Structural Inversions in Western Hungary and Eastern Slovenia: Their Impact on Hydrocarbon Trapping and Reservoir Quality*

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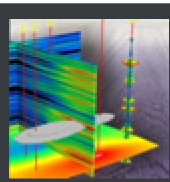
Abstract

The first major oil field discovered in Hungary, Budafa, is an inverted anticline found based on surface dip measurements in the western Pannonian Basin in the 1930's. Surface anticlines were known in this area for a long time as they were referred to as the “Sava Folds” after a local river crossing the border zone between Hungary, Slovenia and Croatia. As this particular exploration play was relatively simple, i.e. E-W trending anticlines with relatively shallow Pliocene to Miocene clastic reservoir targets, all these prospects were drilled up as early as in the 1940's and all of them are essentially depleted by now. Current exploration efforts are focusing on the deeper parts of these anticlines where reservoir quality prediction and imaging of viable traps are the main challenges. As most of these anticlines are the products of Late Pannonian (Pliocene) inversion of Middle Miocene syn-rift half-grabens, the proper structural understanding of the core of the anticlines is critical. Recently acquired 3D seismic reflection data over the Lovaszi-Petisovci gas field complex, which straddles the Hungarian-Slovenian border, is used as the critical new data for a case study to illustrate the nature of positive structural inversion in the western Pannonian Basin. The 3D seismic data were also used to find sweets spots in the tight sandstone reservoirs within the inverted Miocene deposits. Whereas the Sava Folds, including Lovaszi-Petisovci anticlines, have map-view dimensions on the scale of 10s of kilometers, the Transdanubian Central Range of western Hungary has also experienced inversion and significant neotectonic uplift during the Quaternary, but at much larger wavelength of about 100 km. The kinematics of this large-scale inversion and its impact on the hydrocarbon exploration potential are poorly understood at present. On the scale of the entire Pannonian Basin, the inverted structures are concentrated at the western margin of the basin gradually propagating eastwards into the basin since the Late Pliocene. The inversions are driven by the ongoing shortening in the broader area, including the Alps, between the Adriatic promontory of Africa and the European plate.



Structural Geology and Traps: Structures

Structural Inversions in Western Hungary and Eastern Slovenia:
Their Impact on Hydrocarbon Trapping and Reservoir Quality

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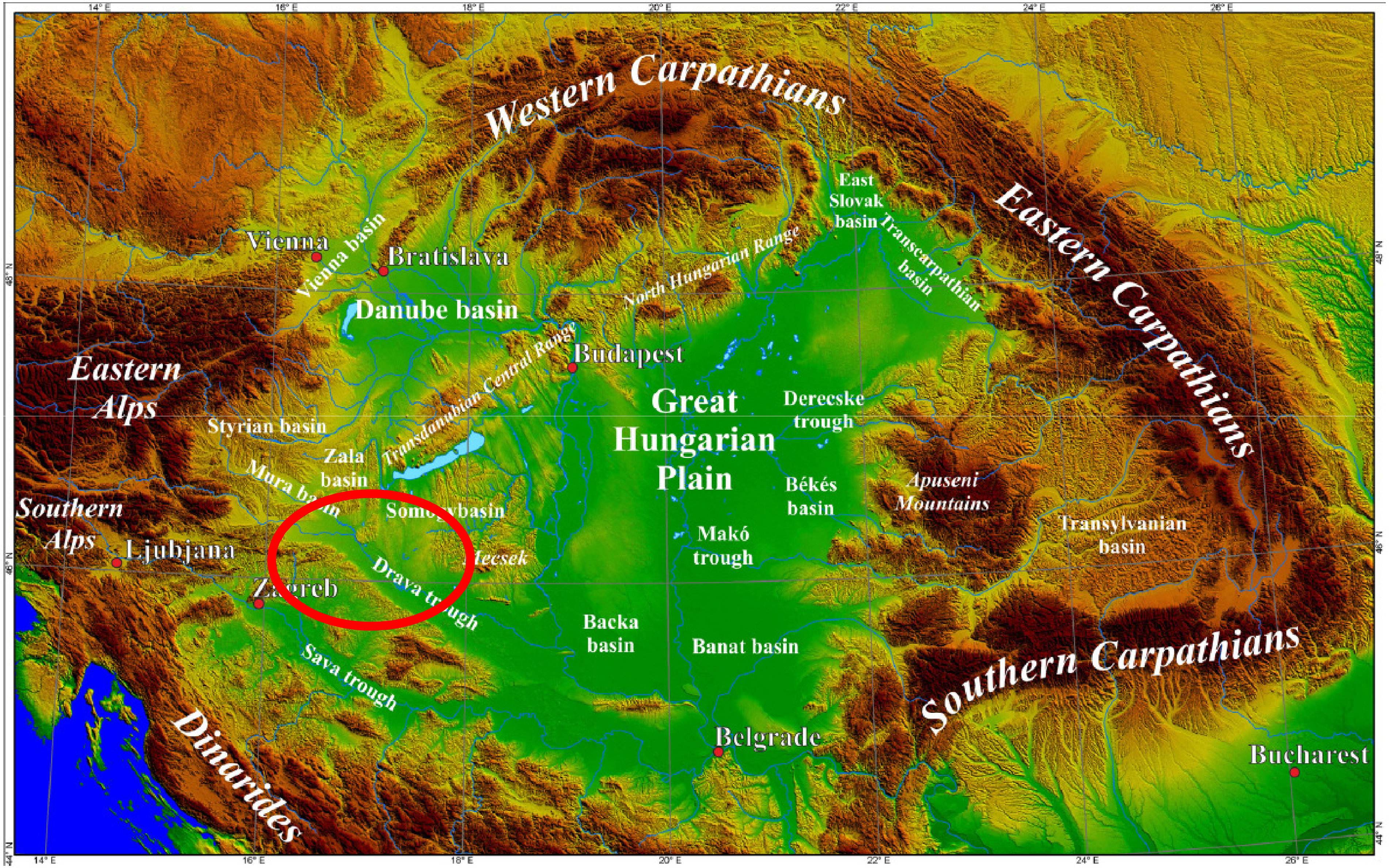
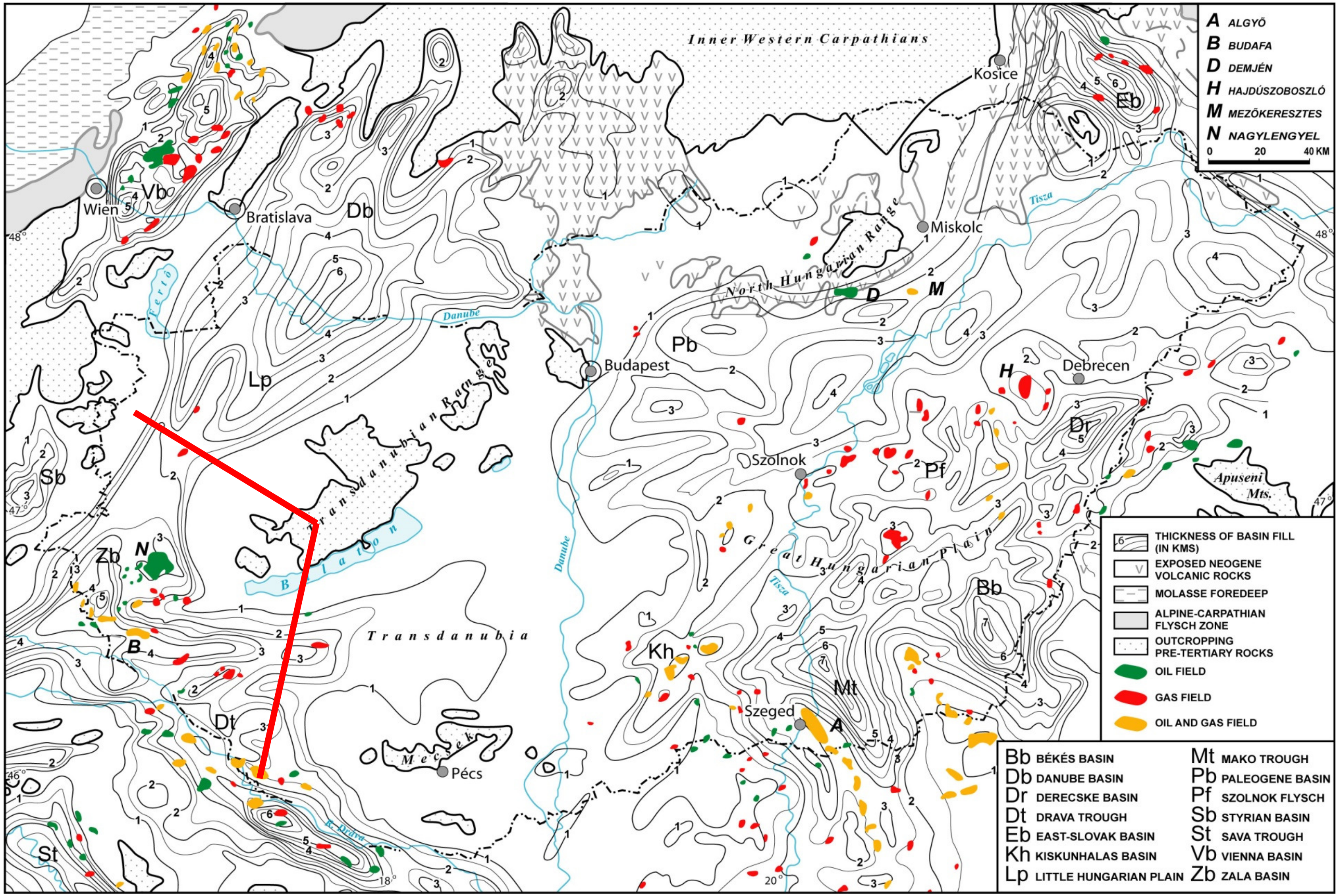
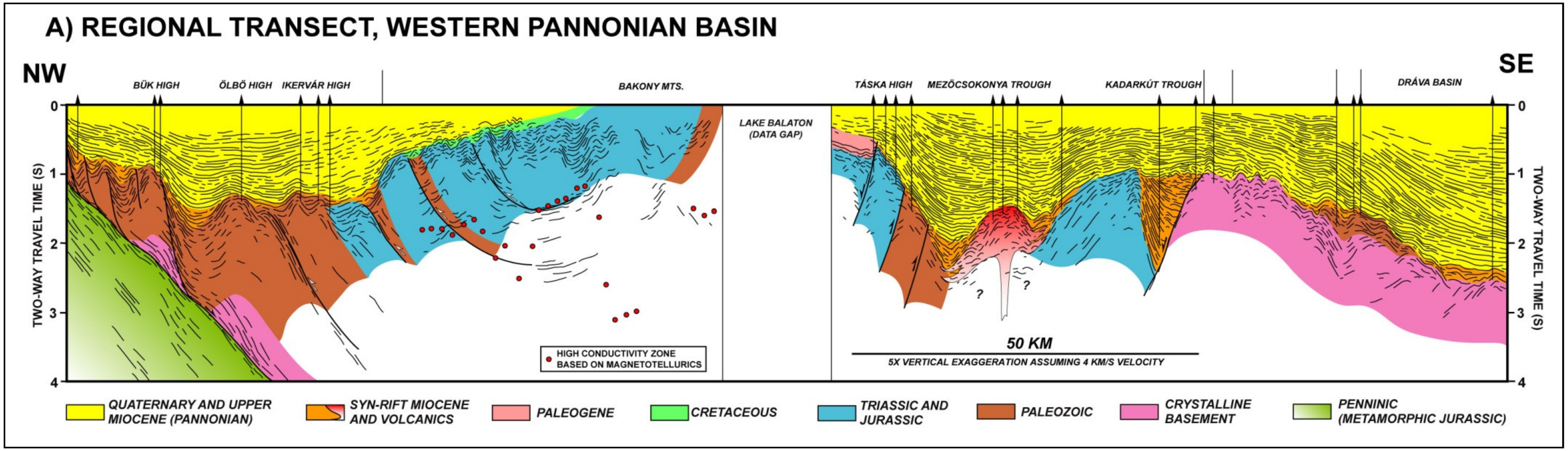


