A Few Remarks on Hydrocarbon Resource Assessment Within the Dinaric Thrust and Fold Belt

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PRELIMINARY COMMUNICATION

The area of the Dinarides or Dinaric Alps (Western Balkans) can be characterized by a cluster of compressional thrusts displacing the Mesozoic and Neogene blocks with different slip rates and age of horizontal movements. Setting aside the structural complexity, the investigated area can be characterized by a proven petroleum system that is, however still underexplored. Modern exploration of hydrocarbons is based on the 2D/3D seismic data, well or borehole data, occasionally organic geochemistry, probabilistic risk assessment. Moreover, structural modelling techniques are needed to interpret, reconstruct, and validate these histories. A relatively new method, petroleum system modelling simulates hydrocarbon generation and migration to improve predictions of unknown hydrocarbon locations, fluid properties, including distribution of overpressure zones. A method provides the best results in full-scale resource assessment, as in basin scale or for the entire prolific province.

Key words: Dinarides, compression, basin modelling, migration, PetroMod, Teclink

1. INTRODUCTION

History of hydrocarbon (HC) exploration across the Western Balkan region is associated with the several phases that were mainly confined to the Pannonian Basin and Adriatic Sea. Except these relatively large HC provinces, the potential of intermediate units remained underexplored, even unknown, like the onshore Dinaric thrust system. Lately, simultaneously with the developments on the worldwide scale, locally, across the Balkan region a relatively higher interest in HC exploration becoming more and more noticeable: traditionally, starting from the well-explored southern realm of the Pannonian Basin, all the way down to the Adriatic Sea. Recently, in 2013 and 2014 the global leader Shell exposes the interest for exploration of the onshore Dinarides (Bosnia and Herzegovina). However, wider area can be characterized by a stratigraphic and tectonic heterogeneity reworked by intensive compression movements, altogether complicating economically plausible HC exploration. One of the key methods for the plausible mitigation of exploration risks is numerical 1D, 2D & 3D petroleum systems modelling.

Petroleum system modelling is a numerical method based on the following key processes: rock (layer) decompaction based on the reproduction of burial history and subsurface simulation of fluid migration. Migration or 3D spatial subsurface flow (whether in the nature or inside the software) of HC's is controlled by the effective porosity, i.e. permeability of rock formations. Porosity i.e. permeability is a function of the Basin subsidence and the deposition of new layers. However, vertical decompaction in the numerical method based on the basin subsidence cannot be applied in the Dinaric system because the system contains horizontal displacements of the layers (reverse faulting) finally resulting in a "double Z coordinate". "Double Z coordinates "effectively requires decompaction of a single layer in two different positions distributed along the reverse fault, which is not possible by the vertically operated grid. The difference between the two Z points is in finite strain, because in either case footwall or autochthon can suffer higher effects of the overburden i.e. have higher amount of the finite strain than the displaced hanging wall of the allochthon. This can effectively induce porosity difference further implicating difference in permeability, i.e. fluid flow. The most significant effect is in differential thermal maturity due to the kinematic uplift (cooling) or relative down lift. The software platform PetroMod® Schlumberger and software add-on called TecLink® almost exclusively allow "block separation" and numerical modelling of the thermal maturity and fluid migration with the autochthon and allochthon, respectively. Such numerical approach allows highly accurate calculations of the layer decompaction (porosity i.e. permeability), differences in thermal history before and after thrusting. Using the timing of thrusting and subsequent separation of the main rock portions (blocks) the software allows simulation of the main HC migration paths in 2D and 3D.

In the complex tectonic conditions accommodated by intensive compressional forces induced by various factors, including salt tectonics, kinematic and palinspastic structural restoration is often used for assessment of predeformational stages. Reconstructed or restored paleogeometries can be directly integrated in petroleum system modelling software. Integration of the restored cross sections allows geochronological overview and better understanding relationship between depositional and petroleum systems.

