USE OF SIGMA METHOD IN THE EVALUATION AND CHARACTERIZATION OF SANDSTONE UNIT A IN ŽUTICA OIL AND GAS FIELD

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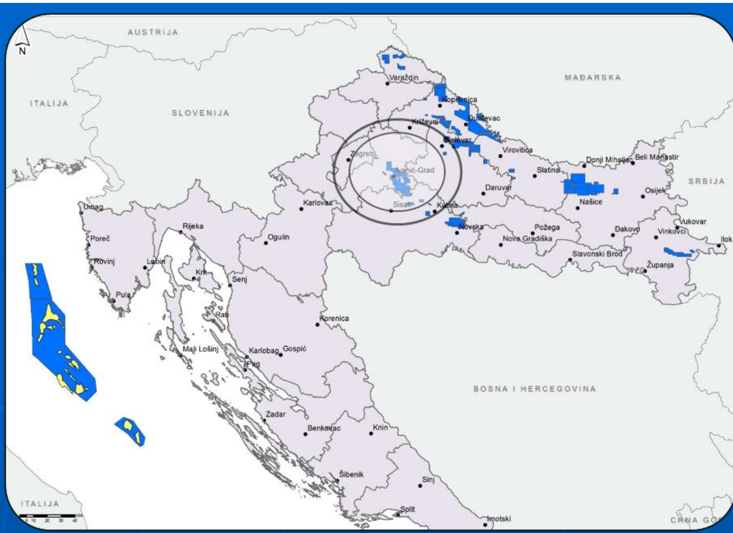
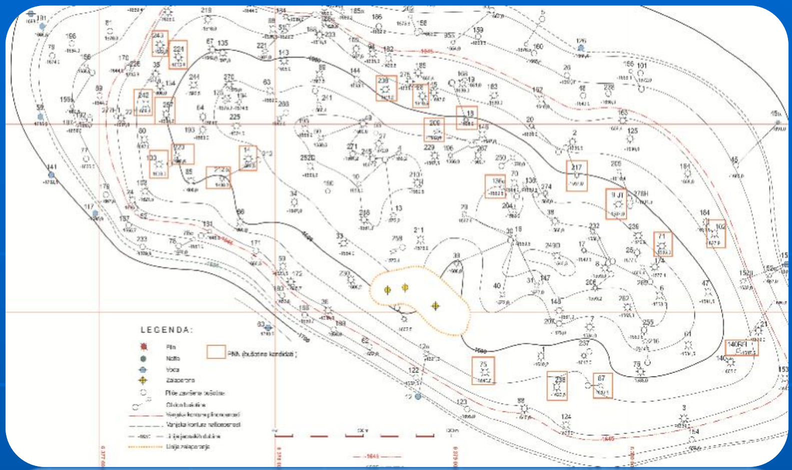
- DEPOSITIONAL MODEL
- SIGMA METHOD BASICS
- WATER SATURATION CALCULATION BY SIGMA METHOD
- SIGMA OF MINERALS, ROCKS & FLUIDS
- USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD
- SIGMA INTERPRETATION VS. TEST RESULTS
- CONSLUSIONS AND RECOMMENDATIONS