Western Carpathians
Eastern Carpathians
Southern Carpathians
Eastern Alps
Southern Alps
Dinarides
Vienna
Vienna basin
Bratislava
Danube basin
North Hungarian Range
East Slovak basin
Transcarpathian basin
Budapest
Transdanubian Central Range
Great Hungarian Plain
Derecske trough
Styrian basin
Zala basin
Mura basin
Somogy basin
Békés basin
Apuseni Mountains
Makó trough
Transylvanian basin
Ljubjana
Zagreb
Mecsek
Drava trough
Backa basin
Banat basin
Sava trough
Belgrade
Bucharest

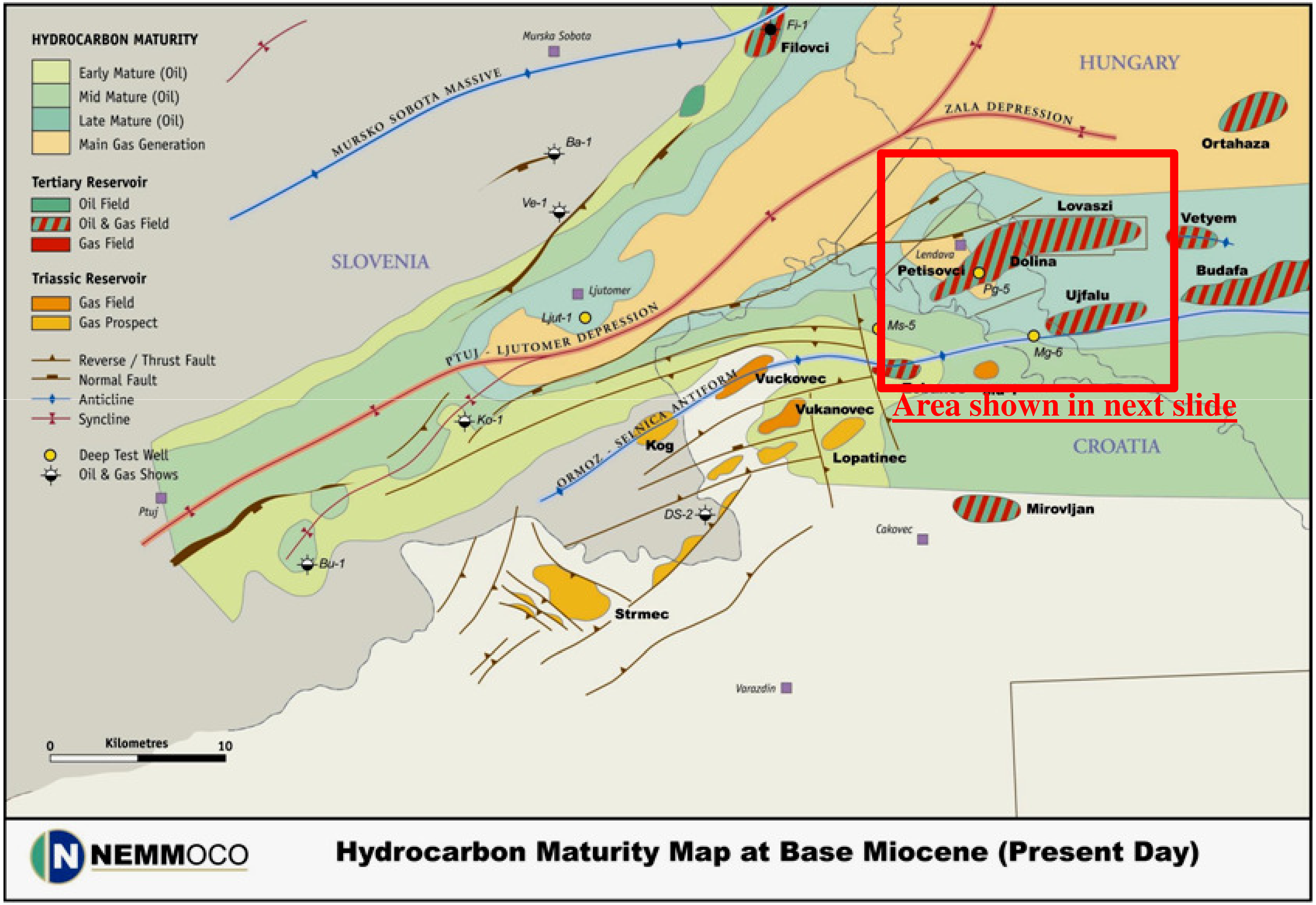
Pre-Tertiary basement depth and hydrocarbon fields



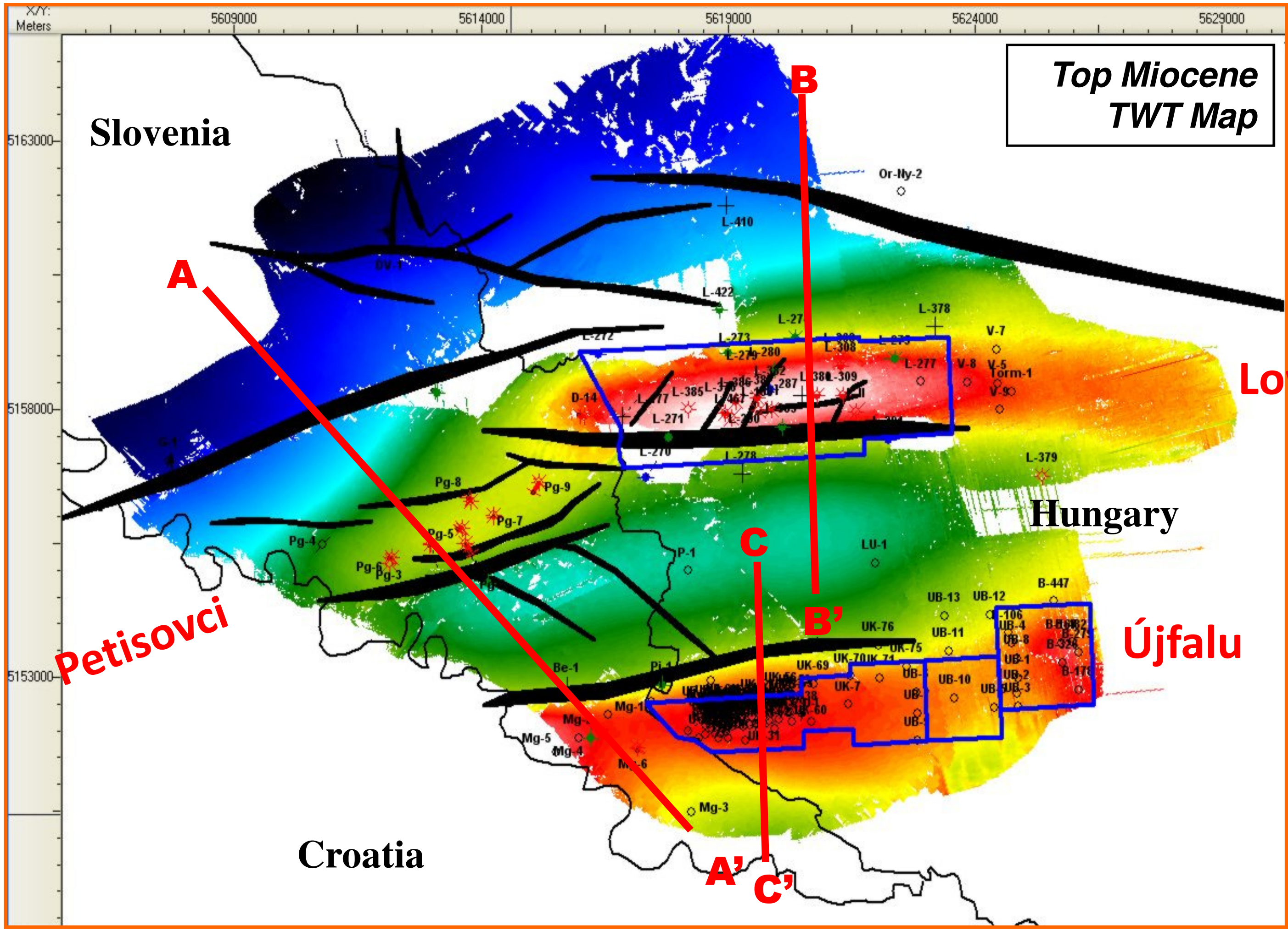
Regional seismic transect, Hungarian Pannonian Basin



