Tallinn University of Technology (TalTech), Department of Geology

New CO_2 and Hydrogen storage site marketing: How to make your storage site unique and attractive

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TAL TECH DEPARTMENT OF GEOLOGY

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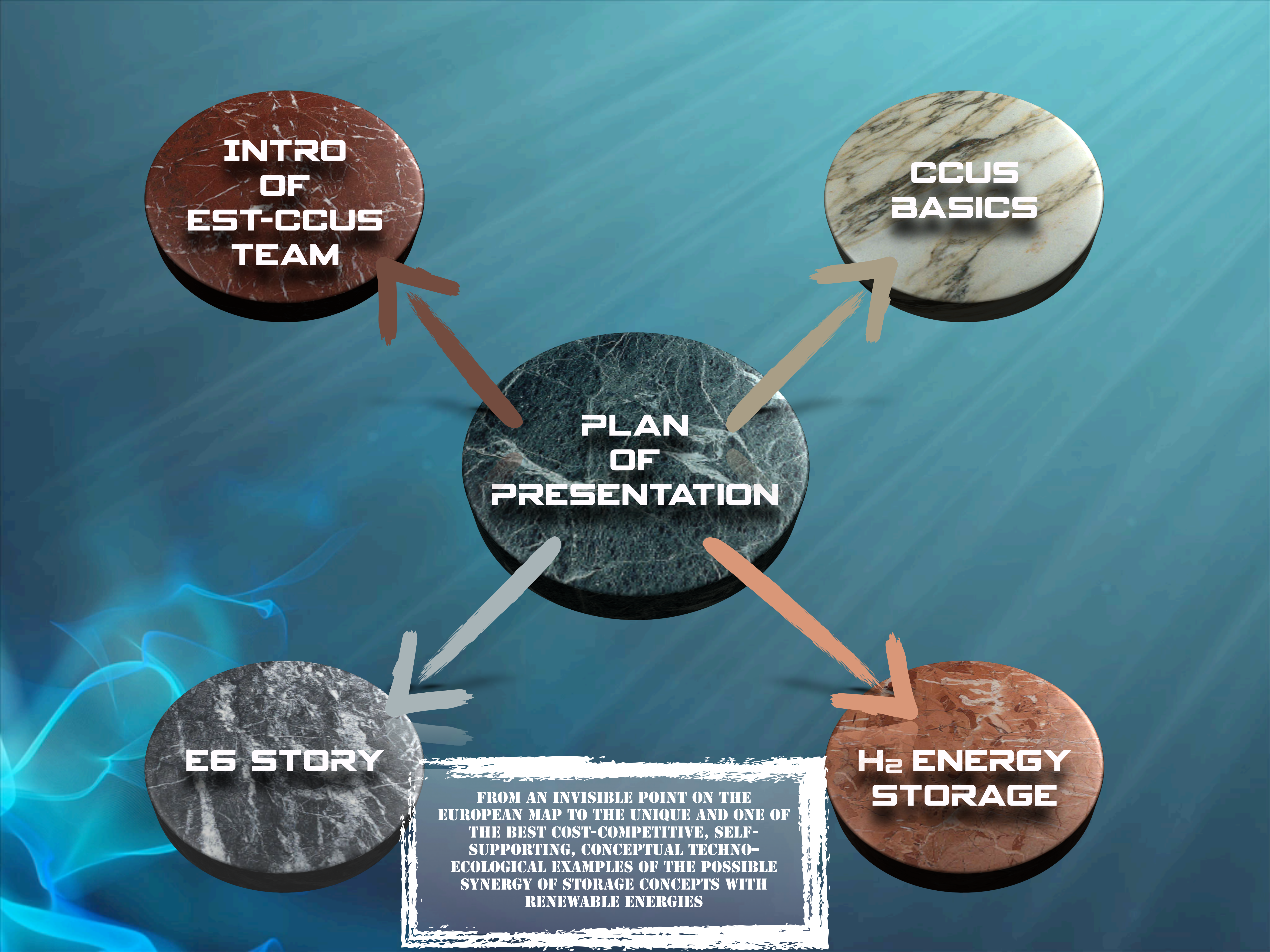
Web: taltech.ee/en/department-geology

SHOGENERGY
Consulting & Solutions for future energy sector
CCUS/H_2/Energy storage/Geothermal energy recovery
SYNERGY CONCEPTS

SHOGenergy, Consulting company
Pae 17A-27, 11414 Tallinn, Estonia
Web: SHOGenergy.eu


INTRO OF EST-CCUS TEAM
CCUS BASICS
PLAN OF PRESENTATION
E6 STORY
H_2 ENERGY STORAGE
FROM AN INVISIBLE POINT ON THE EUROPEAN MAP TO THE UNIQUE AND ONE OF THE BEST COST-COMPETITIVE, SELF-SUPPORTING, CONCEPTUAL TECHNO-ECOLOGICAL EXAMPLES OF THE POSSIBLE SYNERGY OF STORAGE CONCEPTS WITH RENEWABLE ENERGIES

OUR EXPERTISE

INTRO OF EST-CCUS TEAM

CO_2 CAPTURE, TRANSPORT & GEOLOGICAL STORAGE

>16 years

I CCUS REGULATIONS

- European countries
- United States
- Other countries

II TECHNO-ECONOMIC MODELLING

- Transport
- CO_2 Use
- Storage & monitoring

III CAPTURE, COMPRESSION & TRANSPORT

IV GEOLOGICAL STORAGE

- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties
- Reservoir characterisation and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations
- 4D time-lapse rock physics and numerical seismic modelling
- Coupling of the chemically induced petrophysical alteration effect of CO_2– hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- Modelling of the possible shape of CO_2 plume migration in the storage site

SCIENTIFIC PROJECTS [2006-2028]

INTRO OF EST-CCUS TEAM

1. 2023 (01.01)-2028. Horizon Europe HER**CCU**LES (29 mln €). SHOGenergy is a partner
2. 2022 (1.09)-2025. Horizon Europe CCUS ZEN (CCUS Zero Emission Network). TalTech is WP3 leader
3. 2020-2023- Strategic partnership for fostering circular economy approach in extractive industry-related study programmes (VERT20047)
4. 2021-2022- Hydrogen Storage In European Subsurface (VFP20055)
5. 2020-2022- Routing Deployment of Carbon Capture, Use and Storage CCUS in the Baltic Sea Region (BSR)
6. 2018-2023- The Website of the ENeRG Network
7. 2017-2023- CLEANKER - CLEAN clinKER production by Calcium looping process (CCUS Work package, Leader of techno-economic modelling task), Horizon 2020, (extended for 1.5 year)
8. 2016-2020- ENOS (ENabling Onshore CO_2 Storage in Europe), Horizon 2020
9. 2016-2017- CO_2 Geological Storage in the Baltic Sea Region/CGS Baltic (Seed money project, V16022)
10. 2015-2016- ESTMAP, Horizon 2020
11. 2014-2019- Estonian Ministry of Education & Research programme (SF0320080s07, IUT19-22)
12. 2012-2017- The Newsletter of the ENeRG Network (LEPGI 299)
13. 2012-2013- CO2STOP, EC FP7 sub-contract
14. 2011-2013- CGS EUROPE, (http://www.cgseurope.net), EC FP7
15. 2006-2009- CO2NET EAST (http://co2neteast.energnet.com), EC FP6
16. 2006-2008- EU GEOCAPACITY (http://nts1.cgu.cz/geocapacity), EC FP6

INDUSTRIAL PROJECTS

2009 - CO_2 geological storage in Estonia and neighbouring regions: analysis and options and storage recommendations (in English and Estonian, confidential)- Eesti Energia AS

NETWORKS

INTRO OF EST-CCUS TEAM

1. BASRECCS (Board Member)
2. CO2GeoNet (TalTechDG representative)
3. ENeRG – TalTech and SHOGenergy
4. COST Action Geothermal-DHC (We are coordinating the Ad-HOC WG – Unconventional Geothermal (CO_2 for Geothermal, Enhanced Geothermal Systems (EGS-Geothermal)).
5. COST Action CA21127 – TrANsMIT. Techno-economic analysis of carbon mitigation technologies. Managing Committee Members

CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES: CLIMATE CHANGE AND CCUS IN ESTONIAN MEDIA (2019)

POSTIMEES МНЕНИЕ СПОРТ ВИДЕО КУЛЬТУРА КРАСОТКА LIMON КИНОЗАЛ ЗДОРОВЬЕ БАРБОС

Rus.Postimees.ee > Экономика > Ученые знают, как спасти сланцевую энергетику Эстонии не в ущерб экологии, но их не слыша

269 1 17 октября 2019, 18:31

Ученые знают, как спасти сланцевую энергетику Эстонии не в ущерб экологии, но их не слышат

Добавлен комментарий Eesti Energia

Олеся Лагашина

Казбулат Шогенов со своей докторской диссертацией, посвяще... углекислого газа.
ФОТО: Олеся Лагашина

В ТТУ утверждают, что знают, как решить про... неэкологичной сланцевой энергетики, не закр... производство. Однако пока ученым не внемл... энергетики. О том, почему так происходит и к...

SCIENTISTS KNOW HOW TO SAVE ESTONIAN OIL SHALES ENERGY PRODUCTION WITHOUT HARMING THE ENVIRONMENT, BUT THEY ARE NOT HEARD

Ярослав ...ень • 7 ноября 2019 Поделиться:

Только для подписчиков

Группа захвата CO_2

В США разработаны технологии, позволяющие устранить 90% выбросов CO_2 в атмосферу. Их можно применять и в Эстонии. Но есть проблема: они невероятно дорогие.

SPECIAL FORCES OF CO_2 SEQUESTRATION

SCIENTIST: IT IS POSSIBLE TO STORE CO_2 AND RECOVER GEOTHERMAL ENERGY IN ESTONIAN UNDERGROUND

EestiPäevaleht UUDISED ARVAMUS VÄLISMAA ÄRILEHT ...ASULIK KULTUUR SPORT LP

KLIIMA 31. OKTOOBER 2019

Teadlane: ka Eesti maapõues saaks CO_2 ladustada ja siis näiteks maasooja toota 23

Maasooja tootmine CO_2 abiga on Alla Šogenova sõnul täiesti võimalik. „Seda pole ma veel kellelegi Eesti rääkinud. Ol... juba rääkinud teile rohkem, kui peaks!"

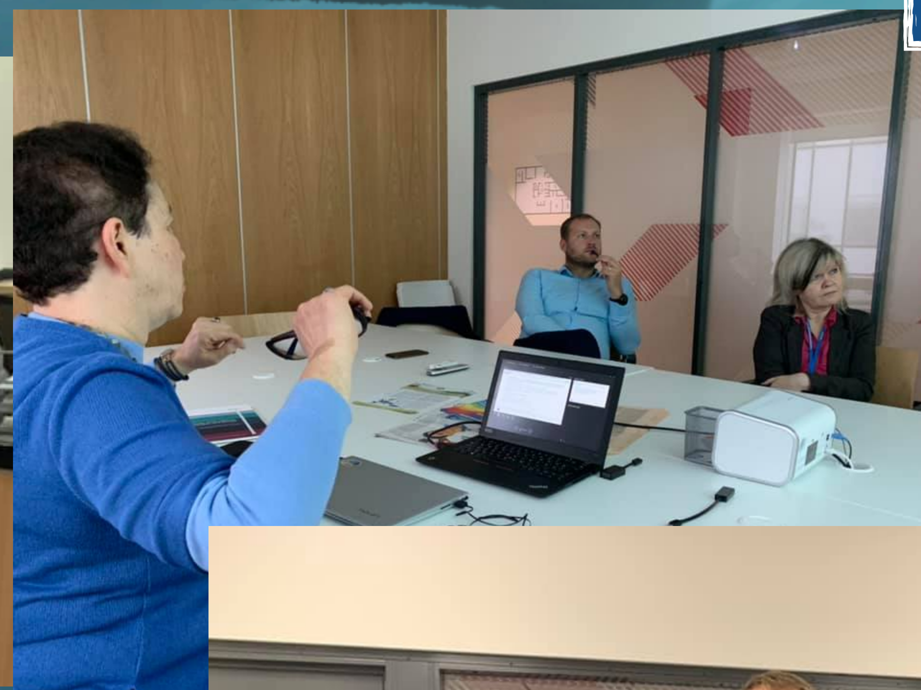
RAIMO POOM
raimo.poom@epl.ee

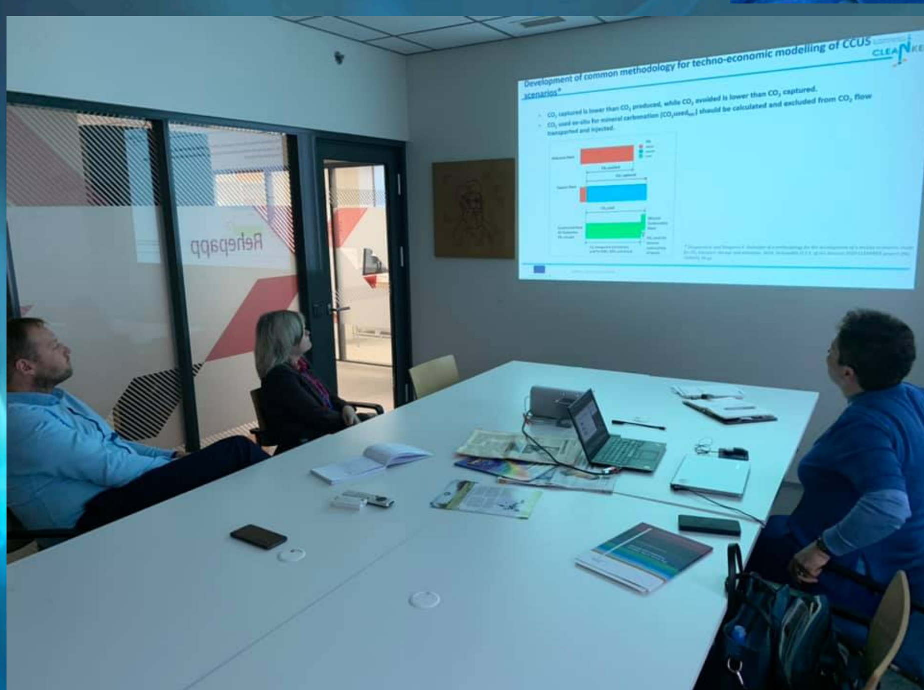
JAGA 56

CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES

PRESENTATION AT THE ESTONIAN MINISTRY OF ECONOMIC AFFAIRS AND COMMUNICATIONS, TIMO TATAR - DEPUTY SECRETARY GENERAL





CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES

PRESENTATIONS OF CCUS TO ESTONIAN PARLIAMENT MEMBERS–VIKTORIA LADÕNSKAJA & FUTURE MINISTER OF ENVIRONMENT (2021-2022) ERKI SAVISAAR

CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES

MEETING WITH THE AMBASSADOR OF NORWAY

NEW NORWEGIAN AMBASSADOR TO ESTONIA, ELSE BERIT EIKELAND, AND COUNSELLOR OF THE NORWEGIAN EMBASSY IN TALLINN, OLE ØVERAAS, INVITED RESEARCHERS DR ALLA SHOGENOVA AND DR KAZBULAT SHOGENOV TO THE NORWEGIAN EMBASSY ON 15.10.19 TO DISCUSS ESTONIA'S PROSPECTS FOR IMPLEMENTING CCS TECHNOLOGY AND COOPERATION WITH NORWAY.

CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES

DEFENDED MASTER AND PHD THESIS'S UNDER SUPERVISION OF OUR TEAM

TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

School of Science
Department of Geology

Estonian-Latvian Transboundary Carbon Dioxide Capture, Transport and Storage (CCS) Scenario for the Cement Industry

Master thesis

Student: Karl Simmer, 162972YAEM
Supervisor: Alla Shogenova, Department of Geology, senior researcher
Study program: Earth Sciences and Geotechnology

Tallinn 2018

TALLINN UNIVERSITY OF TECHNOLOGY

SAPIENZA UNIVERSITÀ DI ROMA

North Italian CCS scenario for the cement industry

Student: Martina Mariani
Supervisors:
Dr. Kazbulat Shogenov, researcher
Dr. Alla Shogenova, senior researcher
(Tallinn University of Technology)

Roma, 2020

TAL TECH
GEOLOOGIA INSTITUUT

Integration of cement plants into CCUS hubs and clusters in Europe: case study from United Kingdom

Master thesis

Student: Glea Habicht, 192230LARM
Supervisor: Alla Šogenova, Department of Geology, senior researcher
Study program: Georesources

2021

THESIS ON INFORMATICS AND SYSTEM ENGINEERING

Conformity analysis of E-learning Systems at Largest Universities in Estonia and Turkey on the basis of EES Model

FATİH GULLU

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CO_2 & H_2 & GEOTHERMAL - ESTONIAN UNCONVENTIONAL GLOBAL WARMING FIGHTING SPECIAL FORCES

DISSEMINATION ACTIVITIES

DEFENDED MASTER AND PHD THESIS'S UNDER SUPERVISION OF OUR TEAM

THESIS ON NATURAL AND EXACT SCIENCES B186

Petrophysical Models of the CO_2 Plume at Prospective Storage Sites in the Baltic Basin

KAZBULAT SHOGENOV

TUT PRESS

SHOGENERGY.EU

EST. 2021

👑SHOGENERGY👑 - THE FUTURE KING IN THE CO_2 & H_2 GEOLOGICAL STORAGE CONSULTING!

NEW, ESTABLISHED IN 2021, CONSULTING & RESEARCH COMPANY

Dr Kazbulat Shogenov, The founder and t… research scientist at Tallinn University… Department of Geology, with experience i… more than 20 years, has defended his PhD thesis in T… His PhD is in the field of CCS (CO_2 capt… storage and seismic numerical modelling… geol… prospective storage site in the Batic sedime…

SERVICES

I CCUS REGULATIONS

II EDUCATION

III EVENTS

IV CONSULTING

…d-famous CCUS … of only experts … packages of more than 15 …

…author of the unique CCUS educational program for students, and successfully supervised a number of Master's and PhD Estonian and international students.

She has unique expertise in the world of the full chain of CCUS technology.

WE WISH YOU … CARBON-FREE JOURNEY

WE OFFER:

SERVICES

SHOGenergy

I CCUS REGULATIONS

- Advisory support in policies and regulations development (for policymakers)

II EDUCATION

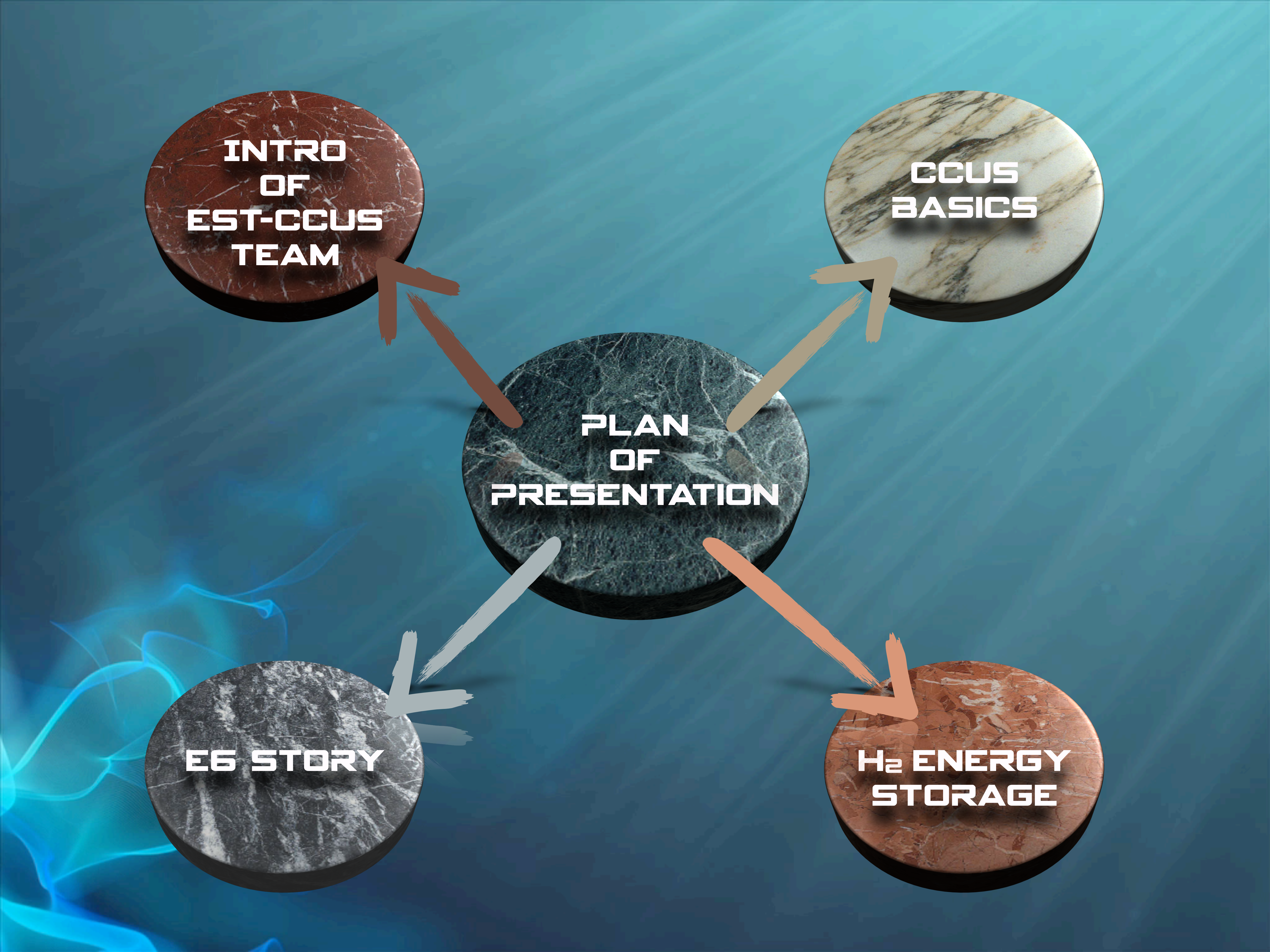
- Short courses organised in Tallinn, at the place of the client, online or hybrid
- Full study modulus (very detailed course, containing more precocious knowledge)
- Seminars and workshops for a small and big enterprises
- Development of E-learning and regular courses
- Master and PhD studies supervising, analysis and improvement

III EVENTS

- Support in the organisation, full management or chairing of the particular sessions, etc., of big events (conferences, workshops, exhibitions)

IV CONSULTING

- Establishing of CCUS strategy for the company, region or the country
- Development and supporting, review, analysis and improvement of research and dissemination of projects proposals writing, policies drafts development, scientific papers, reports, research thesis, etc., improvement.
- Participation in the research and dissemination projects in the field of CCUS, H_2 storage, renewable energy recovery and storage, the synergy of these technologies
- Development of strategical management to make the prospective storage site more attractive for the publicity, stakeholders and policymakers
- Management service of the geological storage site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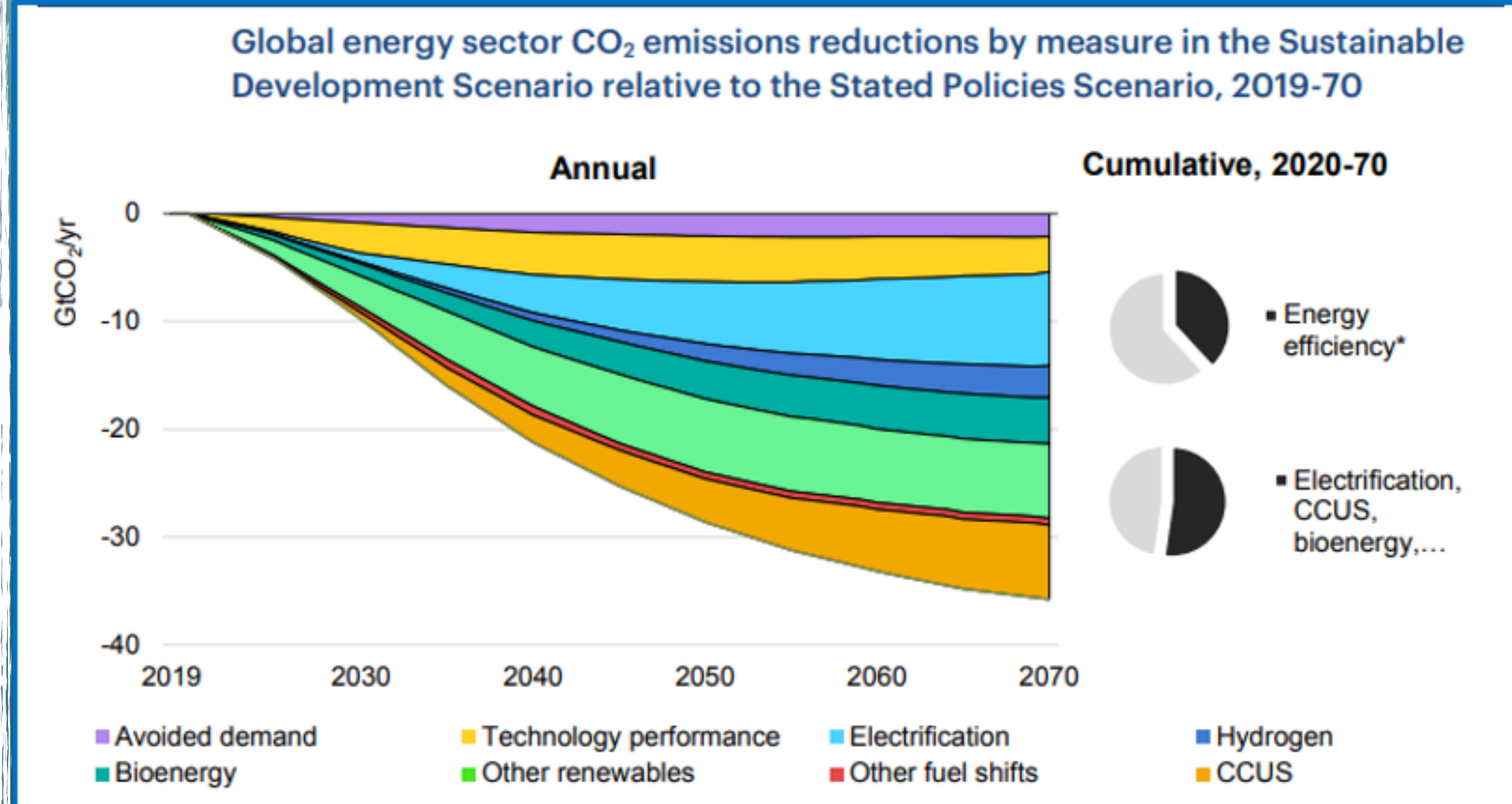
H_2 ENERGY STORAGE

THE ROLE OF CCUS IN CLEAN ENERGY TRANSITION

CCUS BASICS

- Carbon Capture, Utilisation and Storage (CCUS) is one of the key technology areas:
  - to put energy systems in the world on a sustainable way
  - to meet international climate goals
  - and to reach "net" zero carbon targets

- CCUS is the only one group of technologies that can both:
  - reduce emissions in key sectors directly and
  - remove CO_2 emissions that cannot be avoided



Source: IEA 2020

In total, CCUS contributes nearly 15% of the cumulative reduction in CO_2 emissions worldwide compared with the Stated Policies Scenario, which takes into account current national energy- and climate-related policy commitments.

The contribution of CCUS to the transition to net-zero emissions grows over time, accounting for nearly one-sixth of cumulative emissions reductions to 2070

MOTIVATION FOR CCUS

CO_2 emissions per capita (2020)

Russia: 11.6 t
Estonia: 11.1 t
Norway, Germany, Poland: 7.7 t
Finland: 7.3 t
Belarus: 6.3 t
Lithuania: 4.8 t

CO_2 emissions per capita (2020)

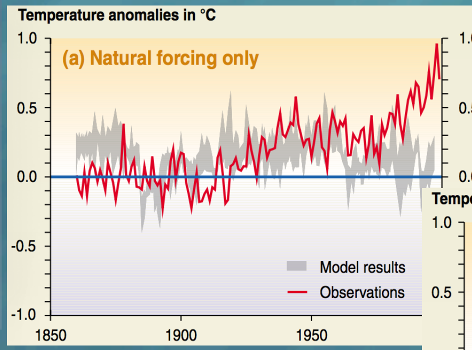
Denmark: 4.4 t
Sweden: 4.2 t
Latvia: 3.9 t

Reduction of industrial CO_2 emissions in the atmosphere

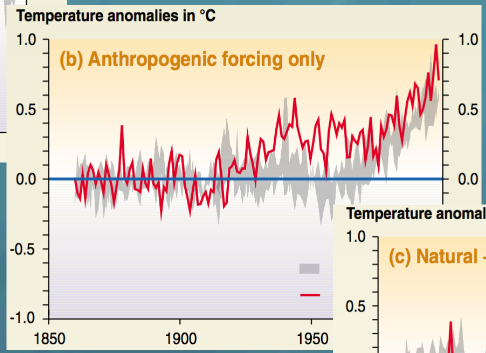
CO_2 emissions per capita (2020)

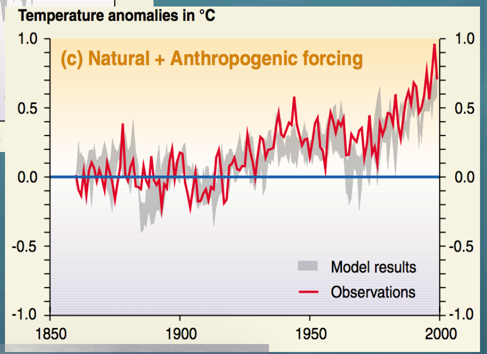
WORLD: 4.6 t   EUROPE: 5.9 t

Mitigate global climate change induced by greenhouse gases



Models of Earth's temperature since 1860 (IPCC, Summary for Policy Makers)



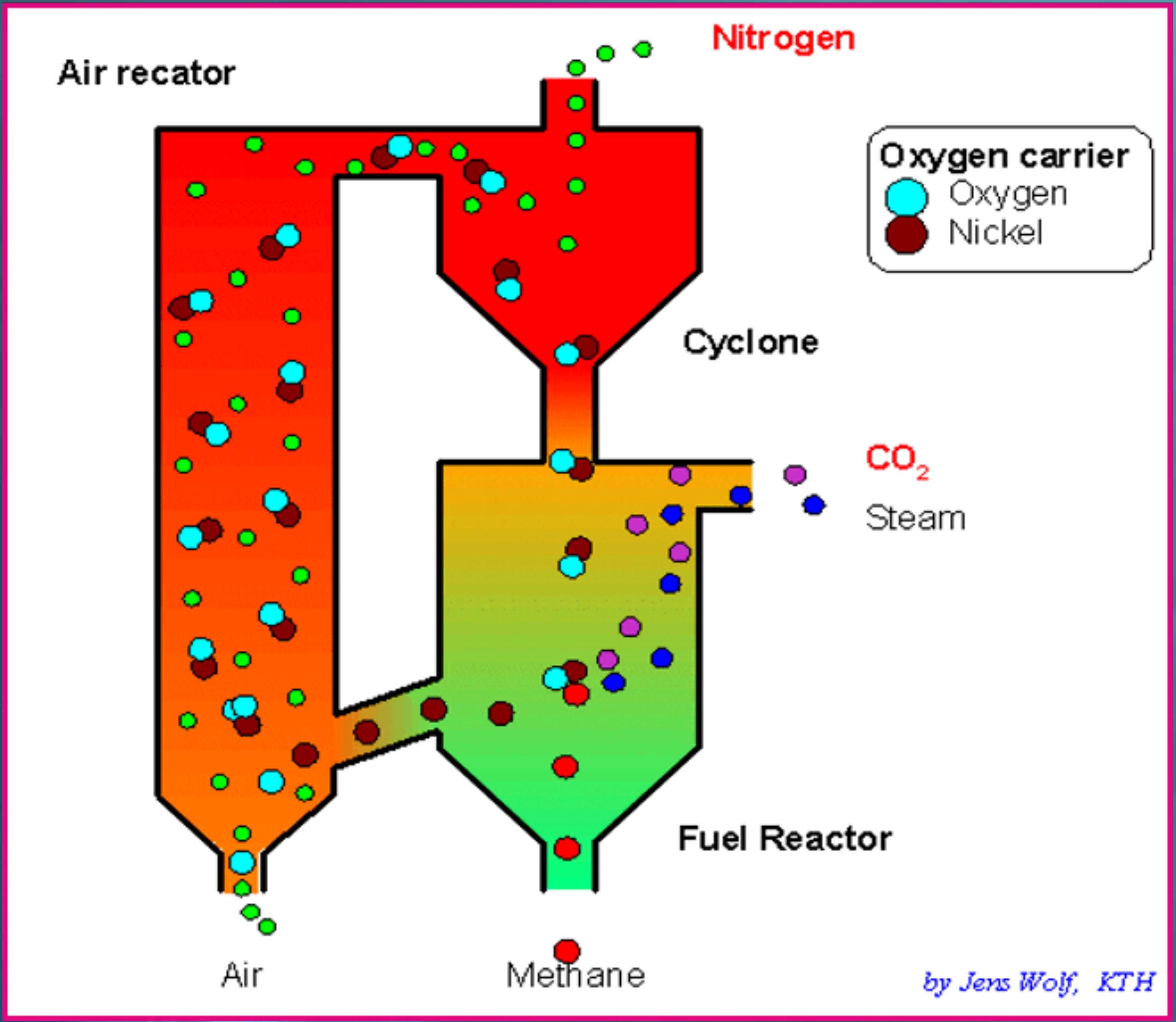


- ☑ Energy efficiency use
- ☑ Renewable energy
- ☑ **CO_2 Capture and Geological Storage**

- ☑ (1) deep saline aquifers
- ☑ (2) depleted oil and gas fields
- ☑ (3) geothermal energy recovery

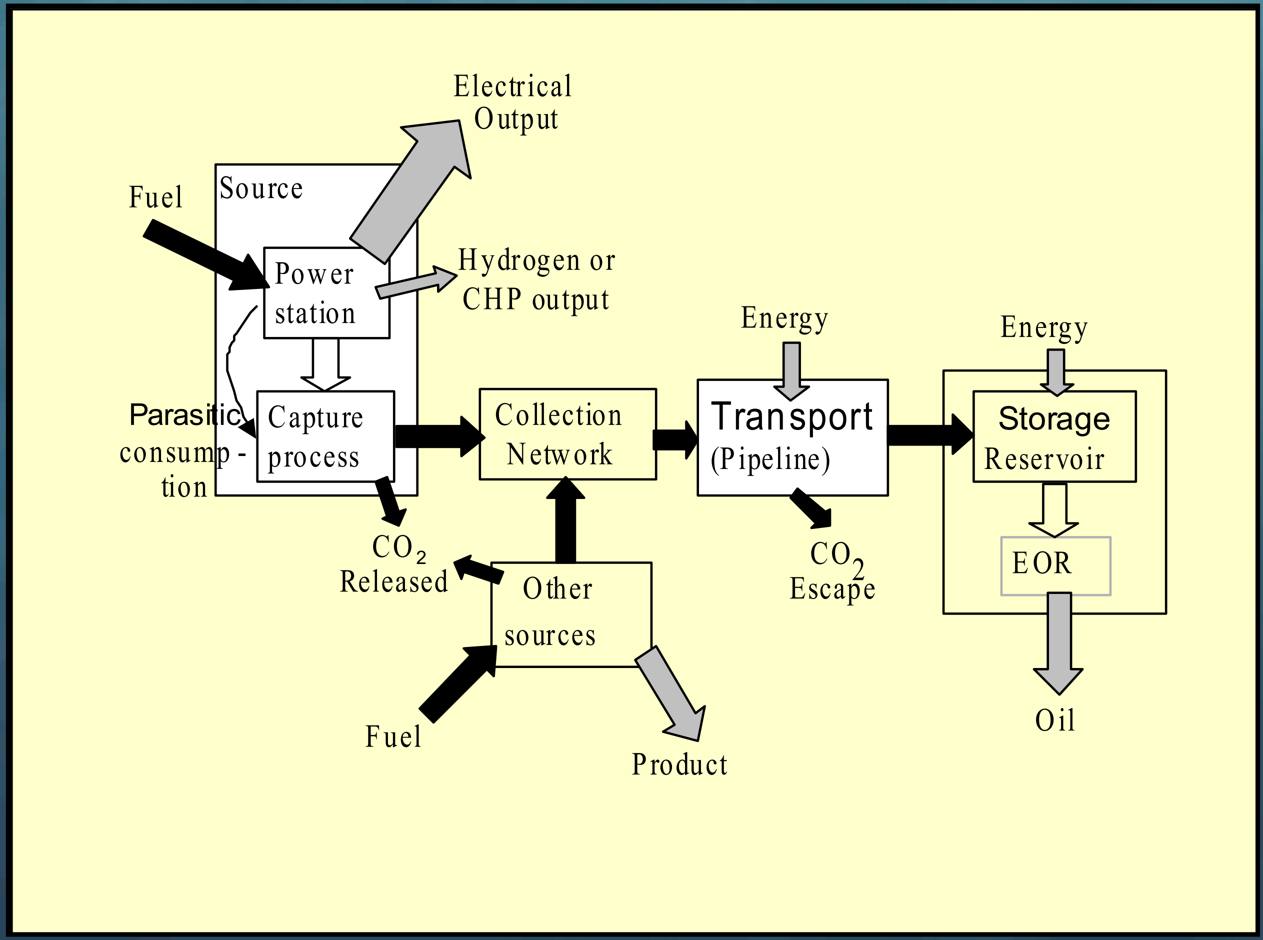
CARBON CAPTURE, UTILISATION AND STORAGE (CCUS) TECHNOLOGY

CCUS BASICS



OXYFUEL COMBUSTION: CHEMICAL LOOPING COMBUSTION

CO_2 CAPTURE AND STORAGE PROCESS



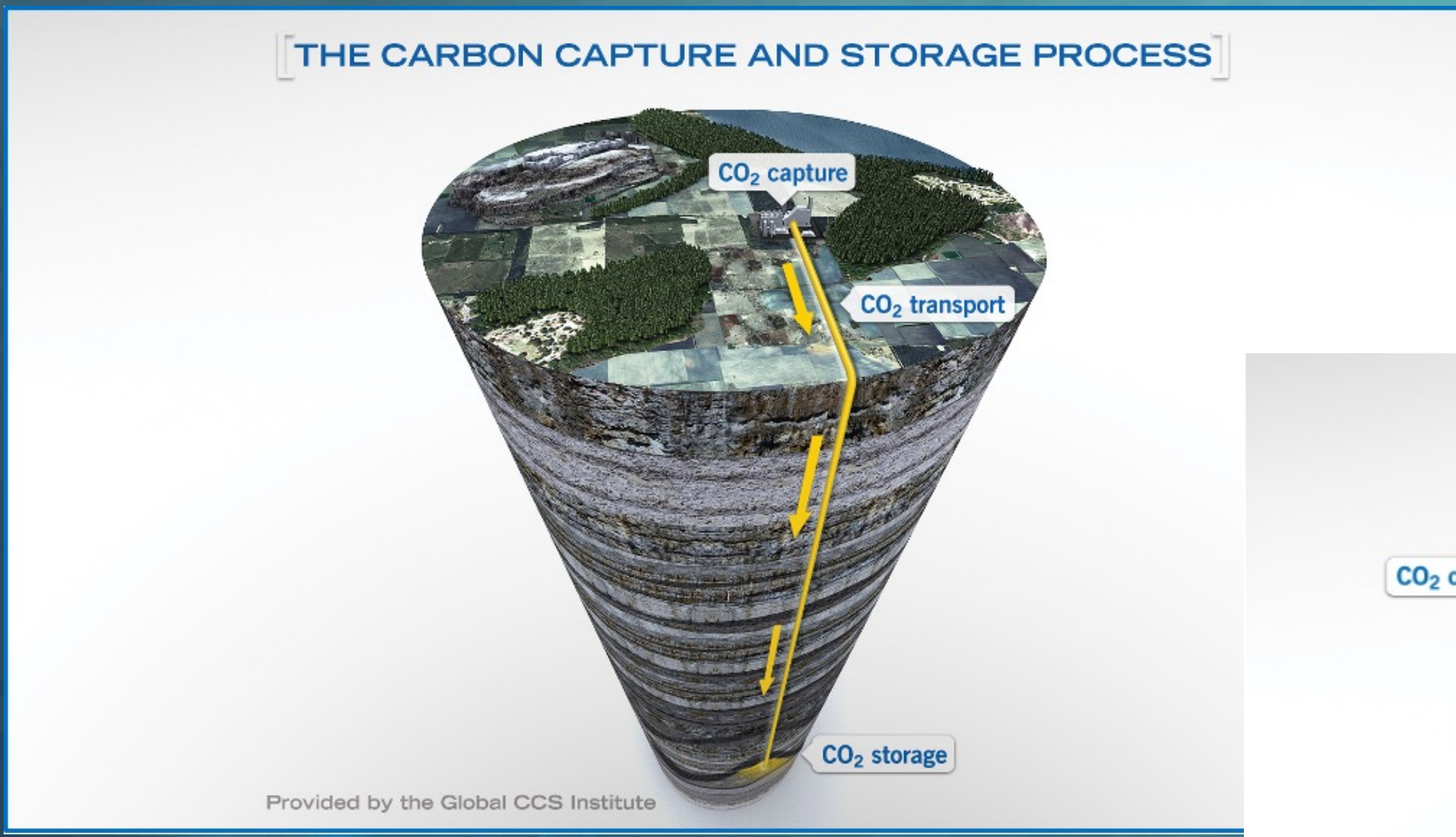
Acceptance of CO_2 Capture and Storage, Economics, Policy and Technology

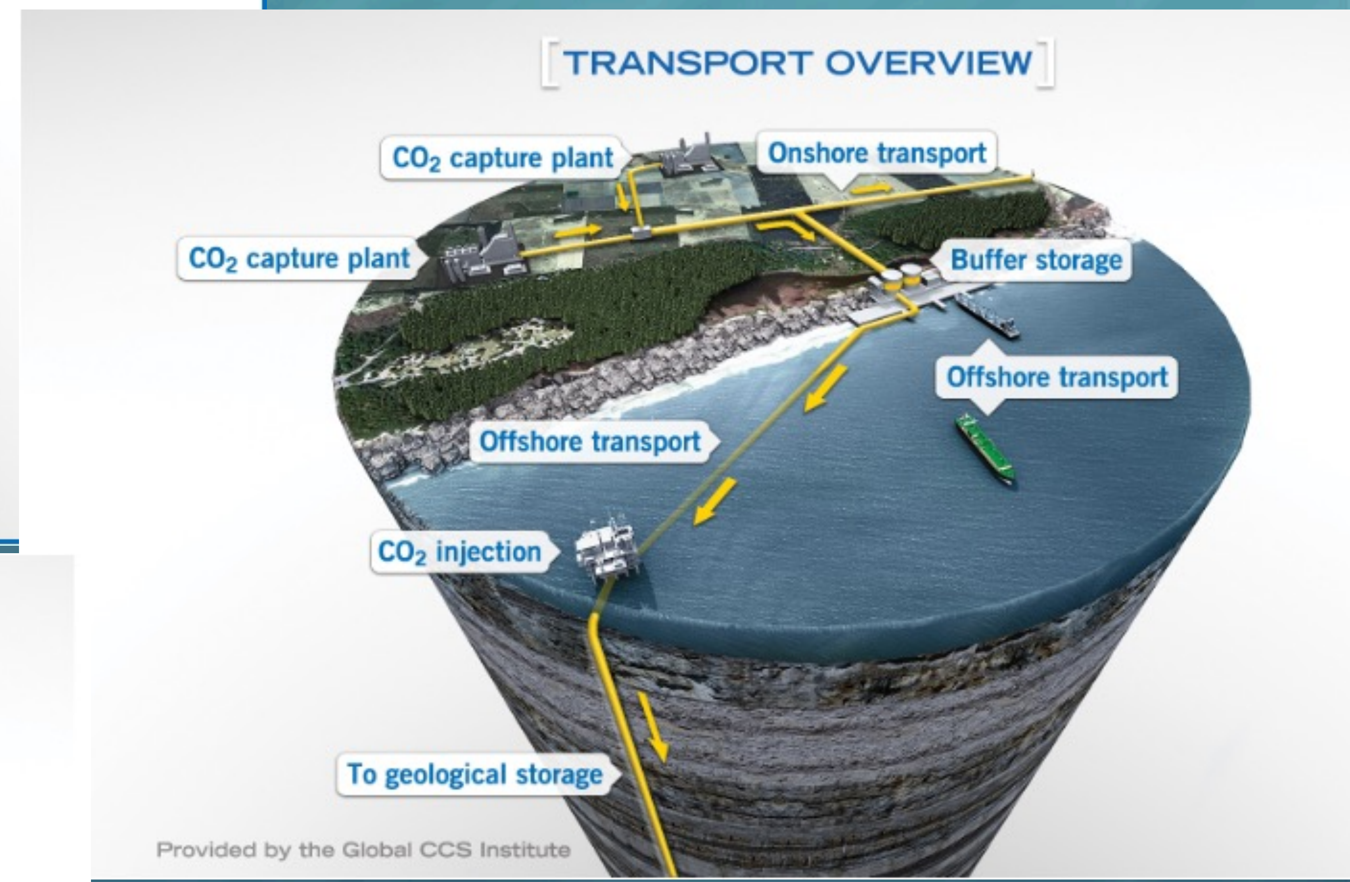
Accsept

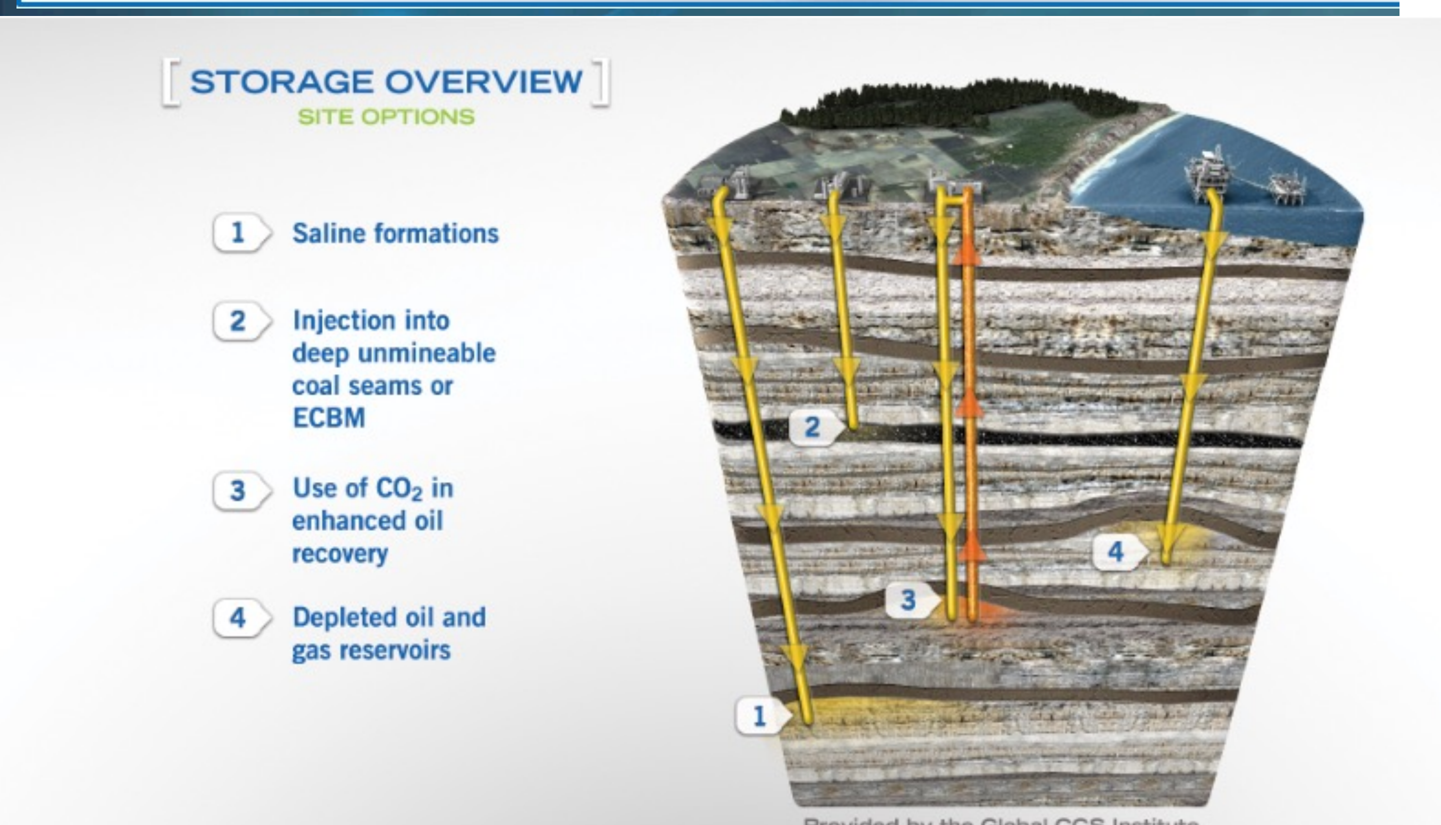
Project sponsor:

CARBON CAPTURE, UTILISATION AND STORAGE (CCUS) TECHNOLOGY

CCUS BASICS

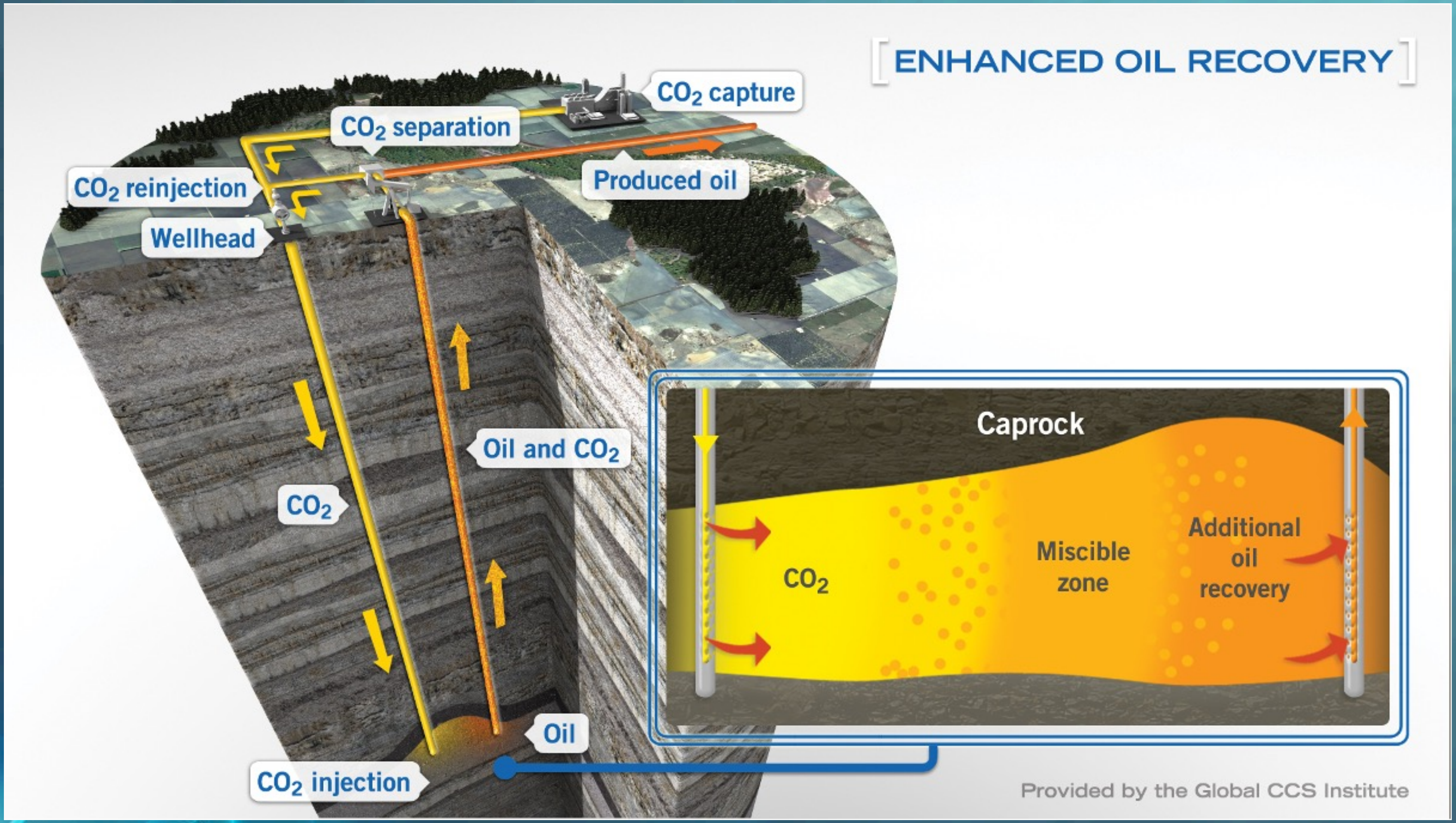






CO_2 USE FOR EOR AND CO_2 STORAGE IN DEPLETED OIL AND GAS FIELDS

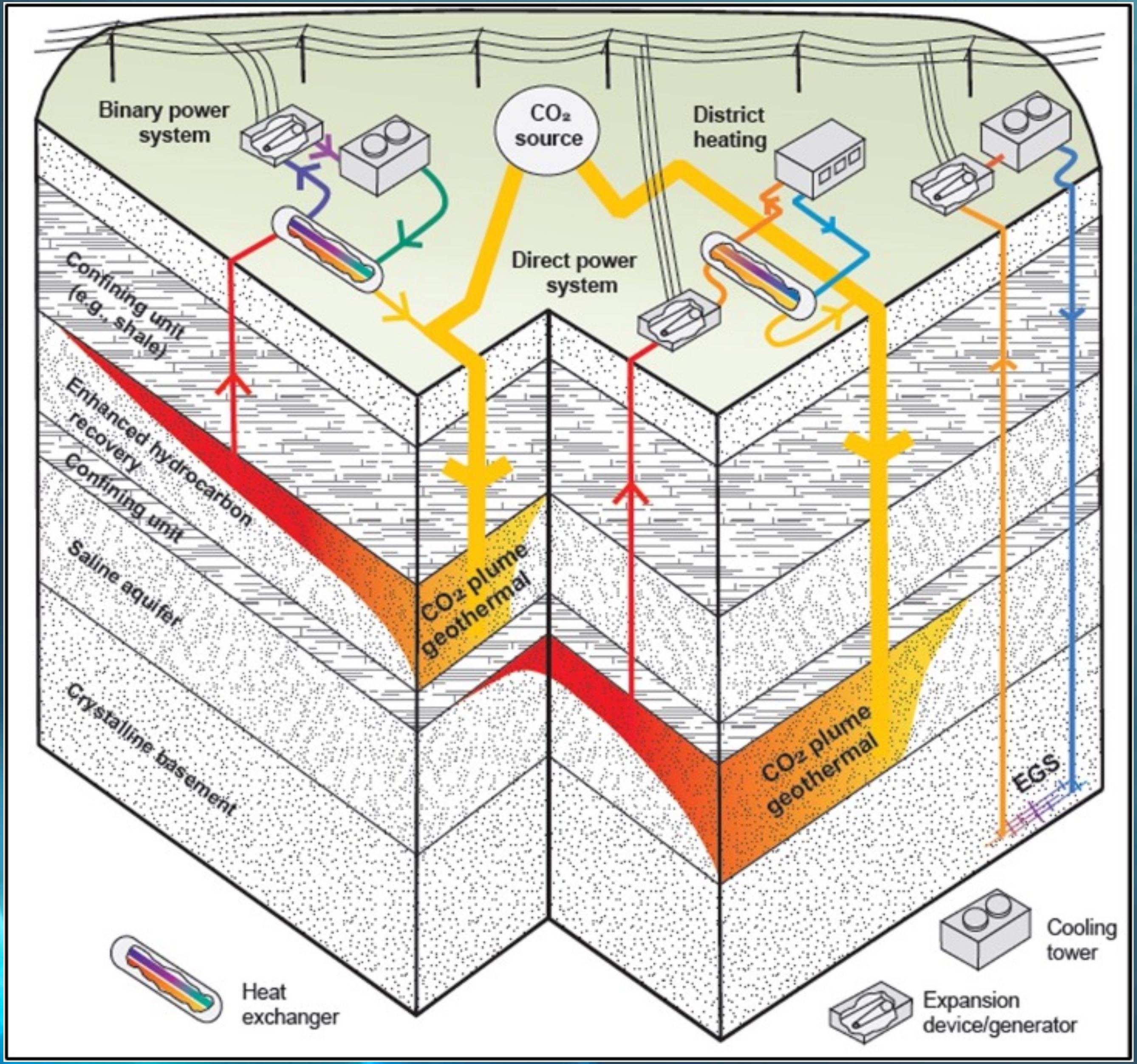
CCUS BASICS

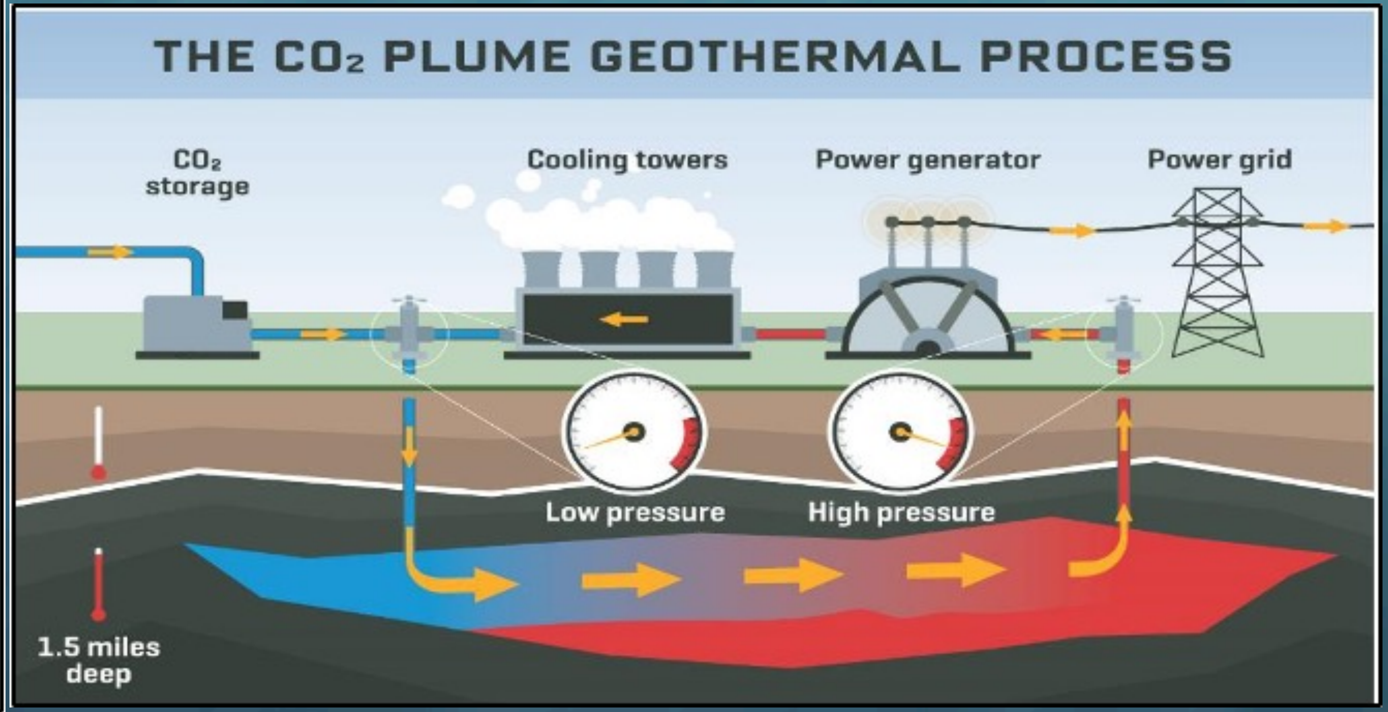


WHEN CO_2 INJECTED UNDERGROUND 20%-80% CO_2 IS STAYED UNDERGROUND. HOWEVER, TO PROVE CO_2 STORAGE, THE STORAGE SITE SHOULD BE MONITORED BEFORE AND AFTER CO_2 INJECTION

CO_2 PLUME GEOTHERMAL (CPG) PROCESS

CCUS BASICS

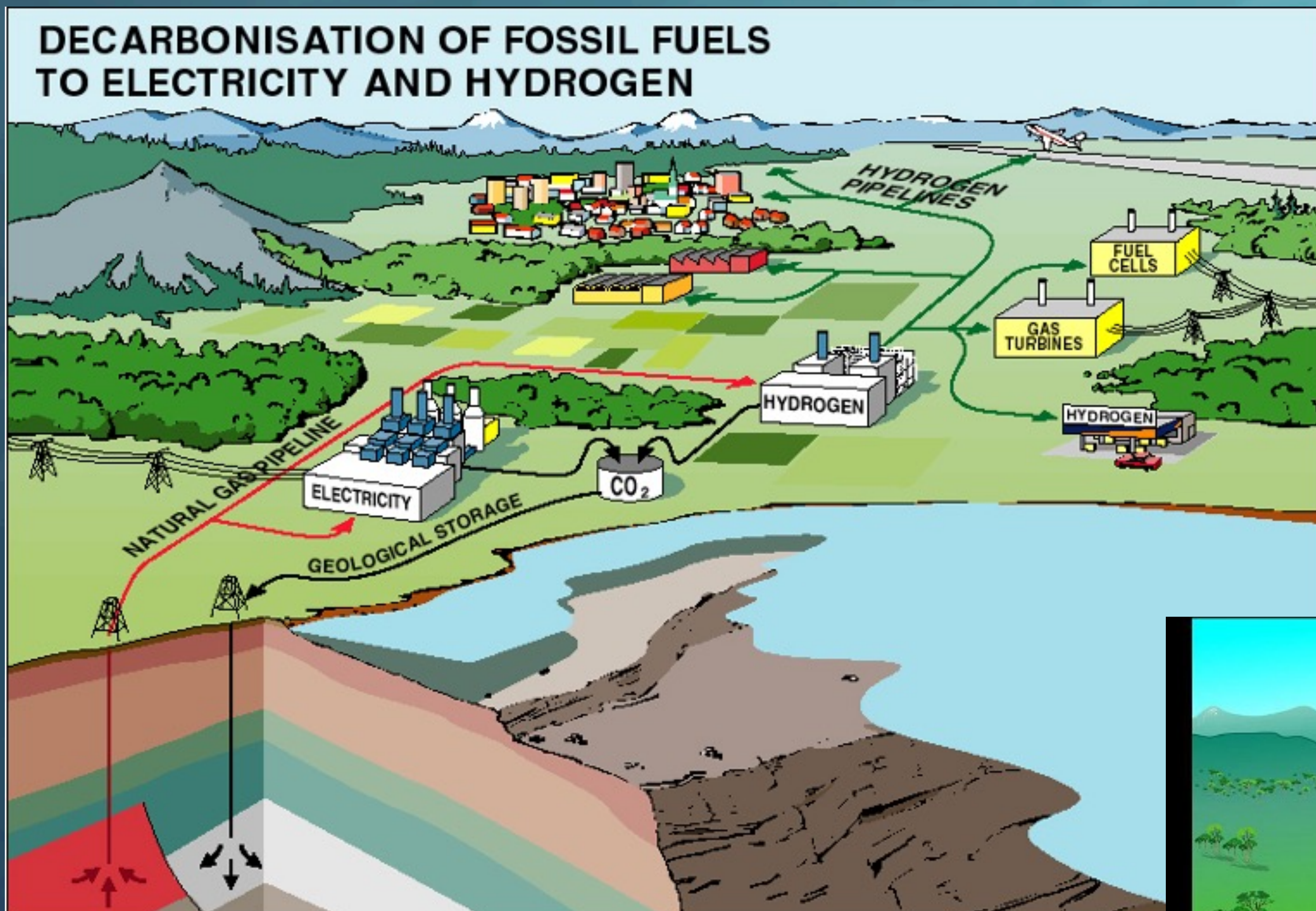




WWW.TERRACOH-AGE.COM

CCUS TECHNOLOGY

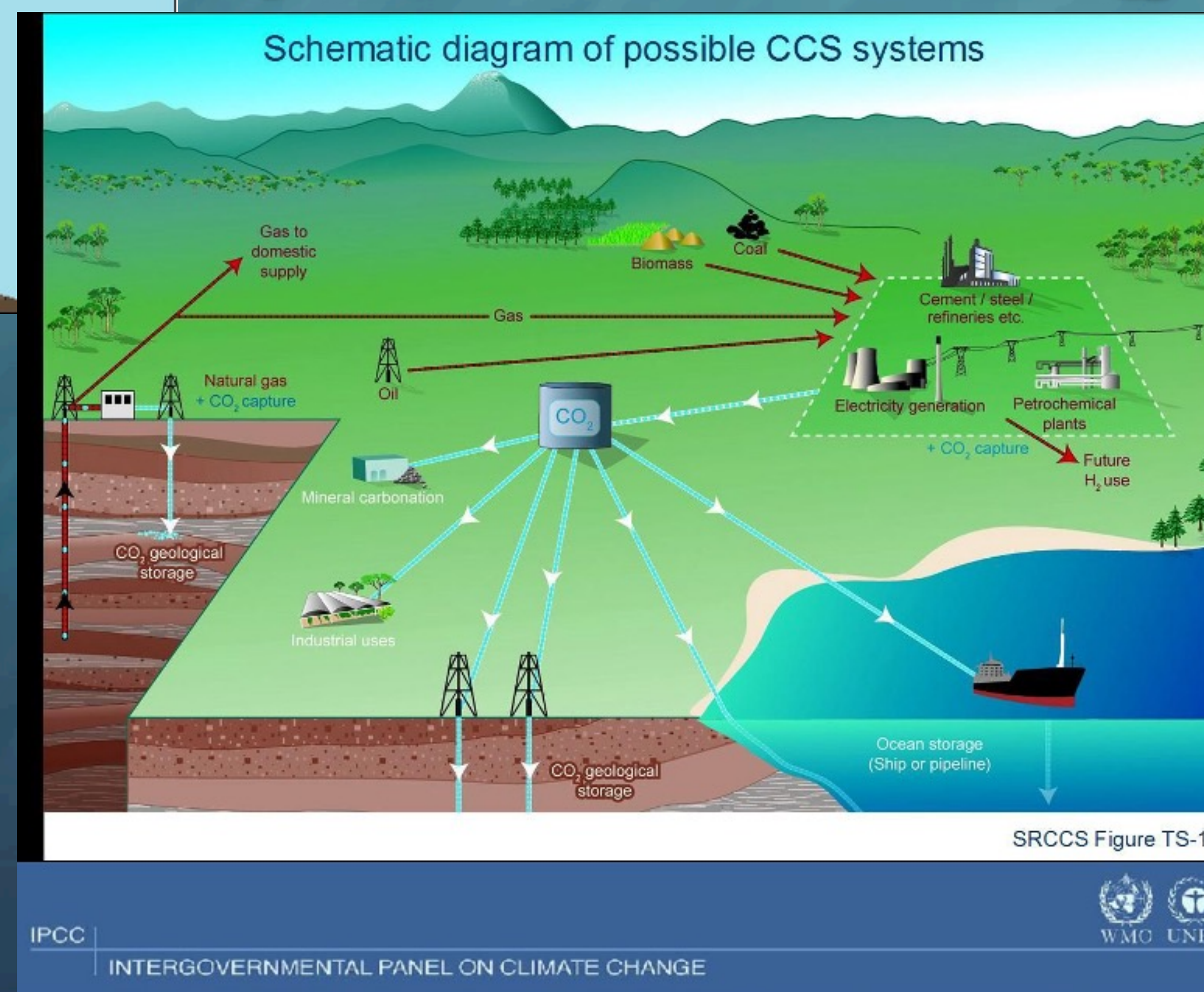
CCUS BASICS



Courtesy of Statoil

FOSSIL FUEL WITH CCS, BIOMASS WITH CCS (BIO-CCS) – OPTION FOR NEGATIVE EMISSIONS.

(COURTESY CO2CRC), IPCC 2005



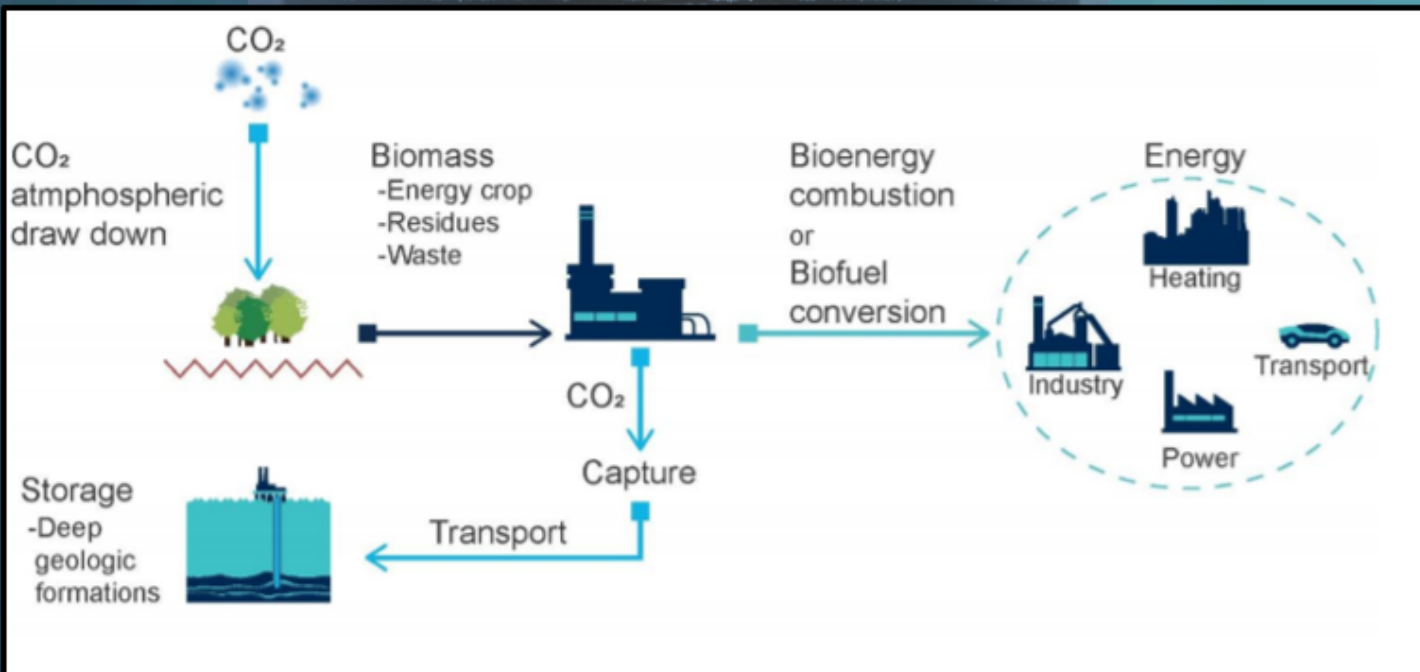
THE CCS CONCEPT IN SHORT:

THE PRODUCTION OF ELECTRICITY AND HYDROGEN WHILE CAPTURING AND STORING THE CO_2

NEGATIVE EMISSION TECHNOLOGIES (NETS)

CCUS BASICS

BECCS - BIO-CCS



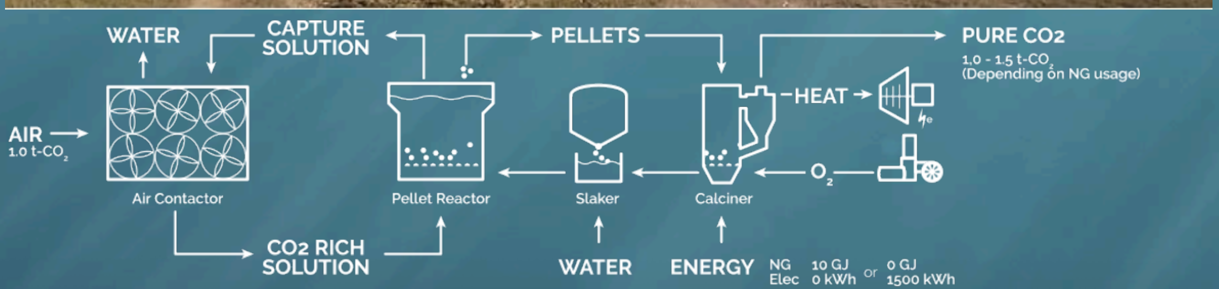
BECCS TYPICALLY REFERS TO

- THE INTEGRATION OF TREES AND CROPS THAT EXTRACT CO_2 FROM THE ATMOSPHERE AS THEY GROW
- THE USE OF THIS BIOMASS IN POWER AND/OR INDUSTRIAL PLANTS
- AND THE APPLICATION OF CARBON CAPTURE AND STORAGE VIA CO_2 INJECTION INTO GEOLOGICAL FORMATIONS

TODAY, THERE ARE 19 LARGE-SCALE FACILITIES IN OPERATION, FIVE UNDER CONSTRUCTION AND 20 IN VARIOUS STAGES OF DEVELOPMENT.

BECCS CAN BE APPLIED TO DIVERSE INDUSTRIAL SECTORS SUCH AS COMBUSTION BIOMASS POWER PLANTS, COMBINED HEAT AND POWER PLANTS, PULP INDUSTRY, BIOMASS GASIFICATION AND ETHANOL FERMENTATION, WASTE TO ENERGY PLANTS, CEMENT PLANTS, ETC.

DIRECT AIR CAPTURE (DAC)



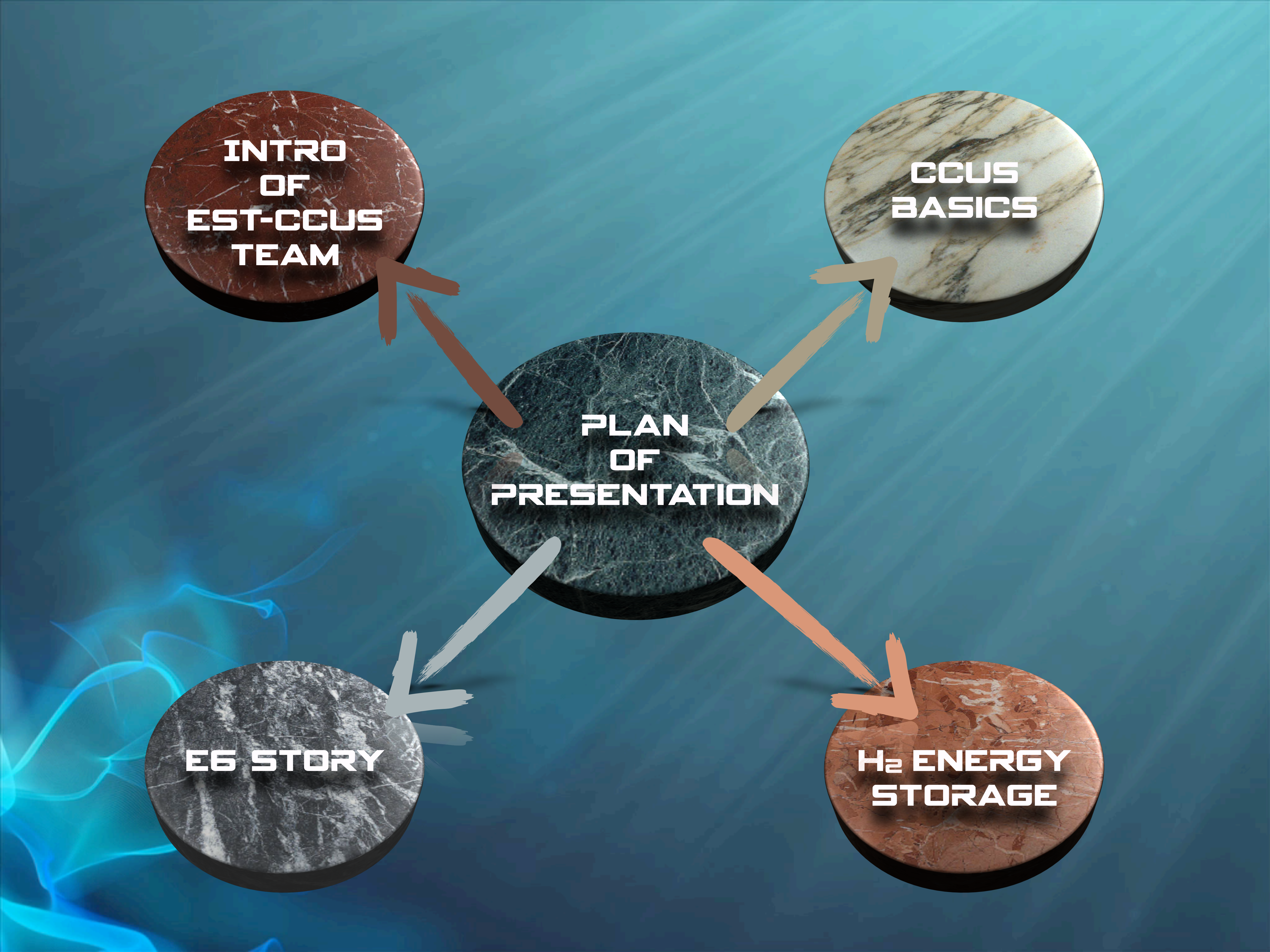
DAC IS A TECHNOLOGY THAT CAPTURES CO_2 DIRECTLY FROM THE AIR.

DAC TECHNOLOGY PULLS IN ATMOSPHERIC AIR, THEN THROUGH A SERIES OF CHEMICAL REACTIONS, EXTRACTS CO_2 FROM AIR, WHILE RETURNING THE REST OF THE AIR TO THE ENVIRONMENT.

THIS IS WHAT PLANTS AND TREES DO EVERY DAY AS THEY PHOTOSYNTHESISE.

DAC TECHNOLOGY DOES IT MUCH FASTER, WITH A SMALLER LAND FOOTPRINT, AND DELIVERS THE CO_2 IN A PURE, COMPRESSED FORM THAT CAN THEN BE STORED UNDERGROUND OR REUSED.

THE ENERGY REQUIREMENTS FOR CONCENTRATING CO_2 FROM SUCH LOW LEVELS ARE CONSIDERABLY HIGHER THAN THOSE FROM MORE CONCENTRATED SOURCES (GCCSI, 2020).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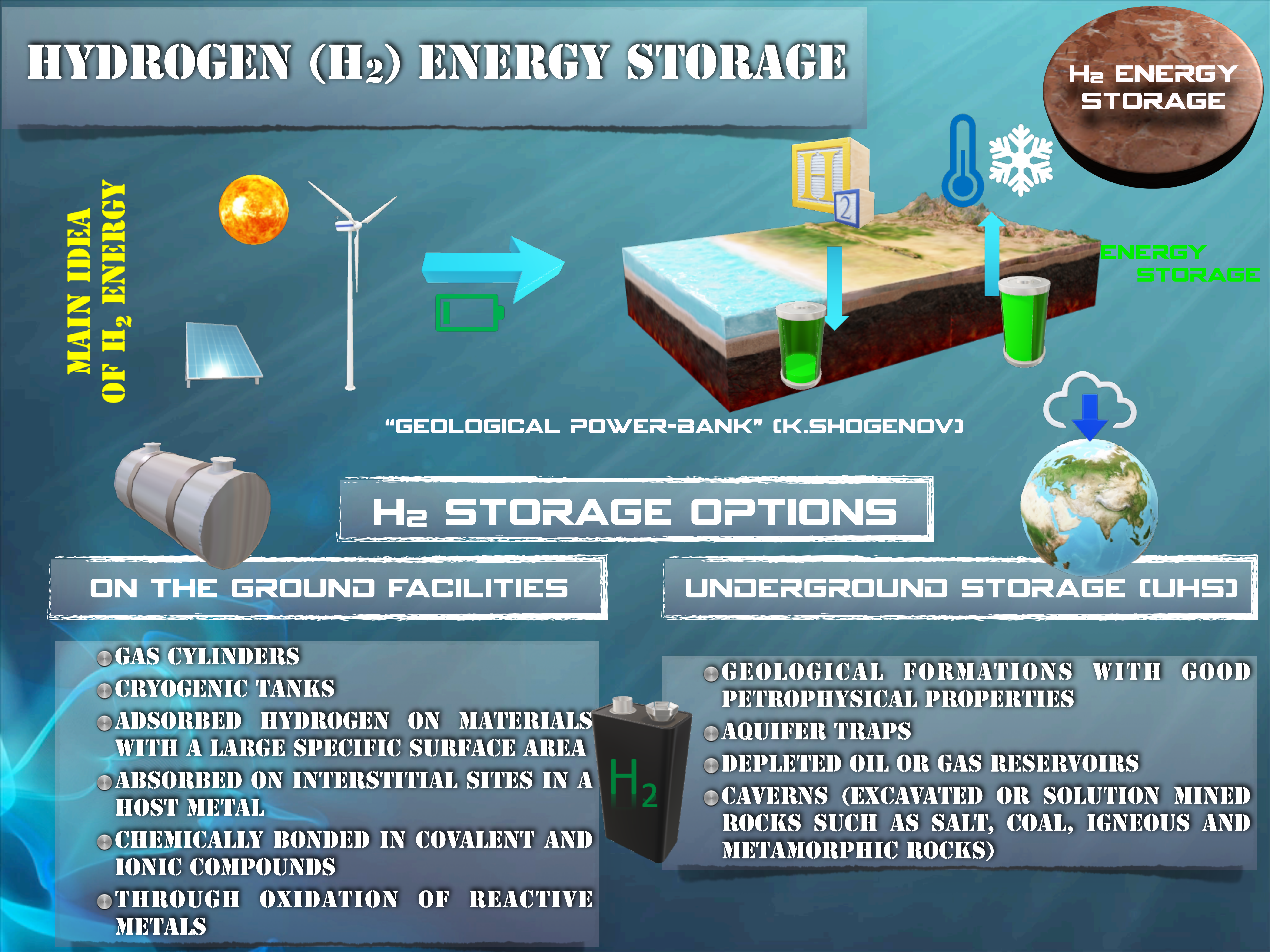
HYDROGEN (H_2) ENERGY IDEA

H_2 ENERGY STORAGE

COMBUSTION OF HYDROGEN

COMBUSTION OF METHANE

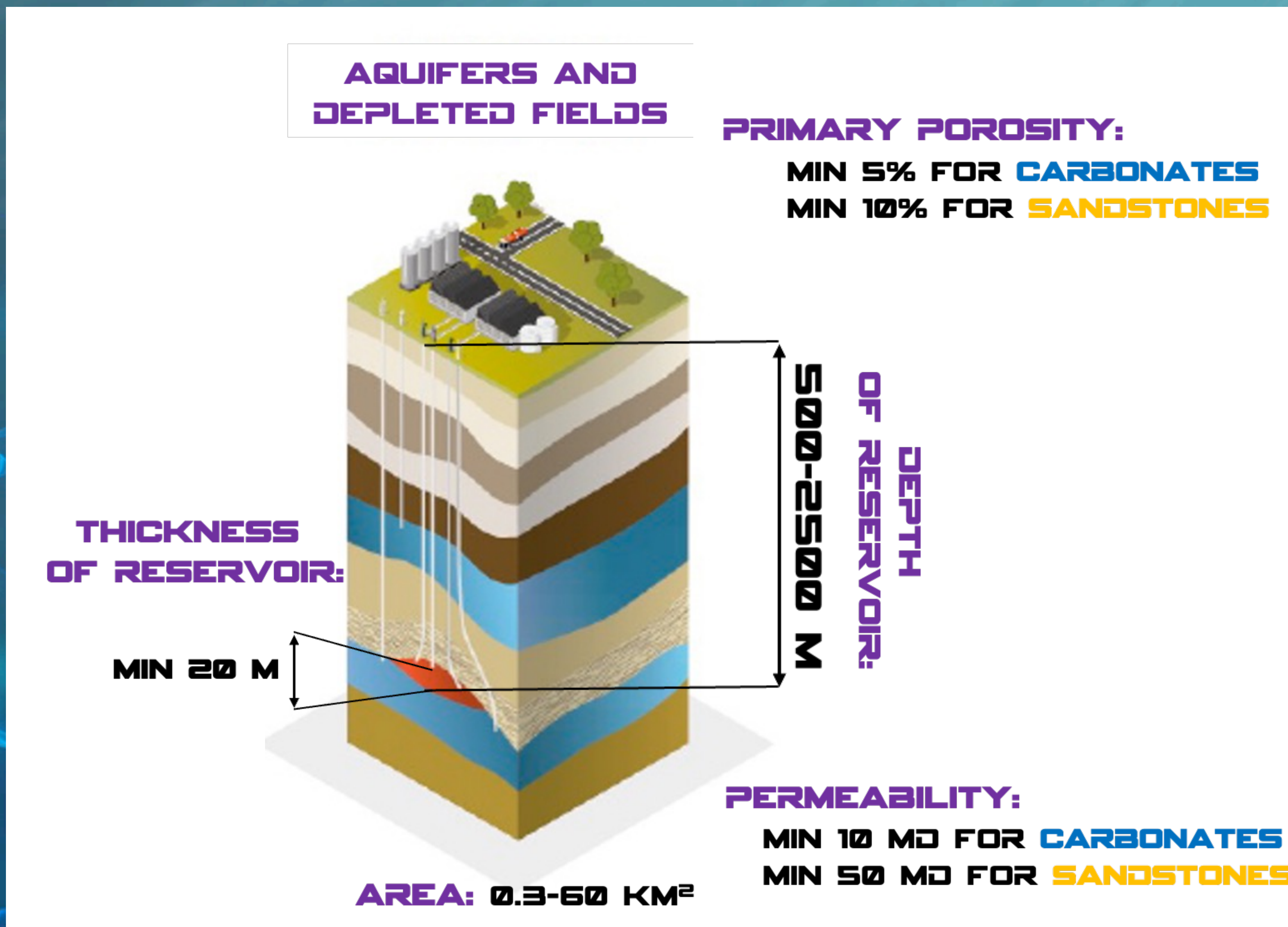
PRODUCTION OF HYDROGEN

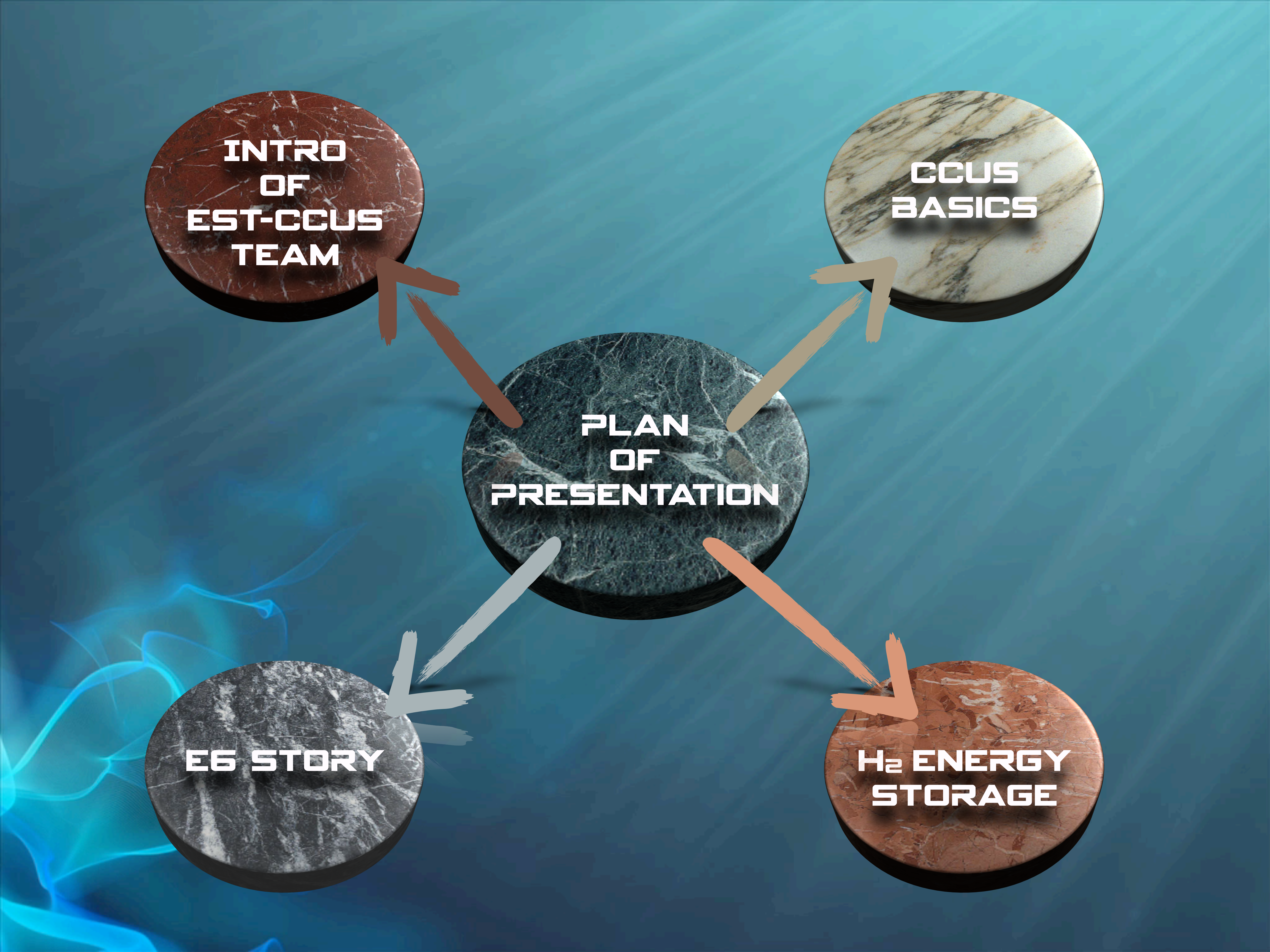

HYDROGEN (H_2) ENERGY STORAGE
H_2 ENERGY STORAGE
MAIN IDEA OF H_2 ENERGY
ENERGY STORAGE
"GEOLOGICAL POWER-BANK" (K.SHOGENOV)
H_2 STORAGE OPTIONS
ON THE GROUND FACILITIES
UNDERGROUND STORAGE (UHS)
GAS CYLINDERS
CRYOGENIC TANKS
ADSORBED HYDROGEN ON MATERIALS WITH A LARGE SPECIFIC SURFACE AREA
ABSORBED ON INTERSTITIAL SITES IN A HOST METAL
CHEMICALLY BONDED IN COVALENT AND IONIC COMPOUNDS
THROUGH OXIDATION OF REACTIVE METALS
GEOLOGICAL FORMATIONS WITH GOOD PETROPHYSICAL PROPERTIES
AQUIFER TRAPS
DEPLETED OIL OR GAS RESERVOIRS
CAVERNS (EXCAVATED OR SOLUTION MINED ROCKS SUCH AS SALT, COAL, IGNEOUS AND METAMORPHIC ROCKS)