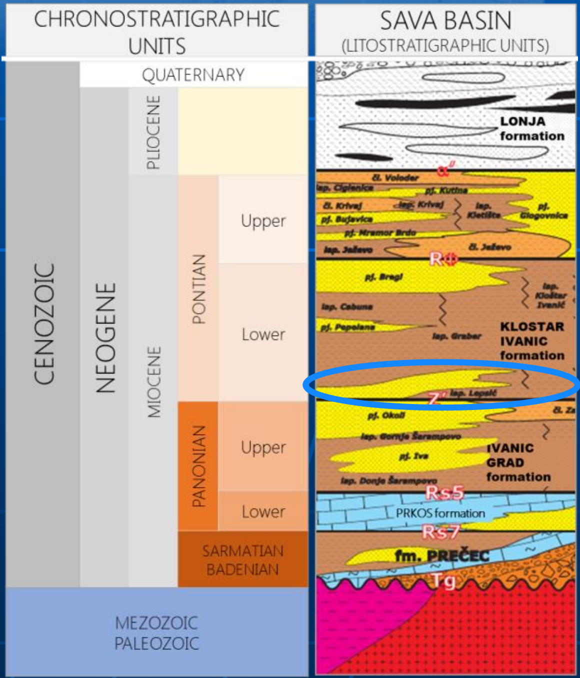
FIELD & GEOLOGICAL DATA





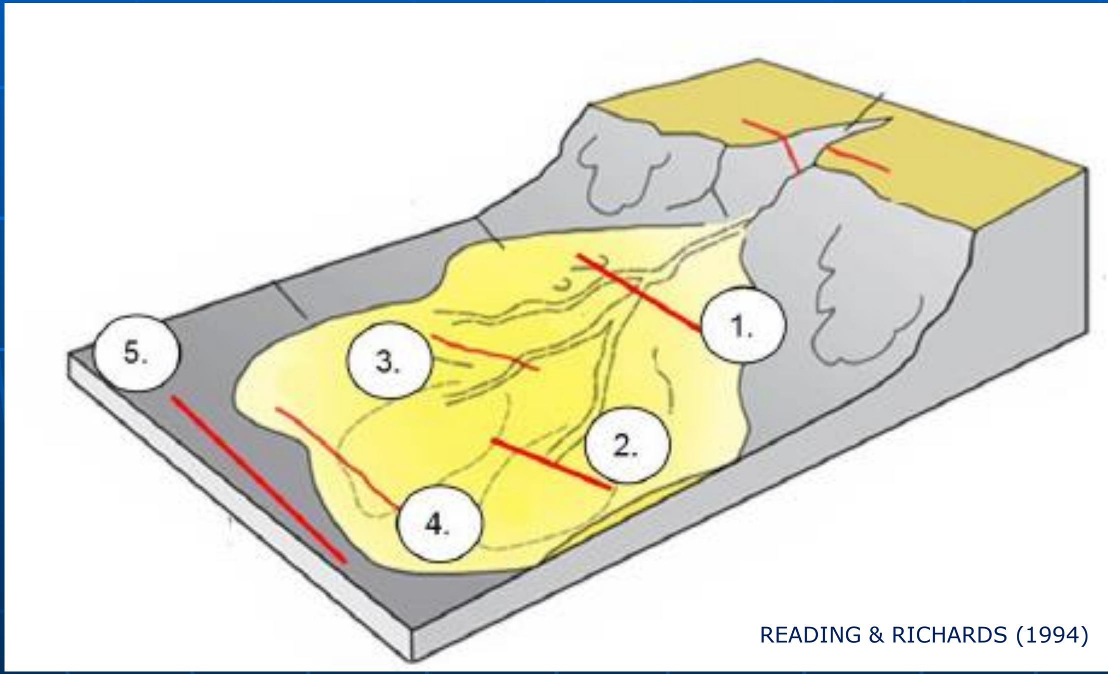
- FIELD DATA
  - placed in central part of Croatia, in Sava Basin
  - mature field, in production since 1966
  - chosen for EOR project: CO_2

- GEOLOGICAL DATA
  - Upper Pannonian deepwater sediments
  - composed of sandstones, siltstones and marls
  - Sandstone Unit A (Poljana sandstones Member), subdivided into A_3, A_2, A_1, A and A'



DEPOSITIONAL MODEL

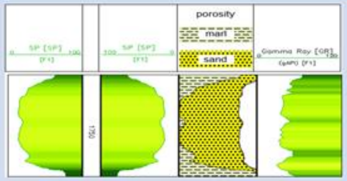
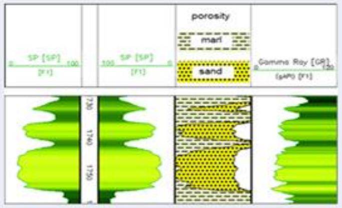
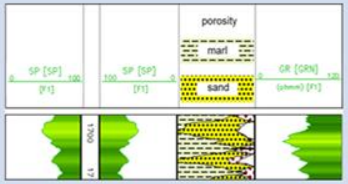
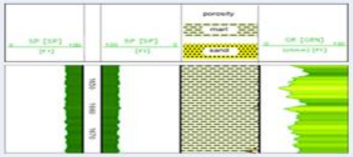
- Sediments were deposited in deepwater environment by turbiditic mechanism (Šimon, 1980; Vrbanac, 1996)
- Coarse-grained sand detritus was deposited within channels and fine-grained along levees. Occasinally, due to a more intense influx of the clastic material, sandstones were deposited in the form of turbiditic splays/lobes



1) Channel, 2) Lobe, 3) Levee, 4) Distal lobe and 5) Basin marls

DEPOSITIONAL MODEL

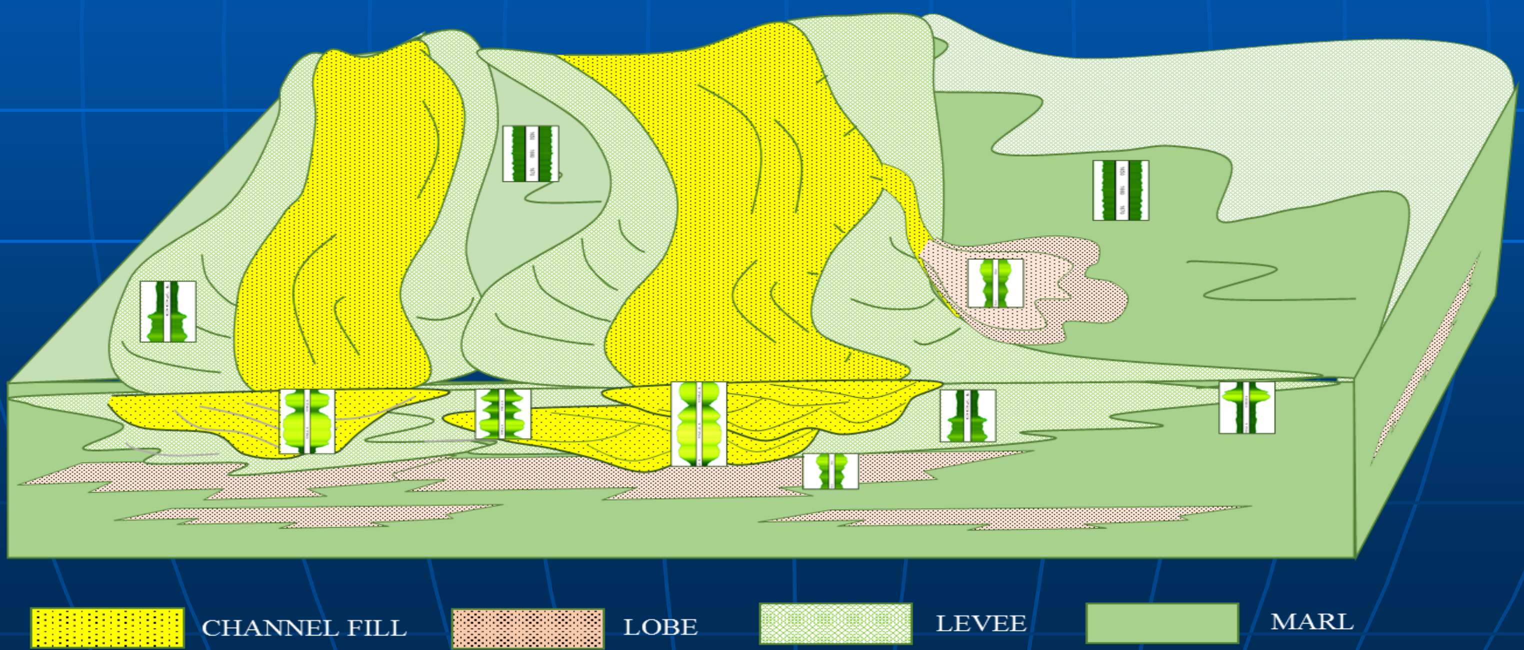
- Shape of SP/GR curves indicates depositional facies – shape of well log is related to the grain size of rock successions (Rider, 1986)
- Cylindrical, bell, funnel and irregular SP/GR log shape have been identified
- According to SP/GR log shapes the following depositional elements have been recognized: CHANNELS, LEVEE, SPLAYS/LOBES AND BASIN MARLS

