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ABSTRACT BOOK

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Petroleum Geology Student Contest - 3rd edition

Petroleum Geology III edition student contest

Shell

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ABSTRACT INDEX

2st SESSION – MSc Student Session

PREFACE TO THE VOLUME

The present manuscript includes all the abstracts submitted to the 3rd edition of the Petroleum Geology Student Contest, which was held on October 23rd - 25th 2019 in the characteristic town of Calvello (Potenza).

Thanks to the support of Shell Italia E&P, of the Science Department of the University of Basilicata, of the Georesources and Energy Section of the Italian Geological Society, and of the Calvello city hall, we organized a 3 day-long workshop in the ancient Santa Maria de Piano Monastery. The PGSC workshop, an unique event of this kind in Italy, was aimed at offering the opportunity to young researchers to show the results of their research to an audience of academic and industrial geologists. The PGSC workshop was also designed to gather together experts of Petroleum Geology to discuss and exchange novel research ideas and breakthroughs.

The original research works reported in this book deal with several fields of the Earth Sciences. They cover a variety of disciplines, including Geodynamics, Regional Geology, Basin Analysis, Sequence Stratigraphy, Applied Sedimentology, Structural Geology, Geophysics, Palaeontology, and Geochemistry. These topics were used to tackle topics of outcrop analogues, data processing and interpretation, petrophysics and rock physics, reservoir modelling, fluid flow simulation, etc.

Among all abstracts included in this book, 16 were selected by the Scientific Committee to compete for the 5,000 EURO and 2,000 EURO grants assigned by a Judging Committee to the best PhD and MSc student presentations. The 8 PhD students provided 30 minute-long oral presentations, whereas the 8 MSc students illustrated the results of their work in a poster presentation. The Scientific Committee was composed of colleagues working in a number of Italian and foreigner universities and research centres, who have enthusiastically offered their cooperation to the workshop.

Many researchers and students, who formed a lively atmosphere and a stimulating setting, attended the workshop. During the last day of the workshop, Giuseppe Palladino and Giacomo Prosser (University of Basilicata) led a fieldtrip through the Agri Valley of Basilicata, which included several stops aimed at deciphering the geological setting of a significant portion of the southern Apennines fold-and-thrust belt. We are grateful to the following colleagues and friends of the Scientific Committee: Alejandro Escalona and Nestor Cardozo (University of Stavanger), Alessandro Incarbona (Università di Palermo), Andrea Bistacchi (Università di Milano Bicocca), Andrea Brogi (Università di Bari), Attilio Sulli (Università di Palermo), David Iacopini (University of Aberdeen), Davide Scrocca (IGAG-CNR), Domenico Chiarella (Royal Holloway University, London), Edoardo Perri and Francesco Muto (Università della Calabria), Emanuele Tondi (Università di Camerino), Enzo Rizzo (IMAA-CNR), Filippos Vallianatos (University of Athens), Giovanna Rizzo and Giovanni Mongelli (Università della Basilicata), Giovanni Barreca and Rosanna Maniscalco (Università di Catania), Juliette Lamarche (Aix-Marseille University), Marcello Tropeano (Università di Bari), Marco Patacci (University of Leeds), Mariano Parente and Stefano Tavani (Università di Napoli Federico II), Nicola De Paola (University of Durham), Pascal Barrier (Université La Salle), and Sveva Corrado (Università di Roma TRE).

Our gratitude also goes to the components of the Judging Committee: Sandro Conticelli (President of the Italian Geological Society – Università di Firenze), Luisa Sabato (Università di Bari), Giorgio Minelli (Coordinator of the Georesources and Energy Section of the Italian Geological Society – Università di Perugia), Alessandro Amorosi (Università di Bologna), Stefano Mazzoli (Università di Napoli "Federico II"), and Giacomo Prosser (Università della Basilicata).

Finally, we would like to thank all PhD and MSc students who enthusiastically attended this 3rd edition of the workshop. Their fervent participation confirmed the importance that an event like this may have for young researchers who are moving their first steps in the world of the Petroleum Geology, as well as for the entire scientific and industrial community.

Potenza, late October 2019

Fabrizio Agosta & Sergio G. Longhitano
Department of Science, University of Basilicata, Potenza, Italy

1st SESSION – PhD Student Session

Detailed outcrop characterization of high-frequency sequence boundaries in the Pliocene Peri-Adriatic shallow marine succession revealed through UAV cliff-side digital outcrop mapping

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Keywords: Sequence stratigraphy, Digital Outcrop Model, southern Marche.

Sequence stratigraphy principles applied to shallow marine clastic successions represent a powerful tool for understanding the signals of base level change recorded by marine sedimentary systems. However, when dealing with large cliff sections, the subtle details such as stratal termination geometry, grain size jumps, and bed-scale sedimentary structures that characterize sequence boundaries are often just beyond the reach field geologists. By taking advantage of the range of highly accessible Unmanned Aerial Vehicles (UAV) for conducting aerial surveys and Digital Outcrop Model (DOM) construction can bridge the gap to enable the detailed inspection of previously inaccessible outcrop sections.

We present an integrated study focused on the middle Pliocene (Piacenzian) shallow-marine succession superbly exposed on the cliffs below the town of Montefalcone Appennino (southern Marche). This work involves facies analysis and sequence stratigraphy revealed by combining detailed stratigraphic field methods and the use of Unmanned Aerial Vehicle (UAV) cliff-side scanning using Structure from Motion (SfM) photogrammetry to create high-resolution Digital outcrop Models. These DOMS are constructed by the collection of close range (<10 meters) cliff-side photo sets used to build immersive outcrop reconstructions which enable the close inspection of bed scale details which characterize the largest elements visible on the outcrop. These DOMs are used as a resource that is paired with other data sets such as measured logs and laboratory analysis of collected samples

The studied section is about 100 m thick and comprises a dominantly aggradational stack of shoreface deposits truncated by a series of laterally extensive wave-cut ravinement surfaces interpreted to have formed during transgressive erosion. These surfaces form the boundaries of stratal units regarded as high-frequency sequences controlled by minor relative sea-level changes. The internal architecture of individual sequences is characterized by the presence of three main facies associations, which are differentiated by grain size and by physical and biogenic sedimentary structures. The basal unit of each sequence (FA-A) comprises amalgamated, fine- to medium-grained sandstones exhibiting predominantly plane-parallel lamination and swaley cross-stratification and well-segregated granules and small pebbles forming laterally discontinuous layers. FA-A grades upward into FA-B consisting of thoroughly bioturbated, fine- to coarse-grained sandstones with pebbles and broken shells (pectinids and ostreids) scattered throughout. In the upper sequences, FA-A grades upward into FA-C consisting of fine-grained hummocky-bedded sandstones with thin, laterally discontinuous stringers and isolated clusters of small pebbles.

Refined oil releases: a new approach for their management and for nuclear forensics

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Keywords: NAPL releases, radiometric dating, natural attenuation.

During upstream and downstream activities unwilling oil leakages or spills may occur, leading to legal controversial about environmental contamination. Once crude oil or its refined products enter in contact with the environment, they are classified as Non-Aqueous Phase Liquids (NAPLs). Their tendency to insolubility and immiscibility in water represents the main problem during the remediation procedures, which are often slightly effective and take many years. Considering the difficulties in the allocation of the environmental recovery costs and in managements of polluted areas over time, total costs related to legal and technical issues are still very high. A drastic decrease in the economic loss could be achieved by obtaining three main information on each contaminated situ: the age of the contamination, the evaluation of subsurface distribution and/or quantification of the residual contaminant and the forecast of the environmental attenuation of the pollutant. This research develops an innovative approach to subsoil and groundwater contaminations caused by NAPLs integrating these different aspects. First, the accumulation in lekead NAPLs of recoiled ^{228}Ra from soil is studied to develop and propose a specific radiometric dating method (^{228}Th/^{228}Ra disequilibrium radioactive pair clock) by preliminary tests and dating tests on soil and water samples contamined in laboratory and in situ. All tests were performed to verify the reliability of the method, the applicability of theoretical background, and to value its possible constrains. Secondly, Rn deficit technique is applied to monitoring an old contamination involving the superficial groundwater for a year, improving the knowledge about some crucial aspects of this method in order to estimate the residual NAPL content from collected data. Finally, all the information were used to forecast the natural attenuation in situ (Metcalf et al., 2016). Two main results can be considered in this work. The development of a specific radiometric method that is based on environmental radioactivity due to the natural content of ^{232}Th. The physical process on which is based overcome all limits and uncertainties due to the dependence of previous dating methods (such as chemical degradation, additives and so on, Morrison, 2000a,b) on environmental parameters or casualities. Moreover, the comparison between different features of a complex multiphase system determined by a NAPL pollution offers a more complete scientific understanding of the problems. The possible solutions deriving from this new point of view can positively improve the management of a contaminated site and the future related scientific research with relevant implications for nuclear forsensics.

Metcalf M.J., Stevens G.J., Robbins G.A. (2016) - Application of first order kinetics to characterize MTBE natural attenuation in groundwater. Journal of Contaminant Hydrology 187:47–54.

Morrison R. (2000a) Critical Review of Environmental Forensic Techniques: Part 1. Environmental Forensics 1:157-173. http://doi.org/10.1006/enfo.2000.0017

Morrison R. (2000b) - Critical Review of Environmental Forensic Techniques: Part 2. Environmental Forensics 1:175-195. http://doi.org/10.1006/enfo.2000.0018

Fracture stratigraphy and DFN modelling of tight carbonates; the case study of the Lower Cretaceous carbonates exposed at the Monte Alpi (Basilicata, southern Italy)

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Keywords: Photogrammetry, Fractured carbonates, Apulian Platform.

