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3D BASIN MODELLING IN INTERNATIONAL AND HUNGARIAN CASE STUDIES

SUMMARY OF THE DOCTORAL (PHD) DISSERTATION

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1. INTRODUCTION

The main objectives of 3D basin modelling include the assessment of hydrocarbon generation in sedimentary basins, the understanding of timing of generation related to trap formation, the genetic relationships between source rocks and hydrocarbons, the amount and type of generated hydrocarbons and the migration and preservation issues. The understanding of all the inter-related processes and their timing is essential for successful basin modelling studies. The formation and preservation of a petroleum reservoir is the favourable outcome of many inter-related processes. The knowledge of all these processes, inter-relationships and timing of events is necessary for a successful basin modelling study. The exploration costs can be significantly reduced if basin modelling is applied in the early phase of exploration.

2. AIMS & METHODS

The first objective in basin modelling is in many times the identification and assessment of potential hydrocarbon source rocks. I could analyse the deposition of potential Jurassic – Lower Cretaceous source rocks and the spatial and vertical variation of organic matter in the Australian North Carnarvon basin. I could calibrate the observed organic matter content and type in areas where large amount of measured Rock-Eval data existed from wells, and predict them in undrilled locations using the OF-Mod software developed by Sintef. We published the results at the XI. ALAGO (Latinamerican Congress On Organic Geochemistry) Conference in Venezuela in 2008 (INTHORN et al. 2008).

The presence of a mature good-quality source rock is not enough to create a hydrocarbon accumulation. The primary and secondary migration of hydrocarbons, the formation and existence of traps and the timing of trap formation are also essential for a hydrocarbon accumulation to exist. If the trap formation occurred much later than the generation and migration of hydrocarbons, after a prominent erosion event, then the preservation of hydrocarbons is unlikely. I investigated the timing of trap formation and hydrocarbon generation in an Iranian case study, when we collected and measured apatite fission-track data in order to identify the so-far unknown erosion and uplift events of the Zagros Foldbelt. I could apply the results in a regional 3D basin modelling study, to constrain the areas of favourable trap formation and hydrocarbon generation (HOMKE et al. 2010).

I investigated the timing of hydrocarbon generation and trap formation, the genetic relationships between different source rocks and their generated products and likely volume and type with two different full 3-dimensional regional basin modelling case studies in Iran. The first area was the eastern part of the Persian Gulf, the Hormuz Strait (BADICS et al.

2004a), where I had to predict before drilling whether oil or gas and condensate could be found in the mapped undrilled structures of the area, and which source rocks could have generated the hydrocarbons.

The second case study focused on the Anaran license on the Iraq-Iranian border, where the main objectives were to identify and map the potential and effective source rocks, to prove the relationships between them and the known accumulations with organic geochemical methods, and calculate whether oil or gas would be found in the mapped structures. My detailed case studies carried out between 2004 and 2007 aimed to map the lateral distribution and vertical heterogeneities of the potential source rocks, and to investigate the burial and thermal evolution of the area to find out the amount of generated hydrocarbons within the drainage areas of the prospects. I also attempted to predict the volume, phase (oil vs. gas) and properties of hydrocarbons (like gas-oil-ratio, API gravity) in the undrilled structures – before drilling. The results have been published in BADICS et al. (2006, 2007).

The last international case study focused on the Oseberg field and its satellites in the Norwegian sector of the North Sea. The detailed organic geochemical correlations and integrated basin and petroleum systems modelling analysed the hydrocarbon migration along faults and unconformities, and the sealing or leaking nature of faults, which govern the fill-and-spill of the numerous fault-bounded reservoirs of the area (STODDART et al. 2005). The ambitious aim was to predict all the oil-water contacts, pore pressure cells and hydrocarbon column heights with the use of hydrocarbon migration softwares (PetroMod, Permedia, SEMI). The volume and type of generated hydrocarbons and the timing of generation versus trap formation needed to be understood for the migration modelling.

