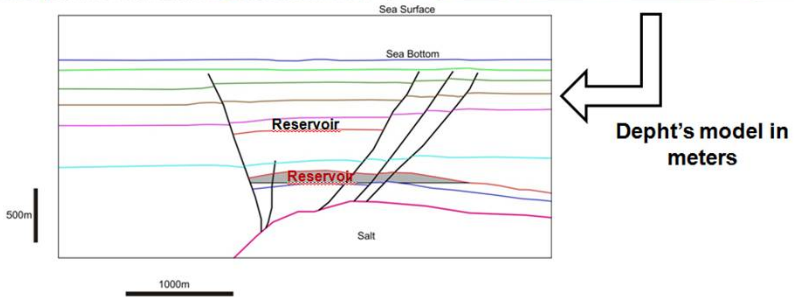


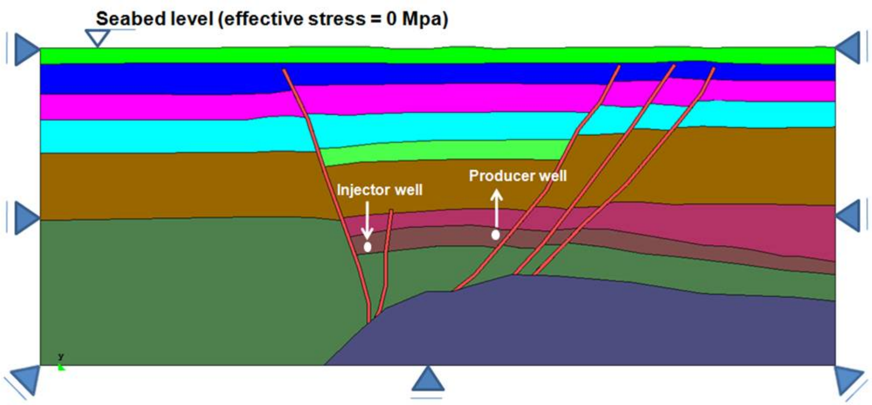
Fault Reactivation

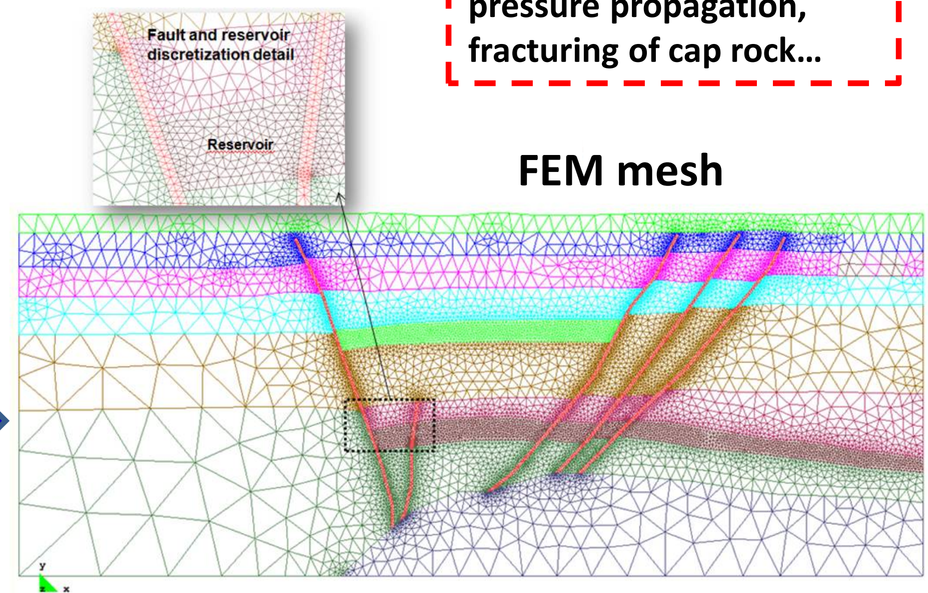
HM Problem

(Geological Survey of Canada, 2006)









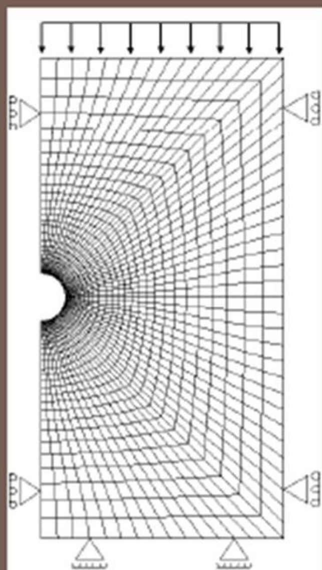
In oil reservoirs with fault reactivation possibility, coupled hydro-geomechanical analysis is a important tool in the definition of maximum bottom hole pressure of the injectors as it takes into account the main phenomena and material parameters involved in the physical problem.