HC Fields of the Ormoz-Budafa Anticlinal Complex



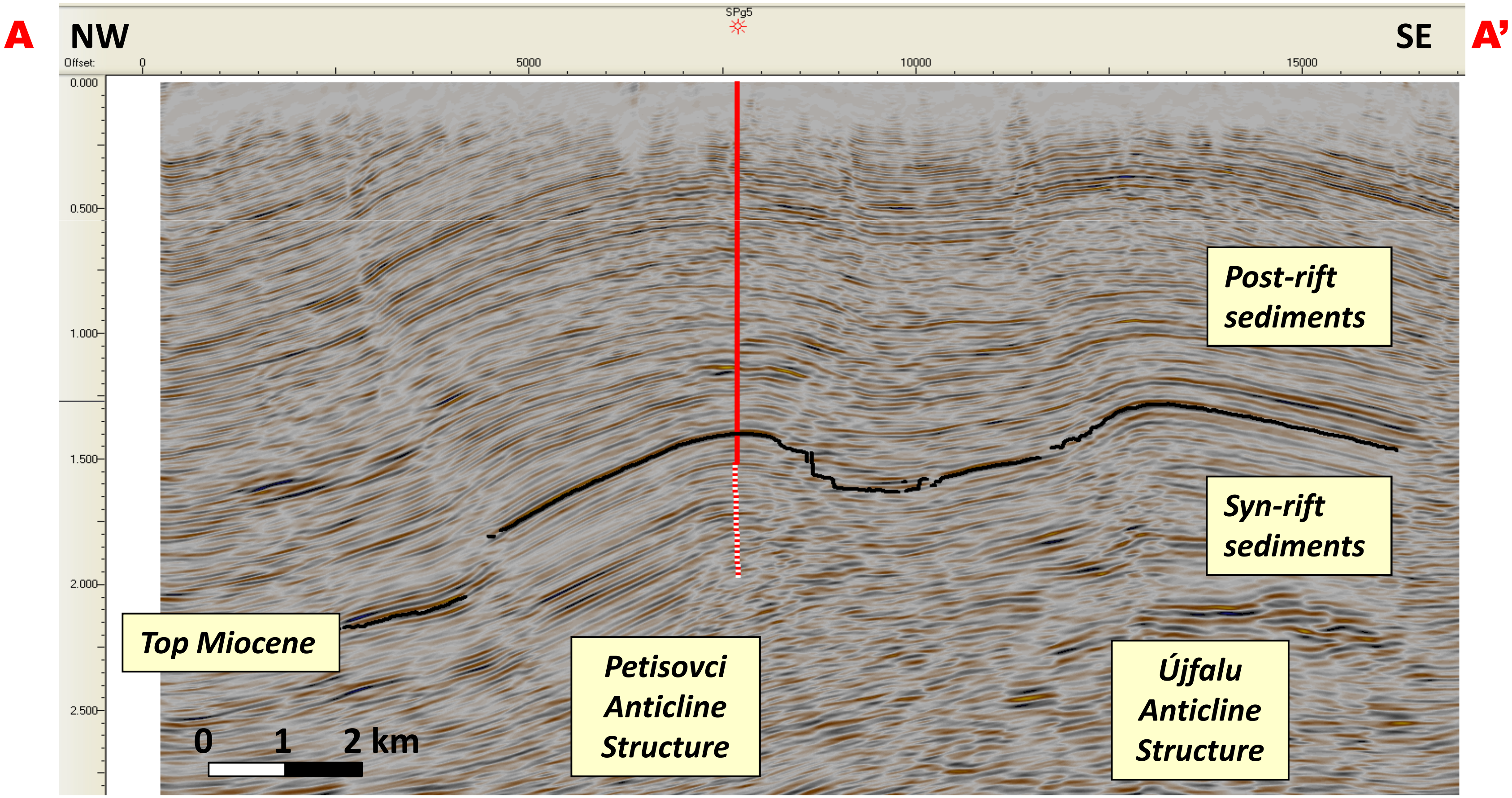
Structural Setting of the Petisovci-Lovászi and Újfalu anticlines



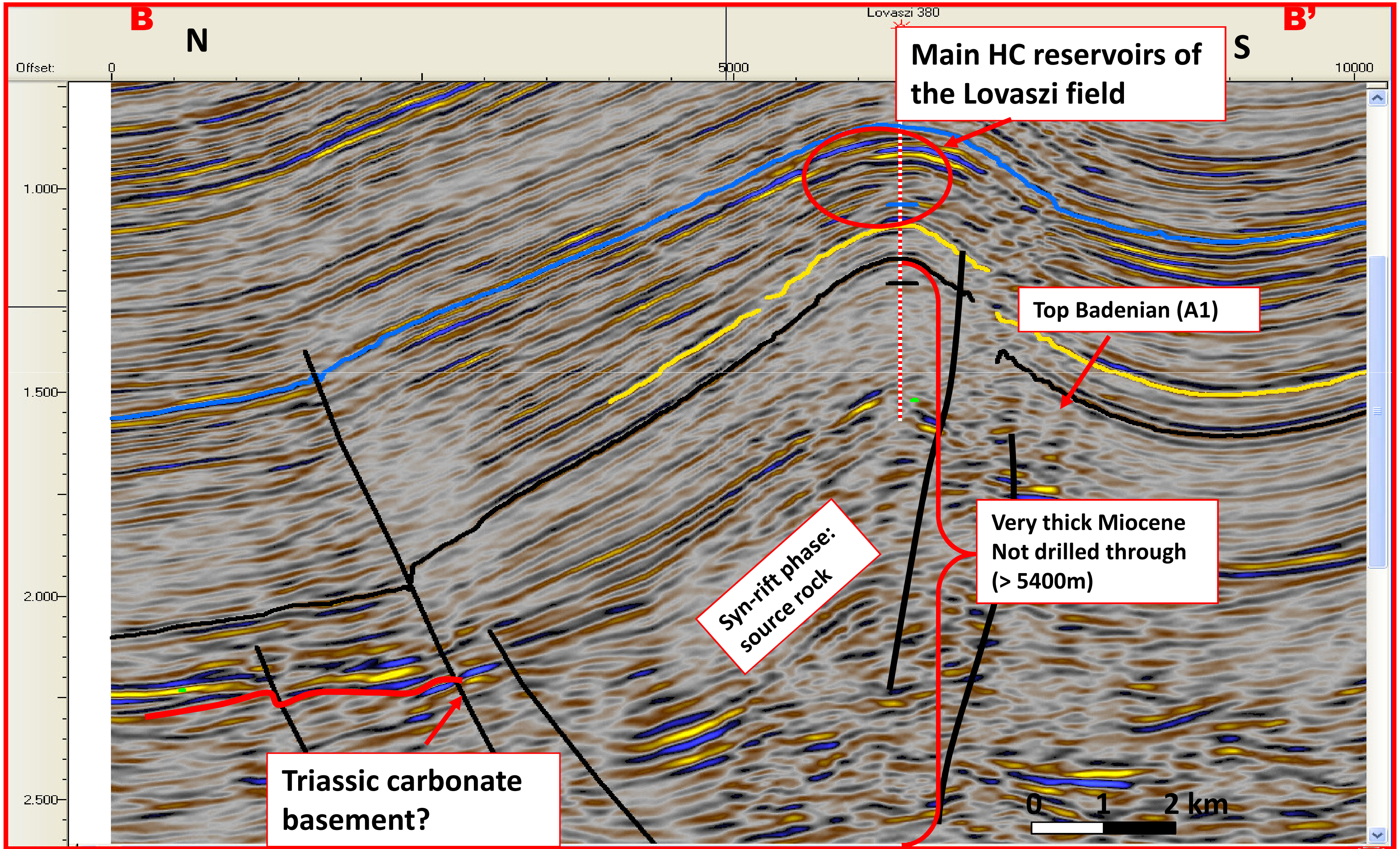
- Lovászi anticline is thrusted over the Petisovci structure
- Two separate inverted Miocene grabens with different structural orientations

Tectonic Evolution

- Pre-Miocene sediments consist of Triassic platform carbonates and basinal shales resting mainly on basement
- The Pannonian Basin was filled first by syn-rift clastics and carbonates intercalated with volcanics in the Miocene
- Post-rift sediments of Late Miocene and Pliocene age are dominantly clastics sourced from deltas filling the basin from the north

