Application of regression analysis and hypothesis tests in prediction of rock elastic moduli behavior
(Применение регрессионного анализа и статистических гипотез для прогноза модулей упругости горных пород)

М.Ф. Гасеми*, Т.Р. Ялаев*,**, Д.Р. Гилязетдинова*,**,***, И.А. Березина*, И.О. Баюк*
*Институт физики Земли им. О.Ю. Шмидта, **МФТИ(ГУ), ***МГУ

Goal

The aim of this work is to explain the role of mineralogical and structural parameters in elastic properties of carbonate reservoir rocks
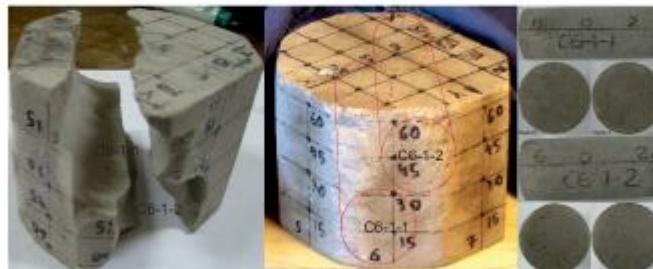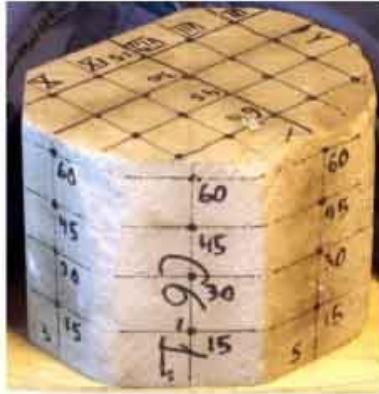
Problems to be solved

- Preparation of rock samples
- Measuring of static and dynamic elastic properties
- Obtaining of mineral composition
- Construction of relations between elastic properties and known parameters
- Analysis of variance (ANOVA)
- Defining parameters with the most contribution
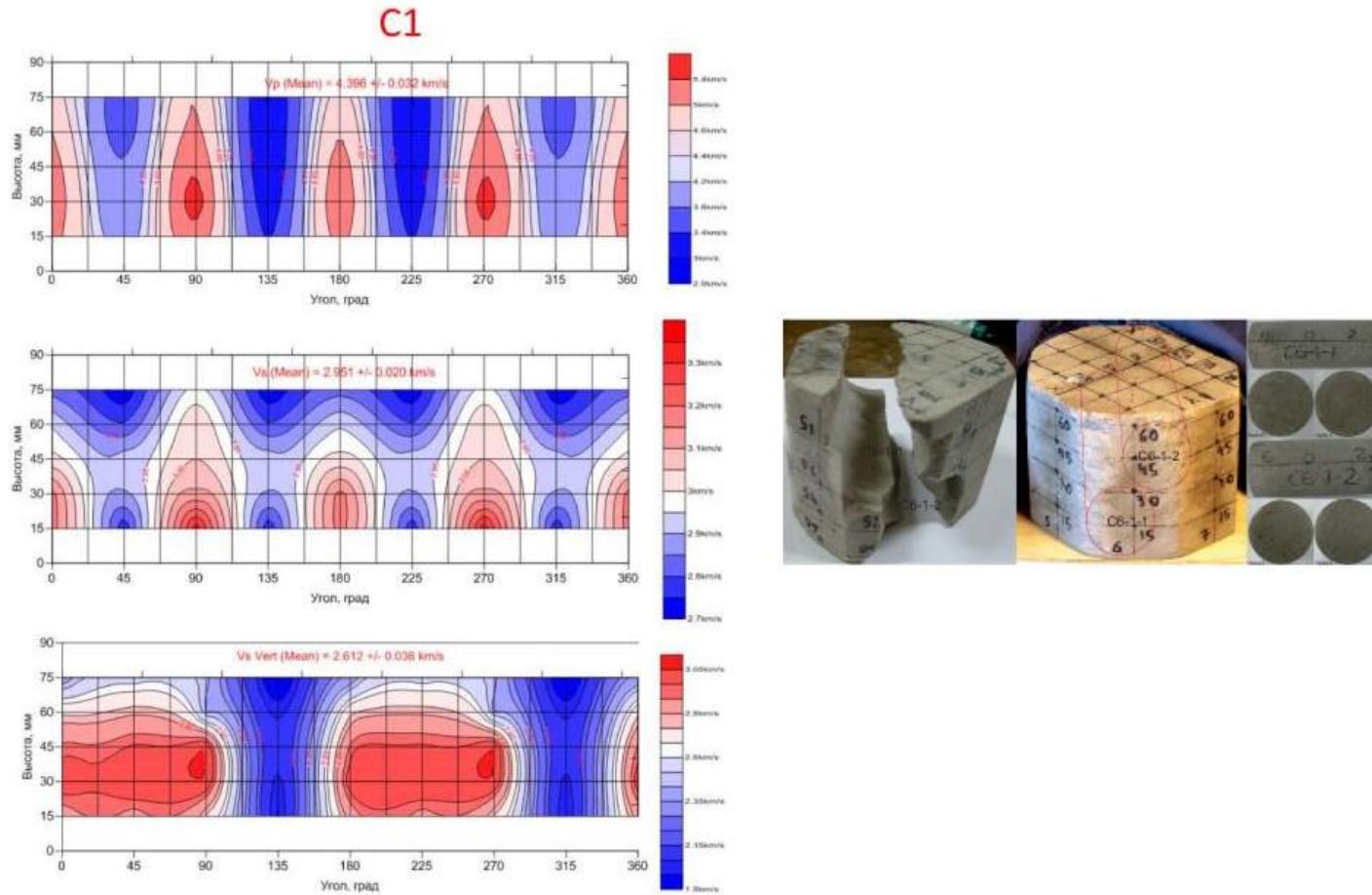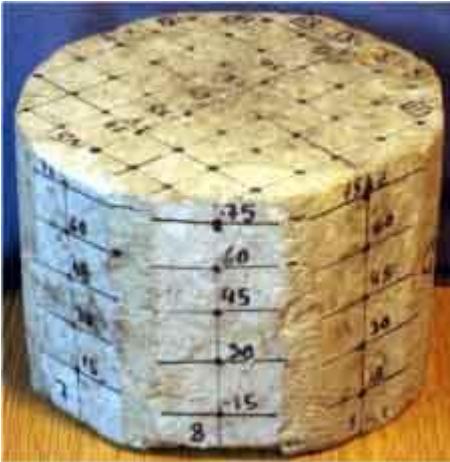
Rock sampling and preparation for the experiment