HYDROGEN (H_2) ENERGY STORAGE

H_2 ENERGY STORAGE

REQUIREMENTS FOR UNDERGROUND HYDROGEN STORAGE

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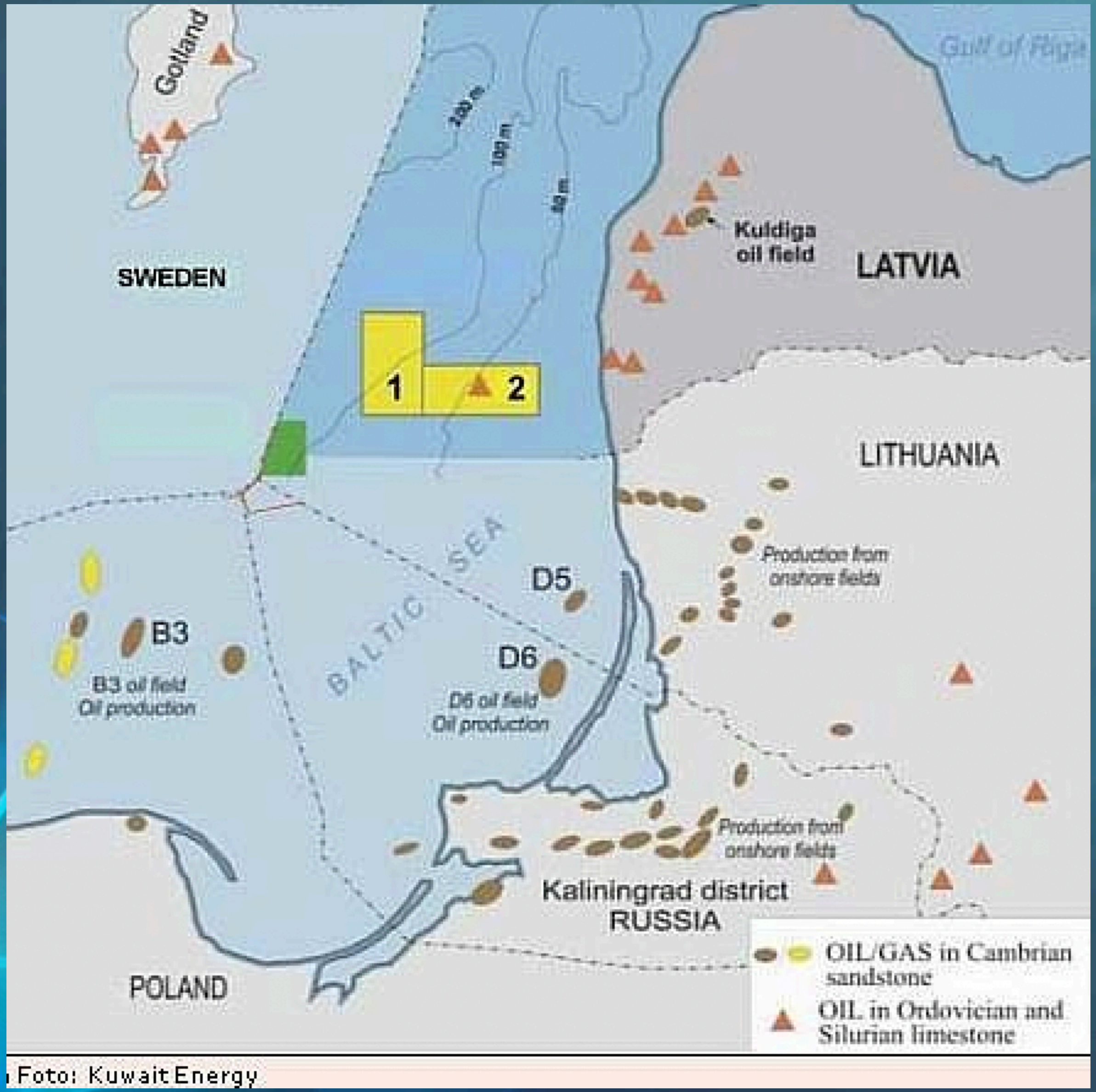
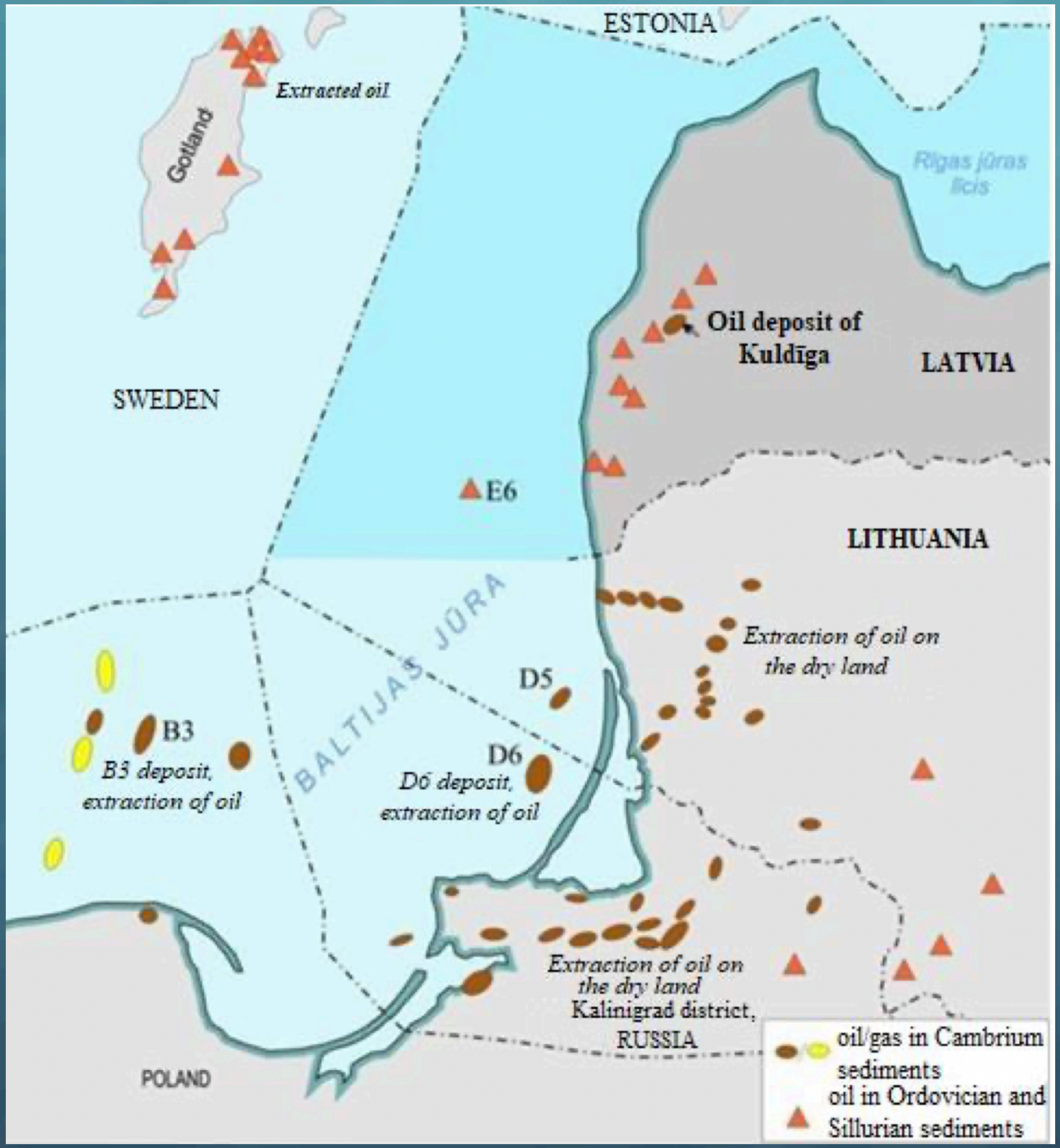
E6. STORY OF SUCCESS

E6 STORY

E6 - LATVIAN OFFSHORE NOT PROSPECTIVE OIL BEARING STRUCTURE (IN THE BEGINNING OF STUDY-2010)



Source: Kuwait Energy



Latvian Environment, Geology and Meteorology Centre

STAGE I

The aim

To compose petrophysical models of the CO_2 plume during possible CO_2 geological storage (CGS) in prospective on- and offshore deep subsurface structures in the Baltic sedimentary basin. The modelling results will support the implementation of CO_2 Capture and Geological Storage (CCS) technology in the Baltic States as one of the effective measures to mitigate climate change.

Objectives

I. Selection of storage sites and data collection
- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties

II. Characterization of the selected structures
- Reservoir characterization and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity

III. Estimation of the influence of CGS on the properties of rocks
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations

IV. Numerical seismic modelling to support the monitoring of CGS
- 4D time-lapse rock physics and numerical seismic modelling
- Coupling of the chemically induced petrophysical alteration effect of CO_2– hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- Modelling of the possible shape of CO_2 plume migration in the storage site

Geological background

Objectives

I — Selection of storage sites and data collection

II — Characterization of the selected structures

III — Estimation of the influence of CO_2 on the properties of rocks

IV — Numerical seismic modelling to support the monitoring of CGS

Selection of CO_2 geological storage sites

- Rock sampling
- Measurement of geochemical and petrophysical properties
- Reservoir characterization and risk assessment
- 3D geological static modelling
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- Modelling of the possible shape of CO_2 plume migration in the storage site

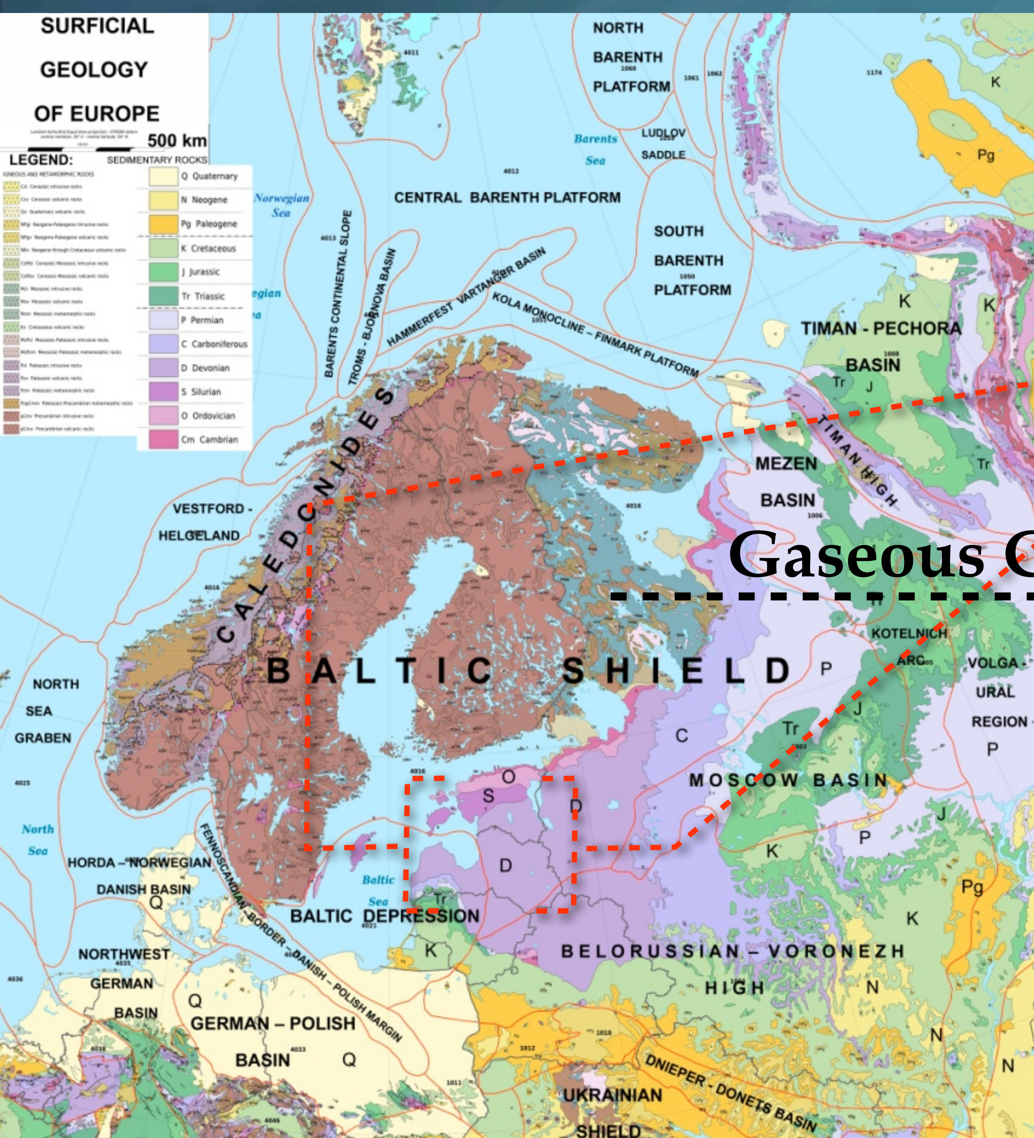


Fig. Geological map (modified after Eric Gaba, Wikimedia Commons (2010)

Structure map of the Baltic Basin

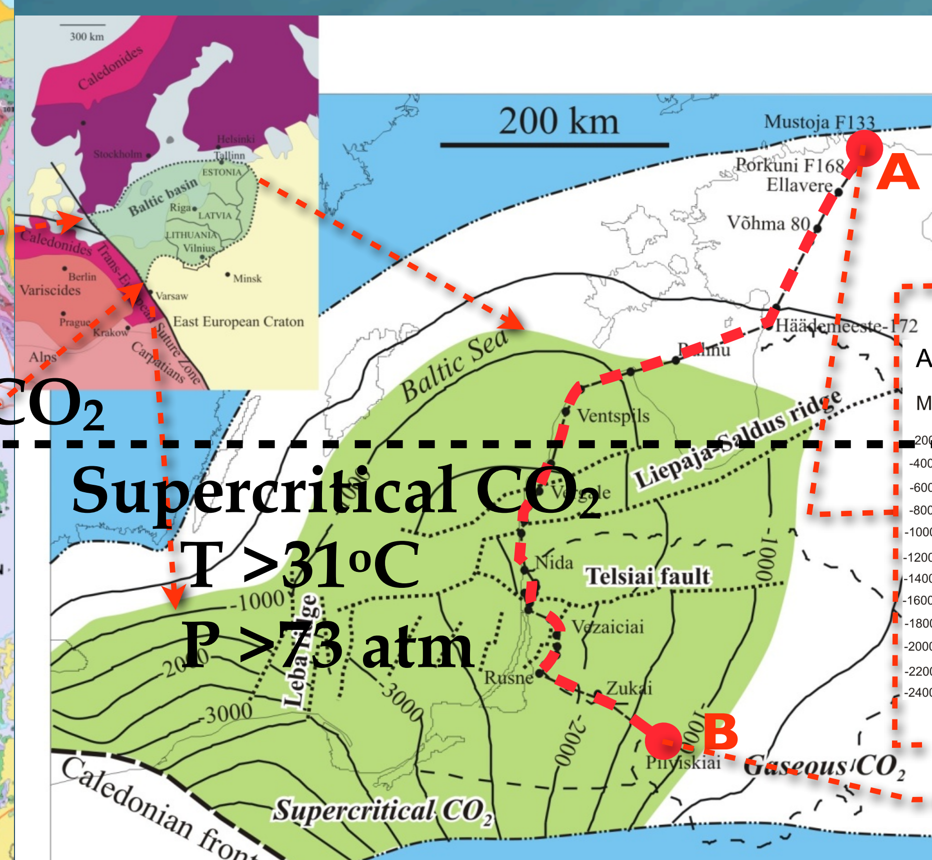


Fig. Depths of top of Cambrian aquifer (modified after Šliaupa et. al, 2008)

Baltic sedimentary basin- 700x500 km synclinal structure

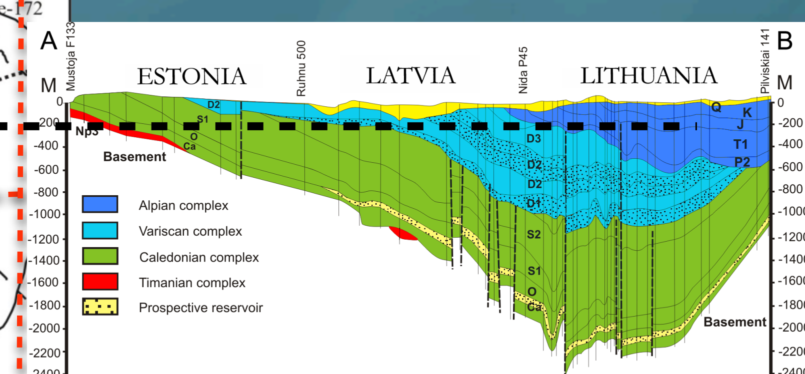


Fig. Geological cross-section across Estonia, Latvia, and Lithuania (modified after Shogenov et. al, 2013b)

Storage sites selection

Objectives

I. Selection of storage sites and data collection

II. Characterization of the selected structures

III. Estimation of the influence of CGS on the properties of rocks

IV. Numerical seismic m… support the monitor…

Selection of CO_2 geological storage sites

- Rock sampling
- Measurement of geochemical and petrophysical properties
- Reservoir characterization and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations

Dobele onshore structure

Fig. Prospective structures for CO_2 geological storage in the Baltic Region (modified after Šliaupienė & Šliaupa, 2011)

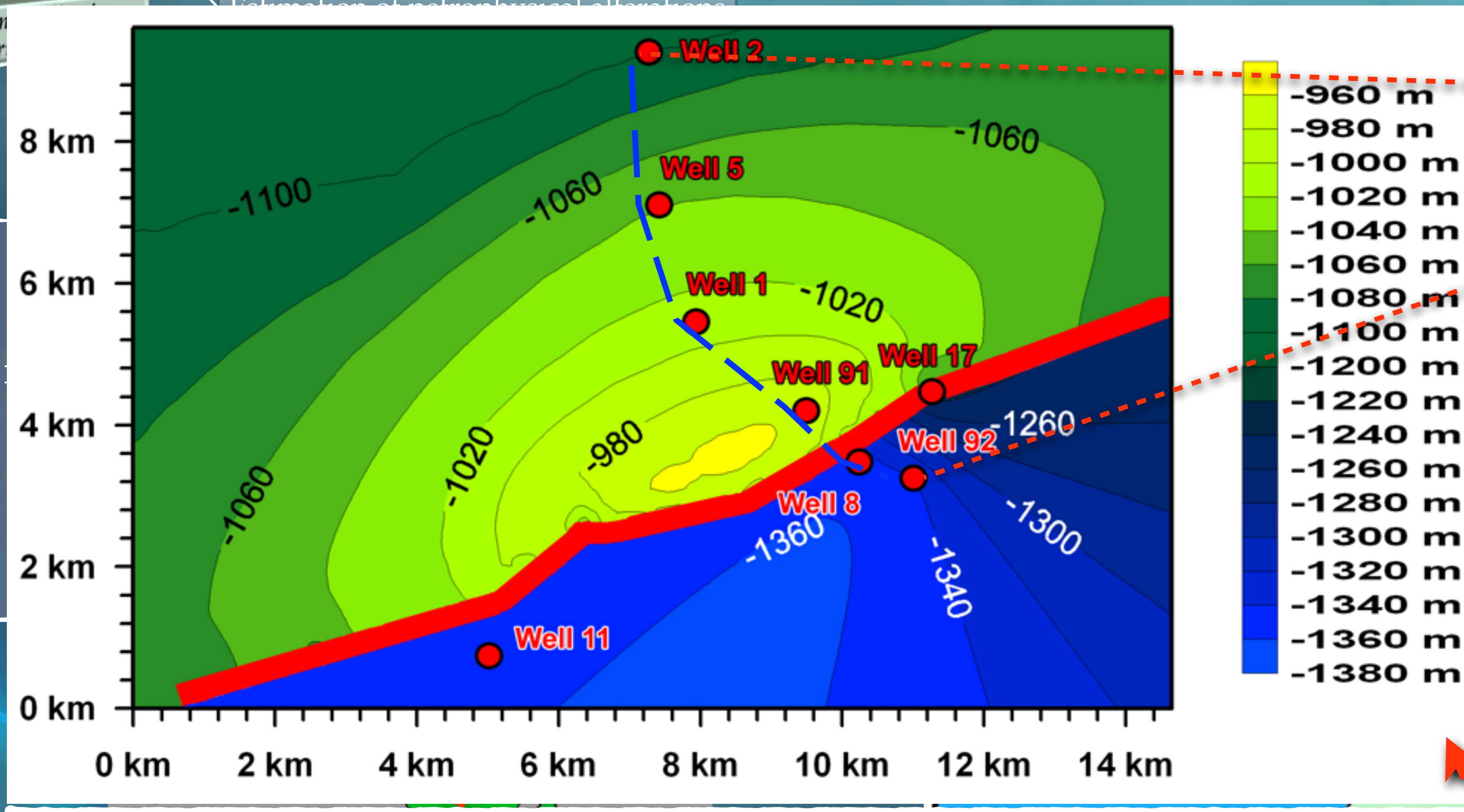


Fig. Structural map of the Dobele onshore local structure (modified after Shogenov et. al, 2013a)

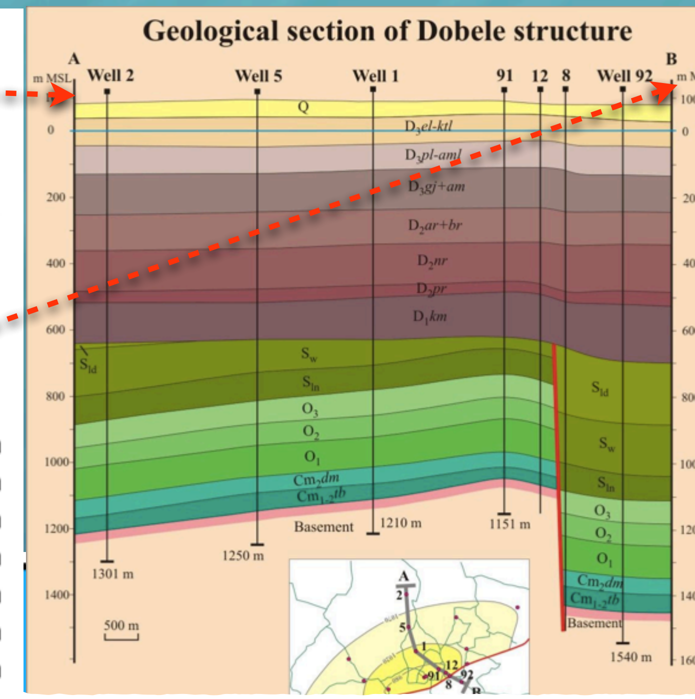


Fig.12. Geological cross-section of the Dobele onshore structure (LEGMC, 2007)

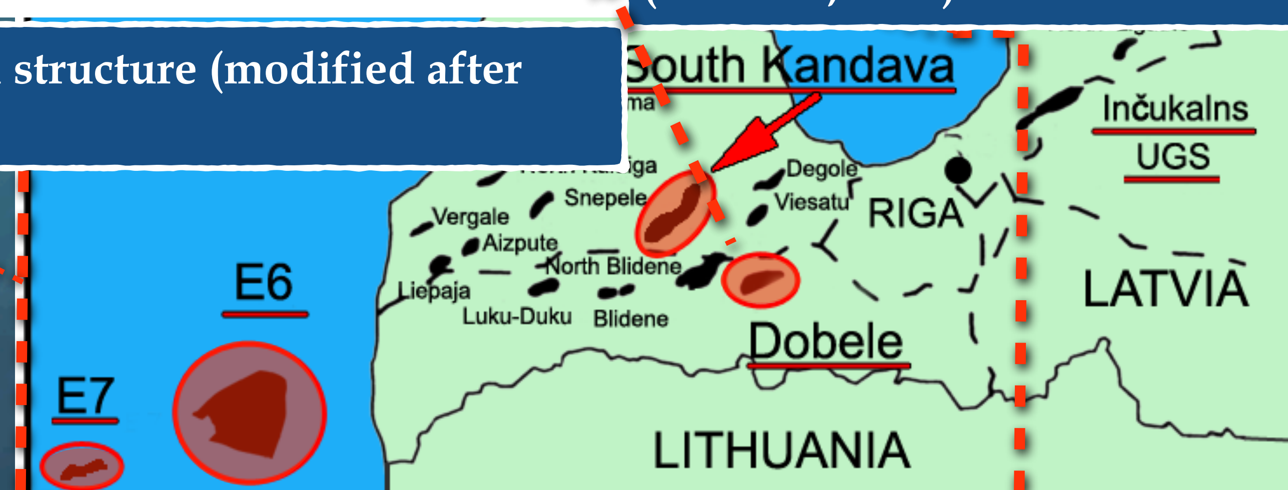
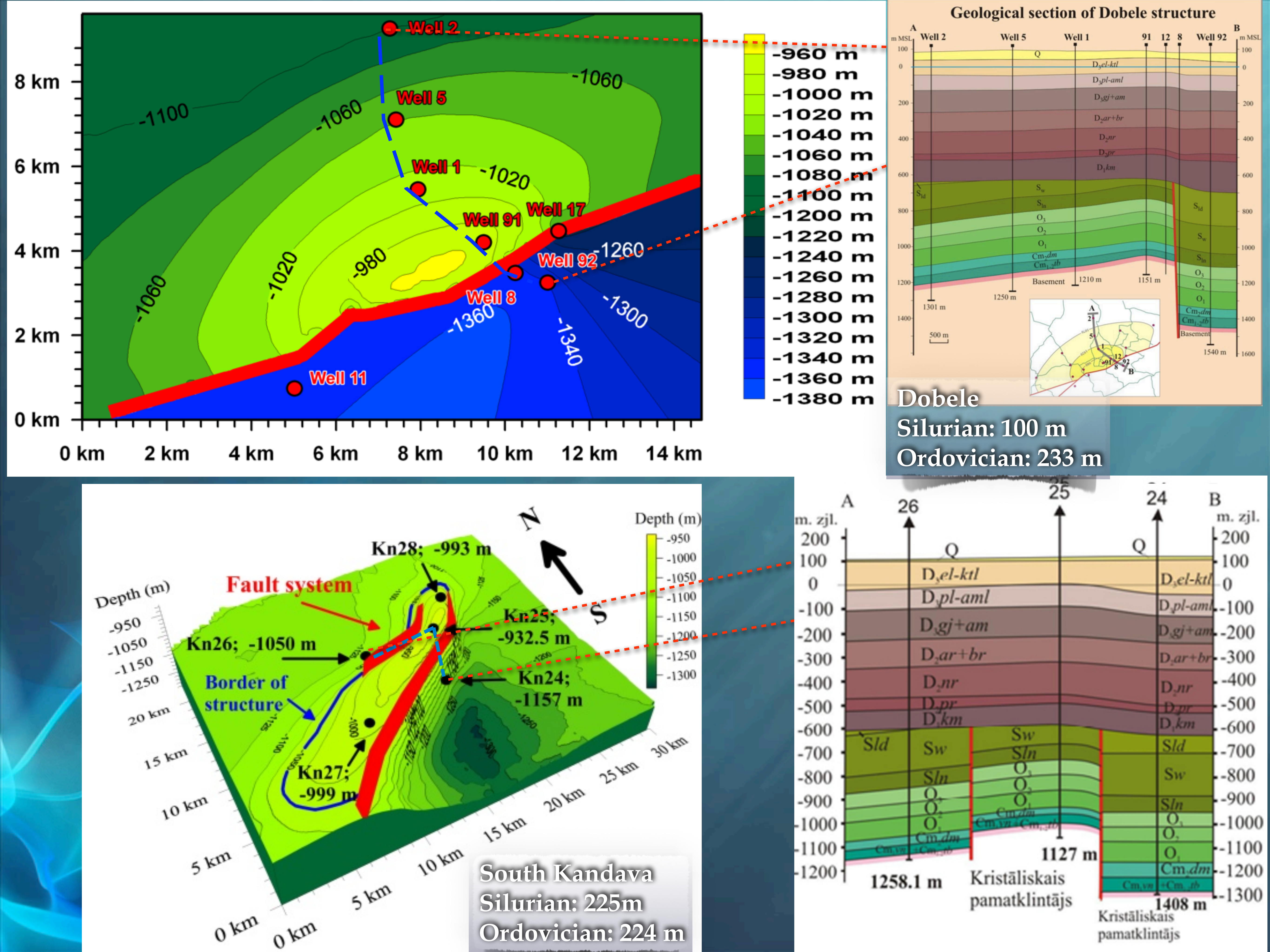


Fig. Prospective structures in the Cambrian aquifer and Inčukalns underground natural gas storage (UGS) in Latvia (Shogenov et. al, 2013a)



Well 2
Well 5
Well 1
Well 91
Well 17
Well 92
Well 8
Well 11
-1100
-1060
-1020
-980
-1260
-1300
-1340
-1360
8 km
6 km
4 km
2 km
0 km
0 km 2 km 4 km 6 km 8 km 10 km 12 km 14 km
-960 m
-980 m
-1000 m
-1020 m
-1040 m
-1060 m
-1080 m
-1100 m
-1200 m
-1220 m
-1240 m
-1260 m
-1280 m
-1300 m
-1320 m
-1340 m
-1360 m
-1380 m
Geological section of Dobele structure
Well 2 Well 5 Well 1 91 12 8 Well 92
Basement
1301 m
1250 m
1210 m
1151 m
1540 m
Dobele
Silurian: 100 m
Ordovician: 233 m
Fault system
Kn28; -993 m
Kn25; -932.5 m
Kn26; -1050 m
Kn24; -1157 m
Kn27; -999 m
Border of structure
Depth (m)
N
S
South Kandava
Silurian: 225m
Ordovician: 224 m
A
B
26
25
24
m. zjl.
Q
$D_3el\text{-}ktl$
$D_3pl\text{-}aml$
D_3gj+am
D_2ar+br
D_2nr
D_2pr
D_1km
Sld
Sw
Sln
O_3
O_2
O_1
Cm₂dm
1258.1 m
1127 m
1408 m
Kristāliskais pamatklintājs

Rock sampling

Objectives

- I — Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - **Rock sampling**
  - Measurement of geochemical and petrophysical properties
- II — Characterization of the selected structures
  - Reservoir characterization and risk assessment
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  - Estimation of CO_2 storage capacity
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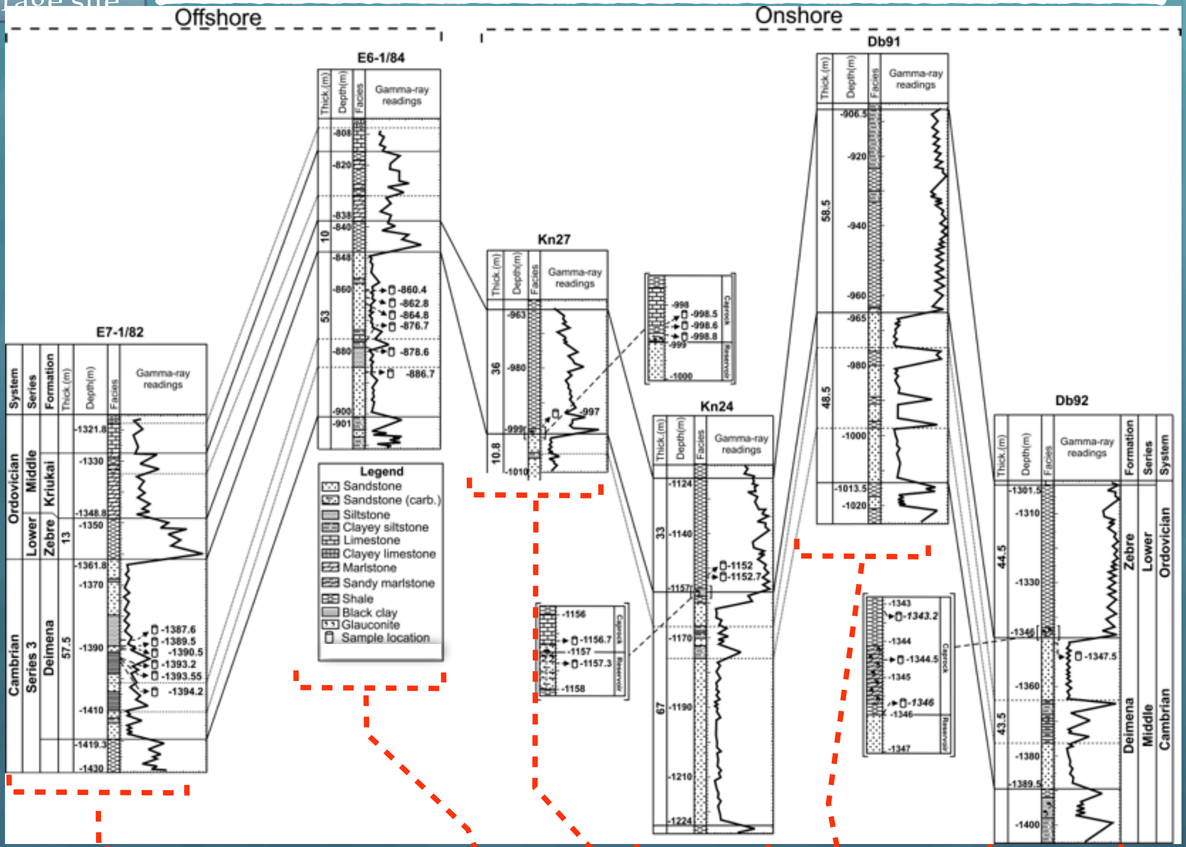
  - Modelling of the possible shape of CO_2 plume migration in the storage site

Selection of CO_2 geological storage sites

- 5 cores were described
- 24 samples selected (LEGMC – Latvian Environmental, Geological and Meteorological Center)

Fig. Cross section of the studied wells showing the correlation of the Deimena Formation reservoir and Zebre Formation primary cap rock



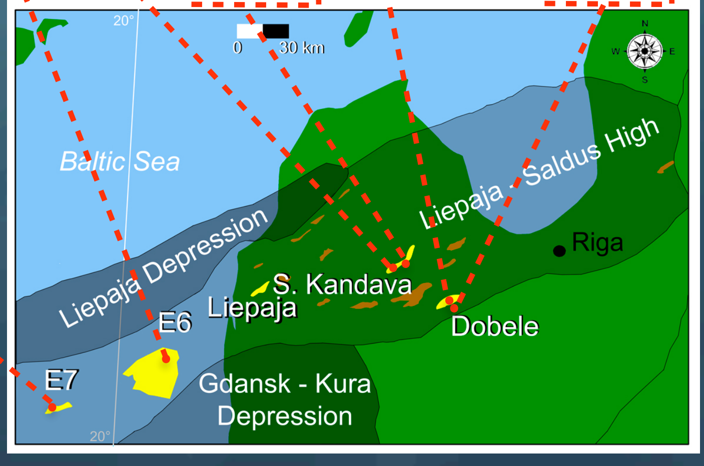


Fig. Location of Latvian onshore structures prospective for CGS in the Cambrian aquifer and the studied structures (Shogenov et. al, 2015)

Laboratory research

Objectives

- I — Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - **Measurement of geochemical and petrophysical properties**
- II — Characterization of the selected structures
  - Reservoir characterization and risk assessment
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  - Estimation of petrophysical alterations
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  - 4D time-lapse rock physics a… g
  - Coupling of the chemically in… eff… hosting rocks measured in the… me… modelling
  - Modelling of the possible sha… he


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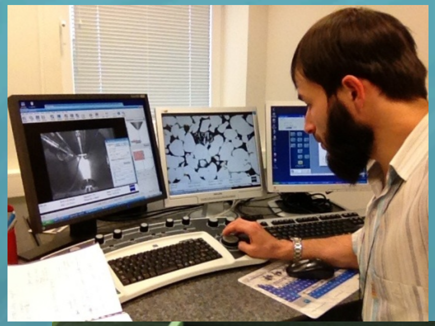
PUSHING BEYOND THE BARRIERS

…ome is …ths of 2013 – …d 'State of play …n 28 countries …will provide … current …rch in Europe, …mes and …well-known …ddition, an …ted activities …n projects …tion are …t a "CO_2 …ope" could …e level of … of individual …report will be …e on the CGS

Fig. 4 "Thanks to my CGS Europe study visit at IFPEN, I was able to perform first-class laboratory experiments on my rock samples that represent an important part of my PhD research." - Kazbulat Shogenov, PhD student of Tallinn University of Technology, Estonia (pictured at IFPEN laboratory in Rueil-Malmaison, France).

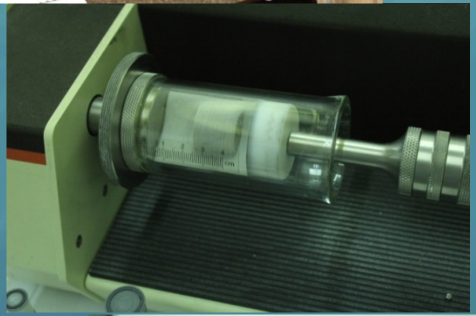
CO_2GeoNet Open Forum – European top event on CO_2 storage research

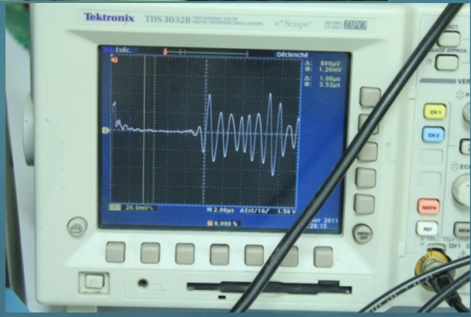


Estimation of petrophysical parameters

1. Solid volume (V_s): gas displacement helium pycnometer AccuPyc 1330
2. Grain or matrix density: $\rho_g = m / V_s$
3. Total volume (V_{total}): powder pycnometer GeoPyc 1360
4. Density of dry samples: $\rho_{dry} = m / V_{total}$
5. Volume of pores: $V_{pore} = V_{total} - V_s$
6. Effective porosity (%): $\varphi_{ef} = (V_{pore} / V_{total}) \times 100$
7. Permeability (mD), Darcy law:

$$K_{gas} = Q \times (1/S) \times \mu_{gas} \times ((2 \times P_{atm})/(P_1^2 - P_2^2))$$





Institution	Analyses type
Institute of Geology at Tallinn University of Technology	- Geochemical analyses: Titration method: CaO, MgO; Gravimetric method: Insoluble residue - Thin-section study (TEM, SEM)
IFPEN (French Institute of Petroleum), France	Rock physical analyses: Grain and bulk density, porosity, permeability, V_P and V_S
Acme Analytical Laboratories Ltd. (Vancouver, http://acmelab.com),	XRD, XRF (SiO_2, Al_2O_3, Fe_2O_3total, K_2O, Na_2O, MnO, TiO_2, P_2O_5, Ba)

Laboratory research

Objectives

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Selection of CO_2 geological storage sites

Rock sampling

Measurement of geochemical and petrophysical properties

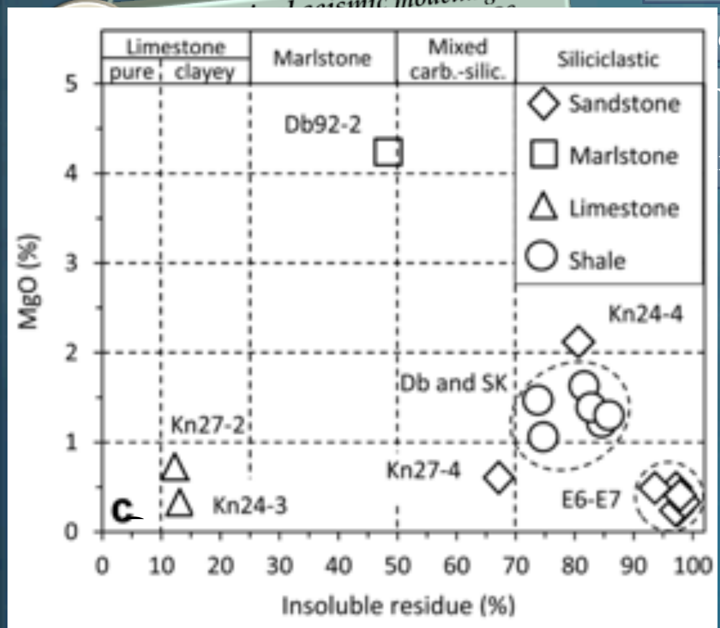
Reservoir characterization and risk assessment

3D geological static modelling

Es…

Labo…

Estim…



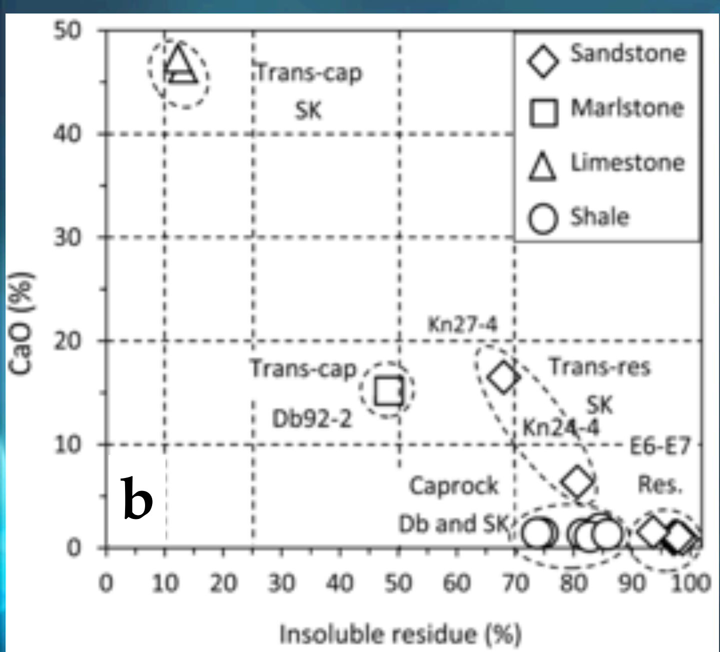
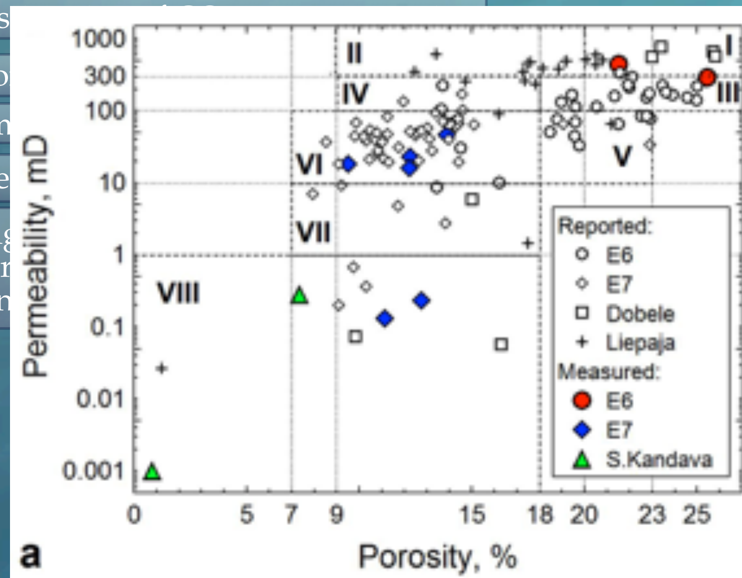


Fig. (a, b) Composition of the studied rock samples before the alteration experiment



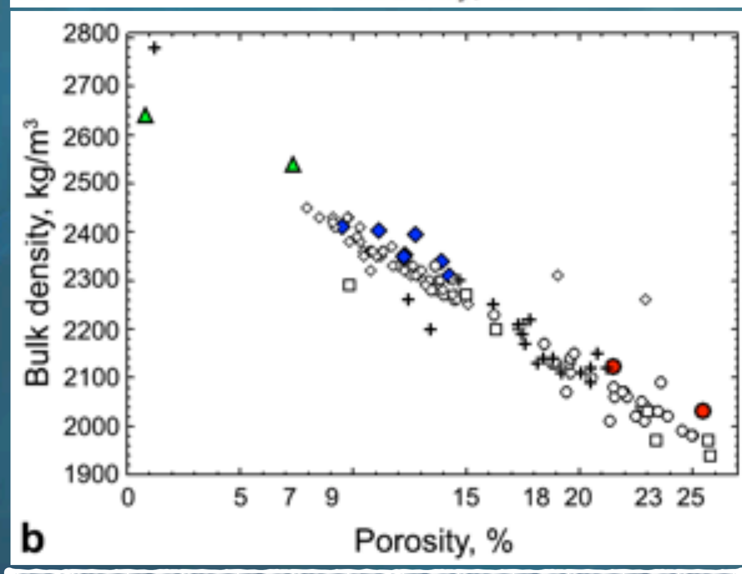


Fig. Petrophysical properties of the reported and measured sandstones before the alteration experiment (Shogenov et. al, 2015). Data are based on 115 sandstone samples from the Deimena Formation of 2 offshore and 3 onshore structures from 7 boreholes