SP/GR LOG SHAPE	LITHOFACIES ASSOCIATION	DEPOSITIONAL ELEMENT	SP/GR LOG SHAPE AND DEPOSITIONAL ELEMENT
CYLINDRICAL	thick beded masive sandstones; sharp top and base with consistent trend; thickness up to 20 m	CHANNEL AXIS	
BELL	masive and layered sandstone and siltstone; abrupt base with fining upward trend – SP/GR values increase upward indicate increasing in the shale content upward	CHANNEL MARGIN, LEVEE	
FUNNEL	thick and thin layered sandstones and siltstones; SP and GR values decrease upward indicating decrease of shale content, forming coarsening upward trend with abrupt top	SPLAY/LOBE	
IRREGUALAR	marls with rare layers of siltstones	BASIN DEPOSIT	

DEPOSITIONAL MODEL

- Each depositional element is characterized by a unique set of attributes:

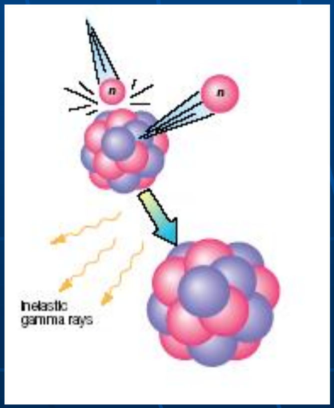
  1. CHANNEL FILLS - cylindrical/bell SP/GR shape; erosional bases, thick bedded massive sands
  2. LEVEE DEPOSITS - bell SP/GR shape; thin-bedded turbidites deposited outside channels; increased content of clay and silt
  3. SPLAYS/LOBES - funnel/symmetrical SP/GR shape; bedded turbidites, sheet geometry
  4. BASIN MARLS - irregular SP/GR shape; marls with rare layers of silts



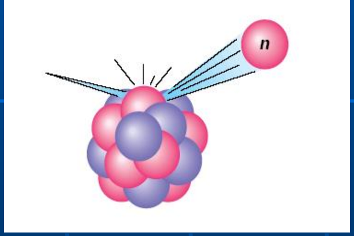
SIGMA METHOD BASICS

- a pulsed neutron logging method
- high energy neutron source (minitron) emits fast neutrons
- interactions with the atomic nuclei within reservoir rocks and fluids in the pore space
- loss of energy, partial capture of neutrons by atomic nuclei of the surrounding media (reservoir rocks and fluids)
- thermal neutrons registered by the detectors
- SIGMA (neutron capture cross section) – the capacity of the minerals and fluids to capture the neutrons