7 full samples of carbonate rocks
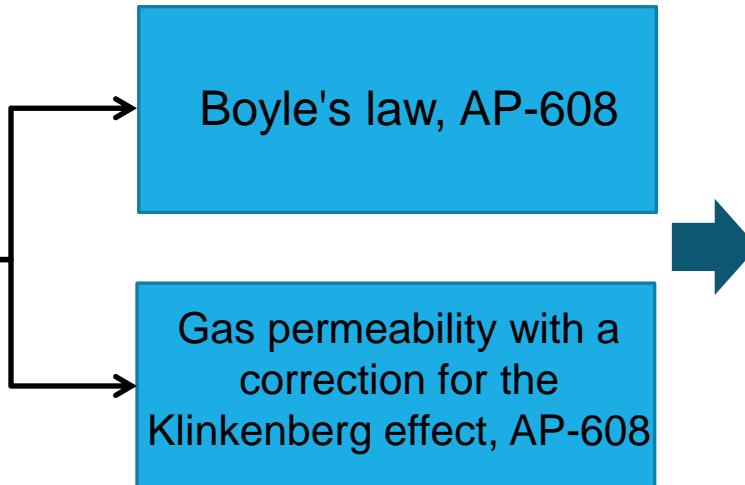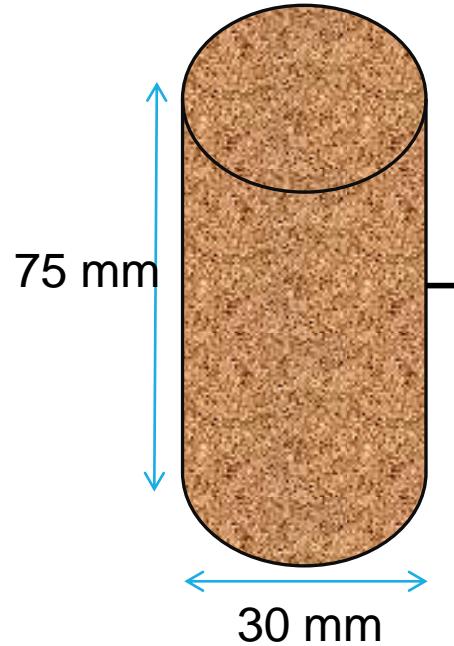
Ultrasonic tomography of the full length core samples and its application to determine the zone heterogeneity

