The effect of pore compressibility on CO2 storage and EOR in Croatia

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This presentation is based on three previously published/presented works:

1) Goričnik, B. (INA-Naftaplin, University of Zagreb**), 2000.:**
EOR by CO_2 Injection - Potential in Croatian Oilfields

2) Domitrović, D., Šunjerga, S. (INA-Naftaplin) & **Goričnik D., Vulin, D.**
(University of Zagreb), 2005.:
Simulation Study of CO_2 Retention During Tertiary EOR Flood in Ivanić Oil Field

3) Vulin, D., Kolenković, I., Kurevija, T., (University of Zagreb), 2011.:
The Effect of Mechanical Rock Properties on CO_2 Storage Capacity

Overview of EOR Efforts in Croatia

Goricnik B., Domitrovic D., Sarapa M. (1999.): “Possible improvements of CO2-flood performance in Ivanić oilfield, R. Croatia”,

- Laboratory tests - since late 1977
- Pilot CO2 injection project at Ivanić field (from1993 to 1995, and from 2005-)
- CO2 injection study - Ivanić and Žutica in 1997
- Simulation studies from 2000

Overview of EOR Efforts in Croatia

- Laboratory tests - since late 1977

Phase 1 - Field Screening

(General criteria, supported by related basic lab testing)

Phase 2 - Detailed Lab Studies

(Potential of CO_2 process in selected fields)

Overview of EOR Efforts in Croatia

Phase 1 - Field Screening

- Using published criteria* on reservoir and fluid property requirements for CO_2 implementation as well as location considerations, 14 fields were singled out;

- Fluid samples from these reservoirs were tested to determine physical and PVT properties of current reservoir fluid in each case, i.e.:

  - Effect of CO_2 in terms of CO_2 solubility, oil swelling and oil viscosity reduction,

  - Oil displacement efficiency of CO_2 as obtained by the *basic* slim tube test

*(*e.g. Geffen,1973; Lewin&Ass.,1976; NPC,1976; Klins,1980; Taber&Martin. 1983*)

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Phase 2 - Detailed Lab Studies

- Additional PVT on CO_2 : oil mixtures, related to current depletion status. EOS modeling of phase behavior.

- Related more *detailed* slim-tube oil displacement tests. Simulation of the displacement tests.

- Core flood tests at reservoir conditions and different CO_2 process implementation scenarios.

*(*e.g. Geffen,1973; Lewin&Ass.,1976; NPC,1976; Klins,1980; Taber&Martin. 1983*)

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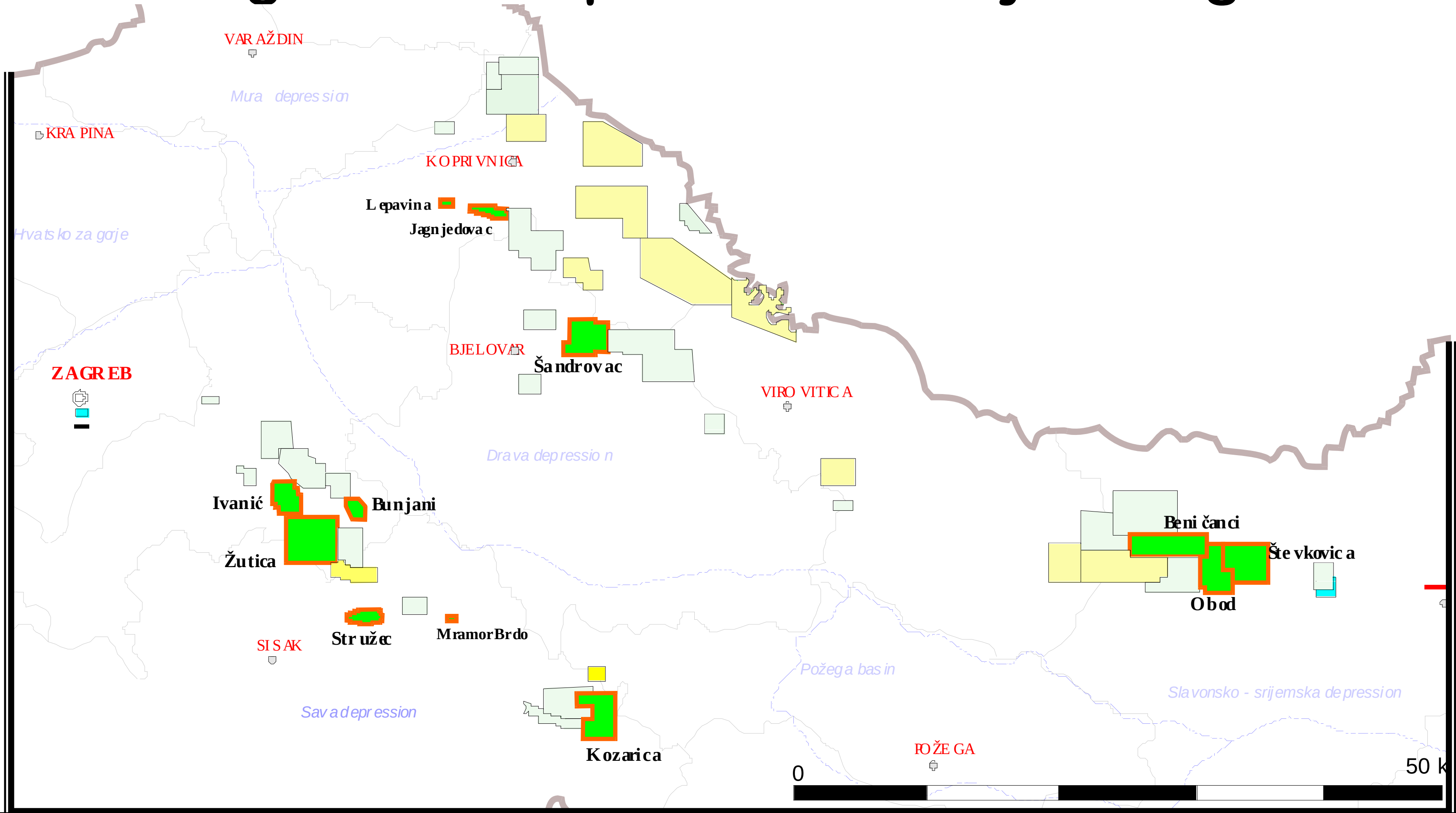
Locations of oilfields ( ), selected by preliminary screening for subsequent laboratory testing:



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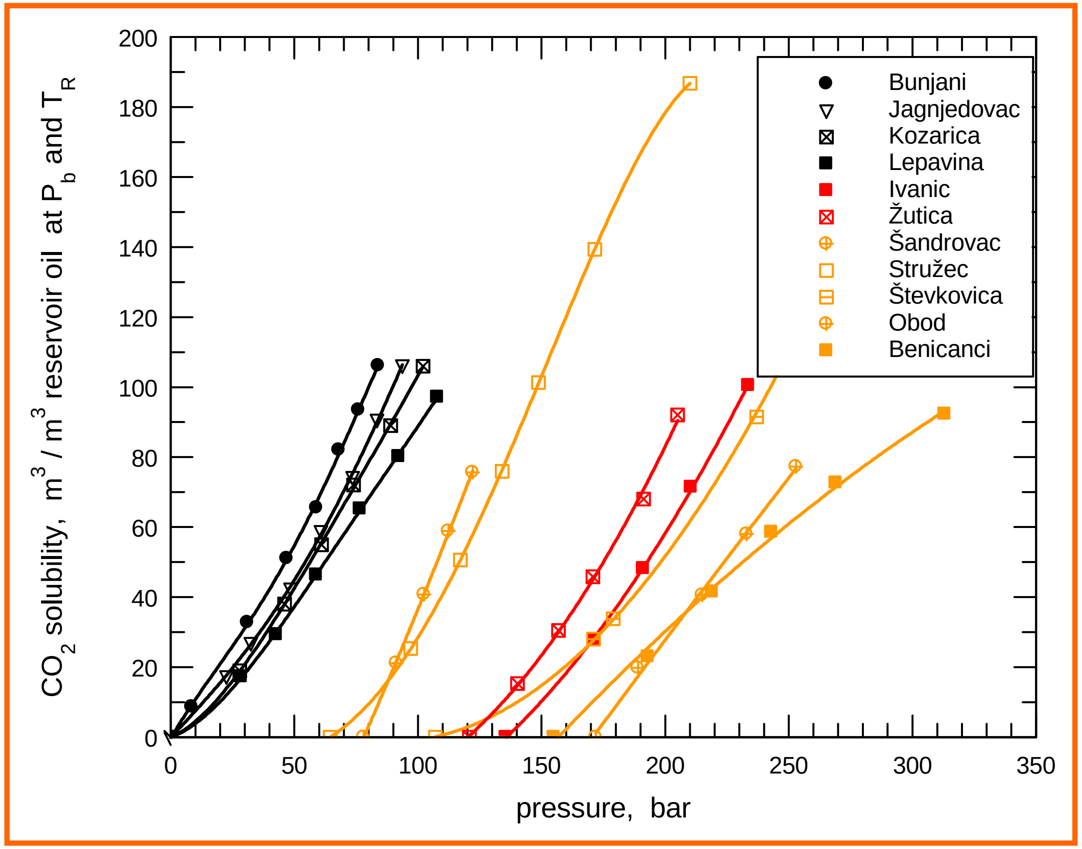
Results of laboratory testing . . .

(Sensitivity of oils examined to CO_2 injection)

CO_2 solubility in oil



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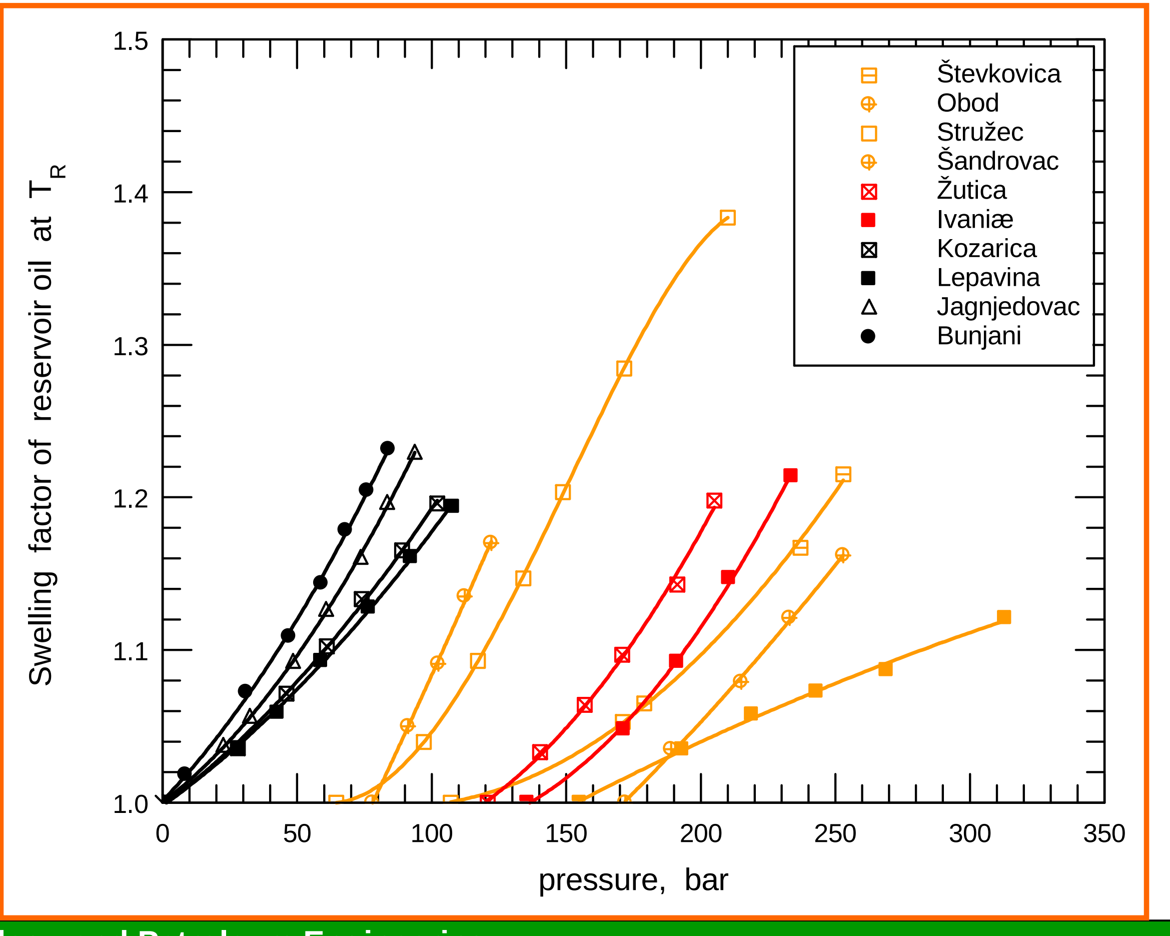
Results of laboratory testing . . .