Field development, geo-hazard mitigation, and reserve estimation represent fundamental issues regarding the reservoir optimization. Since both fluid flow and storage properties of fractured carbonate reservoirs are profoundly affected by their depositional, diagenetic and tectonic histories, the study of an outcrop analogue permits to fill the gap between core and seismic data. In fact, this type of studies often provides a very useful information on the sub-seismic domain (i.e. below common seismic resolution scales). The present work focuses on the role played by depositional/diagenetic heterogeneities on the vertical growth of high-angle structural elements such as joints, sheared joints, small faults, and well-developed faults in tight carbonates of Lower Cretaceous age. The study carbonates crop out along the 100's m-high and km-long western cliff of the Monte Alpi, in southern Italy, and pertain to the Inner Apulian Platform. They hence form a surface structural analogue of the carbonate reservoirs currently exploited for hydrocarbon production in nearby areas of the Basilicata Region. Choice of the sampling sites for traditional field stratigraphic and structural analyses and subsequent photogrammetric and 3D digital outcrop analyses was dictated by the results of a detailed line drawing of the whole western of Monte Alpi, which highlighted the lateral distribution of primary heterogeneities (Fig.1). As a result, we assessed the abutting and crosscutting relationships among primary heterogeneities such as bed interfaces, Transgressive Surfaces (TS) and Prominent Transgressive Surfaces (PTS) with the aforementioned structural elements.

Primary heterogeneities are interpreted as flooding surfaces forming sequence boundaries of different orders. Specifically, bed interfaces extend laterally for a few 10's of m, bound 10's of cm-thick beds, and form 4-to-5th order boundaries. TSs extend laterally for 100's of m, include mm-thick terrigenous material, bound a few m-thick bed packages, and form 3rd order boundaries. PTSs are laterally continuous for km's, include up to a few cm-thick, clay-rich levels and collapsed breccia, bound 10's of m-thick bed package associations, and form 2nd order boundaries. At the mesoscale, joints are stratabound elements, whereas sheared joints crosscut multiple beds but abut against TSs. At a larger scale, small faults form persistent fracture zones abutting against PTSs. Differently, well-developed fault zones crosscut multiple PTSs. Results after DFN modelling of representative geocellular models highlight that fluid compartmentalization is mainly provided by background SB and NSB structural elements, while small and well-developed faults play a fundamental role on fluid migration properties giving rise to the so called mega events.

Reducing uncertainties concerning reservoir and trap integrity in potential Devonian reservoirs of the Inner Moray Firth Basin using field and drone-based onshore analyses

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Keywords: onshore analogues, fault reactivation, hydrocarbon play.

Devonian continental sandstones that underlie the Inner Moray Firth Basin (IMFB) provide petroleum reservoirs locally in the North Sea (e.g. Claymore, Buchan, Stirling fields). The development of reservoir-quality sandstones and local Devonian source rocks provide encouragement that the play could be more extensive, but uncertainties exist concerning reservoir and trap integrity. This is mainly due to the perceived complex, superimposed deformation history in the area.

New detailed field observations augmented with drone photography and creation of 3D digital outcrops of the Old Red Sandstone strata bordering the onshore IMFB have been used to explore the role of inherited Devonian faults in IMFB development during the Mesozoic-Cenozoic. Previously the influence of structures related to the older Orcadian Basin on the kinematics of later IMFB opening has received little attention due to the poor resolution of seismic reflection data at depth and sparse well data. Onshore studies are able to reveal sub-seismic structural styles and provide a structural template for interpretation of the subsurface. They also provide new information concerning the earlier kinematic history of the basin, better constraints on the influence of reactivation and ultimately lead to reductions in subsurface uncertainties.

Key fieldwork findings include dip-slip N-S to NE-SW striking faults, some of which are demonstrably syn-sedimentary, related to the opening of the Orcadian Basin. These trends show evidence of later dextral reactivation during NW-SE extension, with sinistral WNW-ESE to NW-SE striking faults and folding developed at the same time. The folds are open and gently plunge NW. They become tighter, moderately plunging (40º) and the hinge line rotates towards N-S close to major faults. This later deformation is consistently associated with calcite mineralization (e.g. slickenfibers, tensile veins or Riedel shear fractures).

The onshore approach used here shows that widespread oblique reactivation of earlier Orcadian Basin structures has occurred. This will create reservoir-scale structural heterogeneity in potential Devonian reservoirs and can be used to further explore sub-surface Devonian plays elsewhere in the North Sea. This onshore-offshore approach can significantly enhance future offshore exploration in other areas of superimposed rift basin development worldwide.

Neural network technique and seismic attributes, west offshore Nile Delta, Egypt

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Keywords: Eastern Mediterranean; neural network; seismic attributes; Nile Delta.

Eastern Mediterranean area is considered one of the most prolific provinces for gas production and for future petroleum exploration. Seismic attributes supported by composite logs are the best way that can enable the interpreter to understand the seismic data and generate a new view of the output results especially for the identification of gas chimneys and gas zones as channels by using physical and hybrid attributes while the faults and fractures detection enhancement applied using geometrical attributes. Identification of the reservoir zone enhanced by analyzing wells log data based on Gamma-ray, Resistivity, and Vp sonic logs respectively. Composite logs of five wells indicates the lateral and vertical variation of the gas reservoirs which helped in 2D seismic data to well tie and in construction of the synthetic seismogram after data conditioning processes which included check-shot correction, wavelet extraction and the application of filtering methods in order to improve the resolution of the reflection events and signal to noise ratio. Additionally, AVO attributes as a direct hydrocarbon indicator including AVO gradient analysis, AVO crossplot, and AVO attributes (A/B (Two term Aki-Richards), A+B and A*B for Scaled Poisson ratio change and Scaled S-wave reflectivity (aA-bB)) to separate the gas levels in the sand-shale sequences from wet sand and shale levels, evaluation of the hydrocarbon potentiality and habitat of the study area and recommending the possible exploration and development activities of the considered area on the light of the conclusions and deductions arrived through this study by analyzing various seismic attributes families and Artificial Neural Network (ANN) method.The 2D seismic data and the wells in the area of study are not enough to understand the distributions of sandstone layers and lithologic change across the whole seismic survey area. So, we utilized an Artificial Neural Network (ANN) method supported by the well logs data. We have used the Fluid Replacement Modeling (FRM) to analyze the changing of the fluid type and its saturation value at the reservoir and creating synthetic logs relating to these changes to predict reservoir seismic properties changes in density, compressional and shear wave velocity caused by fluid replacement. The main contribution of this work is to provide a more detailed analysis related to the process established for the relationship between sandstone lithology from logs and various types of seismic attributes supported by ANN to define the change of the physical properties such as porosity, lithology and fluid content.

A multi-proxy palaeoenvironmental analysis during deposition of the Mahogany Oil Shale interval of Eocene Lake Uinta, Green River Formation, Utah

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Keywords: Unconventionals, Geochemistry, Source Rocks.

The Lower Eocene Green River Formation of Utah, Colorado and Wyoming represents a ~15 million-year record of unusually large, productive lakes which deposited an estimated 750 billion barrels of oil equivalent, one of the largest oil shales in the world. Multiple drill cores through the Parachute Creek Member, Utah, taken from both the basin margin and center, offer an excellent opportunity to construct high-resolution records of terrestrial conditions and explore their influence on organic matter deposition and preservation.

These drill cores record several negative carbon isotope excursions in the carbon isotopic composition of bulk organic carbon that can be potentially correlated to the marine record of hyperthermals through a radiosotopically anchored astrochronolgy. One of these transient intervals of rapid greenhouse warming occurred during deposition of the Mahogany Oil Shale, an unusually organic carbon-rich deposit (up to 40%) of interest for unconventionals.

In this study, the isotopic expression of mid-latitude hydrological change during rapid warming is investigated through compound-specific hydrogen isotopic analyses of n-alkanes extracted from the Mahogany Oil Shale Zone, Uinta basin, Utah. Comparison of this novel record with high-resolution sedimentary logs will allow for greater understanding of the hydrological cycle at the time of deposition of this key oil shale. We seek to merge a multitude of scales, from field outcrops to microscopic imaging to molecular analysis, to bridge novel proxies with traditional methods in answering fundamental questions about unusually high organic matter burial events. Variations in organic matter distribution and its interaction with a fluctuating carbonate and siliciclastic matrix should be mirrored in the biomarker records. We would expect variations in key biomarkers (e.g. isoprenoids, n-alkanes, hopanes) at the molecular scale when observing changes in the organic matter at a microscopic scale with detailed thin section imaging and analysis.

Disentangling the factors controlling deposition and preservation of organic matter in the Green River Formation will lead to greater understanding and predictability of the organic-rich layers in the oil shale. As a potential future target for unconventional exploration and the use as a source rock analogue (e.g. Pre-Salt Offshore Brazil plays), understanding these factors will support the development of the U.S unconventional hydrocarbon industry, and petroleum independence in the region.

Tectonics, sedimentation and magmatism of the Canterbury Basin, New Zealand

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Keywords: Seismic data; Tectonics; sedimentation; magmatism; Canterbury Basin; New Zealand.

The Canterbury Basin, east coast of New Zealand's South Island, is a Late Cretaceous rift basin, mildly affected by Recent plate boundary compression. The most recent open-file petroleum data in the region allows a continuous imaging of undeformed Late Cretaceous to Paleogene rift to drift sequences, that in turns have a potential for hydrocarbon exploration.

Extension of eastern Gondwana stretched the Canterbury Basin from ~110 to ~85 Ma, creating NE-SW, E-W and NW-SE trends of rift faults. Analysis of 2D and 3D seismic reflection lines tied to wells indicates that these three fault sets are synchronous with primarily normal fault geometries and displacements. With the onset of breakup (~85 Ma), extension transferred along the spreading centres of New Zealand margin and multi-directional stretching in the Canterbury Basin ceased or continued at much diminished rates.

The displacement along syn-rift faults was 1.5 times greater than the sedimentation rate and contributed to the under-filled nature of the rift where the availability of sediments was not enough to keep pace with the formation of accommodation space. The under-filling resulted in a basin and range topography produced by normal faulting that persisted through the Late Cretaceous post-rift phase. Early syn-rift sedimentation was dominated by short fluvial drainage systems. Thereof were sourced from within the basin and inter-fingered with lake deposits in more central portions of the basin, that over time were transgressed from the east. The post-rift sequence of the Canterbury Basin displays three distinct shelf-edge clinoform packages that developed during Late Cretaceous to Eocene times. Contemporaneously, detrital sediments were sourced from structural highs and ultimately, pelagic sedimentation draped and buried most of the earlier-formed horsts. Towards the south-east offshore, on the basin floor, deep-water fans were recognised for the first time within Paleocene and Eocene strata of the Canterbury Basin.