Research methodologies to determine porosity and permeability of rock samples

20 core samples from the main rock samples

75 mm

30 mm

Boyle's law, AP-608

Gas permeability with a correction for the Klinkenberg effect, AP-608
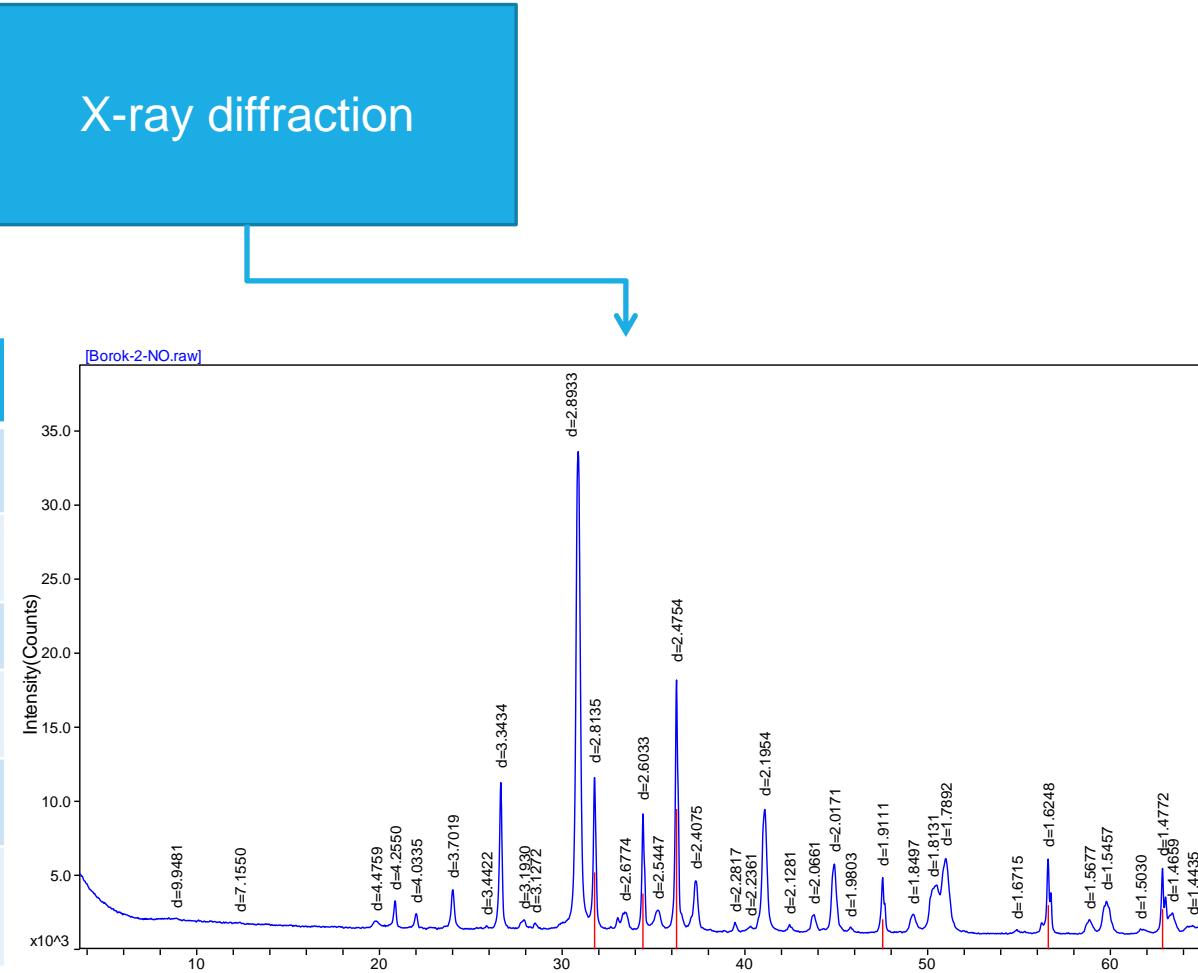
Core sample	Average Porosity (%)	Average permeability (mD)
C1	6-14%	2.12
C2	4%	0.031
C3	4%	0.031
C4	4%	0.031
C5	6-14%	2.12
C6	23%	10

Lithological description of the rock samples

Scanning electron microscope (SEM) «Jeol JSM-6480LV»