MAXIMUM BHP?

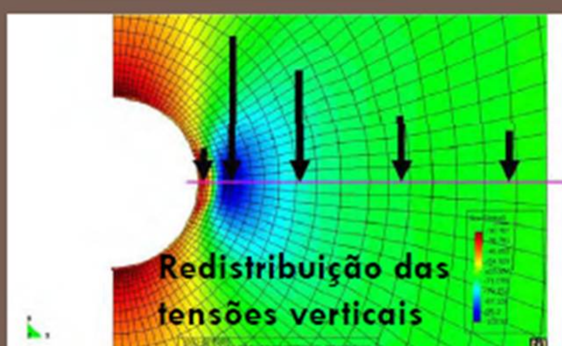
Relevant phenomena: shearing, dilatation, increase of permeability, pressure propagation, fracturing of cap rock…

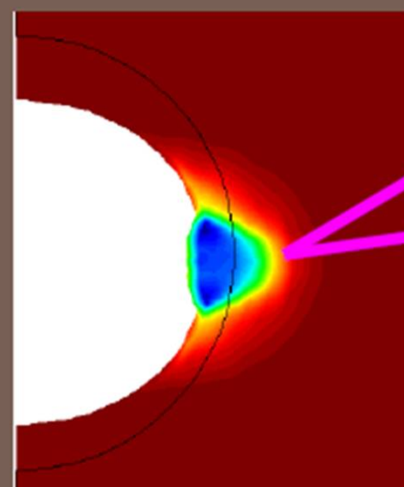
Wellbore Stability (Breakout)

HM Problem

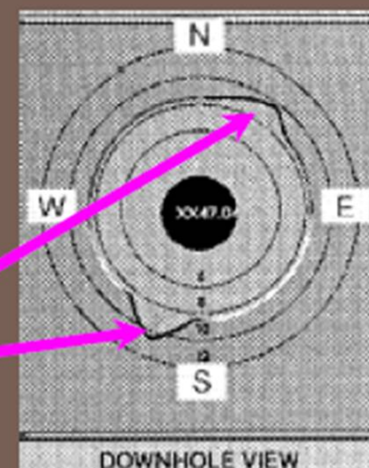


Hydro-mechanical modeling of well drilling in elasto-plastic material.





Brittle rock: localized yielding in well wall.



Ultrasonic image of well profile showing breakout in the direction of the minimum principal stress.

(Soliman e Boonen, 2000)

HM FORMULATION

Problem domain:
Coupled hydro-mechanical analysis of deformable porous media

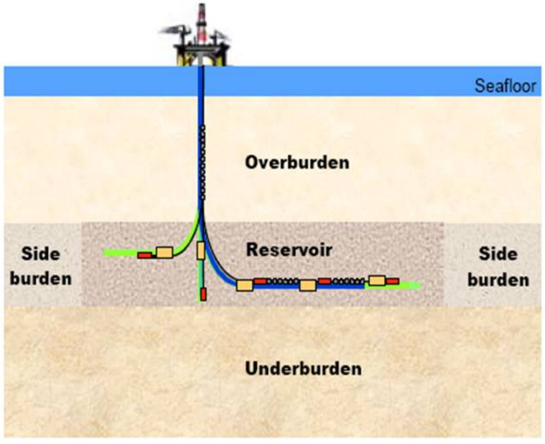
Wellbore stability

Compaction and subsidence

Fault reactivation

Hydraulic fracturing

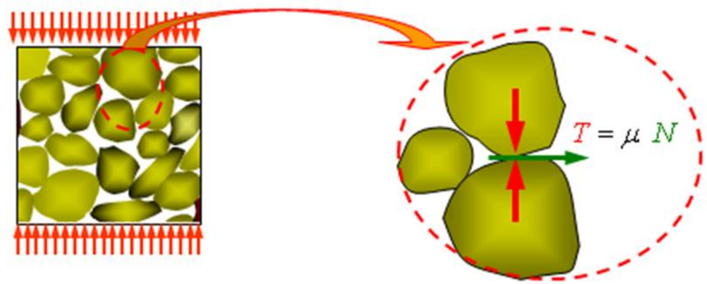
...