Oil swelling



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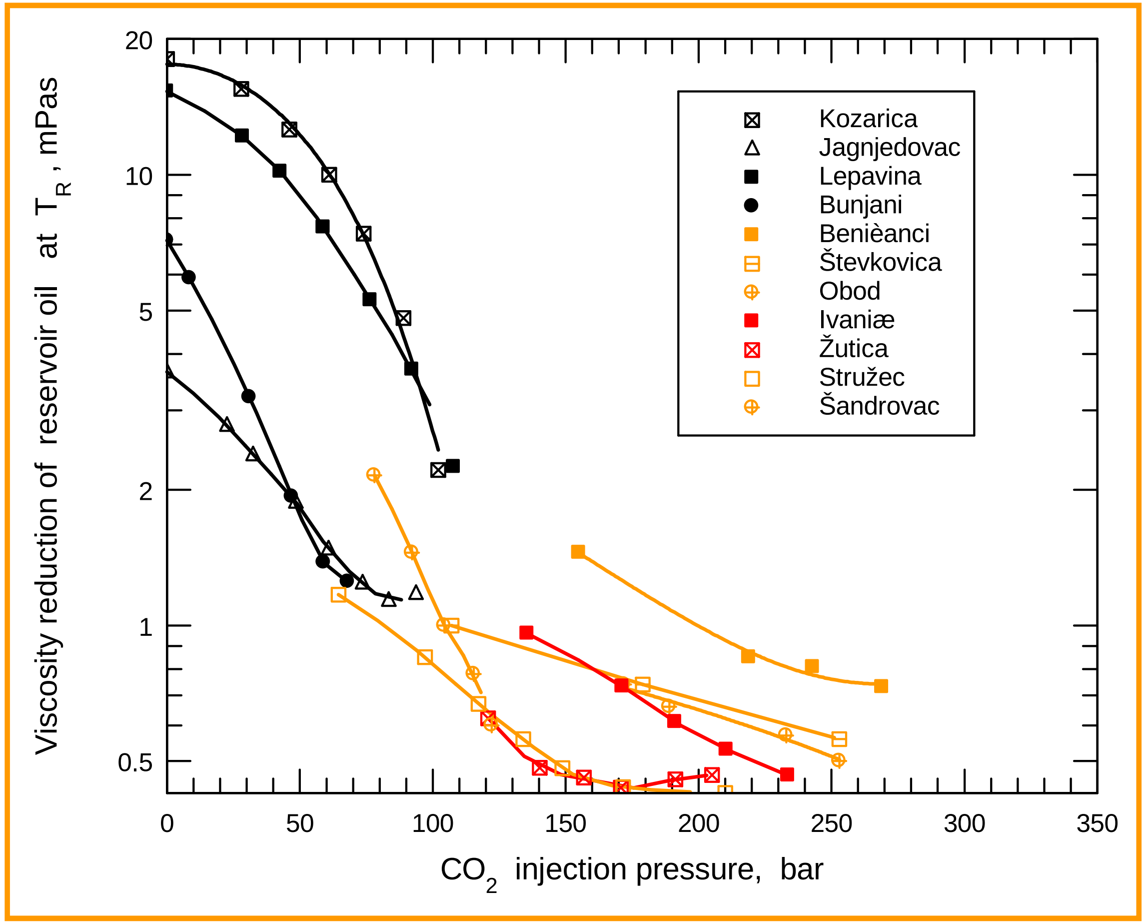
Results of laboratory testing . . .

Oil viscosity



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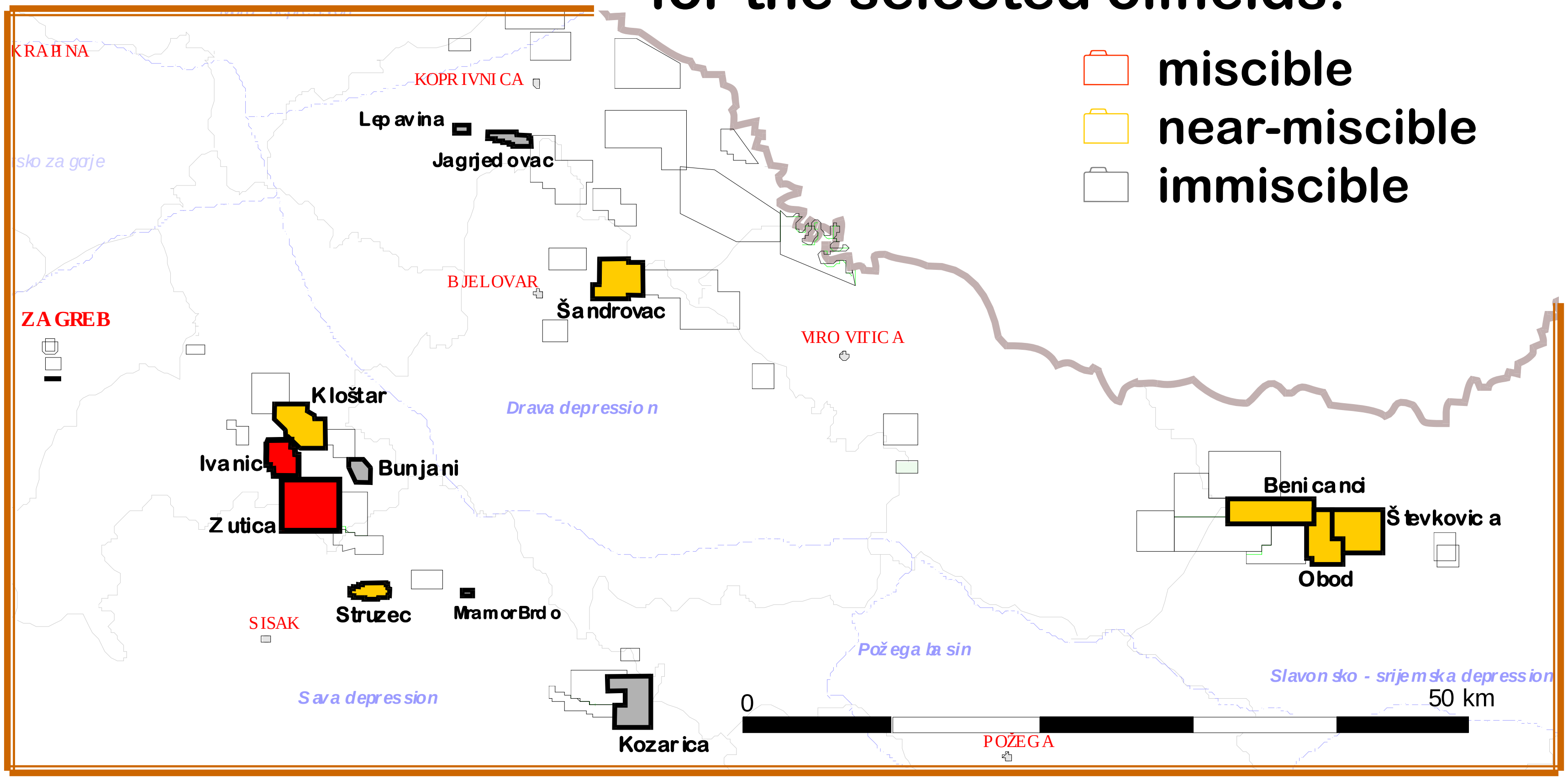
Summary of the lab screening data

CO_2 process type assignments for the selected oilfields:

- miscible
- near-miscible
- immiscible



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EOS Modeling of Phase Behavior

- **Peng-Robinson EOS**
- **EOS was tuned to experimental oil PVT (CCE, DLE, Sep.Test) and oil swelling data**
- **Several compositional formulations i.e. oil+CO2 mixtures** were **examined**
- **Proper EOS description of a mixture phase behavior validated (through multiple-contact vaporization calculations and slim-tube displacement simulations).**

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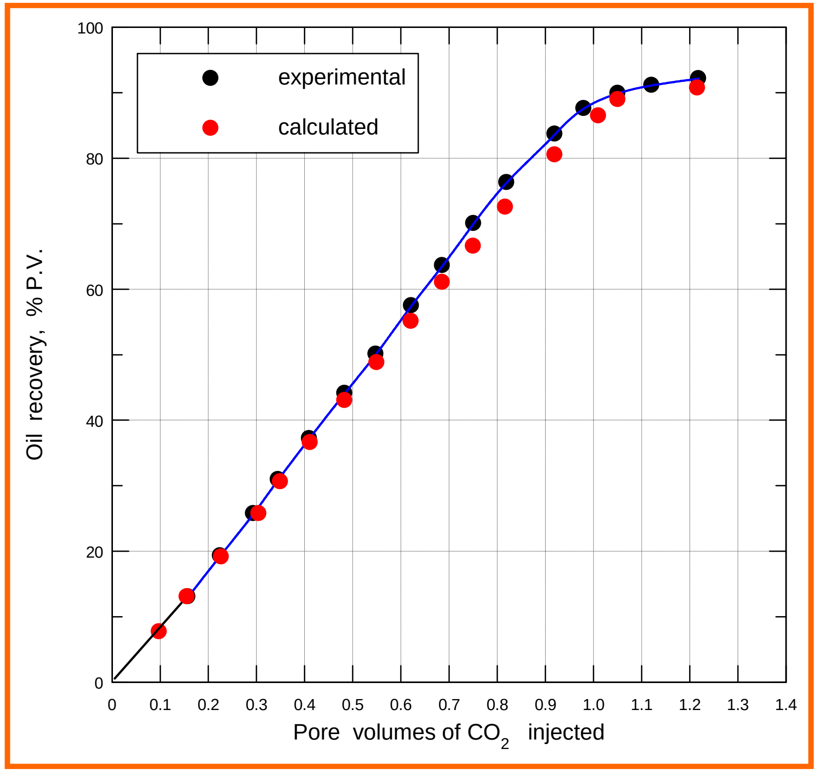
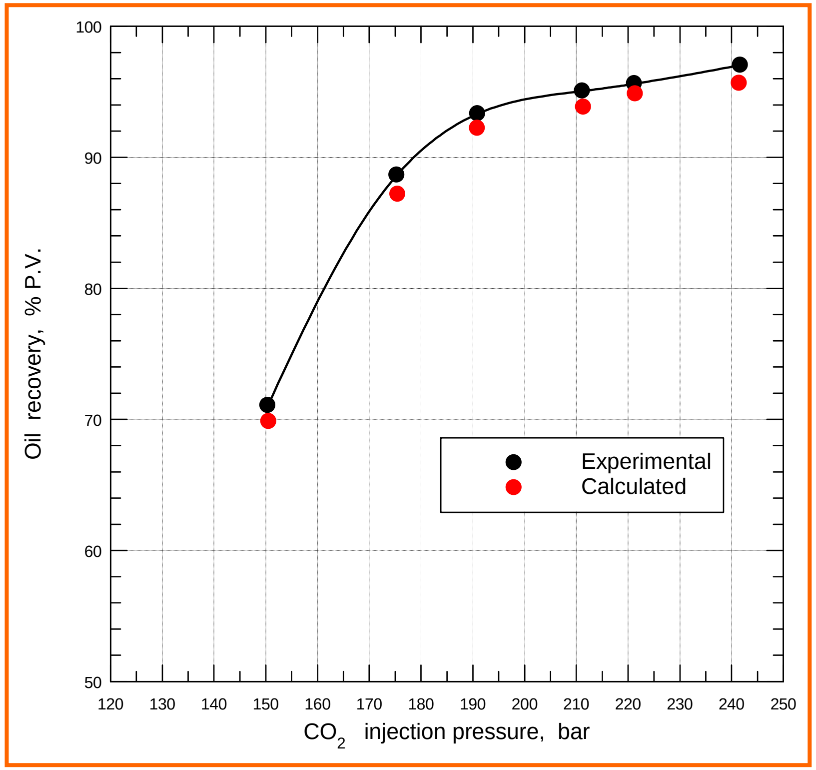
Example validation of regression tuned PR EOS