The modelling starts by the restoration of the present day basin geometry (e.g. seismic data). Geometry visual-

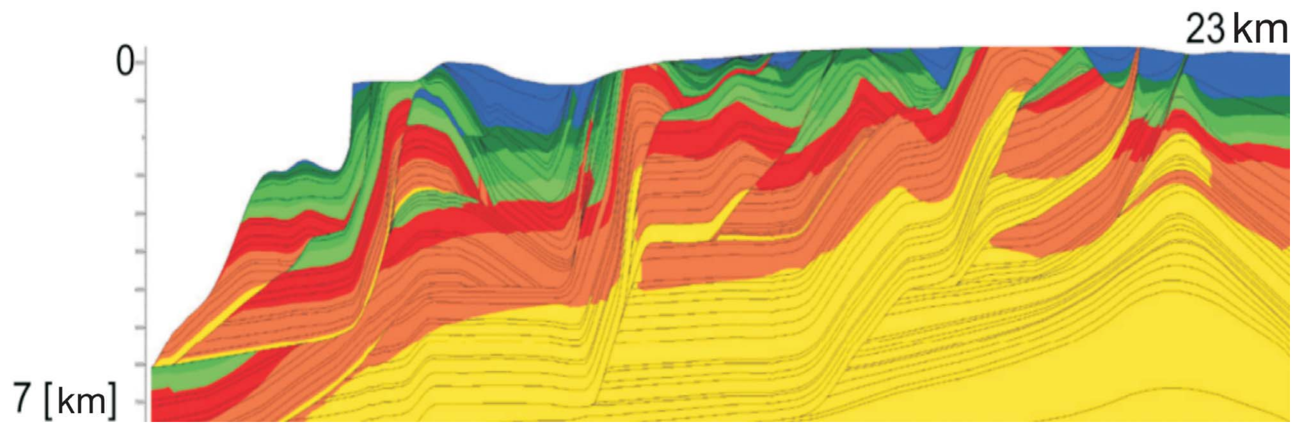

Fig. 1. An example of thermal modelling (PetroMod® 2D PetroViewer interface). Cross section depth is 7 km with over 2 km of relief elevation that is a result of compression movements. Thermal maturity is disclosed by thermo catalytic zones (catagenesis) referred to as "Easy Ro%" (Sweeney , Burham, 1990).[10]
Legend: Blue - no maturation; Dark green - late oil window, Green - main oil window, Light green - early oil window; Dark red -main gas window; Light red - late gas window or "dry gas"; Yellow - over mature, overheated zone without generation potential.

Sl. 1. Primjer termičkog modeliranja (PetroMod® 2D PetroViewer interface) na profilu dubine 7 km. Elevacija terena od preko 2 km je posljedica kompresijskih pokreta. Termalna zrelost je prikazana u vidu termo-katalitičkih zona prema "Easy Ro%" .[10]
Legenda: Plavo - bez maturacije, tamno zeleno - kasni naftni "prozor", zeleno - glavni naftni "prozor", svijetlo zeleno - rani naftni "prozor", tamno crveno - glavni plinski "prozor", svjetlo crveno - kasni plinski "prozor" ili "suhi plin", žuto - pregrijana zona bez potencijala.

ized by seismic data provides better insight in layer geometry wherein throughout the layer decomposition the original geometry and layer thickness is computed. In addition to the realistic layer paleogeometry of each stratigraphic event (stratigraphic interval), the result allows validation of the geological/geometrical interpretation. Finally, the tool allows insight into the tectonic evolution of the basin, generation (thermo catalytic kerogen maturity), migration and accumulation of hydrocarbons (oil and gas).