The assumed basin-centred gas accumulation in the Makó Trough in south-eastern Hungary got a lot of attention in the media and in exploration companies. Unfortunately, the drilling so far has not resulted in any economic gas flow rates. Therefore my objectives in the detailed Hungarian case study were to asses the hydrocarbon potential of the Makó Trough with the most up-to-date 3D basin and petroleum systems modelling tools. My main tasks were to identify and assess the potential Lower Pannonian source rocks of the area, to understand their burial and thermal history and to calculate the amount of generated hydrocarbons and compare them with the pore-volume of the assumed basin-centred gas accumulation (BADICS et al. 2010a, b, c, d).

3. NEW SCIENTIFIC ACHIEVEMENTS (RESULTS)

3.1. Results from the Australian North Carnarvon basin

3.1.1. I mapped in detail the Jurassic – Lower Cretaceous source rocks, and their lateral and vertical variability, the type and amount of organic matter in the North Carnarvon basin. This is essential to understand the petroleum system of the area and to delineate future discoveries.

3.1.2. I created a detailed 3-dimensional grid, containing 2,8 million cells, which shows the amount and type of organic matter in the investigated 67 million-year period, comprising 30 maps.

3.1.3. I achieved good match in the wells used for calibration and predict the amount and type of organic matter in areas where the Rock-Eval data were "hidden" during the modelling. The results have been shown in detail at the ALAGO conference (INTHORN et al. 2008).

3.1.4. I pointed out that the shallow water depth, the proximity to the shoreline and the presence of several deltas lead to the dominance of terrestrial-derived, type III kerogen, creating a poor or fair-quality, gas-prone, although very thick source rock sequence in the area.

3.1.5. I could predict with the OF-Mod modelling the amount and type of organic matter in the Lower Jurassic Athol Formation and in the Lower Cretaceous sediments with high precision. The organic matter content of the Upper Jurassic Dingo Claystone could be explained with three different scenarios: In the first scenario, the low primary plankton productivity and fully oxic water column lead to the best match between the predicted and the observed organic matter type and amount. In the second scenario, the modelled primary productivity was higher, and in the third, the bottom waters were anoxic. The second and third scenarios lead to the deposition of several 100 m thick, good-quality, oil-prone source rock, but it overestimated the organic matter content in the calibration wells. The results confirm, that in the studied area, the water could only be periodically anoxic, and only in the deepest parts of the rift grabens, which were protected from the bottom currents, therefore the source rocks of the area are mainly gas-prone with some layers of oil-prone kerogen.

3.2. Results from the Iranian Zagros Foldbelt

3.2.1. Our first apatite fission-track (AFT) results from the Zagros Foldbelt identified several, so-far unknown uplift and erosion events, which were described in detail in our article in Basin Research (HOMKE et al. 2010).

3.2.2. We confirmed that the first Early Jurassic uplift event at 202 Ma could be connected to the closure of the Paleo-Tethys Ocean. The later cooling and uplift events took place in the

Late Cretaceous (91 – 66 Ma) and in the Early Miocene (22 Ma). These events were identified in apatite samples from the Agha Jari Formation. The most important, so-far unknown uplift event identified by us was the Late Eocene (45 – 35 Ma).

3.2.3. The AFT ages indicating cooling between 45 and 35 Ma confirmed a long lasting uplift and erosion event in the Zagros Foldbelt in Lurestan. This event was probably related to the closure of the local branch of the Neo-Tethys Ocean.

3.2.4. According to our new results, the second erosion and uplift event at 22 Ma, in the Early Miocene was co-eval with the large deepening of the foreland basin, where the Gachsaran and Agha Jari Formations were deposited. This event marked the end of the marine sedimentation of the area by 19 Ma.

3.2.5. Using the AFT-ages and the vitrinite-reflectance data from wells and outcrops, I could reconstruct the burial and uplift evolution of the area in a 3D regional basin model and could understand the areal differences between the timing of hydrocarbon generation and trap formation, highlighting non-prospective, gas-prone and oil-prone areas.