Seismic reflection data enabled us to identify buried volcanoes and intrusions, ranging in age from Late Cretaceous to Pleistocene. Five eruptive phases can be recognized using geomorphological, volumetric and chronological parameters. These eruptive phases formed monogenetic and polygenetic volcanoes that erupted >10's to >1000's km^3 of magma.

Collectively the results help improve the understanding of the regional processes that led to eastern Gondwana breakup, precise how sediments were distributed within the under- filled rift basin and propose maps of buried volcanoes which has implications for heat flow and maturity of petroleum systems in the Canterbury Basin.

Early exploration techniques to constrain petroleum system evolution: unlocking values in the Namibe Basin (Angola)

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Keywords: Early Exploration, Petroleum System, Namibe Basin.

The Namibe Basin (southern Angola) developed as part of the Cretaceous South Atlantic evolution and within one of the most prolific hydrocarbon provinces in the world. Although the Basin is still underexplored, it has a significant hydrocarbon potential due to key favourable geological elements occurring regionally. Since no hydrocarbon wells have been drilled, the petroleum system evolution needs to be understood from the onshore geology. Field campaigns in the Namibe Basin have identified key petroleum system elements and evidence for migrated hydrocarbons, typical indicator of a working petroleum system. The Namibe Basin is characterised by syn-rift to sag continental/lacustrine facies and post-rift marine sediments, separated by Aptian evaporites. Pre- and Post-Salt intervals with source rock potential have been observed and can be regionally correlated to actual source rocks, charging some of the main oil fields in the other basins of the hydrocarbon province. These include Aptian paper-shales, deposited in the immediate Pre-Salt within a lacustrine/microbial-dominated depositional environment, and Albian dark mudstones, deposited in a restricted marine environment in the immediate Post-Salt. Bitumen and oil seeps are found in pores and fractures within Pre- and Post-Salt intervals at different localities along the basin strike.

Preliminary biomarker analyses on bitumen and seeps suggest generation from a lacustrine source rock, due to presence of tetrapolyprenoids, although other diagnostic biomarker parameters suggest that contribution from marine intervals should not be excluded. Hypotheses for the hydrocarbon generation in the Namibe Basin include: 1) Local forced maturation of onshore source rocks due to magmatic activity, suggested by presence of magmatic events in the basin evolution and some of the bitumen occurring at short distance from the onshore source rocks; 2) Burial thermal maturation of offshore source rocks and hydrocarbon migration into the onshore basin, supported by deep offshore grabens highlighted in seismic and onshore sandy palaeovalleys that could have provided migration routes for the oil generated offshore. These two generation mechanisms could co-exist, both contributing to the bitumen and oil seep emplacement observed in the outcrops, as supported by petrographic analyses on the hydrocarbons, showing different degrees of reflectivity and fluorescence, possibly suggesting multiple hydrocarbon generation events. A phase of offshore oil generation due to source rock burial thermal maturation would unlock the resource potential of the Namibe Basin, as some hydrocarbon migration routes could have fed into pre-existing traps.

Crustal wedging in the Italian Western Southern Alps: possible implications for the Po Plain thermal evolution?

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Keywords: Thick-skinned, Crustal Wedging, Southern Alps.

The reconstruction of the thermal history in the Po Plain oil system reflects strengths and weaknesses of our general knowledge on the hydrocarbon thermal evolution in rifted-derived continental-collisional orogenic belts.

The Po Plain Mesozoic oil system reached full thermal maturity through a multistage process that started during an early stage of the Tethyan rifting and ended up with the Meso-Neoalpine continental collisional phase.

While it's accepted that in rifted-derived orogenic belts the major contribution to the hydrocarbon thermal maturity is provided by a sin-rifting positive thermal anomaly the source of heat during later orogeny is still object of debate. The heat advection by accretion during continental collisions can be effective where thick-skinned tectonics affect a relatively hot continental crust, particularly if previously thinned and exhumed during. Thus, characterizing an accretionary wedge in terms of thick vs thin-skinned tectonics could be crucial for interpreting the thermal evolution of a hydrocarbon system as well.

The Western Southern Alps preserves a complete mantle-to-crustal section almost continuously exposed from the Ivea-Verbano Zone to the Generoso basin area. Here, the Mt. Campo dei Fiori area (CdF) is a crucial knot to understand the structural relationship between the buried terminations of the Southern Alps below the Po Plain and to unravel the contribution of the orogenic accretionary stages to the Paleogene-Neogene hydrocarbon thermal maturation.

We here focus on the Marzio Fault (MF) in the CdF, a tectonic line that experienced polyphasic reactivations and that runs along the easternmost tip of the Cremosina Line. A series of cross sections shows that MF is a deeply-rooted high-angle structure, with an associated hanging wall anticline. Detailed field mapping and the elaboration of a brand-new geological map provide evidence that MF, possibly active since the Carboniferous, was active during early stages of the Mesozoic rifting (Norian) and finally was re-activated during collision as a reverse fault. The extrapolation at depth of near-surface observations, based on the integration with public seismic reflection lines, well logs and deep crustal architecture inferred from seismic tomography, show that the MF is presently arranged in a deep break-through fault-propagation fold, connected at depth to a south-verging crustal wedge closely related to the more westerly Ivrea Mantle Wedge.

The proposed indentation of a crustal wedge at depth can i) provide an alternative explanation to the final stage oil maturation during the Meso-Neoalpine phase, ii) provide an explanation of the presence of a positive thermal anomaly in the region.

3D Fault Modelling of Lower and Middle Benue Trough of Nigeria using Magnetic and Gravity Data

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Keywords: Aaeromagnetic, matched bandpass filter, fault kinematics.

The study area is an intra-continental rifted trough located to the north of the Niger delta where most of Nigeria's hydrocarbon reserves are found. Exploration of this area has been neglected over the years due to difficulties in geological and geophysical mapping owing to insecurity, thick vegetation and sediment cover as well as flooded plains. We combined high-resolution aeromagnetic and compiled land gravity data sets in delineating, modelling and characterizing the geometry of the subsurface fault systems. The data sets were separated into apparent depth slices representing near-surface, shallow and deep solutions, using matched bandpass filtering. For each depth slice, derivatives such as vertical derivative, analytic signal, horizontal gradient magnitude and local wavenumber were calculated to characterize and map edges of geologic features (igneous bodies, faults etc.) and terranes. Results from magnetic data show significant faults that are modelled to link from the surface to about 8 km depth (Fig. 1 a). These faults primarily trend in a NE-SW direction and are extensive, deeply seated and found to be located within areas of thick sediments and high geothermal gradient. There are concentrations of magmatic intrusions composed of dykes, sills, volcanic plugs etc. towards the eastern part of the trough which we interpreted as a zone of magmatism indicative of tectonic activity and the possibility of the presence of a major fault system. Fault models based on depth separation of gravity data show major fault systems that penetrated from the surface to about 30 km (Fig. 1 b). They are found mostly towards the western part of the trough within areas of low density which we interpreted sub-basins or areas of thick sedimentation. Simple kinematic analyses of the fault system using the Riedel shear model show a sinistral movement from Aptian to Recent age, thereby, confirming the sinistral strike-slip fault system of the area of study. The general tectonic trend directions of the structures and the locations of the intra-sedimentary intrusive/extrusive rocks agree well with the NE-SW general trend of the Chain and Charcot fracture zones emanating from the Mid Atlantic Ocean, hence, showing the possibility of these deep-seated basement structures influencing the evolution of the rift and fault systems. These deep-seated and extensive fault systems modelled from gravity and magnetic data are possible conduits for the free flow of hydrocarbons and as such may have a significant impact on the petroleum systems within the Benue trough.

Pore network evolution within carbonate fault rocks

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Keywords: carbonate fault rock, porosity, permeability.

Although the influence of faulting on the subsurface fluid accumulation and flow pathways in carbonate reservoirs often receives a significant attention, a few data are available in literature on the controls exerted by fault rocks and their microstructures on both porosity and permeability. In this work, the microstructural, petrophysical and ultrasonic properties of carbonate fault rocks pertaining to extensional fault zones responsible of destructive earthquakes in the Italian peninsula are investigated. The goal is deciphers, for the first time, the relative role played by the individual cataclastic mechanisms and diagenetic processes on the pore networks of carbonate fault rocks exhumed from shallow crustal levels (< 1.5 km). Furthermore, by computing the amount of soft porosity due to the rapid exhumation, the pore network configuration of carbonate fault rocks buried at depth can be inferred.

In order to understand the relationships among deformation, diagenesis and petrophysical properties, this work focuses on both calcite-rich fault rocks exposed along the Fucino, Sulmona and Agri Valley basins; and on dolomite-rich fault rocks cropping out along the Mercure Basin and at the Vietri di Potenza relay ramp zone. In the field, structural analysis is aimed at deciphering the inner architecture of the exposed fault cores, the main fault rock textures, their spatial distribution, crosscutting relationships and multi-scale dimensional properties. In the laboratory, the representative hand samples collected along each identified structural domain of individual fault zones are studied by mean of X-Ray diffraction, optical microscopy, SEM-Cathodoluminescence and digital image analyses. The goal is to document the composition and texture of the sampled fault rocks, compute the dimensional properties of survivor grains, characterize the nature and timing of cements, as well as the fluid patterns during the exhumation history of the fault zones. The results of this multi-disciplinary work are integrated with those arising from petrophysical analysis (porosity and permeability measurements, ultrasonic test at increasing confing pressures), aimed at deciphering the amount of effective porosity, pore geometry and type, dimension of pores, and cross-fault permeability.

Altogether, both structural, diagenetic and petrophysical data are discussed to understand the spatial and temporal evolution of permeability in carbonates according to cataclasis and structural diagenesis. These processes variably modify the pore networks and hence control the temporal evolution of permeability in the fault zones. Such an understanding can be applied to subsurface reservoirs to improve reservoir quality predictions and to better assess the sealing potential of carbonate fault zones.