2. A SHORT REVIEW OF STRUCTURAL AND TECTONIC SETTINGS

Dinaride system is positioned at the convergent tectonic plate boundary, and separates the Adriatic and the Tisza - Dacia micro plates in the central part of the (Figure 2).[8] Its distribution, as a complex thrust - belt towards the Alps is not clearly defined.[2] Some authors consider regional faults as a border between neighbouring megablocks.[7] Modern geometry of Dinarides is a result of rotation of the Africa plate, which was implied the separation of the Adriatic micro plate into two parts, each of which moves at different speeds directly influencing the deformation.[7]

According to the official classification, Dinarides are divided into Outer, Inner and Central Dinarides. Within the Dinarides, for example, Tomasic et al. (2011) recognized over 30 thrust zones. Hrvatović and Pamić (2005) identifies a set of geological units within the Dinarides: (I) Adriatic - Dinarides carbonate platform, (II) Bosnia flych zone (III) Ophiolite zone, (IV) Sava - Vardar zone, (c) Palaeozoic and Mesozoic allochthonous of the Internal Dinarides. Both the Outer Dinarides and the Adriatic Sea are regarded as a foreland system, often characterized by HC sites. Growth and thrusts moving of external Dinarides and Apennines is directed towards the sea area. As a result of these directions, the anticline structures with NW-SE direction, regional reverse faults (thrusts) and back thrusts were formed during the late Pleistocene (Kastelic et al., 2013).[3]

Dinaride system can be divided into Mesozoic and Palaeogene complex that are affected by the compression regime in the Eocene time, which has consequently resulted in the formation of intra - montagne basins during the Neogene. Compression and shear events were carried out by "incompetent" layer of evaporates (salt), which was migrated most likely due to the burden of covering rock blocks. The differences between the moving blocks can be large, and so, in some parts, the entire Cretaceous sediments are missing (see Figure 3, the central block between Paklenica and Una), indicating the possibility of erosion as well as the timing of compression movements. Proper quantification of erosion also has a large share in a correct restoration of the thermo-catalytic maturity of source rocks and consequential migration and accumulation of UV. All the deformation events (i.e. Permian-Triassic rifting, Jurassic opening of the Dinarid Tethys, etc. (Hrvatović and Pamić, 2005)[2] must be an integral part of the basin modelling.

3. MAIN HYDROCARBON PLAYS

Oil and gas, i.e. petroleum systems are comprised of the 4 basic elements connected with geological processes: source rocks with generation potential, reservoir rocks, suitable trapping time that would accommodate the trap formation and theirs subsequent charge.[5] "Play" stands for a system of potential hydrocarbon reservoirs with potential or known source rocks.

Presence of hydrocarbons is detected across the Balkan Peninsula whereby the Pannonian Basin has been one of the highly explored domains of this central-southern European realm. The yearly production, e.g. from Croatian part of the Pannonian Basin reached around 3 million tons of crude oil. However, the area of External Dinarides - starting from the vicinity of the city of Zadar, spreading up to the Montenegro section of the Adriatic coast, could also be characterized by the proven petroleum systems. These systems are most likely accommodated around different depo-centers.[1] Depositional system (sedimentary pile) of the External Dinarides (including Adriatic) reaches over 15 km in depth.[9] Most probably, the total petroleum system is represented as by the thermogenic, but also with biogenic Pliocene and Pleistocene plays. Biogenic play is confirmed in Croatian and Italian offshore. According the type of reservoirs, the plays could be further separated on clastic and carbonate systems.

The Montenegro area of the southern Adriatic has direct HC indicators presented in a form of seismic-related flat-spots within Oligocene, Pliocene and Pleistocene sequences. Structural traps are mainly represented by ramp-anticlines, but also structural, fault-associated traps. Eocene and Oligocene clastic reservoirs are developed as stratigraphic and in a form of structural traps. However, successful exploration and resource assessment, including the confirmation of the main leads requires further research, before all organic geochemistry, relationship between source rocks and known fluids, generation, migration and accumulation, including fluid volumes and in situ and surface properties. It is necessary to keep in mind that all the aforementioned steps need to be constrained as for alochton, but also potentially to autochton.