3.3. Results from the Iranian Hormuz Strait

3.3.1. I could construct a detailed regional basin model of the area, identified the main potential source rocks and understood their burial and thermal history and the regional differences in source rock deposition and maturity evolution (BADICS et al. 2004a).

3.3.2. According to my regional work and 3D basin modelling case study, the most likely source rocks of the Hormuz Strait are the Bab Member of the Aptian Shuaiba Formation and the Cenomanian Shilaif Formation. These source rocks started to generate oil in the beginning of the Middle Miocene and gas from the Late Miocene. Trap formation started in the Late Cretaceous, while the size of anticlines increased during the Late Oligocene to Middle Miocene period, in connection with the Zagros orogeny (BADICS et al. 2004a).

3.3.3. I could understand the genetic relationships between source rocks and their related products, and the likely expelled volume within the drainage areas of the undrilled and drilled structures. In the western areas the Shuaiba reservoirs of the Tusan and Mubarek oil fields have been charged from the Bab Member, while the Mishrif reservoirs from the Shilaif source rock. Here the two source rocks have not been buried to the gas generation zone, so only oil has been generated from the Middle Miocene, thus the two discovered and many undrilled structures will contain oil. In the eastern areas, the Henjam and Hangam gas-condensate fields were located closer to the deep Oman Foredeep, where the source rocks reached the gas-generation zone in the Pliocene, when the traps were also formed, so the discovered fields and the undrilled structures will contain gas and condensate.

3.3.4. I could also forward model the phase (oil vs. gas) and physical properties (density, gas-oil-ratio) of petroleum in the known accumulations and predict the same parameters in the undrilled structures. Based on these predictions, Norsk Hydro modified the exploration strategy in the area.

3.4. Results from the Iranian Anaran area

3.4.1. I managed to map the lateral, thickness and richness variations of the source rocks of the study area. I created detailed maps for the Middle Jurassic Sargelu, the Upper Jurassic Naokelekan/Najmah, the Tithonian-Berriasian Basal Garau, the Barremian Gadvan, the Aptian-Albian Kazhdumi, the Cenomanian Ahmadi, the Coniacian Surgah, the Campanian Gurpi and the Paleogene Pabdeh source rocks (BADICS et al. 2006, 2007).

3.4.2. My 3D regional basin modelling revealed for the first time, that the mentioned source rocks of the area started generating oil at the end of the Middle Miocene, and reached the peak of oil generation in the synclines between 7 and 4 Ma. The Sargelu and Basal Garau are generating gas and oil in the deepest synclines, depending on the burial depth, and the Kazhdumi and Ahmadi are generating oil, and the shallowest Pabdeh is immature.

3.4.3. I identified that the trap formation took place in the Late Miocene and Pliocene, between 8 and 2 Ma, during the formation of the frontal zone of the Zagros Foldbelt. As the trap formation was at the same time as the main phase of hydrocarbon generation, very large undersaturated oil fields have been formed at Badrah (Iraq) and at Azar, Changuleh and Dehluran in Iran.

3.4.4. I could calculate the expelled volume of hydrocarbons and their genetic relationships: In the north-western areas around the Badrah, Azar and Changuleh fields and their drainage areas the Sargelu, Garau and Ahmadi source rocks charging the Sarvak reservoirs have been generating only oil since the Middle Miocene, thus the discovered fields are undersaturated oil fields. In the south-eastern areas, around Dehluran, Abu Ghirab and Paydar, the Kazhdumi is much better quality and thicker source rock, therefore the sulphur-rich oil generated from the Kazhdumi appeared in the shallower Asmari reservoirs.

3.4.5. Based on the 3D basin modelling in 2005 I could predict the volume, the phase (oil), and the physical properties (API-gravity and gas-oil-ratio) of the Azar structure. The prospect was drilled in 2006 August, and found the largest oil field found in 2006 worldwide. The oil density and gas-oil-ratio values measured during testing were very close to the predicted ones.

