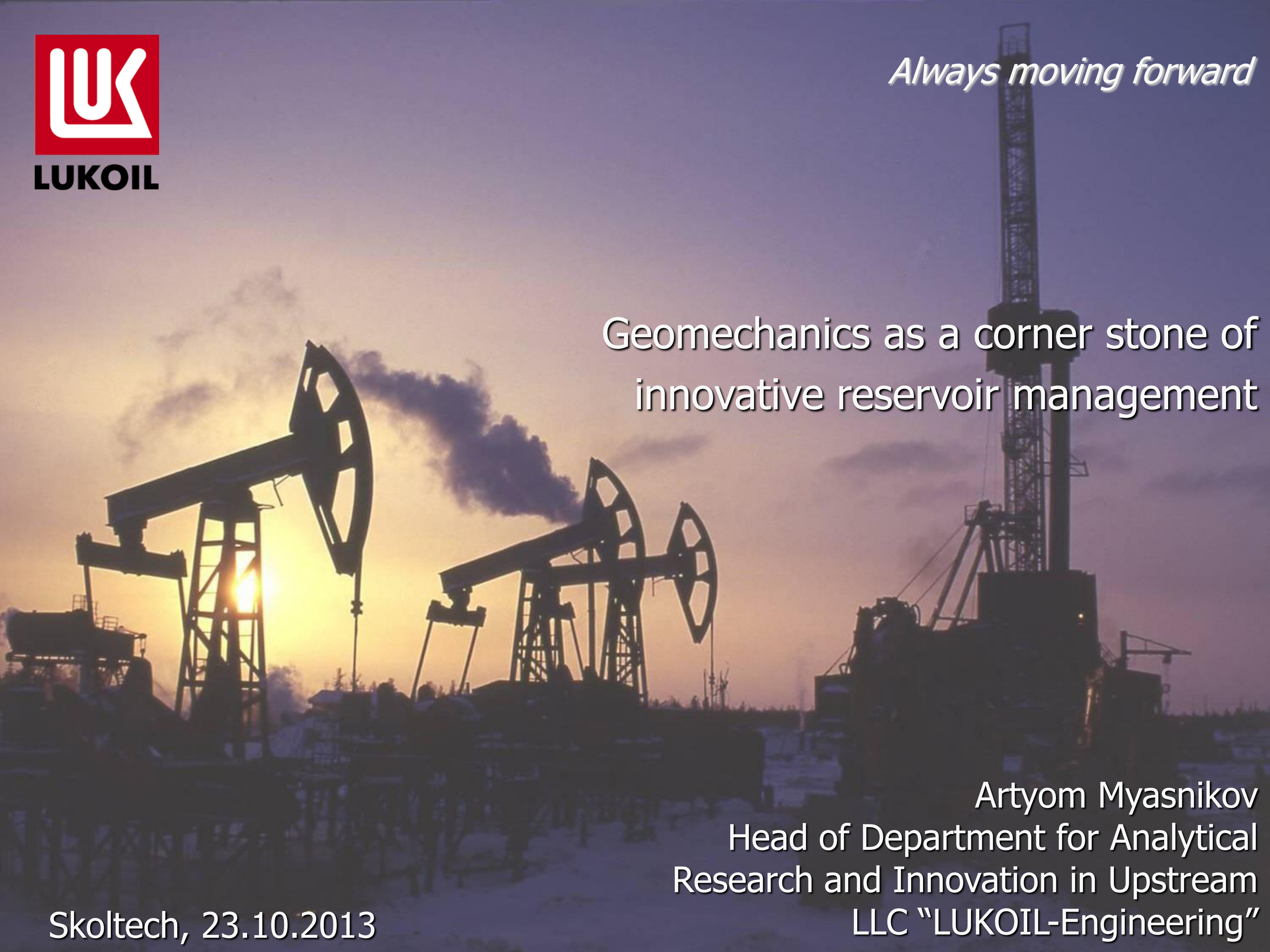


Always moving forward

Geomechanics as a corner stone of innovative reservoir management

Artyom Myasnikov
Head of Department for Analytical Research and Innovation in Upstream
LLC "LUKOIL-Engineering"

Skoltech, 23.10.2013

Innovations are the necessary and sufficient condition for the prosperity – *the LUKOIL's understanding*

- ☐ A competitive environment for vertically integrated oil companies is presently formed up both at Russian and worldwide markets.
- ☐ Successful survival and further development of a company depends on its ability to reveal and make use of additional source for competition in this environment.
- ☐ On of such sources (but not the only one) is turning on an innovative way of development

- ☐ The Russian President instructed state-owned companies to develop the innovative programs and to allocate significant stokes of money R&D activity.
- ☐ The State created legislative and organizational basis of the national innovative system. Innovative development of the country is recognized as the high level priority and this understanding is set up at the top political and management levels of the Government and the presidential administration.

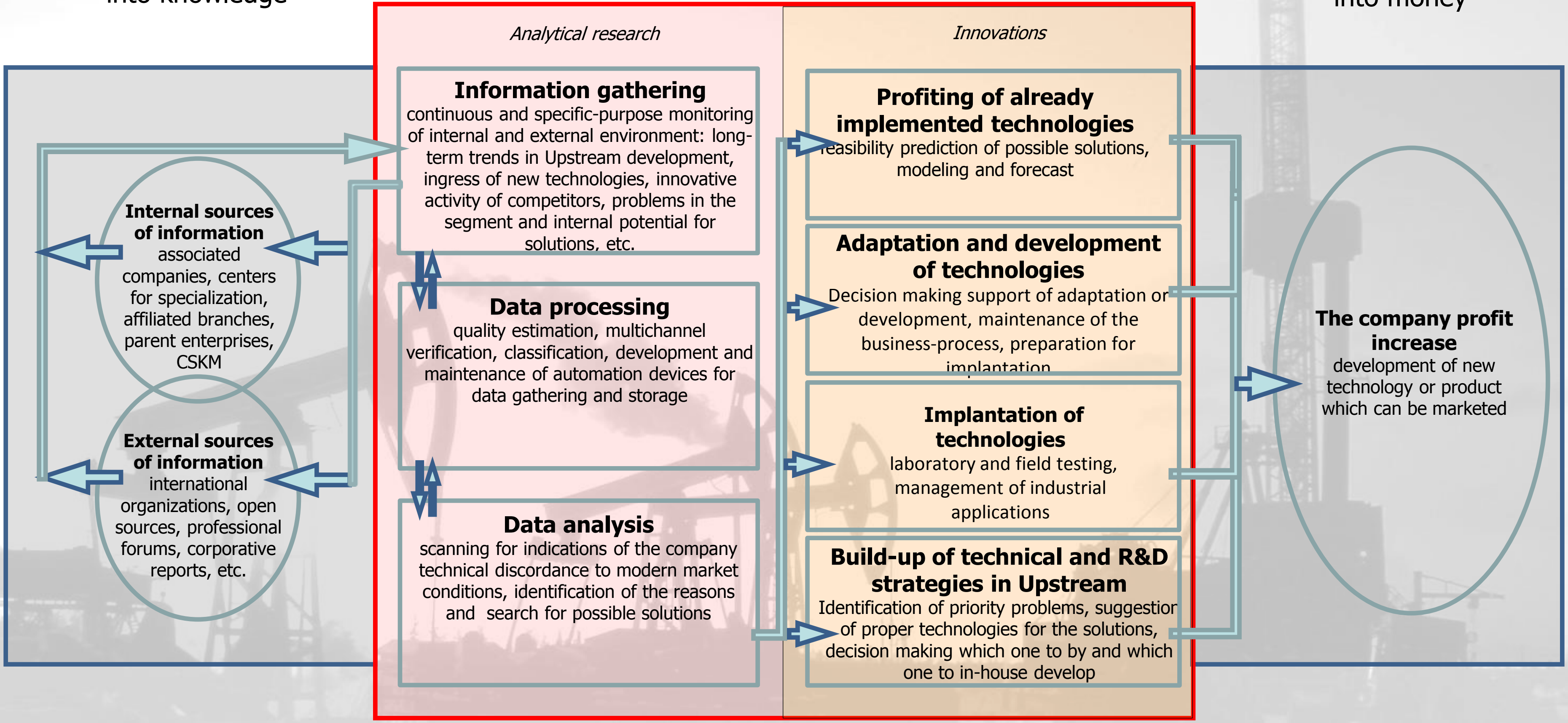
- ☐ State-owned companies are already involved in the innovative process, whenever they like it or not. In the friendly environment for the involved companies, all other private companies should be involved as well if the want to win in the permanently growing competition .