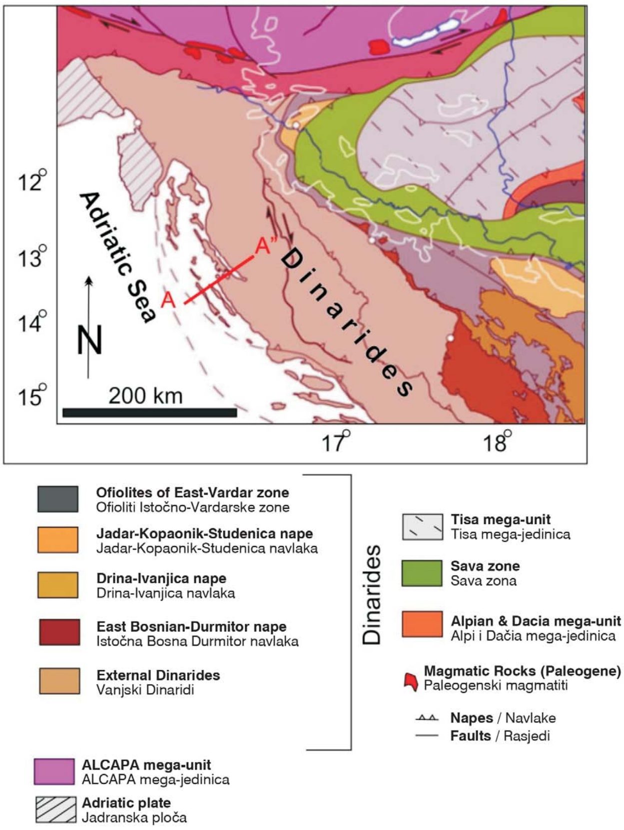

Fig. 2. A section of the tectonic map Alps and Dinarides (modified after Schmid et al., 2008).[8] Geological cross section A - A" is perpendicular to the main direction of tectonic transport.

Sl. 2. Dio tektonske karte Alpa i Dinarida (izmijenjeno prema Schmid i dr. (2008).[8] Geološki profil A - A" je okomit na pravac tektonskog transporta.

4. STRUCTURAL RESTORATION OF THE REGIONAL SECTION A - A'

The chosen regional 2D section (Tomašić et al., 2011) transects central Adriatic up to the western part of the state line between Croatia and Bosnia and Herzegovina. The line is perpendicular to the deformation thrust front. Also, geological interpretation is partially correlated with several wells located in the Adriatic Sea and the Basic Geological Map of SFRJ, in scale 1: 100.000. The 2D section strikes NE-SW and crosscuts the main reverse faults. Having a sparse database, the lithology is approximated to mimic roughly the mechanical rock properties of different layers. The most important mechanical rock criteria like the Poisson ratio, Young's modulus, shear stress and rock density. The values used in the presentation are taken from software Dynel® 2D (http://www.software.slb.com/products/foundation/pages/igeoss.aspx).

Structural restoration is performed in Dynel® 2D software that allows not only

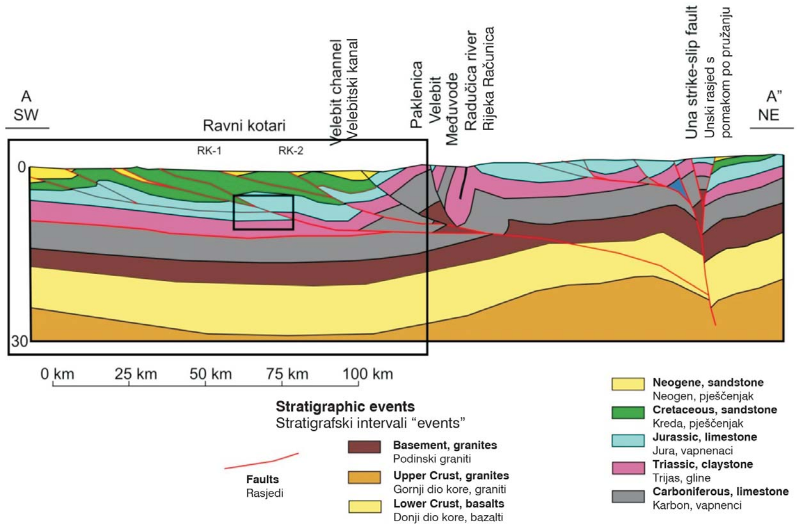

Fig. 3. Geological cross section A-A": Adriatic Sea - Central Bosnia-Southwestern Croatia