(Ivanić oil + CO_2; 5-component model)

Slim-tube oil recovery



Minimum miscibility pressure



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Coreflood Scenarios

Initial conditions: Core saturated with live oil at S_{wi} and "aged" for 48 hr at T_R

1. **Secondary CO_2 - oil displacement tests**

   •CO_2 <u>continuously</u> injected at a constant pressure
   •Incremental fluid recovery measured and final saturations determined

2. **Tertiary CO_2 - oil displacement tests**

   a) Core waterflooded to S_{or}
   b) CO_2 injected
   •continuously
   •alternatively with water (WAG)
   Incremental fluid recovery measured and final saturations determined

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CORE DATA:

D = 9.8 cm	**k = 73.3 mD**	**S_{wi} = 31 % PV**
L = 17.8 cm	**ϕ = 20.2 %**	**S_{or} (WF) = 38 % OOIP**

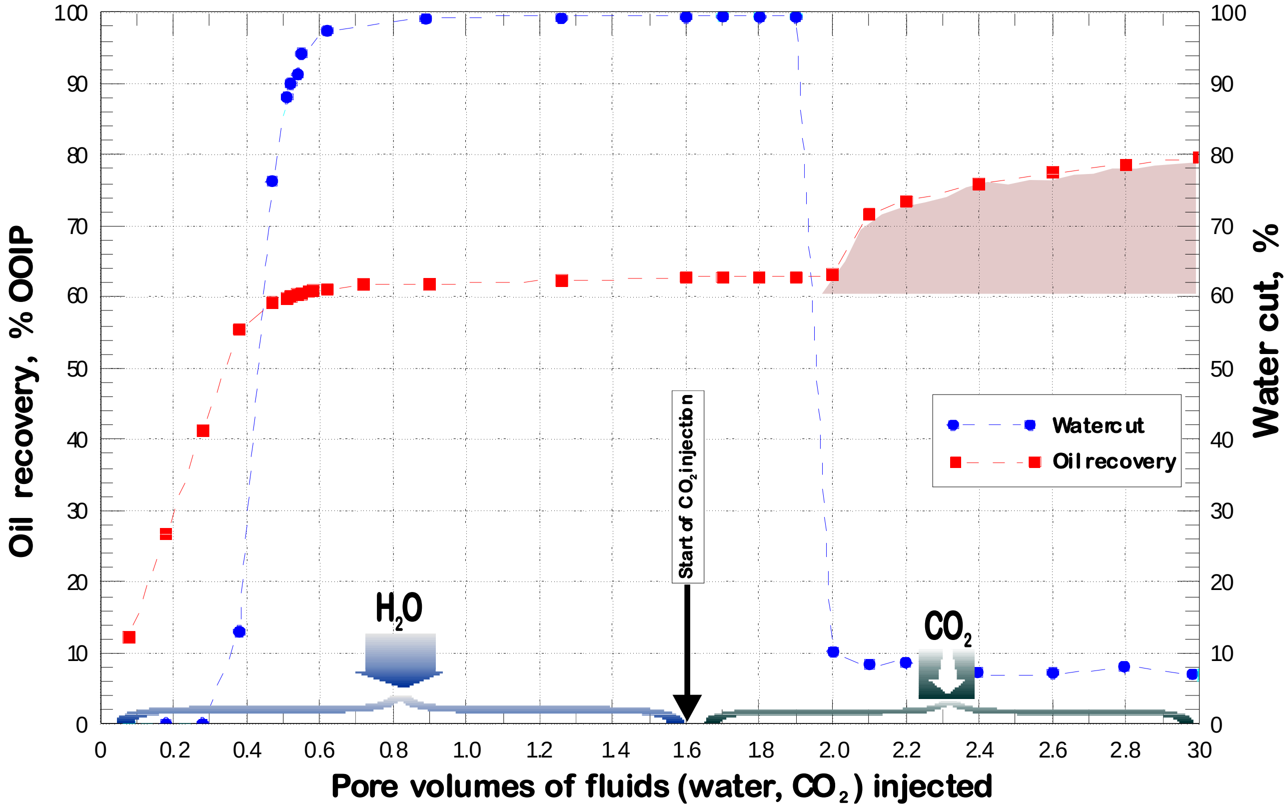
TEST SEQUENCE

1 **Waterflood at 150 bar to S_{or}**

1 **Repressuring to 200 bar with water**

1 **Continuous injection of CO_2**

Continuous CO2 Injection Coreflood Test (Ivanic)



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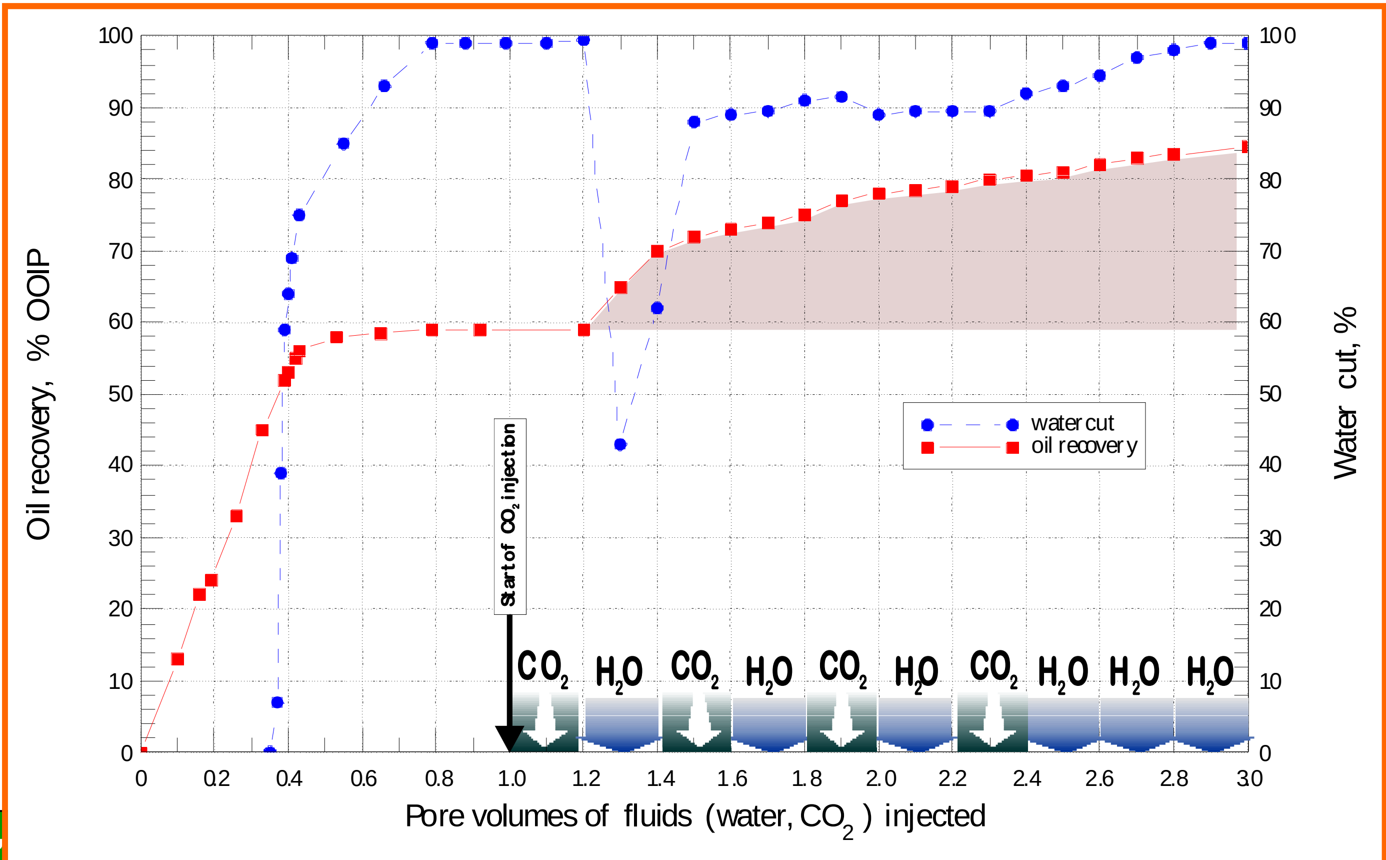
CORE DATA:

D = 9.8 cm	k = 36.7 mD	S_{wi} = 34 % PV
L = 18.3 cm	ϕ = 21.6 %	S_{or} (WF) = 42 % OOIP

TEST SEQUENCE:

1) Waterflood at 150 bar to S_{or}
2) Repressuring to 200 bar with water
3) WAG injection of water and CO_2

Results of a WAG CO_2 Injection Coreflood Test (Ivanic)