X-ray diffraction
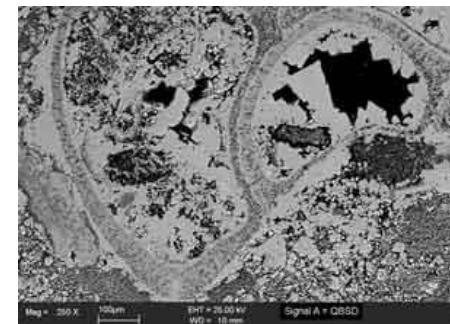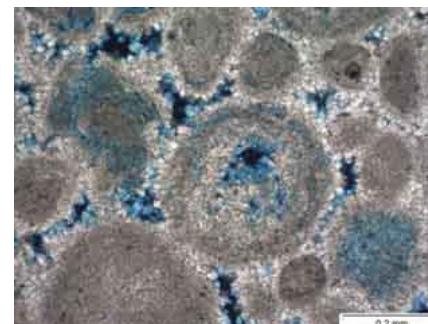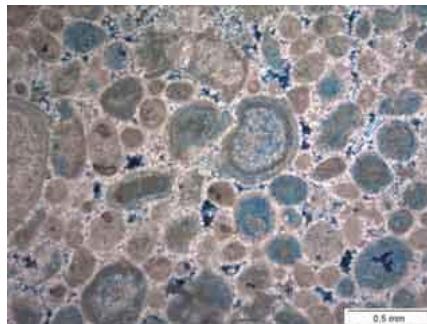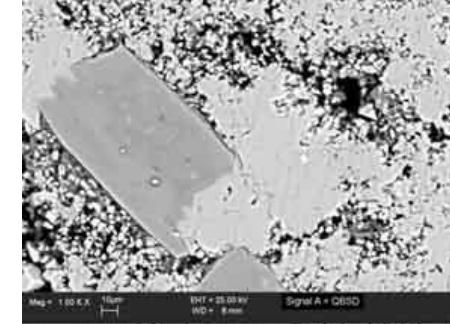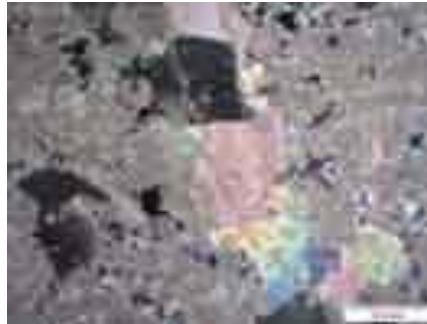
	C1-1	C1-2	C2-1	C3-3	C4-2	C4-2-1	C5-2	C5-3	C6-1-2
Calcite	52	59.5	97.6	100	0	0	82.4	52	99.5
Dolomite	47.5	40.1	1.3	0	37	33.6	14.5	34.6	0
Illite	0	0	0.5	0	5.5	4.8	0.7	4	0
Chlorite	0	0	0	0	1.9	3.4	0	2.3	0
Quartz	0.5	0.4	0.6	0	49.9	48.1	2.4	7.1	0.5
K-feldspar	0	0	0	0	5.8	10	0	0	0