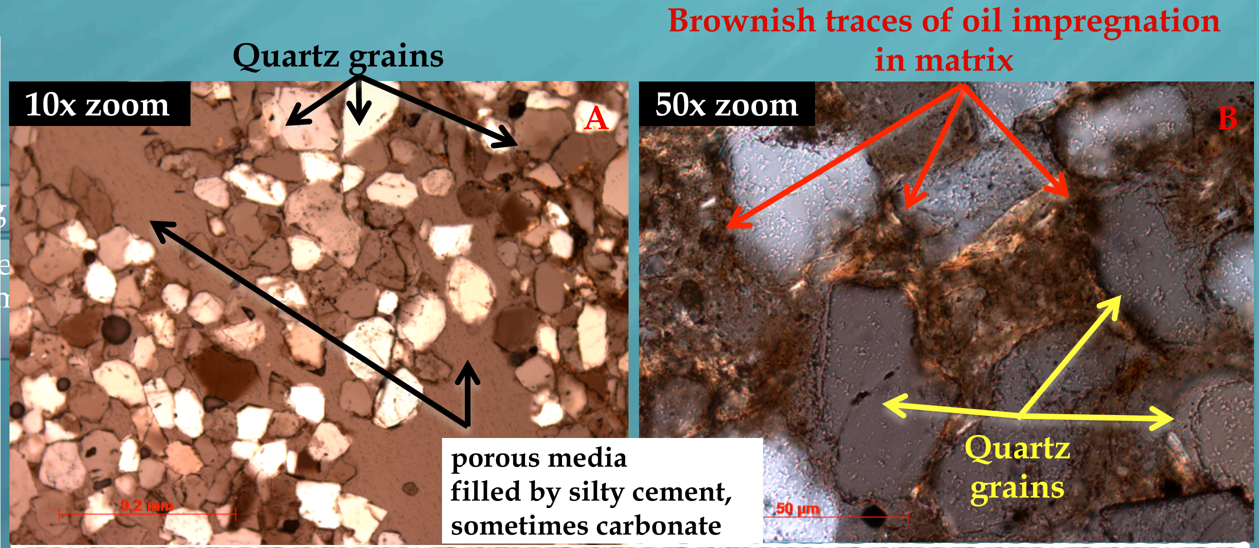


Fig. Example of thin-section photos (10x (A) and 50x (B) zoom, in Epi-illumination polarized light) sample E6 876.7 (made at TUT GI lab) (A: not published; B: Shogenov et. al, 2013a)

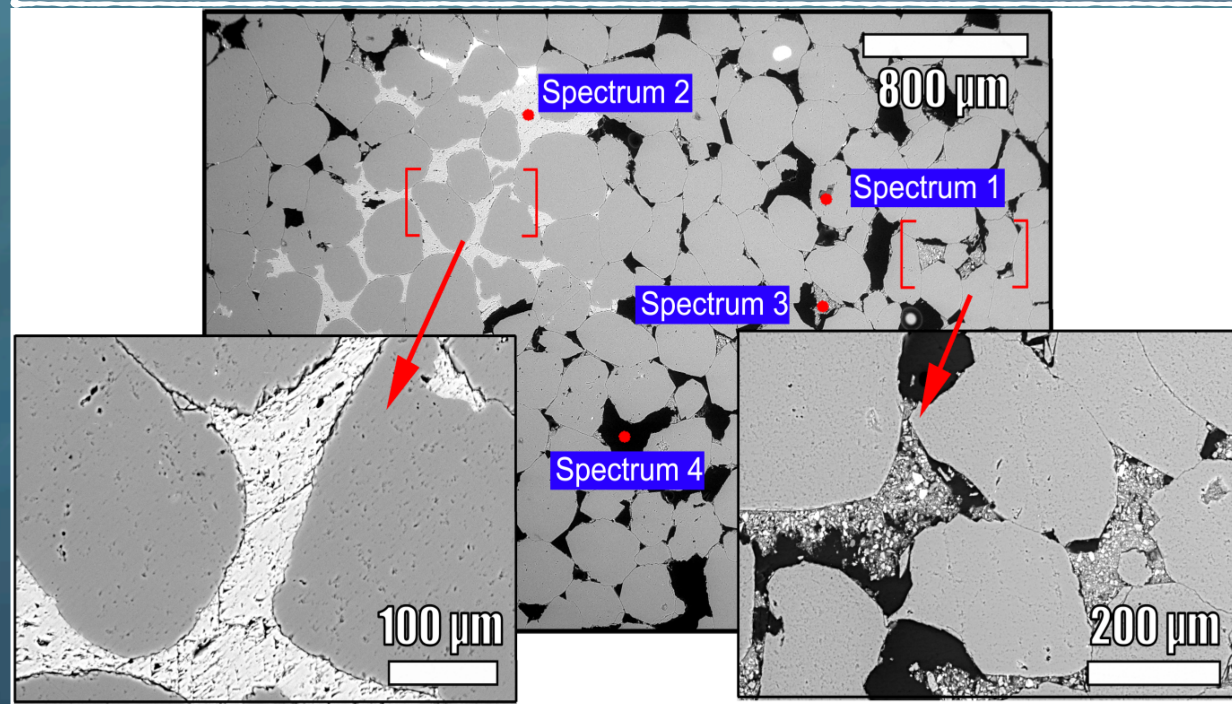


Fig. Example of SEM microphoto-graphs of the thin section of Deimena sandstone sample in well E7/1-82 (1390.5 m) E7 structure (Shogenov et. al, 2013b)

Laboratory research

Objectives

- **I** *Selection of storage sites and data collection*
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- **II** *Characterization of the selected structures*
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  - Estimation of CO_2 storage capacity
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  - Estimation of petrophysical alterations
- **IV** *Numerical seismic modelling to support the monitoring of CGS*
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - possible shape of CO_2 plume migration in the storage site

X-ray diffraction (XRD) analysis

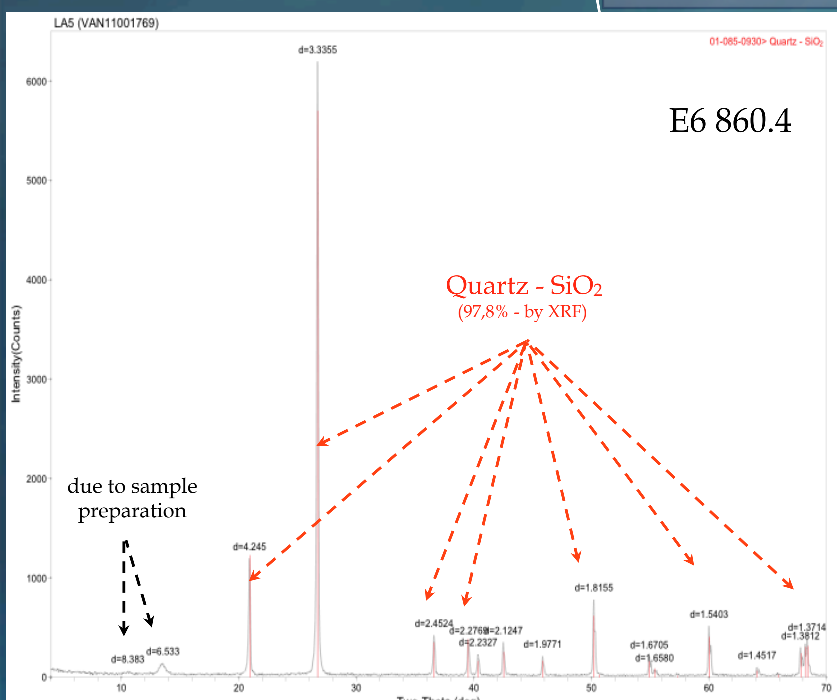

Fig. XRD analyses showing high content of SiO_2, interpreted as essentially pure quartz sandstone (sample 860.4, well E6-1/84)

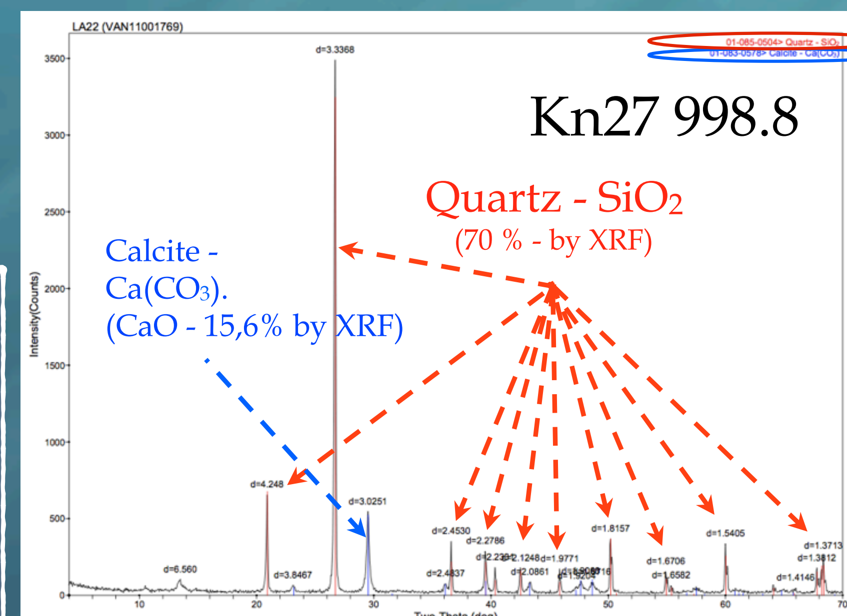

Fig. XRD analyses showing high content of SiO2, interpreted as abundant quartz content in sandstone. One small peak reflects minor calcite content (cement) in the sample (sample 998.8, well Kn27

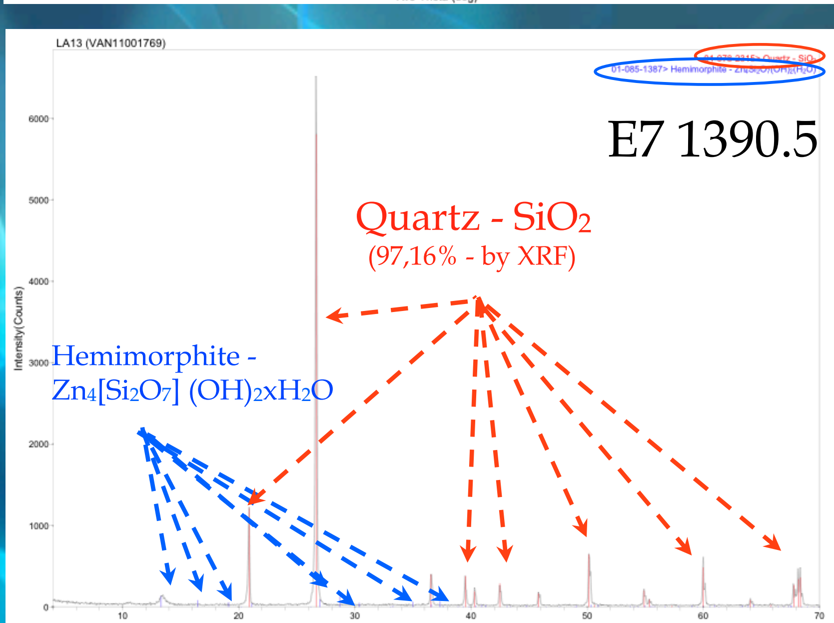

Fig. XRD analyses showing high content of SiO2, interpreted as nearly pure quartz sandstone (sample 1390.5, well E7-1/82)

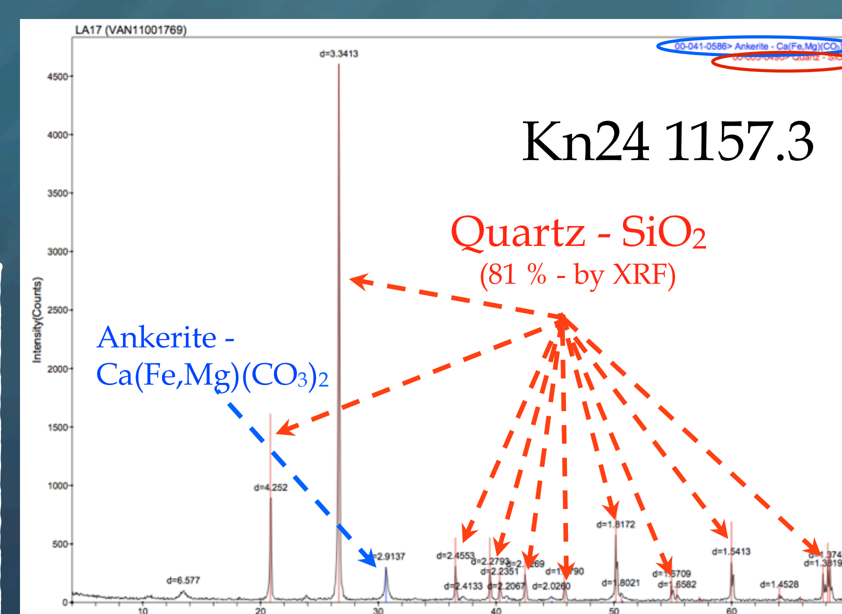

Fig. XRD analyses showing high content of SiO2, interpreted as almost pure quartz sandstone. One small peak reflects minor ankerite content in the sample (sample 1157.3, well Kn24)

Reservoir characterization

Objectives

- **I** – Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- **II** – Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
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- **III** – Estimation of the influence of CGS on the properties of rocks
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  - Modelling of the possible shape of CO_2 plume migration in the storage site

Reservoir characterization and risk assessment

New classification

139 samples

7 boreholes (offshore E6-1/84 and E7-1/82 and onshore Kn24 and Kn27, Db91 and Db92, and Liepaja-San)

———

- k - 127 samples
- ϕef - 128 samples
- grain density - 102 samples
- bulk density - 129 dry samples
- VPdry - 60 samples
- VSdry - 10 samples

Table. Classification of the reservoir rocks by permeability and porosity

Hydrocarbon reservoirs (Ханин 1965, 1969)

Group	Class	Reservoir quality	κ (mD)	φ_{ef} (%)
1	I	Very high	≥1000	≥20
	II	High	500–1000	18–20
	III	Average	100–500	14–18
2	IV	Reduced	10–100	8–14
	V	Low	1–10	2–8
	VI	Very low	<1	<2

CO_2 storage standards*

Group	Class	Reservoir quality	κ (mD)	φ_{ef} (%)
1	I	High Preferred	>500 >300	>25 >20
	II	Good	50–250	15–20
	III	Moderate	50–250	10–15
2	IV	Cautionary	<200 <50	<10
	V	Low	<10	<15

Classification of the studied rocks for CO_2 storage**

Group	Application for CGS	Class	Reservoir quality	κ (mD)	φ_{ef} (%)
1	Very appropriate	I	High-1	>300	≥20
		II	High-2		9–20
2	Appropriate	III	Good	100–300	>18
		IV	Moderate		9–18
3	Cautionary	V	Cautionary-1	10–100	18–23
		VI	Cautionary-2		7–18
4	Not appropriate	VII	Low	1–10	7–18
		VIII	Very low	<1	<18

*CO2 storage standards modified after Van Der Meer (1993), Chadwick et al. (2006), Vangkilde-Pedersen & Kirk (2009), Tiab & Donaldson (2012), Halland et al. (2013): group 1, acceptable for CGS; group 2, cautionary.

** New classification based on the studied data (reported and measured in laboratory before the alteration experiment)

3D geological modelling

3D geological models of the top of the Deimena Formation in the studied structures (Paper I, Paper II)

Surfer® software:
digitizing structural maps
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Objectives

II Characterization of the selected structures

III Estimation of the influence of CGS on the properties of rocks

IV Numerical seismic modelling to support the monitoring of CGS

Reservoir characterization and risk assessment

3D geological static

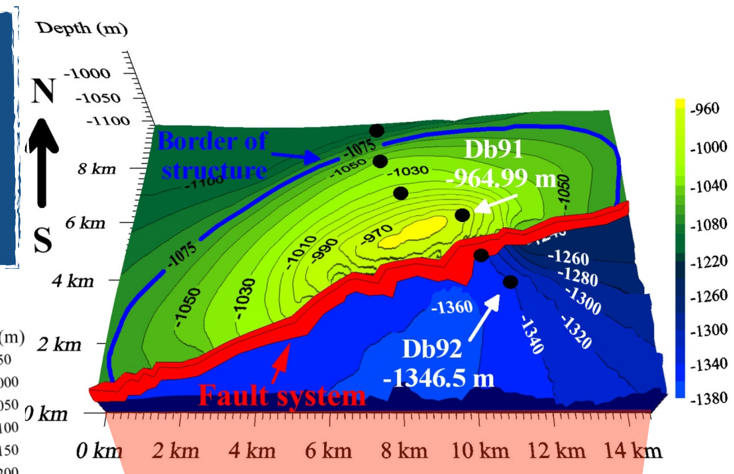
Estimation of CO_2 storage capacit

Laboratory CO_2 injection-like alterat

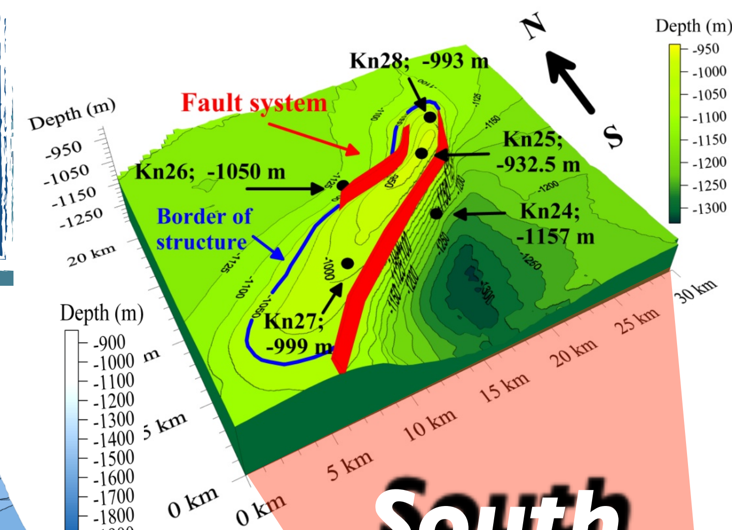
Estimation of petrophysical alteratio

4D time-lapse rock physics and numerical seismic modelling

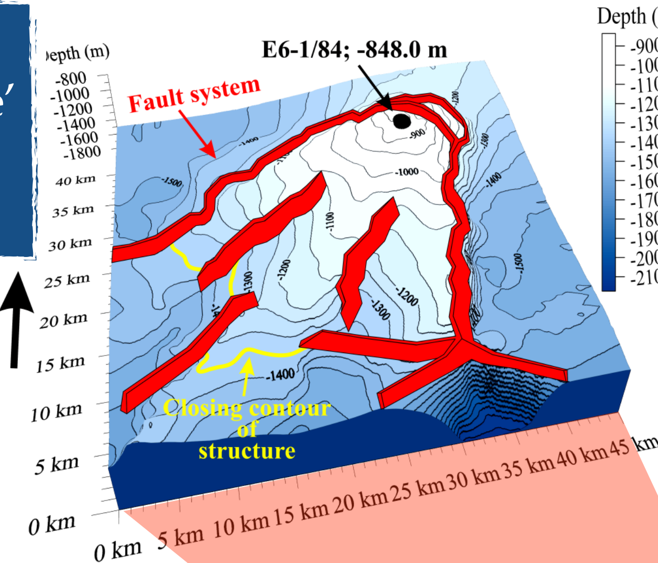
Reservoir quality: 'high-2'
Application for CGS: 'very appropriate'
(average porosity 19%;
permeability 360 mD)



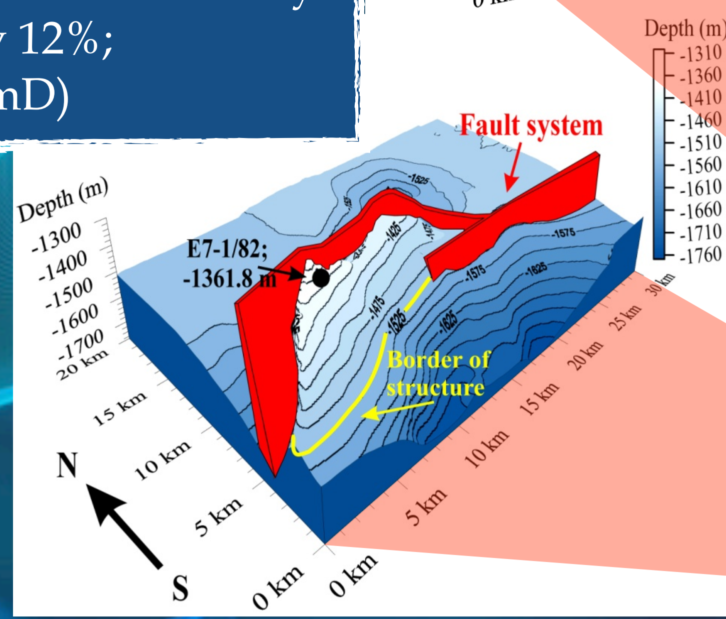
Reservoir quality: 'good'
Application for CGS: 'appropriate'
(average porosity 21%;
permeability 300 mD)



Reservoir quality: 'good'
Application for CGS: 'appropriate'
(average porosity 21%;
permeability 150 mD)



Reservoir quality: 'cautionary-2'
Application for CGS: 'cautionary'
(average porosity 12%;
permeability 40 mD)

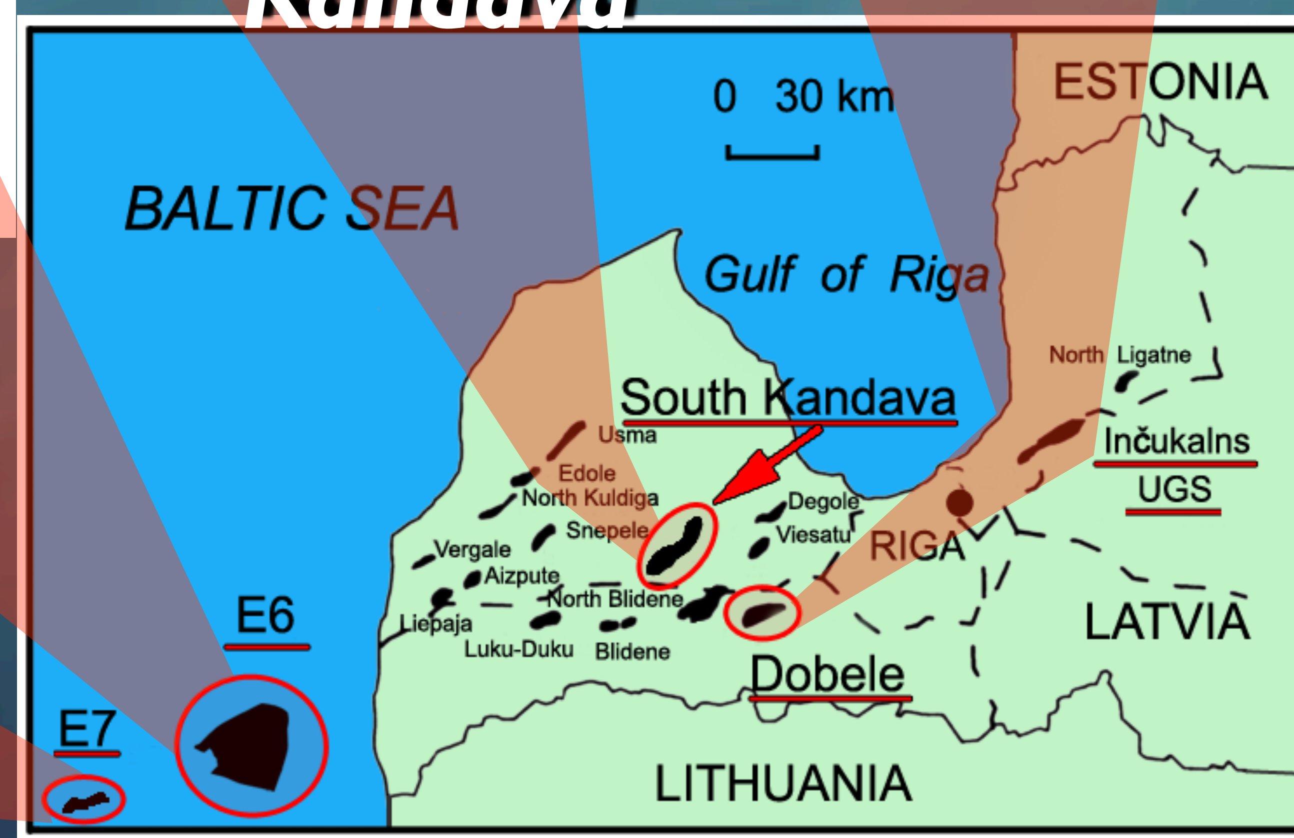


Dobele

South Kandava

E6

E7



3D geological modelling

Objectives

I. Selection of storage sites and data collection
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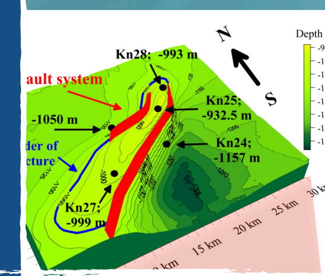
- 4D time-lapse rock physics and numerical seismic modelling
- ...ed petrophysical alteration effect of CO_2– hosting ...atory with time-lapse numerical seismic modelling

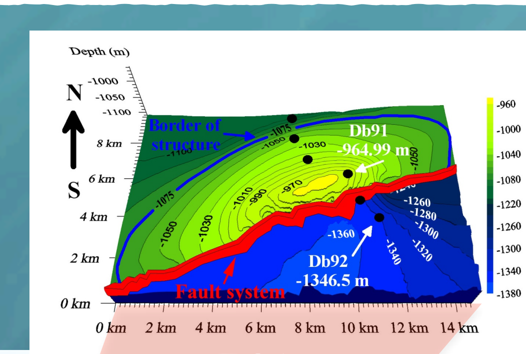
Surfer® software: digitizing structural maps
Golden Software

3D geological models of the top of the Deimena Formation in the studied structures with the estimated closing contour of the structures. Faults bordering the structure are shown by a red wall. Location of the well is shown by a black circles with the depth of the top of the formation (Shogenov et al., 2013 a, b)

Salinity – 114 g/l
Thickness – 52 m
Density of CO_2 in situ – 900 (kg/m³)
Net Gross ratio of aquifer – 0.85
Reservoir temperature in situ – 18°C
Reservoir pressure in situ – 13 mPa
Area – 70 (km²)
Porosity – 19%
Permeability – 360 mD

Salinity – 113 g/l
Thickness – 42 m
Density of CO_2 in situ – 820 (kg/m³)
Net Gross ratio of aquifer – 0.90
Reservoir temperature in situ – 24.5 °C
Reservoir pressure in situ – 10.5 mPa
Area – 97 (km²)
Porosity – 21%
Permeability – 300 mD

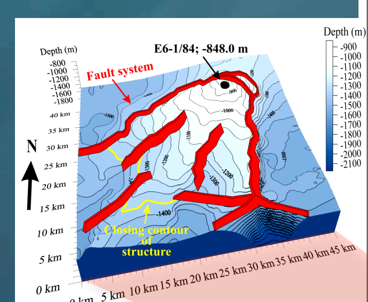




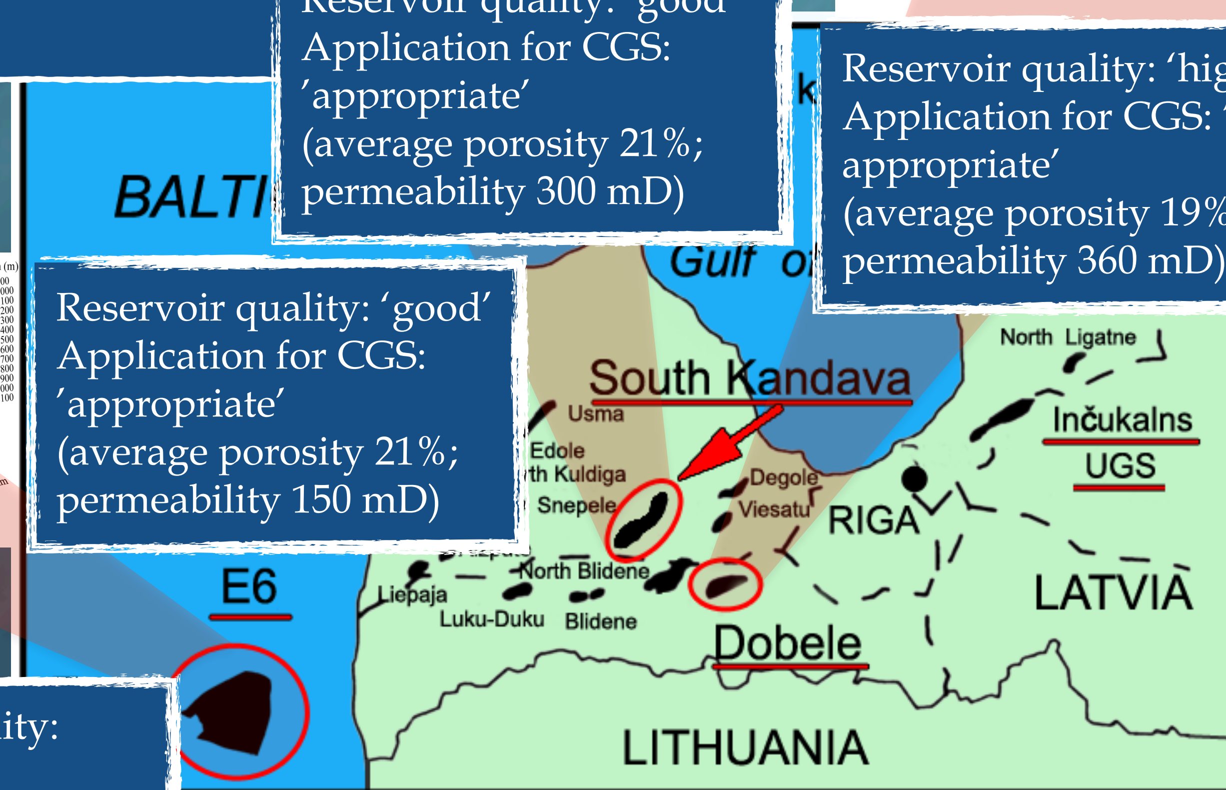
Reservoir quality: 'good'
Application for CGS: 'appropriate'
(average porosity 21%; permeability 300 mD)

Reservoir quality: 'high-2'
Application for CGS: 'very appropriate'
(average porosity 19%; permeability 360 mD)

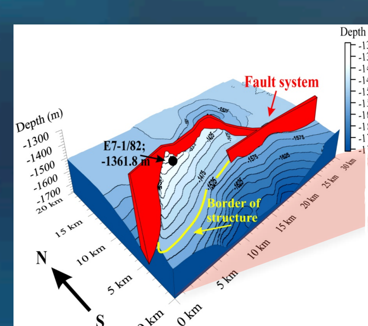
Salinity – 99 g/l
Thickness – 53 m
Density of CO_2 in situ – 658 (kg/m³)
Net Gross ratio of aquifer – 0.90
Reservoir temperature in situ – 36°C
Reservoir pressure in situ – 9.3 mPa
Area – E6: 600 (km²)
E6-A: 553 km²
E6-B: 47 km²
Porosity– 21%
Permeability– 150 mD



Reservoir quality: 'good'
Application for CGS: 'appropriate'
(average porosity 21%; permeability 150 mD)



Salinity – 125 g/l
Thickness – 58 m
Density of CO_2 in situ – 727 (kg/m³)
Net Gross ratio of aquifer – 0.80
Reservoir temperature in situ – 46°C
Reservoir pressure in situ – 14.7 mPa
Area – 43 (km²)
Porosity – 12%
Permeability – 40 mD



Reservoir quality: 'cautionary-2'
Application for CGS: 'cautionary'
(average porosity 12%; permeability 40 mD)

...ective structures in the Cambrian aquifer (CO_2 storage potential exceeding ... Inčukalns underground natural gas storage (UGS) in Latvia. The dashed ...s gas pipelines. Red circles shows locations of the studied offshore and ...ructures (Shogenov et al., 2013)

Objectives

- **I** Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
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- **II** Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - **3D geological static modelling**
  - Estimation of CO_2 storage capacity
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  - Estimation of petrophysical alterations
- **IV** Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

E6 offshore structure

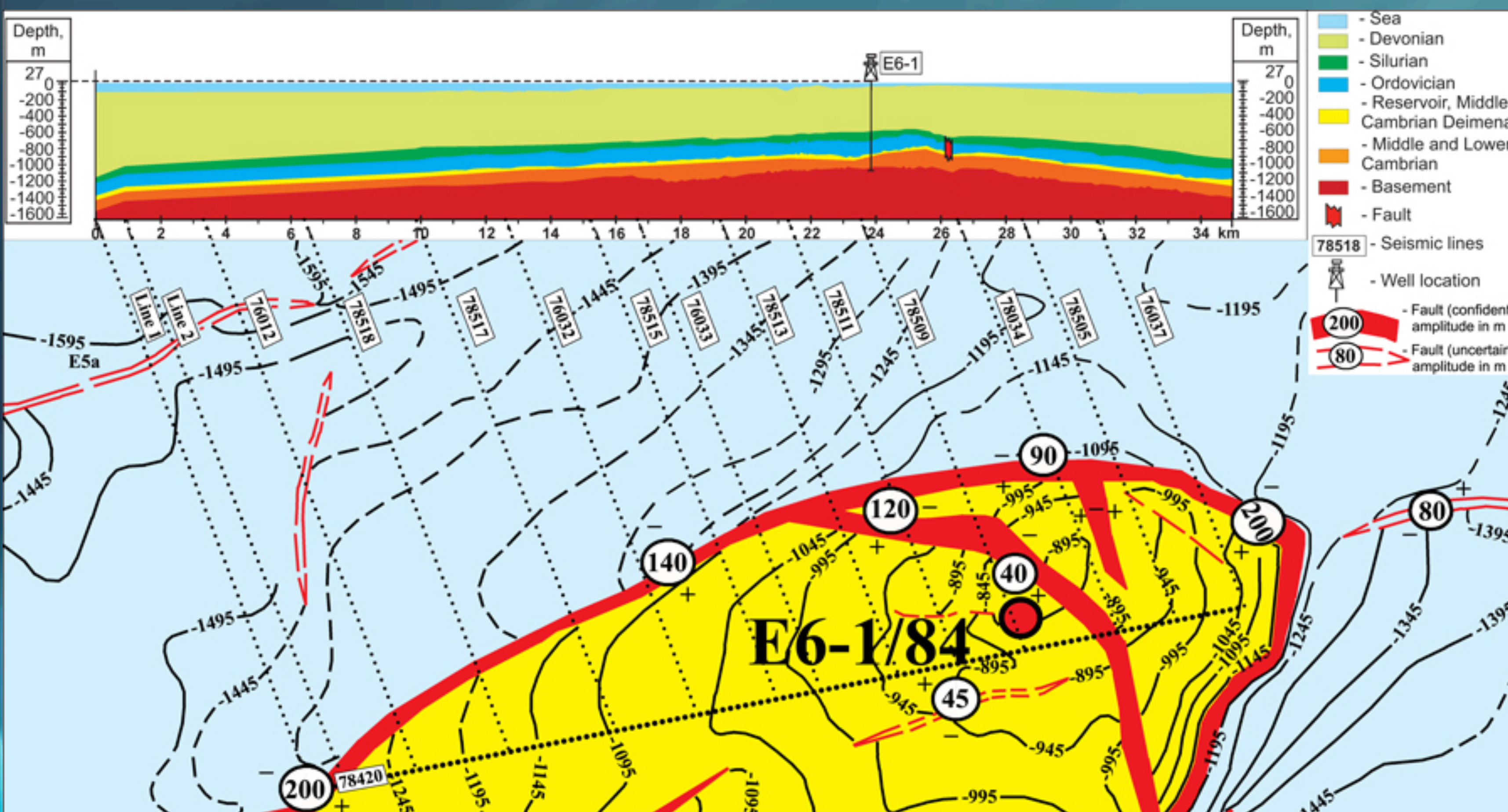


Fig. Geological cross section of the E6 structure corresponding to seismic line 78420, interpreted using reported seismic data, local structure map and lithological cross section in the well E6-1/84 (Shogenov et. al, 2013b)

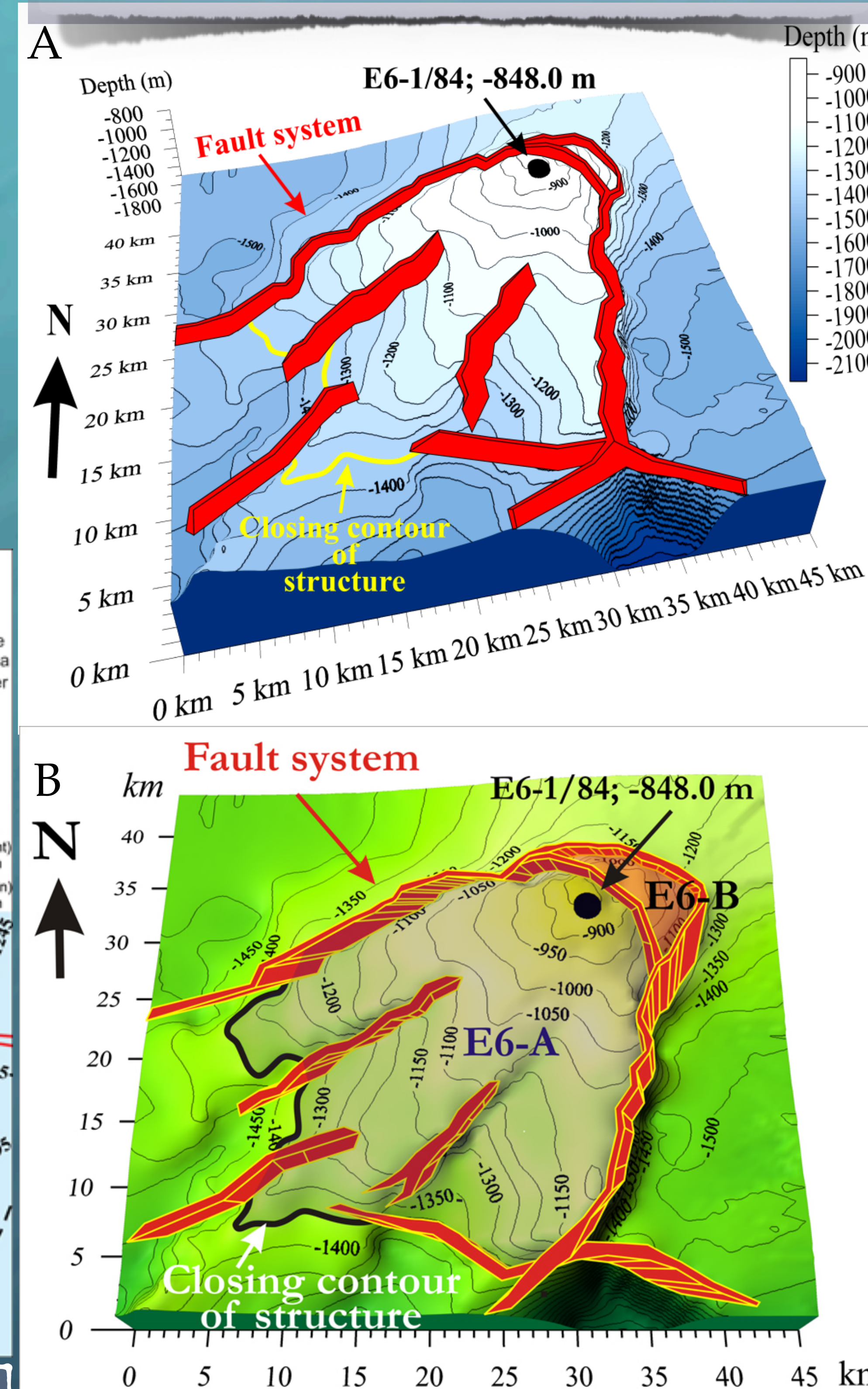


Fig. 3D geological models of the top of the Deimena Formation in the E6 structure. Two split by faults compartments of the E6 structure (B) were considered as separate substructures defined as E6-A and E6-B

3D geological modelling

E6-A

Petrel® software: geological, lithological and petrophysical modelling

Schlumberger

Volumetric grid parameters implemented in the 3D geological modelling

Size:
- 29371.5 m (X-axis)
- 26534 m (Y-axis)
- 826 m (Z-axis)

Depth range: 693 – 1519 m

Area: 541 km^2

Cells dimension: 500 x 500m

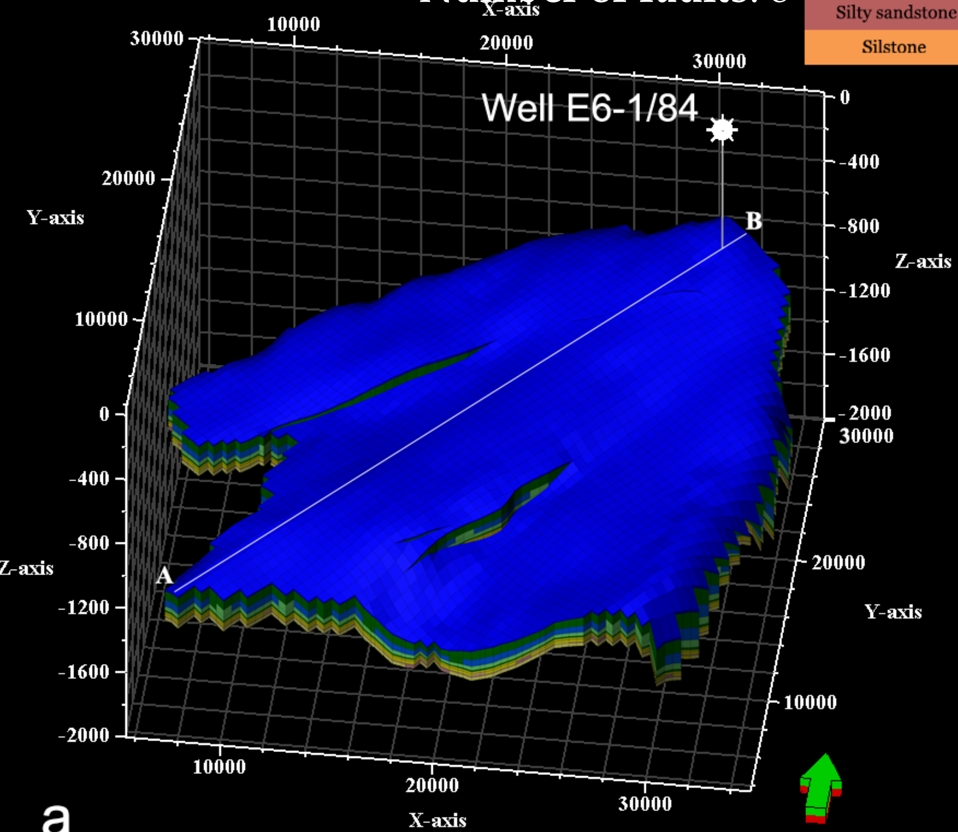
Cells: 67 x 59 x 10

Total number of 3D cells: 39530

Number of faults: 8

To populate the model with facies and petrophysical properties, three modelling algorithms of Geostatistical Software Library were applied (Deutsch & Journel, 1998):

- **Truncated Gaussian Simulation**
- **Sequential Indicator Simulation**
- **Gaussian Random Function**



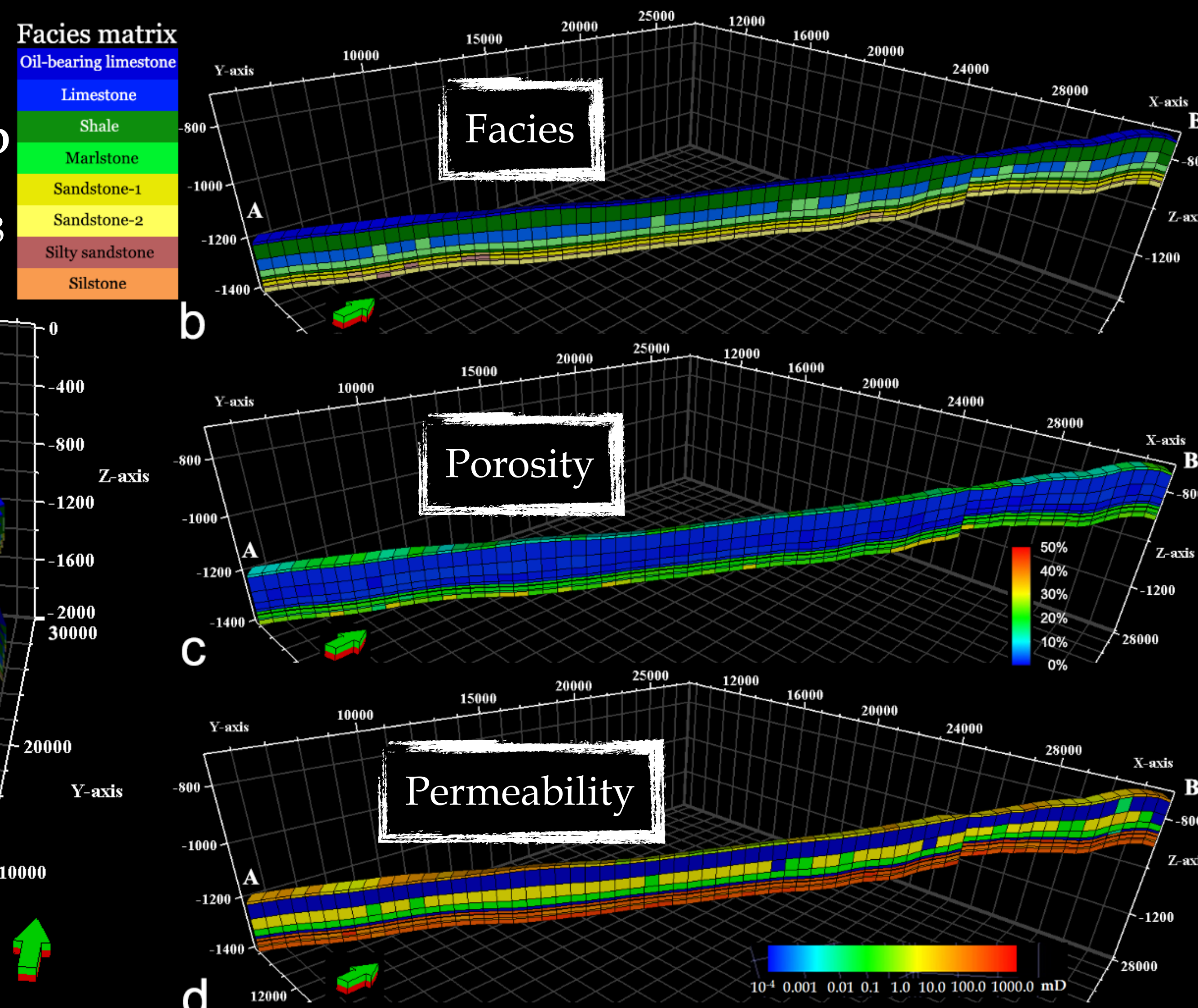


Fig. (a) 3D geological static facies model of the E6-A compartment of the E6 offshore structure with location of the well E6-1/84. All layers of the 3D model are shown. The white line A−B represents the geological cross section shown in Fig. 4b-d. Cross sections of (b) facies, (c) porosity and (d) permeability distribution along the line A−B

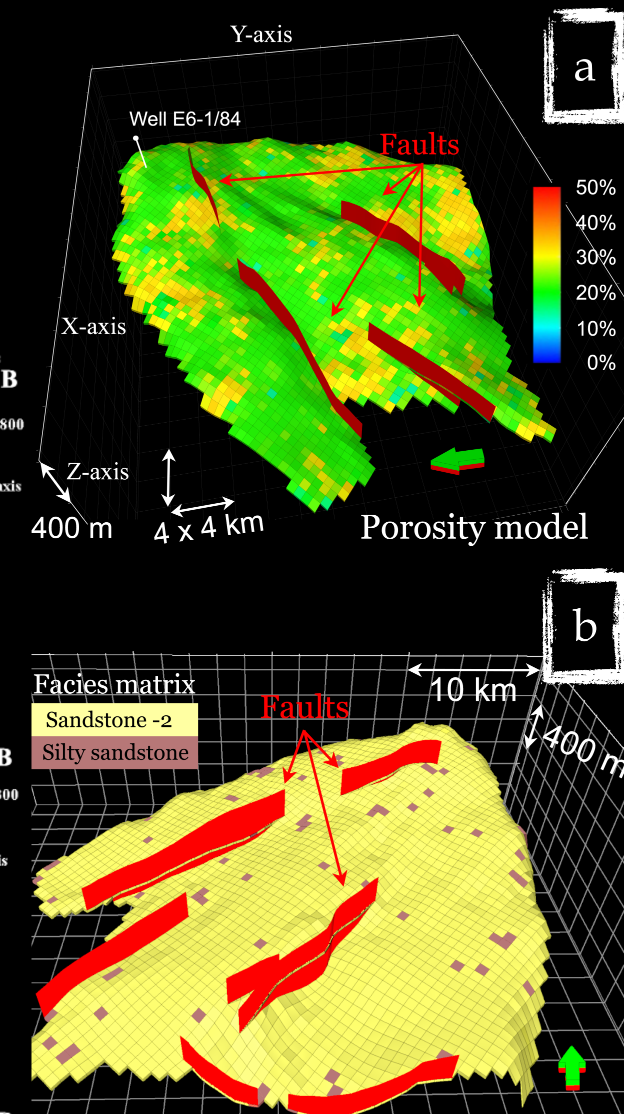


Fig. (a) 3D geological static facies model of the E6-A compartment, showing the lowermost layer 10 of the Cambrian Deimena. (b) 3D geological static porosity model with the lowermost layer 10 of the Deimena Formation

CO_2 storage capacity

Objectives

I — Selection of storage sites and data collection
- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties

II — Characterization of the selected structures
- Reservoir characterization and risk assessment
- 3D geological static modelling
- **Estimation of CO_2 storage capacity**

III — Estimation of the influence of CGS on the properties of rocks
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations

IV — Numerical seismic modelling to support the monitoring of CGS
- 4D time-lapse rock physics and numerical seismic modelling
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- Modelling of the possible shape of CO_2 plume migration in the storage site

$$M_{CO2t} = A \times h \times NG \times \varphi \times \rho_{CO2r} \times S_{ef}$$

M_{CO2t} - storage capacity (kg)
A - area of an aquifer in the trap (m^2)
h - average thickness of the aquifer in the trap (m)
NG - average net to gross ratio of the aquifer in the trap (%)
φ - average porosity of the aquifer in trap (%)
ρ_{CO2r} - in situ CO_2 density in reservoir conditions (kg/m^3)
Sef - storage efficiency factor (for trap volume, %)

Optimistic approach

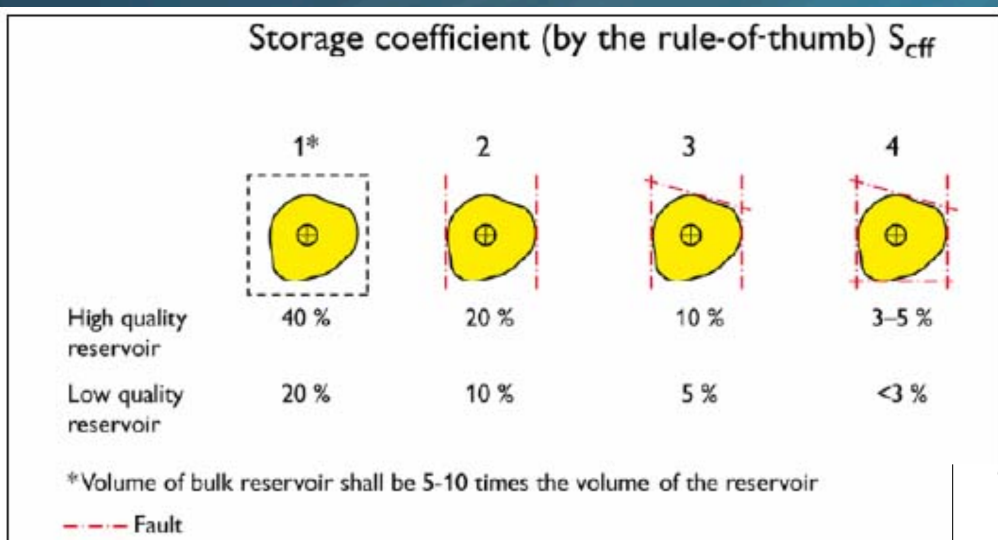

Figure 4: Illustration of the "cartoon approach" for storage efficiency factor.