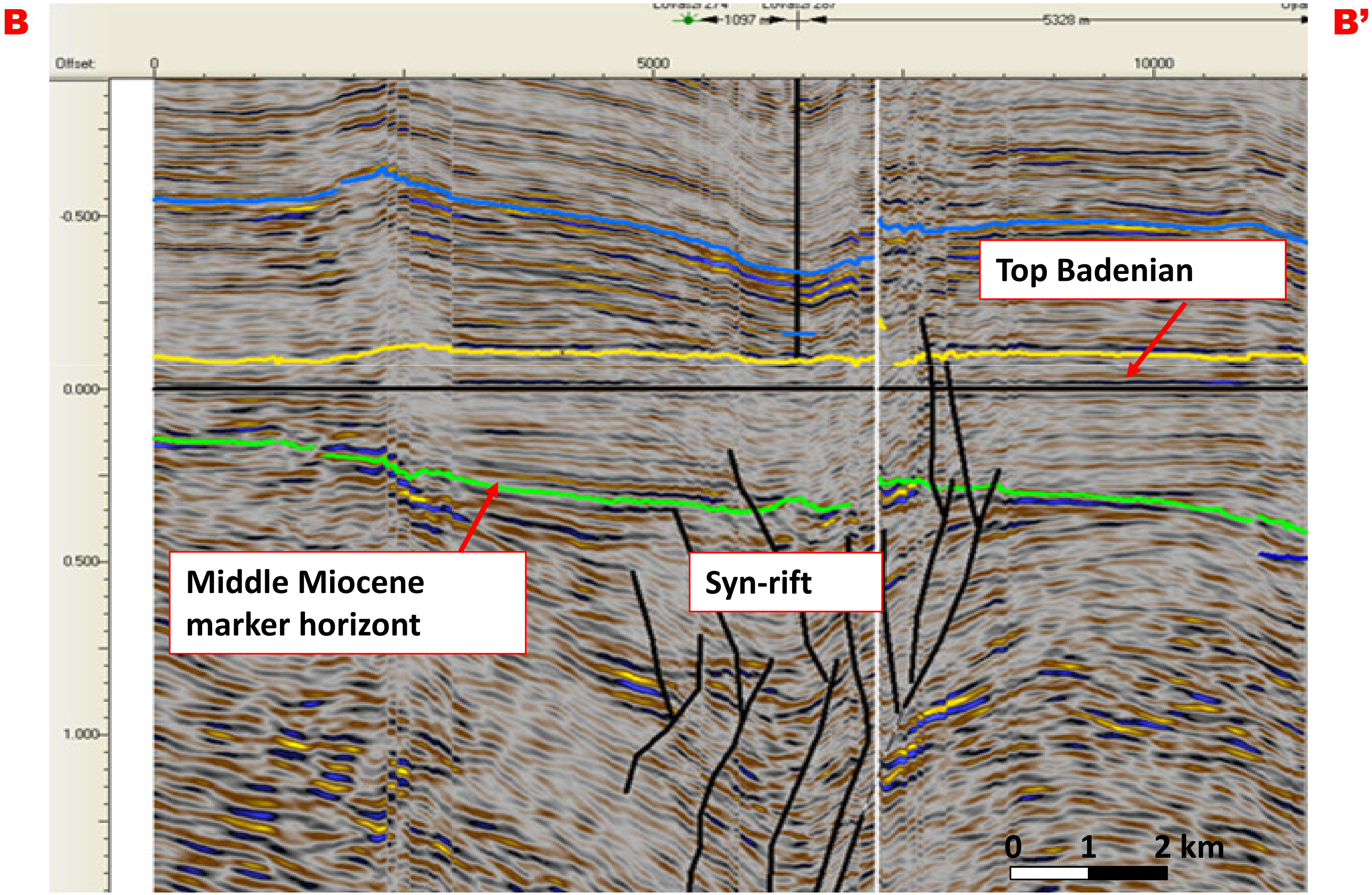


Lovászi Anticline: Tectonic Evolution



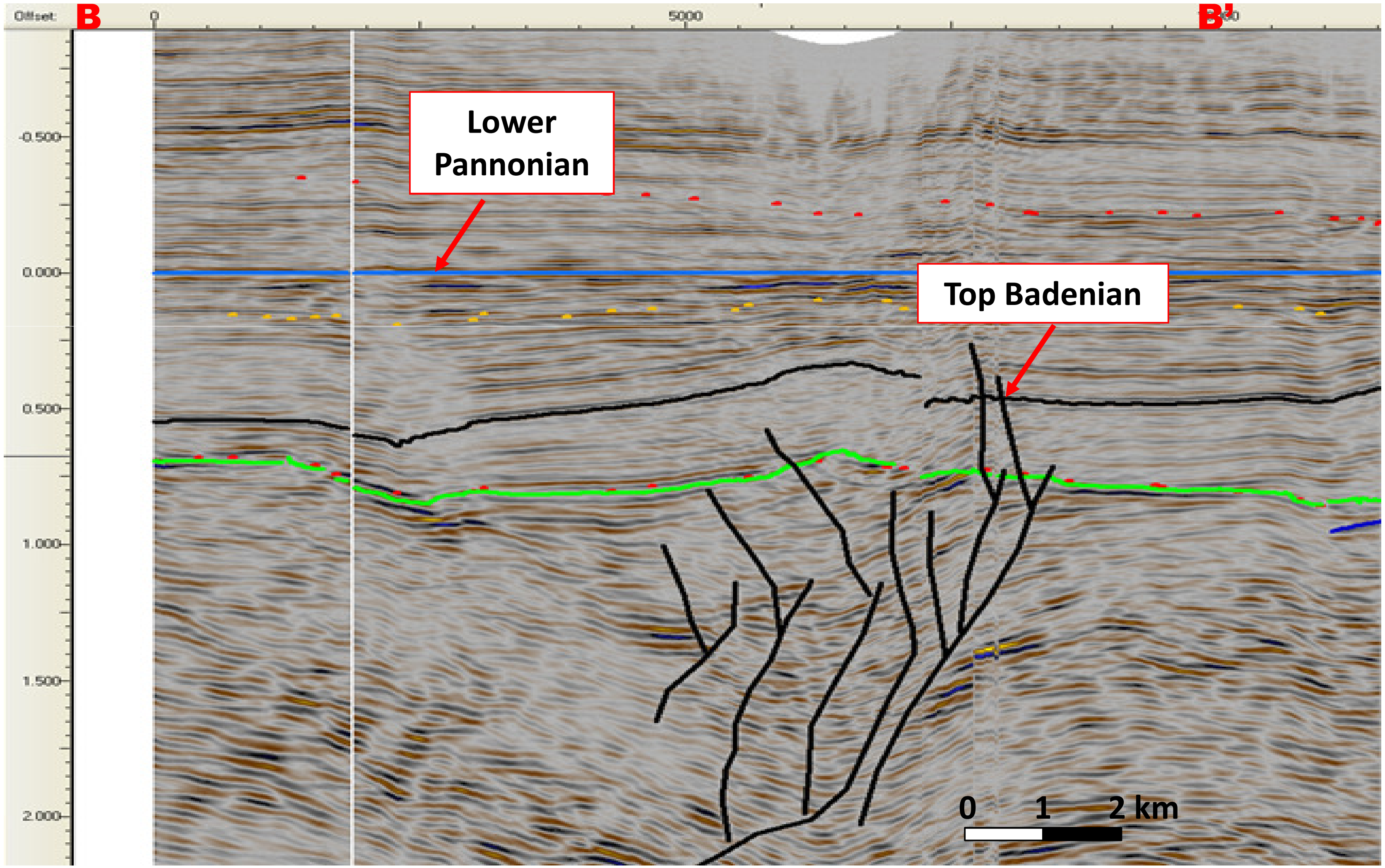
Lovászi Anticline: Tectonic Evolution

Badenian paleogeography



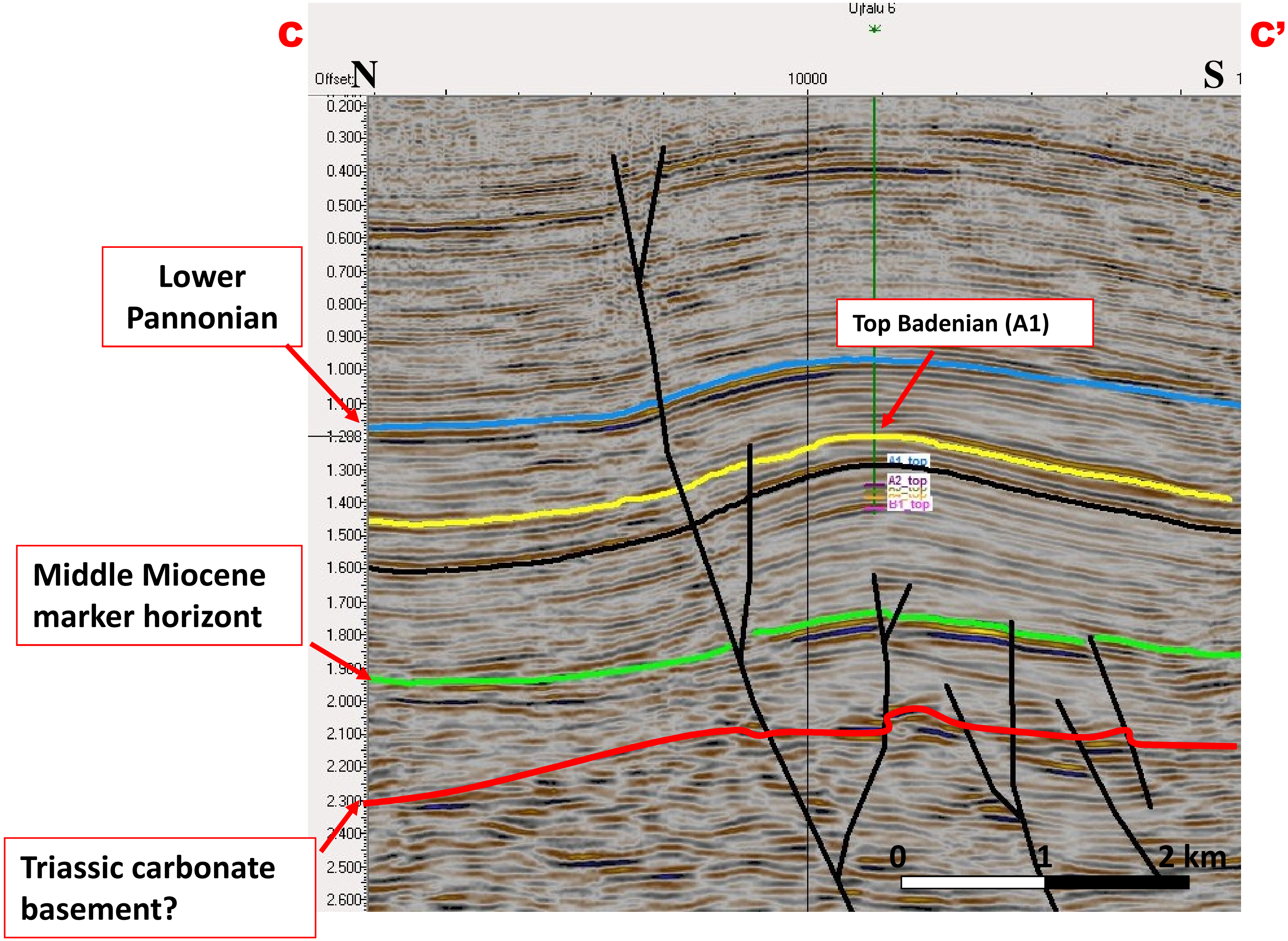
Lovászi Anticline: Tectonic Evolution

- Evidence for an early structural deformation (Lower Pannonian)
- Early HC migration into the paleo-structures?