Microstructural description of the rock samples

Microstructural description of the rock samples
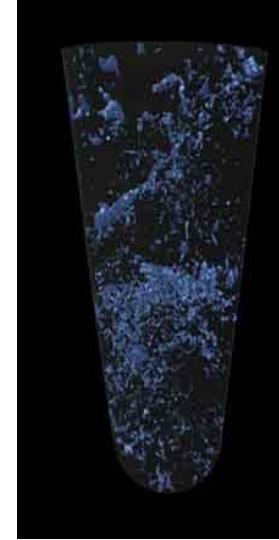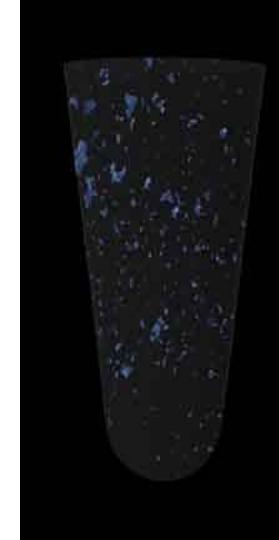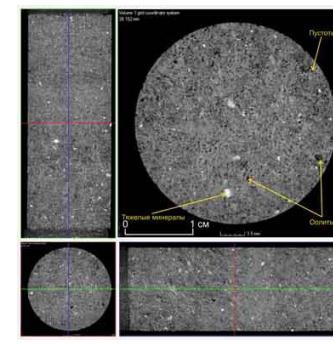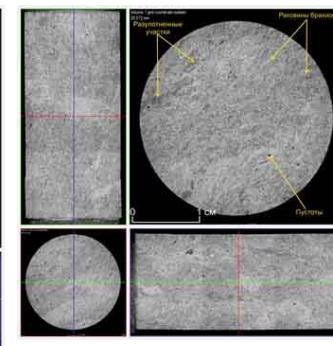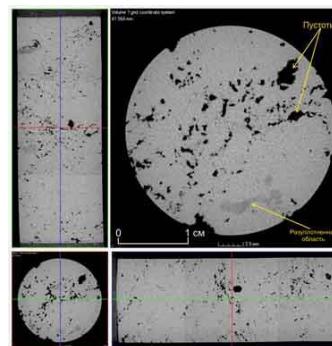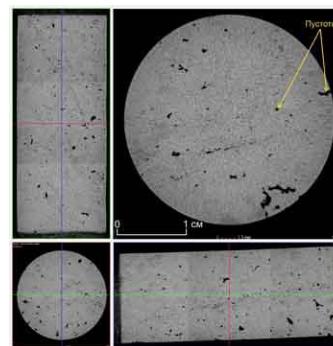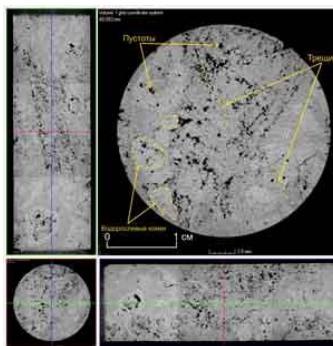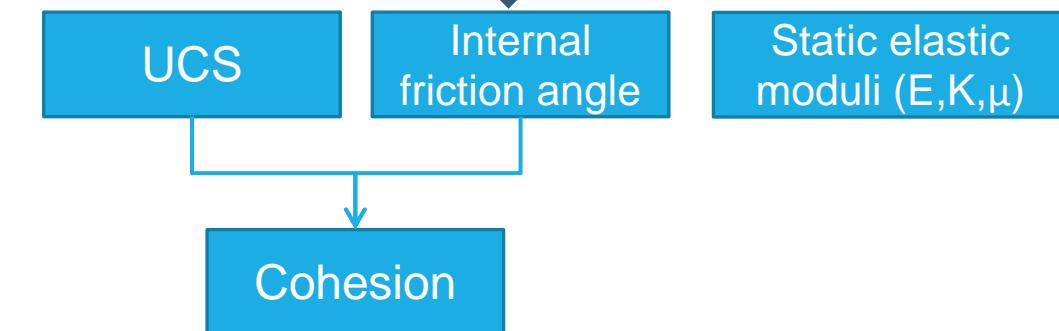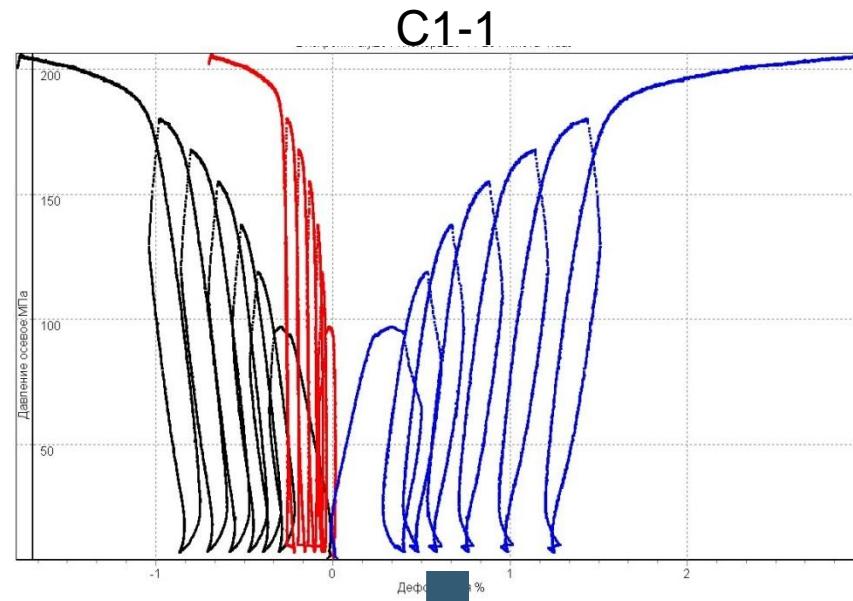
C1-1   C2-1   C3-2   C5-1   C6-1-1