Fig. Illustration of the „Cartoon approach" for storage efficiency factor (Bachu, S. et al. 2007. International Journal of Greenhouse Gas Control, 1)

Conservative approach

Based on Monte Carlo simulations (US Department of Energy (DOE) 2008. Methodology for development of geological storage estimates for carbon dioxide)

Structure	Optimistic	Conservative
	Efficiency factor	
S.Kandava	15	4
Dobele	20	4
E6-A	10	4
E6-B	4	2
E7	20	4

Table. Storage efficiency factors for trap volume (%) estimated for the studied structures according to Optimistic and Conservative approaches

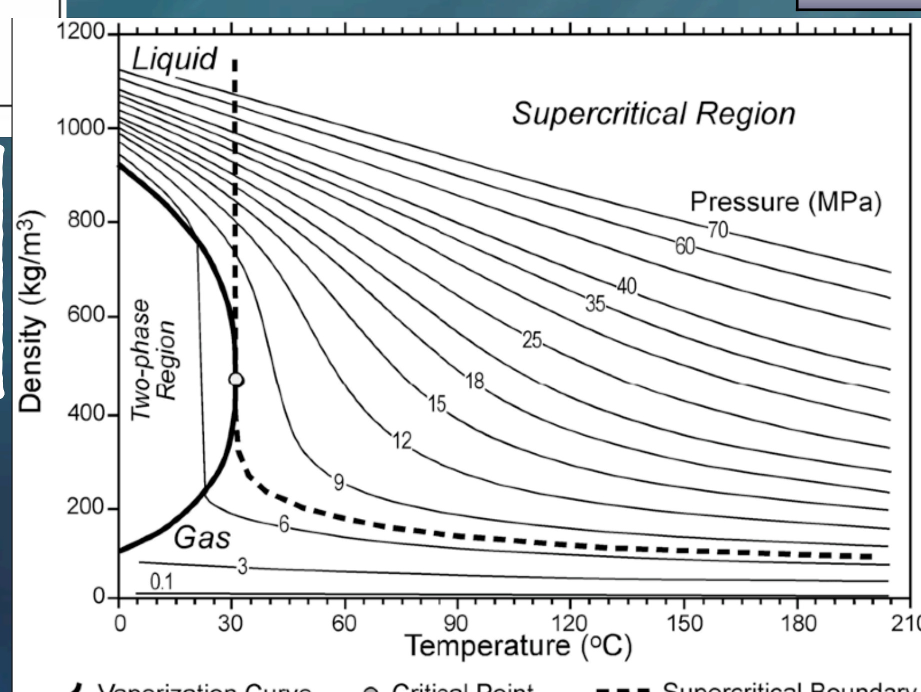

Fig. Estimation of in situ CO_2 density in reservoir conditions (Bachu, 2003)

CO_2 storage capacity

Objectives

- I — Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
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  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - **Estimation of CO_2 storage capacity**
- III — Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV — Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2-hosting rocks measured in the laboratory with time-lapse numerical seism modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

$$M_{CO2t} = A \times h \times NG \times \varphi \times \rho_{CO2r} \times S_{ef}$$

Table. Properties of Latvian onshore structures most prospective for CO_2 storage (Shogenova et al., 2009)

Structure	Depth m	Thickness m	Area, km²	CO_2 storage capacity, Mt
Aizpute	1096	65	51	14
Blidene	1050	66	43	58
Degole	1015	52	41	21
Dobele	950	52	67	56
Edole	945	71	19	7
Kalvene	1063	45	19	14
Liepaja	1072	62	40	6
Luku-Duku	937	45	50	40
N. Kuldiga	925	69	18	13
N. Ligatne	750	50	30	23
N.Blidene	920	40	95	74
S.Kandava	983	25-30	69	44
Snepele	970	30	26	17

	Reservoir parameters								CO_2 storage capacity (Mt)					
Structure	*Depth of top (m)*	*Thickness (m)*	*Trap area (km²)*	*Salinity (g/l)*	*Pressure (mPa)*	*T (°C)*	*CO_2 density (kg/m³)*	*S_{ef} Opt./ Cons. (%)*	*Optimistic estimates*			*Conservative estimates*		
									Min	*Max*	*Mean*	*Min*	*Max*	*Mean*
E6-A	848	53	553	99	9.3	36	658	10/4	243	582	365	97	233	146
E6-B	848	53	47	99	9.3	36	658	4/2	8	20	12	4	10	6
E6 total	848	53	600	99	9.3	36	658	10; 4/4; 2	251	602	377	101	243	152
E7	1362	58	43	125	14.7	46	727	20/4	14	66	34	3	13	7
Total CO_2 storage capacity of the studied offshore structures (Mt)									***265***	***668***	***411***	***104***	***256***	***159***
S. Kandava	933	42	97	113	10.5	24.5	820	15/4	5	122	95	1	32	25
Dobele	950	52	70	114	13	18	900	20/4	56	145	106	11	29	21
Total CO_2 storage capacity of the studied onshore structures (Mt)									***61***	***267***	***201***	***12***	***61***	***46***
Total CO_2 storage capacity of four structures (Mt)									**326**	**935**	**612**	**116**	**317**	**205**

Physical parameters of the studied Latvian offshore and onshore structural traps. The S_{ef} Opt./Cons. is a storage efficiency factor used for optimistic (Opt.) and conservative (Cons.) capacity calculation (Shogenov et. al, 2013a, b)

Alteration experiment

Objectives

I Selection of storage sites and data collection
- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties

II Characterization of the selected structures
- Reservoir characterization and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity

III Estimation of the influence of CGS on the properties of rocks
- **Laboratory CO_2 injection-like alteration experiment**
- Estimation of petrophysical alterations

IV Numerical seismic modelling to support the monitoring of CGS
- 4D time-lapse rock physics and numerical seismic modelling
- Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- Modelling of the possible shape of CO_2 plume migration in the storage site

Homogenous alteration method

The "alteration" experiment or retarded acid treatment (RAT) with placement of samples into the acid solution, simulating CO2-rich brine in aquifer was conducted at IFPen:
- flushing of the sample with fresh retarded acid at ambient temperature (amount equivalent to about 3 times the sample porous volume);
- activation of the acid under temperature (60°C for at least 1 day);
  - flashing of the sample with NaCl brine at ambient temperature (= 3 times the sample porous volume)
  - drying samples in an oven for 3 days
  - Procedure was repeated 3 times

Device and process: (Egermann et al. 2006, Bemer and Lombard, 2010)

- Total 15 reservoir rock and transitional cap rock samples from 5 wells (offshore E6-1/84 and E7-1/82, and onshore Dobele and South Kandava 24 and 27)

- Bulk and grain helium density, helium porosity, gas permeability and acoustic P- and S-wave velocities in dry samples, the chemical and mineralogical composition and surface morphology were studied in the samples both before and after the alteration experiment

Objectives

I Selection of storage sites and data collection
- Selection of CO_2 geological storage sites
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II Characterization of the selected structures
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- Estimation of CO_2 storage capacity

III Estimation of the influence of CGS on the properties of rocks
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- **Estimation of petrophysical alterations**

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- Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- ...on in the storage site

Alteration experiment

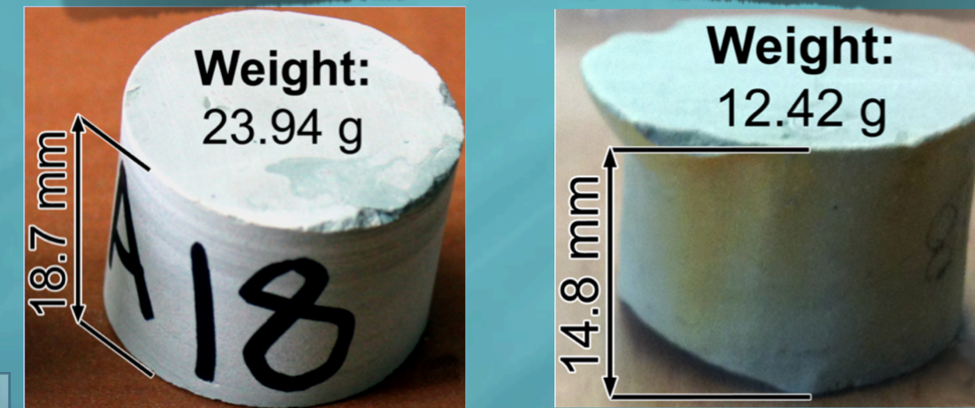

Fig. Trans-cap limestone sample Kn24-3 before (left) and after (right) the alteration experiment

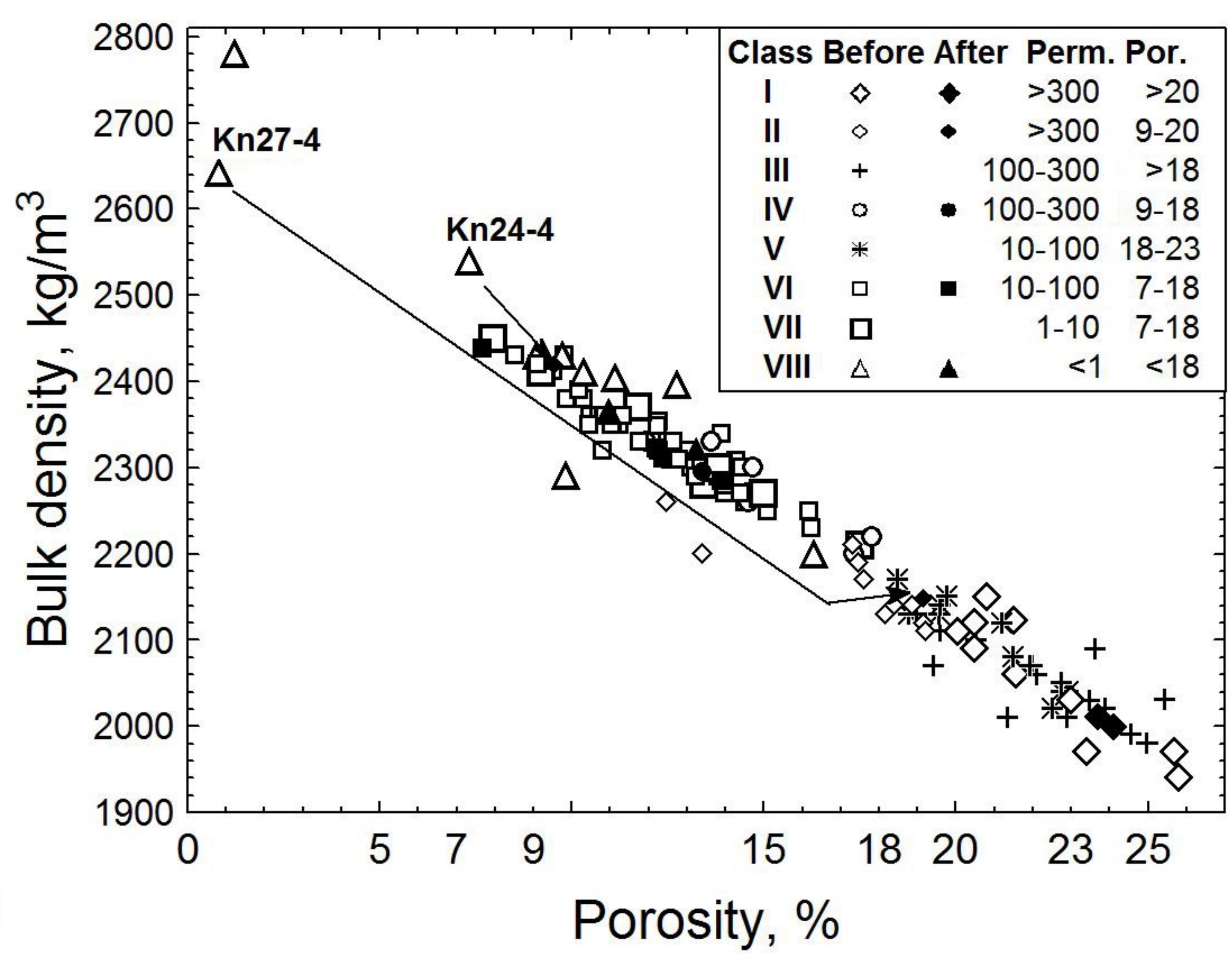

Fig. Bulk density measured on dry samples vs porosity of the sandstones of the Deimena Formation from two offshore and three onshore structures for 115 samples reported and measured before alteration (empty symbols) and 12 samples measured after alteration (black symbols) (Shogenov et. al, 2015)

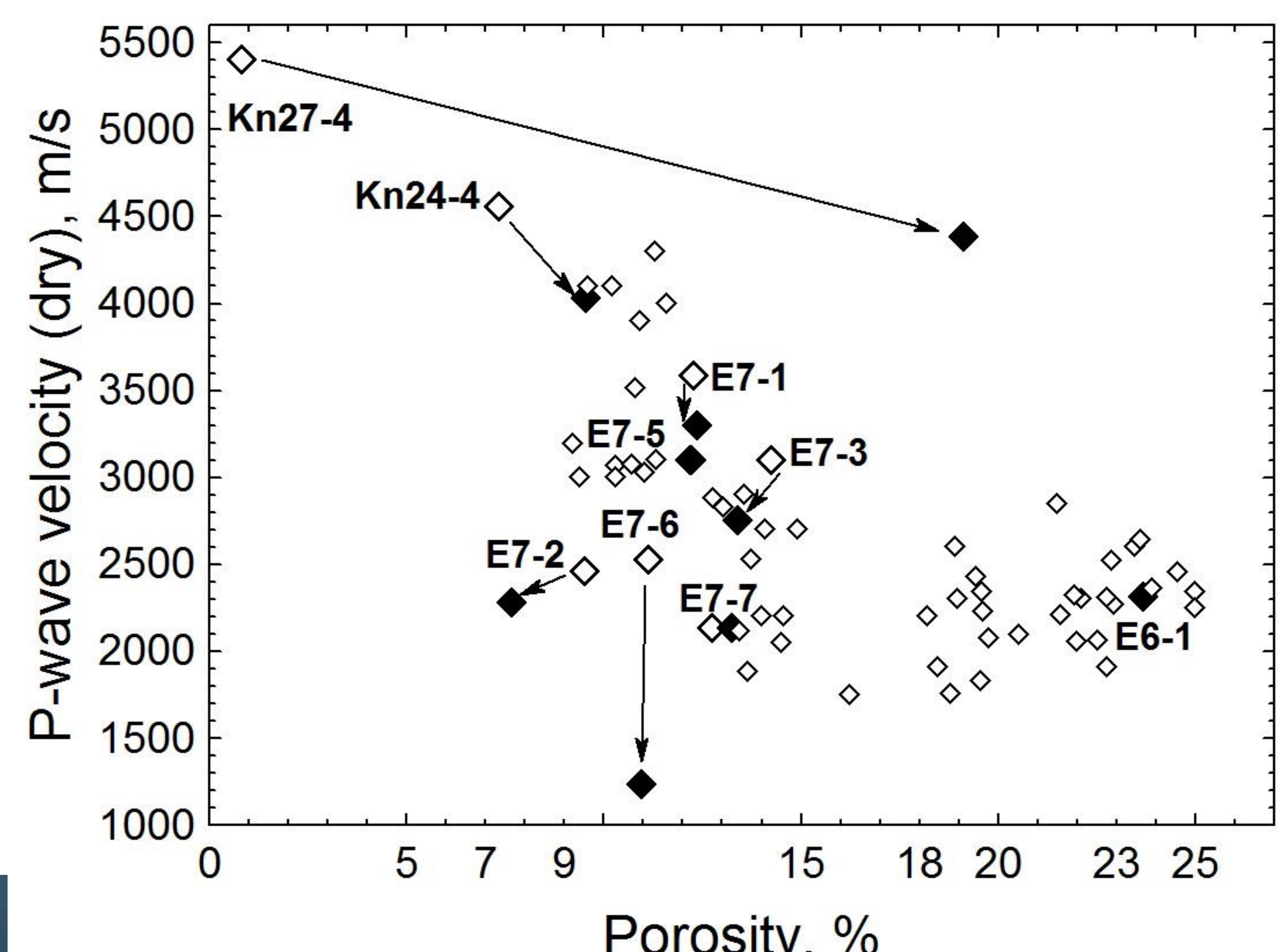

Fig. P-wave velocity versus porosity in dry sandstones reported (52 samples) and measured before (8 samples) and after the alteration experiment (9 samples)

Alteration experiment

THIN SECTION STUDY

Objectives

- **I** Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
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Scanning electron microscope - SEM

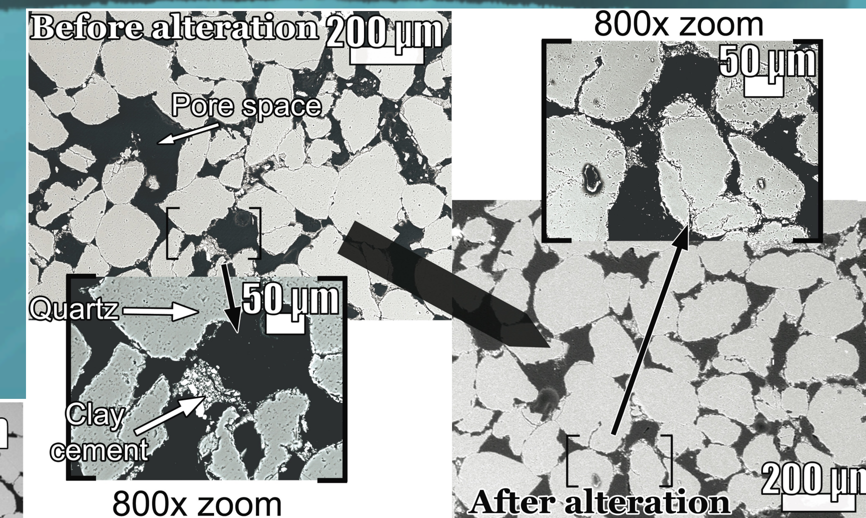


Fig. SEM microphotographs of thin sections of reservoir fine-grained poorly sorted Deimena Formation sandstone sample E6-3 before (left) and after (right) the alteration experiment. The sample is of 'high-1' (class I) reservoir quality sandstone, very appropriate for CGS with no changes in the reservoir quality after the experiment

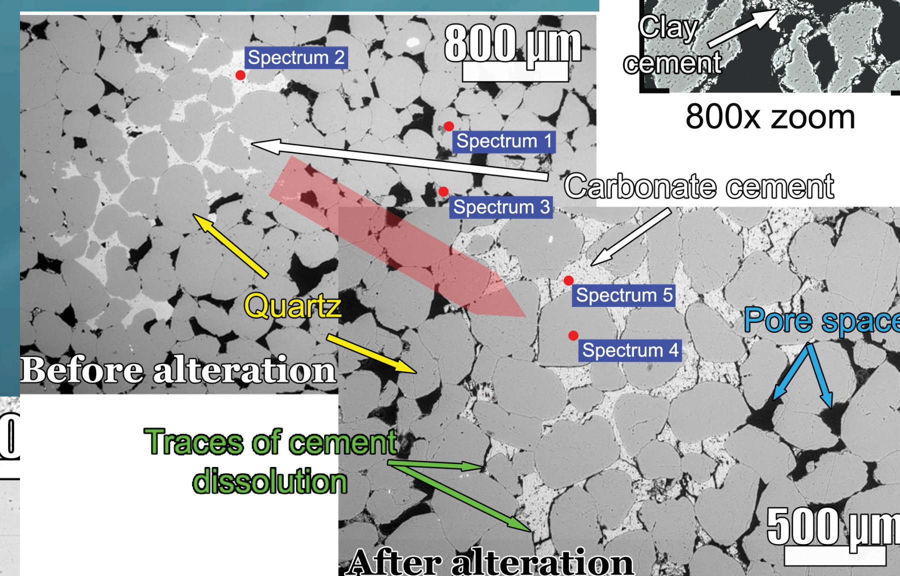
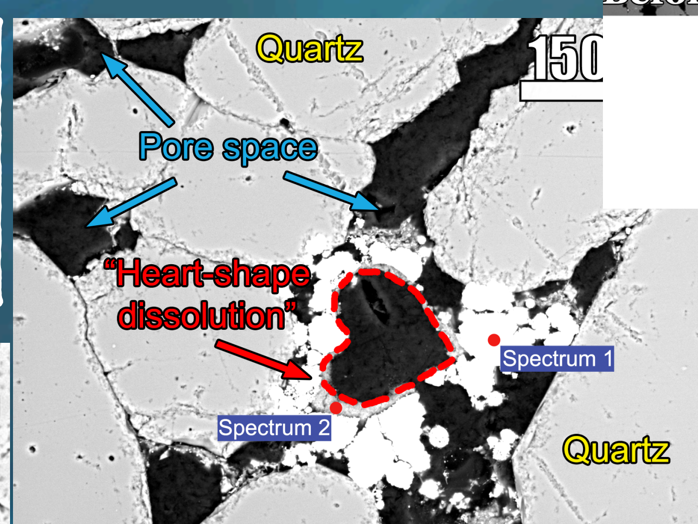


Fig. SEM microphotographs of thin sections of fine-grained Deimena reservoir sandstone sample E7-3 before (left) and after (right) the alteration experiment



Spectrum	C	Al	Si	S	Cl	Ca	Ti	Fe	Zr	O
Spectrum 1	6	-	3	20	-	-	-	16	1.1	54
Spectrum 2	20	0.1	3.2	0.9	0.1	0.1	9	1.4	-	65

Fig. SEM microphotograph of the thin section of reservoir sandstone sample E7-4 after the alteration experiment

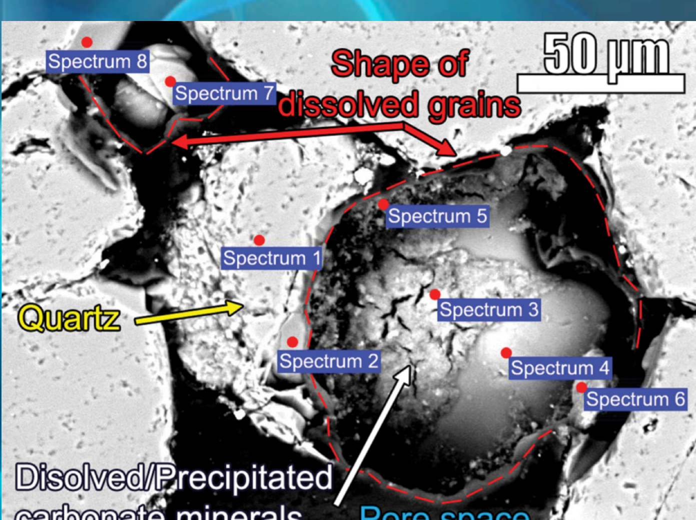


Fig. SEM microphotograph of the thin section of fine-grained Deimena reservoir sandstone sample E6-3 after alteration

Alteration experiment

THIN SECTION STUDY

Objectives

- I Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
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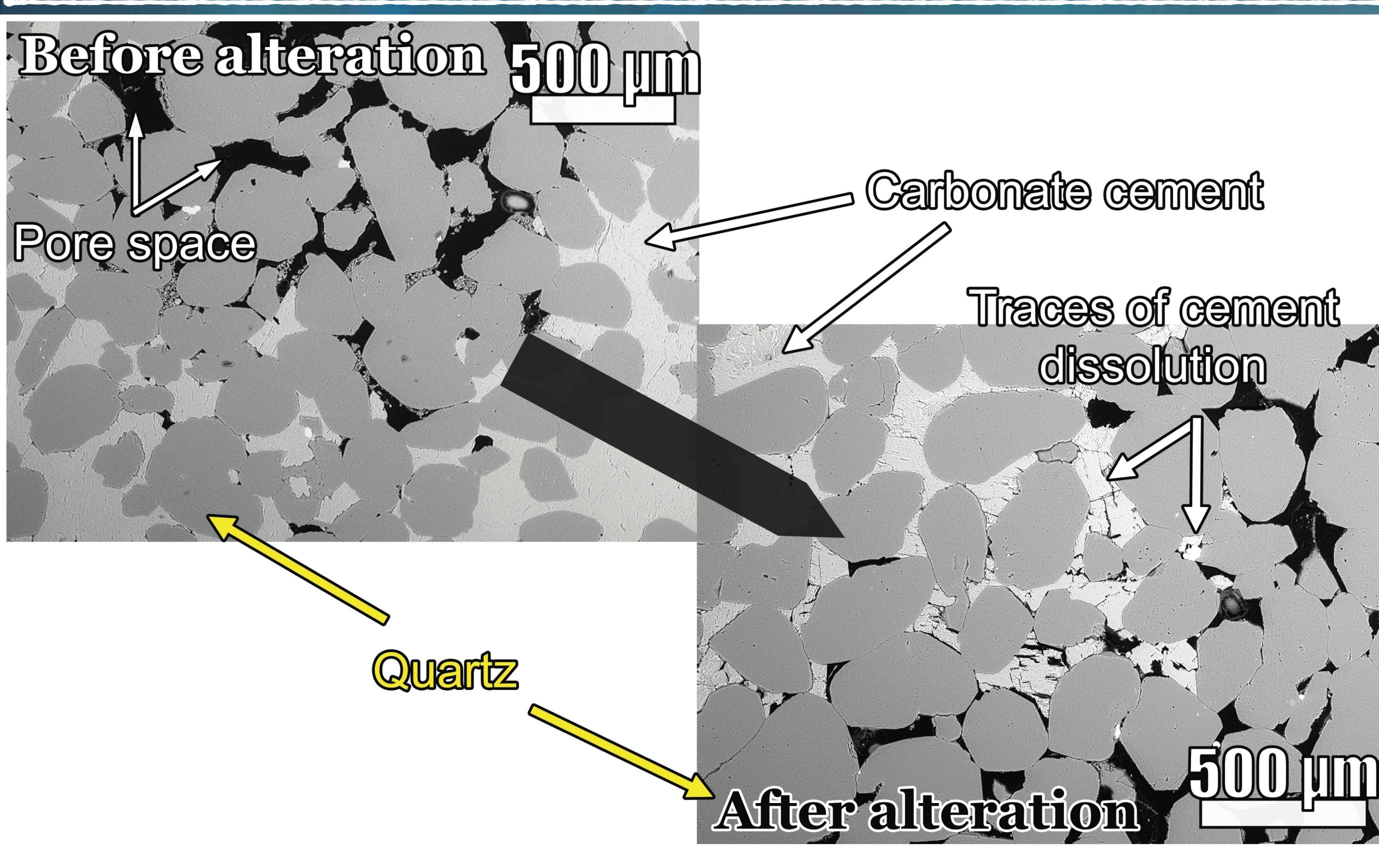
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - **Estimation of petrophysical alterations**
- IV Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration

Fig. SEM microphotographs of thin sections of trans-reservoir carbonate-cemented fine-grained Deimena sandstone sample Kn24-4 before (left) and after (right) the alteration experiment



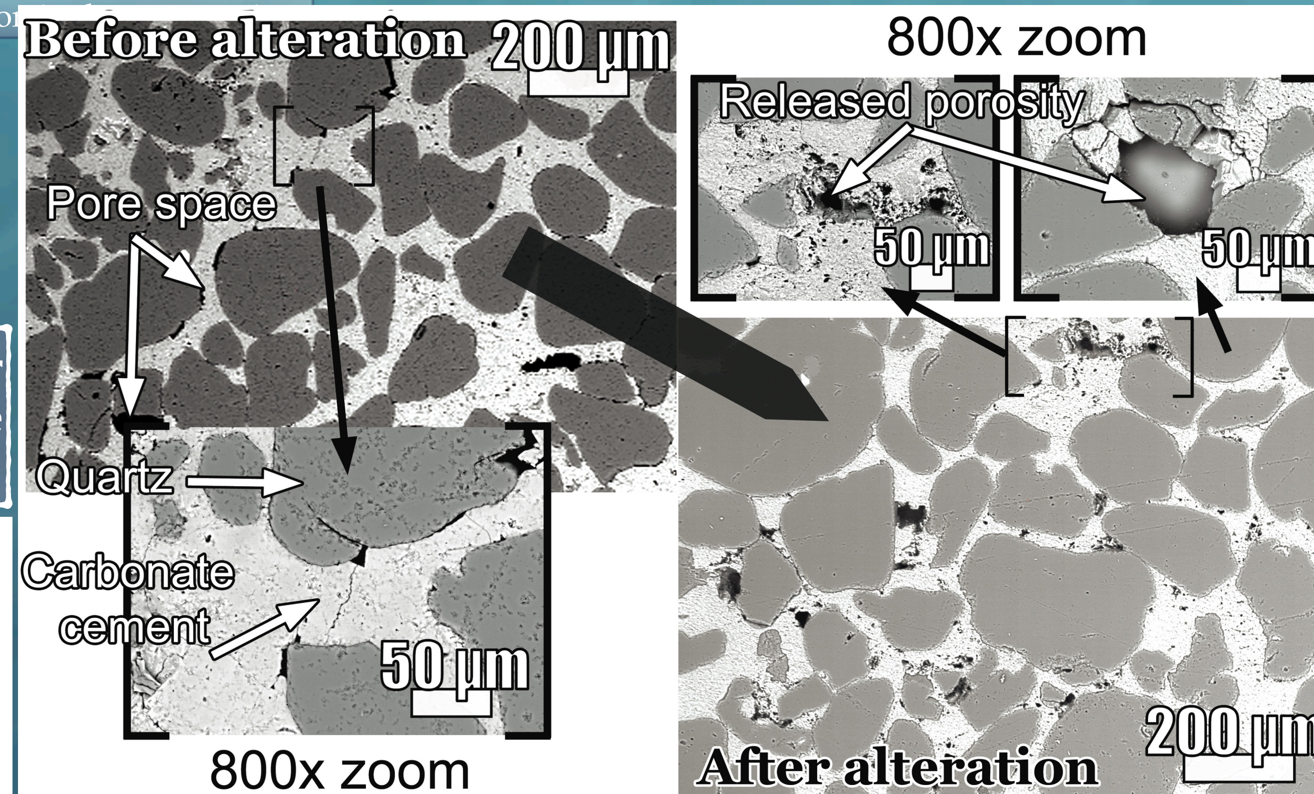


Fig. SEM microphotographs of thin sections of trans-reservoir carbonate-cemented sample Kn27-4 from medium- to very fine-grained (fine-grained in general) unsorted Deimena sandstone from the South Kandava structure before (left) and after (right) the alteration experiment

Alteration experiment

PETROPHYSICAL ALTERATIONS

Objectives

- **I** *Selection of storage sites and data collection*
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- **II** *Characterization of the selected structures*
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- **III** *Estimation of the influence of CGS on the properties of rocks*
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  - **Estimation of petrophysical alterations**
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  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

Table. Reservoir quality classes and petrophysical properties of sandstones of the Deimena Formation studied in the alteration experiment

Sample	Depth (m)	Reservoir quality class		Weight (kg*10⁻³)		Bulk density (kg/m³)		Grain density (kg/m³)		Porosity (%)		Permeability (mD)		V_P (m/s)		V_S (m/s)	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
E6-1	860.4	I	I	17.6	**17.5**	2123	**2011**	2705	**2635**	21.5	**23.7**	440	*380*	–	2310	–	–
E6-2	886.7	III	III	12.0	*6.4**	2031	**1863**	2725	**2661**	25.5	**30.0**	290	–	–	–	–	–
E6-3	886.7	I	I	10.2	**10.0**	–	**1999**	2718	**2633**	–	24.1	400	**490**	–	–	–	–
E7-1	1387.6	VI	VI	16.8	**16.7**	2354	**2310**	2683	**2636**	12.3	*12.4*	23	*26*	3583	*3300*	–	–
E7-2	1389.5	VI	VI	26.5	*26.5*	2412	*2439*	2666	**2641**	9.5	**7.7**	18	*16*	2457	*2280*	1725	–
E7-3	1390.5	VI	IV	24.8	**24.6**	2309	*2295*	2693	**2650**	14.3	**13.4**	66	**130**	3096	**2750**	2194	**1850**
E7-4	1390.5	VI	VI	15.6	**15.5**	2339	**2284**	2716	**2653**	13.9	*13.9*	46	**78**	–	–	–	–
E7-5	1393.2	VI	VI	24.9	*24.8*	2349	*2323*	2676	**2646**	12.2	*12.2*	16	*19*	3097	*3100*	2230	*2020*
E7-6*	1394.2	VIII	VIII	24.7	**24.3**	2403	*2367*	2704	**2659**	11.1	*11.0*	0.13	**0.18**	2524	**1230**	–	–
E7-7*	1394.2	VIII	VIII	24.8	*16.1**	2395	**2322**	2746	**2676**	12.8	**13.3**	0.23	*0.23*	2130	*2130*	–	–
Kn24-4**	1157.3	VIII	IV	35.3	**31.6**	2642	**2148**	2741	**2675**	7.3	**9.6**	0.28	**300**	4556	**4030**	3225	–
Kn27-4**	998.8	VIII	II	35.0	**27.1**	2539	**2419**	2664	*2658*	0.8	**19.1**	0.001	**550**	5400	**4380**	3600	**2540**

Before, samples measured before the alteration experiment; after, samples measured after the alteration experiment; V_P, P-wave velocity; V_S, S-wave velocity; * clay-cemented; ** carbonate-cemented sandstones from the South Kandava structure;
Bold and *italic* numbers in the table correspond, respectively to 'reliable' and 'not reliable' changes in petrophysical parameters after the alteration experiment according to measurement errors. 'Not reliable' values also correspond to the parameters not subjected to alteration.

Numerical seismic modelling

Objectives

- **I** – *Selection of storage sites and data collection*
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- **II** – *Characterization of the selected structures*
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- **III** – *Estimation of the influence of CGS on the properties of rocks*
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- **IV** – *Numerical seismic modelling to support the monitoring of CGS*
  - **4D time-lapse rock physics and numerical seismic modelling**
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

I - Homogeneous CO_2 reservoir saturation of the reservoir (uniform model)
II - CO_2 plume accumulation (plume model)

+

ALTERATION EFFECT

Scenarios:

(I) Uniform model without the alteration effect
(II) Uniform model with the alteration effect
(III) Plume model without the alteration effect
(IV) Plume model with the alteration effect

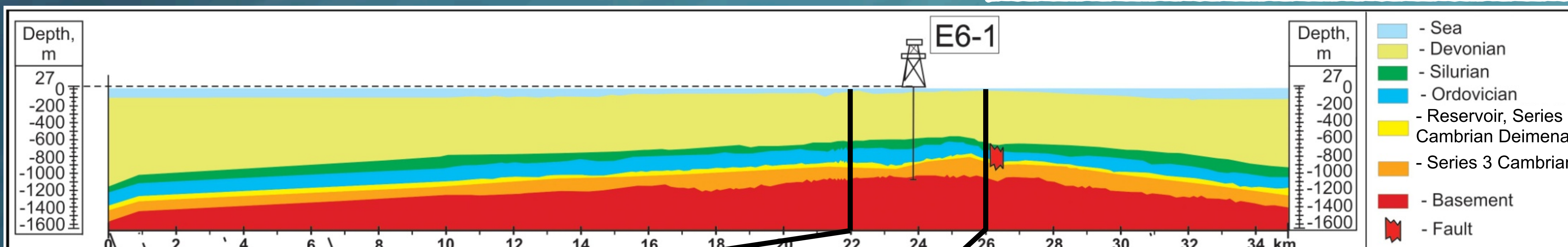
Numerical seismic modelling

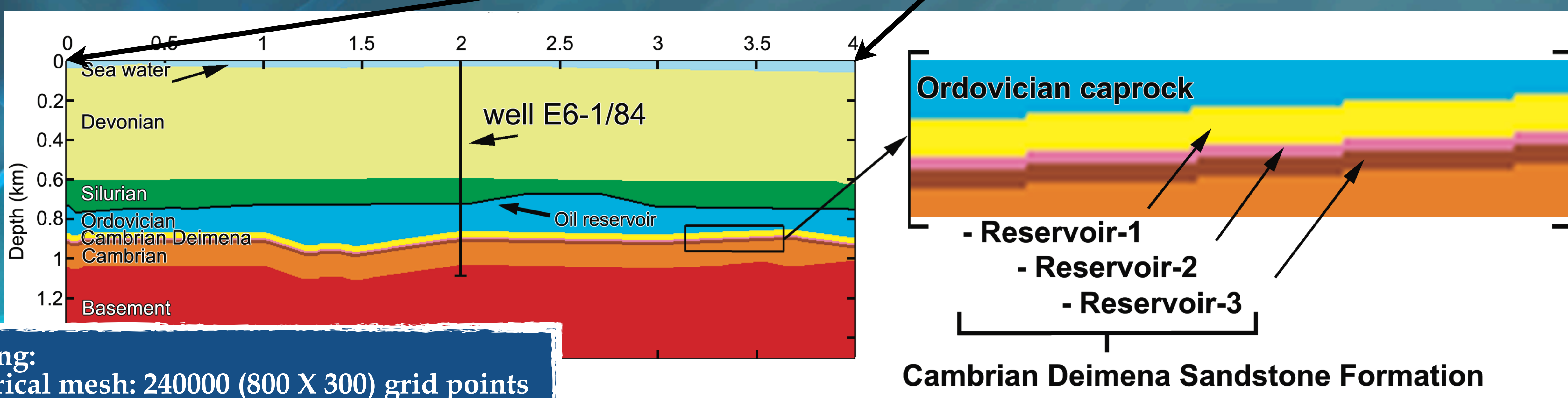
2D GEOLOGICAL MODEL

Objectives

- I. Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II. Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III. Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV. Numerical seismic modelling to support the monitoring of CGS
  - **4D time-lapse rock physics and numerical seismic modelling**
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

Fig. Geological cross section of the E6 structure (modified after Shogenov et. al, 2013)





Meshing:
Numerical mesh: 240000 (800 X 300) grid points
Layers: 10
Grid spacing: 5 m
Absorbing boundaries: 40 grid-point lengths (bottom, left and right sides)

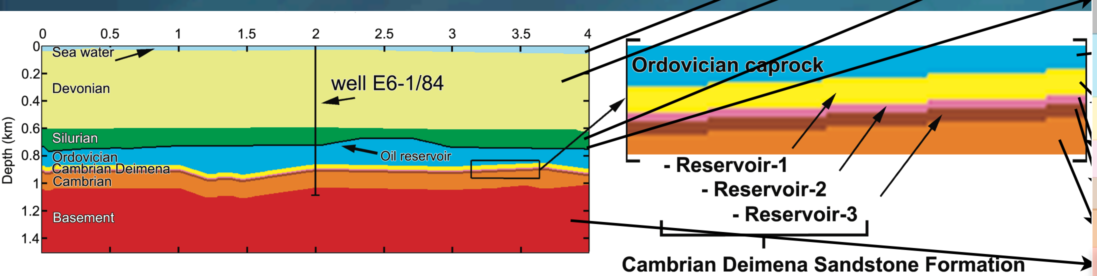
Fig. 2D geological model, applied in the seismic modelling. Extrapolated from the E6 seismic section with well E6-1/84 in the centre (Shogenov & Gei, 2013, Shogenov et. al, 2016)

Numerical seismic modelling

Objectives

- **I** Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- **II** Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- **III** Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- **IV** Numerical seismic modelling to support the monitoring of CGS
  - **4D time-lapse rock physics and numerical seismic modelling**
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

PHYSICAL PROPERTIES OF THE LAYERS



Formation	Lithology	Depth (m)	T (°C)	P (MPa)	ρ_{wet} (kg/m³)	φ_{ef} (%)	κ (mD)	V_P (m/s)	V_S (m/s)	Q_P	Q_S	μ (Gpa)	K_{dry} (Gpa)
Sea water	-	0	10	0.1	1030	-	-	1480	-	-	-	-	-
Devonian	Sandstone	36.5	7	0.8	2226	15	2	2474	1133	66	18	2.86	-
Silurian	Carbonate shales	580	31	6.3	2244	6-16	<0.1	2570	1043	71	16	2.44	-
Ordovician Saldus Fm. (Oil reservoir)	Limestone	702	35	8.4	2342	18	6	2970	1395	95	28	4.56	-
Ordovician (Cap rock)	Carbonate shales	712.5	35	8.6	2540	3	<0.01	2628	1093	74	17	3.04	-
Deimena (Reservoir-1)	Sandstone	848	37	9.3	2341	21	160	2836	1400	250	94	4.59	4.21
Deimena (Reservoir-2)	Sandstone	876	37	9.7	2400	17	60	2873	1349	761	255	4.37	4.00
Deimena (Reservoir-3)	Sandstone	885	37	9.8	2306	25	230	2872	1510	211	87	5.26	4.82
Cambrian	Siltstone	901	38	10	2324	3-18	0.2-23	2746	1675	81	40	6.52	-
Basement	Granite	1018	41	11.2	2675	-	-	5800	3454	362	171	31.9	-

* Depth of the top of the formation in well E6-1/84

All formations except for the Oil reservoir are saturated with brine. Temperature (T) and pressure (P) of the formations top; ρ_{wet} – the bulk density of brine-saturated rock samples; φ_{ef} – effective porosity; κ – permeability; V_P and V_S – compressional (P) and shear (S) waves velocities, respectively; Q_P and Q_S – quality factors of P- and S-waves, respectively; μ and K_{dry} – shear and bulk modules of dry rocks, respectively (K_{dry} estimated only for reservoir formations).