Sl. 3. Geološki profil A-A": Jadransko more - Centralna Bosna-Hrvatska

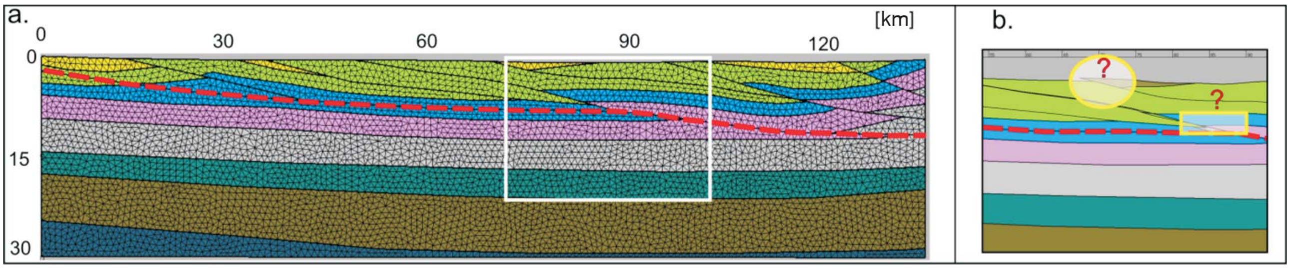

Fig. 4. a. Geological cross section in Dynel® 2D software. The triangles represent the density if numerical meshing (Finite Element Method, "FEM"). Each of the layers contains mechanical properties of differentially distributed stratigraphic intervals: dark blue - basalt; brown - gneiss; olive green - granite; grey - Lower Triassic; pink - Upper Triassic; blue - Jurassic limestone; light green - Cretaceous sandstone; yellow - Neogene sandstones. The red dotted line represents the main thrusting zone. b. Zoom on the central part of the geological cross section after the first restoration step (removal of the topmost layer) assigning the "unfault" for the main detachment. The main thrusting front (red line, figure 3) is used for the horizontal tectonic movement and restoration. However, lack, and the mass sufficiency indicate the differences in the layer thickness that are most probably not balanced during the interpretation.

Sl. 4. a. Geološki profil u Dynel® 2D softveru. Trokuti označavaju gustoću numeričke mreže (metoda konačnih elemenata "FEM"). Svaki od slojeva sadrži geomehanička svojstva stratigrafski separiranih stijenskih masa.: tamno plavo - bazalt, oker smeđe - gnajs, maslinasto zelena - granit, siva (d. trijas) - vapnenac, roza(trijas) - gline, plavo (jura) - vapnenac, svjetlo zeleno (kreda) - pješčenjak, žuto (neogen) - pješčenjak. Crvena isprekidana linija predstavlja glavnu zonu navlačenja. Povećani centralni dio geološkog profila nakon prvog koraka restauracije ili tzv. "unfault" po odvajanju (detachment) (granica trijas-jura) . Glavni pravac navlačenja (crvena linija, slika 3) je korišten za horizontalno kretanje i restauraciju. Nedostatak, kao i višak mase ukazuje na postojanje razlika u interpretiranim debljinama.

the pure layer geometrical balancing, but also involves the mechanical rock properties (Poisson ratio and Young's modulus, rock density). The software uses aforementioned rock mechanical properties for sedimentary layers like limestone, sandstone, claystone and for magmatic intrusions like granite, basalt etc. (Figure 4a). In our work, we roughly approximated limestone zone (Triassic and Jurassic) and clastic zone with sandstones and clays (Cretaceous and Tertiary).