Structure of R&D activity in Upstream – *the LUKOIL's vision*

Science – is a transformation of money into knowledge

R&D activity

Innovations – is a transformation of knowledge into money



Analytical research

Information gathering
continuous and specific-purpose monitoring of internal and external environment: long-term trends in Upstream development, ingress of new technologies, innovative activity of competitors, problems in the segment and internal potential for solutions, etc.

Data processing
quality estimation, multichannel verification, classification, development and maintenance of automation devices for data gathering and storage

Data analysis
scanning for indications of the company technical discordance to modern market conditions, identification of the reasons and search for possible solutions

Innovations

Profiting of already implemented technologies
feasibility prediction of possible solutions, modeling and forecast

Adaptation and development of technologies
Decision making support of adaptation or development, maintenance of the business-process, preparation for implantation

Implantation of technologies
laboratory and field testing, management of industrial applications

Build-up of technical and R&D strategies in Upstream
Identification of priority problems, suggestion of proper technologies for the solutions, decision making which one to by and which one to in-house develop

Internal sources of information
associated companies, centers for specialization, affiliated branches, parent enterprises, CSKM

External sources of information
international organizations, open sources, professional forums, corporative reports, etc.

The company profit increase
development of new technology or product which can be marketed

External sourcing of information: *how does this works*

- *SPE Forum & Meetings **"Petrophysics meets Well Testing"** (27.06.2010-02.07.2010);*
- *SPE & EAGE & SEG publications*
- *Discussions in LinkedIn and other forums groups etc*
- *Monitoring Industrial Research: The EU Industrial R&D Scoreboard», JRC*

economics of Industrial Research & Innovation

Welcome

The Economics of Industrial Research & Innovation (IRI) is a scientific action carried out within the Institute for Prospective Technological Studies (IPTS), one of the seven scientific institutes of the European Commission's Joint Research Centre (JRC).

Meet the IRI Team >>

Highlights

- NEW: The 2010 EU Survey on R&D Investment Business Trends
- CONCORD 2011 Conference - Call for abstracts now open
- Summary of Workshop on The dynamics of EU industrial structure and the growth of innovative firms
- The 2010 EU Industrial R&D Investment Scoreboard
- The 2010 CONCORD Summary Reports

What do we do?

The action aims at providing EU policy-makers and the business and academic communities with robust empirical evidence and analysis on the contribution of private-sector R&D to the growth and employment of the European economy.

This should lead to the elaboration of medium and long-term evidence-based policy options to support the development and implementation of the Europe 2020 strategy which considers investment in knowledge and innovation a main driver for achieving a smart, sustainable and inclusive growth.

This fits into one of the seven thematic areas of the new JRC Strategy 2010-2020: "Towards an open and competitive economy".

Click here to find out more.

How?

The action provides a platform for the long-term collection, monitoring, analysis and reporting of information on private-sector research and innovation activities in the EU, with particular emphasis on the relation between research, innovation and economic performance.

Sources of information include: data from statistical offices (national, Eurostat, OECD, EPO, etc.), companies' annual financial reports, surveys (own survey, access to CIS, and other surveys), experts opinions, published reports and scientific papers, commercial databases (e.g. Compustat).

The research methodologies are based on quantitative economic and financial analyses using statistics, econometrics, modelling, input-output matrices and data panels. We also use qualitative analysis using for example expert-panels.

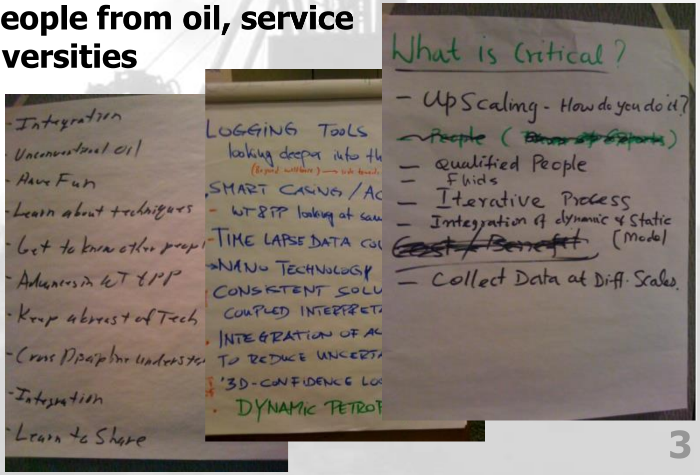
Main activities

- The EU Industrial R&D Investment Scoreboard, and The EU Surveys on R&D Investment Business Trends
- IPTS Working Papers on Corporate R&D and Innovation
- Conference on Corporate R&D (CONCORD)

The main activities of the Economics of Industrial Research and Innovation Action are a result of a close co-operation between the Joint Research Centre (JRC) and Research & Innovation (DG-RTD) Directorates-General of the European Commission.

❑ **Nonformal contacts with people from oil, service companies and leading universities**

❑ **40 hours of open discussions of major problems in the industry**



- Integration
- Unconventional oil
- Have Fun
- Learn about techniques
- Get to know other peop
- Advances in WT & PP
- Keep abreast of Tech
- Cross Discipline understa
- Integration
- Learn to Share

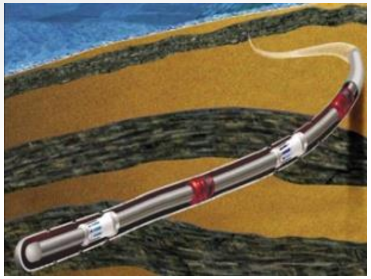
LOGGING TOOLS
looking deeper into th
(Beyond wellbore) →
SMART CASING / AC
- WT & PP looking at sam
- TIME LAPSE DATA CO
NANO TECHNOLOGY
CONSISTENT SOLU
COUPLED INTERPRETA
INTEGRATION OF AC
TO REDUCE UNCERTA
'3D-CONFIDENCE LO
DYNAMIC PETROP

What is Critical?
- UpScaling - How do you do it?
~~People~~ (~~[illegible]~~)
- Qualified People
- Fluids
- Iterative Process
- Integration of dynamic & Static (Model
~~Cost / Benefit~~
- Collect Data at Diff. Scales.