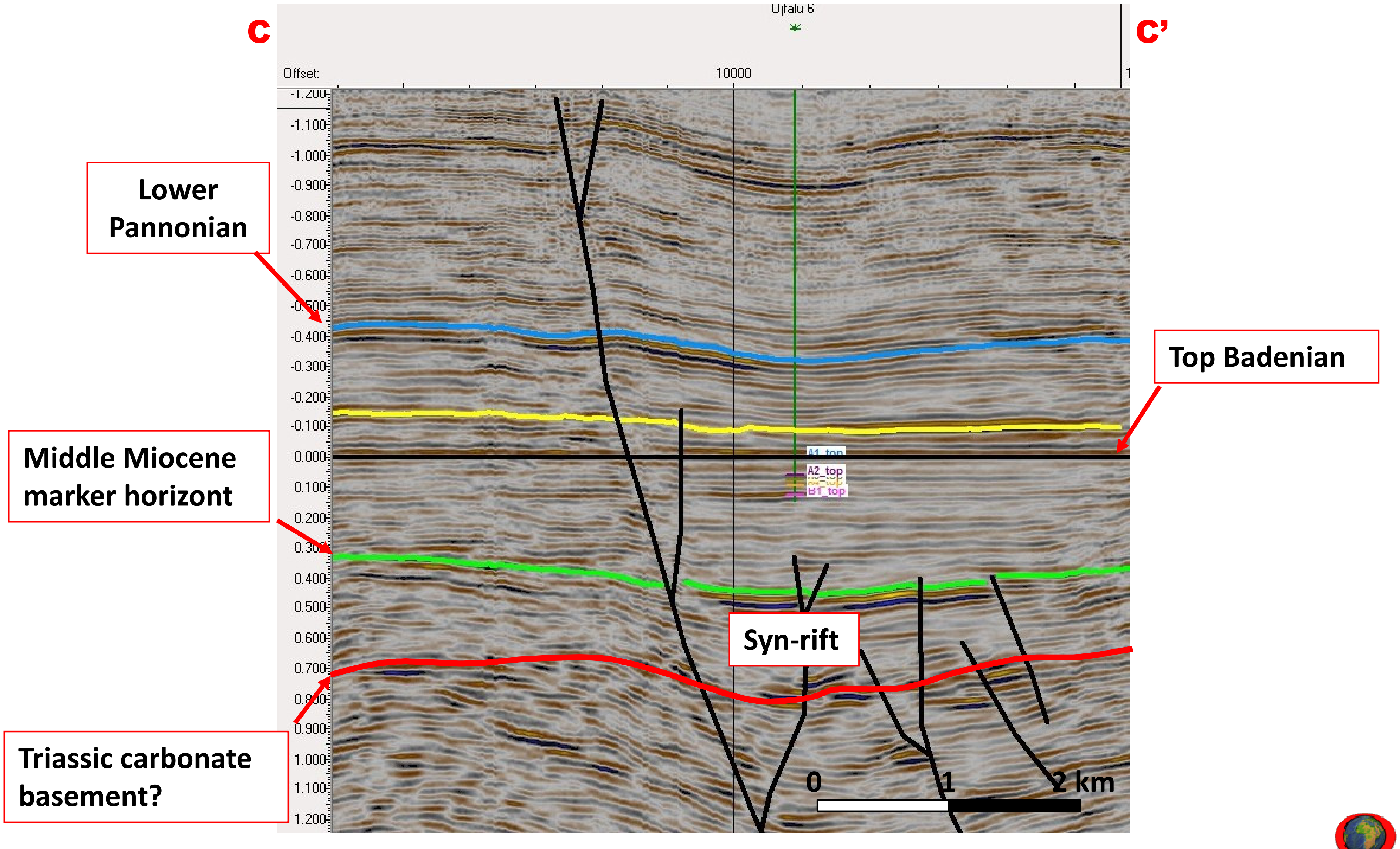
Újfalu Anticline: Tectonic Evolution

- Similar to Lovászi anticline, but smaller scale deformation



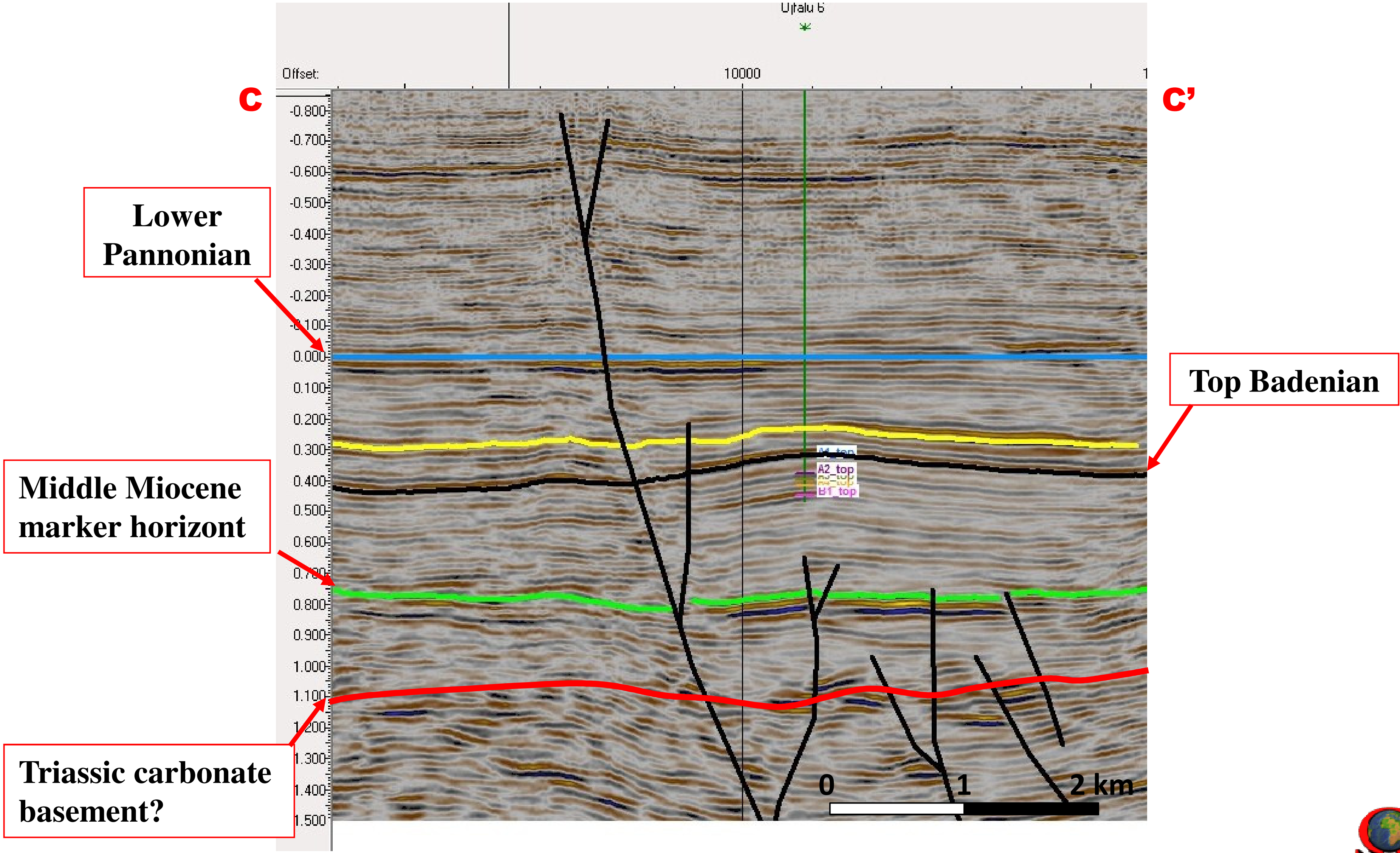
Újfalu Anticline: Tectonic Evolution

Badenian paleogeography



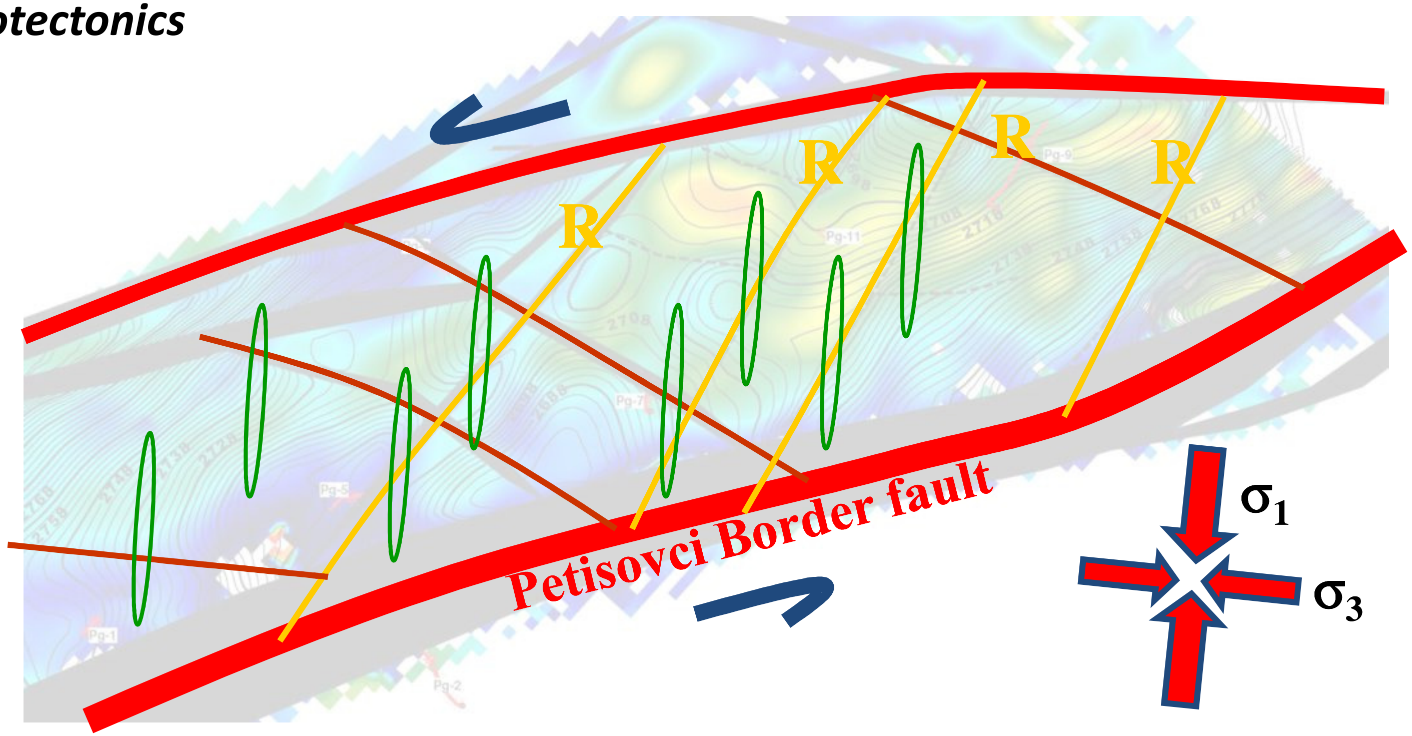
Újfalu Anticline: Tectonic Evolution

- Lower Pannonian, fault related structural deformation
- Similar to Lovászi structure, possible early HC migration into the paleo-structures



Petisovci Anticline: Current Stress Field

Stress field and microtectonics



- **Current knowledge**
  - **Regional stress studies as well as breakout data (Torm-1 FMI, Pg-10 FMI) indicate a ~N-S oriented s1 with a s3 also being horizontal (transpressional strike-slip regime)**
  - **In this regime ~E-W oriented faults experience maximum compression and are likely closed (dark brown faults)**
  - **~N-S oriented tensile fractures are expected to be induced during the frac**