Sequence stratigraphic controls on reservoir-scale mechanical stratigraphy of shallow-water carbonates

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Keywords: fractured carbonates; mechanichal stratigraphy; reservoir analogues.

Studies on mechanical stratigraphy of shallow-water carbonates have shown that the distribution of fractures can be controlled by depositional facies, sedimentary cycles/sequences, and diagenesis. Understanding the role of these sedimentary controls is therefore crucial in the characterization of matrix-tight reservoirs, where fractures may represent the main conduits for fluid flow. Nonetheless, the relation between fracture distribution and sedimentary controls is not always investigated at scales that are relevant to reservoir and fluid-flow characterization.

In this dissertation, is provided a solution to this problem by integrating sequence stratigraphic analysis with the multi- scale fracture characterization of two carbonate platform exposures outcropping in the Sorrento Peninsula (southern Italy). These outcrops represent the surface analogue of subsurface hydrocarbon reservoirs of the Basilicata region (southern Italy), and consist of nearly vertical cliffs (hundreds of meters wide and high) exposing shallow-water limestones and dolostones, crossed by several sub-vertical fractures ranging in height from few centimetres up to few tens of metres. Due to the partial inaccessibility of this cliff, field measures have been combined with remote sensing on virtual outcrop models. The study allowed to identify the key control exerted by sedimentary sequences on the thickness of mechanical units and the position of their boundaries, which implies that sequence stratigraphy can be used to predict the distribution of large-scale fractures.

The applicability of this concept has been tested on a subsurface dataset from the Basilicata region. Performing a sequence stratigraphic analysis on image logs calibrated with core data, the main mechanical boundaries were predicted in a portion of fractured stratigraphic units. The thickness of predicted mechanical units showed a clear relation to the distribution of fractures. Indeed, in the investigated stratigraphic interval, an increase in the mean thickness of mechanical units corresponds to an increase in the mean spacing of fractures, of a comparable order of a magnitude.

The main outcome of this study is the proposal of a new approach to estimate large-scale fracture intensity in carbonate reservoirs, based on the evaluation of the thickness of mechanical units through sequence stratigraphy.

Fracture stratigraphy of Claromecó Basin, PANG 0003 well, Buenos Aires province, Argentina

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Keywords: Claromecó Basin, Permian record, fracture attributes.

Claromecó Basin is located in the southeast of Buenos Aires province, Argentina. Between 1995 and 2005, three exploratory wells drilled upper Paleozoic sedimentary record (Pillahuincó Group, Carboniferous-Permian). In particular, PANG 0001 and 0003 wells reached a depth of 901.78 meters below wellhead (m.b.w.) and intersected an alternating sequence of sandstones, mudrocks, siltstones, tuffaceous siltstones and coal. Vitrinite reflectance values obtain in coal analysis from PANG 0001 well point out values of Ro 1.3%-2.4%, meaning a catagenesis-metagenesis stage with wet gas and dry gas fluid generation. In PANG 0003 coal beds were reached between 681 and 899 m.b.w and have an accumulated thickness of approximately 16 meters. According to vitrinite reflectance data, unconventional reservoirs for Claromecó Basin could be focused in the future associated with coal beds and its diagenesis process. The aim of this study is to characterized fracture attributes for 200 basal meters of PANG 0003 cores in order to identify fracture stratigraphy and its impact on diagenetic fluid flow through permian sedimentary record. Attributes considered are: orientation respect well axis, density of fracturing, aperture and infilling mineral. Four (4) sets showing different orientation are present: Set I, subvertical fractures; Set II, bedding-parallel fractures; Set III, low angle fractures (30º respect bedding) and Set 4, high angle fractures (70º respect bedding). Set 3 and Set 4 can form conjugates sets. Different responses to fracture density were observed: sandstones have an average density of 40 fractures per meter while shales an average density of 70 fractures per meter. Aperture measured has a millimeter order of hierarchy (low hierarchy) to centimeter order (high hierarchy). Dominant cementing mineral is calcite, with pyrite and minor quantities of quartz. Kinematic of fractures were recognized: ModeI/II and Mode III types (extensional/tensional and shear) are present. Slickensides, fault mirrors, micrometrics drag folds and foliation in the cores indicate the presence of fault-related tectonic features. For sandstones Set I represents principal fracture orientation, with low density and high hierarchies; in siltstones/mudstones, Set II constitutes main fracture orientation with high fracture density and low hierarchies. Set III and IV has low hierarchies according to its aperture and are present in all lithologies. Calcite is the common cement. Tectonics as main driving process would be responsible for fracture development in the case of sandstones, while local field stresses, fluid pore pressure, TOC (Total Organic Carbon) content and diagenetic processes combination is related to shale fracture attributes.

Structure and Neogene-Quaternary tectonic-sedimentary evolution of the north edge of Villa Unión-Ischigualasto Basin, La Rioja, Argentina

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Keywords: structure, tectonics, Ischigualasto-Villa Unión basin.

Field geology, structural analyses, gravity, and 2D seismic reflection data were used to characterize the structural style and discuss the tectonic-sedimentary evolution of the San Isidro-Tucumanesas basement high, a subsurface feature located in the northern border of the Ischigualasto-Villa Unión Basin (IVB) of the western Sierras Pampeanas, Argentina.

The results show that the northern border of IVB is bounded by three WSW-ENE to SW-NE trending and SE-vergent reverse blind fault zones that imbricated basement creating fault-propagation folds, obliquely oriented to the typical N-S trending thick-skinned "Pampean" structural style. However, SE-NO trending folds contribute to the overall structural grain of the region, which are closely related to extensional features, likely inherited from the Permo-Triassic rifting episode in the IVB.

Fault-slip data and structural seismic interpretation indicate that the study area records NW-SE shortening related to transpression distributed along oblique-slip thrusts and NE trending en-echelon folds. Despite contrasting styles of deformation between the study area and the neighboring regions of the Argentine Precordillera and the Famatina ranges, there is a structural and substantial temporal overlap of shortening between these regions that continue today.

From a extensive review of previous works, the inner sector of the Andean orogen at 30° S, displacement along thrusts began in the Late Eocene, and continued until middle to late Miocene time toward the Precordillera and thus temporally overlapped the main phase of basement deformation in the study area that occurred in the Late Miocene-Pliocene to present, as demonstrated by dated syntectonic (growth) strata.

This study allows not only understand the tectonic-sedimentary evolution of the region between 29°-30° S in the Chilean-Pampean flat slab segment but also has implications in the exploration of hydrocarbons, proposing new structural models and/or exploration targets.

Fracturing and fluid-flow in an exhumed Jurassic basin: An integrated field, microstructural, geochronological and isotopic study of vein mineralisation

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Keywords: Geochronology, Fracturing, Fluid-flow.

Organic-rich mudrocks are of great significance to the petroleum industry, acting as top seals, source rocks and/or unconventional reservoirs. Natural fractures within mudrocks can strongly influence top seal integrity, primary migration and the performance of unconventional (e.g. shale gas) reservoirs. This project studies the exhumed, early-mature, Jurassic mudrock succession of the Cleveland Basin, NE England, combining structural geology with isotope geochemistry and geochronology. The primary objective is to provide an absolute chronology of faulting and fracturing through novel U-Pb geochronology of fracture-fill calcite. The abundance of well-exposed, natural fractures with different orientations and failure modes provides an opportunity to investigate the properties of these fractures, and provide a basin-wide temporal and spatial framework of evolving deformation. The second objective is to use trace element, stable isotope, and clumped isotope analyses, to constrain fluid composition and temperature. In combination, these objectives will provide an integrated understanding of fracturing, faulting and fluid migration during burial and exhumation of a sedimentary basin.

The current results provide intriguing insights into the history of the Cleveland Basin. The E-W trending Flamborough Head Fault Zone (FHFZ) bounds the basin to the south, and calcite preserved in one of the major extensional faults provides ages of 65-56 Ma. Calcite from N-S to NNW-SSE trending normal faults and associated fractures in the north of the Cleveland Basin provide ages of 44-24 Ma, revealing a previously unknown phase of Cenozoic faulting. Structural and petrographic information suggest that the E-W and N-S trending faults have contrasting fracture-fluid-flow systems. Large (up to 30 cm), chalk hosted, vuggy calcite cements with geopetal sediments fills in the E-W fault zone suggest it acted as an open fluid conduit with voluminous fluid-flow. In contrast, typically thin (<5 mm) vein fills with varying crack-seal-slip type textures in the N-S mudstone-hosted fractures of the Cleveland Basin provide evidence of episodic small-displacement slip; these may be controlled by pore fluid pressures. Ongoing structural and microstructural analyses, combined with trace element and stable isotope tracing of fluid sources, will allow the testing of these initial hypotheses. By producing a comprehensive and systematic analyses of faulting, fracturing and fluid-flow across the entire basin at all stratigraphic levels, this project will be able to provide a detailed understanding of fluid-flow architecture and its evolution during the basin's formation and exhumation. The results will provide important insights into our understanding of the relationship between deformation and fluid-flow in sedimentary basins.

Machine-learning algorithm for estimating oil-recovery factor using a combination of engineering and stratigraphic dependent parameters

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Keywords: Machine learning, recovery factor.