Acoustic measurements of rock samples

	Lithology description	V_p-(30*60)	V_s-(30*60)
C1	Limestone organogenic-clastic, carbonate rocks	4.19/0.34	2.85/0.18
C2	Micritic limestone. carbonate rocks	5.79/0.4	3.06/0.26
C3	Micritic limestone. carbonate rocks, calcite	5.21/0.36	3.26/0.22
C4	Quartz Sandstone. Breed dolomite, clay and sandy. Carbonate cement - 33%	4.93/0.36	3.07/0.16
C5	Limestone organogenic-detrital clastic (brachiopod). carbonate composition	3.56/0.26	2.16/0.15
C6	Oolitic limestone. The mineral composition mainly calcite oolites. Cement rock - basal, fine-crystalline (with crystal size of 0.01 mm). Calcite composition	3.8/0.2	2.2/0.16
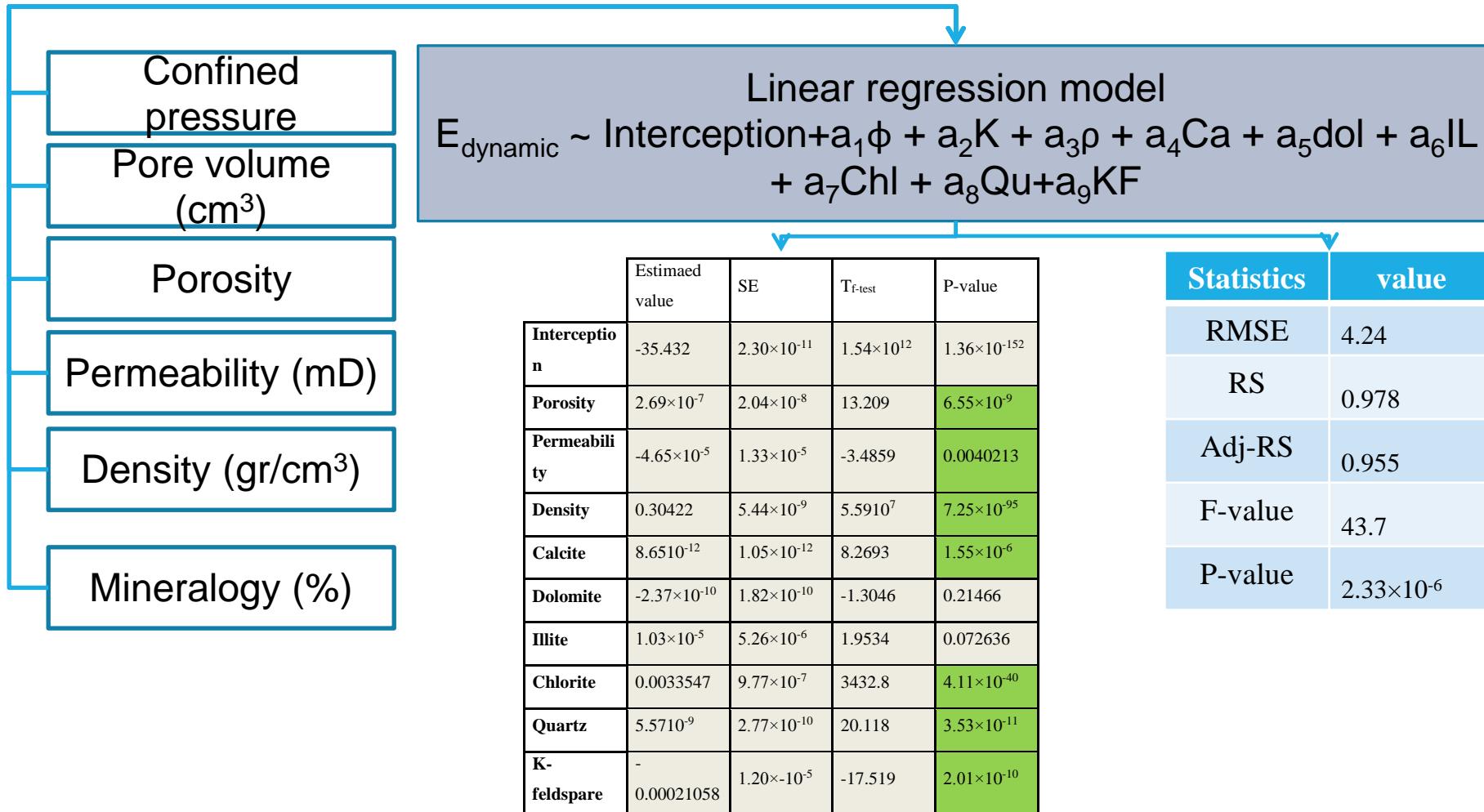
Tri-axial confined and unconfined compressive experiments

C1-1

UCS

Internal friction angle

Static elastic moduli (E,K,μ)