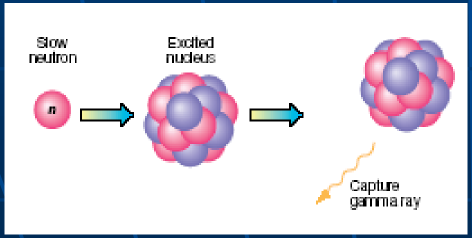
a) inelastic scatter

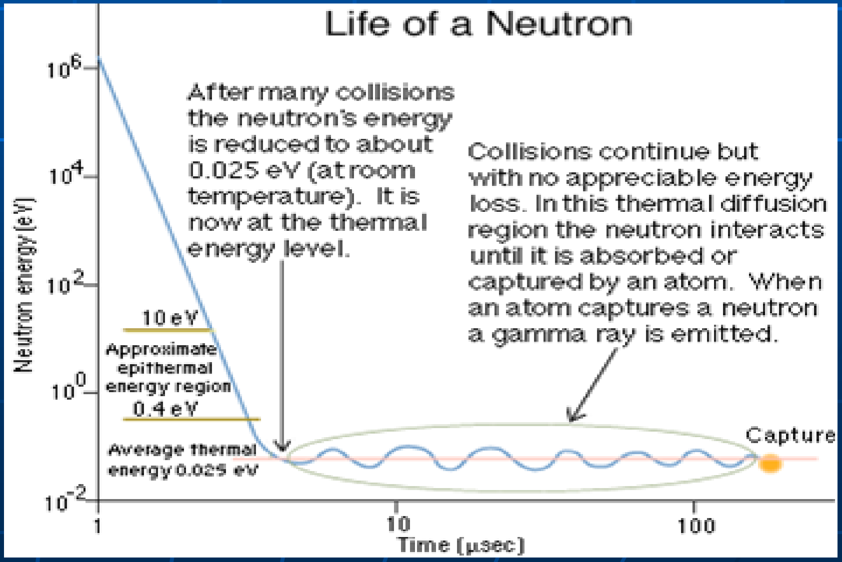


b) elastic collision



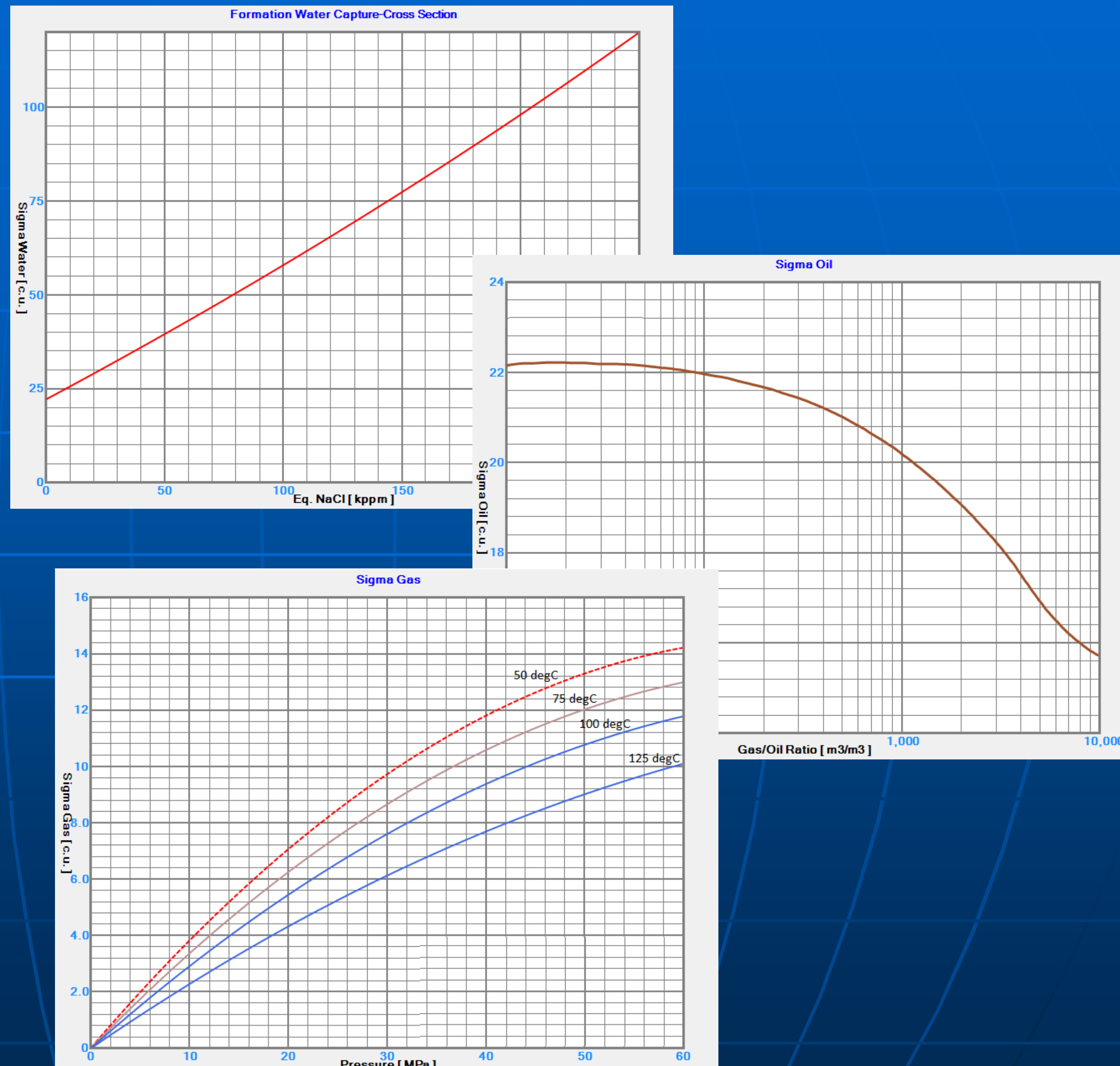
c) neutron capture



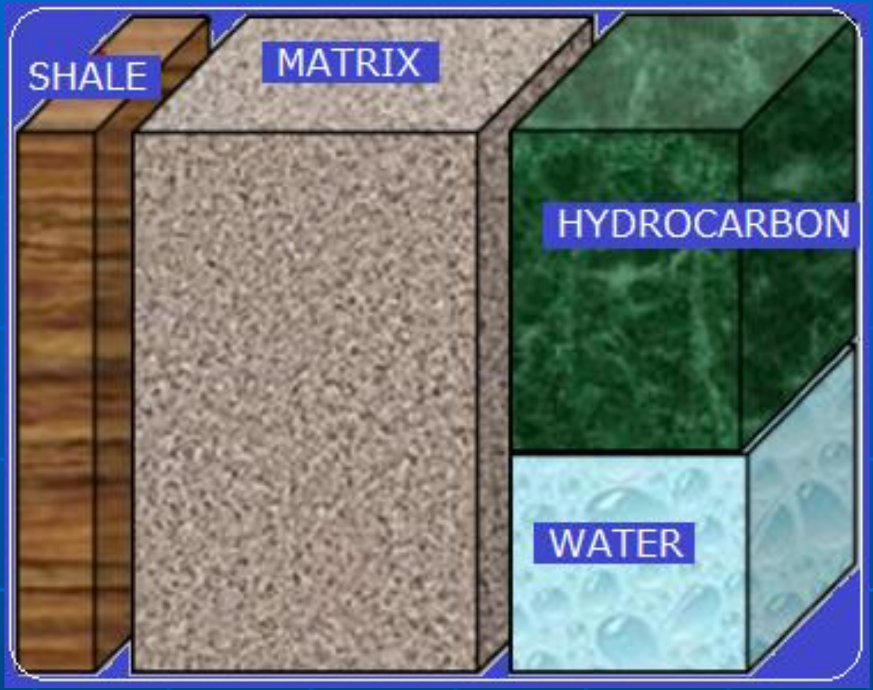


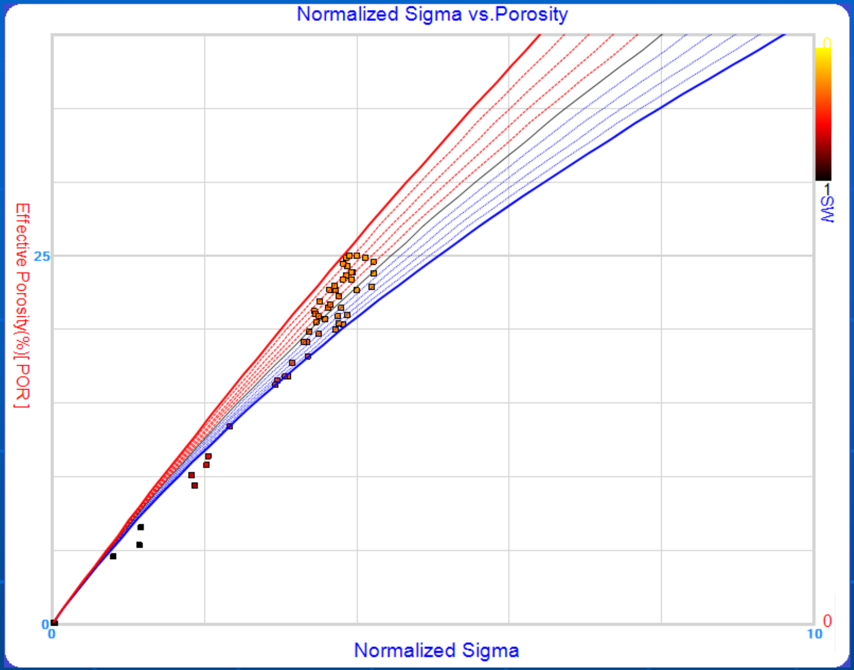
SIGMA OF MINERALS, ROCKS & FLUIDS

Material	SIGMA @ 20°C
quartz	4.26
calcite	7.07
dolomite	4.7
anhydrite	12.5
gypsum	18.4
magnesite	1.44
muscovite	16.9
biotite	30.0
chlorite	25.3
glauconite	23.4
kaolinite	12.8
montmorillonite	14.5
illite	15.5
iron	193
tourmaline	4,310 - 7,450
rock salt	753
sandstone	7 - 16
limestone	7 - 11
dolomite	6 - 10
shale	25 - 45
fresh water	22
salt water	25 - 138
oil	17 - 22
gas	5 - 17



WATER SATURATION CALCULATION BY SIGMA METHOD





$$\Sigma_{log} = V_{sh}\times\Sigma_{sh} + (1-V_{sh}-\Phi)\times\Sigma_{ma} + \Phi\times S_w\times\Sigma_w + \Phi\times(1-S_w)\times\Sigma_{hc}$$

SHALE | MATRIX | PORE SPACE

$$S_W=[V_{sh}\times(\Sigma_{sh}-\Sigma_{ma})+\Phi\times(\Sigma_{hc}-\Sigma_{ma})+(\Sigma_{ma}-\Sigma_{log})]/[\Phi\times(\Sigma_{hc}-\Sigma_w)]$$

USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD

- Continuous oil production from the oil ring and periodic gas production/injection from/into the gas cap of Unit A reservoirs in the past five decades
- Changes of the original positions of oil/water and gas/oil contacts
- Main objectives of SIGMA logging/interpretation campaign:
  - identification and quantification of residual hydrocarbons
  - defining current oil/water and gas/oil contacts
- Extent of the capaign:
  - 34 wells loggged
  - 20 Unit A reservoir intervals/groups of intervals in 14 wells tested
  - in other 20 wells testing/production targets in deeper reservoir units (B & gama)

USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD

- Challenges & limitations:
  - low SIGMA contrast between oil and water zones due to:

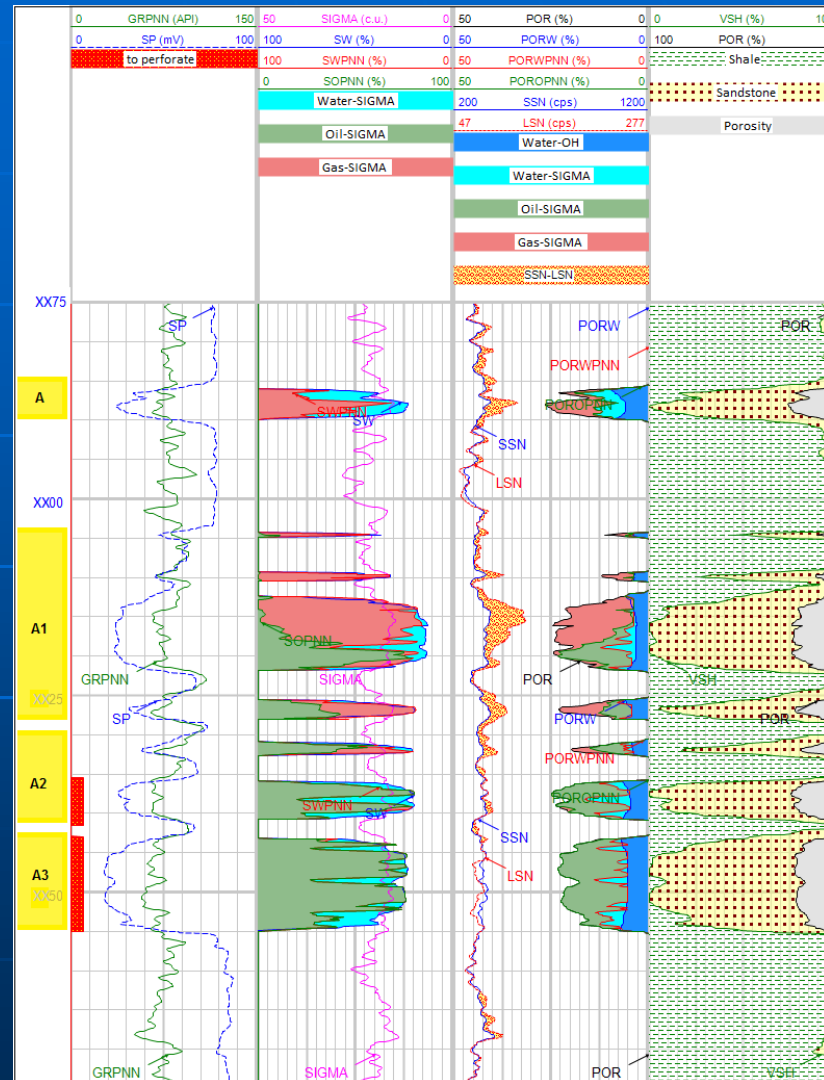
    a) low salinity of reservoir water (14-18 g/l NaCl equivalent)

    b) contribution of unrecoverable oil in the depleted oil zones to the measured SIGMA
  - mineralogical/sedimentological heterogeneity of reservoir rocks
  - limited mineralogical data needed for reliable selection of rock matrix SIGMA available
  - inconsistent log data quality due to increasing working hours of neutron generator (minitron)

- Key solutions:
  - selection of matrix SIGMA characteristic of depositional elements, based on SP/GR/SIGMA log shapes/values
  - detailed local knowledge and experience gradually developed during the execution of the project

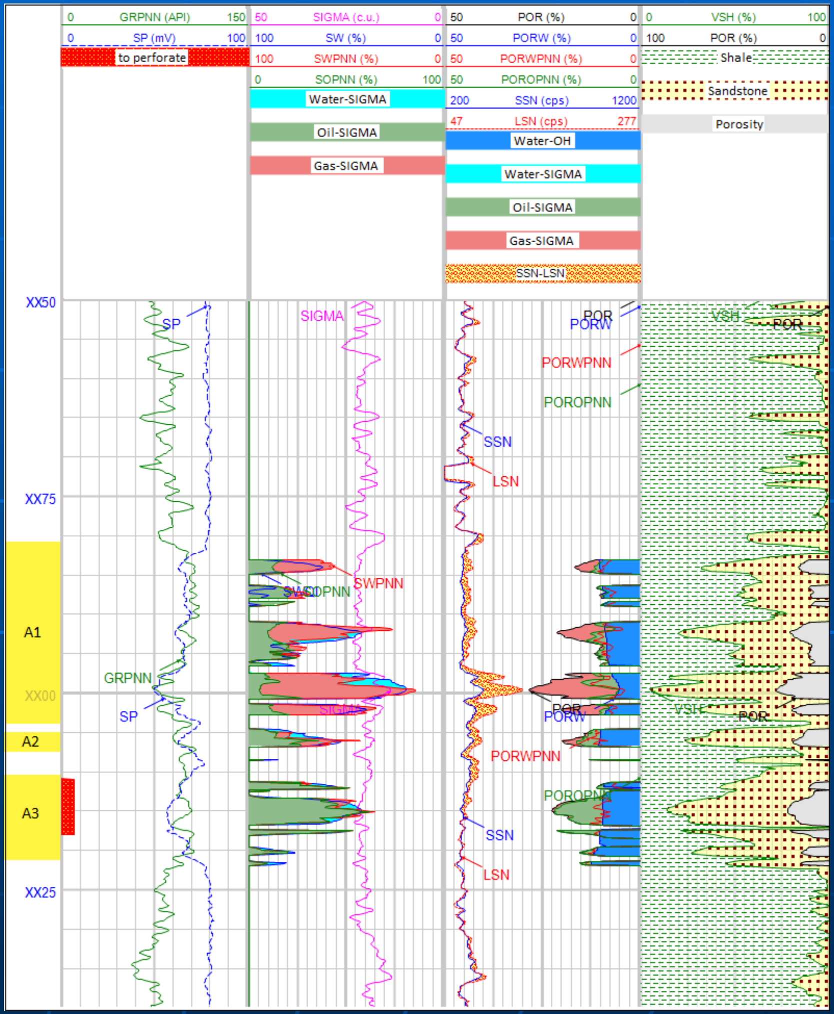
USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD

- **Well-11:**
  - channel fills in the botom/middle parts of the reservoirs (clean quartz/mica sandstones) – relatively low matrix SIGMA values (11-12 c.u.) used in the interpretation
  - transition to levee deposits in the top parts (silty/clayey sandstones) – slightly higher matrix SIGMA values (13-14 c.u.) used
  - based on SIGMA interpretation A_3 and A_2 (bottom part) reservoirs selected for testing
  - 8 m^3/day of oil produced
  - log shape and fluid distribution suggest that the sandstone considered the bottom layer of A_1 is actually the top layer of A_2



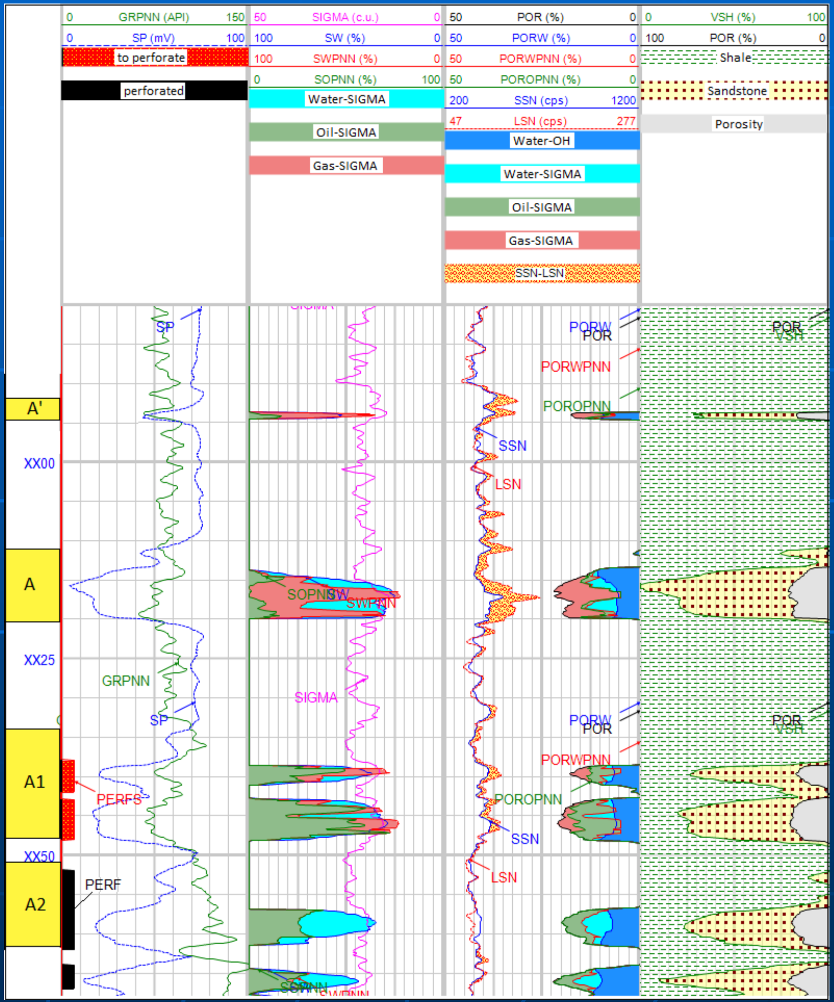
USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD

- **Well-5:**
  - levee deposits (silty/clayey sandstones)
  - medium matrix SIGMA values (13-14 c.u.) used in cleaner parts
  - higher matrix SIGMA values (15-20 c.u.) used in more silty/clyey zones
  - based on SIGMA interpretation A_3 reservoir selected for testing
  - 3000 m^3/day of gas produced!!?
  - possible causes of log analysis vs. well test result mismatch:
    1. mineralogical heterogeneity influencing the interpretation
    2. low relative permeability for liquid phase
    3. behind casing communication



USE OF SIGMA METHOD IN UNIT A OF ŽUTICA FIELD

- **Well-12:**
  - splay/lobe deposits (layered clean quartz/mica sandstones, silty/clayey sandstones and siltstones)
  - zonation and variation of matrix SIGMA values used in the interpratation based on SP/GR/SIGMA log shape and values
  - based on SIGMA interpretation A_1 reservoir selected for testing
  - 3.5 m^3/day of oil produced