The methods used to estimate recovery factor change through the life cycle of a field. During appraisal, prior to development when there are no production data, we typically rely on analog fields and empirical methods. Given the absence of a perfect analog, these methods are typically associated with a wide range of uncertainty. During plateau, recovery factors are typically associated with simulation and dynamic modeling, whereas in later field life, once the field drops off the plateau, a decline curve analysis is also used. The use of different methods during different stages of the field life leads to uncertainty and potential inconsistencies in recovery estimates. A wide range of interacting, partially related, reservoir and production variables controls the production and recovery factor. Machine learning allows more complex multivariate analysis that can be used to investigate the roles of these variables using a training data set and then to ultimately predict future performance in fields. To investigate this approach, we used a data set consisting of producing reservoirs all of which are at plateau or in decline to train a series of machine-learning algorithms that can potentially predict the recovery factor with minimal percentage error. The database for this study consists of categorical and numerical properties for 93 reservoirs from the Norwegian Continental Shelf. Of these, 75 are from the Norwegian Sea, the Norwegian North Sea, and the Barents Sea, whereas the remaining 18 reservoirs are from the Viking Graben in the UK sector of the North Sea. The data set was divided into training and testing sets: The training set comprised approximately 80% of the total data, and the remaining 20% was the testing set. Linear regression models and a support vector machine (SVM) models were trained with all parameters in the data set (30 parameters); then with the 16 most influential parameters in the data set, the performance of these models was compared from results of fivefold cross validation. SVM training using a combination of 16 geologic/engineering parameters models with Gaussian kernel function has a root-mean-square error of 0.12, mean square error of 0.01, and R-squared of 0.76. This model was tested on 18 reservoirs from the testing set; the test results are very similar to cross validation results during models training phase, suggesting that this method can potentially be used to predict the future recovery factor.

Fault-fracture scaled analogue modelling with new Granular Rock-Analogue Material (GRAM)

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Keywords: Faulting; fracturing; GRAM; brittle rocks; lab-scale analogue.

Scaled analogue modelling represents an important tool to investigate geological deformation processes, simulating their geometric and kinematic evolution through space and time, whereas an outcrop represents only a single "frame" of the deformation process. In these experiments, granular cohesion-less silica sands are commonly applied as rock-analogue materials, providing a geometrical scaling ideal to simulate regional fault-scale processes but not suitable to resolve small-scale fracture processes.

This study proposes the development of new Granular Rock-Analogue Materials (GRAM, Chemenda et al., 2011), with mechanical properties geometrically scaled to natural brittle rocks into a range between the field and the outcrop scale, suitable for the simulation of simultaneous fault and fracture processes in lab-scaled experiments. GRAM must be capable to show tensile and shear failure under different stress conditions. Silica sand is considered an ideal rock-analogue material to simulate fault systems under natural gravity conditions, providing geometric, kinematic and dynamic similarity between analogue and prototype. Therefore, GRAM development is based on silica sand. To achieve the required experiment resolution (1 mm in the model corresponding to 1 - 10 m in nature), GRAM must have a much smaller geometrical scaling factor (L* = L prototype/L model), ranging from $L^* = 10^3 – 10^4$, than sandbox experiments ($L^* = 10^5 – 10^6$). Our GRAM design is using sand aggregates cemented with gypsum powder. Mixing ratios and preparation workflows are tested to adjust the key material properties, such as shear, compressional and tensile strength, Young modulus and Poisson ratio. In fig.1 a 30x40x10 cm sample, 98% sand and 2% gypsum, was tested in a strike-slip rig. The development of a Riedel shear zone can be observed during different deformation stages. A displacement of 6 cm was applied, after which the deformed sample was consolidated with a water-gelatine mixture improved with coloured ink to highlight the created voids, and then sliced, in order to analyse the deformation related structures through the entire model. During the experiment, DIC (Digital Image Correlation) techniques allowed a detailed time analysis by measuring heterogeneous displacement, strain and porosity changes in the model (Adam et al., 2005). Following future improvements related to the scaling of material mechanical properties, sample preparation and handling, experiment set-up and analysis, the new GRAM will provide an additional application of lab-scaled analogue experiments, allowing the investigation of fault and fracture processes and their interaction in fault zones and damage zones during different stages of fault evolution.

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Long-term vertical movements and construction of the continental margin along the forearc of the central Peruvian Andes (6-10°S)

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The Forearc of the North-Central Peruvian Andes (6-10°S) provides an exceptional opportunity to study the long-term processes that affect a convergent plate boundary. First, it shows large- scale depocenter migration and superimposition. Second, characterized as a typical erosive margin, the FNCPA shows a complex relationship between uplift and subsidence resulting from the temporal and spatial interactions between the unroofing Paleozoic-Cretaceous Coastal Cordillera and wide-spread subsidence along adjacent forearc depocenters. The FNCPA is affected by major and regional extensional processes, alternating with more localized compressional events next to the slope break. Cretaceous/Paleogene deformation is expressed by basement horst and grabens disposed in a complex geometry with a patchy distribution along the so-called Main Deformation Zone. It believed to result from strike-slip tectonics related to subduction partitioning. The deep transtensional depocenters formed are well-known to be petroliferous, with mature Cretaceous and early mature Eocene sedimentary successions as source rocks. Then, a long-lived episode of regional subsidence, coeval with the documented installation of the subduction-erosion regime (~20 Ma), affected the forearc and led to the relatively thick and regional deposition of the Lower Miocene series. This period was followed by trench-parallel uplift of restricted parts of the Main Deformation Zone by the end of the Lower Miocene. Uplift individualized the trench-slope basins, mainly corresponding to the preceding transtensional depocenters, from an eastern forearc depocenter where offshore seepages were located but no source rock was identified. It means that oil migrated from the petroliferous sedimentary units of the transtensional depocenters, most likely during the uplift of the Main Deformation Zone. It is also responsible for landward tilting of strata west of this forearc basin. Indeed, the effects on basin geometry of this raised zone resembles that of typical Outer Forearc Highs along accretionary margins such as the Kumano basin in Japan. OFH uplift may be explained either by (i) a change in convergence obliquity, (ii) localized underplating, (iii) the onset of the Peruvian slab flattening, or by a combination of these processes. The uplift period, continuous through time, ended during the Pleistocene south of 8°S and is still ongoing north of 8°S. Hence, the FNCPA seems to record coetaneous contractional and extensional activity from Lower Miocene to at least Pleistocene, affecting inherited basement structures from previous tectonics. It results in the complex architecture of the margin which strongly influenced the migration of hydrocarbons across the FNCPA. Finally, the flat geometry of the current shelf seafloor indicates an overfilled basin where erosion and deposition keep pace with vertical movements along the forearc.

Structural-Thermal evolution of the Apenninic-Maghrebian fold-and-thrust belt in NW Sicily: insight from 1D to 3D modelling

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Keywords: 3D modelling, burial-thermal history, northern Sicilian fold-and-thrust belt.

The complexity of structural style, uncertainties in seismic interpretation and petroleum system evaluation in fold-and- thrust belts (FTBs) make these areas a real challenge for hydrocarbons exploration. Hence, a comprehensive approach for validating structural models and seismic interpretations is necessary.

Balancing and restoration techniques have been widely adopted to verify the correctness of structural interpretations but their integration with thermal and burial reconstruction of sedimentary units is still lacking. This integration may help in discriminating the amount of tectonic/sedimentary loads, nowadays removed by erosion or extensional tectonics and determining which structural style in FTBs is the most viable.

A further challenge is represented by non-cylindrical FTBs, where bi-dimensional investigation does not provide a full description of along strike structural style variations and cannot account for out-of-plane movements.

In this work, we investigated two complex areas of the northern Sicilian fold-and-thrust belt, the Termini-Imerese and the Kumeta-Busambra areas, by using a new 3D multi-method approach. We combined geological modelling techniques for determining the present-day structural architecture and compatibility of fault systems and 1D to 3D thermal modelling reconstructions. The aims were to unravel the original configuration of tectonic units and constrain their kinematic evolution.

Optical, geochemical and X-ray diffraction analysis of the Mesozoic-Cenozoic deep-water basin and platform (respectively, Imerese and Trapanese) units and Cenozoic wedge-top basin successions revealed levels of thermal maturity consistent with diagenetic conditions.

Calculated maximum overburden (nowadays removed by erosion) is ca. 1.6-2.0 km for the Imerese unit, ca. 1.3 km for Trapanese unit and ca. 0.8 km for the wedge-top basin.

3D geological modelling of the study areas allowed to represent and describe the structural complexity characterized by different fault sets detaching at different structural levels. Furthermore, 3D geomechanical restoration allowed to validate the 3D geological model reconstructed in the Kumeta-Busambra area and to evaluate low shortening amounts (<15%) affecting the platform unit.

The combination of burial and thermal histories with 3D geological models allowed to: i) validate previous structural interpretations proposed in the Termini-Imerese area; ii) validate a new structural interpretation and propose a new kinematic evolutionary scenario for the Kumeta-Busambra area; iii) point out the key role played by inherited Mesozoic configuration into the FTB evolution.

In conclusion, this multimethod approach highlights the importance to gather and integrate paleothermal data with 2D to 3D structural interpretations for hydrocarbon exploration purposes. It allows indeed to discriminate among several structural interpretations and validate structural models mitigating exploration risk in complex settings.

Structural and depositional models validation for reservoir study: uncertainty quantification through alternative discrete scenarios

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Keywords: Uncertainty, modelling, tectonic inversion.

The quantification of uncertainties is presently one of the main challenges in petroleum geoscience.

The purpose of the research project is to devise alternative 3D models/scenarios for reservoir studies and new structural interpretations of the study area. Models should be geologically consistent and viable from a structural and depositional point of view, also considering the evolution through time (e.g., Bond et al. 2007).In order to face the evaluation of uncertainties in structural interpretation, we adopt, for a considered case study, a multistep workflow, that: i) combine possible stratigraphic and structural interpretations in discrete scenarios,

ii) perform a 2D sequential restoration to check interpretation viability, iii) generate alternative 3D models and populate them with reservoir properties and associated uncertainties (e.g., obtained from well data analysis). Alternative models and associated variables will then be compared with production history, in order to check the consistency of the assumed models and parameters. Alternative scenarios will be included in a Bayesian Evaluation Learning procedure (Scheidt et al., 2018).

The considered case of study is the Accettura Gas Field (AGF), located within the Garaguso Concession, hold by Edison E&P as operator. AGF is located in the Bradanic Foredeep of the Southern Apennines where outcropping frontal Allochtonous units overly foredeep deposits and the underlying Apula Platform. The interpretation of the available data is strongly affected by: i) the low quality of 2D seismic data, due to the presence of Allochthonous overthrust units; ii) difficulty in correlating well logs, due to a marked stratigraphic and sedimentological complexity within the foredeep deposits; iii) the structural and sedimentological compartmentalization within the Plio-Pleistocene sequence; iv) different views in literature on the characterization and evolution of the Apulian platform below the Allochtonous and its possible involvement in the thrust belt.