Cohesion
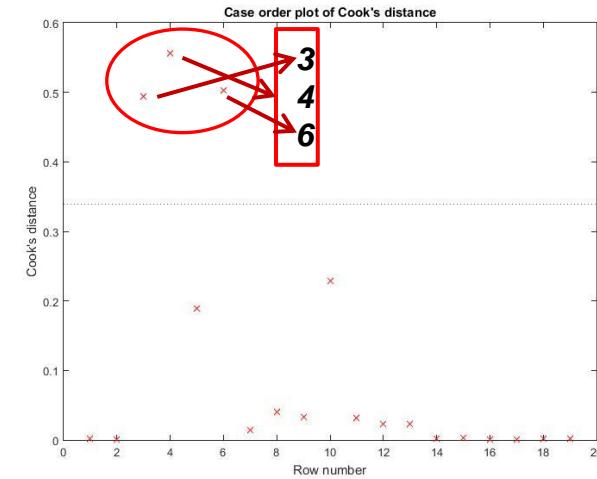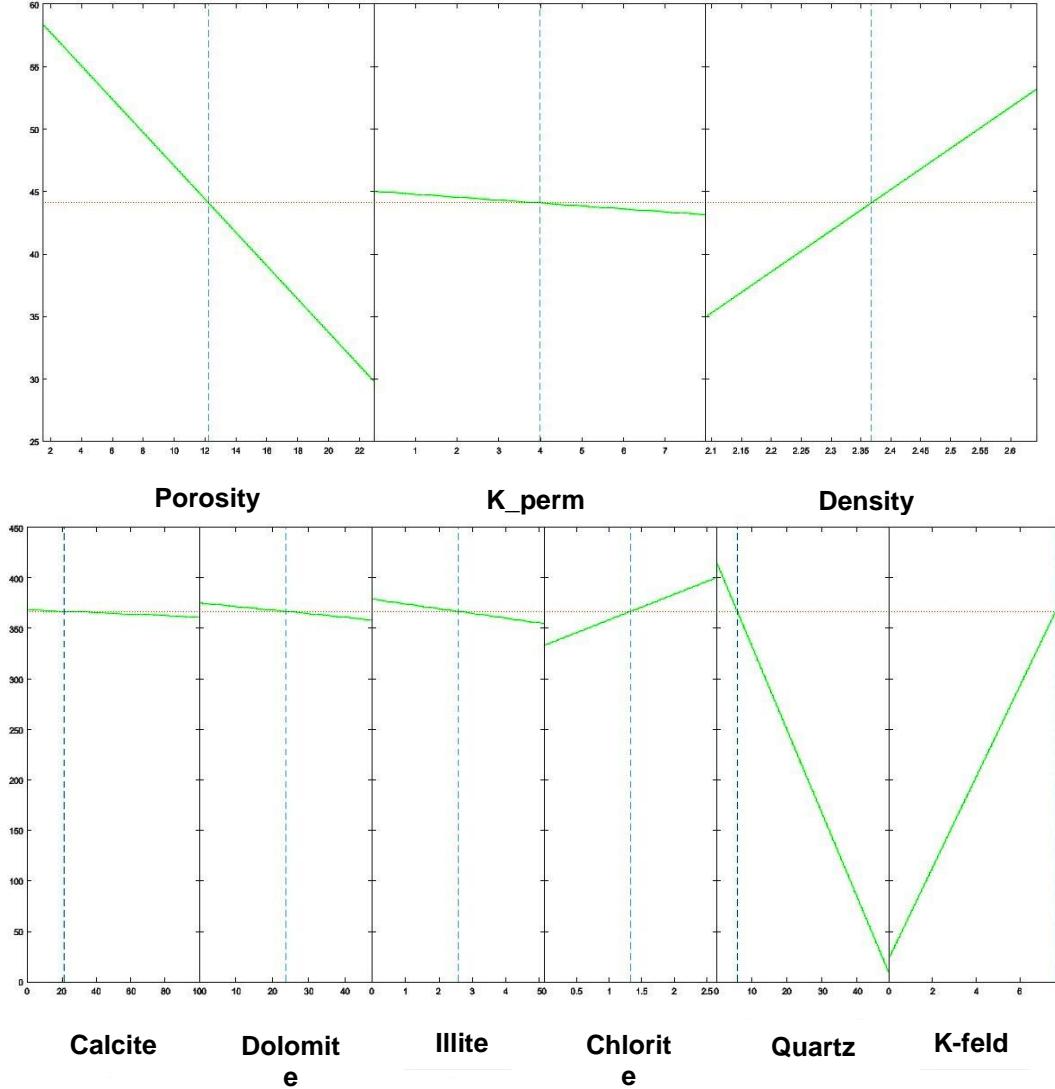
Summary of petrophysical-mineralogical-elastic properties

|	P_conf (psi)	V_pore (cm3)	Porosity	K_corrected	density	Calcite	Dolomite	Illite	Chlorite	Quarts	K-feldspare	E_dynamic	E_static	K=D_dyn/E_stat
C1-1	487.1	5	7.64	1303	2.57	52	47.5	0	0	0.5	0	49.194	29.3	2.411
C1-2	480.5	4	6	431	2.57	59.5	40.1	0	0	0.4	0	54.344	36.77	1.922
C2-1	491.6	2	4	38	2.603	97.6	1.3	0.5	0	0.6	0	64.005	17.83	4.711
C2-2	487.9	1	3.09	1	2.603	97.6	1.3	0.5	0	0.6	0	68.466	17.83	4.712
C3-1	482.8	1	2	31	2.644	100	0	0	0	0	0	73.554	46.76	2.145
C3-2	477.7	2	3	1	2.644	100	0	0	0	0	0	79.136	43.94	2.278
C3-3	481.4	1	2	11	2.644	100	0	0	0	0	0	78.675	47.11	2.125
C4-1	460.6	1.4	3	2	2.45	0	35.3	5.15	2.65	49	7.9	56.902	38.23	1.947
C4-2	487.8	1	2	1	2.45	0	35.3	5.15	2.65	49	7.9	57.951	27.5	2.707
C4-3	469.2	2	3	1	2.45	0	35.3	5.15	2.65	49	7.9	50.097	48.83	1.524
C4-4	471.9	1	2	1	2.45	0	35.3	5.15	2.65	49	7.9	57.959	38.35	1.941
C5-2	482.6	6	12	37	2.421	82.4	14.5	0.7	0	2.4	0	29.733	17.72	2.663
C5-3	467.5	7.46	14	54	2.421	52	34.6	4	2.3	7.1	0	26.69	22.4	2.109
C5-4	484.1	9	13	38	2.421	67.2	24.55	2.35	1.15	4.75	0	26.359	23.5	2.01
C6-1-1	478.8	11.85	23	7564	2.09	99.5	0	0	0	0.5	0	24.903	23.5	1.289
C6-1-2	476.8	9.3	21.761	6364	2.09	99.5	0	0	0	0.5	0	26.959	23.5	1.289
C6-2-1	489	11	23	7966	2.09	99.5	0	0	0	0.5	0	25.339	17.83	1.868
C6-2-2	497.5	11	23	7800	2.09	99.5	0	0	0	0.5	0	25.823	8.45	3.585
C6-2-3	488.9	11	22	5225	2.09	99.5	0	0	0	0.5	0	26.953	16.62	1.64