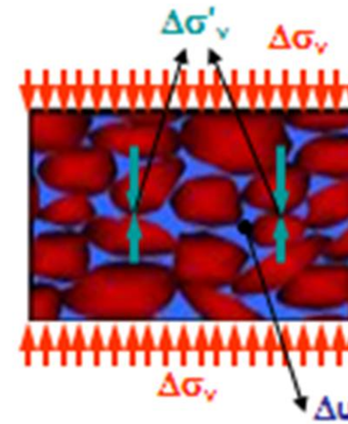


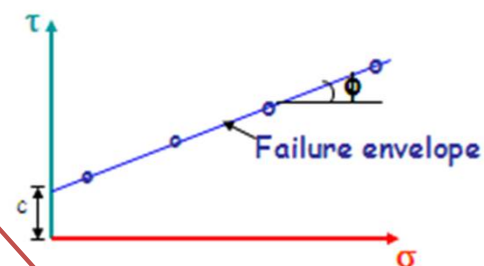
HM FORMULATION

Requirements for this type of analyses

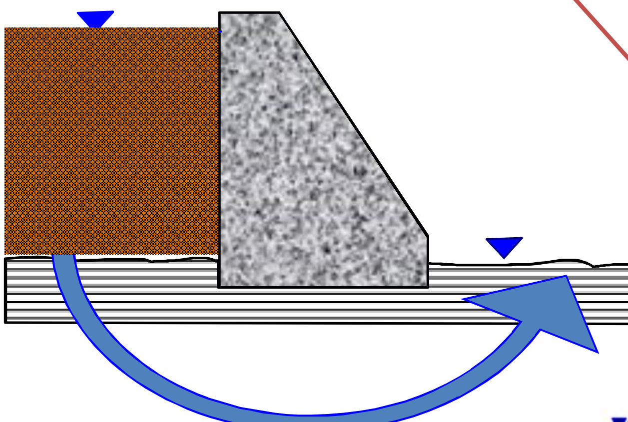
1) Mastering the physics of the HM problem
(conservation and constitutive equations)





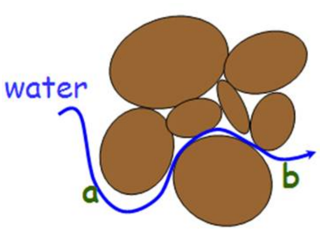


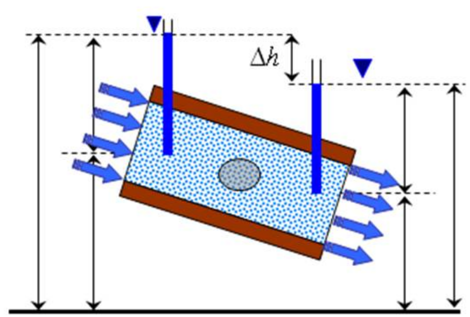
$$\Delta\sigma_v = \Delta u + \Delta\sigma'_v$$