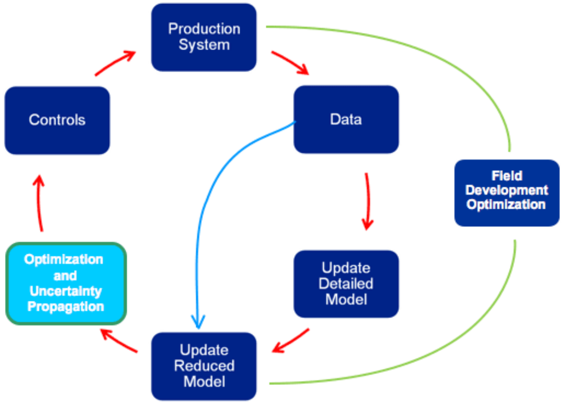
Пример №2 (1/2)
Анализ внешней среды: долгосрочные тенденции научно-технического развития отрасли

	Horizon I (2011-2013)	Horizon II (2014-2016)	Horizon III (2017-2021)
Business Strategy	Increase the fraction of active stocks in the resource base	Expansion of the resource base. Exploration of new regions (including Arctic) and new offshores (including north seas)	Diversification of the resource base. Exploration of nontraditional hydrocarbon sources
Technological Strategy	Cost and energy effective oil production at wasted fields and at fields with reduced activity of hydrocarbons	Exploration and production in complicated geological and climatic conditions under the extended ecological requirements	Exploration and production under puzzling physical and chemical conditions with requirement of the technological flexibility
R&D Strategy (examples)	1. Thermal methods for high viscous oils; 2. Water flooding for fields with complicated pore space structure; 3. EOR for low-permeable reservoirs (e.g. refracturing) 4. …	1. New drilling technologies 2. Selfconsistent interpretation of core, log, testing and seismic measurements 3. Gas hydrates 4. …	1. New technologies for shale resources 2. New methods for bitumen 3. …
Solution technology	Development of a smart field technology		

Smart fields technology – the ultimate goal for the next decades



- ❑ Smart fields technology (i-fields, e-fields, Field of the Future, Closed-Loop Reservoir Management, etc):
  - Optimization at any stage of field development. Ideally, a continuous cycle for field exploration, development and production.
  - A decision making with taking into account all components (reservoir, well, infrastructure and logistics) on the economical performance of the project
  - Defining of wells localization , number , type andoperating mode



Production System

Data

Update Detailed Model

Update Reduced Model

Optimization and Uncertainty Propagation

Controls

Field Development Optimization

- ❑ “Reservoir Simulation System for the Next Decades”, 9th International Forum on Reservoir Simulation, Dec 9-13 2007, Abu Dhabi, UAE by CMG, Shell, Petrobras/Cenpes:
  - Unified approach for black-oil, compositional, thermal and chemical simulation;
  - The ability of perform full field (Wellbore/Reservoir) simulation of thermal, EOR or unconventional processes with multiscale physics;
  - The potential to analyze recovery mechanisms with coupling of fluid flow with geomechanics

- ❑ Traditional approaches for developing and operating oil and gas fields which are based on combinations of commercial software (ECLIPSE, Roxar etc) are rarely optimal. The positional gains of deploying these new technologies are very significant.

Smart Fields Consortium

1

NTNU Norwegian University of Science and Technology

Shell

CMG Computer Modelling Group Ltd.

Chevron

BR PETROBRAS

BAKER HUGHES

BG GROUP

أرامكو السعودية Saudi Aramco

ConocoPhillips

eni

bp

IBM

2

Chevron + Schlumberger

= INTERSECT

(2000-настоящее время

3

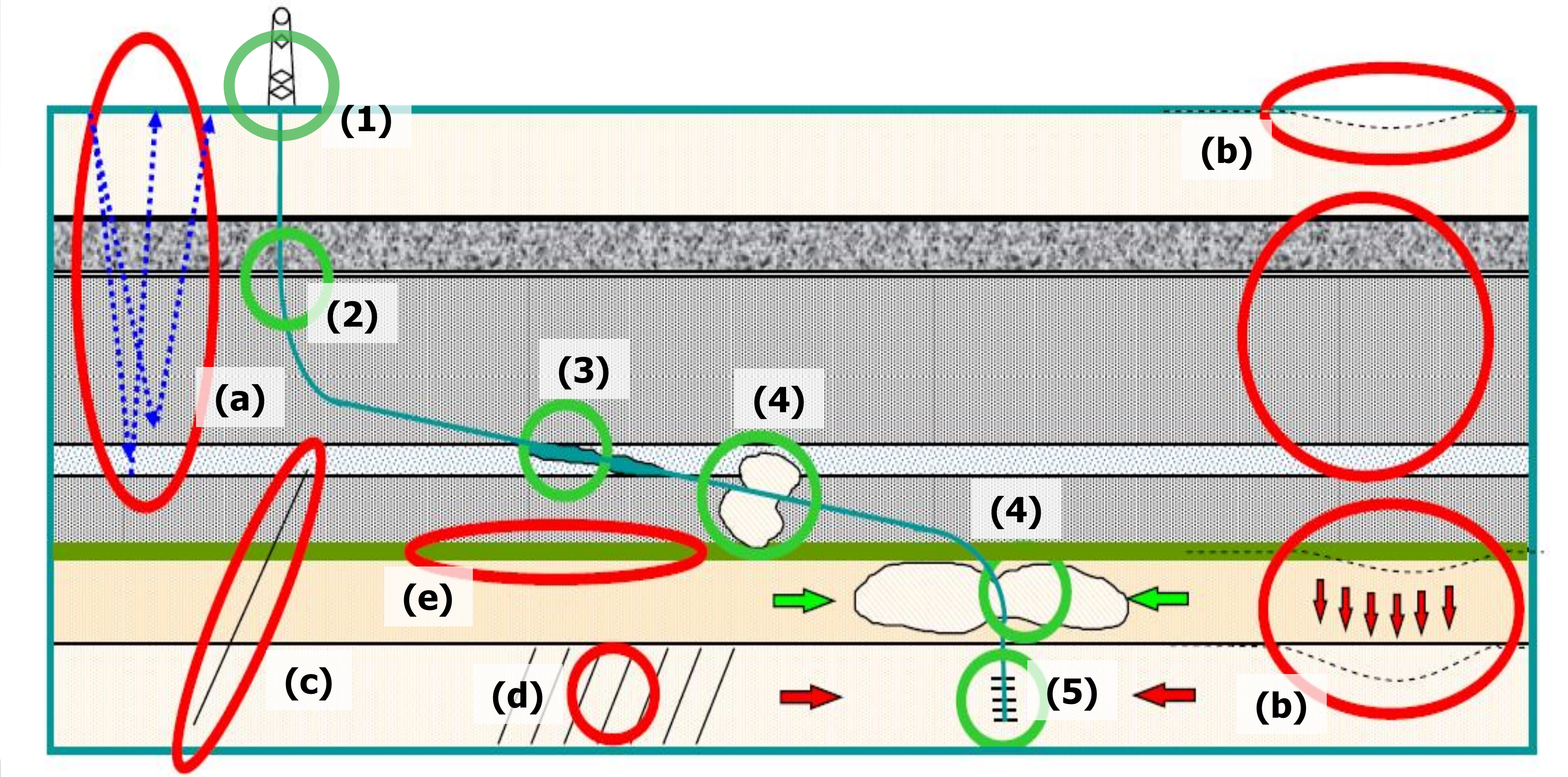
ExxonMobil

EMpower

- ✓ from 1990th
- ✓ System reservoir + well + completion
- ✓ “Upstream Research Company”

LUKOIL

What is geomechanics and Where does it impact?



At Near Wellbore scale:

🟢

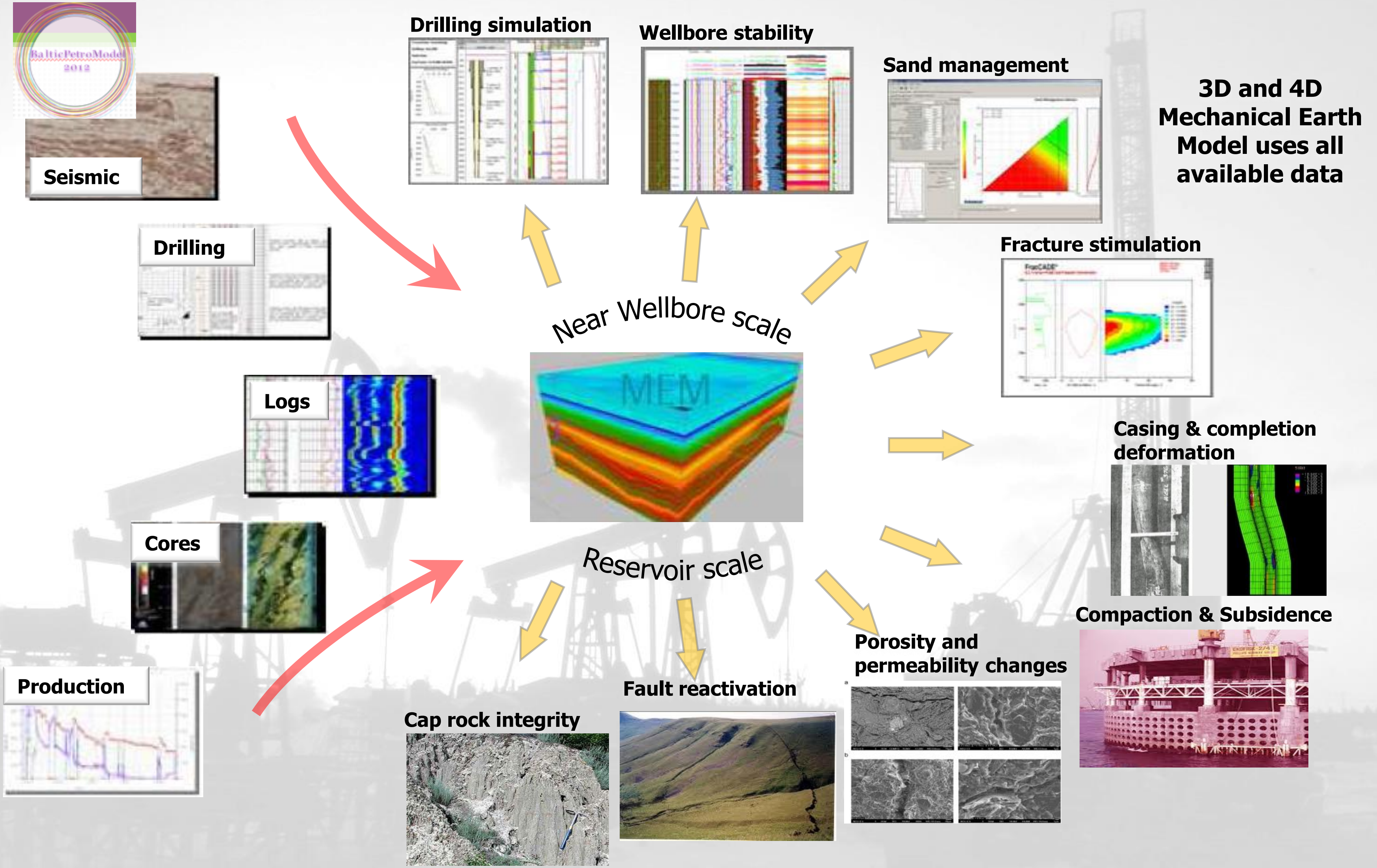
1) Well Placement & Trajectory
2) Drilling bit and fluid selection
3) Wellbore Stability
4) Reservoir Stimulation
5) Sand Production Control

At Reservoir scale:

🔴

a) 3D, 4D seismic, microseismic
b) Compaction and subsidence
c) Fault reactivation
d) Fractured reservoirs
e) Slips along soft layers and bedding places

Iterative loop of initiation of the MEM initiation



Seismic

Drilling

Logs

Cores

Production

Drilling simulation

Wellbore stability

Sand management

Fracture stimulation

Casing & completion deformation

Compaction & Subsidence

Porosity and permeability changes

Fault reactivation

Cap rock integrity

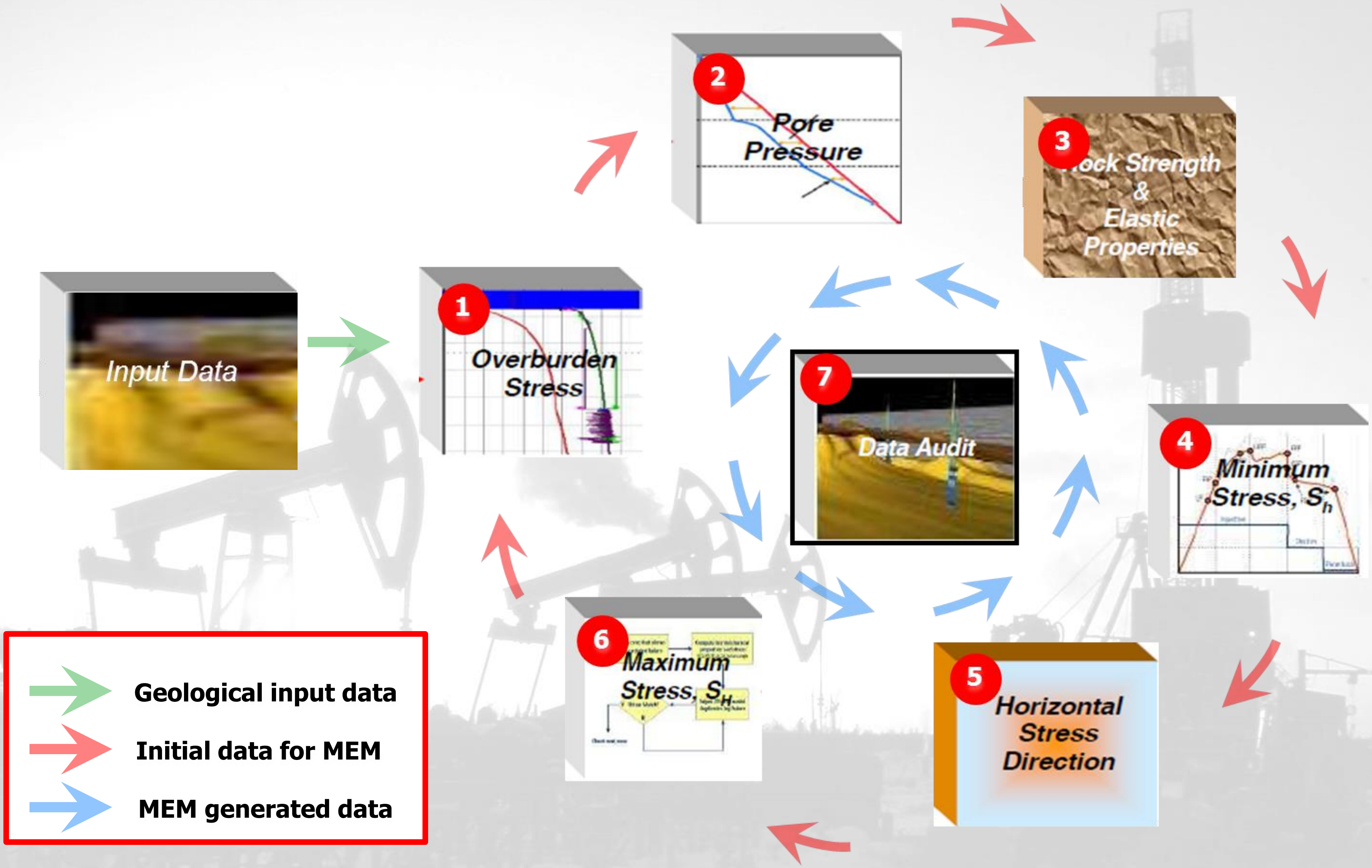
Near Wellbore scale

MEM

Reservoir scale

3D and 4D Mechanical Earth Model uses all available data

Building and calibrating of the MEM



Input Data

1 Overburden Stress

2 Pore Pressure

3 ock Strength & Elastic Properties

4 Minimum Stress, S_h

5 Horizontal Stress Direction

6 Maximum Stress, S_H

7 Data Audit

→ Geological input data

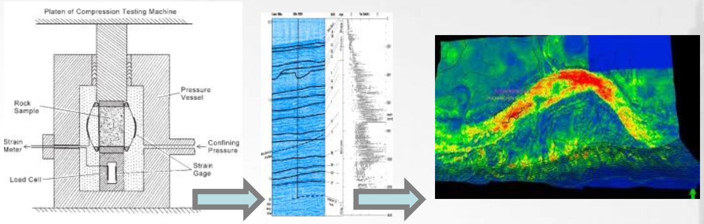
→ Initial data for MEM

→ MEM generated data

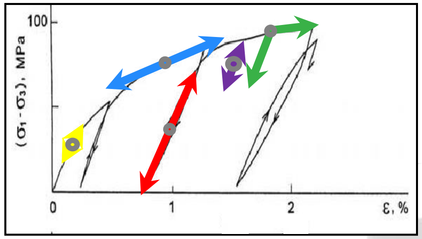
Building and calibrating of the MEM:

3. Rock strength and elastic properties

- ☐ **Input data for elastic properties:**
  - Core – static elastic properties
  - Log – sonic and bulk density
  - Seismic – low resolution but large volume



$$E_{dyn} = \rho V_S^2 \frac{3V_P^2 - 4V_S^2}{V_P^2 - V_S^2}$$



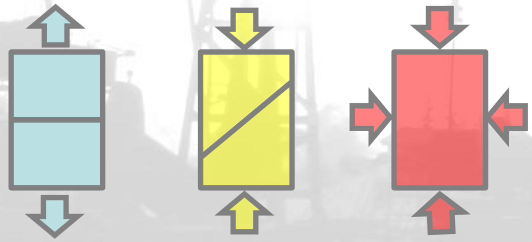
↔ *Plona T., Cook J. (1995)*

$$E_{stat} = \frac{E_{dyn}(1-F)}{1+PE_{dyn}}$$ *Fjaer E. (1999)*

↔ *Myasnikov V, Oleinikov A (2007)*

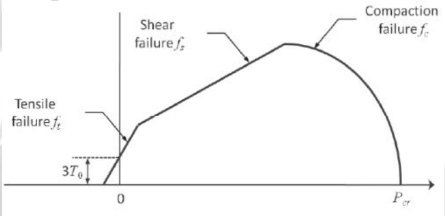
- ➢ **Two types of scaling problems:**
  - Dynamic vs. Static
  - Consistency with other upscaled parameters
- ➢ **Need to consider fluid effect, especially with compressional**

- ☐ **Rock strength: lab, logs and computations**



Fjaer E. (2008)

$$q = \frac{1}{2}\sqrt{(\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2 + (\sigma_1' - \sigma_3')^2}$$



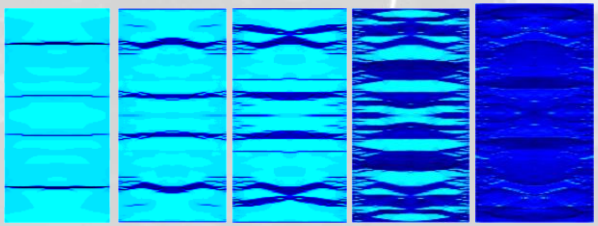
$$p' = \frac{1}{2}(\sigma_1' + \sigma_2' + \sigma_3')$$

Mogi K. (2007),
Kwasniewski M. et al (2012)

- ➢ **Correlations for cohesion and friction angle** *Khaksar et al. (2009)*

$$C_0 = C_0(\Phi), \quad \phi = \phi(\Phi)$$

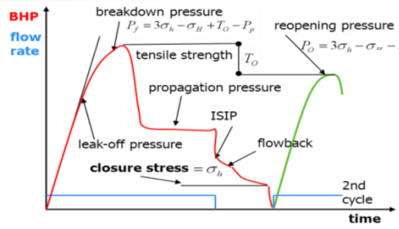
- ➢ **Numerical modeling** *Stefanov Yu. et al (2011)*



Building and calibrating of the MEM:

6. Maximum horizontal stress

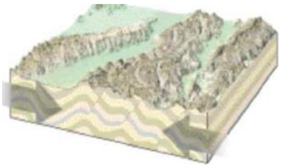
Estimations of σH:



$$\sigma_H = 3\sigma_h - P_O - P_p$$

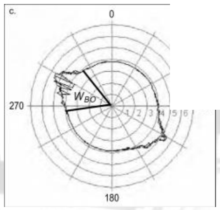
Bredehoeft W. et al. (1976), Baumgartner R. et al. 1990

- ❑ **From a XLOT test**
  - ➢ Needs very precise estimaation of breakdown pressure the value



$$\sigma_H = \sigma_h + \alpha \Delta P$$

- ❑ **From measured overpressure and the least stress**
  - ➢ Skempton's parameter to be measured in triaxial test
  - ➢ Tectonics is not the unique reason for overpressure
  - ➢ Mechanism valid preferably in young sediments

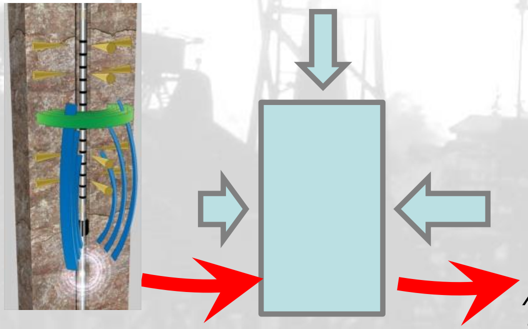


$$\sigma_H = \frac{\left(C_0 + 2P_p + \Delta P\right) - \sigma_h(1 + \cos 2w_{BO})}{1 - 2\cos 2w_{BO}}$$

$$\sigma_H = 3\sigma_h - 2P_p - \Delta P$$

Zoback M. et al. (1993), Zoback M. (2007)

- ❑ **Using detailed observations of wellbore breakouts**
  - ➢ Not possible to apply if breakouts are absent but can still provide constraints on the stress magnitudes
  - ➢ Need more validation for deviated wells



$$\sigma = E(\varepsilon)\varepsilon$$

$$V^{P,S}_{r,\theta,\varphi} \mapsto \sigma_{r,\theta,\varphi}$$

Alsos T. et fl (2007), Schlumberger marketing broshure (2012)

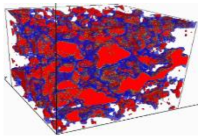
- ❑ **Using advanced ultrasonic measurements combined with TOE theory predictions**
  - ➢ Needed to be calibrated by core measurements too complicated for orthotropic media (9 free parameters. *Tsvankin, 1997*)

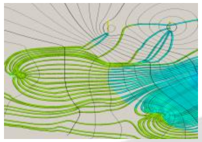
Building and calibrating of the MEM:

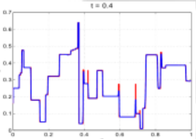
7. Data audit. General structure

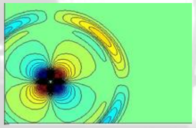
What is data audit?:

❑ **MEM model construction**:









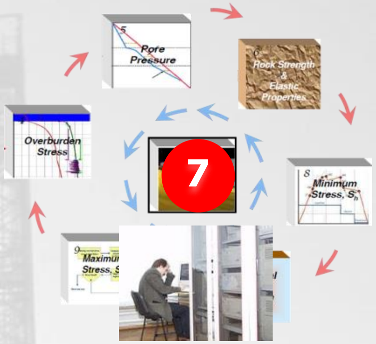
- **Data processing**
  - ❖ Estimation of adequacy, sufficiency and consistency of the data for the problem under consideration
  - ❖ Classification of the data and determine free parameters in the space of solutions to be obtained.
- **Chose of physical model for data incorporation**
  - ❖ Should we incorporate NCA into reservoir simulations?
- **Chose of physical model for modeling and prediction**
  - ❖ Should we accept knowingly wrong physical models for estimate predictions?
  - ❖ Should the model be the simplest one among all appropriate for the problem under consideration?
- **Optimization of computational models**
  - ❖ Finite volume vs finite difference vs finite elements
  - ❖ Coupling strategy between geomechanical and hydrodynamical modulus
  - ❖ Using of commercial software?
- **Chose of quality control criteria**
  - ❖ Reservoir simulations vs computational mathematics