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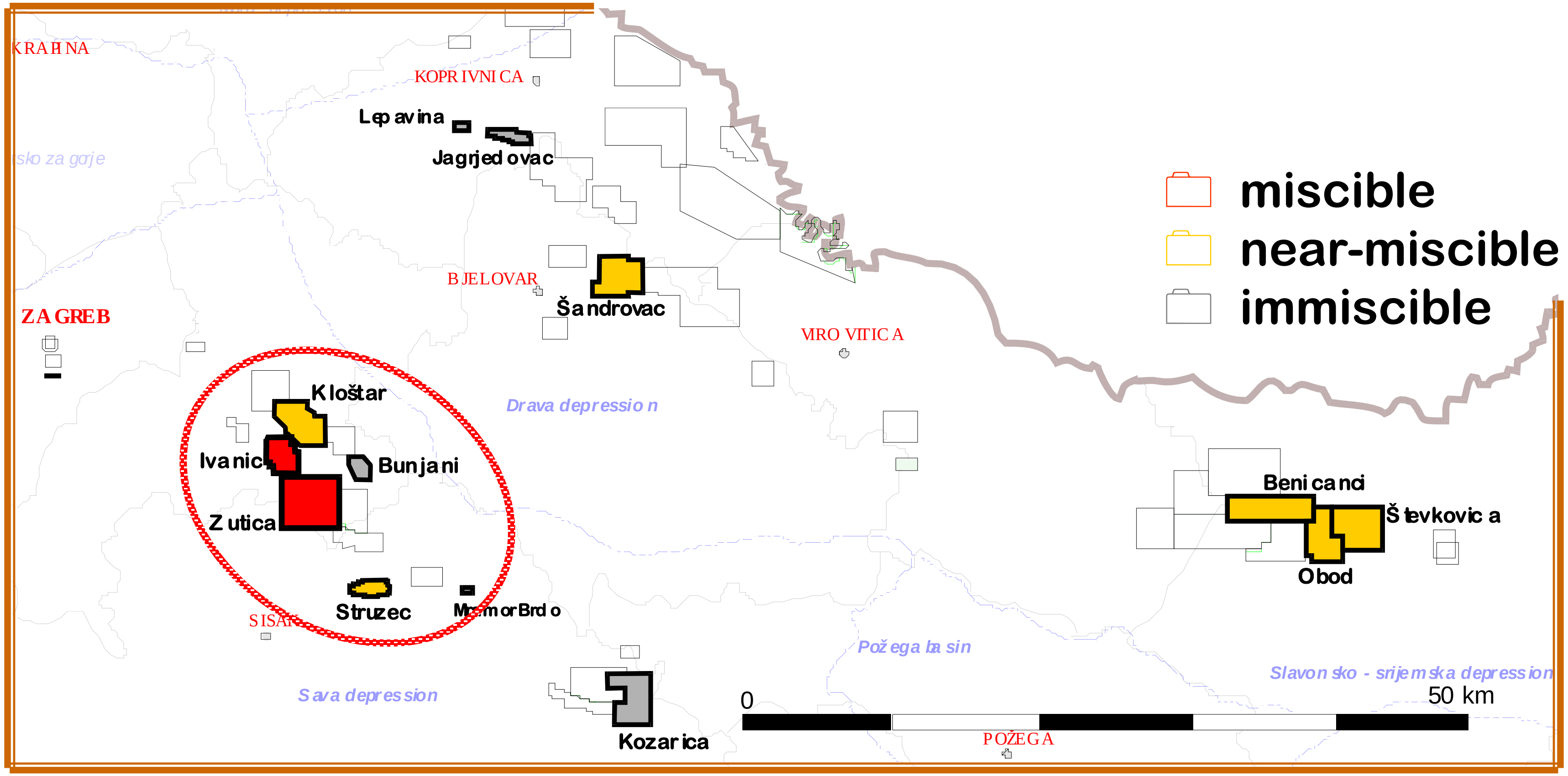
The outcome of the laboratory study for Sava depression oilfields



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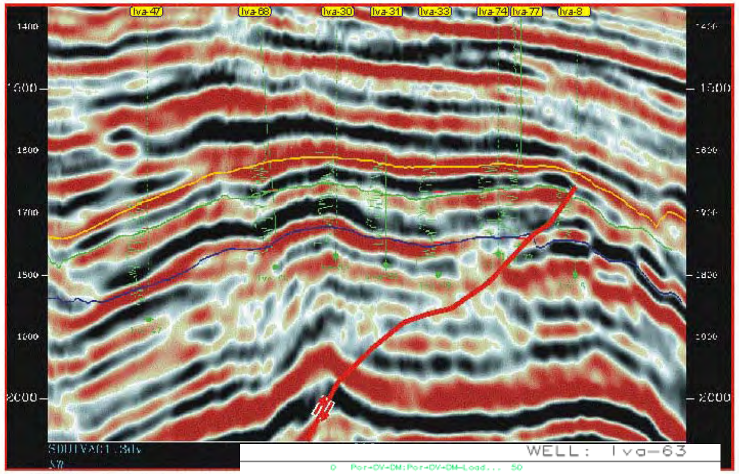
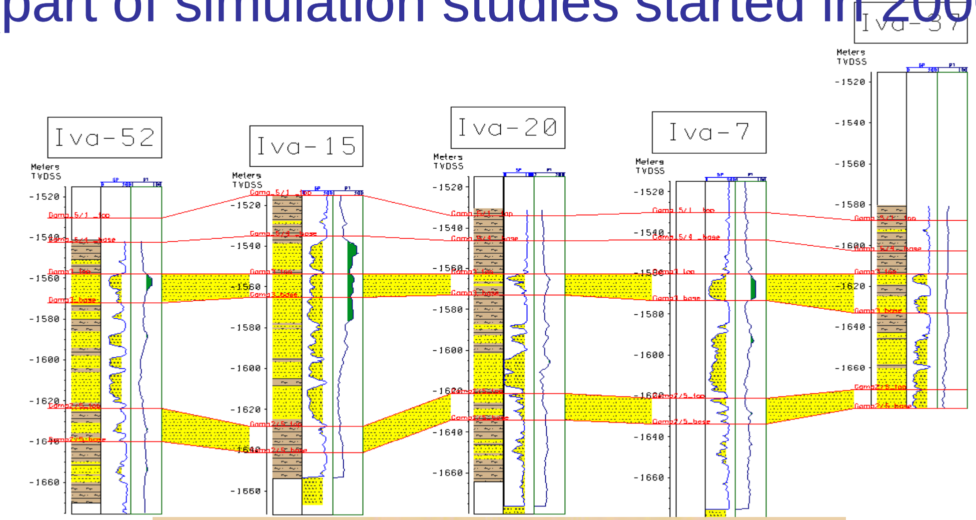
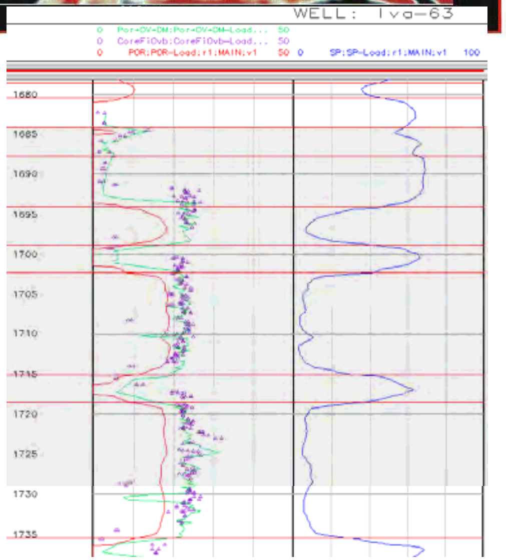
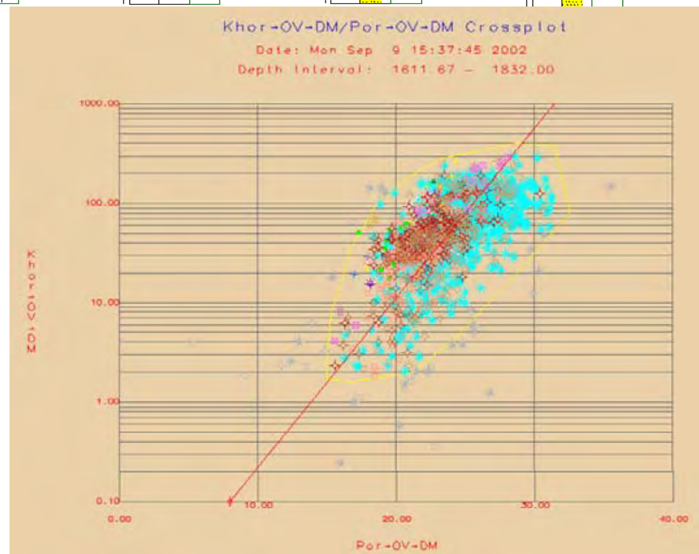
Ivanić – New Geological model (part of simulation studies started in 2000)









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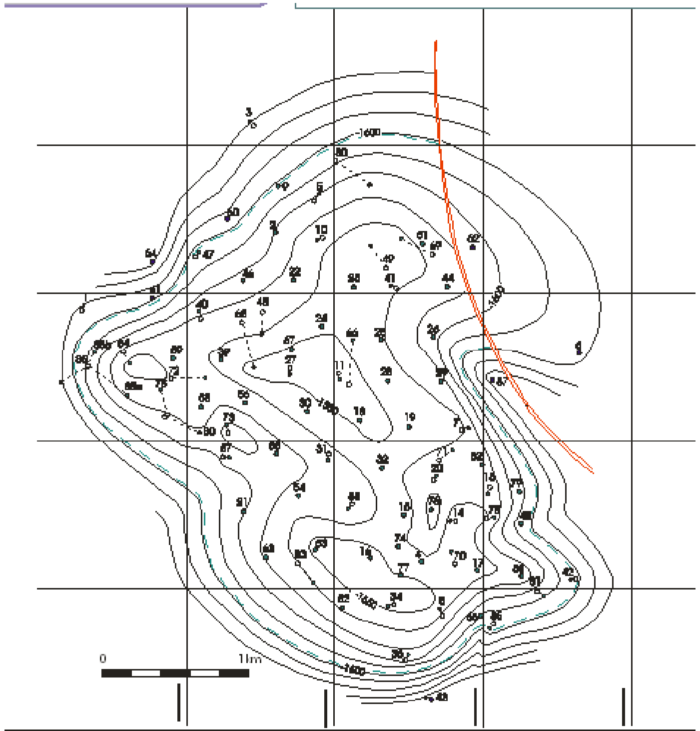
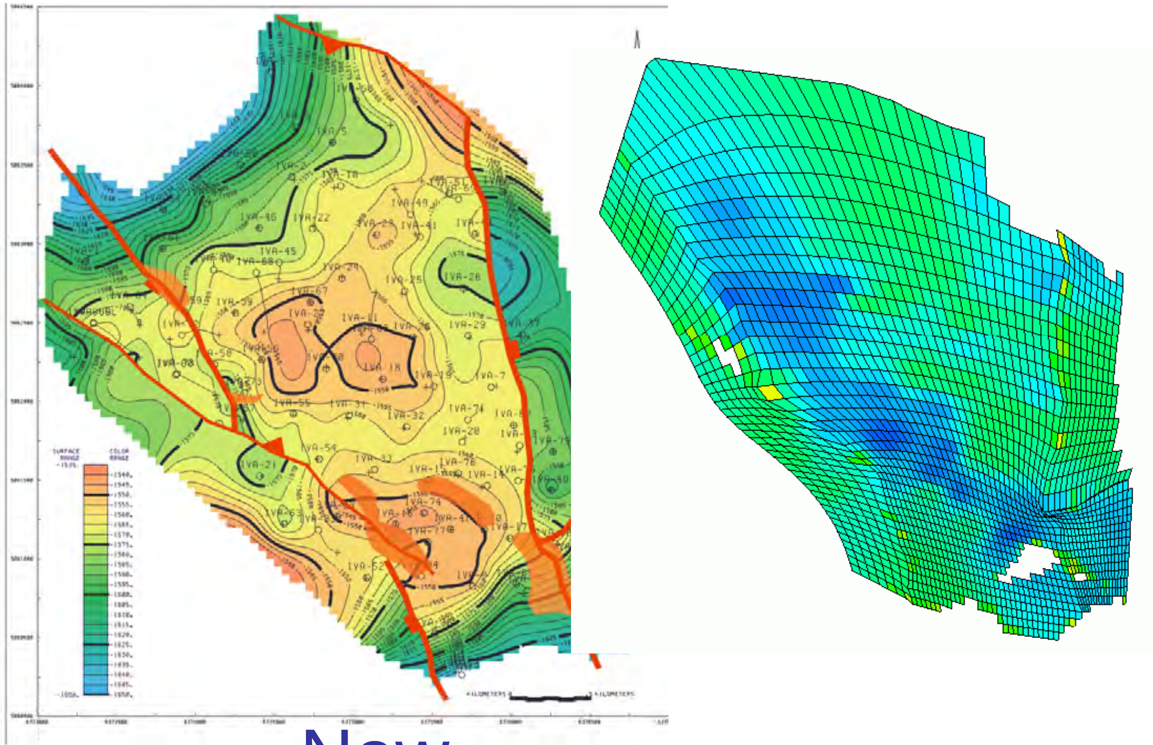
Ivanić – geological setting