M

H





$$\mathbf{v} = -\mathbf{K}\ \nabla h$$

$$h = z + \frac{u}{\gamma_w}$$

HM FORMULATION

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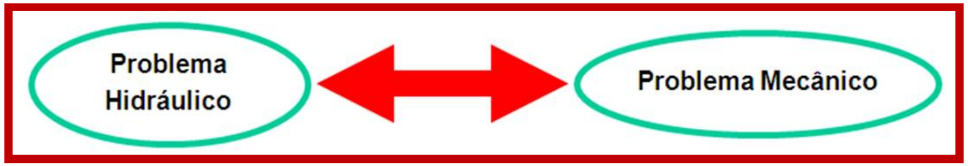
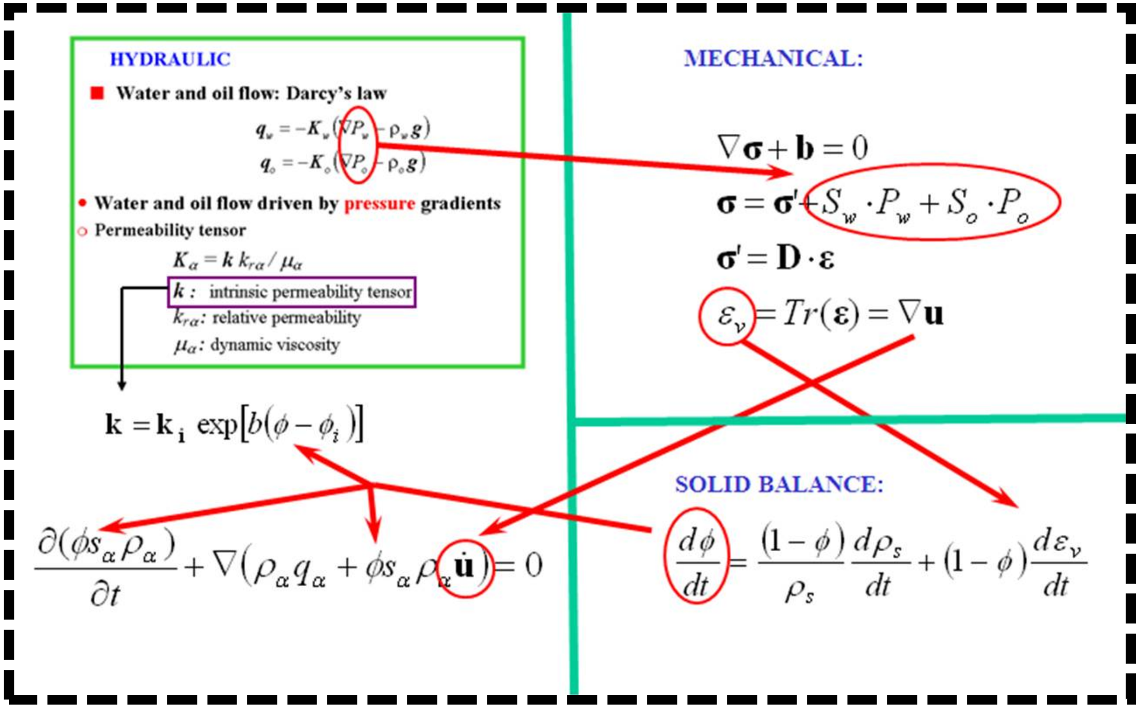
1) Mastering the physics of the HM problem
(conservation and constitutive equations)

High level of physical coupling





High level of numerical coupling

HM FORMULATION

Requirements for this type of analyses

1) **Mastering the physics of the HM problem** (conservation and constitutive equations)

2) **Discretization technique → FEM**

M: (u)

$$\nabla \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$$

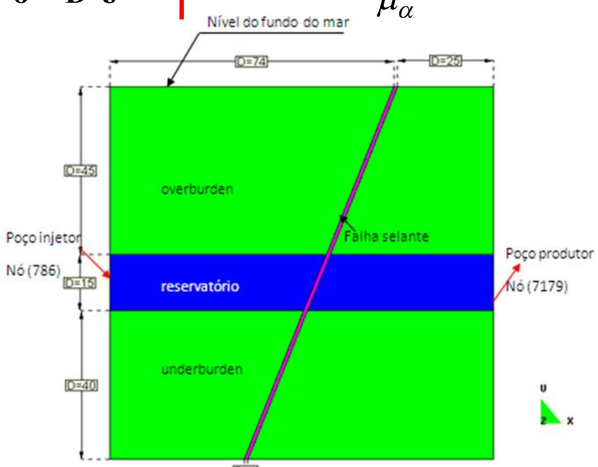
$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + p_f \cdot \mathbf{I}$$

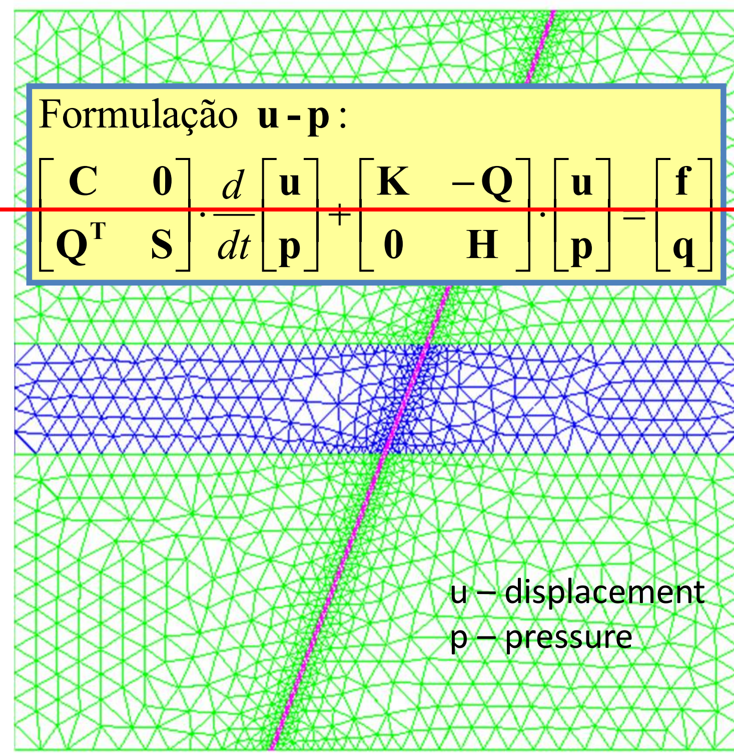
$$\boldsymbol{\sigma}' = \mathbf{D} \cdot \boldsymbol{\varepsilon}$$