3.5. Results from the Oseberg cluster, Viking Graben, Norwegian North Sea

3.5.1. The greatest result was the successful collection and organisation of the huge amount of pressure, temperature, Rock-Eval, vitrinite, biomarker, isotope and PVT data from the area, which has lead to numerous internal reports and published articles since then.

3.5.2. I created 9 very detailed source rock maps (thickness, immature TOC & HI, maturity) of the Oxfordian Heather hot-shale and the Lower and Upper Draupne sediments based on the ca. 100 wells in the area.

3.5.3. I successfully used the PVT data together with the biomarkers and isotopes to identify and correlate the oil families and detect the possible migration and fill-spill routes of the area.

3.5.4. We could identify and describe 4 significant hydrocarbon migration routes: 1.) Oseberg Main – C-Structure – Brage field (Fensfjord and Sognefjord reservoirs) – Troll West Oil Province 2.) Tune field - Oseberg South, 3.) Veslefrikk field (Brent, Cook and Statfjord reservoirs) – Oseberg East (Brent reservoirs) – Brage Horst (Statfjord reservoir), 4.) South Brage fault-zone. Some of the Troll oil could have came via the Oseberg – Brage migration pathway, while most of the gas and some part of the oil from the north, from the Sogn Graben to the area. The results have been shown in detail by STODDART et al. (2005) at the AAPG Calgary Conference.

3.5.5. We could identify several prospective undrilled structures, and identify their hydrocarbon phase and volume, and determine whether the faults bounding them were sealing or leaking.

3.6. Results from the Makó Trough, Hungary

3.6.1. I could create a very detailed 3D basin model of the Makó Trough, and calculate the burial and thermal evolution of the source rocks of the area. The results have been published in BADICS et al. 2011a, b; 2010c, d. According to my 3D basin modelling investigation the potential Endrőd Marl source rock was buried into the oil generation zone first by the deposition of the Szolnok Formation between 8 and 6 Ma, then to the gas-generation zone by the thick Újfalu, Zagyva and Nagyalföld Formations from 5 Ma.

3.6.2. In the deepest parts of the Makó Trough, the base of the Endrőd Marl is now at 250-270°C temperature, in the dry gas generation zone, while on the flanks it is in the wet gas generation zone, on the Algyő and Battonya-Pusztaföldvár Highs in the oil generation zone. The top of the Endrőd Marl is in the dry gas generation zone in the central parts of the Trough and in the oil zone on the flanks. The Szolnok Formation is in the oil zone only in the deepest parts of the Trough, while all the younger sediments are immature.

3.6.3. I created immature TOC and HI maps from the available TOC and Rock-Eval data for the Makó, Dorozsma, Tótkomlós and Nagykörü Members of the Endrőd Marl, including the lateral and vertical heterogeneities in the organic matter content and type. The highest immature TOC could have existed in the Makó Member, but only in the central parts of the Trough (Hód-I and Makó-7 wells), as the observed data from the surrounding wells show much lower TOC values.

3.6.4. According to my calculations in the Mindszent, Tisza and Makó license areas 490-650 Billion Sm^3 gas was generated, mainly from the Makó and Tótkomlós Members of the Endrőd Marl.

3.6.5. I could also calculate (with probabilistic, Monte-Carlo methods) the free pore volume in the same 3 license areas using the available depth and thickness maps. In only the sand layers of the Szolnok Formation the free pore-volume is around 14 000 Billion Sm^3. The combined free pore-volume of the Szolnok, Upper and Lower Endrőd, Békés Conglomerate and Syn-Rift sediments is 34 000 Billion Sm^3 in the sand layers only, while up to 52 000 Billion Sm^3 in the sand, silt and clay layers altogether.