The mechanical-based 2D cross section balancing indicated a necessity of the reinterpretation of the 2D section, especially in the deeper section parts. The results pinpointed a mismatch of the layer thickness, highlighting the importance of thickness distribution around reverse faults, but also pointing to the eroded parts of the section (Fig. 4b). Nevertheless, such interpretation problems are common in typical, highly deformed compressional setting, even in the highest quality seismic subsurface visualizations. It is very difficult to trace the spatial distribution of discontinuity and additionally correlate with thicknesses, which are again a function of depositional environment that in this case of Dinarides had been highly deformed during regional evolution.

5. TEMPERATURE MARKERS AS A MODELING CONTROL: AN EXAMPLE OF "MONGAS"FOLD (VENEZUELA)

Once palinspastic and regional basin restoration/evolution is quantified (including general quantification of paleotemperature), the stratigraphic sections are used for the basin and petroleum system modelling. Initially, each stratigraphic event for each restored section geometry during post-, syn- and pre-deformation imports inside PetroMod® by using module TecLink. Subsequently, each event needs to be discretized (gridding) by using "block" structure inside Teclink (e.g. hanging wall and footwall around reverse fault). The next step is fast automatic decompaction inside the software platform.

Due to a lack of key data, like the composition of organic matter, quality and positioning of reservoir and seal rocks, etc, as a compressional analogue, here we gave a short overview of the 2D model from Mogas hydrocarbon province located in Venezuela.[6] The main reason is Mongas field data availability, especially sufficient calibration data that largely control the quality of modelling results.

Successful modelling and calibration of the basin (petroleum system) models in compressional setting, predominantly depends on the thermal history of the each fault-adjacent, horizontally and vertically moved blocks (alochton and autochton). Critical data are presented in temperature measurements obtained from well data, vitrinite reflectance data, but separately obtained for each tectonically transported block. Note that one of the most common features for such thrusted systems is a relatively low heat flow ranging around 35 mW/m^2. Such low heat flow values could be associated with thin-skin type of folding, thus making the prediction of the hanging wall (alochton) and footwall (autochton) temperature extremely important. The position of the key thermocatalictic oil window actually controls drilling depths. Vitrinite reflectance is the most commonly used as a thermal calibration marker. Vitrinite reflectance can be produced from most commonly well data, and sometimes from exhumed outcrops (Fig. 5).

The thermal maturation of the structurally differentiated autochton and alochton (blocks) (predominant horizontal offset) is mainly the function of the kinematical events, i.e. the quantity of tectonic exhumation/burial. The pre-deformation maturity could significantly vary after the thrusting/reverse faulting.