H: (p)

$$\frac{\partial(\phi s_\alpha \rho_\alpha)}{\partial t} + \nabla\left(\rho_\alpha q_\alpha + \phi s_\alpha \rho_\alpha \dot{\mathbf{u}}\right) = 0$$

$$q_\alpha = -\frac{k k_{r\alpha}}{\mu_\alpha}\left(\nabla p_\alpha - \rho_\alpha \tilde{g}\right)$$





Formulação **u - p**:

$$\begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{Q}^T & \mathbf{S} \end{bmatrix} \cdot \frac{d}{dt}\begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & -\mathbf{Q} \\ \mathbf{0} & \mathbf{H} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{q} \end{bmatrix}$$

u – displacement

p – pressure

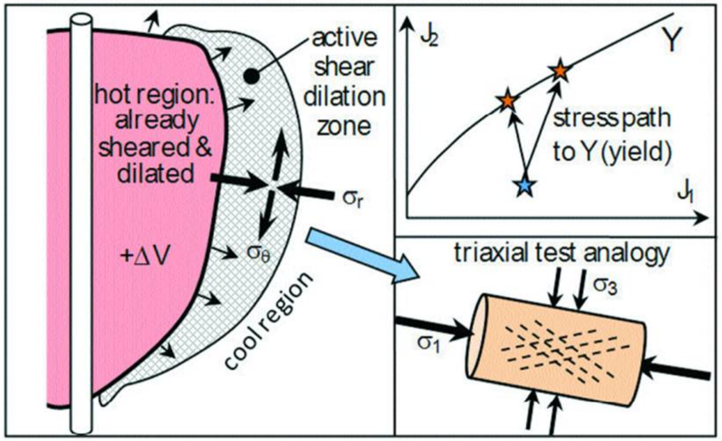
Thermal Oil Recovery

THM Problem

(Dusseault and Collins, 2008)

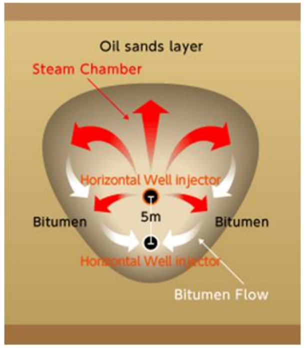
Steam Processes	Other ΔT Processes
Steam drive (pattern, line drive, alternating..) Steam flood, steam soak Cyclic steam stimulation • Vertical wells – CSS • Horizontal wells – HCS Steam-assisted gravity drainage methods • SAGD • SAGD plus gas injection Hybrid methods (e.g. HCS + cyclic solvent injection)	Combustion methods • Toe-to-heel air injection - THAI™ • Other approaches Electrical heating • Closed-well Ω heating • Inductance, RF heating Hot solvent or hydrocarbon vapour injection Closed-well steam injection Hybrid methods (e.g. electrical heat + solvent)

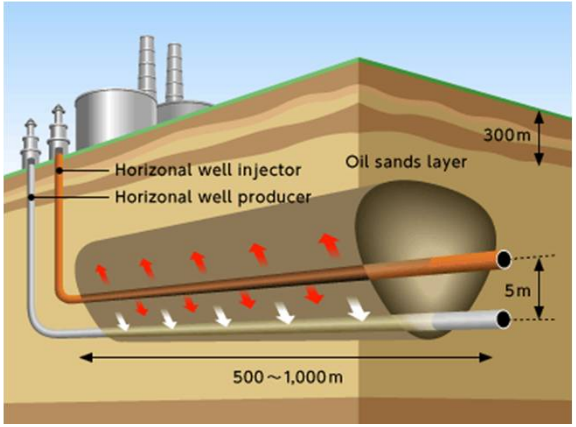
Geomechanical effects:
Shearing, Dilation, and
Mechanical Damage of the Rock