We considered also relatively unexplored structural solutions, including a late reactivation of inherited normal faults in transpression, in the Apulia Platform (Milia et al., 2017) forming positive flower structures with a right-stepping *en-échelon* array and the formation of structural traps within the Pliocene-Pleistocene foredeep deposits.

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Depositional patterns, diagenetic evolution, physical properties and quantitative seismic analysis of the early Miocene Yadana carbonate gas reservoir (Offshore Myanmar)

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The Yadana carbonate gas field is located in the Andaman Sea, offshore Myanmar and producing since 1998. The reservoir is an isolated carbonate buildup, Miocene in age, sealed below 1200 m of siliciclastic sediments. Predicting hydrocarbon resources and water flows during the production has become a major challenge for such mature gas field. The PhD work involves the implementation of a methodology allowing the construction of a detailed reservoir architecture that accounts various type of heterogeneities. The work is multi-scale and multidisciplinary, covering disciplines such as sedimentology, stratigraphy, diagenesis, geochemistry, rock physics, geophysics and based of a large and comprehensive data.set including, cores, well logs, petrophysical measurements, production and seismic data.

First, carbonate production was dominated by oligo-mesophotic carbonate factories. The limited lateral changes in facies and the layer-cake depositional architecture inferred from well correlations, and the seismic expression suggest a deposition on a flat shelf. Carbonate production was mainly controlled by light penetration, nutrient and hydrodynamic conditions directly related to changes in terrestrial runoff. Secondly, with an average porosity of 28%, diagenesis appears an important controlling factor of the reservoir propert ies. Coral-rich sediments record early marine dissolution and early lithification. The geochemical analysis suggests that the long-term depositional hiatus at the top of the platform was related to platform drowning and a major decrease in porosity (up to 10%) below the gas-water contact is indicative of a porosity evolution during and/or after the hydrocarbon emplacement. By modifying drastically porosity, diagenesis largely controls the seismic expression of the reservoir. \Vell-to-seismic tie allowed to precisely evidencing the origin of seismic reflectors. They may form at the boundary between two diagenetic units or result from interferences between the reflect ion of base and top of such intervals. Finally, help to detailed calibration between depositional/diagenetic attributes, a petrophysical inversion based on Differential Effective Medium theory has been developed and performed on the 3D seismic data. This approach allows a relevant prediction of geological seismic-scale heterogeneities impacting for example the water rise during the production.

Providing a robust geological framework for the reservoir characterization of Yadana field, the thesis gives further insights into the understanding of geological and environmental factors controlling Cenozoic, isolated carbonate systems in South East Asia. This work highlights once aga.in the interdependence existing between geology and seismic imaging and demonstrates that an integrated geological/geophysical characterization of carbonate reservoirs remains crucial in 2019, for both the exploration and the production of hydrocarbon resources.

Integrated multiscale Structure from Motion (SfM) photogrammetry for characterization of fractured reservoir analogues.

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Keywords: Multiscale Photogrammetry, Fracture Analysis, Fluid Flow Simulations.

The fracture analysis of outcrop analogues has some drawbacks, such as accessibility, time and accuracy of obtained data. This work proposes a multiscale workflow for assessing the fracture properties (orientation, fracture intensity, roughness, and permeability) by integrating Structure from Motion (SfM) photogrammetry with field-based measurements, fracture modelling and fluid flow simulation at reservoir and pore scale. The work is presented in three study cases, with different scale and lithologies, as follow:

The first case study (hundreds of meters scale), is located at Roman Valley quarry (Majella Mountain, Central Italy) where ramp carbonates of the Bolognano Formation (Oligocene – Miocene in age) are exposed. The study is focused on the analysis, stochastic modelling and fluid flow simulation of the fracture networks in the outcrop. A static model was built using a SfM-based virtual outcrop model (VOM) for limiting the different stratigraphy and the relationship with the two main oblique faults present in the area. Finally, a dual-porosity/permeability flow simulation was run to investigate the role exerted by lithological and structural heterogeneities on fluid flow (Volatili et al., 2019).

In the second case study (meters scale), the SfM technique has been upgraded using a drone to reconstruct a high-resolution digital outcrop of a fault zone. In this case, the studied rocks consist of sandstones and clays alternations belonging to the Pollica Formation in Southern Italy (Miocene in age). Digital scan lines have been performed in strata with different thickness and lithology in order to investigate how mechanical boundaries affect the fracture intensity in sub seismic scale fault zones in heterolithic rocks.

The third case study (single fracture scale) represents the most innovative approach of SfM photogrammetry where this technique has been used for mapping surfaces of fractures (Zambrano et al., 2019). The collected fracture surfaces were used to run fluid flow simulations of synthetic fractures aimed to evaluate the control on permeability exerted by fracture roughness. The fracture roughness resulted to be one of the most critical fracture parameters affecting hydraulic aperture on the first case study. Therefore, the results obtained from this small-scale case study could improve the results obtained from large scale modelling and hydraulic properties upscaling.

To sum up, the presented workflow demonstrates to be suitable for different lithologies and field conditions providing field data that in normal circumstances cannot be obtained. Therefore, the present work provides an important contribution for characterizing reservoir analogues by means of cutting-edge technologies.

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Zambrano M., Pitts A.D., Salama A., Volatili T., Giorgioni M., & Tondi E. (2019) - Analysis of Fracture Roughness Control on Permeability Using SfM and Fluid Flow Simulations: Implications for Carbonate Reservoir Characterization. Geofluids (Online), 2019. Geofluids, Volume 2019, Article ID 4132386, 19 pages. DOI: https://doi.org/10.1155/2019/4132386

Regional transect across the Quirquincho Arch (NW Argentina): consequences for Hydrocarbon exploration

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Keywords: HC exploration; tectonics; magmatism; Quirquincho Arch; NW Argentina; Paleozoic and Mesozoic source rocks.

The Chaco-Pampean plain of the Argentine Andean foreland covers the Chaco-Paranaense intracratonic basin (CPB) and the eastern portion of the Cretaceous Salta Rift basin (SRB). At surface, there is no direct evidence for a complex tectonic history of this region. Subsurface data, however, document a rich geological history of magmatic episodes, multiple tectonic events and sedimentation controlled by tectonics. The Quirquincho Arch (also known as the Rincón-Caburé High) is an inherited subsurface structure characterized by a preferential NE-SW orientation. This structure is an extensive and prominent basement ridge that constitutes the boundary between the CPB and the SRB. This orientation is also broadly reflected by the overall trends of the adjacent Sierras Pampeanas broken-foreland province, the Colonia-Aldao High and the Las Breñas depocenter. This study compiles and reviews available subsurface information from oil exploration, including borehole data, 2D seismic-reflection lines and topographic data to reconstruct the tectono-sedimentary history along a regional NW-SE transect between Tartagal (Salta province) and Formosa city (Formosa province); key focus is the analysis of the multi-episodic activity of the Quirquincho Arch. Tectonic activity along the Quirquincho Arch is interpreted to have controlled the facies distribution of syntectonic sequences in the two adjacent basins during the Paleozoic and Mesozoic.

The interpretation of 2D seismic-reflection data and well-log information allowed to identify the subsurface position and shape of the Quirquincho Arch. Its presence is unambiguously reflected on various seismic-reflection lines. The arch is characterized by multiple reflection terminations at its top and flanks; the interpretation of onlaps and truncations enables the reconstruction of its tectonic history.

The tectonic activity and its consequence for the architecture of sedimentary units in both sedimentary basins adjacent to the Quirquincho Arch have not been described in detail in literature nor by exploration of hydrocarbons. Nevertheless, the structures generated by the tectonic activity of the Quirquincho Arch could have a major impact on the formation of stratigraphic traps that could store petroleum formed in Paleozoic and Mesozoic source rocks.. From our evaluations the onlap, truncation and pinch out structures of sedimentary units towards the Quirquincho Arch are an interesting objective for future prospection for hydrocarbon accumulations.

Carbonate Mass Transport Deposits and Facies Features: The Cretaceous Example from Western Sicily (Southern Italy)

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Keywords: MTDs, Carbonates, Slope, Tectonics, Facies, Cretaceous.

Mass Transport Deposits (MTDs) are emplaced along slopes-toe of slopes by non-newtonian fluids and commonly made of significant amounts of sediments resulting in thick stratigraphic sequences. In carbonate settings, these sedimentary bodies reflect distinct variations in both production and export of sediments from the source areas. In addition, it is common knowledge that these gravity-induced processes have a key role in the development of petroleum systems pointing to the great economic significance. Seismic-scale observations of MTDs display facies features and sedimentary structures providing essential templates in predicting the potential of subsurface reservoirs. MTDs from Cretaceous carbonate records are typically rich in rudists aragonite fragments determining high percentages of early mouldic and interparticle pores, and non-fabric selective pores due to late dissolution processes. Wide carbonate systems (platforms and slopes) prevailed in the peri-Tethyan realm during Cretaceous times. In Italy, these sedimentary series are exposed in well studied outcrops (e.g. Maiella Mountains, Gargano) and host important hydrocarbons resources in the subsurface (e.g. Val D'Agri oil field). In westernmost Sicily (Southern Italy), an extensive volume of MTDs (up to 250 km^2 and 500 m in thickness) is well-exposed on the 2D and 3D wire-cut walls of hundreds of quarries extracting ornamental limestones (i.e. Perlato di Sicilia, San Vito Lo Capo Peninsula). These until now poorly known MTDs consist of huge bodies of massive megabreccias and bedded calcidebrites that alternate with finer grained skeletal rudstone/grainstone and floatstone/packstone emplaced by turbidity currents. Skeletal grains (mainly rudist fragments) and intraclastic packstone-grainstone constitute some 95% of the megabreccia/calcidebrite matrix. An anorogenic magmatic activity associated to the evolution of the escarpment is documented by TiO_2 enriched alkali basalts (tuffites and pillow lavas) intercalations within the resedimented carbonate series. It suggests a major role of crustal shears as a trigger for the creation of a stepped fault escarpment and of the MTDs emplacements. Thanks to a detailed biostratigraphic characterization, the skeletal shedding along the escarpment has been documented from the Berriasian until the Maastrichtian. The age of extraclasts account for the involvement of a Triassic to Lower Cretaceous rock succession in the collapse phenomena along the faulted escarpment.