3.6.6. In the Makó Trough, within the 3 license areas 490-650 Billion Sm^3 gas was generated while in the same area, only the sand layers of only the Szolnok Formation represent 14 000 Billion Sm^3 free pore-volume, which need to be saturated with gas. It is clear that much more gas would be needed to saturate the pore-space with gas. We confirmed that only 5-10% of the required gas was generated in the same 3 license areas.

3.6.7. Based on our data, the Algyő and Szolnok Formations have very low average TOC values; therefore they cannot be considered as shale-gas play. The calcareous marl parts of the Endrőd Marl and the syn-rift Makó Member contained on average low TOC (0,75-0,95%), but in certain basinal areas around the Hód-I and Makó-7 wells more (1,3-1,5% TOC), but most of the kerogen could have been terrestrial, type III, gas-prone kerogen, which parameters make the Endrőd Marl an unlikely candidate for a successful shale-gas play.

3.6.8. The Zagyva and Újfalu sandstones are very thick in the Makó Trough, but they do not form any structural traps within the Trough, so there is no focused accumulation for the generated gas within them. The Szolnok Formation sands are also very thick, therefore their free pore-volume is also very large, about 14 000 Billion Sm^3 , which would need much more gas for a full saturation, than was generated in the same area. Based on the above mentioned details the Makó Trough does not contain either an economic shale-gas play in the Endrőd

Marl, nor an economic basin-centred tight gas accumulation in the Szolnok Formation (BADICS et al. 2010a, b, c, d).

4. CONCLUSIONS

I have achieved the following scientific results in the discussed 5 international and one Hungarian basin modelling case studies:

During the Australian basin modelling study I have mapped in detail the lateral and vertical heterogeneities of the Jurassic – Lower Cretaceous source rocks of the North Carnarvon basin, and the variation of organic matter type and amount in these source rocks. I could predict the organic matter content of the sediments in areas without wells with the OF-Mod method. The deposition and facies changes of the source rocks were then better understood.

Our new apatite fission-track results identified several so-far unknown erosion and structuration events in the Zagros-Foldbelt in Iran, and determined the absolute geological age of these events. These erosion events significantly influenced the timing of trap formation and hydrocarbon generation, and also the type of trapped hydrocarbons.

I could calculate the amount and type of generated hydrocarbons in the Hormuz Strait during my second Iranian 3D basin modelling study, and predict the phase in the undrilled traps, which modified the exploration strategy in the area.

In my third Iranian 3D basin and petroleum systems modelling study, which focused on the Anaran area, I could map the Jurassic – Cretaceous – Tertiary source rocks using well and outcrop data in detail, and then calculate the amount and type of hydrocarbons generated within the different drainage areas of the prospects. I could also predict the type and physical properties of the hydrocarbons in the prospects – before drilling. Norsk Hydro found the largest oil field of 2006 with the Azar-2 well, and the test results confirmed the predicted gas-oil ratios and densities.

In the Norwegian Oseberg 3D basin modelling study I could create 9 detailed source rock maps of the Heather hot-shale and the Upper and Lower Draupne Formations. I interpreted the regional PVT data together with the biomarkers in order to identify the oil families and the 4 main hydrocarbon migration routes of the area. We could identify several prospective structures of the area, and determine whether the faults bounding these structures were sealing or leaking. The Oseberg case study showed that the integrated basin and petroleum system modelling can identify new exploration opportunities even in areas which have old producing fields.

In the Makó Trough 3D basin modelling study in Hungary I pointed out that the Lower Pannonian sediments of the area are mainly poor- to fair quality, gas-prone source rocks. I reconstructed the geologic evolution, the burial, and thermal and maturity evolution of the area and could calculate the amount of generated hydrocarbons. In the Makó Trough, in the combined 3 license areas of TXM, 490-650 Billion Sm3 gas could have been generated, but this is much less than the free pore-volume of the sediments of the same area, therefore a producible basin-centred gas accumulation is unlikely to exist.

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