Table. Characteristics and physical properties of the main rock formations shown in the seismic model

After alteration

Formation	Lithology	ρ_{wet} (kg/m³)	φ_{ef} (%)	κ (mD)	V_P (m/s)	V_S (m/s)	Q_P	Q_S	μ (Gpa)	K_{dry} (Gpa)
Reservoir-1	Sandstone	2270	23	140	2743	1319	189	68	3.95	3.62
Reservoir-2	Sandstone	2388	16	90	2856	1283	1163	360	3.93	3.61
Reservoir-3	Sandstone	2188	30	280	2735	1415	202	81	4.38	4.01

All reservoir formations are saturated with brine

Table. Estimated seismic (poro-viscoelastic) properties of the reservoir rock formations after the alteration experiment shown in the seismic model

Numerical seismic modelling

PETROPHYSICAL MODELLING

Objectives

- I — Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II — Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III — Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV — Numerical seismic modelling to support the monitoring of CGS
  - **4D time-lapse rock physics and numerical seismic modelling**
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - Modelling of the possible shape of CO_2 plume migration in the storage site

RESERVOIR

a

Reservoir properties estimation

Dry P-wave velocities (V_{Pdry}), dry bulk density (ρ_{dry}), density of rock solid part (ρ_s) and porosity (ϕ) were estimated using measured properties at IFPEN petrophysical laboratory (**Shogenov et al., 2013a**) and reported data. Dry S-wave velocities (V_{Sdry}) and in situ rock physical parameters of CO_2 storage reservoir rocks, as wet P- and S-wave velocities (V_{Pwet} and V_{Swet}, respectively), wet bulk density (ρ_{wet}), wet bulk modulus (K_{wet}) and shear modulus (μ) were estimated by rock physics theories:

$$K_{dry} = V_{P\,dry}^2 \times \rho_{dry} - \frac{4}{3}\mu_{dry} \quad , \textbf{III}$$

$$K_{wet} = K_{dry} + \frac{\left(1-\frac{K_{dry}}{K_0}\right)^2}{\frac{\phi}{K_{fl}} + \frac{1-\phi}{K_0} - \frac{K_{dry}}{K_0^2}} \quad , \textbf{II}$$

$$\rho_{dry} = m/V_{total} \quad , \textbf{IV}$$

$$K_{fl} = c^2 \times \rho_{fl} \quad , \textbf{V}$$

$$V_{P(wet/dry)} = \sqrt{\frac{K_{(wet/dry)} + \frac{4}{3}\mu_{(wet=dry)}}{\rho_{(wet/dry)}}} \quad , \textbf{I}$$

$$\mu_{dry} = V_{Sdry}^2 \times \rho_{dry} \quad , \textbf{VI}$$

$$V_{Sdry} = \frac{V_{Pdry}}{1.73} \quad , \textbf{VII}$$

$$\rho_{wet} = \rho_s \times (1-\phi) + \rho_{fl} \times \phi \quad , \textbf{VIII}$$

$$\rho_{fl} = \rho_w + S(0.668+0.44S+10^{-6}(300P-2400PS+T(80+3T-3300S-13P+47PS))) \quad , \textbf{X}$$

$$\rho_s = m/(V_{total} - V_{pores}) \quad , \textbf{IX}$$

$$\rho_w = 1+10^{-6}(-80T-3.3T^2+0.00175T^3+489P-2TP+0.016T^2P-1.3\cdot 10^{-5}T^3P-0.333P^2-0.002TP^2) \quad , \textbf{XI}$$

$$V_{Swet} = \sqrt{\frac{\mu_{dry}}{\rho_{wet}}} \quad , \textbf{XII}$$

K_{fl}-bulk modulus of brine at in situ conditions, c -speed of sound in the fluid at in situ conditions within the E6 reservoir (1633 m/s), K_0-bulk modulus of rock sample grains. Average K_0 of quartz = 37 GPa, **m**-sample weight (g), V_{total}-sample total volume (cm³), V_{pores}-sample pore volume (cm³), ρ_{fl}-density of brine at in situ conditions (within the reservoir layers 1066.7 kg/m³), **S**-weight fraction (ppm/1000000) of sodium chloride(99000 ppm)

OTHER FORMATIONS

b

Non-reservoir properties estimation

To evaluate specific properties of non-reservoir layers we have used reported active seismic data (V_{Pwet}) and reported laboratory measurements of dry and wet samples (Oil reservoir), obtained from the well E6-1/84, and reported measurements of more than 2000 samples of Baltic Basin (**Shogenova et al., 2001**).

Devonian sandstones

$$V_{Swet} = 0.804 \times V_P - 0.856 \ \text{(km/s)} \quad , \textbf{XIII}$$

Silurian shales

$$\rho_{wet(shales)} = -0.0261 \times V_{Pwet}^2 + 0.373 \times V_{Pwet} + 1.458 \quad , \textbf{XIV}$$

$$V_{Swet} = 0.862 \times V_P - 1.172 \ \text{(km/s)} \quad , \textbf{XV}$$

Ordovician oil limestones

$$V_{Swet} = -0.055 \times V_{Pwet}^2 + 1.017 \times V_{Pwet} - 1.031 \ \text{(km/s)} \quad , \textbf{XVI}$$

Ordovician claystones, marlstones and limestones , **VIII, XV**

Cambrian siltstones , **VIII, XII**

Basement

$$\rho_{wet} = 1.6612 \times V_{Pwet} - 0.4721 \times V_{Pwet}^2 + 0.0671 \times V_{Pwet}^3 - 0.0043 \times V_{Pwet}^4 + 0.000106 \times V_{Pwet}^5 \quad , \textbf{XVII} \ \text{(kg/m}^3)$$

$$V_{Swet} = 0.7858 - 1.2344 \times V_{Pwet} + 0.7949 \times V_{Pwet}^2 - 0.1238 \times V_{Pwet}^3 + 0.0064 \times V_{Pwet}^4 \quad , \textbf{XVIII} \ \text{(km/s)}$$

Fig. Example of (a) reservoir and (b) non-reservoir petrophysical, petro-acoustical and seismic properties estimation (Shogenov & Gei, 2013) a

Reservoir properties estimation

Dry P-wave velocities (V_{Pdry}), dry bulk density (ρ_{dry}), density of rock solid part (ρ_s) and porosity (ϕ) were estimated using measured properties at IFPEN petrophysical laboratory (**Shogenov et al., 2013a**) and reported data. Dry S-wave velocities (V_{Sdry}) and in situ rock physical parameters of CO_2 storage reservoir rocks, as wet P- and S-wave velocities (V_{Pwet} and V_{Swet}, respectively), wet bulk density (ρ_{wet}), wet bulk modulus (K_{wet}) and shear modulus (μ) were estimated by rock physics theories:

$$K_{dry} = V_{Pdry}^2 \times \rho_{dry} - \frac{4}{3}\mu_{dry} \quad \text{, III}$$

$$K_{wet} = K_{dry} + \frac{\left(1-\frac{K_{dry}}{K_0}\right)^2}{\frac{\phi}{K_{fl}} + \frac{1-\phi}{K_0} - \frac{K_{dry}}{K_0^2}} \quad \text{, II}$$

$$\rho_{dry} = m/V_{total} \quad \text{, IV}$$

$$K_{fl} = c^2 \times \rho_{fl} \quad \text{, V}$$

$$V_{P(wet/dry)} = \sqrt{\frac{K_{(wet/dry)} + \frac{4}{3}\mu_{(wet=dry)}}{\rho_{(wet/dry)}}} \quad \text{, I}$$

$$\mu_{dry} = V_{Sdry}^2 \times \rho_{dry} \quad \text{, VI}$$

$$V_{Sdry} = \frac{V_{Pdry}}{1.73} \quad \text{, VII}$$

$$\rho_{wet} = \rho_s \times (1-\phi) + \rho_{fl} \times \phi \quad \text{, VIII}$$

ρ_{fl} = ρ_w+S(0.668+0.44S+10-6(300P-2400PS+T(80+3T-3300S-13P+47PS))) , **X**

$\rho_s = m/(V_{total} - V_{pores})$, **IX**

ρ_w=1+10-6(-80T-3.3T2+0.00175T3+489P-2TP+0.016T2P-1.3 • 10-5T3P-0.333P2-0.002TP2) , **XI**

$$V_{Swet} = \sqrt{\frac{\mu_{dry}}{\rho_{wet}}} \quad \text{, XII}$$

K_{fl}-bulk modulus of brine at in situ conditions, **c** -speed of sound in the fluid at in situ conditions within the E6 reservoir (1633 m/s), K_0-bulk modulus of rock sample grains. Average K_0 of quartz = 37 GPa, **m**-sample weight (g), V_{total}-sample total volume (cm[3]), V_{pores}-sample pore volume (cm[3]), ρ_{fl}-density of brine at in situ conditions (within the reservoir layers 1066.7 kg/m[3]), **S**-weight fraction (ppm/1000000) of sodium chloride(99000 ppm)

Numerical seismic modelling

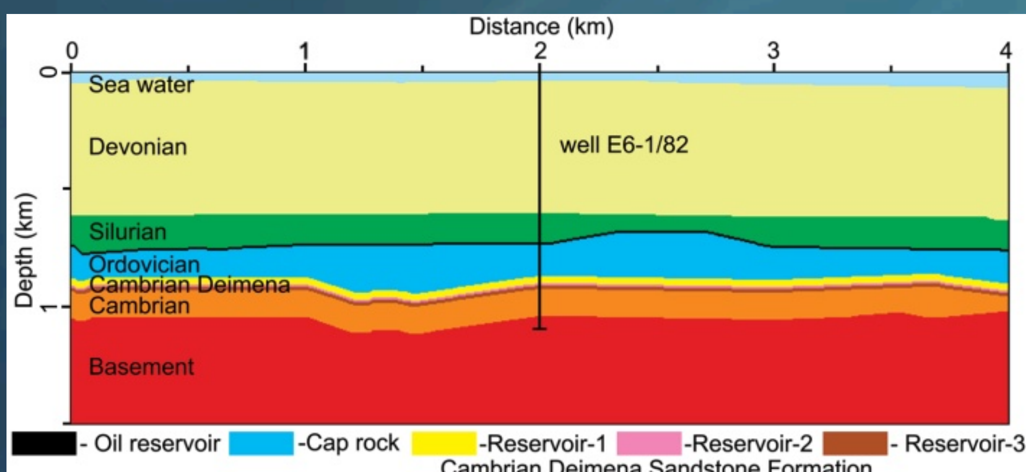
PETROPHYSICAL MODELLING

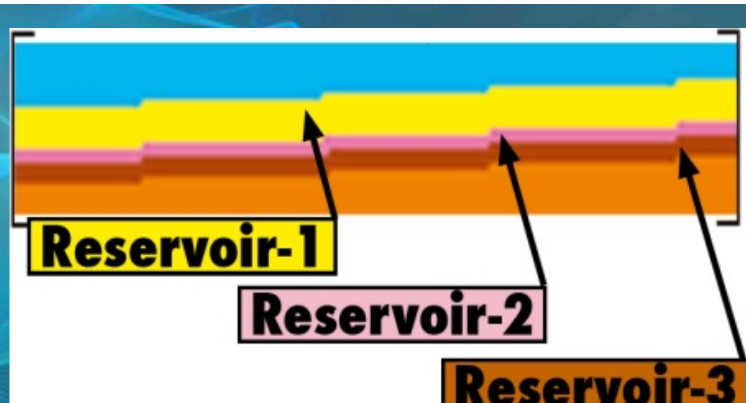
Objectives

- I — *Selection of storage sites and data collection*
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II — *Characterization of the selected structures*
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III — *Estimation of the influence of CGS on the properties of rocks*
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV — *Numerical seismic modelling to support the monitoring of CGS*

4D time-lapse rock physics and numerical seismic modelling

- Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- Modelling of the possible shape





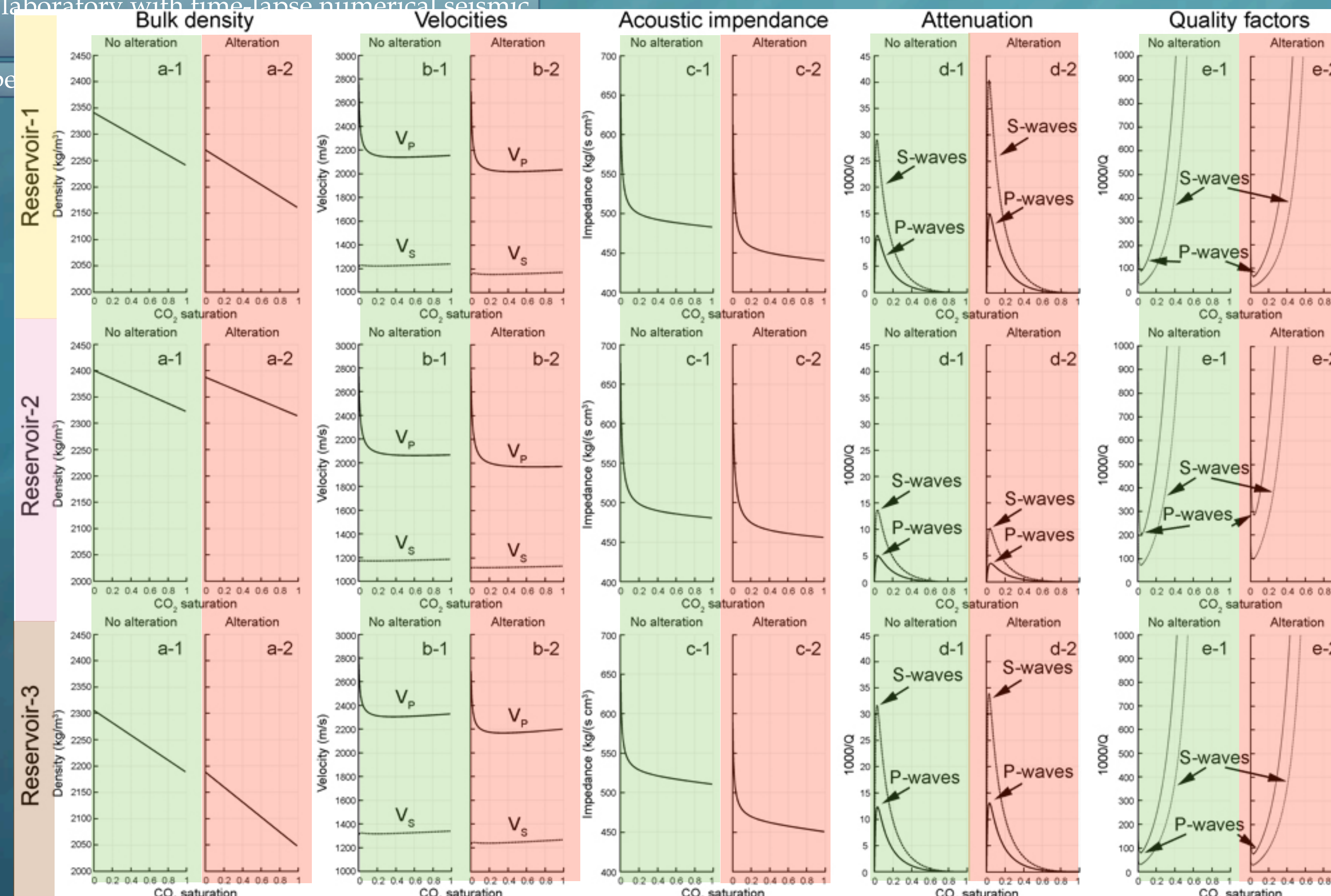
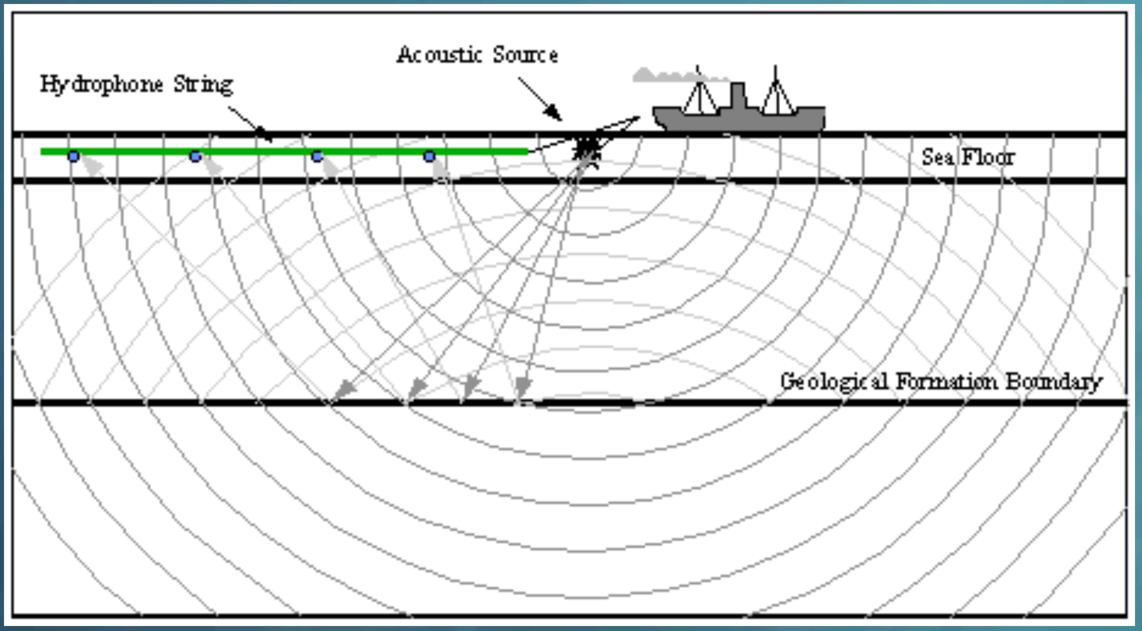


Fig. Estimated petrophysical and seismic properties of the Deimena sandstones versus CO_2 saturation for different reservoir sub-layers (Reservoir-1, -2 and -3) without (a-1, b-1, c-1, d-1 and e-1, respectively) and with petrophysical alteration effect (a-2, b-2, c-2, d-2 and e-2, respectively). Brine and CO_2 are the saturating fluids (NOT PUBLISHED DATA)

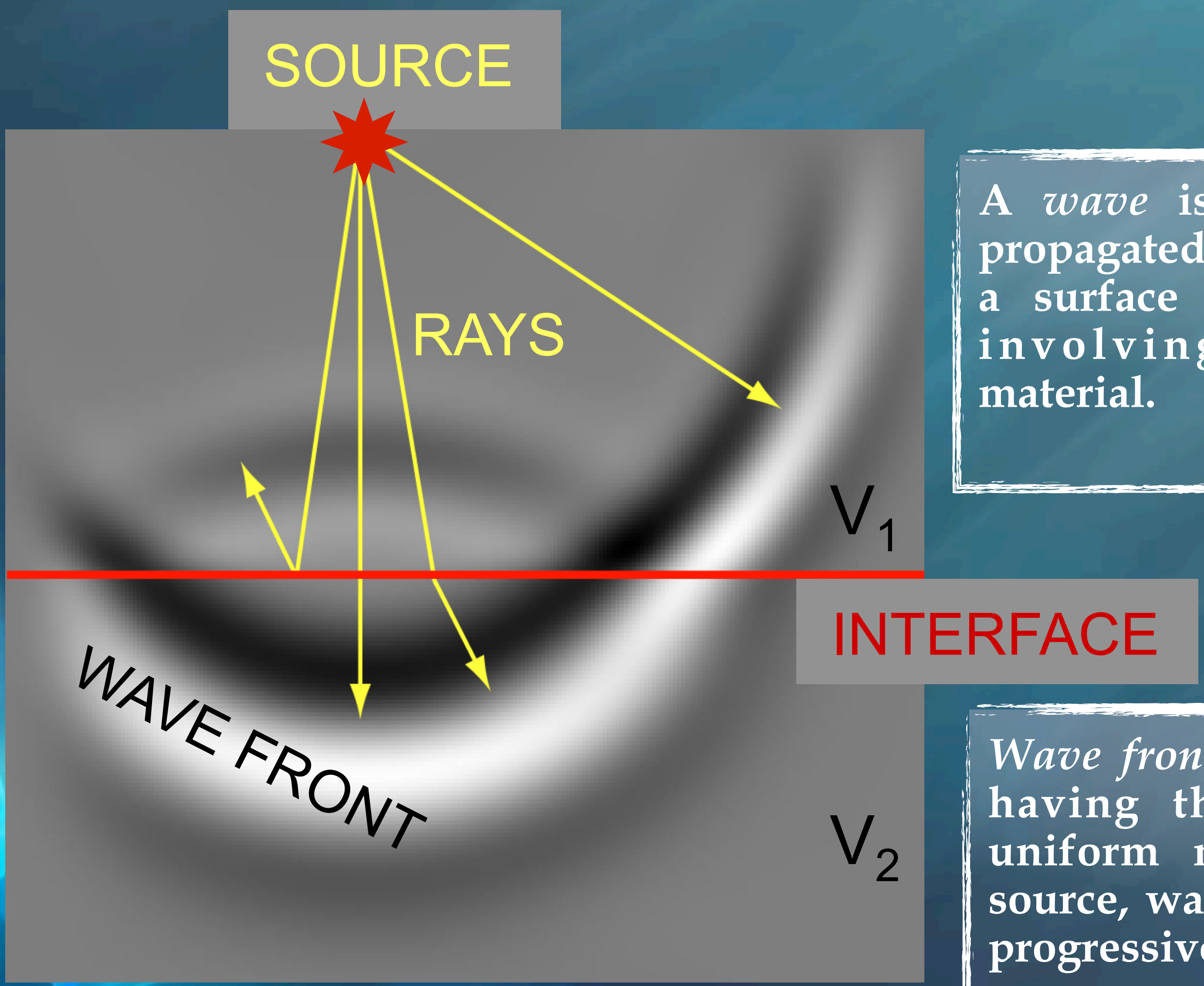
Numerical seismic modelling

PLANE-WAVE SIMULATION

PRINCIPLES



Seismic data acquisition



$V_2 > V_1$

A *wave* is a disturbance that is propagated through the body or on a surface of a medium without involving net movement of material.

Sheriff, 1984

Wave front is a surface of points having the same phase. In a uniform medium with a point source, wave fronts are spheres of progressively increasing radii.

0.1 sec

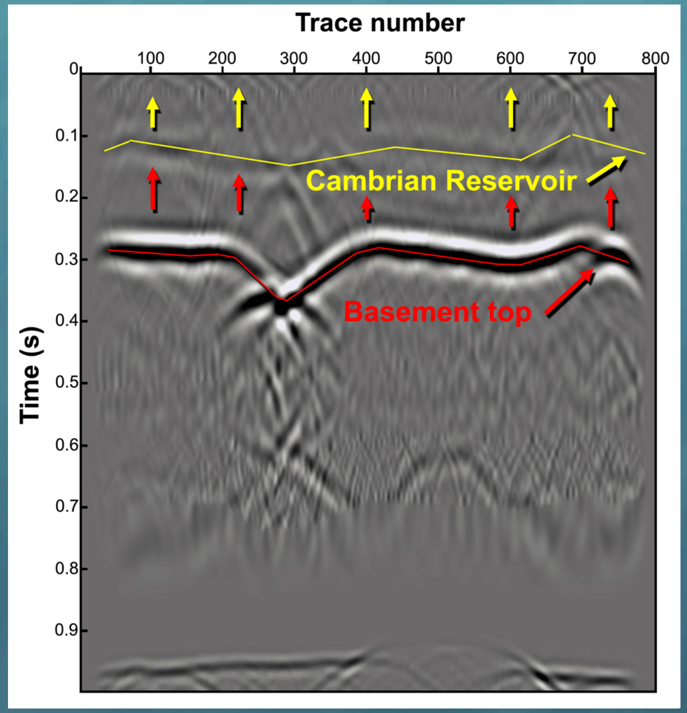


Fig.42. Example of snapshots at 0.1, 0.2, 0.3, 0.4, 0.5 and 0.7 seconds of the plane-wave simulation of the 1st scenario (Uniform model without the alteration effect) before CO_2 injection. Seismic reflections of geological layers are shown

Numerical seismic modelling

Objectives

I. Selection of storage sites and data collection
- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties

II. Characterization of the selected structures
- Reservoir characterization and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity

III. Estimation of the influence of CGS on the properties of rocks
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations

IV. Numerical seismic modelling to support the monitoring of CGS

4D time-lapse rock physics and numerical seismic modelling

- Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
- Modelling of the possible shape of CO_2 plume migration in the storage site

SCENARIO-1

PLANE-WAVE SIMULATION

Scenarios:

(1)Uniform model without alteration effect

(2)Uniform model with alteration effect

(3)Plume model without alteration effect

(4)Plume model with alteration effect

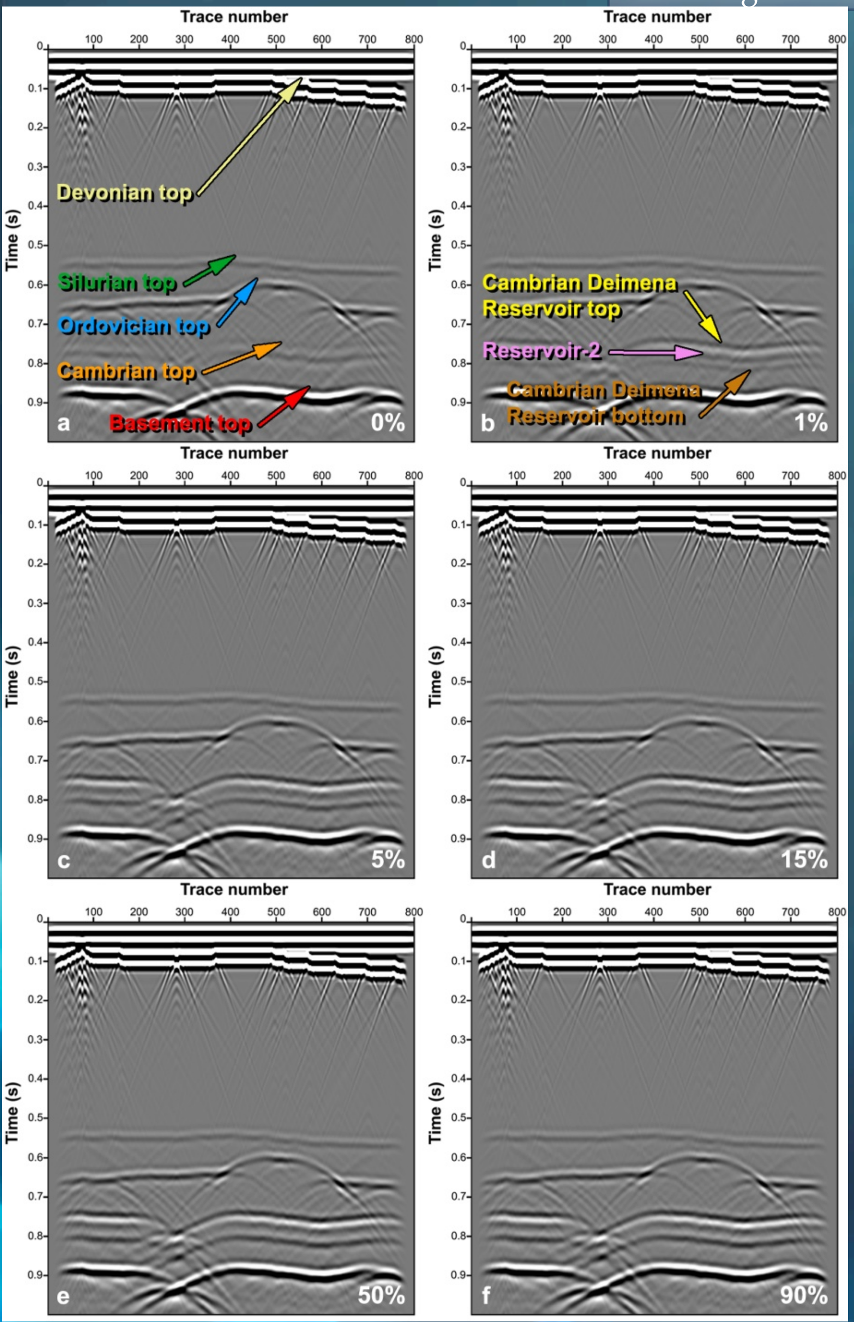


Fig. (a ,b, c, d, e, f). Synthetic plane-wave sections of Scenario-1 (Uniform model without the alteration effect) with 0% (a), 1% (b), 5% (c), 15% (d), 50% (e), 90% (f) of CO_2 saturation

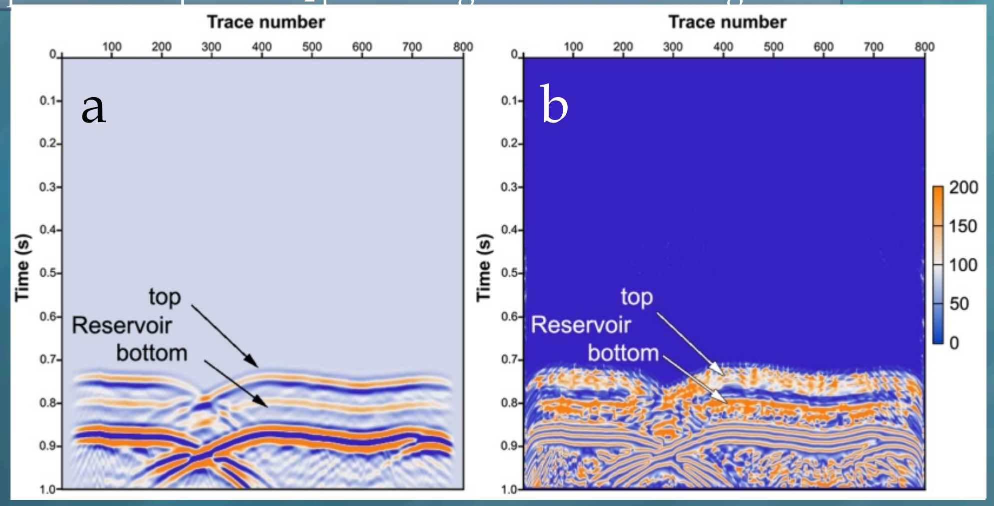


Fig.(a, b). Difference between the synthetic baseline (0% of CO_2) and the synthetic seismic line of Scenario-1 with 1% of CO_2 in the saturating fluid (a) and corresponding NRMS section (b)

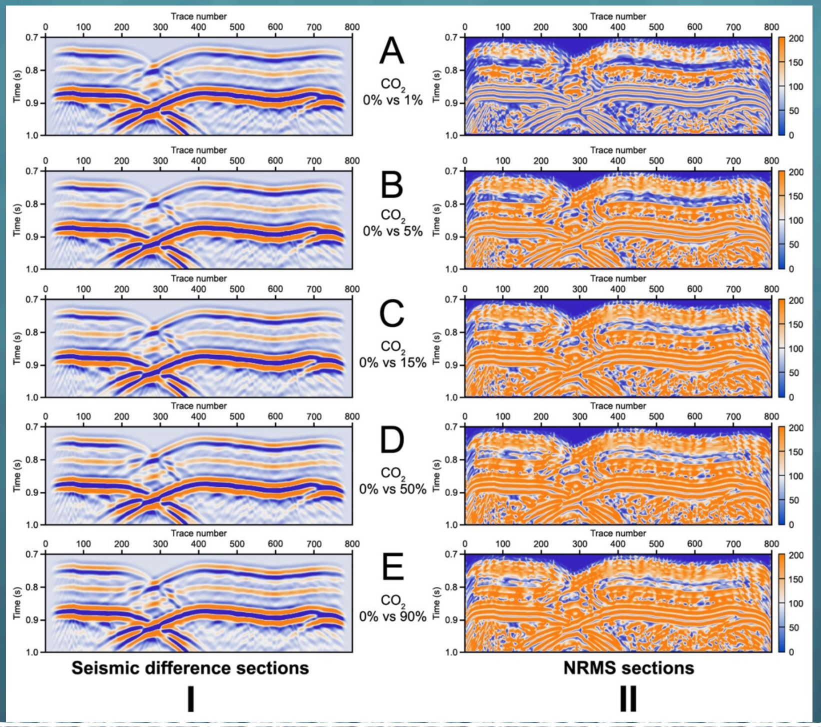


Fig. Difference between the synthetic baseline and the synthetic seismic lines of Scenario-1 with 1% (I-A), 5% (I-B), 15% (I-C), 50% (I-D) and 90% (I-E) of CO_2 in the porous space presented on the left part of the figure (I). The corresponding NRMS sections are shown on the right part in panels (II-A), (II-B), (II-C), (II-D) and (II-E), respectively. Panels are focusing on reservoir level of the section

Numerical seismic modelling

Objectives

I. *Selection of storage sites and data collection*
- Selection of CO_2 geological storage sites
- Rock sampling
- Measurement of geochemical and petrophysical properties

II. *Characterization of the selected structures*
- Reservoir characterization and risk assessment
- 3D geological static modelling
- Estimation of CO_2 storage capacity

III. *Estimation of the influence of CGS on the properties of rocks*
- Laboratory CO_2 injection-like alteration experiment
- Estimation of petrophysical alterations

IV. *Numerical seismic modelling to support the monitoring of CGS*
- 4D time-lapse rock physics and numerical seismic modelling
- **Coupling of the chemically induced petrophysical alteration effect of CO_2– hosting rocks measured in the laboratory with time-lapse numerical seismic modelling**
- Modelling of the possible shape of CO_2 plume migration in the storage site

SCENARIO-2

PLANE-WAVE SIMULATION

Scenarios:

(1) Uniform model without alteration effect

(2) Uniform model with alteration effect

(3) Plume model without alteration effect

(4) Plume model with alteration effect

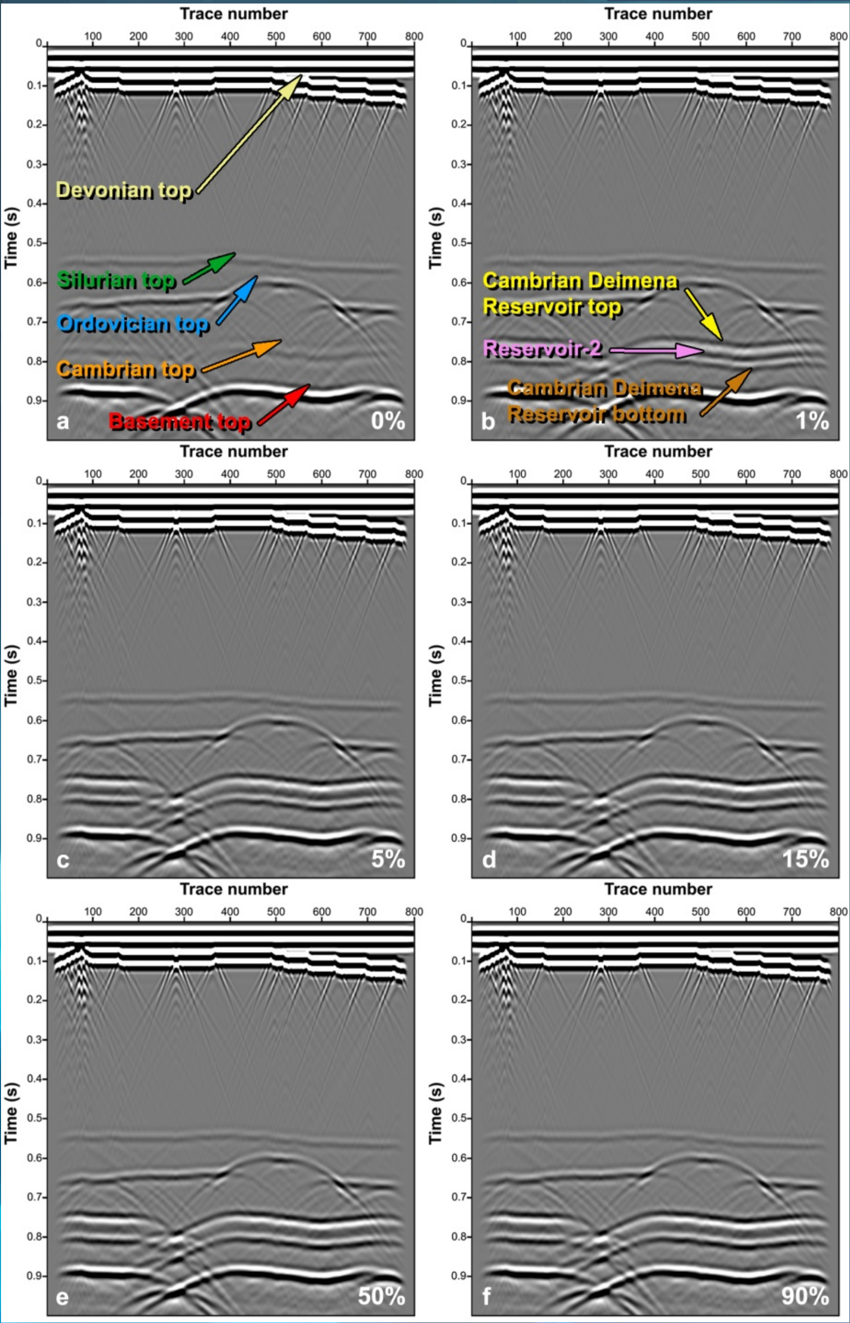


Fig. (a, b, c, d, e, f). Synthetic plane-wave sections of Scenario 2 (Uniform model with the alteration effect) with 0% (a), 1% (b), 5% (c), 15% (d), 50% (e), 90% (f) of CO_2 saturation

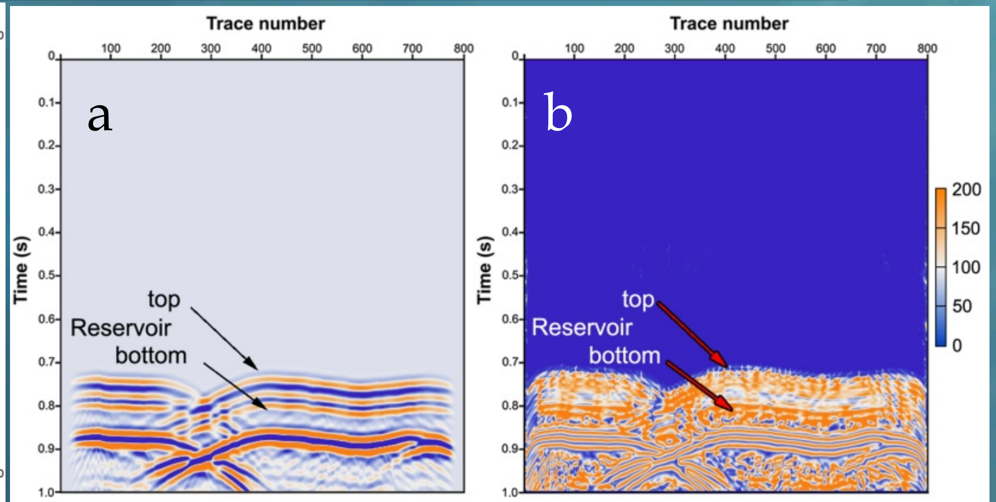


Fig. (a, b). Difference between the synthetic baseline (0% of CO_2) and the synthetic seismic line of Scenario-2 (Uniform model with the alteration effect) with 1% of CO_2 in the saturating fluid (a) and corresponding NRMS section (b)

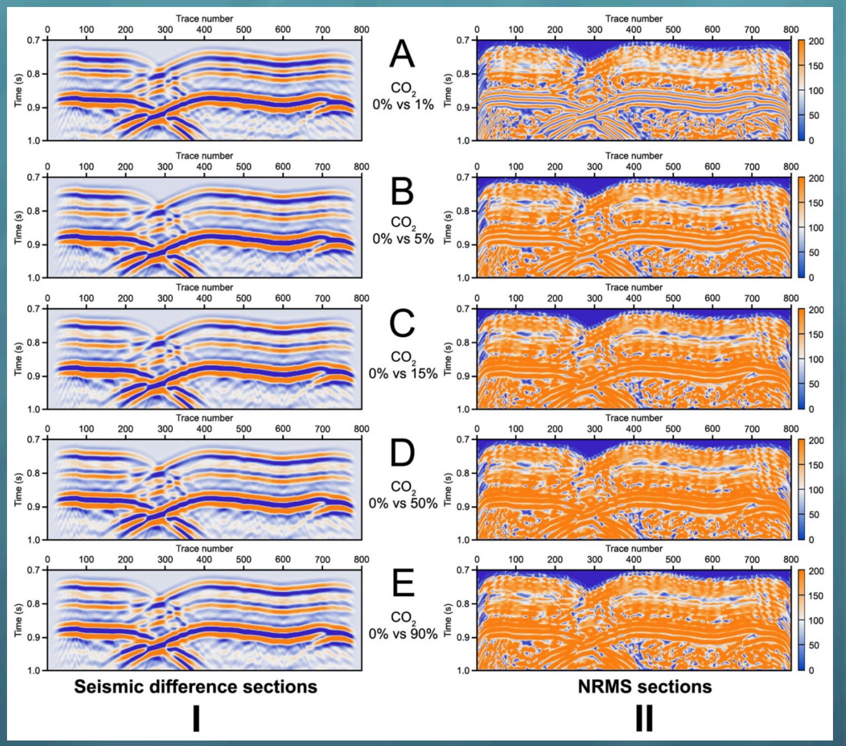


Fig. Difference between the synthetic baseline and the synthetic seismic lines of Scenario-2 with 1% (I-A), 5% (I-B), 15% (I-C), 50% (I-D) and 90% (I-E) of CO_2 in the porous space presented on the left part of the figure (I). The corresponding NRMS sections are shown on the right part in panels (II-A), (II-B), (II-C), (II-D) and (II-E), respectively. Panels are focusing on reservoir level of the section

Numerical seismic modelling

Objectives

- **I** Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- **II** Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- **III** Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- **IV** Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - **Coupling of the chemically induced petrophysical alteration effect of CO_2– hosting rocks measured in the laboratory with time-lapse numerical seismic modelling**
  - Modelling of the possible shape of CO_2 plume migration in the storage site