Dynamic elastic moduli prediction based on the microstructural and mineralogical properties

Confined pressure

Pore volume (cm³)

Porosity

Permeability (mD)

Density (gr/cm³)

Mineralogy (%)

Linear regression model

$E_{dynamic} \sim Interception + a_1\phi + a_2K + a_3\rho + a_4Ca + a_5dol + a_6IL + a_7Chl + a_8Qu + a_9KF$

	Estimaed value	SE	T_{f-test}	P-value
Interception	-35.432	2.30×10^{-11}	1.54×10^{12}	1.36×10^{-152}
Porosity	2.69×10^{-7}	2.04×10^{-8}	13.209	6.55×10^{-9}
Permeability	-4.65×10^{-5}	1.33×10^{-5}	-3.4859	0.0040213
Density	0.30422	5.44×10^{-9}	5.5910^7	7.25×10^{-95}
Calcite	8.6510^{-12}	1.05×10^{-12}	8.2693	1.55×10^{-6}
Dolomite	-2.37×10^{-10}	1.82×10^{-10}	-1.3046	0.21466
Illite	1.03×10^{-5}	5.26×10^{-6}	1.9534	0.072636
Chlorite	0.0033547	9.77×10^{-7}	3432.8	4.11×10^{-40}
Quartz	5.5710^{-9}	2.77×10^{-10}	20.118	3.53×10^{-11}
K-feldspare	-0.00021058	1.20×-10^{-5}	-17.519	2.01×10^{-10}

| Statistics	value
RMSE	4.24
RS	0.978
Adj-RS	0.955
F-value	43.7
P-value	2.33×10^{-6}

Dynamic elastic moduli prediction based on the microstructural and mineralogical properties

Porosity   K_perm   Density

Calcite   Dolomite   Illite   Chlorite   Quartz   K-feld

Static elastic moduli prediction based on the microstructural and mineralogical properties

Confined pressure

Pore volume (cm^3)

Porosity

Permeability (mD)

Density (gr/cm^3)

Mineralogy (%)

Linear regression model

$$E_{static} \sim Interception + a_1\phi + a_2K + a_3\rho + a_4Ca + a_5dol + a_6IL + a_7Chl + a_8Qu + a_9KF$$

	Estimaed value	SE	T-stat	P-value
Interception	-51.024	0.50981	-100.08	2.43×10^{-16}
Porosity	0.37762	3.9052	0.096695	0.92488
Permeability	-1.6516	3.0865	-0.53512	0.60426
Density	57.362	124.59	0.4604	0.65508
Calcite	-0.5537	3.3694	-0.16433	0.87274
Dolomite	-0.92303	3.5313	-0.26139	0.7991
Illite	-70.415	18.452	-3.8161	0.0033951
Chlorite	73.683	16.683	4.4166	0.001301
Quartz	14.571	11.108	1.3117	0.21892
K-feldspare	-71.675	50.501	-1.4193	0.18623

Statistics	value
RMSE	6.35
RS	0.851
Adj-RS	0.732
F-value	7.15
P-value	2.76×10^{-3}

Static elastic moduli prediction based on the microstructural and mineralogical properties

Description of K-value based on the microstructural and mineralogical properties

Confined pressure

Pore volume (cm^3)

Porosity

Permeability (mD)

Density (gr/cm^3)

Mineralogy (%)

Linear regression model
$$K\sim \text{Interception}+a_1\phi + a_2K + a_3\rho + a_4Ca + a_5dol + a_6IL + a_7Chl + a_8Qu+a_9KF$$

	Estimaed value	SE	T-stat	P-value
Interception	-0.15186	0.41288	-0.36779	0.078094
Porosity	0.37044	0.32632	1.1352	0.009945
Permeability	-1.8834	13.172	-0.14298	0.964860
density	0.075791	0.35624	0.21275	0.026222
Calcite	0.096086	0.37337	0.25735	0.03074
Dolomite	7.5232	1.9512	3.8556	0.004283
Illite	-7.6398	1.7638	-4.3315	0.001438
Chlorite	-1.5927	1.174	-1.3566	0.0010838
Quartz	8.003	5.3397	1.4988	0.027223
K-feldspare	-0.15186	0.41288	-0.36779	0.078094

Statistics	value
RMSE	0.671
RS	0.769
Adj-RS	0.6
F-value	4.16
P-value	1.96×10^{-2}

Description of K-value based on the microstructural and mineralogical properties

Thank You!