Old



New

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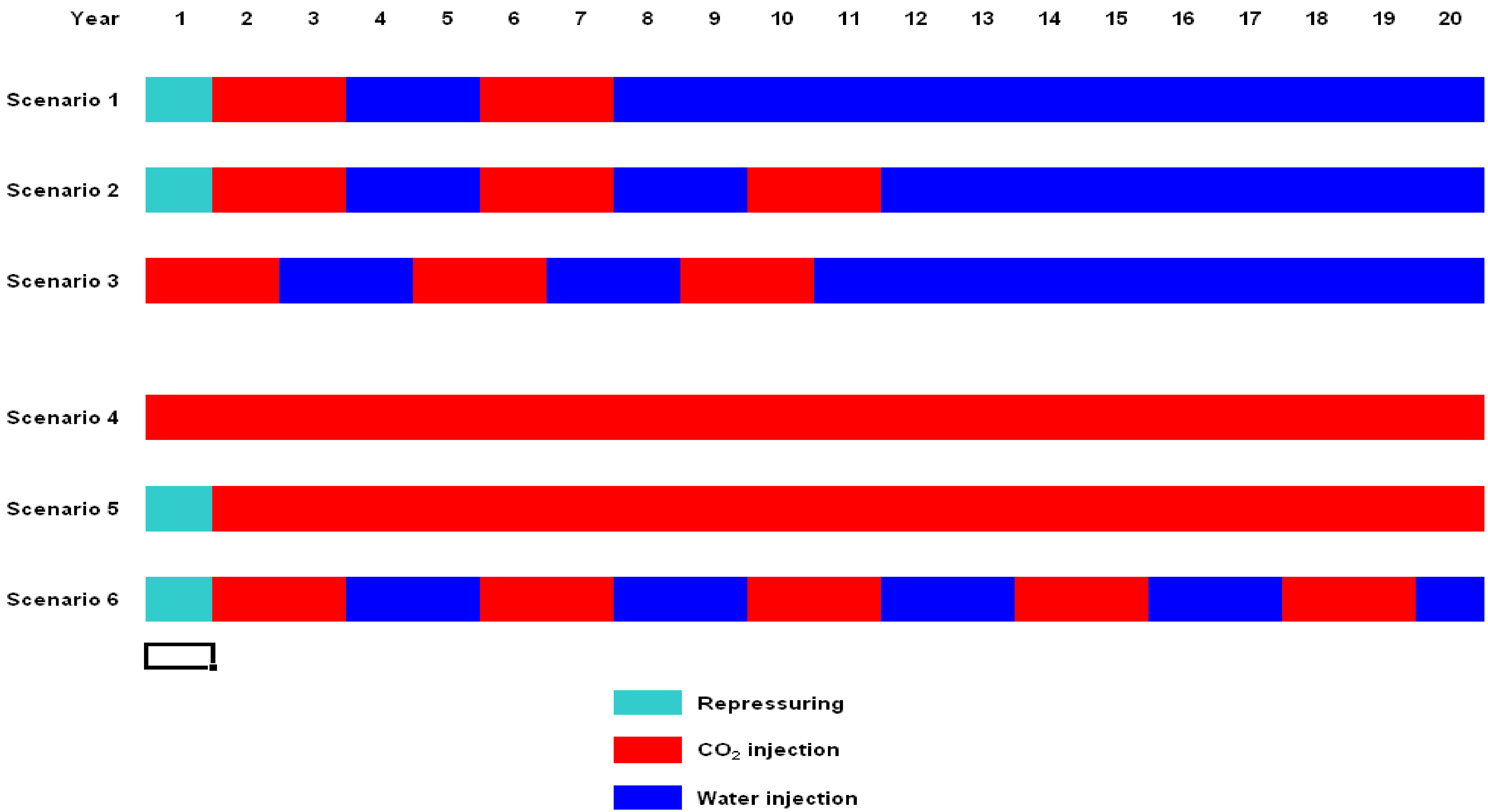
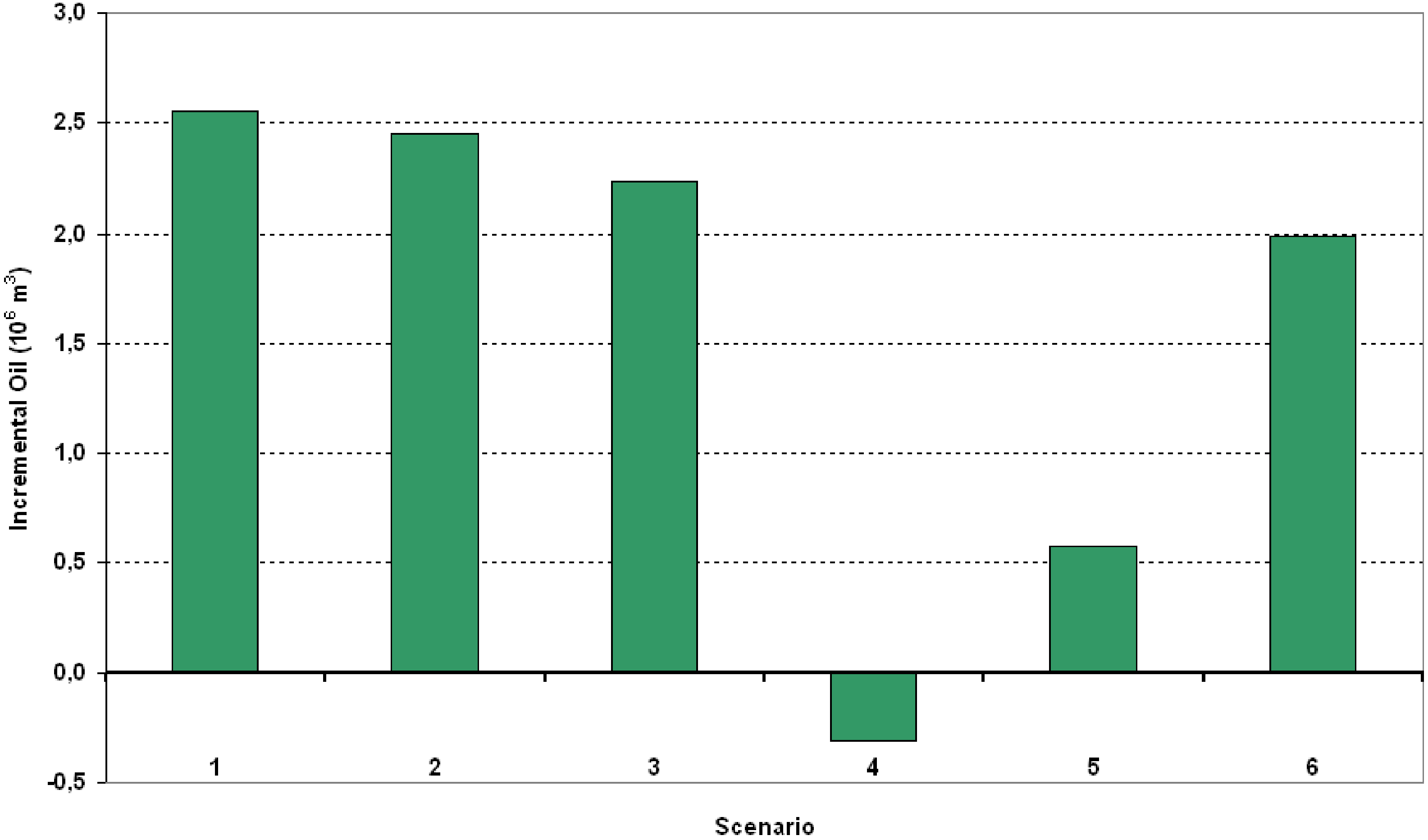
6 prediction scenarios



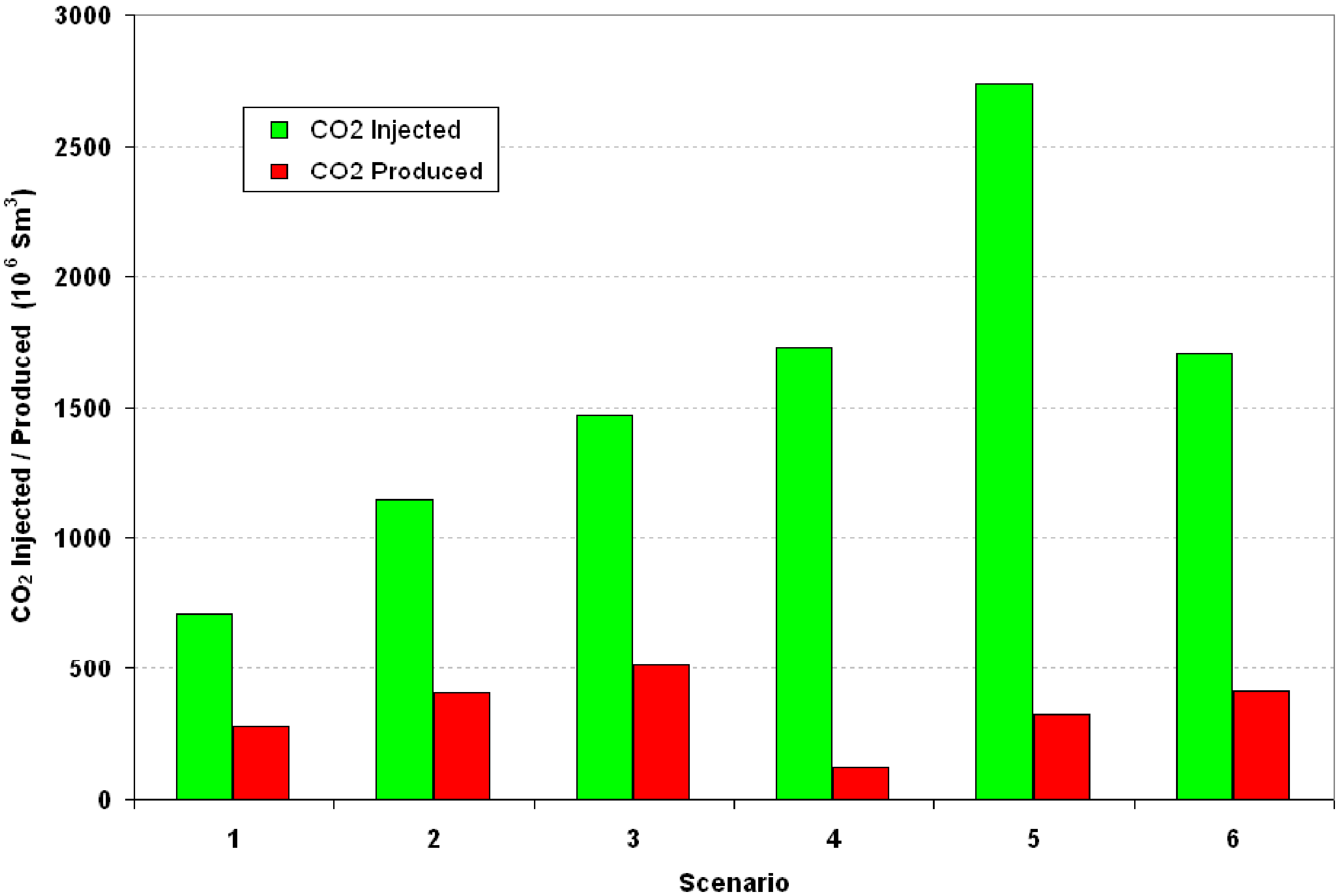
Overview of EOR Efforts in Croatia

6 prediction scenarios



Overview of EOR Efforts in Croatia

6 prediction scenarios



The effect of pore compressibility on CO_2 storage

Volumetric approach

USDOE (U.S. Department of Energy, Office of Fossil Energy) Carbon Sequestration Atlas of United States and Canada, 2006, 86 p.

$$m_{CO2} = A \times h \times \phi \times E \times \rho_{CO2(p,T)}$$

CSLF (Carbon Sequestration Leadership Forum) Estimation of CO2 storage capacity in geological media, June 2007, 43 p.

$$V_{CO2t} = V_{trap} \times \phi \times (1 - S_{wirr}) \equiv A \times h \times \phi \times (1 - S_{wirr})$$

The effective storage volume

$$V_{CO2e} = C_c \times V_{CO2t}$$

Poroelastic definition of rock

Van der Meer, LGH, Yavuz, H. CO_2 storage capacity calculations for the Dutch subsurface. Energy Procedia 1 2009, pp. 2615-2622.