SCENARIO-1 VS SCENARIO-2

PLANE-WAVE SIMULATION

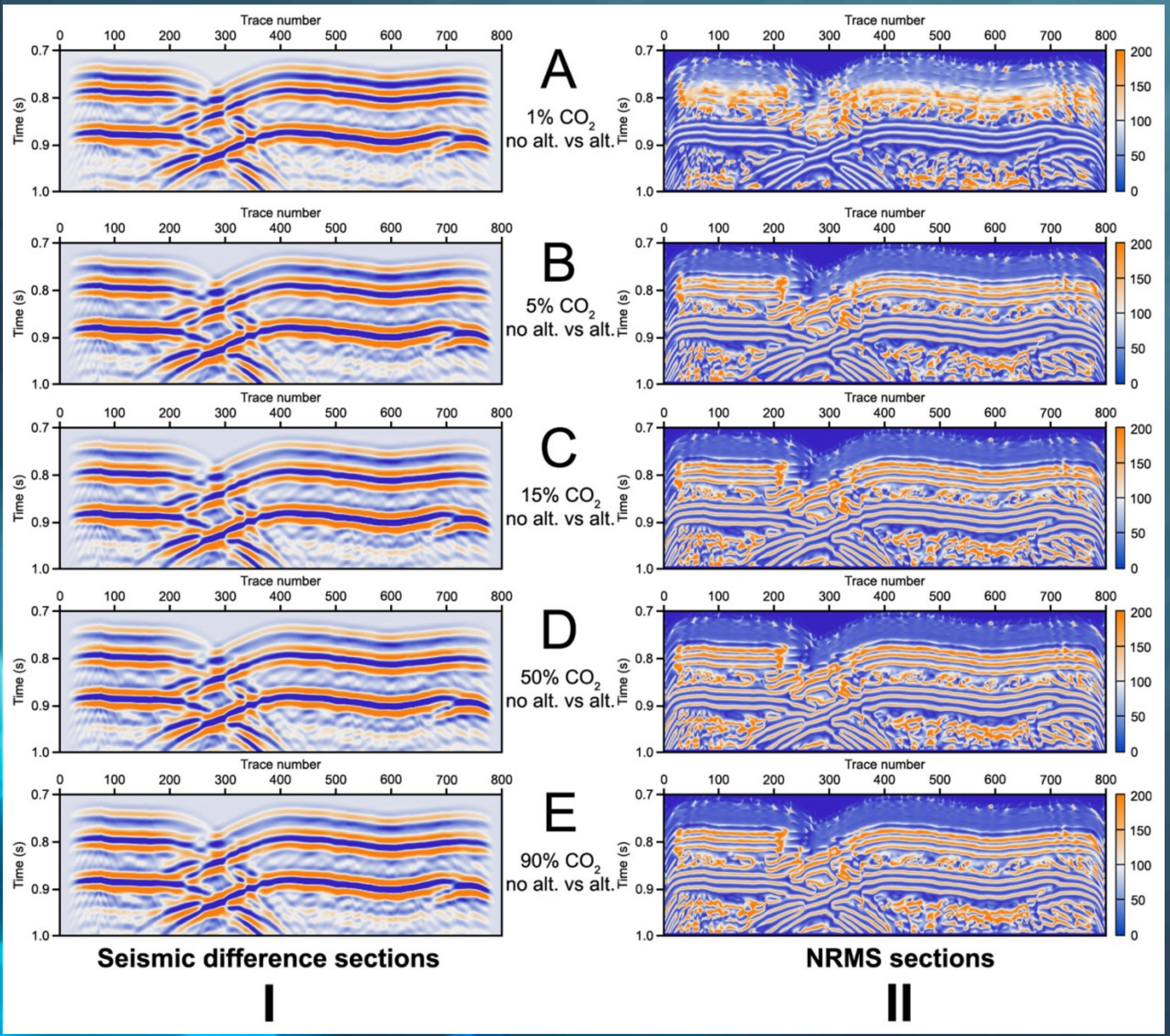
Scenarios:

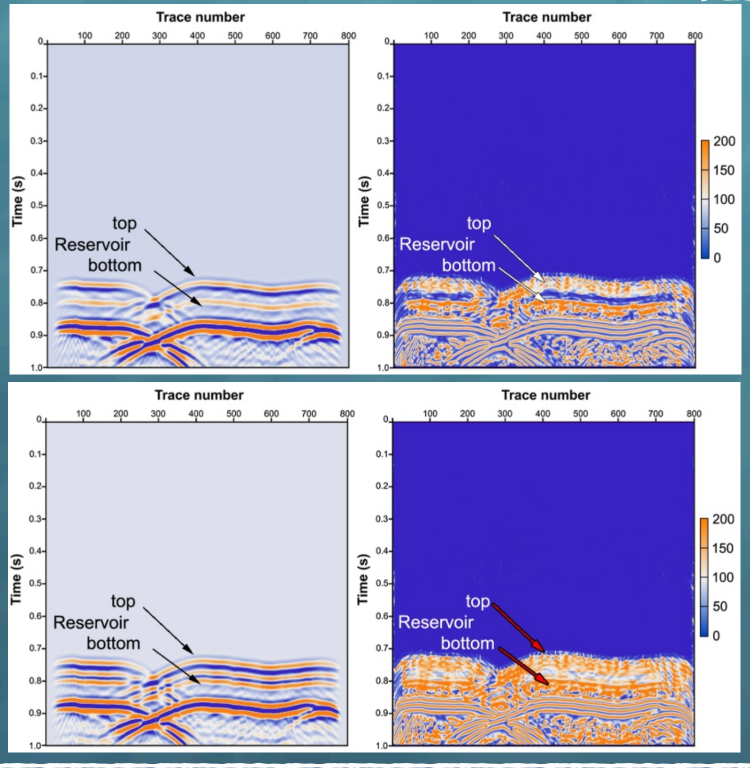
(1) Uniform model without alteration effect

(2) Uniform model with alteration effect

(3) Plume model without alteration effect

(4) Plume model with alteration effect





SCENARIO-1

0% and 1% of CO_2 saturation

SCENARIO-2

Fig. (I-A, I-B, I-C, I-D, I-E, II-A, II-B, II-C, II-D, II-E). Difference between the synthetic seismic lines of Scenario-1 and Scenario-2 with 1% (I-A), 5% (I-B), 15% (I-C), 50% (I-D) and 90% (I-E) of CO_2 in the porous space presented on the left part of the figure (I). The corresponding NRMS sections are shown on the right part of the figure (II) in panels (II-A), (II-B), (II-C), (II-D) and (II-E), respectively. Panels are focusing on reservoir level of the section

Numerical seismic modelling

Objectives

- I — *Selection of storage sites and data collection*
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II — *Characterization of the selected structures*
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III — *Estimation of the influence of CGS on the properties of rocks*
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV — *Numerical seismic modelling to support the monitoring of CGS*
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - **Modelling of the possible shape of CO_2 plume migration in the storage site**

SCENARIO-3

PLANE-WAVE SIMULATION

PLUME MODELLING

Scenarios:

(1)Uniform model without alteration effect
(2)Uniform model with alteration effect
(3)Plume model without alteration effect
(4)Plume model with alteration effect

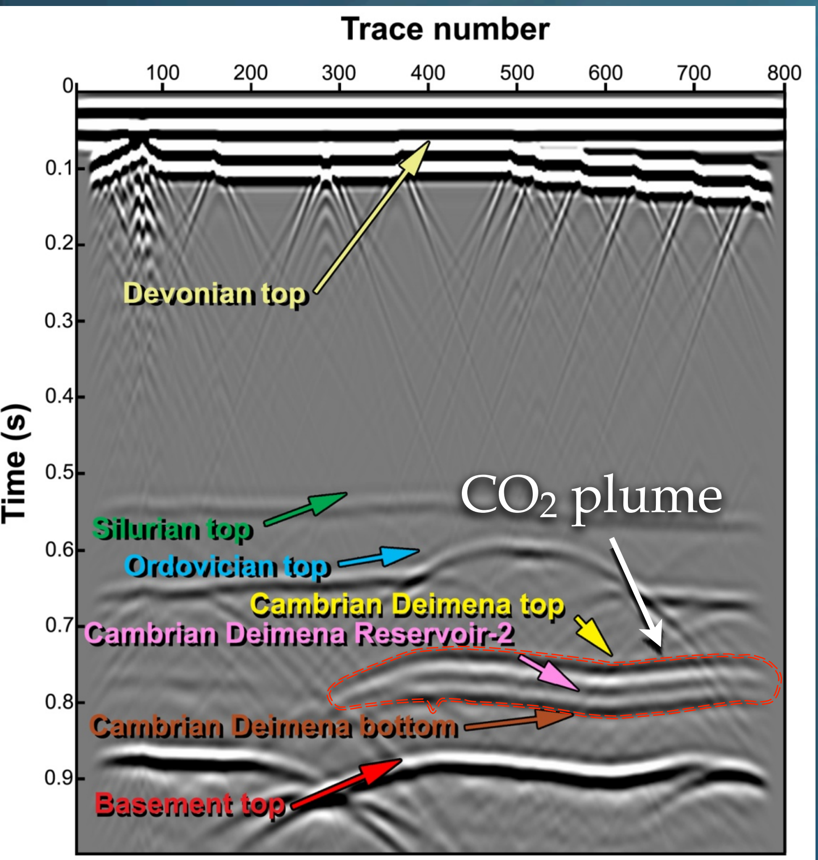


Fig. Synthetic plane-wave section of Scenario-3 (Shogenov et. al, 2016)

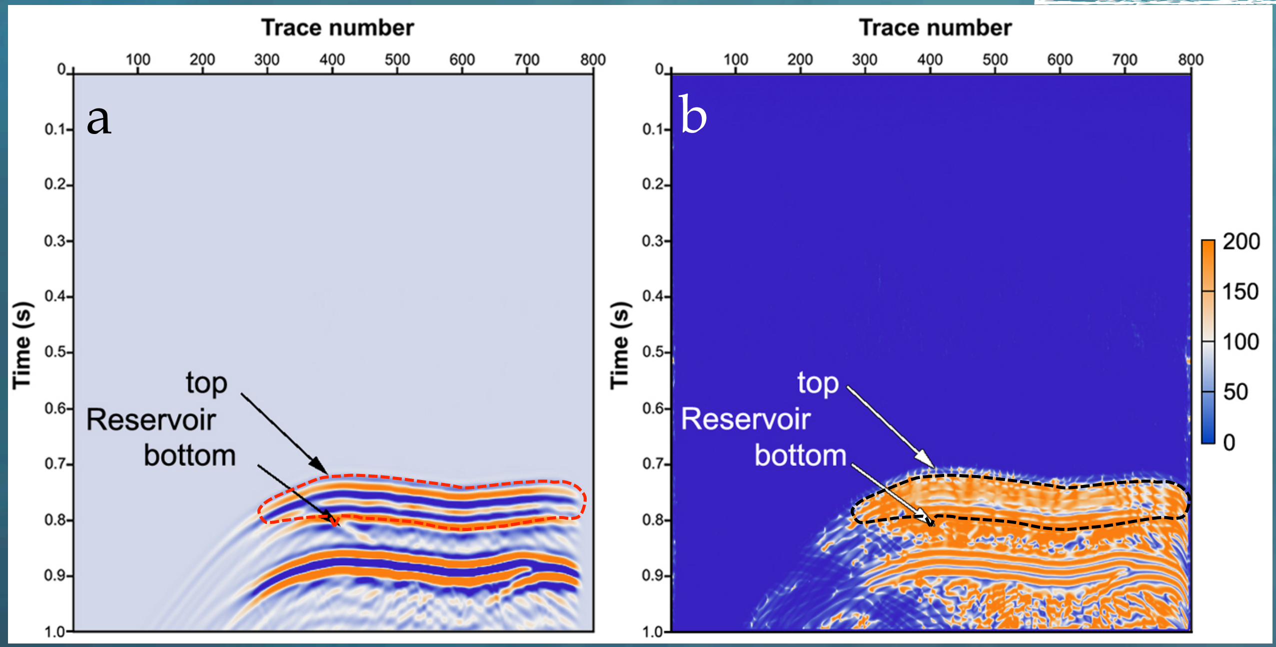


Fig. (a, b). Difference between the synthetic baseline and the synthetic seismic line of Scenario-3 (a) and corresponding NRMS section (b)

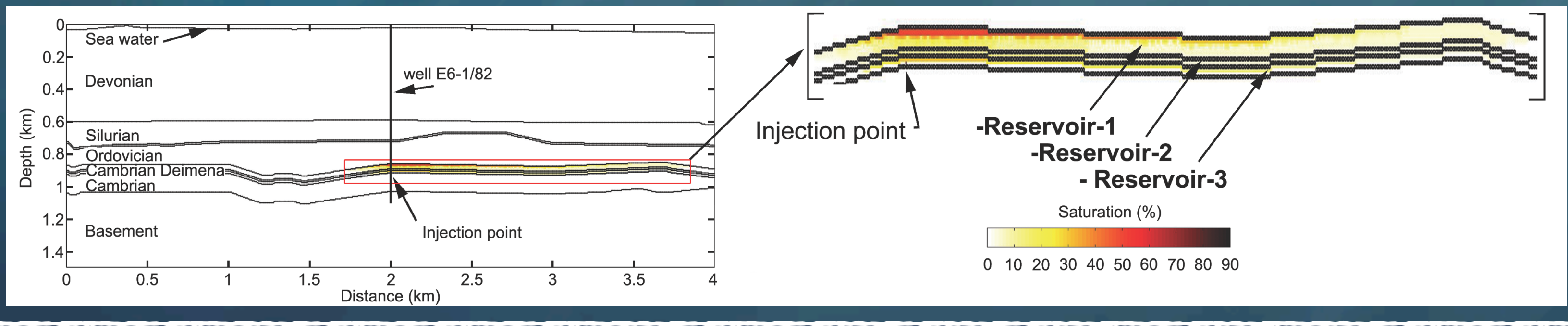


Fig. Plume saturation model of CO_2 injected into the reservoir formation in the E6 structure. Different CO_2 saturation of reservoir formation fluids is indicated. Black lines within the structure are formations borders (Shogenov et. al, 2016)

Numerical seismic modelling

Objectives

- I. Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II. Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III. Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV. Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - **Modelling of the possible shape of CO_2 plume migration in the storage site**

SCENARIO-4

PLANE-WAVE SIMULATION

PLUME MODELLING

Scenarios:

(1)Uniform model without alteration effect
(2)Uniform model with alteration effect
(3)Plume model without alteration effect
(4)Plume model with alteration effect

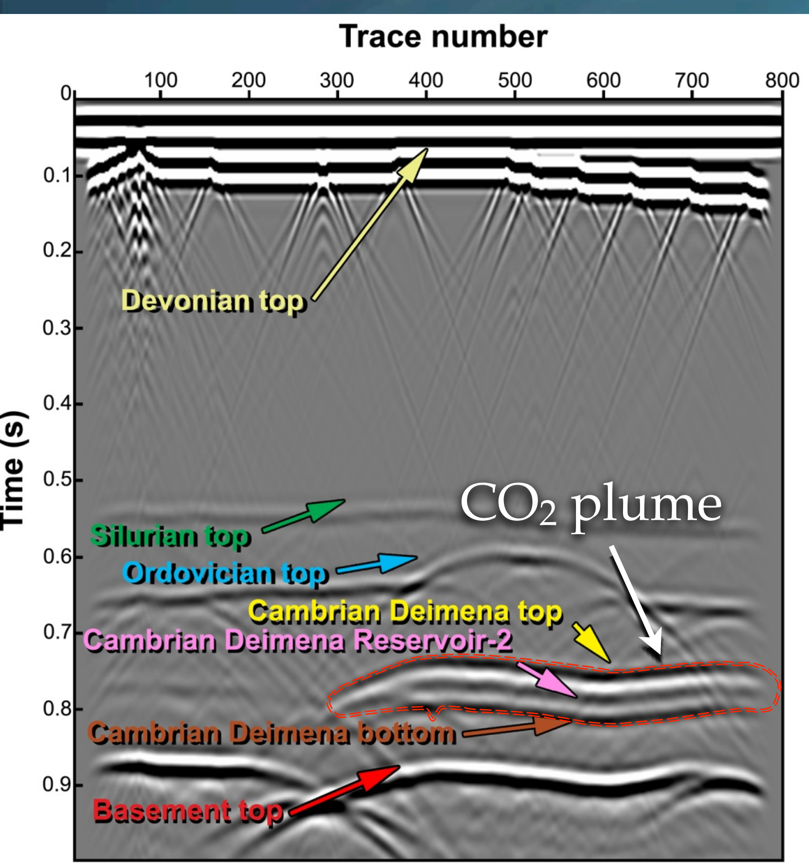


Fig. Synthetic plane-wave section of Scenario-4 (Shogenov et. al, 2016)

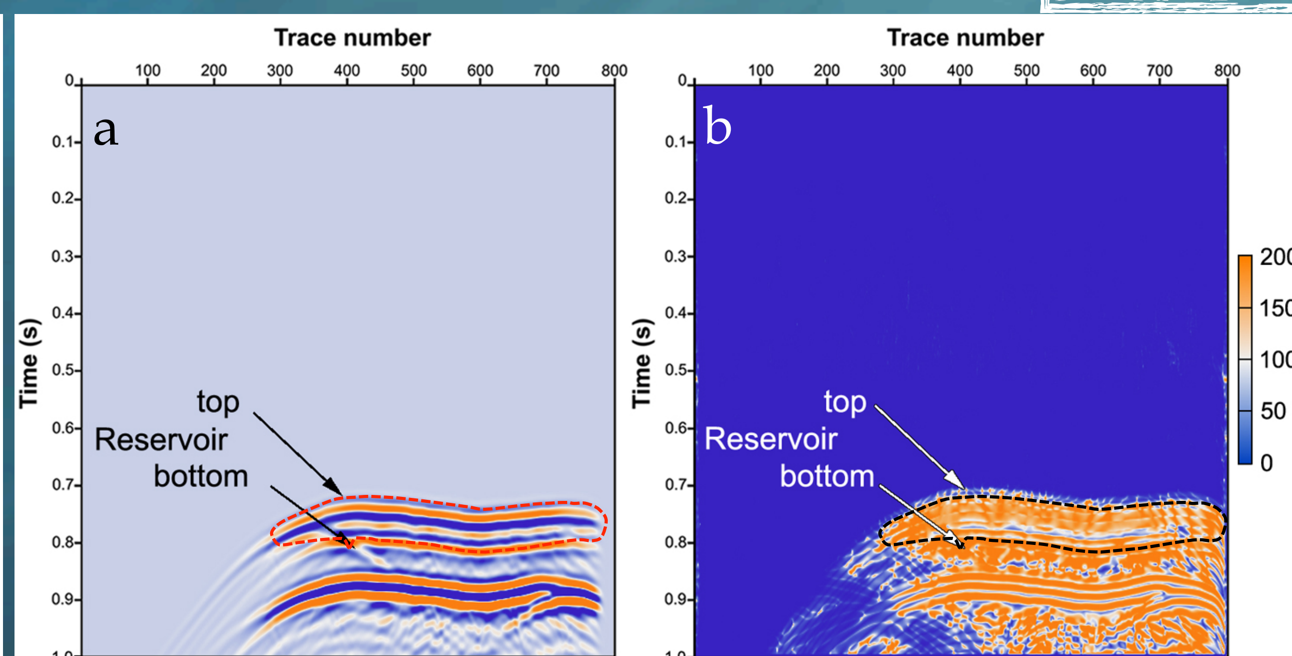


Fig. (a, b). Difference between the synthetic baseline and the synthetic seismic line of Scenario-4 (a) and corresponding NRMS section (b)

Numerical seismic modelling

Objectives

- I — Selection of storage sites and data collection
  - Selection of CO_2 geological storage sites
  - Rock sampling
  - Measurement of geochemical and petrophysical properties
- II — Characterization of the selected structures
  - Reservoir characterization and risk assessment
  - 3D geological static modelling
  - Estimation of CO_2 storage capacity
- III — Estimation of the influence of CGS on the properties of rocks
  - Laboratory CO_2 injection-like alteration experiment
  - Estimation of petrophysical alterations
- IV — Numerical seismic modelling to support the monitoring of CGS
  - 4D time-lapse rock physics and numerical seismic modelling
  - Coupling of the chemically induced petrophysical alteration effect of CO_2–hosting rocks measured in the laboratory with time-lapse numerical seismic modelling
  - **Modelling of the possible shape of CO_2 plume migration in the storage site**

SCENARIO-3 VS SCENARIO-4

PLANE-WAVE SIMULATION

Scenarios:
(1)Uniform model without alteration effect
(2)Uniform model with alteration effect
(3)Plume model without alteration effect
(4)Plume model with alteration effect

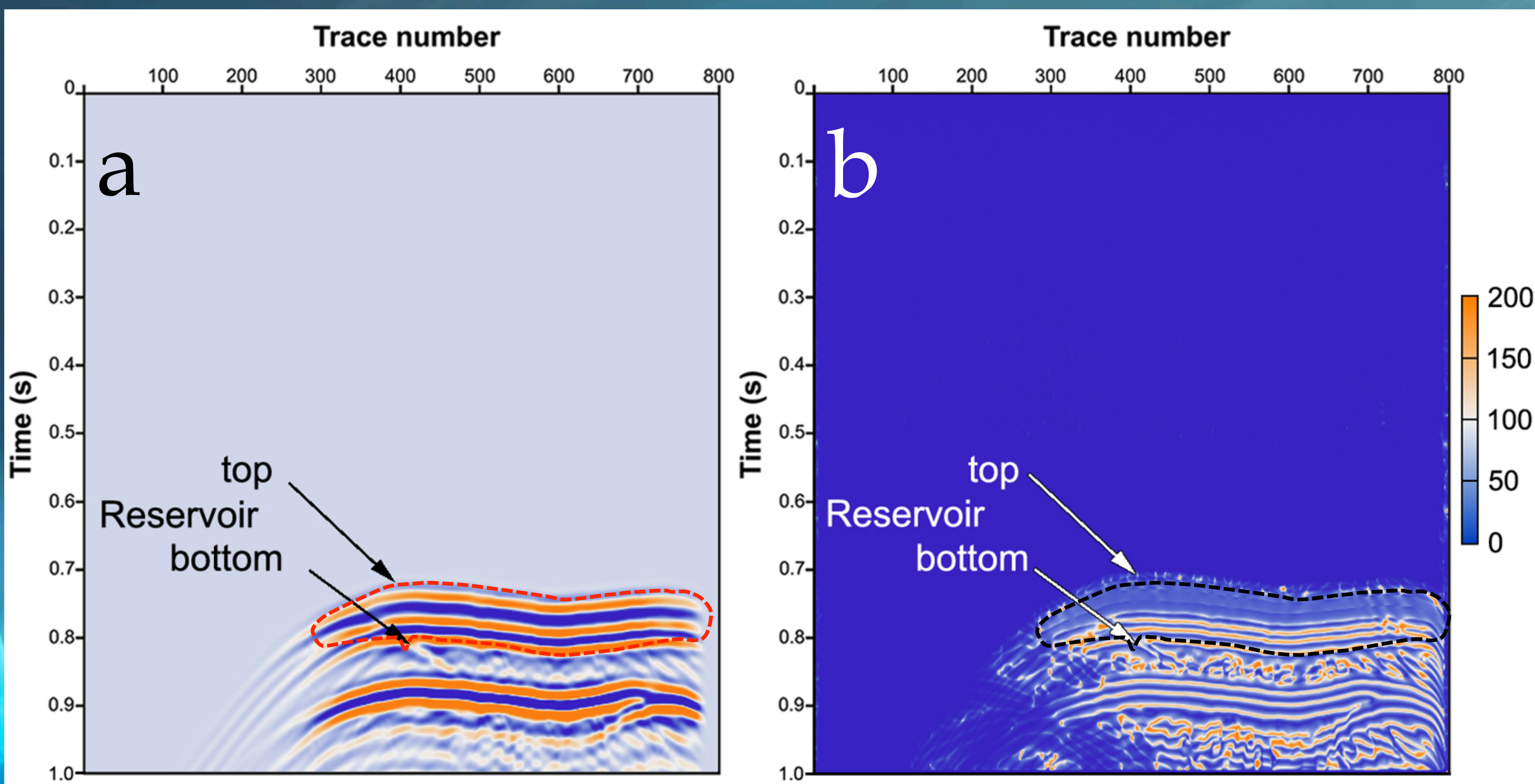
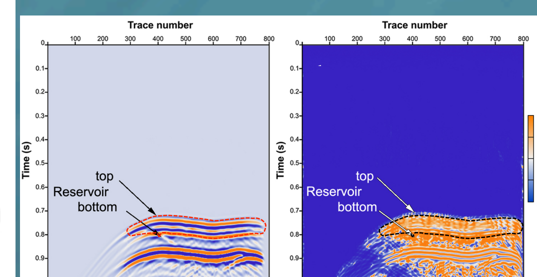
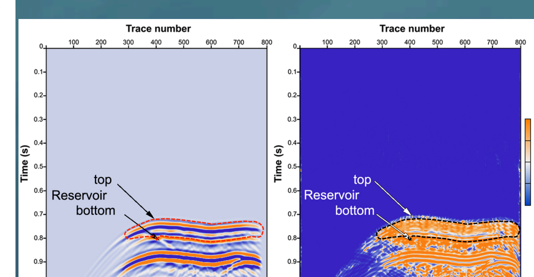


Fig. (a, b). Difference between the synthetic seismic line of Scenario-3 and Scenario-4 (a) and corresponding NRMS section (b) (Shogenov et. al, 2016)



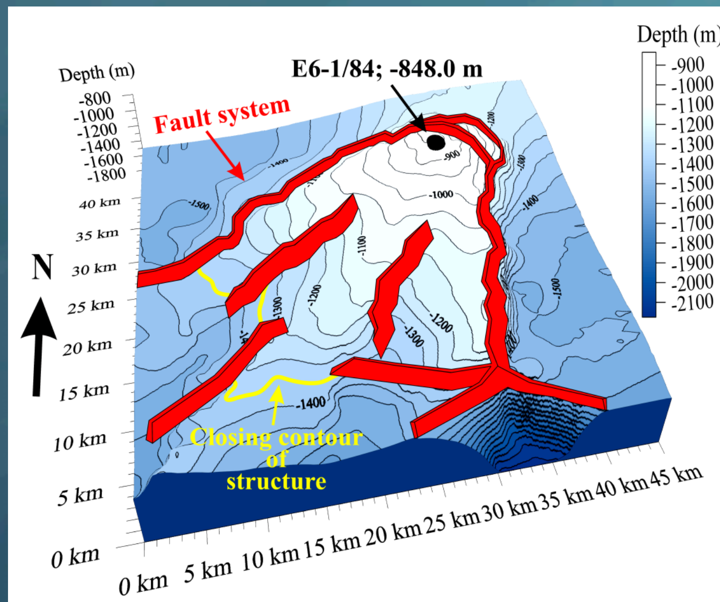
SCENARIO-3



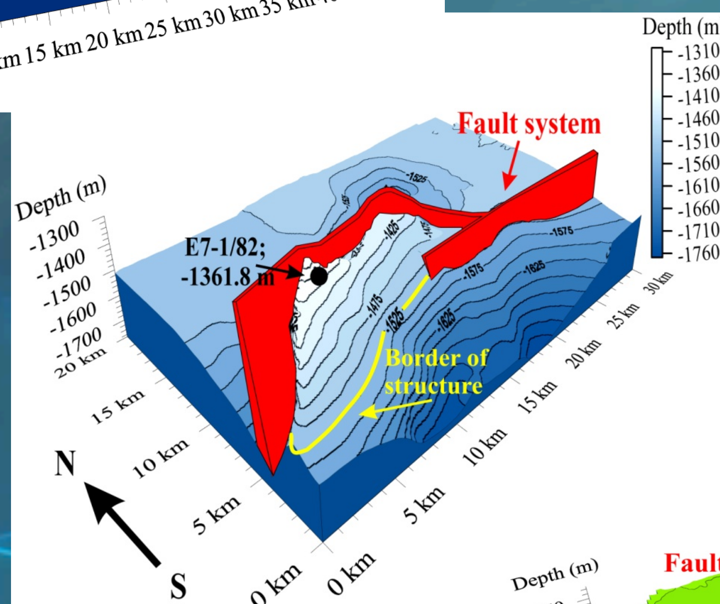
SCENARIO-4

I. The reservoir rocks in the studied structures onshore Latvia (South Kandava and Dobele) and in the Baltic Sea (E6 in Latvia and E7 in Lithuania) were estimated as prospective for gas storage

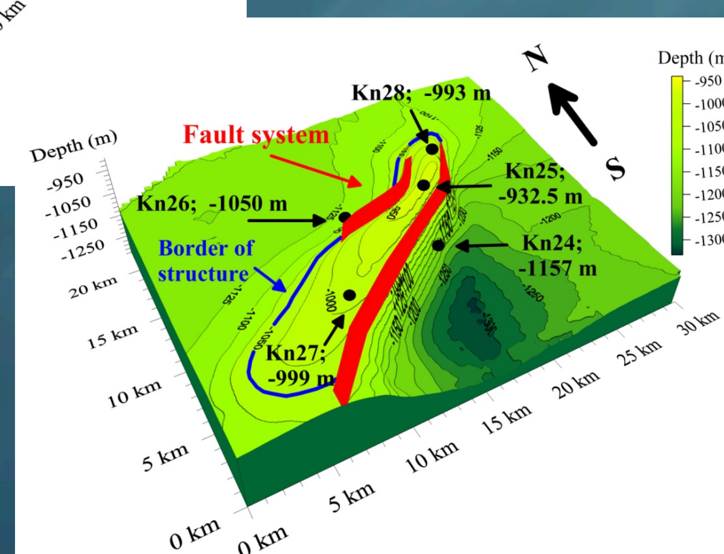
CONCLUSIONS



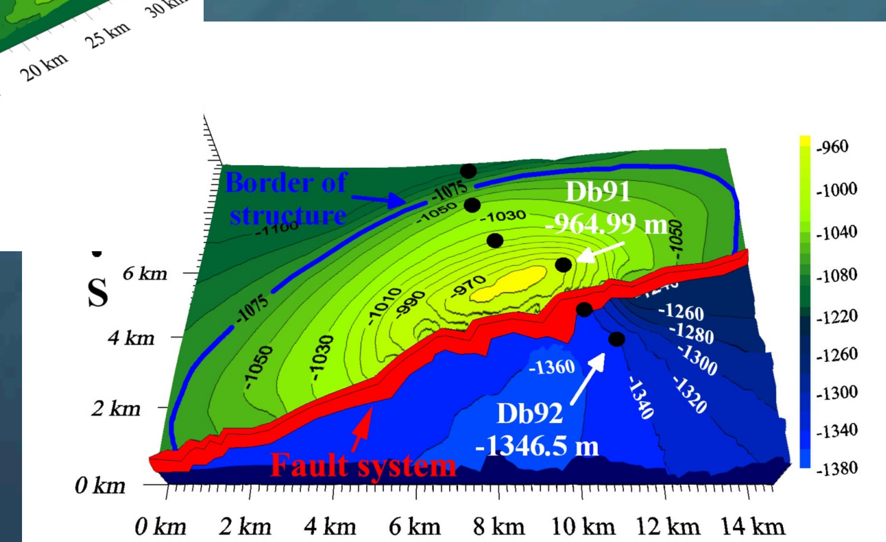
E6



E7



South Kandava



Dobele

PROSPECTIVE

I

II. Based on the recently and earlier measured gas permeability and porosity, a new classification of the reservoir quality for CGS was proposed for sandstones of the Deimena Formation of Cambrian Series 3 in the middle part of the Baltic Basin

CONCLUSIONS

Classification of the studied rocks for CO_2 storage**

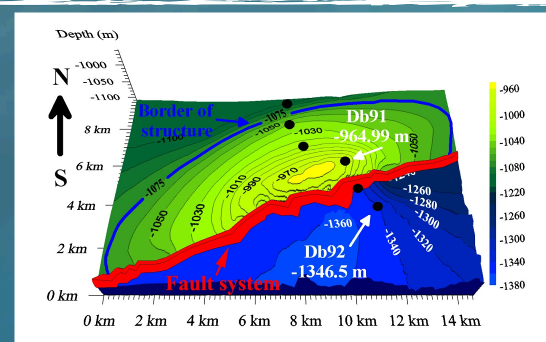
Group	Application for CGS	Class	Reservoir quality	κ (mD)	φ_{ef} (%)
1	Very appropriate	I	High-1	>300	≥20
		II	High-2		9–20
2	Appropriate	III	Good	100–300	>18
		IV	Moderate		9–18
3	Cautionary	V	Cautionary-1	10–100	18–23
		VI	Cautionary-2		7–18
4	Not appropriate	VII	Low	1–10	7–18
		VIII	Very low	<1	<18

II

NEW CLASSIFICATION

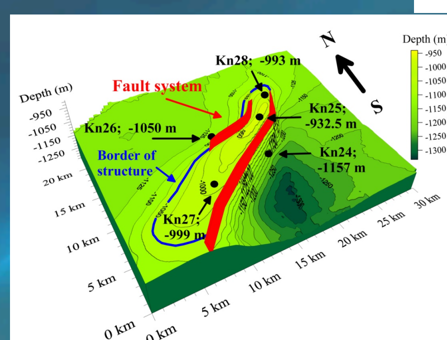
CONCLUSIONS

III.The reservoir sandstones of the Deimena Formation in the Dobele onshore structure was characterized by ‘high-2’ estimated average reservoir quality, assessed as ‘very appropriate’ for CGS (average porosity 19% and permeability 360 mD). The reservoir sandstones in the South Kandava and E6 structures had an identical average porosity of 21%, but their average permeability differed twofold, being 300 and 150 mD, respectively. The good reservoir quality of sandstones in these structures was assessed as ‘appropriate’ for CGS. The reservoir quality of the sandstones of the E7 offshore structure, estimated as ‘cautionary-2’ (average porosity 12% and permeability 40 mD), was the lowest in the studied structures and was assessed as ‘cautionary’ for CGS



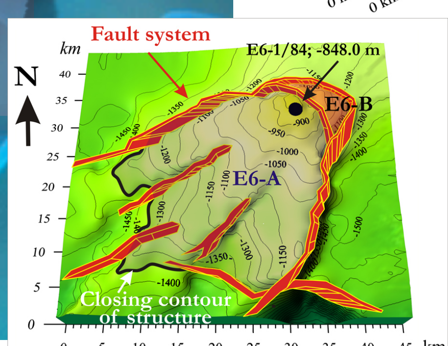
Dobele

Reservoir quality: ‘high-2’
Application for CGS: ’very appropriate’
(average porosity 19%;
permeability 360 mD)



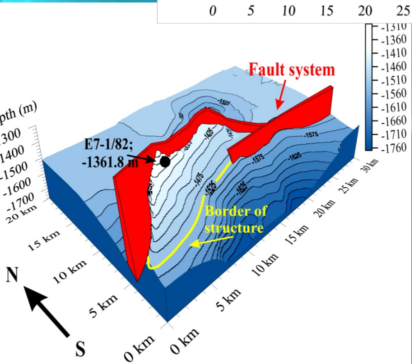
South Kandava

Reservoir quality: ‘good’
Application for CGS: ’appropriate’
(average porosity 21%;
permeability 300 mD)



E6

Reservoir quality: ‘good’
Application for CGS: ’appropriate’
(average porosity 21%;
permeability 150 mD)



E7

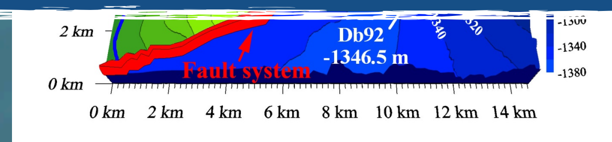
Reservoir quality: ‘cautionary-2’
Application for CGS: ’cautionary’
(average porosity 12%;
permeability 40 mD)

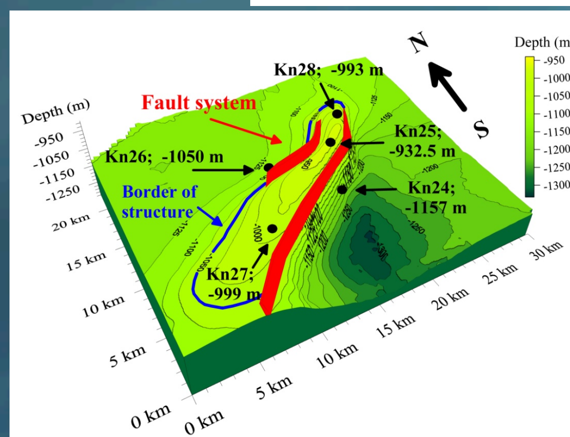
CHARACTERIZED

III

IV. The optimistic maximum and average storage potentials of the E6 structure (602 and 377 Mt) and its larger compartment E6-A (582 and 365 Mt) are higher and nearly the same as the previously reported total potential of all 16 onshore Latvian structures (400 Mt). Even the average conservative capacities of E6 (152 Mt) and E6-A (146 Mt) are the largest among all Latvian onshore and offshore structures studied until now.

CONCLUSIONS

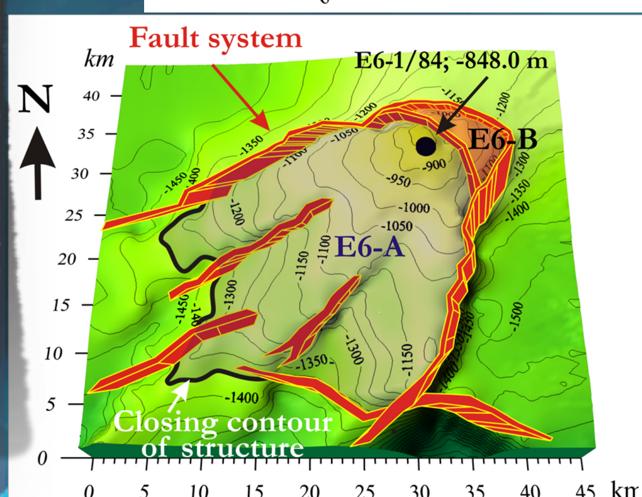




South Kandava

Optimistic approach: 3–122 (mean 95) Mt
Conservative approach: 1–32 (mean 25) Mt

> Total potential of all 16 onshore Latvian structures (400 Mt)



E6

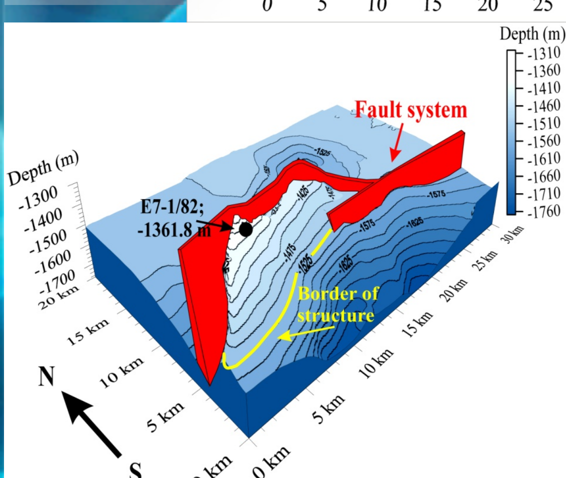
Optimistic approach: 251–602 (mean 377) Mt
Conservative approach: 101–243 (mean 152) Mt

E6-A

Optimistic approach: 243–582 (mean 365) Mt
Conservative approach: 97–233 (mean 146) Mt

E6-B

Optimistic approach: 8–20 (mean 12) Mt
Conservative approach: 4–10 (mean 6) Mt



E7

Optimistic approach: 14–66 (mean 34) Mt
Conservative approach: 3–13 (mean 7) Mt

STORAGE CAPACITY ESTIMATED

IV

V.The E6 structure offshore Latvia was estimated as the most prospective for CGS in the Baltic Cambrian Basin according to the reservoir thickness, area, quality and storage capacity

CONCLUSIONS

E6

Optimistic approach: 251–602 (mean 377) Mt
Conservative approach: 101–243 (mean 152) Mt

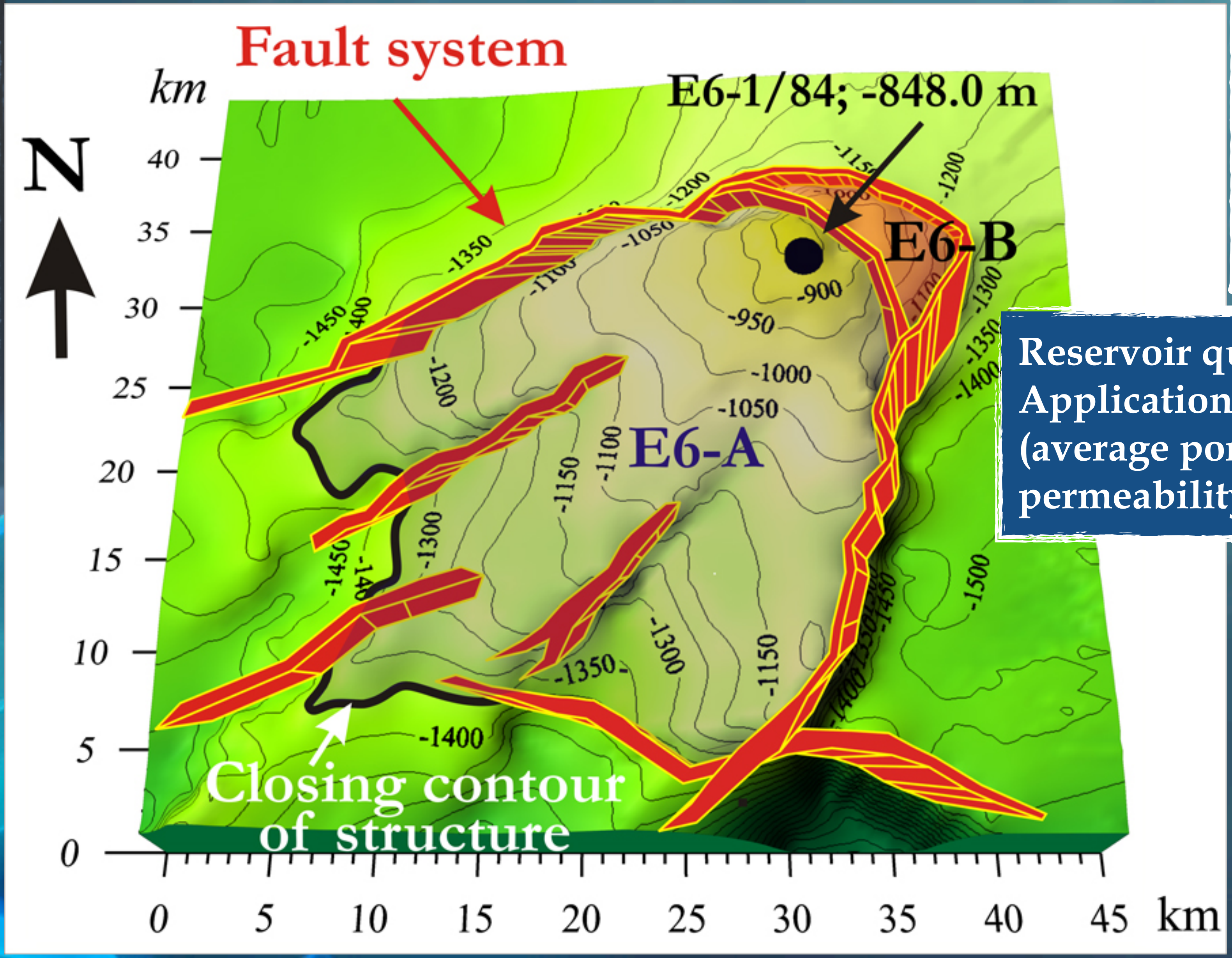
E6-A

Optimistic approach: 243–582 (mean 365) Mt
Conservative approach: 97–233 (mean 146) Mt

Area – E6: 600 (km^2)
E6-A: 553 km^2
E6-B: 47 km^2
Thickness – 53 m
Porosity– 21%
Permeability– 150 mD

Salinity – 99 g/l
Reservoir temperature in situ – 36^{o}C

Density of CO_2 in situ – 658 (kg/m^3)
Net Gross ratio of aquifer – 0.90
Reservoir pressure in situ – 9.3 mPa



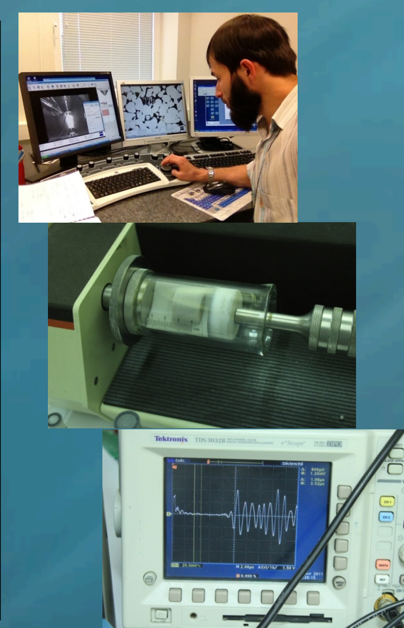
Reservoir quality: 'good'
Application for CGS: 'appropriate'
(average porosity 21%; permeability 150 mD)

THE MOST PROSPECTIVE

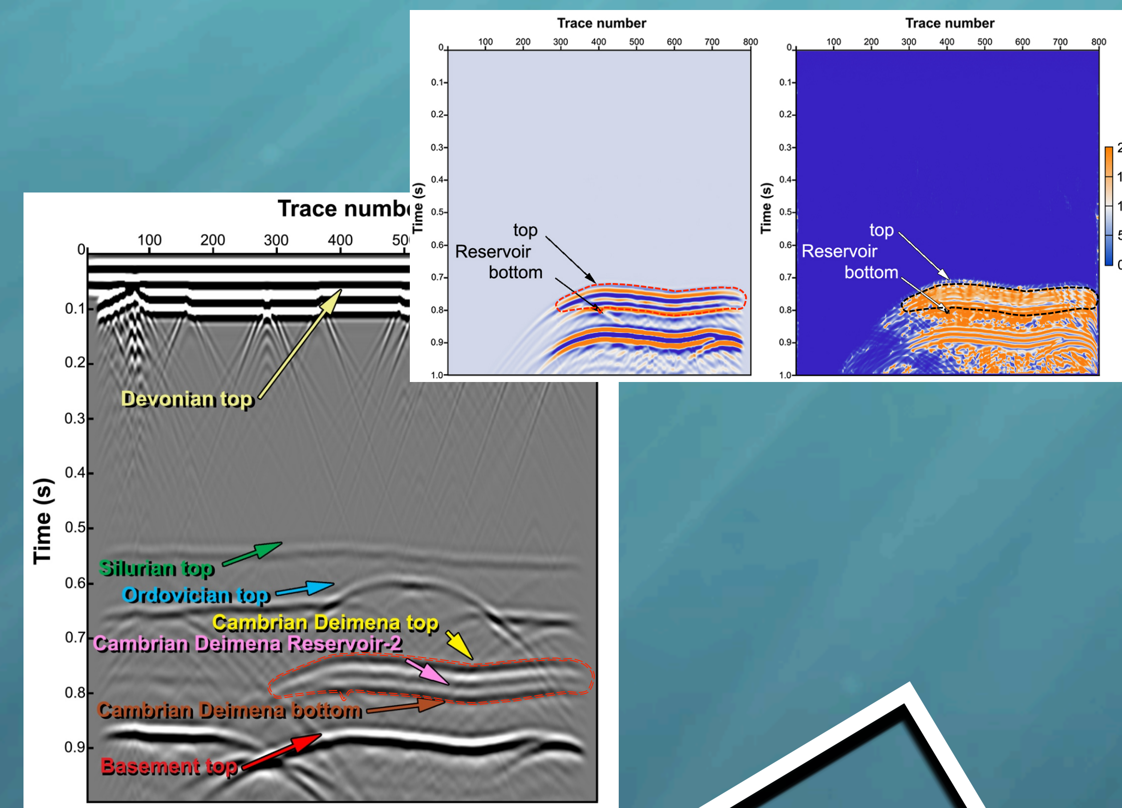
V

VI. The novelty of the applied seismic numerical modelling approach was the coupling of the chemically induced petrophysical alteration effect of CO_2 hosting rocks measured in laboratory with time-lapse numerical seismic modelling