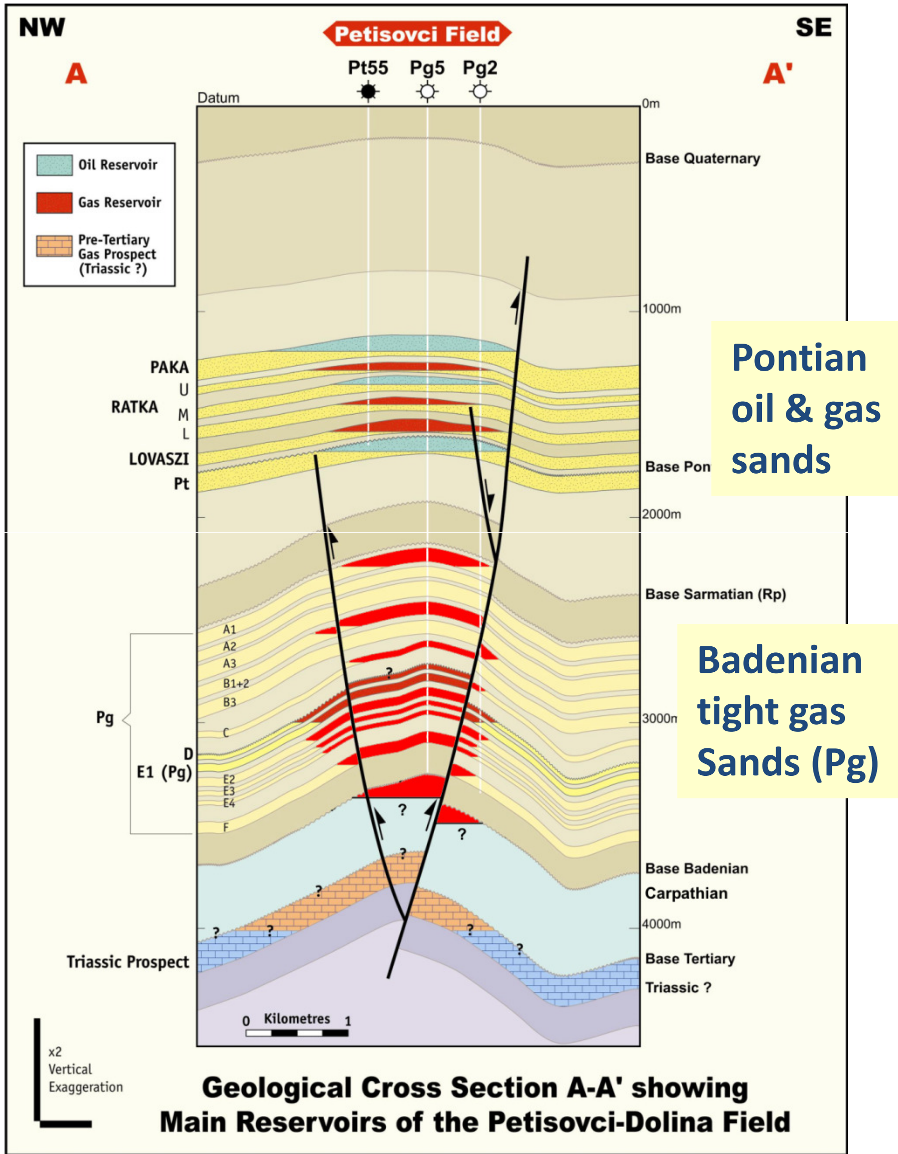
Petisovci Anticline: Current Stress Field

Stress field and microtectonics

- **Only rare natural fractures in cores,**
- **Fractures with fault striae:**
  - **very few: 10 pieces in ~ 65 m core (mostly in K-sand)**
  - **dip of fractures: 5–45º**
  - **sense of movement: reverse orientation: ~E–W?? (on the analogy of seismics)**

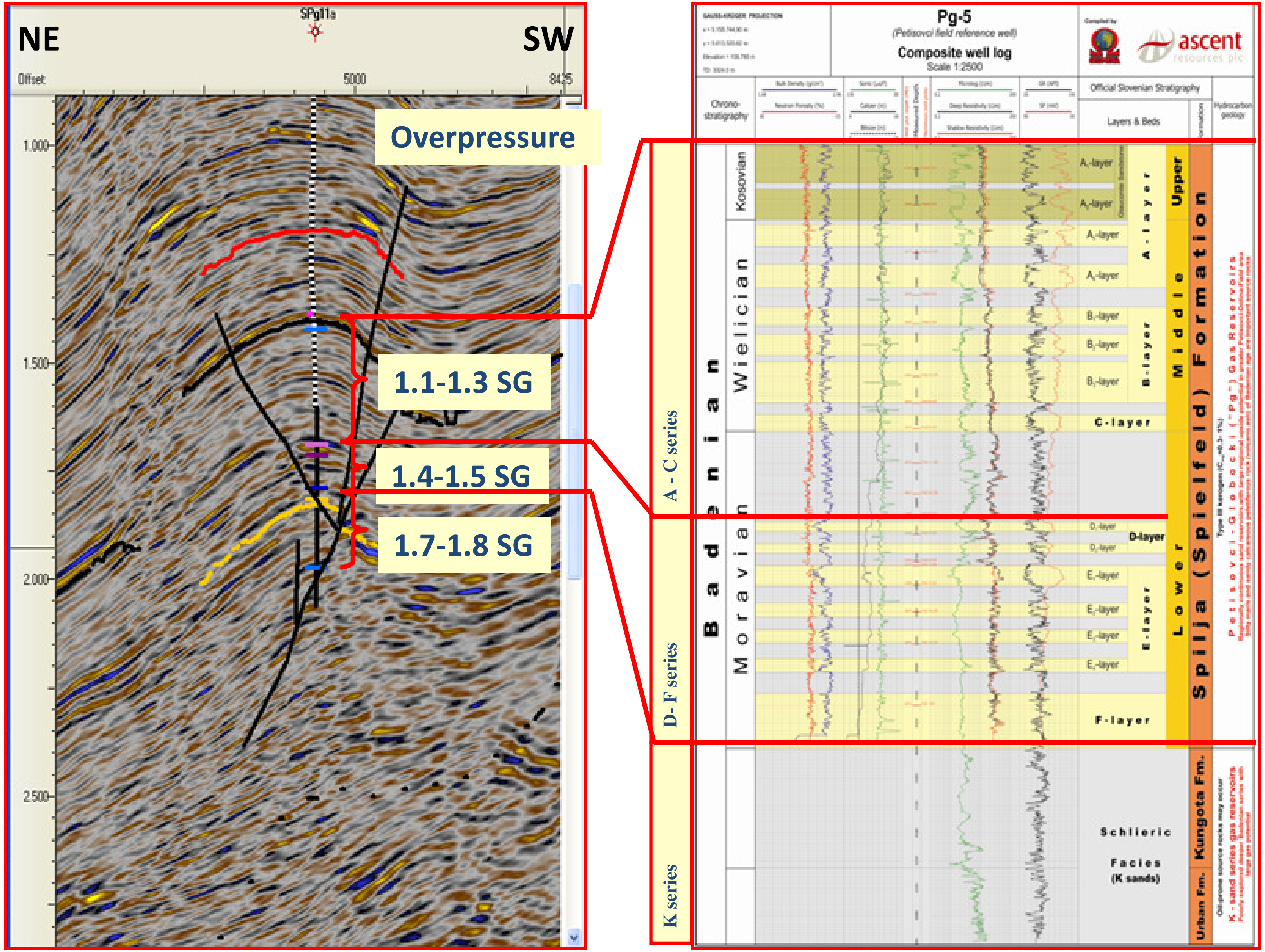
HC System of the Petisovci-Lovászi Field

- Two hydrocarbon intervals:
  - ➢ ~1200-1600m: Pontian oil & gas sands (discovered in 1940; practically depleted)
  - ➢ ~1800-3500m: Badenian (Pg) gas sands
- 136 and ~400 development wells in Slovenia and Hungary respectively targeting the Pontian reservoirs
- 10 wells targeting the Pg reservoirs in Slovenia and 23 wells reached the Sarmatian-Badenian series in Hungary
- Production from Pontian reservoirs:
  - ➢ 50 MMbbl oil and 230 bcf gas from Lovászi (Hungary)
  - ➢ 5.6 MMbbl oil and 34.3 bcf gas from Petisovci-Dolina (Slovenia)
- The Pg reservoir has produced some 8.7 bcf in Slovenia, mostly from two wells, E1 sand unit
- The deep-Lovaszi reservior has produced some 1.5 bcf in Hungary, mostly from two wells, A sand unit
- Historical production and test data show, that the Badenian (Pg) sands are overpressured tight gas sands with low porosity and permeability.

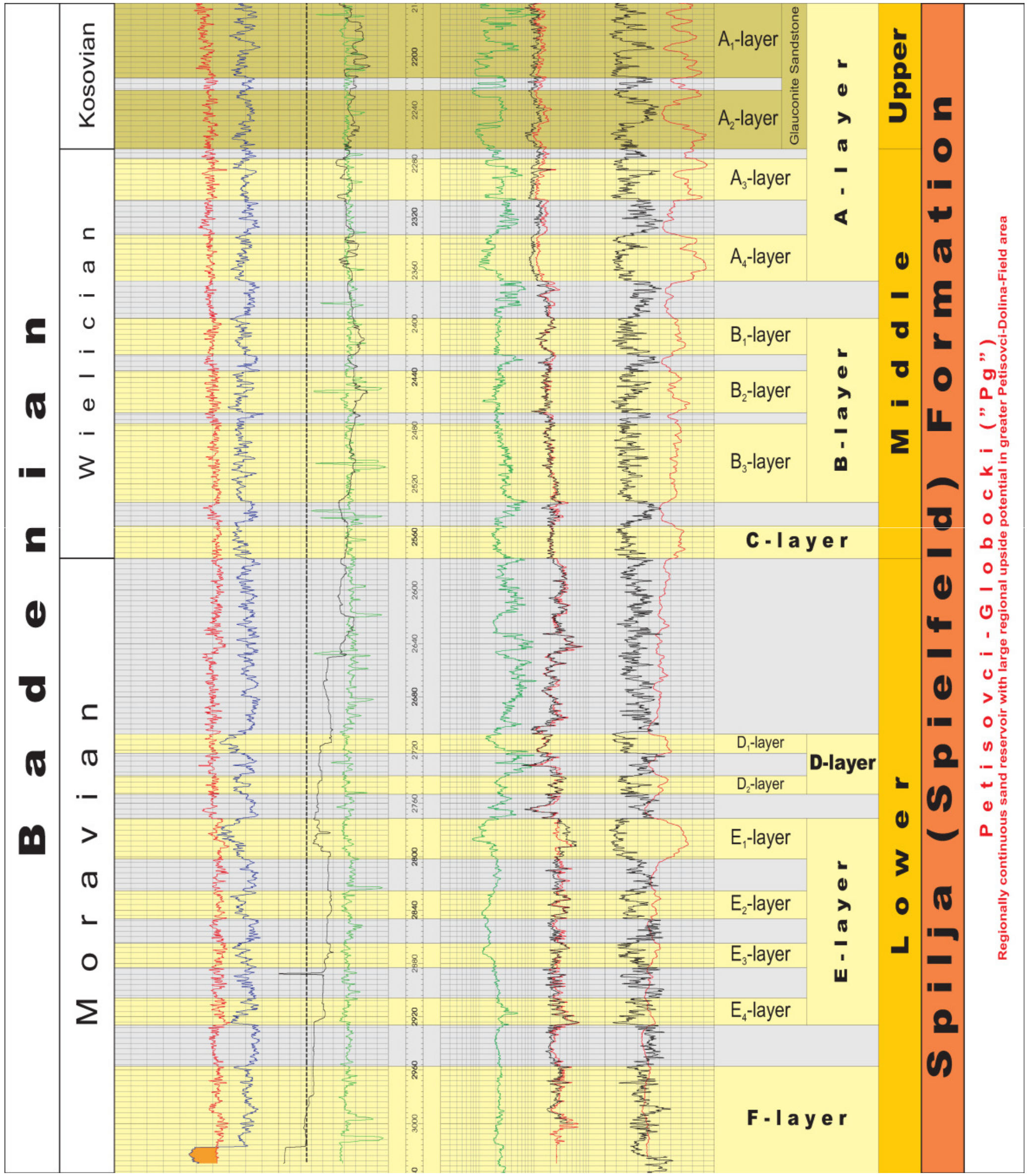


Geological Cross Section A-A' showing Main Reservoirs of the Petisovci-Dolina Field