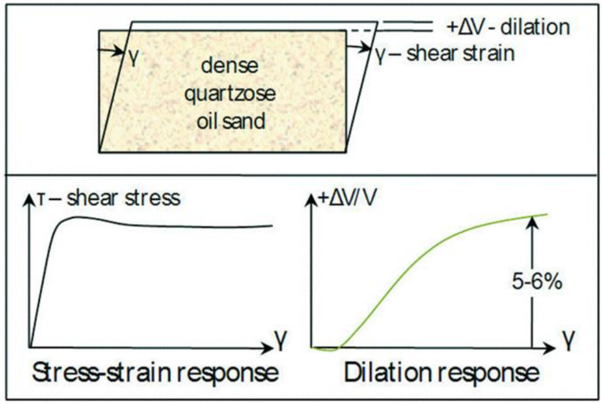


Stress Changes in Advance of a Steam Chamber (e.g. SAGD)

SAGD



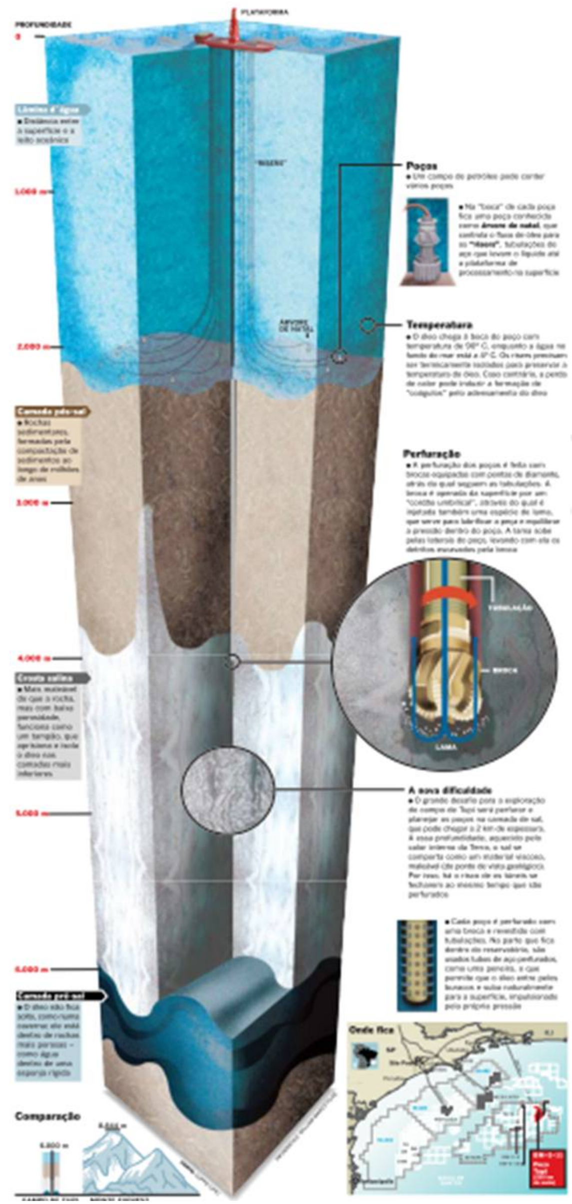


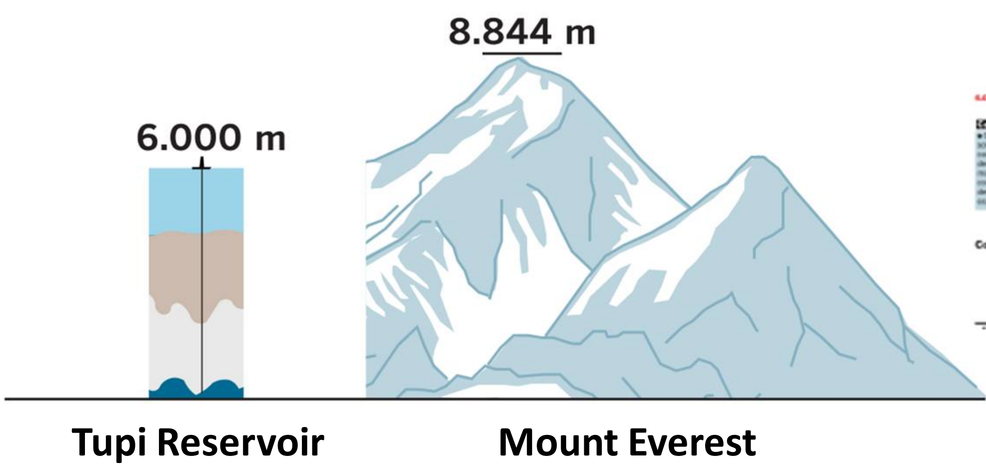


Shear Dilation of an Unconsolidated Sandstone

New Brazilian Pre-Salt Carbonate Reservoirs (ultra-deep waters reservoir):