There are three kinds of compressibility:

- rock matrix compressibility

$$c_r = \frac{1}{V_r}\left(\frac{\partial V_r}{\partial p}\right)_{(\bar{\sigma}-p)} = -\frac{1}{V_r}\left(\frac{\partial V_r}{\partial \bar{\sigma}}\right)_{(\bar{\sigma}-p)}$$

- bulk compressibility

$$c_b = -\frac{1}{V_b}\left(\frac{\partial V_b}{\partial \bar{\sigma}}\right)_p$$

- pore compressibility

$$c_p = -\frac{1}{V_p}\left(\frac{\partial V_p}{\partial \bar{\sigma}}\right)_p$$

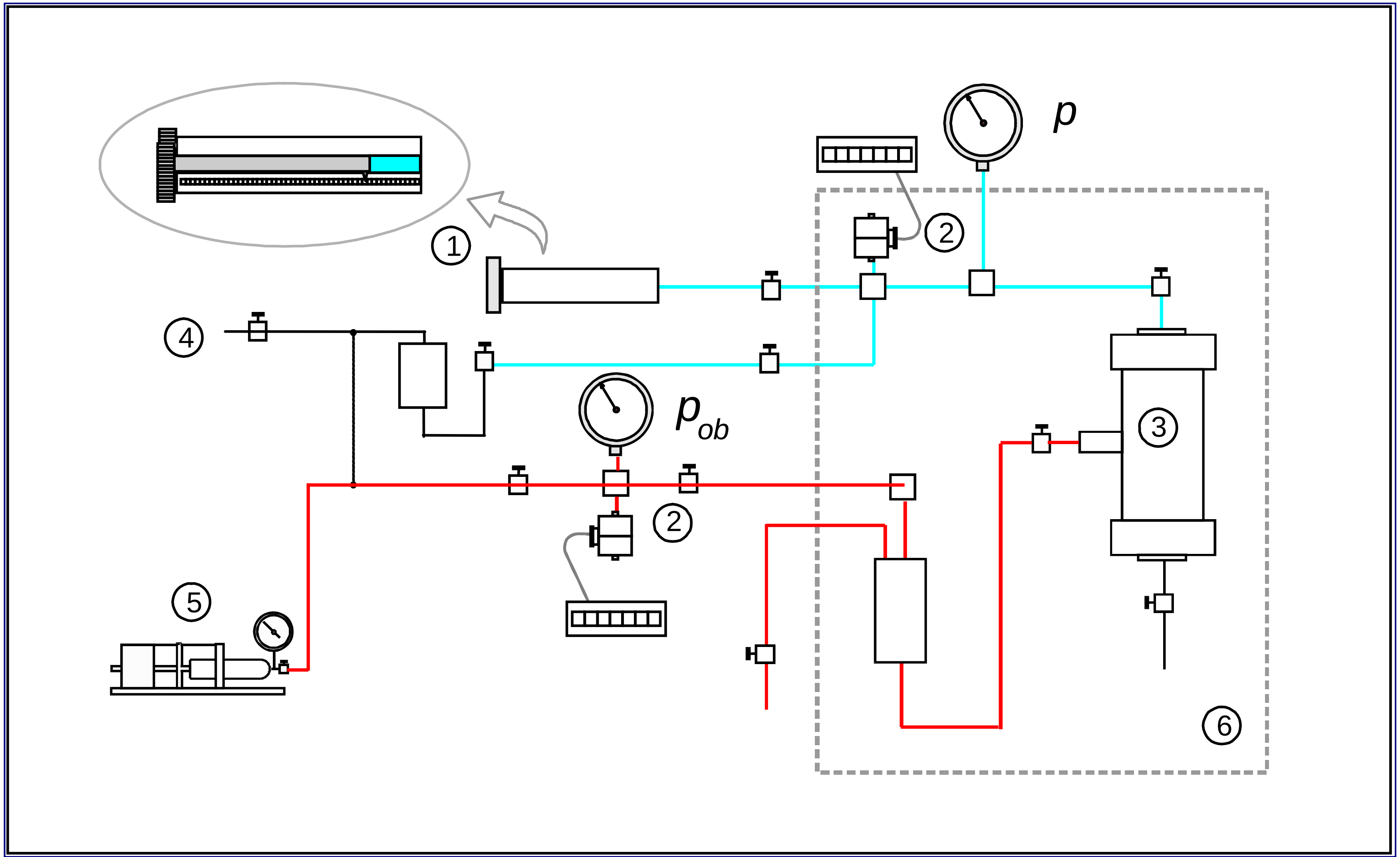
Poroelastic definition of rock

By applying instantaneous pore compressibility for changed (effective) pressure:

$$V_p = V_{p0}\left(1 - c_p p_e\right)$$

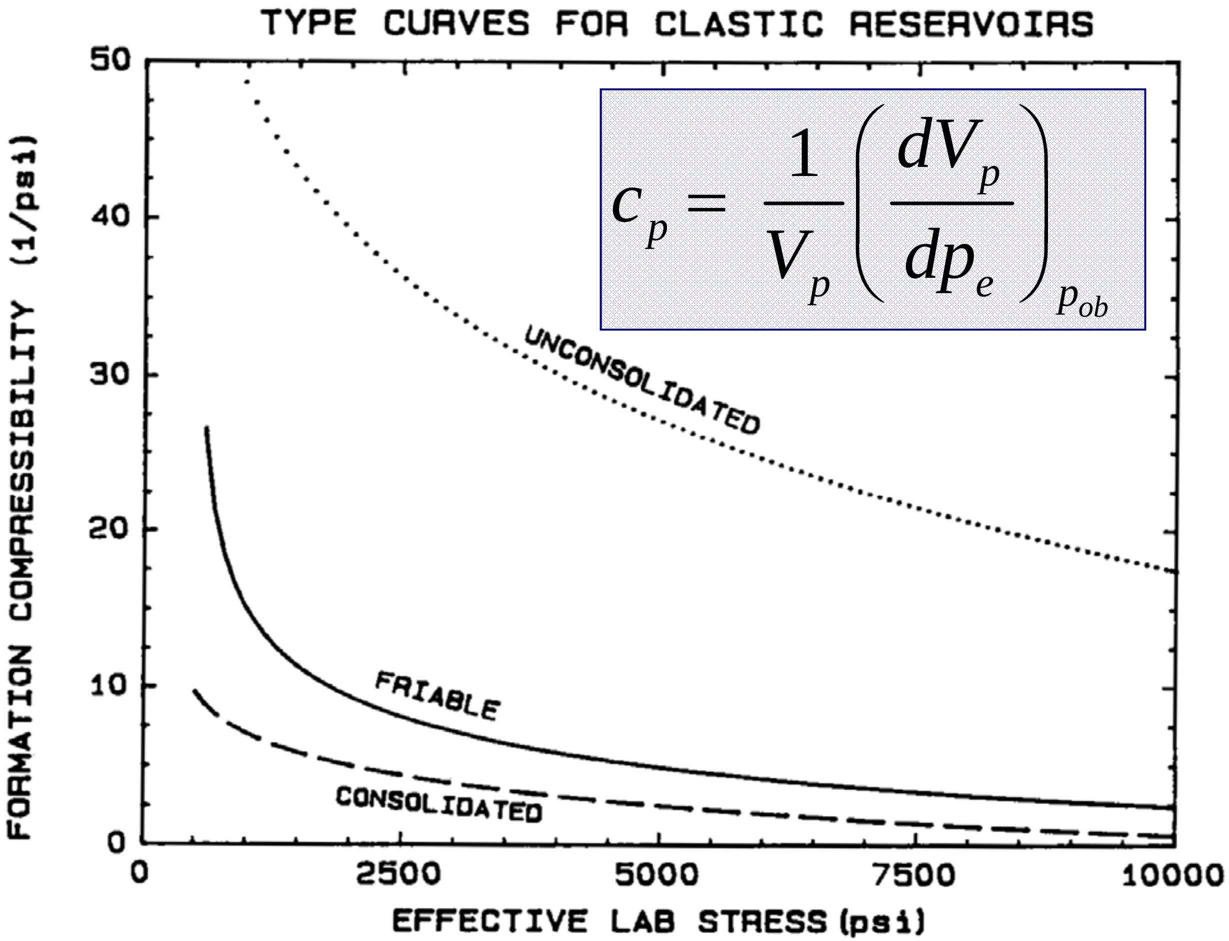
$$\phi = \phi_0\left(1 - c_p p_e\right)$$

Laboratory pore compressibility measurement



Typical (theoretical) p_e-V_p curve

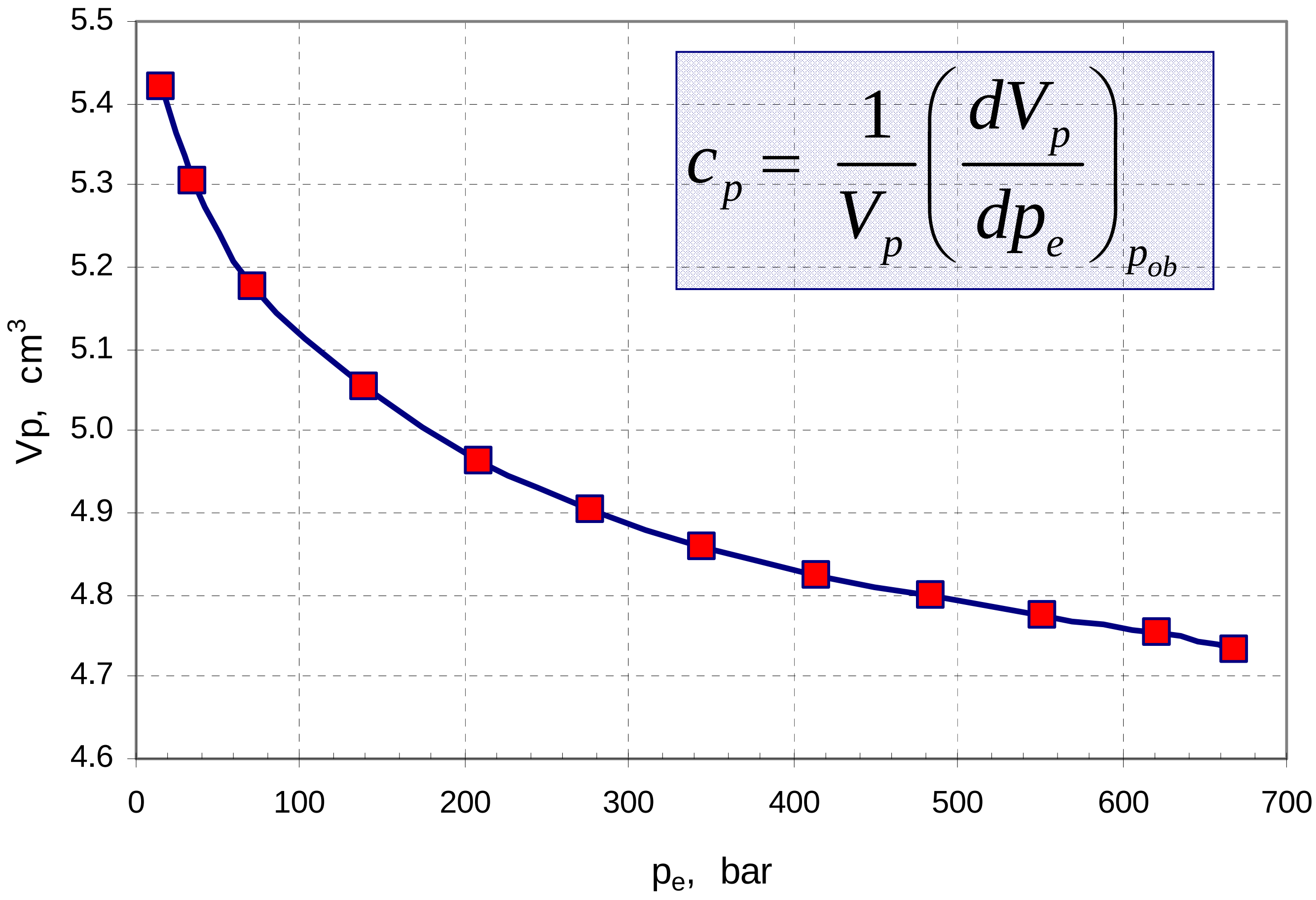
Formation compressibility type curves for a three different degrees of consolidation (**Yale et. al.,1993.**)