CONCLUSIONS



+

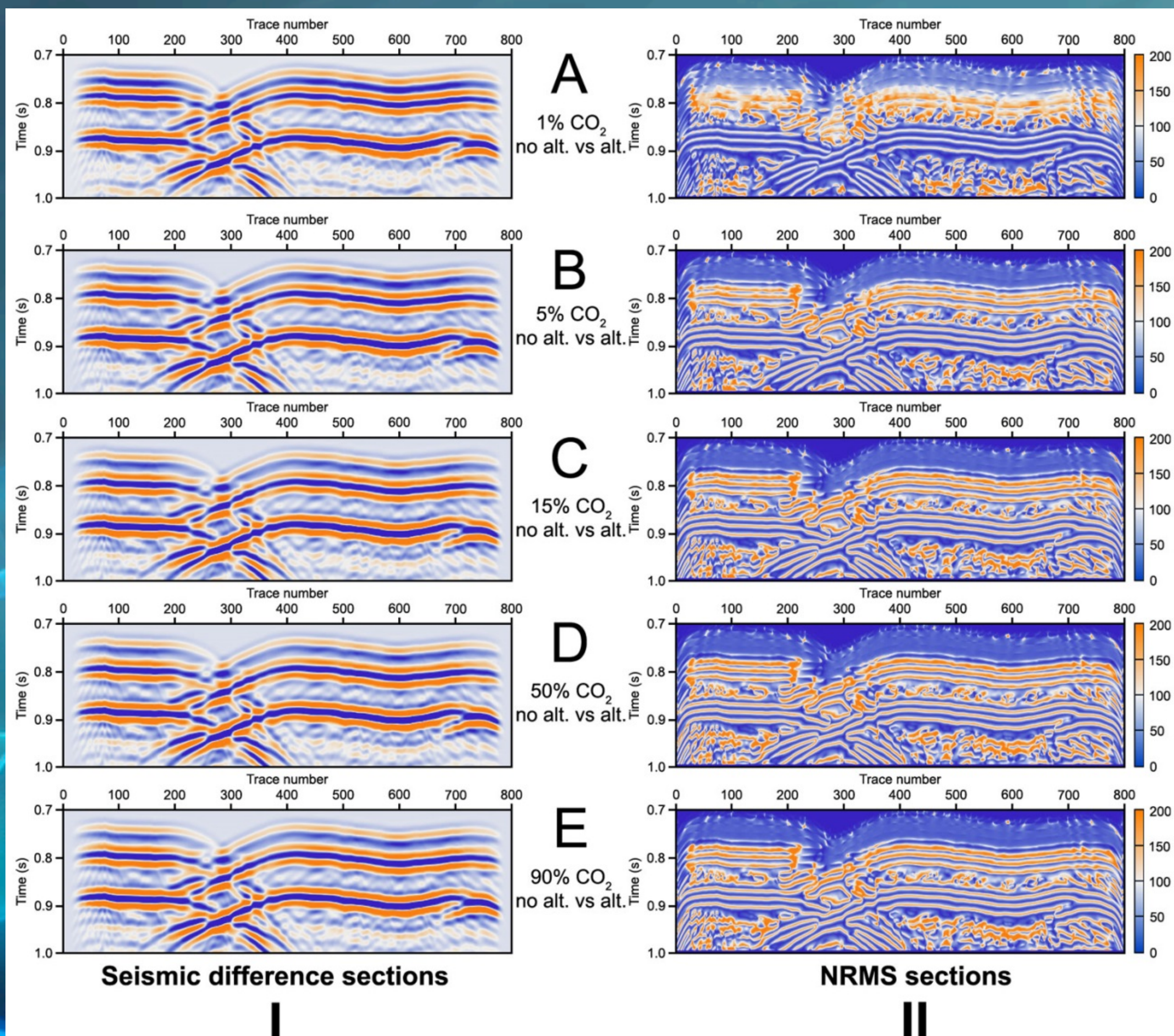


PETROPHYS. ALTERATION + SEISMIC MODELLING

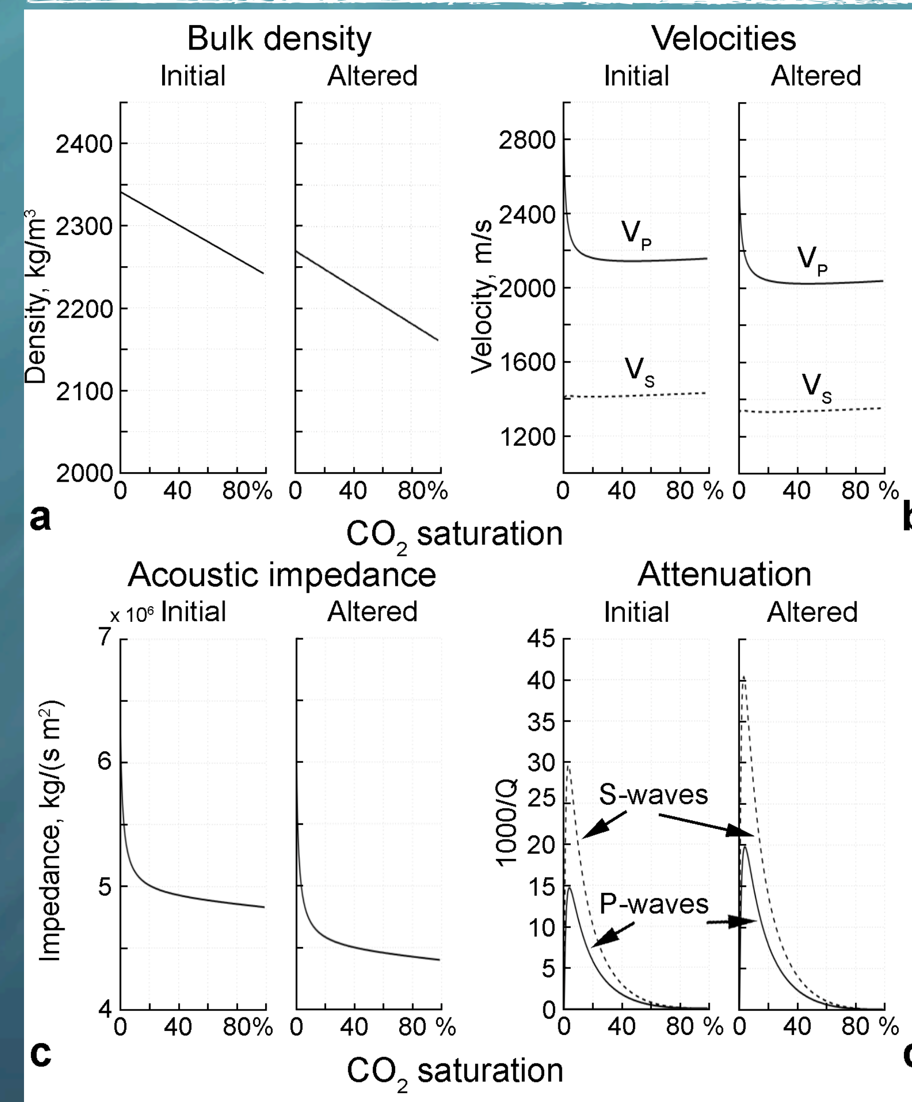
VI

VII. Alteration of the petrophysical properties of the reservoir had a strong influence on the reflected signals in the seismic sections, showing the highest difference on seismic sections with 1% CO_2 saturation, increasing the detectability of the stored CO_2. The difference decreased with increase in CO_2 content. Up to 5% CO_2 saturation could be qualitatively estimated from the synthetic seismic data. For CO_2 saturation higher than 5% qualitative estimations of the saturation level are uncertain

SCENARIO-1 VS SCENARIO-2



PROPERTIES CHANGE



CONCLUSIONS

VII

CONCLUSIONS

VIII. The obtained results, as the first of this type in the central part of the Baltic Basin, have also importance for the southern and western parts of the Baltic sedimentary basin, which have CO_2 storage capacity in the Cambrian aquifer (Lithuania, Sweden, Kaliningrad Region and offshore Poland). However, they should be supported by additional laboratory experiments and fluid-flow modelling of the CO_2 storage in the Cambrian sandstones both in structures and basin-scale for better assessment of the possible storage scenarios and their safety

VIII

PRACTICAL VALUE

The obtained results and their novelty have a practical value for the demonstration of CGS and its monitoring in the Baltic Sea Region. The monitoring, verification and accounting for CO_2 is critical for the widespread application of CGS. The methods applied in this research to single structures and results of the CO_2 injection-like experiment can be useful for the *basin-scale modelling of CGS in the Baltic Basin* and in sandstone reservoirs in other basins

E6. STORY OF SUCCESS

E6 STORY

The aim

To develop a new cost-competitive concept of the pilot project for the common use of the underground and synergy of CGS, CO_2-EOR/EOR+ and CPG in the E6 structure in different geol. formations. Adopt the storage site with several "Win-Win" situations to make it more attractive.

STAGE II

SYNERGY OF CO_2 STORAGE, OIL AND GEOTHERMAL ENERGY RECOVERY IN DIFFERENT GEOLOGICAL FORMATIONS: CASE STUDY IN THE BALTIC SEA

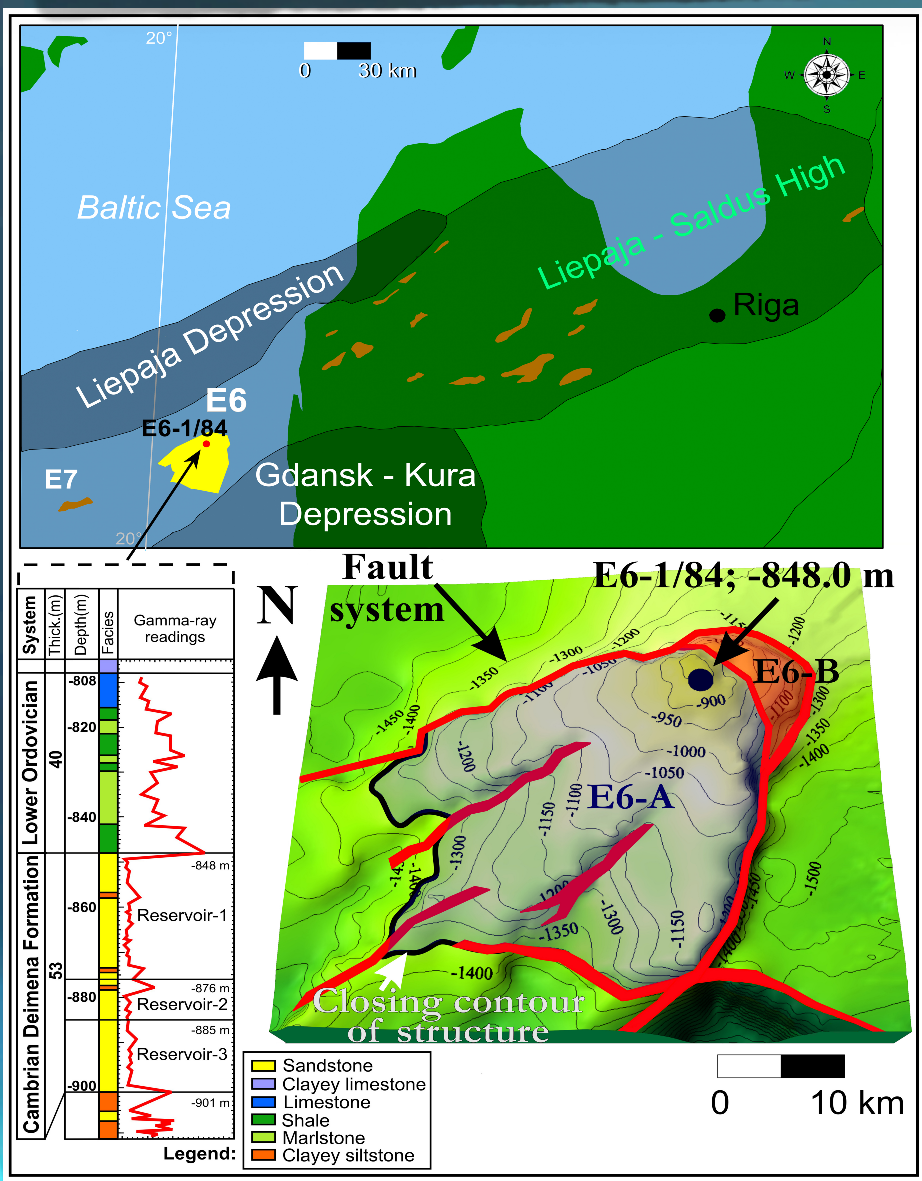
CO_2 + ENHANCED OIL RECOVERY (EOR) = CO_2-EOR

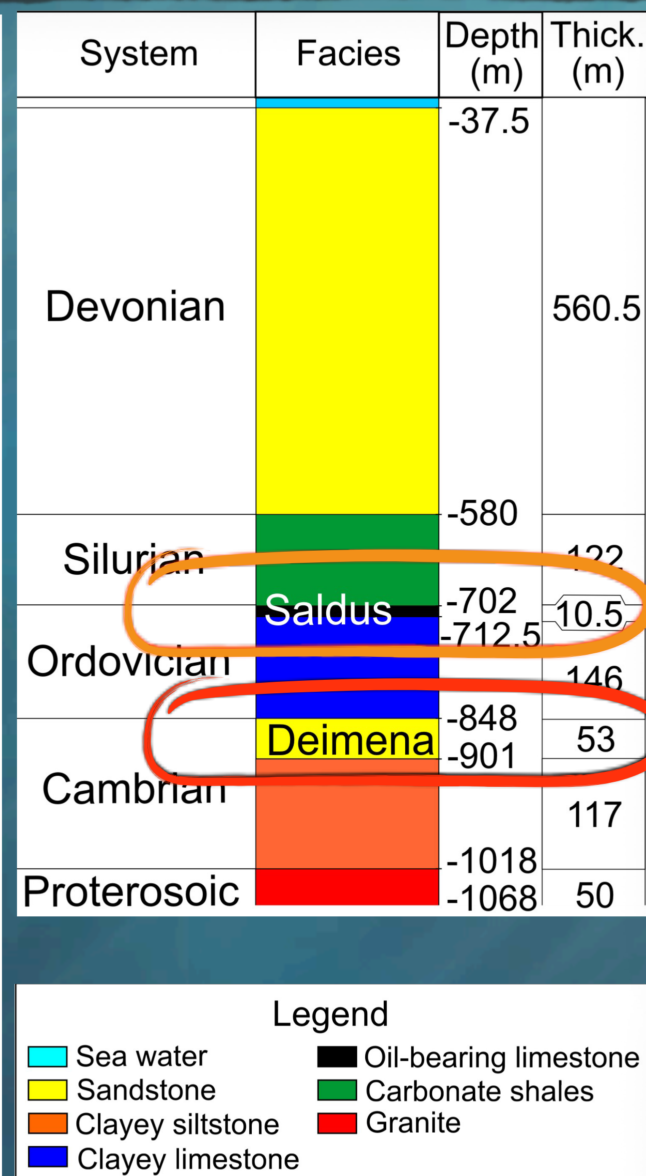
CO_2-EOR + CO_2 GEOLOGICAL STORAGE (CGS) = EOR+

GEOTHERMAL ENERGY RECOVERY + CGS = CO_2 PLUME GEOTHERMAL (CPG)

GEOLOGICAL BACKGROUND

The Liepaja depression is a distinctly asymmetrical depression (length 200 km, width up to 70 km, trough amplitude 800 m) with a gentle northern and a steep near-fault southern edge. **The Liepaja–Saldus zone of highs** crosses the Baltic syneclise, stretching from the Swedish offshore towards the northeast for about 400 km.





- CAP-ROCK:
Ordovician & Silurian Formations
Silurian Formations:
Thickness:
100-125 m (122 m in the well E6-1/84)
- Composition:
mudstones
Ordovician Formations:
- Thickness:
130-230 m (146 m in the well E6-1/84)
- Composition:
limestones, clayey limestones, shales, marlstones
Open porosity: average 3%
Gas permeability: average <0.01 mD
Oil reservs (IV class reservoir) - Upper Ordovician limestones.
Open porosity: 10-24% (av. 18%)
Gas permeability: 39 mD (average 6 mD)

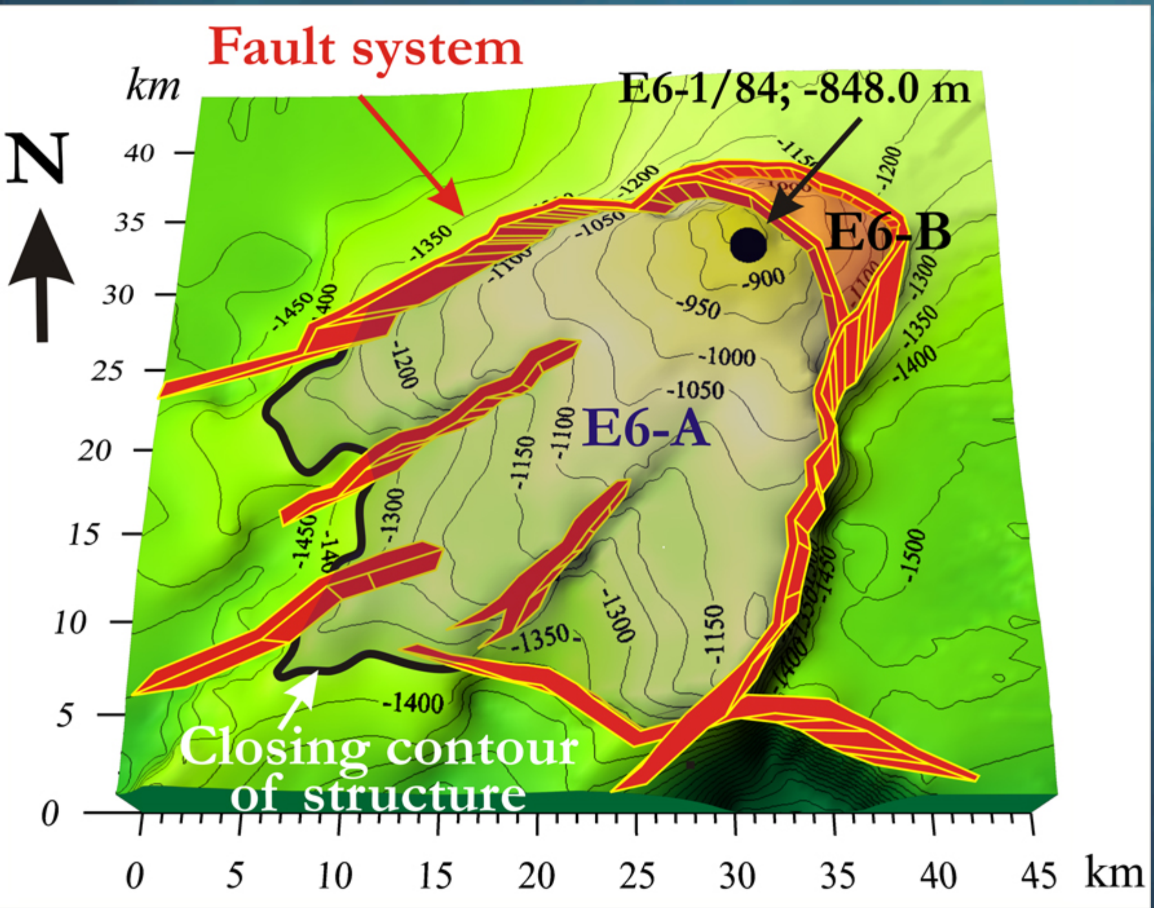
- RESERVOIR: Cambrium Deimena Formation
- Depth interval:
848-901 m (in the well E6-1/84)
- Thickness:
25-80 m (53 m in the well E6-1/84)
- Composition:
light-grey and beige-grey fine-grained, oil-impregnated **quartz sandstones**
Open porosity: 14-33% (av. 21%)
Gas permeability: 10-440 mD (average 170 mD)

OIL RESERVES: 362 MMBO
OIL FLOW: 2.7 M³/DAY

CO_2 STORAGE CAPACITY, MT

E6 PROPERTIES

Salinity: 99 g/l
Thickness: 53 m
Density of CO_2 in situ: 658 (kg/m^3)
Net Gross ratio of aquifer: 0.90
Reservoir temperature in situ: 36°C
Reservoir pressure in situ: 9.3 mPa
Area E6: 600 (km^2)
E6-A: 553 km^2
E6-B: 47 km^2
Porosity: 21%
Permeability: 170 mD



SALDUS F. OIL RESERVOIR

E6	65–144 (mean 110)
E6-A	60–133 (mean 100)
E6-B	5-11 (mean 10)

DAIMENA F. CGS RESERVOIR

E6	Optimistic: 251–602 (mean 377) Conservative: 101–243 (mean 152)
E6-A	Optimistic: 243–582 (mean 365) Conservative: 97–233 (mean 146)
E6-B	Optimistic: 8–20 (mean 12) Conservative: 4–10 (mean 6)

DAIMENA F. + SALDUS F.

E6	Optimistic: 320–745 (mean 490) Conservative: 170–385 (mean 265)
E6-A	Optimistic: 305–715 (mean 470) Conservative: 160–365 (mean 250)
E6-B	Optimistic: 15–30 (mean 20) Conservative: 10–20 (mean 15)

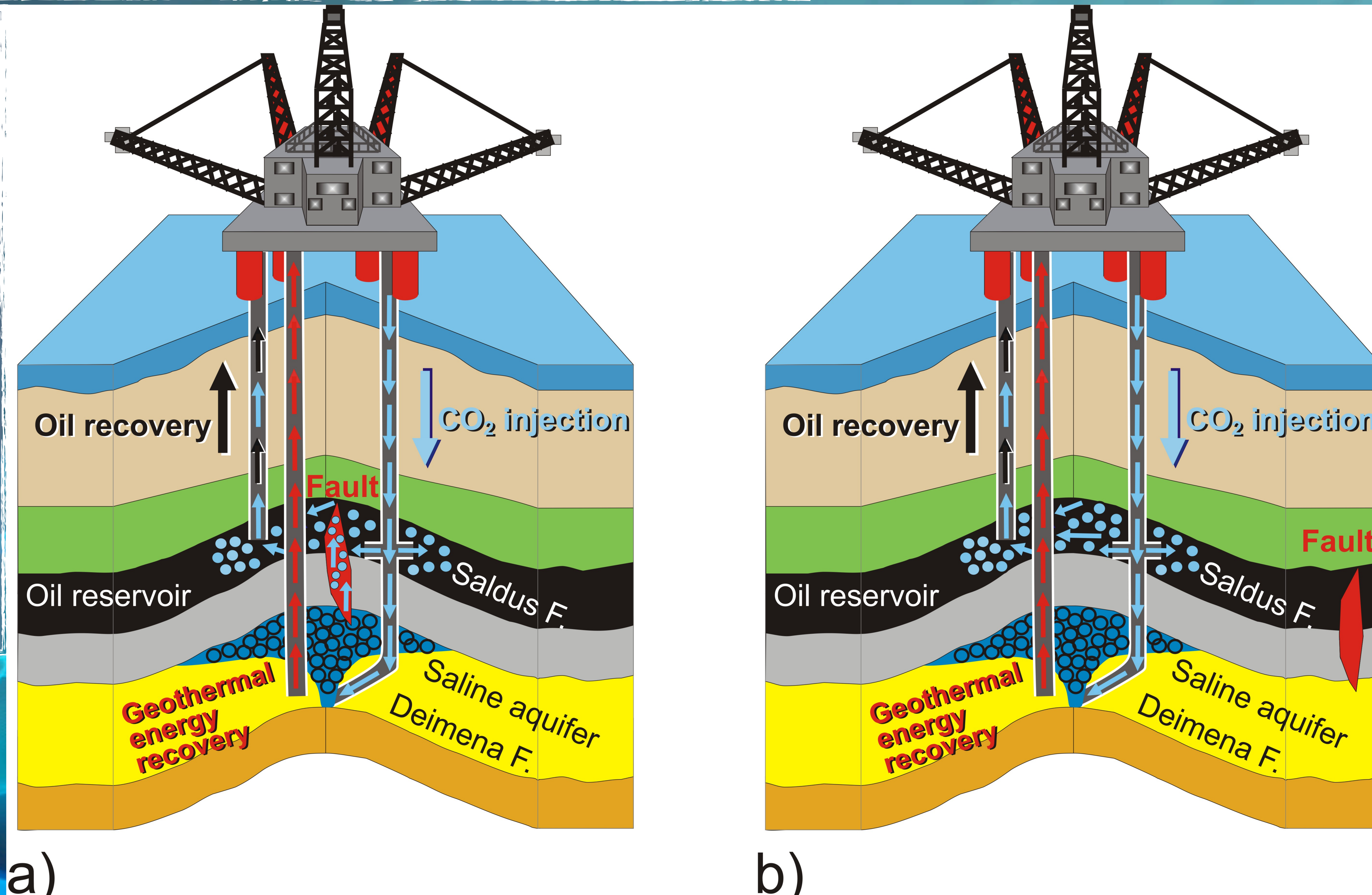
STORAGE SCENARIOS

SURPLUSES

- Testing of integrity of the Deimena formation
- Coverage of operational cost of the rig
- Single injection well reducing overall costs
- Increased CO_2 storage capacity
- Increased oil production (in contrast with conventional CO_2-EOR)
- Geothermal Energy Recovery

New cost-competitive concept of the pilot project for the common use of the underground and synergy of CGS, CO_2-EOR/EOR+ and CPG in the E6 structure in different geol. formations

"FAULT-LEAKAGE" SCENARIO



"NO LEAKAGE" SCENARIO

STORAGE SCENARIOS

WIN-WIN-WIN-WIN-WIN
OR
WIN^5 SITUATION

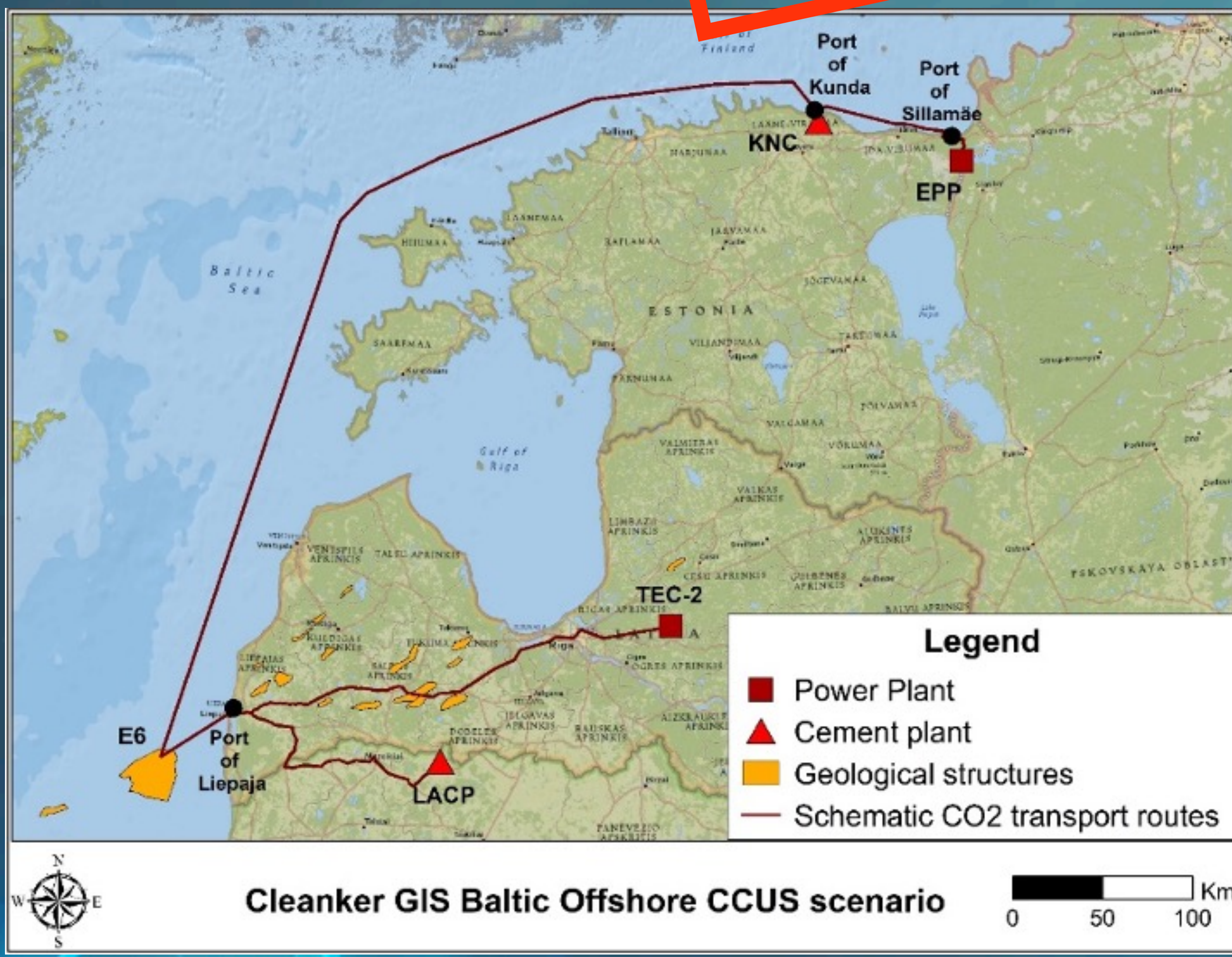


Fig. Transport model of the proposed innovative synergy CCUS and renewable energy project offshore Baltic using CO_2 emissions from the cement industry and energy production from Estonia, Latvia and Lithuania (CLEANKER project, Heidelberg cement)

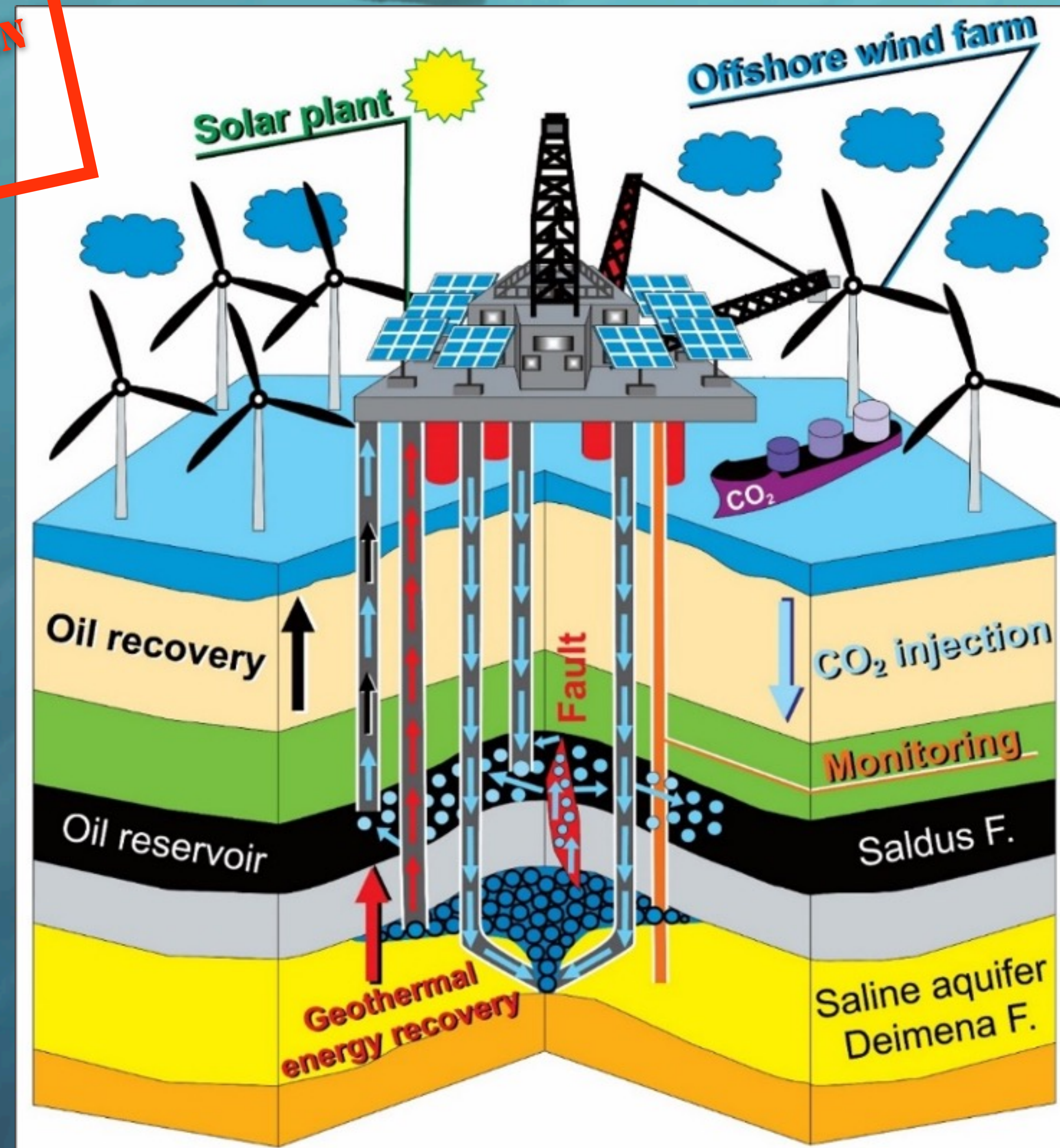


Fig. Conceptual techno–ecological schematic model of CCUS project with different green renewable energy recovery technologies in the structure E6 including synergy of (1) CGS, (2) GCS, (3) CO_2-EOR/EOR+ in different geological formations in the same storage site and (4) solar energy and (5) wind energy recovery

E6. STORY OF SUCCESS

E6 STORY

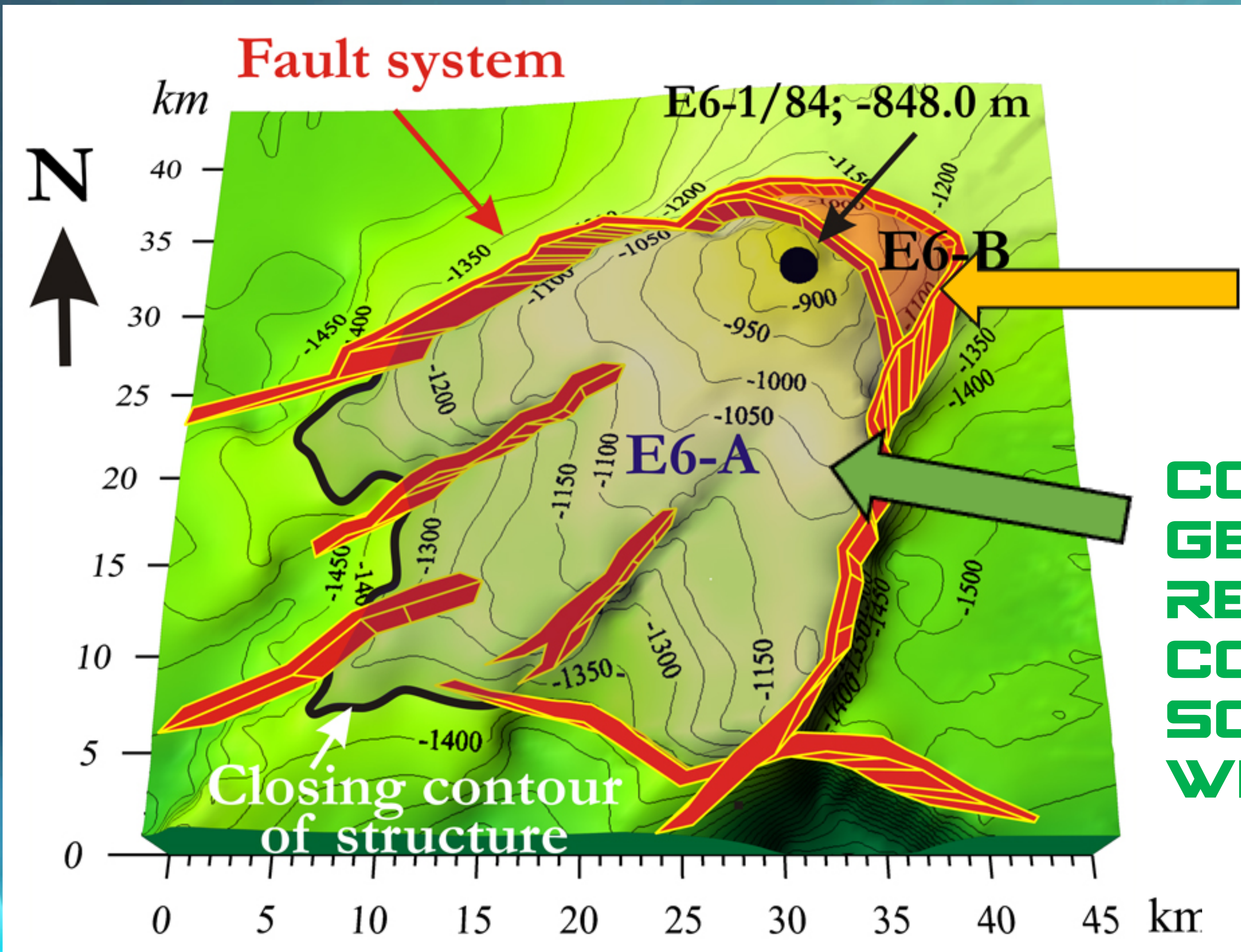
The aim

To update the cost-competitive concept and to add an additional, **6th** "win"- situation in the E6 structure - **Hydrogen storage**

E6 with WIN^{6}

STAGE III

E6 WITH WIN[6]



H_2 STORAGE

CO_2 STORAGE + GEOTHERMAL ENERGY RECOVERY + CO_2-EOR+ SOLAR ENERGY+ WIND ENERGY

E6 WITH WIN6

HYDROGEN STORAGE CAPACITY ESTIMATION

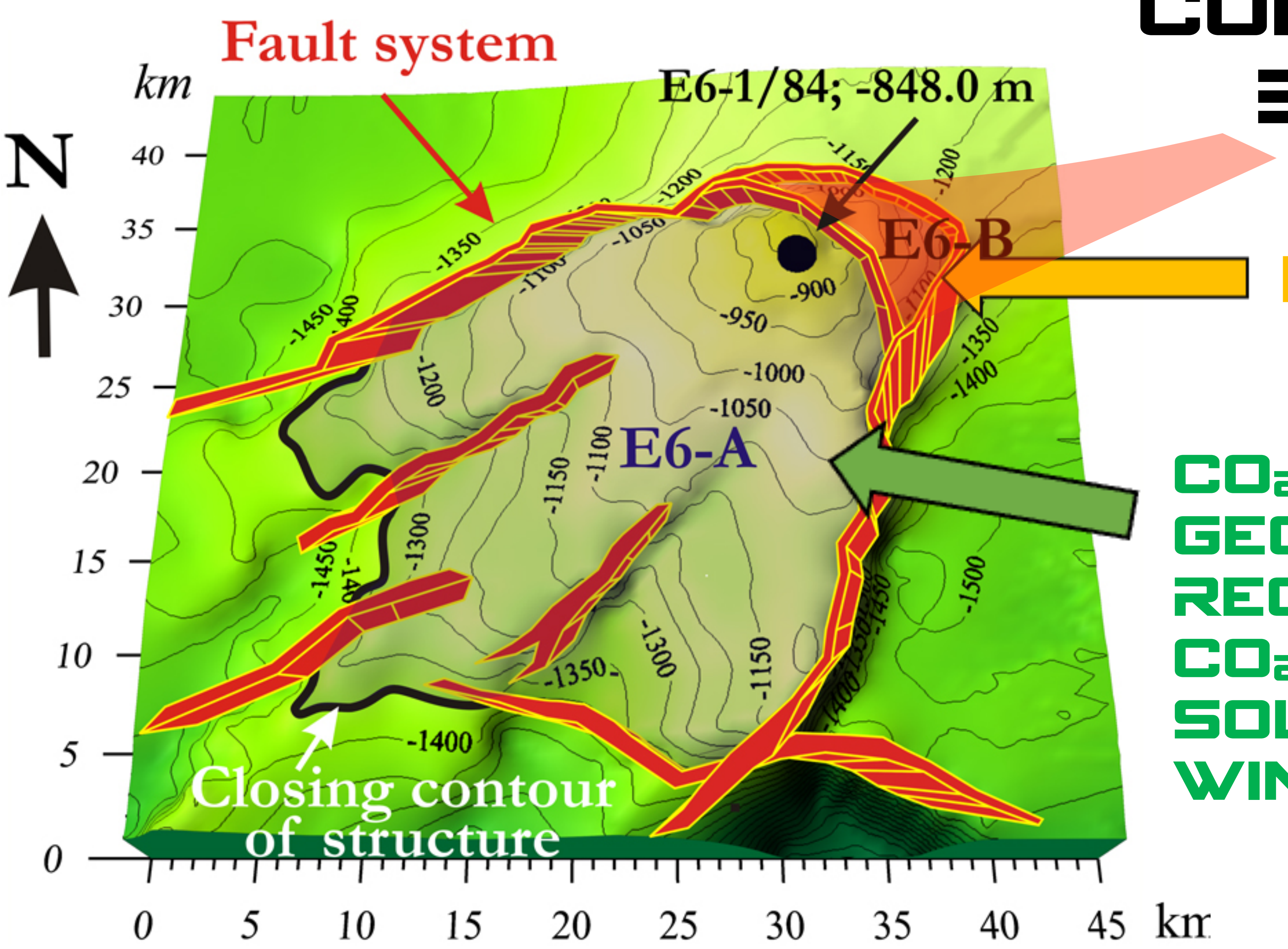
OPTIMISTIC APPROACH

$$M_{H2} = A \times H \times NG \times \phi \times \rho_{H2} \times S_{EF}$$

M_{H2} - storage capacity (kg)
A – an area of an aquifer in the trap (m^2)
h - average thickness of the aquifer in the trap (m)
NG - average net to gross ratio of the aquifer in the trap (%)
ϕ - average porosity of the aquifer in the trap (%)
ρ_{H2} - in situ H_2 density in reservoir conditions (kg/m^3)
S_{ef} - storage efficiency factor (for trap volume, %)
*Conservative **storage efficiency** equal to **1%** was used for calculations*

E6 WITH WIN[6]

H_2 STORAGE CAPACITY



CONSERVATIVE 30 000 T

H_2 STORAGE

CO_2 STORAGE + GEOTHERMAL ENERGY RECOVERY + CO_2-EOR+ SOLAR ENERGY+ WIND ENERGY

E6. STORY OF SUCCESS

E6 STORY

The aim

To update the cost-competitive concept and to add an additional, **7th** "win"- situation in the E6 structure - **CO_2 hydrogenation to fuels**
E6 with WIN[7]

STAGE IV

UNDER CONSIDERATION 2022-...

ACHIEVEMENTS

- For the first time the concept of techno–ecological synergy of the CCUS project with different green renewable energy recovery technologies - modules, which support circular economy targets, was proposed:

(1) CGS, (2) GCS, (3) CO_2-EOR/EOR+, (4) solar energy, (5) wind energy production, (6) Hydrogen storage, (7) CO_2 hydrogenation to fuels

- Maximize efficiency
- Minimize the carbon footprint of the full-chain process
- Demonstrated win^x situation (where x is a number of additional conceptual technological benefits of the project or MODULES) with x=7
- Win^5 global situation: greenhouse gas emissions (GHGE) reduction, (2) economic profitability, (3) increased CO_2 storage capacity, (4) public acceptance, and (5) retargeting of oil and gas businesses

ACHIEVEMENTS

- Compact mobile modules of small wind offshore floating plant installed around the rig and solar panels covering the free surfaces of the rig and a mobile geothermal plant using CO_2 (20 times smaller than a conventional plant) will produce renewable energy added to the project electricity net to cover the energy needs of the project. The excess energy will be used by the compact mobile module of a hydrogen production plant established directly on the rig. The produced hydrogen could be stored underground and when needed, transported by ship to the port. For the first time, we estimated hydrogen storage capacity in the E6-B, the smaller compartment of the E6 offshore structure as 30 Kt.
- Our Baltic offshore scenario is ambitious and innovative, considering proposed new technologies, synergy with renewable energy, techno–ecological synergy, large storage capacity and included cluster of emission sources from the cement industry and energy production from Estonia, Latvia, and Lithuania. These all-listed facts make this concept unique and a pioneer in the region and in the CCUS and GHGE fields of study.
- This scenario is a basis for the new concept of CO_2 and hydrogen storage site marketing: how to retarget fossil fuel business (the depleted oil and gas fields) into the storage-targeted and renewable energy business, permitted to achieve the carbon-free energy transition using principles of circular economy and sustainable use of resources and environment.

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THANK YOU FOR YOUR ATTENTION!

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