Miocene Geology and Stratigraphy



Miocene Reservoirs



- Spilja Formation (i.e. Petisovci-deep, „Pg") reservoir sands are the main reservoirs
- Off-shore (glauconitic) sands of Badenian age
- Laterally continuous, well-correlating layers throughout the greater region
- Laterally variable petrophysical and productivity parameters due to diagenetic or geological reasons
- 7-11% porosity
- 0.01-10mD permeability
- High background gas throughout the interval
- Proven gas reservoir in A sands, produced in Lovászi area only
- Proven gas reservoirs in the D-E sands, produced in Slovenia only
- Proven gas reservoir below E-F sands: K sands, tested in Pg-11A, not produced yet
- Significant upside potential in A-C sands: high mudgas; direct gas indications on logs, tested but not produced in Slovenia
- Significant upside potential in deeper sands
- Fracture stimulation is critical for commercial rate gas production from the Miocene reservoirs

Miocene Field Development History

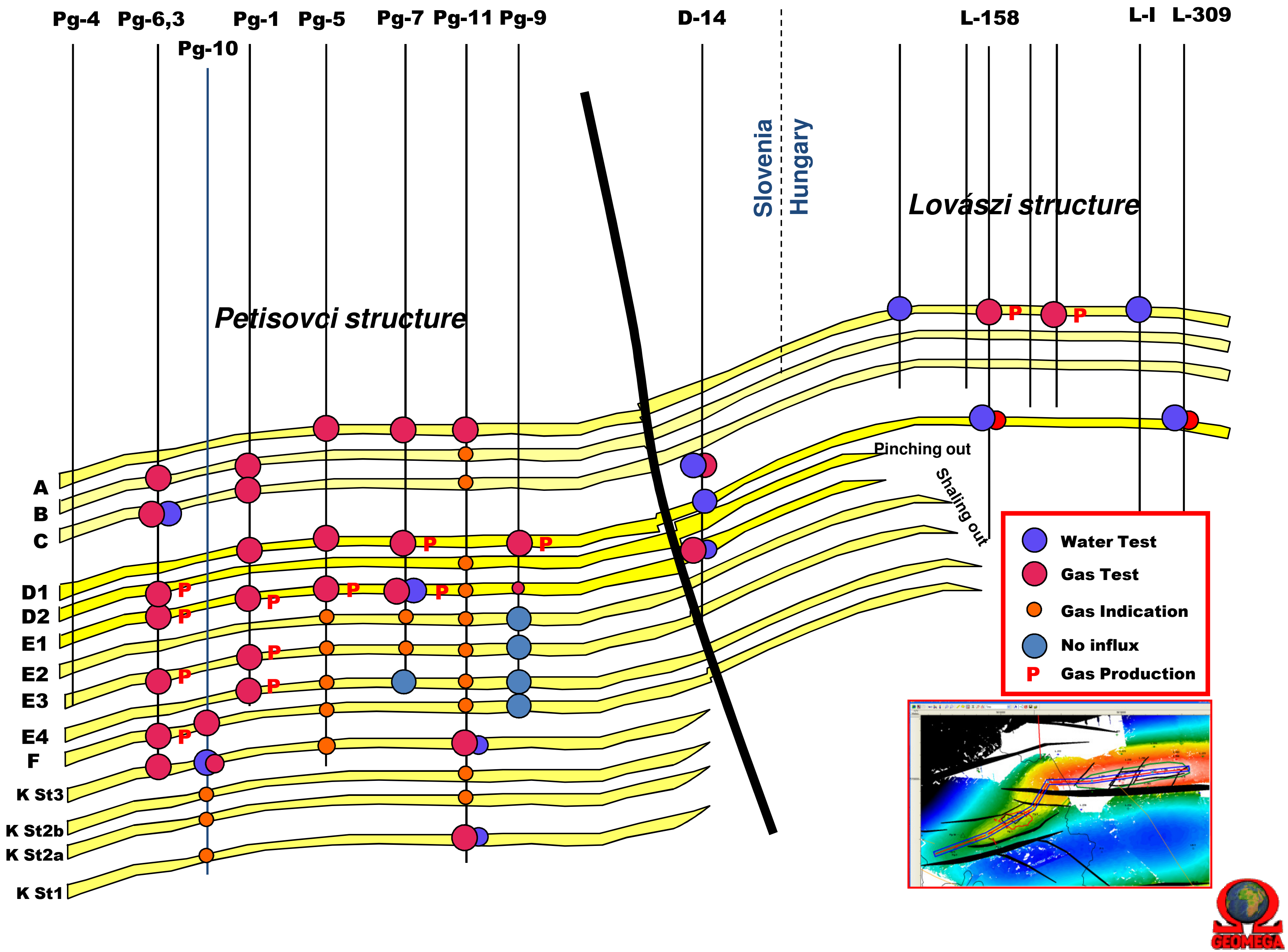
SLOVENIA (Petisovci Field):

- Discovery by drilling of well Pg-1 in 1961 (fracture stimulated)
- Pg-2, -3 and -4 drilled in 1960's
- Pg-5, Pg-6 (re-drill of Pg-3), Pg-7, Pg-8 and Pg-9 drilled in 1980's
- Successful hydraulic fracturing of Pg-5 and Pg-1 in 1987
- A total of 8.7 Bcf produced from the Pg reservoirs in the Petisovci Field

HUNGARY (Lovászi Field):

- Discovery by drilling of well L-158 in 1949, production from A & B reservior in 1960 's
- More than 20 wells reached the Miocene series (mainly A-B-C units) in 1950's
    - 9 wells tested gas mainly in A units
- L-422, L-467, L-I and L-II drilled in 1960's
- Successful hydraulic fracturing and acid stimulation of L-467 in 1967, main gas producer from A sand unit
- L-I and L-II deep-level exploration wells, L-I tested gas in A-C reservoirs with variable amount of water, both wells tested gas in deeper Miocene reservoirs (D-E)
- A total of 1.5 Bcf produced from the Lovászi deep reservoir sections in the Lovászi Field

Regional Geology of the Miocene Reservoirs



Reservoir Geology and Petrophysics

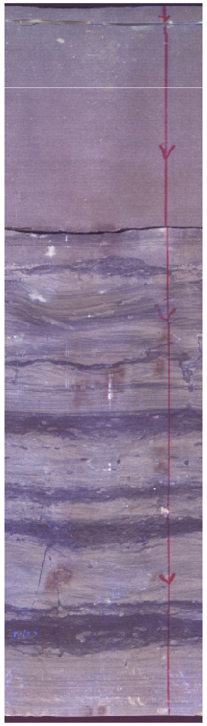
- 4 x 18m long cores drilled in 2011 from the Badenian reservoirs (A1, D1, E1 and K sands)
- These complement the older extensive, but often poorly documented core database
- Extensive geological and petrophysical investigations were undertaken on the new cores to understand and characterise the reservoirs in the highest detail

Key players:

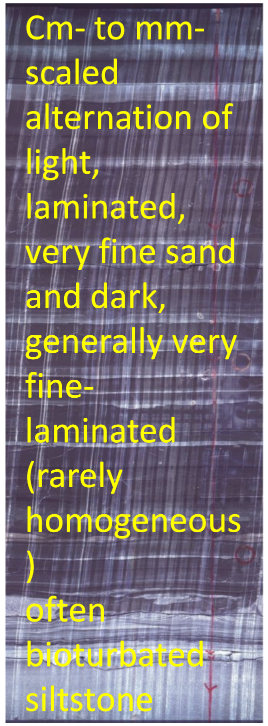
„Massive sands"

Structured sands #1: bioturbated

Structured sands #2: fine-laminated



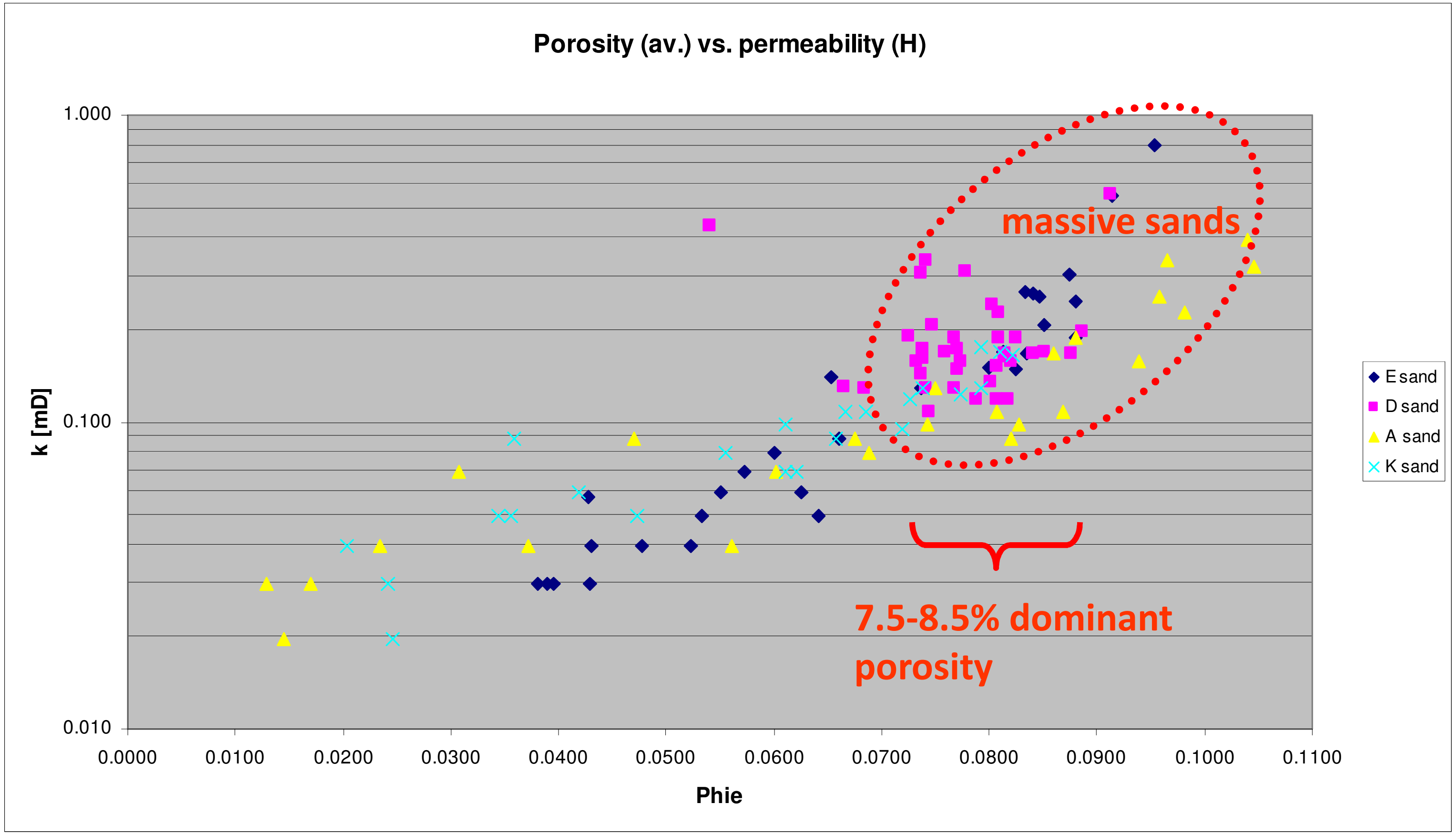
„Shales": calcareous siltstones



- Cyclic sedimentation interpreted as turbiditic (Bouma) sequences
- Very few natural fractures
- Significant petrophysical variability within macroscopically homogeneous intervals