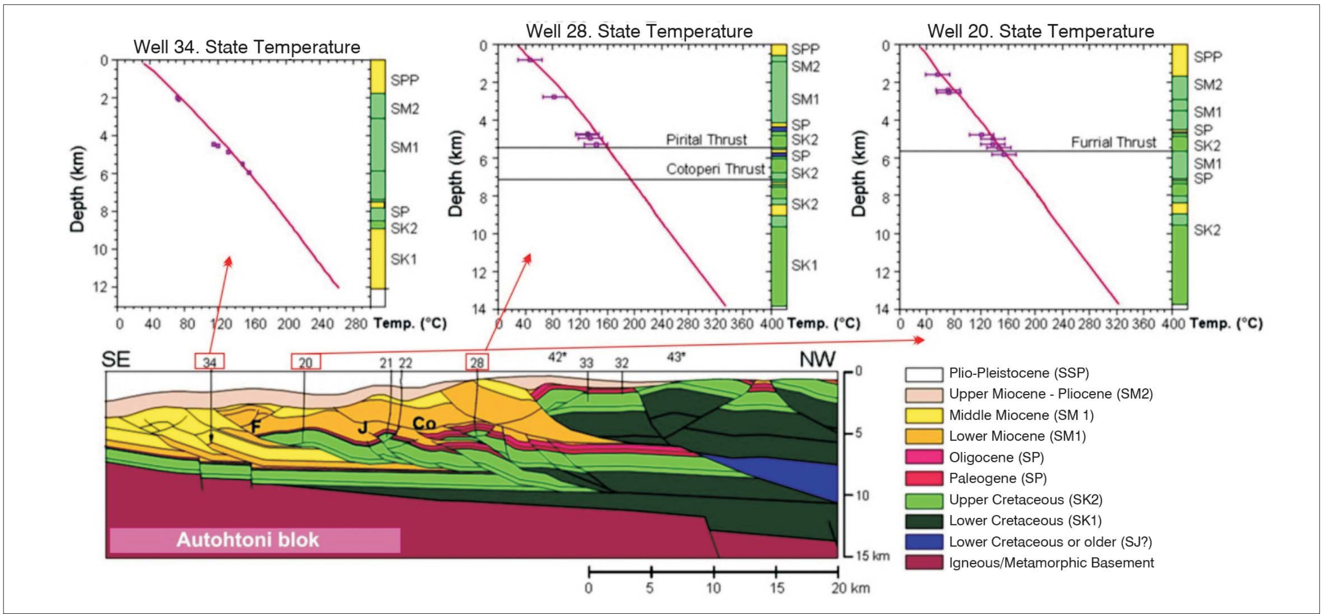

Fig. 5. Low: Well locations and the geological cross section. Wells predominantly are penetrating the alochton. Upper: 1D diagrams and calibrated models and their position within the Mongas complex. Modified after Parra et al.,[6] 2010.

Sl. 5. Pozicije bušotina kroz geološku sekciju koja pokazuje odnos alohtona i autohtona (dolje). Dijagrami 1D kalibrirani modeli i njihova pozicija u okviru Mongas kompleksa (gore). Modificirano prema Parra i dr.[6]

6. CONCLUSION

The HC potential of Dinaric thrust is undoubtedly proven by the many indicators. The goal of this paper is to increase awareness onto the newest scientific methods and tools which could provide a plausible, scientifically-based, cost-effective HC evaluation of the geologically, highly-complex areas such is Dinaric thrust system. In such highly complex geology and associated petroleum systems, the key condition is to moderate exploration risks making NC exploration rentable and within the effective timeframe to reach the production optimum. Consequently, the plausible information could provide a better insight in the resources. Thus, the full, initially 2D petroleum system modelling, and subsequently 3D hydrocarbon resource assessment is strongly recommended:

(i) Regional-geological exploration with a goal of detailed chronostratigraphy and their correlation with seismic and well data;

(ii) Regional and detailed geochemical sampling and investigations. Geochemistry analyses could comprise as the oil samples and eventual biomarker correlation, but most importantly, potential/hypothetical source rocks. The commonly used methods are: Rock Eval, vitrinite reflection, and finally the kinetic reaction.

(iii) Detailed structural and tectonic investigations, kinematic and quantitative analysis of the main thrusted zones, correlation with deformation events. These investigations are followed by the palinspastic restorations and sections balancing. Last phase could be represented by full 3D quantitative balancing of the entire 3D region.

(iv) Basin and Petroleum System Modelling: initially 2D, then 3D simulations and analysis of regional HC potential and main fluid migration routes.

(v) Calibration of the 2D/3D Basin and Petroleum System Models with respect to know the parameters. (Note that calibration often requires full, new simulation).

(vi) Local oil and gas field assessment and fluid calibration (volume, properties, quality, API, GOR).

(vii) Probabilistic evaluation and economic categorization of the potentially prolific areas;

(viii) Exploratory drilling, concept confirmation and increasing the quality of the regional petroleum system model in detail.

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