❑ **MEM model correction:**

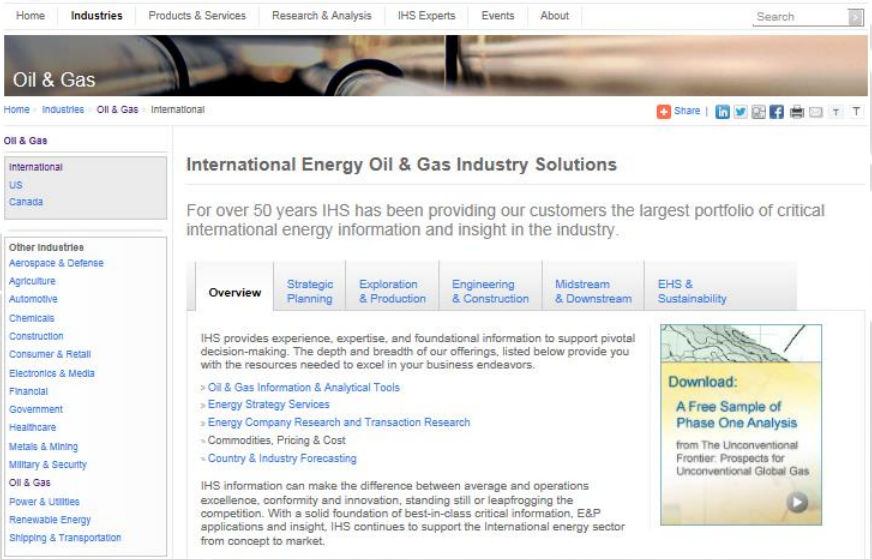
- **Rerun steps 1-6 if needed**

Building and calibrating of the MEM:

7. Data audit. Data processing by origin



- ☐ Collection, processing and analysis of all the input data which differ each other **by origin**
  - Estimation of adequacy, sufficiency and consistency of the data for the problem under consideration
    - ❖ quality estimation
    - ❖ multichannel verification
    - ❖ development and maintenance of automation devices for data gathering and storage



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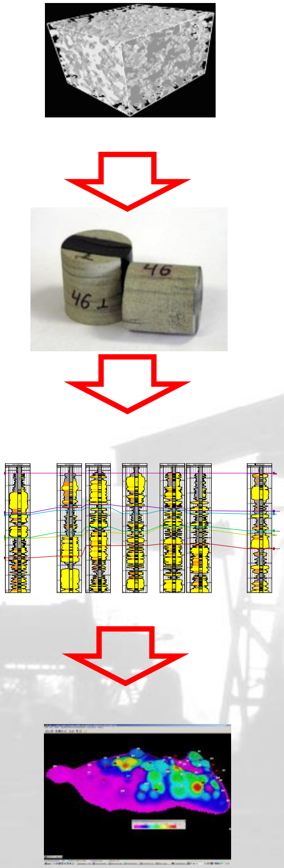
- Classification of the data and determine free parameters in the space of solutions to be obtained.

- Identification of the data which can be iterated in the iterative MEM construction process

Building and calibrating of the MEM:

7. Data audit. Data processing by scale range

☐ Collection, processing and analysis of all the input data which differ each other **by scale** (pore, core, wellbore reservoir

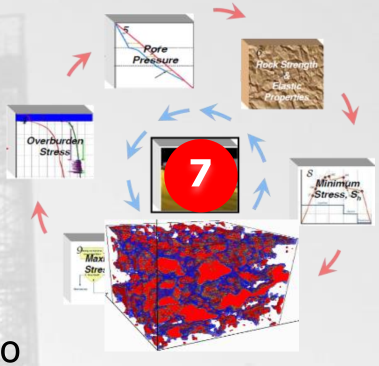


- Date must satisfy the basic upscaling rule (*Kosterin 1986*) :
  - ❖to be homogeneous at small scale and heterogeneous at large scale;
  - ❖large-scale processes should depend on small-scale phenomena;
  - ❖large-scale and small-scale modeling should be consistent
- In conventional approaches upscaling is often considered that small-scale degrees of freedom are negligible and large-scale and small-scale models are postulated (*Bazant & Cedolin, 2005, Berg, 2006, Das & Hassanizadeh 2005*). Results of the modeling at these scales may be inconsistent, (*Steinhauser 2008*).
- Mesoscale theory (*Dinariev & Mikhaylov, 2007,2008,2013*):
  - ❖small-scale properties are retained as internal degrees of freedom at large-scale cells
  - ❖statistical distribution of internal properties
  - ❖mesoscale parameters are obtained from small-scale description

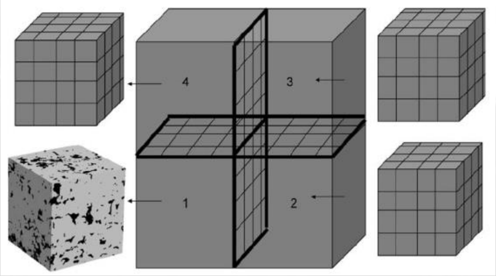
LUKOIL

Building and calibrating of the MEM:

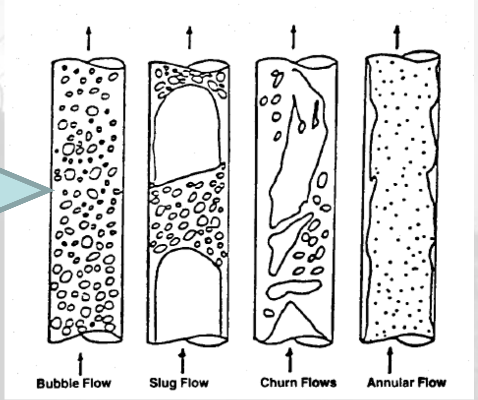
7. Data audit. Chose of physical model for data incorporation



- A concept of "physical model for data incorporation" is a topical subject today
- Heavy capital investments are now made not in what is potentially profitable, but in what is potentially possible
- Modern HPC technologies make it possible to incorporate any "crazy" idea into reservoir simulation loop (*Boreskov & Kharlamov 2010*) if it decrease of uncertainty of the predictions
- Two bright examples can be shown with this relation:
  - Direct incorporating of NCL with reservoir simulations (*Balhoff et al., 2007,2008*)
  - Modeling of wellbore processes with multiphase Navier-Stokes equations instead of conventional multisegment well model (*Bonizzi et al., 2009*)



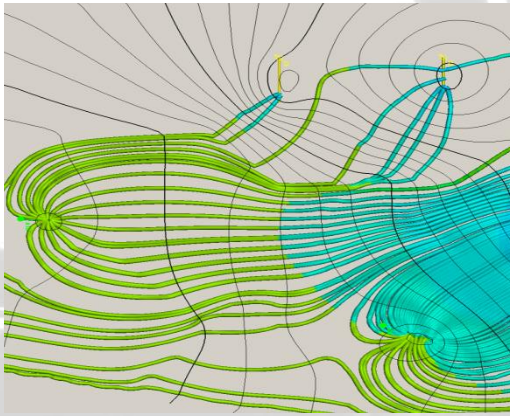
- These examples have one common feature: uncertainty related with nonuniqe solution of fundamental hydrodynamic problem – multiphase flow in pipes



Building and calibrating of the MEM:

7. Data audit. Chose of physical model for modeling and prediction

- ☐ One has to decide if it is possible to make use of methods or models with not proven feasibility
- ☐ The example here is a streamline technology (*Bratvedt et al., 1992*), which is used today for the wide range of applications *(Datta-Gupta 2000, Kozlova et al., 2007, Andrianov et al., 2007,)* although, theoretically is unproved in a general case *(Rykov & Myasnikov, 2008)*:



$$\tau=\tau(t,x,y,z),\quad \varphi=\varphi(t,x,y,z),\quad \psi=\psi(t,x,y,z)$$

$$\nabla\cdot\{f\nabla F\}\to\frac{1}{\sqrt{g}}\frac{\partial}{\partial\tau}\left(\sqrt{\frac{g}{g_{11}}}\cdot\frac{f}{\sqrt{g_{11}}}\frac{\partial F}{\partial\tau}\right)+$$

$$\frac{1}{\sqrt{g}}\frac{\partial}{\partial\varphi}\left(\sqrt{\frac{g}{g_{22}}}\cdot\frac{f}{\sqrt{g_{22}}}\frac{\partial F}{\partial\varphi}\right)+\frac{1}{\sqrt{g}}\frac{\partial}{\partial\psi}\left(\sqrt{\frac{g}{g_{33}}}\cdot\frac{f}{\sqrt{g_{33}}}\frac{\partial F}{\partial\psi}\right);$$

$$\nabla\tau\parallel\nabla P$$

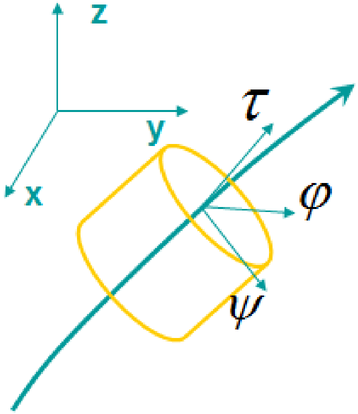
$$\frac{\partial h}{\partial t}\to h_t+h_\tau\tau_t+h_\varphi\varphi_t+h_\psi\psi_t$$

τ

If then $g_{11}=1$

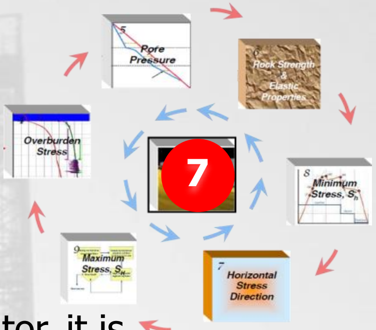
and $g_{22}\cdot g_{33}$ **does not depend on** τ

$$\nabla\cdot\{f\nabla F\}\to\frac{\partial}{\partial\tau}\left(f\frac{\partial F}{\partial\tau}\right),\quad\frac{\partial h}{\partial t}\to h_t$$

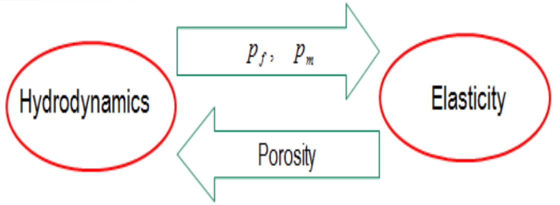


Building and calibrating of the MEM:

7. Data audit. Optimization of the computational model



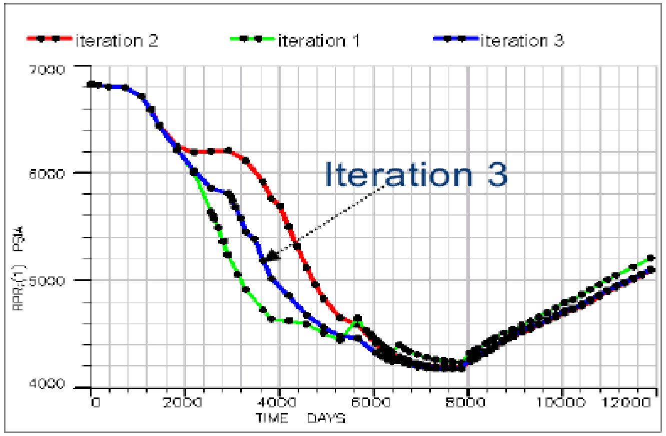
- ☐ Here we consider two algorithms of coupling.

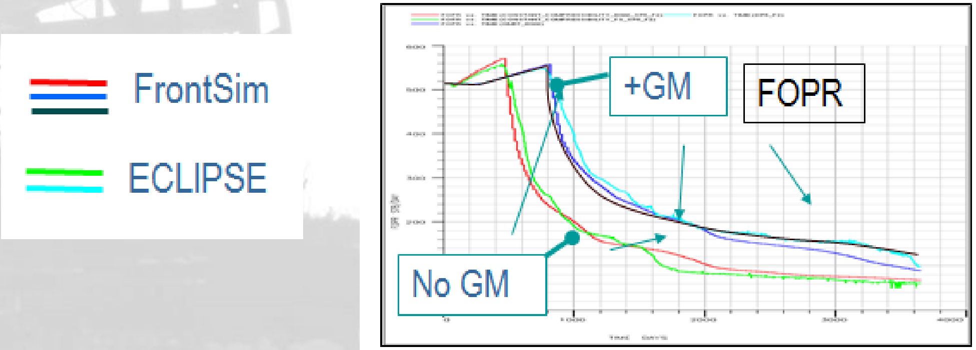


T_k	$p_f^{\ k}, p_m^{\ k}, \boldsymbol{\varepsilon}^k, s_{a,i}^k, \phi_f^{\ k}, \phi_m^{\ k}$	A set of streamlines is generated
	$\left.\begin{matrix} t^k_1 \\ t^k_2 \\ \vdots \\ t^k_N \end{matrix}\right\} \left(s_{\alpha,i}\right)_n^k$	The transport equation along streamlines is solved
T_{k+1}	$p_f^{\ k+1}, p_m^{\ k+1}, \boldsymbol{\varepsilon}^{k+1}, s_{a,i}^{k+1}, \phi_f^{\ k+1}, \phi_m^{\ k+1}$	Pressure and elasticity equations are solved. New values of porosity are obtained.

- ☐ "internal" coupling: geomechanical solver is called inside the basic reservoir simulator.
- ☐ Dealing with streamline-based fluid simulator, it is naturally to arrange "internal" coupling basing on Streamline simulator intrinsic sequential structure

- ☐ The other one will be called "external" because both reservoir simulator and geomechanical solver run completely separately (*Samier & Gennaro, 2007*).
- ☐ Sixth SPE Comparison test (*Firoozabadi & Thomas, 1990)*





Rybdylova & Myasnikov, 2008

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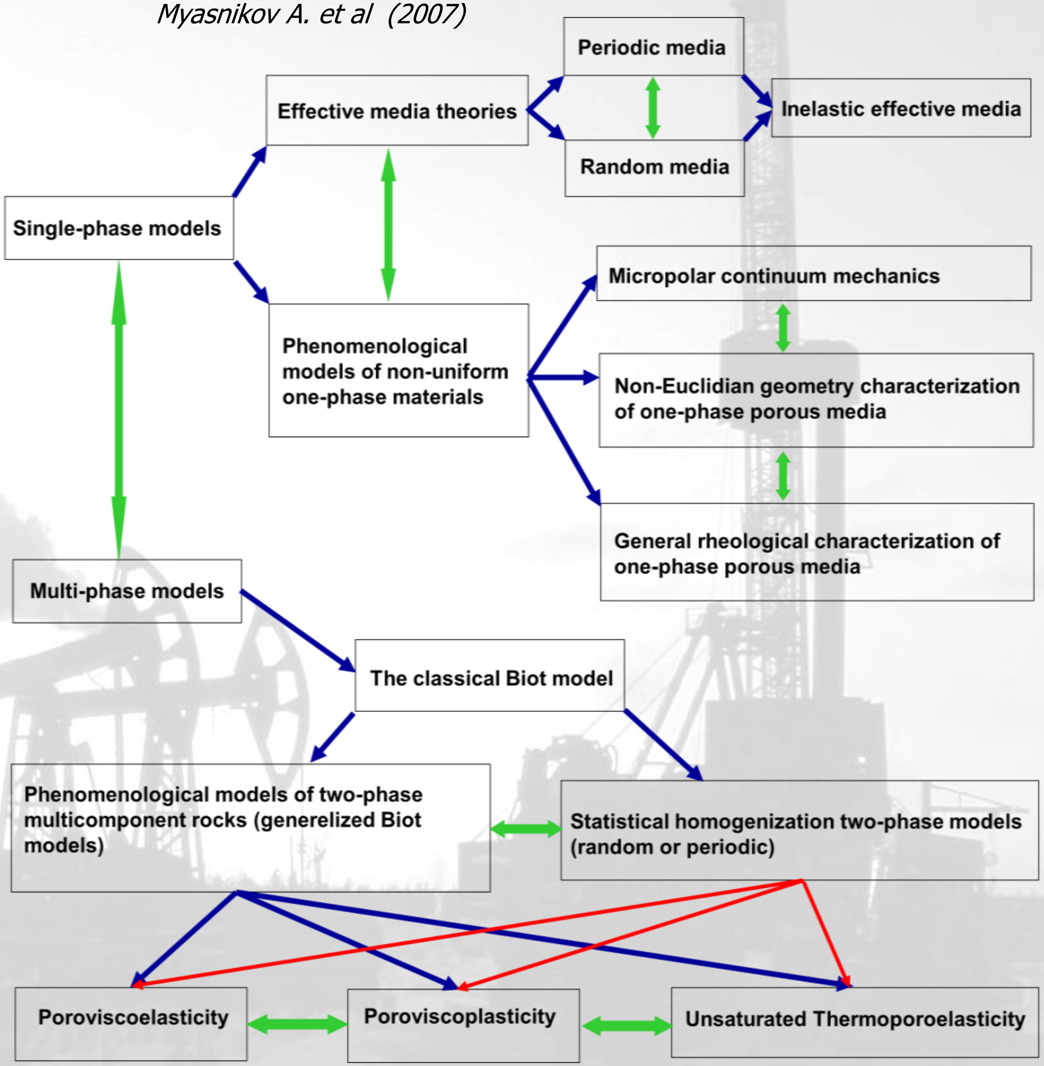
Building and calibrating of the MEM:

7. Data audit. A concept of rheological monitoring

- **The suggestion is to construct a phenomenological model capable for description of large scale deformation of a rock .**
- **To construct a data base of wave propagation properties for each specific rheology**
- **To identify 3D and 4D seismic data by the rheology database**

Myasnikov A. et al (2007)



Periodic media

Effective media theories

Inelastic effective media

Random media

Single-phase models

Micropolar continuum mechanics

Phenomenological models of non-uniform one-phase materials

Non-Euclidian geometry characterization of one-phase porous media

General rheological characterization of one-phase porous media

Multi-phase models

The classical Biot model

Phenomenological models of two-phase multicomponent rocks (generelized Biot models)

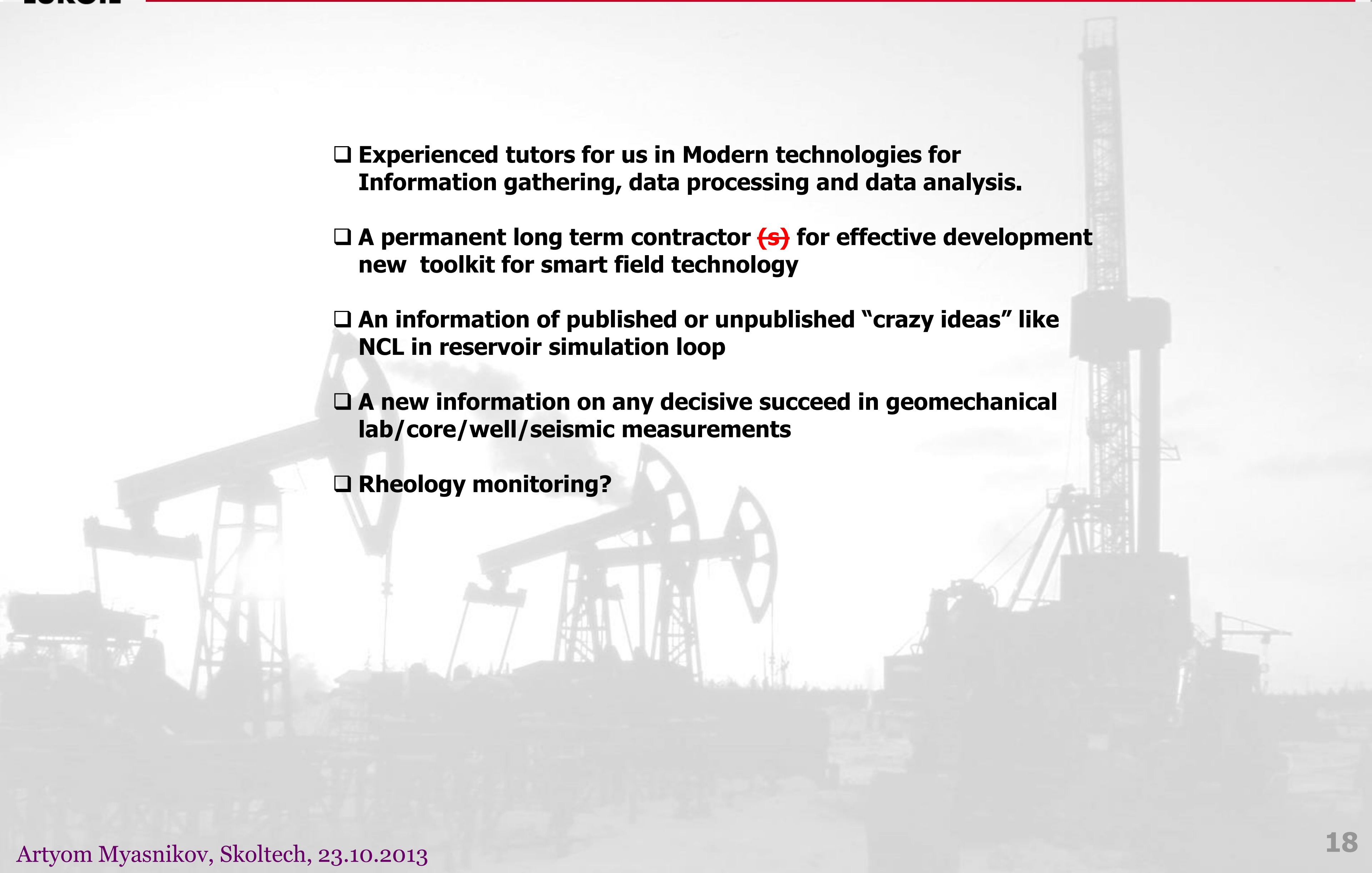
Statistical homogenization two-phase models (random or periodic)

Poroviscoelasticity

Poroviscoplasticity

Unsaturated Thermoporoelasticity

What do we need?



- Experienced tutors for us in Modern technologies for Information gathering, data processing and data analysis.
- A permanent long term contractor ~~(s)~~ for effective development new toolkit for smart field technology
- An information of published or unpublished “crazy ideas” like NCL in reservoir simulation loop
- A new information on any decisive succeed in geomechanical lab/core/well/seismic measurements
- Rheology monitoring?

THANK YOU FOR YOUR ATTENTION

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Пример №2 (1/2)
Анализ внешней среды: долгосрочные тенденции научно-технического развития отрасли

	Горизонт 2011-2013	*Горизонт 2014-2016*	*Горизонт 2017-2021*
Business Strategy	**Увеличение доли активных запасов в ресурсной базе.**	**Освоение новых регионов, в том числе арктических. Шельфы, в том числе северных морей.**	**Расширение ресурсной базы. Освоение нетрадиционных источников углеводородов**
Technological Strategy	**Экономически рентабельная и энергоэффективная добыча на истощенных месторождениях и месторождениях со сниженной активностью УВ.**	**Разведка и разработка в сложных геологических и климатических условиях, при повышенных экологических требованиях**	
R&D Strategy (examples)	1. Development of thermal technologies for high viscous oils; 2. Development of water flooding technologies for fields with complicated pore space structure; 3. Development of EOR technologies for low-permeable reservoirs (refracturing etc)	1. New drilling technologies 2. New technologies for selfconsistent interpretation of core, log, testing and seismic measurments 3.new technologies for gashydrates	1. Создание технологий освоения ресурсов приуроченных к глинистым толщам 2.Разработка новых методов воздействия на отложения битумов и битумных сланцев
Solution technology	**Развитие интегрированного проектирования разработки**		