Reservoir Geology and Petrophysics

Basic reservoir parameters from core plugs at lab conditions



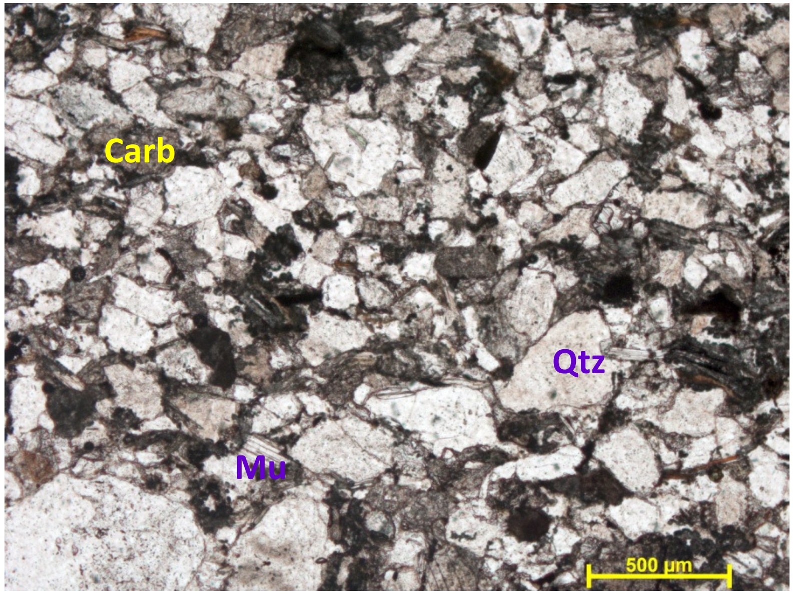
Laminated and structured sands or thin blocky sands inbedded into a shaly environment are very poor reservoirs compared to the thick unstructured sands. This is attributed to:
(1) initially poorer parameters; (2) cement precipitation from degrading diagenetic fluids coming from over and underlying shales

Reservoir Geology and Petrophysics

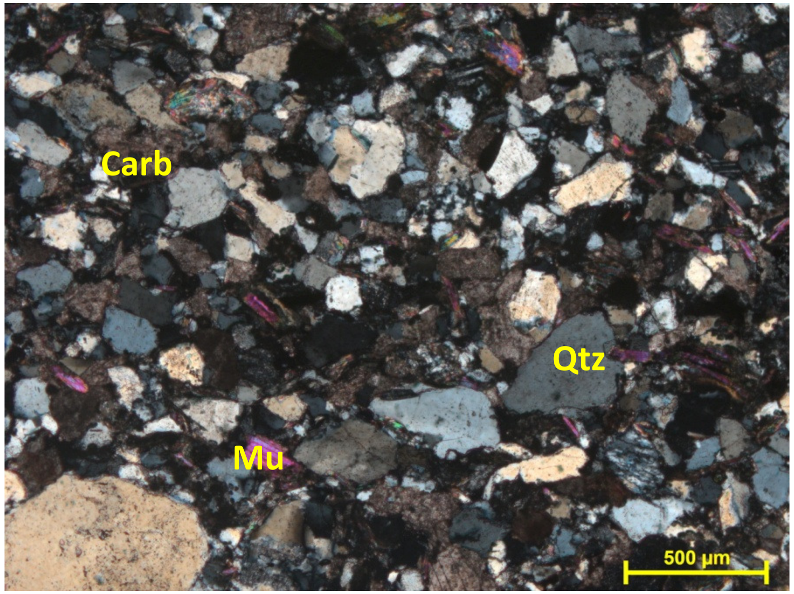
Mineralogical and chemical composition based on XRD and microscopy

- “Avarage” sand (reservoir) composition: quartz: 40-50%, dolomite: 10-15%, Fe-dolomite: ~3-5 % (if present; but it is missing in ~50% of the samples), calcite: 5(-10)%, feldspar: ~5(-10)%, muscovite (±biotite): 10-15%, chlorite: 10(-15)%
- Combining XRD data with thin section and SEM analyses: separation of detrital components (qtz, dol, cc, mu, chl, fp) and newly grown, diagenetic phases (Fe-dol, qtz, cc, chl, ab), reaching up to ~10%

This section from a reservoir sand: unsorted, poorly rounded grains, very small pore throats, only 4-5% visible porosity

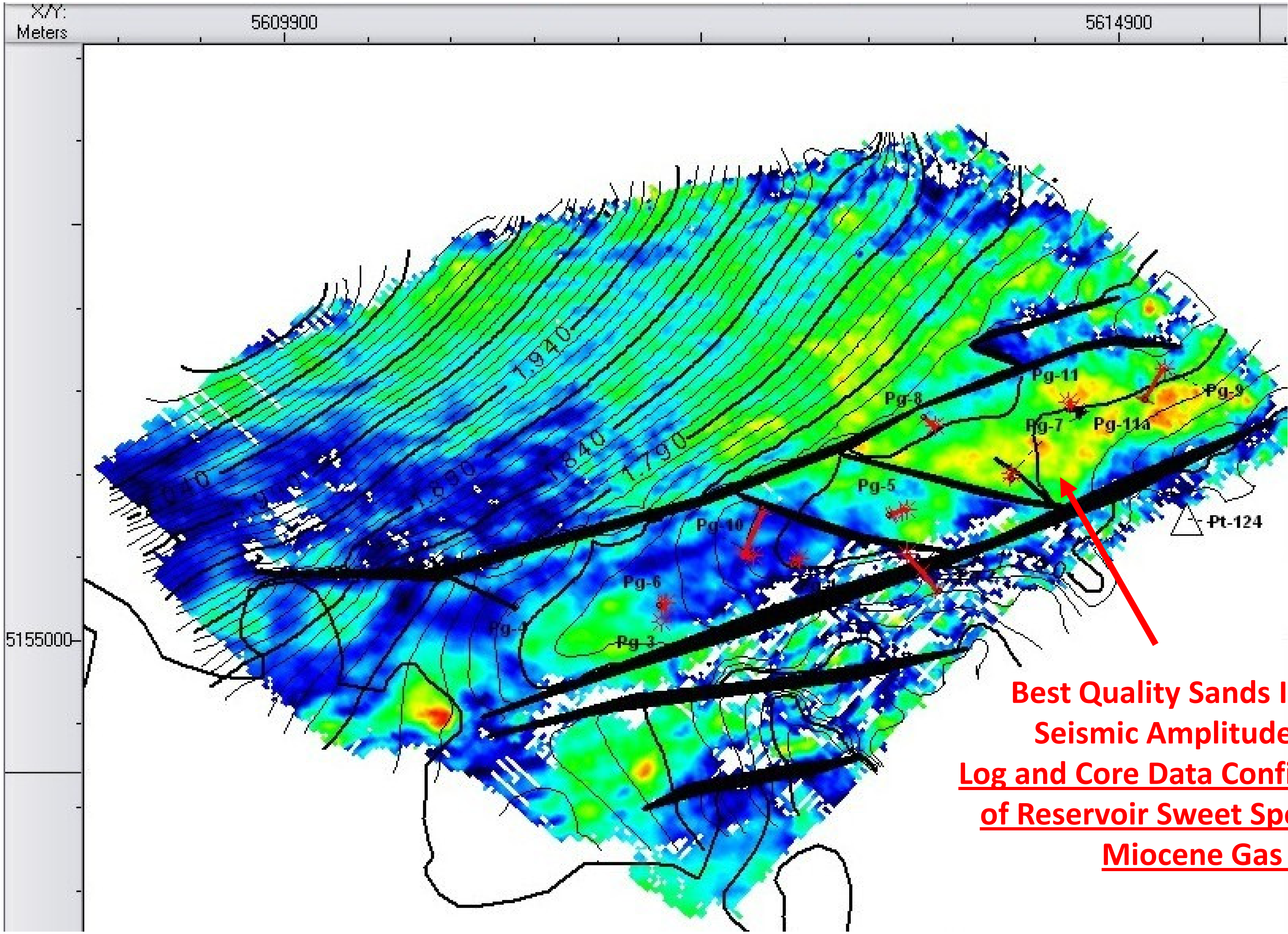


D1 sand: 2734 m, 1N



D1 sand: 2734 m, +N

Reservoir Sweet Spots



Best Quality Sands Indicated by Seismic Amplitude Anomaly

Log and Core Data Confirmed Presence of Reservoir Sweet Spot in the Tight Miocene Gas Sand

Summary

- The Petisovci-Lovászi anticline is an inverted Miocene basin system
- HC trapping is provided primarily by the anticlinal structure and related faults, however borehole and 3D seismic data revealed significant lateral variations in reservoir quality and in some cases also startigraphic component in the trapping mechanism
- Upper part of the anticline is characterized by multiple good quality oil and gas reservoirs, which have been on production since 1940's.
- Lower part of the anticline is characterized by Miocene tight gas sands which can only be produced at commercial rates following frac treatments.
- Key to the success of unlocking the significant gas in place reserves present in these Badenian sands are:
  - High resolution subsurface view by means of 3D seismic survey
  - Data integration and comprehensive geological model
  - Reservoir protection
  - Dedicated reservoir stimulation (fracing)

Acknowledgement

The authors would like to thank Ascent Resources Plc. for permission presenting the results of the study carried out over the Petisovci-Lovaszi and Ujfalu anticlinal structures.
We also wish to thank our colleagues working on the project, with special thanks to Géza Wórum, Zoltán Kádi and Balázs Koroknai for their constructive work.