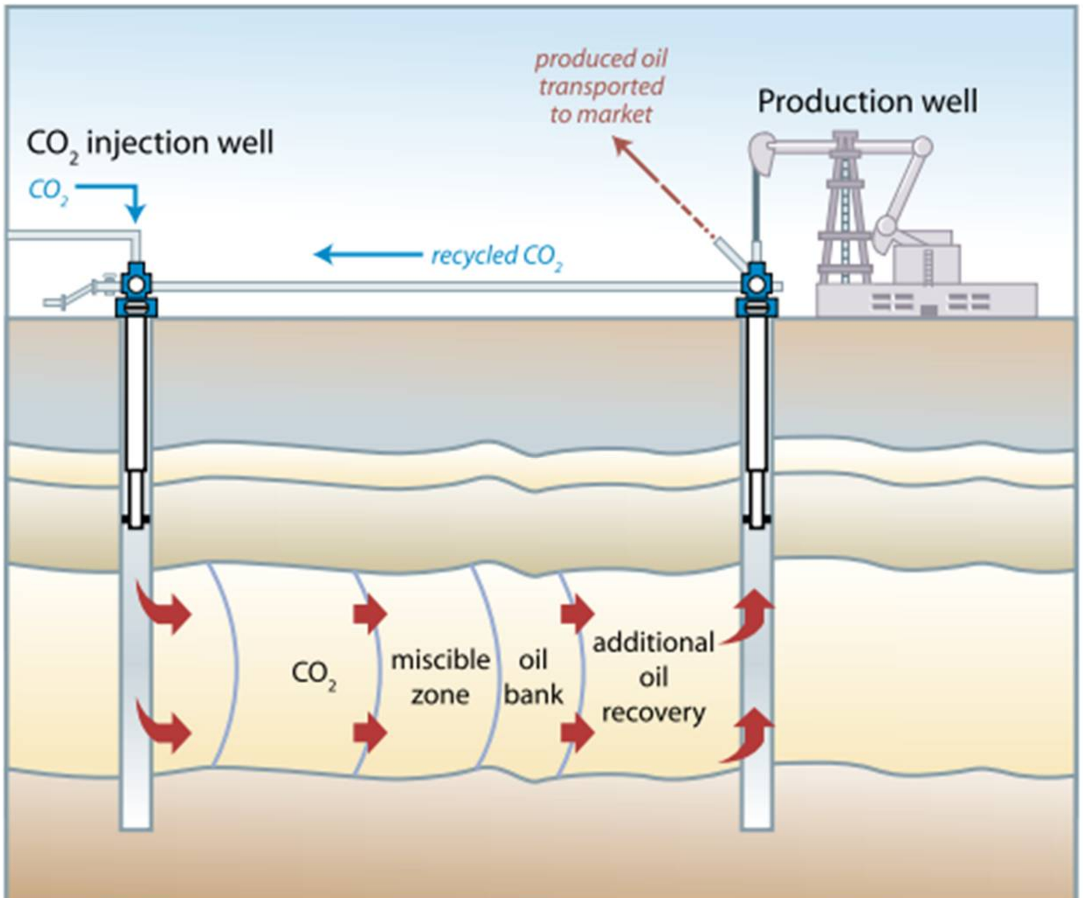
- Reservoir and cap rocks integrity (geomechanical and chemical)
- Reservoir properties (coupled HMC phenomena)
- CO_2 injection (multiphase multispecies modeling)
- 300km from coast (optimazed management)





CO2 underground geological storage:

Carbonate reservoirs: new deformational mechanisms can take place in the medium



$$CO_2 + H_2O = HCO_3^- + H^+$$

(water acidification)

$$CaCO_3(s) + H^+ = Ca^{2+} + HCO_3^-$$

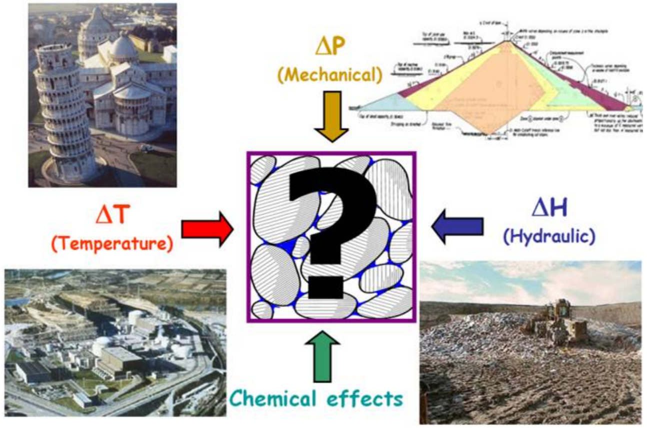
(calcite dissolution)