The escarpment of north-westernmost Sicily provides a detailed model of the vertical and lateral distribution of MTDs along tectonically-controlled Cretaceous carbonate slopes.

2st SESSION – MSc Student Session

Structural control on sinkhole development in Jandaira Fm. carbonates, NE Brazil

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Keywords: Carbonates; sinkhole; fracturing; Jandaira Fm; NE Brazil.

During the last decades, many authors investigated the relationship between tectonics and karst, demonstrating that karst terrains are good recorders of brittle deformation and, in turn, that tectonics may controls the main directions and alignment of karst systems). Despite the numerous researches on this topic, the relationship between fracture intensity and the development of karst features in layered carbonates (e.g., *sinkholes*, caves systems, tufa deposits) has not fully investigated. This study, funded by Petrobras oil company, the *Universidade Federal do Rio Grande do Norte* (Brazil) and the Overworld student program from University of Parma (Italy), focused on karstified fractured carbonates of the Cretaceous Jandaira Formation in the Potiguar Basin (NE Brazil) where a broad range of karst features are superbly exposed in pavements along the Rio Apodi river. In particular, this study was aimed to understand the possible structural control on *sinkhole* development by combining detailed field mapping of fracture pattern, drone imagery with deformation intensity quantification via linear scanlines (in the field) and circular scanlines (on mapped drone images). Furthermore, petrographic observations and mercury-intrusion porosity analysis were integrated with fracture pattern dataset to characterize matrix porosity of carbonates.

In the study area *sinkholes* locally occurs as isolated structures with 15-35 m in diameter. Structural analysis indicates that carbonates are invariably characterized by the presence of N-S veins and E- W stylolites, whose cross-cutting relationships indicate they are contemporaneous and developed during a N-S-oriented compression. Further, a NE-SW joint set overprints the previous structural fabric, consistently with the broad NE-trending regional-scale fold (Apodì fold). Fracture pattern quantification shows that, in studied layered carbonates, fracture density (P20) and intensity (P21) dramatically increase approaching the *sinkholes*. Moreover, the development of *sinkholes* produce a 10-15 m-wide *sinkhole*-related "damage zone" with concentric fractures. This work shows that regional scale folding and local variations in fracture intensity (controlled by the mechanical stratigraphy) may control the spatial distributions of *sinkholes*. This study also indicates that the presence of *sinkholes* can locally modify the subsurface permeability of oil and gas reservoirs, promoting: (i) fracture-related permeability through the circular "damage zone" around the *sinkhole*, (ii) increasing in the overall fracture interconnection, and (iii) focusing deposition of high-porosity (20 – 25%) speleothems such as "tufa" deposits inside the *sinkholes* themselves.

Evolution of the Adriatic offshore Petroleum system through an integrated 2D modelling

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Keywords: Petroleum system; 1D/2D modelling; Thermal and lithological calibration; Adriatic offshore.

The Central Adriatic area has been a target of interest for hydrocarbon exploration since the past century. Although important efforts have been made, uncertainties remain about the evolution of the Petroleum System (PS), in terms of source rock position, oils generation, migration paths and timing.

In this work, we built robust 1D and 2D modelling of the entire PS by using PetroMod mark of Schlumberger.

Thermal and lithological calibration have been set by using the public dataset of the Videpi project and literature historical data, inherited from the past oil&gas explorations. A total of 30 composite logs have been used to build different lithological mixing, while surface heat-flow maps and present-day well temperature have been derived from 50 wells (off-shore/on-shore).

We then performed a 1D PS analysis building 18 1D pseudo-wells, starting from public wells of the area, making also correlations with similar off-shore/on-shore geological contexts (e.g. the preserved platform to basin transition exposed in the outcrops of the Maiella mountain and deep wells (e.g. Puglia1 and Gargano1) to complete the sedimentary succession down to the hypothetical basement.

Afterwards, a 2D off-shore model was built on the base of 1D modelling implemented with commercial seismic lines and depth converted 2D models to laterally extend the 1D knowledge and test the PS evolution along a transect that includes the Apulia carbonate platform and the neighbouring Pescara basin.

The modelling results, for the most likely source rock of the area (Burano fm), shows a transformation ratio (TR) from 7 to 20% and a vitrinite reflectance lower than 0.55%Ro for the foreland platform sector.

Results indicate Apulia platform as a low-maturity/low-hydrocarbon generation area (oil generated in green from the modelling), in contrast with the presence of several important oil pools discovered in the off- shore area (e.g. Rospo Mare, Katia and Ombrina Mare fields).

Therefore, we suggest that lateral migration played a key role for the hydrocarbon accumulations of the area In addition, the 1D/2D modelling reveals that the potential source rocks would be able to reach the expulsion temperature only considering a thicker foredeep succession, from Plio-Pleistocene to present-day after the key regional seals (e.g. the Lower Cretaceous Marne a Fucoidi and the Messinian evaporites formations) were deposited.

Ultra deep geothermics in the Po Plain: a study on the Malossa area

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Keywords: Deep Geothermics, Po Plain, Oilfield.

Ultra deep geothermics is currently considered an interesting possibility to get high temperatures (>150 °C) that could be used for industrial applications. This kind of projects are starting currently in the Netherlands, in Belgium and in Germany, with promising perspectives. An interesting link is the exploitation of Oil&Gas wells that can no longer be exploited.

In this study, I analyze the possibility of ultra deep geothermics in the Po Plain, close to Milan, by using public data in the Malossa area.

The Malossa oilfield was discovered in 1973 and the production ended in the late ‘80s and produced gas and condensates.

This project is focused on three stratigraphic targets showing really variable porosity: the Dolomia Principale, Zandobbio Formation and Maiolica Fm.

Specific petrographic observations about pore texture, between 1% - 6% (average 3%) in Dolomia Principale, 1% - 13% (average 2,5%) in Zandobbio Fm., while the Maiolica has reltively negligible porosity. The reservoir permeability is related to fractures, as the matrix permeability is relatively low (50 mD in the Zandobbio Fm). Production tests showed very good productivity for the wells, with 500000 smc/day of gas and 2800 bbl/day of oil; unfortunately, at the moment, the publicly available data are not allowing any estimation of Kh from the wells.

The available BHT, indicates temperatures (corrected) between 150 and 165°C at a depth of about 6km.

Developing a geothermal system within this former hydrocarbon reservoir is quite challenging, not only for the temperatures, but also because of the important overpressures recorded in this aquifer. The possibility of dealing with a geothermal doublet in this context is clearly complicated by the overpressures, that are in the order of 170 kg/cm^3 in the surface, requiring more complicated technological solutions.

Despite this, the main purpose is to understand through data from oil wells exploited by AGIP, if it can agree the exploitation of deep geothermal energy in this area.

In order to develop a proper study, I was created also a detailed 3D geological model for evaluating the characteristics of the aquifer, the petrophysical characteristics, the geodynamics fluids and create some scenarios about the potential position of the injector and the producer in this doublet.

Carbonate sedimentation in the Oligocene of central Mediterranean area: facies heterogeneity & reservoir properties

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Keywords: carbonates, petrophysic, surface analogous.

Carbonate ramps are considered possible reservoirs due to their geological peculiarities. The oligocenic homoclinal ramp that outcrops in Porto Badisco in Salento (South Italy) offers an excellent opportunity to study facies heterogeneity related to the petrophysics. The aim is to recognize the different facies of the oligocenic Porto Badisco Calcarenite and define them through petrophysical features. The methods used for the study of the different characteristics of the Porto Badisco Formation concern both field surveys and laboratory analysis. During the field work nine stratigraphic sections were measured along the Porto Badisco canyon. The sampling of the different lithotypes allowed the production of over 100 thin sections through which 6 facies were identified. These observations were represented in a correlation between the different measured stratigraphic sections. Some of the main petrophysical characteristics of the recognized facies were measured by using both a helium pycnometer, which allows the density and porosity of the different samples to be calculated, and an oscilloscope to determine the seismic velocities. For a cross-correlation a statistical analysis was carried out on the porosity, in addition to the pycnometer: counting on photos of thin sections impregnated with methylene blue. For further verification of porosity, an image analysis was performed on polished slab surfaces of samples impregnated with methylene blue by scanning. The results of the study suggests high lateral heterogeneity of the components in the samples taken, both fossiliferous and textural, as demonstrated by the differences in density, porosity and seismic velocity. The petrophysical features and their spatial distribution are useful for oil extraction, both to adopt a drilling strategy and to develop models that can be interpreted to exercise control over the migration of fluids over time. These data will be useful for the characterization of a hypothetical carbonate reservoir and therefore for the definition of a surface analogue for other Oligocene oil systems like the productive ones in the offshore of the Adriatic sea.

Sedimentological and petrophysical characterization of submarine lobe deposits, the Mizala outcrop as a reservoir analogue

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Keywords: Turbidite, petrophisic, Tortonian.