$$c_p = \frac{1}{V_p}\left(\frac{dV_p}{dp_e}\right)_{p_{ob}}$$

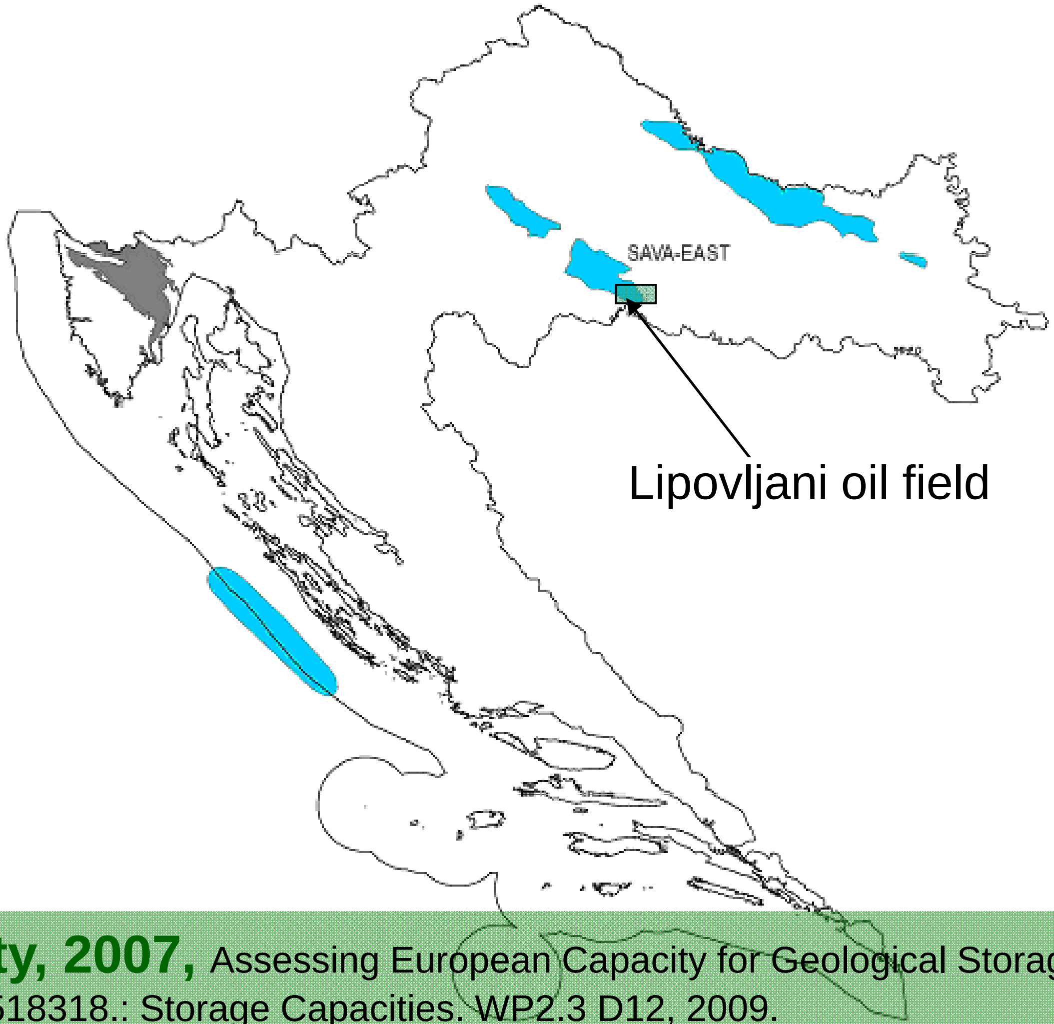
Typical (theoretical) p_e-V_p curve

p_e-V_p plot for one sample (from Lipovljani oil field)



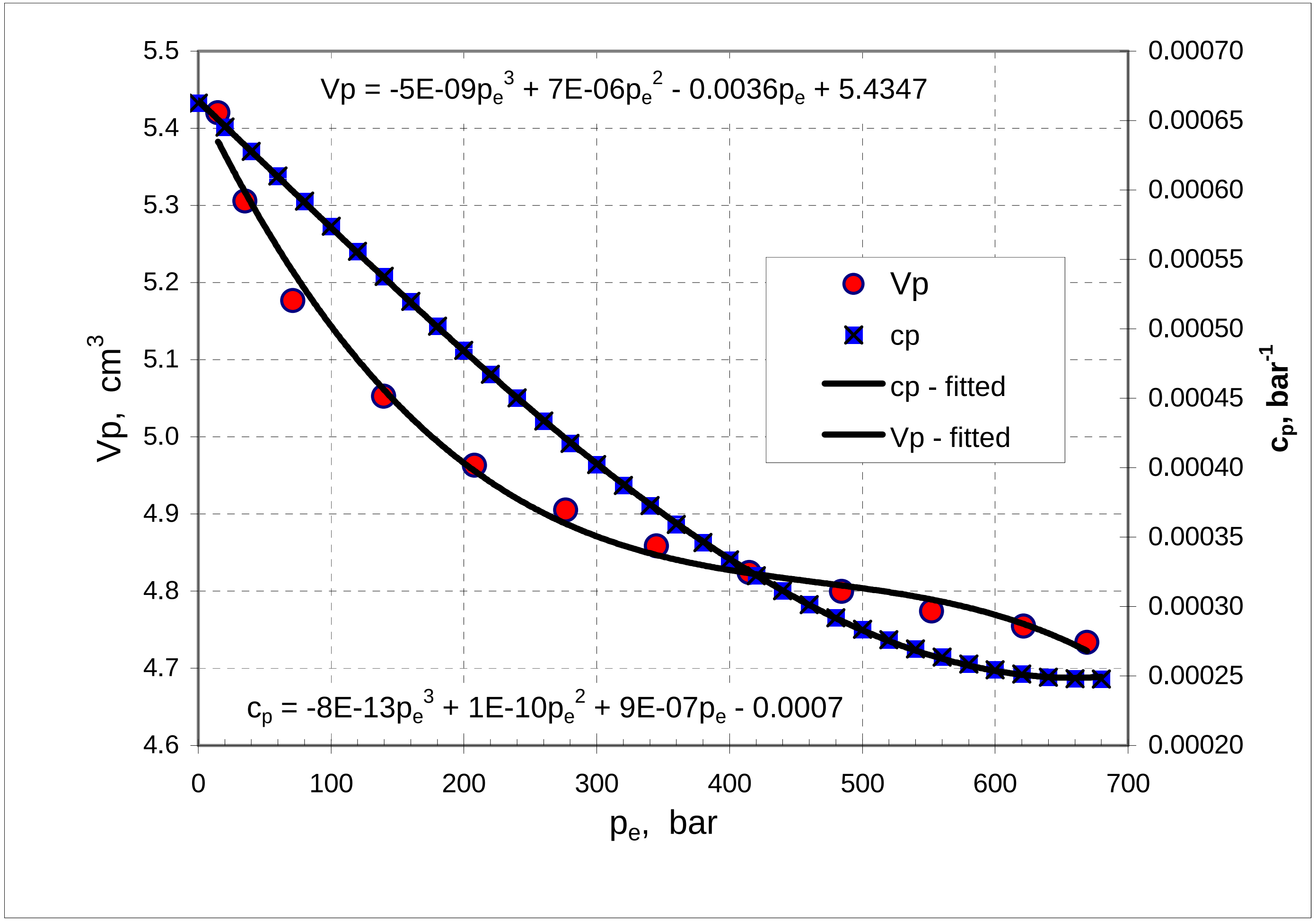
$$c_p = \frac{1}{V_p}\left(\frac{dV_p}{dp_e}\right)_{p_{ob}}$$

Extrapolation of measured data to regional aquifer

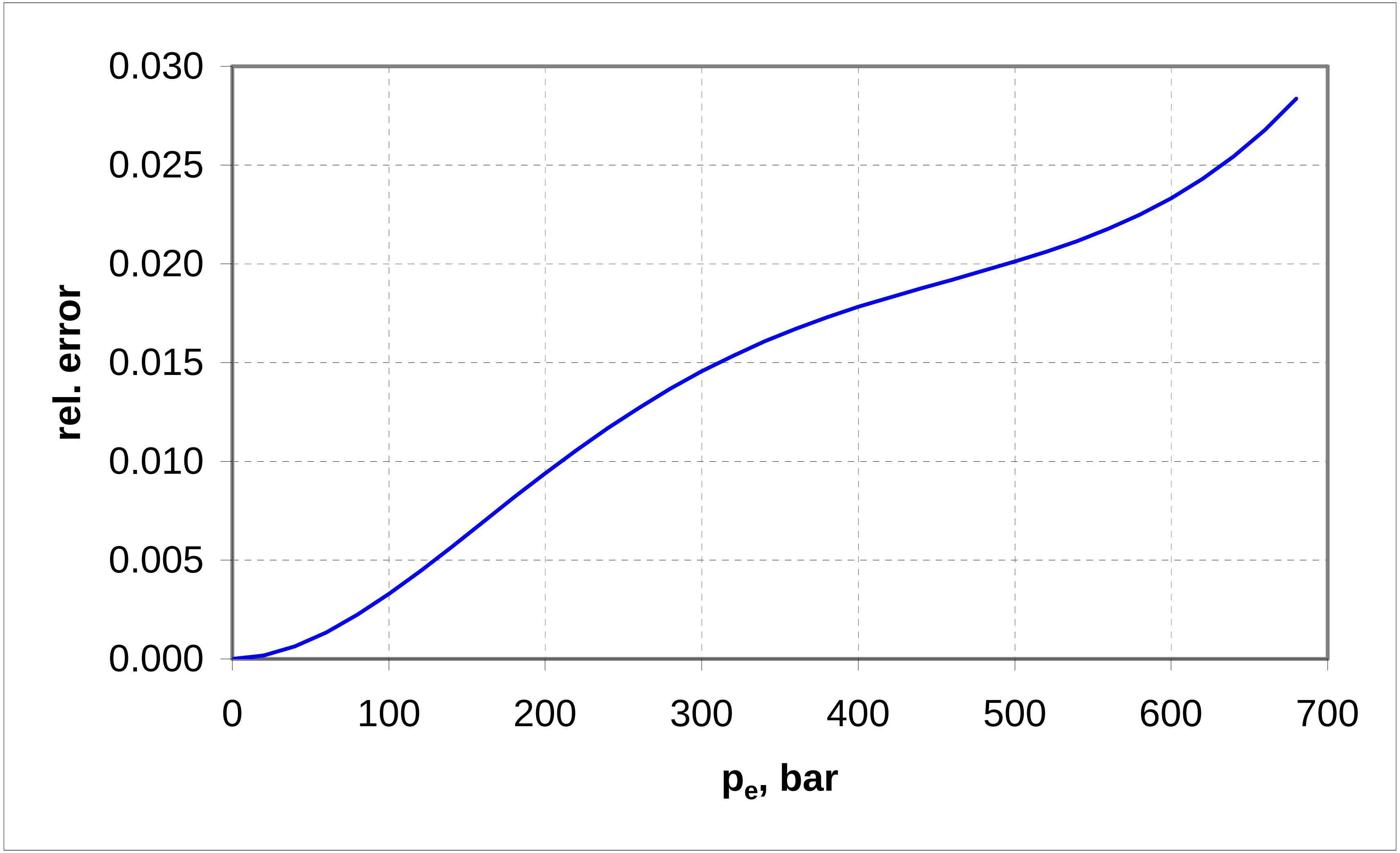


EU GeoCapacity, 2007, Assessing European Capacity for Geological Storage of Carbon Dioxide, Technical reports, FP-518318.: Storage Capacities. WP2.3 D12, 2009.