Waterweakening

[**Chemo-mechanical mechanism**]

Coupled Analysis of Real Problems

How to solve real coupled problems?

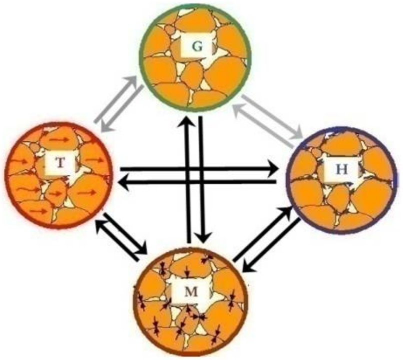


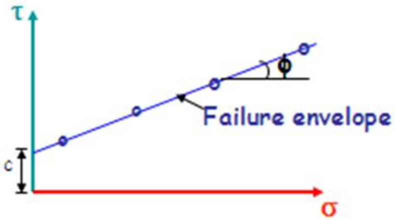
- Select the relevant phenomena

- Perform experiments

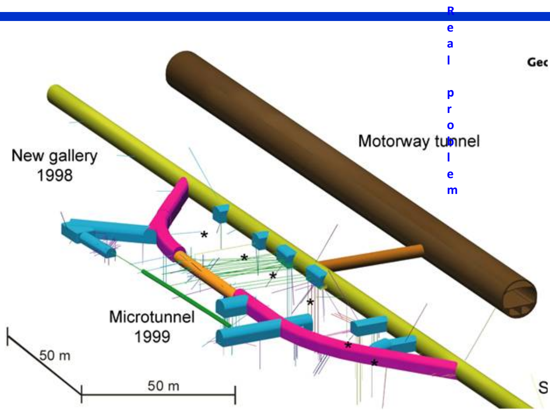
- Formulate constitutive laws

- Develop a numerical tool



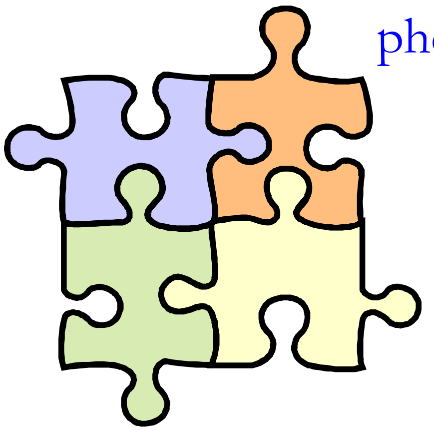


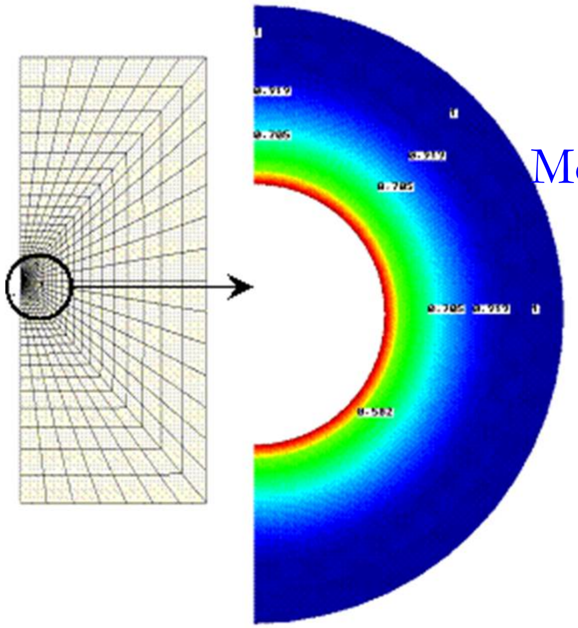
VALIDATION at field and experimental scales



$$\frac{\partial}{\partial t}\left(\theta_l^w S_l \phi + \theta_g^w S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w$$

Relevant phenomena





Modelling

Laboratory tests