SIGMA INTERPRETATION VS. TEST RESULTS

Well	Analysis results	Tested reservoirs	Test results
1	A3 & A2 water, A1 oil with some water in the bottom part	A1	10 m3/day of oil, without water
2	A3 & A2 water, A1 bottom part oil, top part gas, A water (depleted)	A3	the last (2nd) day of testing approx. 0.6 m3 of oil & 0.4 m3 of water (increased water percentage compared to the 1st day, reservoir water salinity - conclusion: water in the reservoir
		A1	approx. 1 m3/day of oil & 1 m3/day of water, without gas
3	A3 & A1 oil+water	A & A1	0.5 m3/day of liquid, 80% oil, 20% water
4	A3, A2 & A1 water, A gas	A3	approx. 10 m3/day of water
		A1	approx. 4 m3/day of oil, without water
5	A3 oil, A2 oil+gas, A1 gas	A3	approx. 3000 m3/day of gas through 3.5 mm choke
6	A3 oil, A2 & A1 gas	A3	0.9 m3/day of oil with traces of water and gas
		A2	approx. 20000 m3/day of gas & 2.4 m3/day of condensate
7	A3 & A2 oil+water, A1 gas, possibly some oil in the bottom part	A3	approx. 6.0 m3/day of liquid, 5.0 m3/day of water & 1.0 m3/day of oil
		A2	
		A2	approx. 2.0 m3/day of liquid, 1.5 m3/day of water & 0.5 m3/day of oil
		A1	approx. 0.9 m3/day of oil, without gas
8	A3, A2 & A1 water with some oil, A gas with some oil	A2 & A1	13.2 m3/day of water & 0.2 m3/day of oil
		A2	5.9 m3/day of water
9	A3 & A2 water, A1 gas+water, A & A' water+gas	A1	approx. 4.5 m3/day of water
10	A3 & A1 water with traces of HC	A3 & A1	3 m3/day of water
11	A3 & bottom part of A2 oil, top A2 & A1 gas, A some gas (partially depleted?)	A3 & A2	approx. 8 m3/day of oil, without water
12	A2 water, A1 oil with some gas, A & i A' gas	A1	approx. 3.5 m3/day of oil
13	A3 oil+some gas in the top part, A1 & A gas	A3	16.6 m3/day of oil & 1050 m3/day of gas
14	A3, A2, A1 & A gas, possibly some liquid phase in the bottom part of A3	A3	gas with some liquid

match	partial match	mismatch

- Given the unfavourable conditions (mineralogical/sedimentological heterogeneity, low water salinity) a reasonably high interpretation success rate achieved

CONCLUSIONS AND RECOMMENDATIONS

- Sandstone Unit A was deposited in deepwater environment by turbiditic mechanism
- According to SP/GR log shape, channels, levees, splays/lobes and basin marls have been recognized
- Each of these depositional elements is characterized by a unique set of reservoir attributes:
    - CHANNEL FILLS - cylindrical/bell SP/GR shape; erosional bases, thick-bedded massive sands
    - LEVEE DEPOSITS - bell SP/GR shape; thin-bedded turbidites deposited outside channels; increased content of clay and silt
    - SPLAYS/LOBES – funnel/symmetrical SP/GR shape; bedded turbidites, sheet geometry
    - BASIN MARLS - irregular SP/GR shape; marls with rare layers of silts

CONCLUSIONS AND RECOMMENDATIONS

- By carefully planned and executed SIGMA logging and interpratation campaign the following has been achieved:
  - current fluid saturation in the reservoirs determined
  - residual oil saturation identified and quantified
  - gas/oil and oil/water contacts redifined
  - oil production increased
  - better understanding of reservoir compartments, communication and flow barriers obtained
  - indications of changes in reservoir zonation
- Key factors in overcoming interpretational chalenges and limitations:
  - good understanding of depositional elements based on SP/GR/SIGMA log shapes/values
  - selection of adequate matrix SIGMA values
  - detailed local knowledge and experience developed during the execution of the project
- Recommended further application of the acquired information:
  - new geological model of Unit A, by integration with seismic and production data

LITERATURE

1. ČOGELJA, Z.: Identifikacija preostalih ugljikovodika u ležištu karotažom pobuđene radioaktivnosti, –Unpub. PhD Thesis, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb, 2011, 159 p.
2. ČOGELJA, Z. & KOSOVEC, Z.: Procjena zasićenja ugljikovodicima u ležištu uporabom puls-neutron metoda [*Hydrocarbon formation evaluation in reservoir using puls-neutron methods*], 5. međunarodni znanstven-stručni skup o naftnom gospodarstvu, Šibenik, Hrvatska, rujan-listopad 2009.
3. HOTWELL Ges.m.b.H: Pulse Neutron – Neutron System, Klingenbach, Austria, 2006.
4. READING, H. G. & RICHARDS, M.: Turbidite systems in deep-water basin margins classified by grain size and feeder system. American Association of Petroleum Geologists Bulletin, 1994, 78, 702-822.
5. RIDER, M. H.:Geological interpretation of well logs:-John Wiley and sons, New York NY, 1986, 175 p.
6. SMOLEN, J. J.: Cased Hole and Production Log Evaluation, PennWell, Tulsa, USA, 1995.
7. ŠIMON, J.: Prilog stratigrafiji u taložnom sustavu pješčanih rezervoara Sava-grupe naslaga mlađeg tercijara u Panonskom bazenu sjeverne Hrvatske [*Contribution to stratigraphy of sandstone reservoirs depositional system in the Sava Group sediments in Late Tertiary of Pannonian basin in the Northern Croatia – in Croatian*]. –Unpub. PhD Thesis, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb, 1980, 66 p.
8. VRBANAC, B.: Palaeostructural and sedimentological analyses of Late Pannonian sediments of Ivanić Grad formation in the Sava depression. -Unpubl. PhD Thesis, Faculty of Natural Sciences, Geol. Dep. Univ. Zagreb, Zagreb, 1996, 303 p.