Extrapolation of measured data to regional aquifer

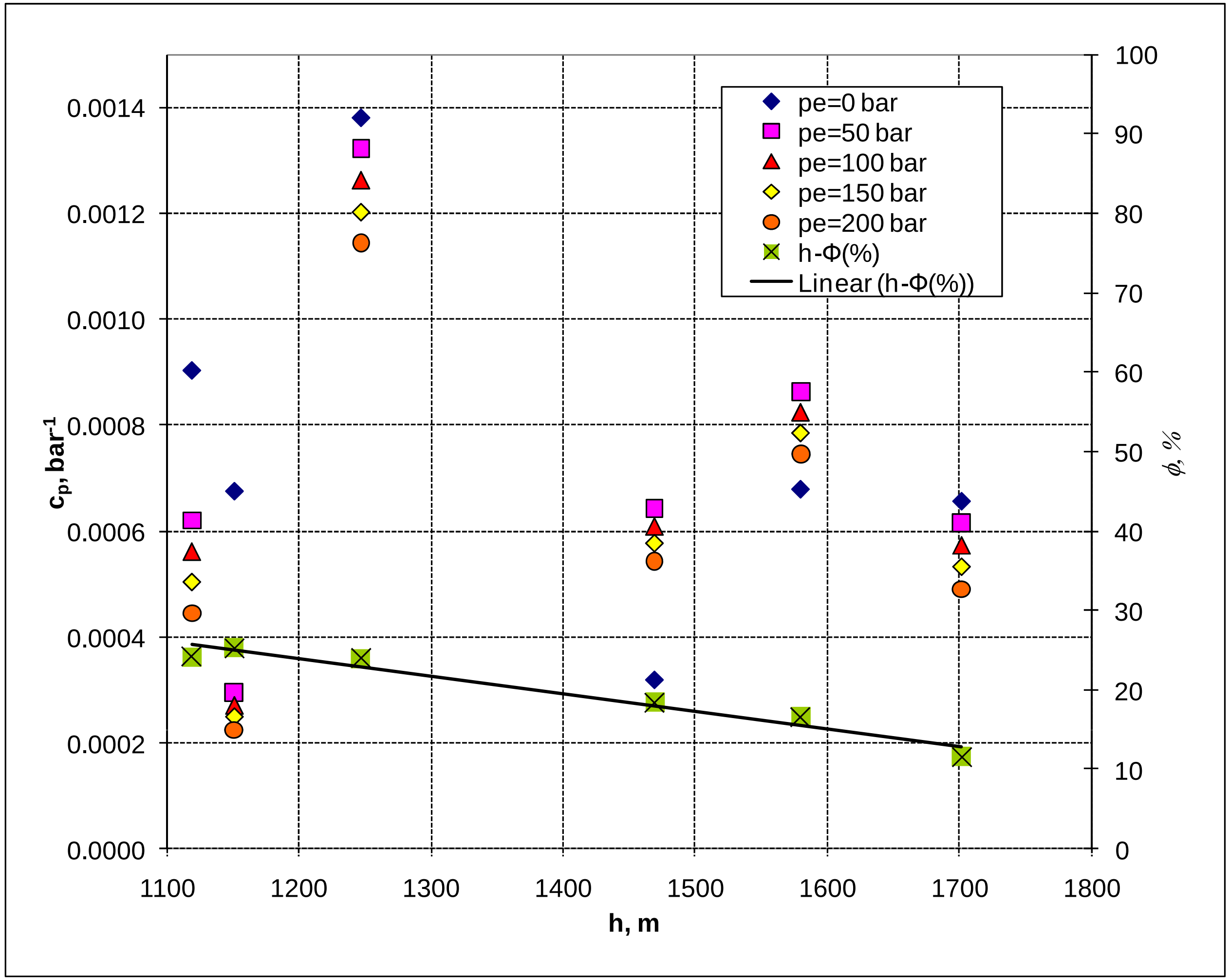


Extrapolation of measured data to regional aquifer



Extrapolation of measured data to regional aquifer

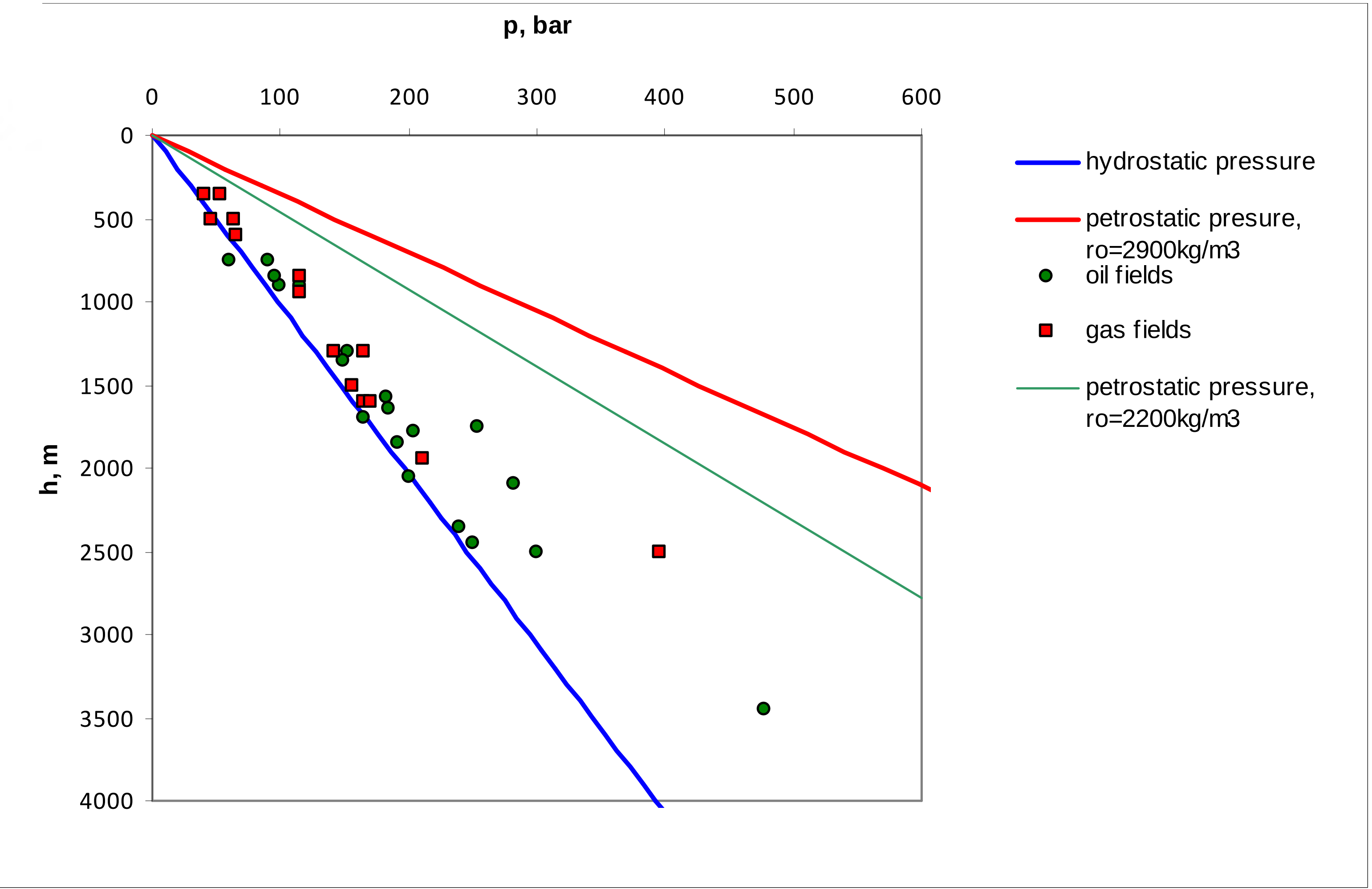
Depth (h) vs. c_p (bar^{-1}) and porosity (fi,%).



Extrapolation of measured data to regional aquifer

Aquifer	Sava – central
Net area, km^2	517
Average depth - H, m	1700
Net to gross thickness - H_{ef}, m	550
porosity.	0.18
Storage capacity coefficient, E	0.03
average pressure, bar	198
Average temperature, °C	87
Density of CO_2, kg/m^3	545.5
Storage capacity, Mt CO_2	**837.6**

Extrapolation of measured data to regional aquifer



Extrapolation of measured data to regional aquifer

Storage capacities without pore compressibility and with pore compressibility

When c_p included

p	p_e	c_p	ϕ	V_p	ρ_{CO2}	m_{CO2}	m_{CO2} increase
bar	bar	bar^{-1}	%	$10^6 m^3$	kg/m^3	Mt	%
198	286	0.000316	18.00	51183	548.07	837.55	0.0
199	285	0.000317	18.02	51252	560.70	842.70	0.6
204	280	0.000319	18.04	51297	572.68	862.87	3.0
214	270	0.000325	18.07	51388	594.80	900.37	7.5
224	260	0.000330	18.10	51481	614.76	934.44	11.6

Conclusions

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- Pore compressibility increases with increased amount of injected fluid, i.e. with aquifer pressure: for first 10 bars increase in table 2, the pore volume will increase by 0.175%, for next 10 bars, pore volume will increase by 0.179%.

- The changes in percents do not seem so dramatic, however results can be compared as capacity with pore compressibility vs. capacity without pore compressibility included:

- The analysis is conducted as pessimistic – petrostatic pressure is probably lower (which would result in higher pore compressibility), the chosen pore compressibility curve is the one with the lowest average compressibility of 6 available curves

Conclusions

• the brine compressibility can be taken into account (also by using pessimistic approach to obtain minimum brine compressibility) by using one of the many published correlations (also adjusted for the actual brine), for example:

•Meehan, DN. *A Correlation for Water Compressibility*, Pet. Eng., 1980, pp. 125-126.
•Kutasov, IM. *Correlation Simplifies Obtaining Downhole Brine Density*, Oil & Gas J., 1991, pp. 48-49.
•Numbere, D, Brigham, WE, and Standing, MB. *Correlation of Physical Properties of Petroleum Reservoir Brines*. Stanford University Petroleum Research Institute, 1977.