This study examines an outcrop analogue (upper Tortonian, Sorbas Basin, SE Spain) of a small submarine lobe system close to the channel-lobe transition and aims to establish the relationship among the sedimentary facies and their petrophysical properties and the heterogeneity of the reservoir. To achieve such aims, a combination of sedimentological (field observations, petrographic analysis and grain size analysis) and petrophysical (porosity, absortion-desortion, capillarity, acoustic properties) studies have been performed. Seven coarse-grained facies that may act as reservoirs have been distinguished (Facies Ta, Tb1 , Tb2, Tb3a, Tb3b, Tb4 , DM) as well as a fine-grained facies that could act as an impermeable seal. The coarse-grained facies correspond to sediment gravity flow deposits that characterize the different subenvironments within the lobes. One lobe complex formed by at least three lobe systems composed of 8-11 lobes was investigated in detail. Most of these lobes are 5 to 14 m thick and can be traced laterally along a few hundreds of metres. The stratigraphic architecture of the lobes and its relationship with the fine-grained sediments have allowed the distinction of a phase of lobe initiation, a phase of progradation with evidence of cyclic steps and, locally, a phase of infilling and avulsion. The lobe deposits comprise mostly facies Tb4 and Ta and their net:gross ratio ranges between 0.76 and 0.98 (0.6 in the whole lobe complex). The average porosity of the coarse- grained facies is 11-26% and it is positively correlated with the absorption velocity. The capillarity parallel to the bedding planes, considered as an estimation of the permeability, is related to the grain size. Facies Tb4 , one of the most abundant facies in the study lobe complex, shows the most interesting reservoir properties because of the combination of goo porosity, good pore interconnection and low acoustic wave velocity.

Tectonic control on bauxite formation during Upper Cretaceous faulting of the Outer Apulian Platform.

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Keywords: syn-sedimentary faulting, Bari Formation, Altamura Formation, Outer Apulian Platform, Cretaceous platform limestones.

The study aims at reconstructing the control exerted by syn-sedimentary, extensional faults on formation of the canyon-filling bauxite deposit cropping out at Spinazzola (BAT), southern Italy. There, a ca. 25 m-thick, Turonian age, bauxite deposit placed in between the topmost portion of the Valanginian-Cenomanian Bari Fm. and the bottom of the Coniacian-Early Campanian Altamura Fm. The bauxite deposit marks therefore a ca. 4 $\pm$ 1.8 My-long depositional hiatus. This deposit is a homogeneous rock volume comprised of Fe and Al oxides and hydroxides and originated from allochtonous mafic igneous protoliths. It recorded three humidity fluctuations as shown by Ce anomalies documented across the Spinazzola deposit. The bauxite accumulated at the hanging-wall of syn-sedimentary, NW-SE striking extensional faults, forming a horst and graben geometry crosscut by an orthogonal, conjugate fault system.

In this work, we performed detailed structural analyses of the Turonian, syn-sedimentary fault network, petrographic characterization of limestone samples collected both at the top and at the bottom of the bauxite deposit, XRD analysis of bauxite powder samples collected along transects across this deposit.

In the field, we paid a particular attention to the bauxite cropping out in proximity of the faults, to the debris-filled paleo-sinkholes and to the bauxite-filled open fractures sub-parallel to the main fault sets.

Results of field structural analysis and petrographic characterization show that basal limestone is moderately to severely affect by karst; top limestone onlaps to SW on some fault surfaces; bauxite shows an internal angular unconformity, gradually disappearing, due to syn-sedimentary activity of normal faults. Limestone shows four sedimentary facies forming a shallowing upward sequence, which sectors are dislocated and put contiguously by a strike-slip right-lateral fault.

XRD analyses elucidate about variations of both texture and mineralogy of the study bauxite, which might clarify about possible effects of syn-sedimentary slip along the bounding extensional faults on its diagenetic evolution. Furthermore, detailed analysis of clay minerals present within the bauxite deposits explain on the possible role played by the paleo-phreatic level on bauxite formation, in order to define the relative alteration rate of the bauxite bodies, and then, their position in the reconstructed timeline. A detail-scale study (both spatial and temporal), will be very useful to accurately understand the processes involved in the evolution of the entire platform in a very narrow lapse of time.

Sedimentological study of the Miocene corals carbonate facies in the Syracuse area (Sicily)

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Keywords: corals, Miocene, Sicily.

This work is an analysis of the coral sequences in eastern Sicily to understand the paleoenvironment. This study contains the sedimentological and compositional informations on the development of coral colonies in the Mediterranean Sea that are also important for oil exploration. The sedimentological study and analysis of facies of the stratigraphic sections located in the Syracuse area made it possible to understand the depositional environments of the analyzed sequences of the lower-middle Miocene (Punta Bonico section) and of the lower Upper-Messinian Tortonian (Faro Santa Croce, Ognina and Plemmirio sections). These facies were afterwards compared with models proposed for the Sicilian and Mediterranean area. The study of the sections has allowed us to characterize that from the compositional and textural point of view. The succession of Punta Bonico resulted composed by the lithofacies FR, in which Miogypsina and Amphistegina would suggest meso-oligophotic environments (mid ramp). The red algae in the FC lithofacies, associated with the order of Miliolids, indicate euphotic environments (inner ramp). Even though the Miogypsina and the rare planktonic discovered in the area would indicate deeper areas. Finally, the composition and texture of GB lithofacies indicates a rather high hydrodynamic energy which is typical of inner ramp - euphotic zone. Comparing these lithofacies with some carbonate systems from the same age the results are both a spread of corals in deeper habitat, the meso-oligophotic zone. The successions of Faro Santa Croce, Ognina and Plemmirio are characterized by the lithofacies BC, that is indicative of a variable depositional depth (mid-inner ramp). In some areas, the presence of Nummulitids, Operculina, planctonics and non-articulated red algae in the matrix hint a meso-oligophotic zone. The components of the PWM lithofacies suggest the presence of shallow clear waters with low hydrodynamic energy (probably a lagoon). The sedimentary structures and components of the lithofacies PO point to the presence of underwater dunes (inner-middle ramp). The peloids, ostracods and fine texture in the PWP lithofacies indicate low-energy environments (inner ramp-lagoon). Finally, the PB lithofacies contains numerous green algae and Pecten, which are typical in low sea environments (euphotic zone). The novelty of this study consists in the discovery of corals that can be associated with the meso-oligophotic zones,

while all previous studies only uncovered corals in more superficial and euphotic areas. While this study is far from exhaustive, it contains elements that shed new light on the Mediterranean coral successions and may spark interest in some outcrops that have not yet been studied.

Best modeling approaches on a carbonate reservoir, a case study from the Maiella Mountain, Central Apennines, Italy.

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Keywords: Carbonate reservoir; deterministic and stochastic modelling; Maiella Mountain; Central Apennines.

During a petroleum exploration campaign a properly reservoir characterization is reached only in the last stages when an oilfield has been investigated by numerous wells. Consequently, it is quite difficult to set a methodology in order to find the best modelling approaches during the first exploration phases when only few data derived by few wells are at disposal of geologists. Furthermore, data derived by these investigations are usually kept secret so it's complex to test or study new modelling approaches on data derived directly from oilfields.

In this work we have at our disposal a public dataset composed by 43 wells drilled on a carbonate ramp reservoir bitumen-bearing. These wells cover a grid of 200 meters per 200 meters with depths ranging from 80 to 250 meters. The grid covers approximately an area of 1.5Km^2. This kind of dataset can be compared to the final stage of a fully developed oilfield that permits to perform several test and numerous 3D model in order to assess the best modelling approaches to compute the oil saturation.

Both deterministic and stochastic approaches were used during the testing phase using respectively Kriging and Sequential Gaussian Simulation. These two approaches were used in all our simulated scenario represented by a base case (mirroring a fully developed scene) and by one-well tests (replicating the first step of an exploration phase). During the base case, various blind well tests were conducted. These latter tests consisted in a removal of one of the wells from the complete dataset in order to verify how the algorithms can replicate that toggled off well in the simulations.

Base case simulation showed how Kriging was faster in terms of computation time despite the excessively smoothed results coinciding with the mean value. On the other hand, SGS gave a better distribution of computed values comparable to the raw value resulting from the frequency histograms.

For the one well case the kriging algorithm has populated almost totality of the cells with mean values SGS algorithm mirrored the expected spatial variability, producing comparable and satisfactory results in terms of hydrocarbon distribution and variance.

In the blind well tests, we observed a high variability and the SGS in some cases did not distinguish the main reservoirs. By adding a vertical trend derived from the up-scaled logs to the SGS the results became more accurate with only a slight mismatch in respect to the real data.

Architecture of the carbonate-hosted Monte Marine fault damage zone and catalogue of active normal faults characterized by thick damage zones in the Central Apennines, Italy

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Keywords: fault architecture, fault rocks, in-situ shattering.

The Central Apennines of Italy are one of the most seismically active areas of the circum-Mediterranean region (e.g., Pizzoli Mw 6.7, 1703; Avezzano M_W 7.1, 1915; L'Aquila M_W 6.1, 2009) . Most of this seismicity is produced by earthquake ruptures propagating along normal faults hosted in dolostones and limestones. Some of these fault zones are characterized by 100s of meters thick *in-situ* shattered rocks (ISRs) (i.e. fault rocks reduced in fragments < 1 cm in size that locally preserve their original sedimentary fabrics in the footwall block and are well-exposed with typical badland morphologies. Both the geometrical properties and the origin of these ISRs (likely formed during particular stages of the seismic cycle) are still poorly understood. This is caused mainly by the lack of data on the fault zone structural architecture (e.g. distribution and thickness of ISRs along the fault strike, relations with fault displacement). A deeper understanding of the ISRs formation and the identification of dynamic signatures within fault zones may (1) improve our understanding on earthquake rupture mechanics, (2) constrain earthquake energy budgets (how much energy is dissipated in off-fault damage vs. on-fault slipping processes?) and (3) contribute to seismic hazard studies. In addition, a better understanding of carbonate-hosted faults architecture together with the determination of their petrophysical properties (e.g. porosity and permeability) ISRs is of relevant interest in oil, gas and water research and exploitation, thus involving economic and society issues.

In this contribution, I present the first catalogue of carbonate-hosted active extensional faults characterized by thick damage zones containing ISRs within the Central Apennines. The catalogue contains geological and seismological data (e.g. main fault plane dip dir/dip and length, total fault displacement, etc.) from the literature. Further, I present the structural map of the central sector of the Monte Marine Fault Zone (MMFZ), a ~14 km long extensional fault system developed along the Aterno Valley, near L'Aquila. The fault segment, re-activated during the 1703 M_W 6.7 earthquake, is wonderfully exposed for ~ 8 km between the villages of Barete and Arischia, and cuts through the Mesozoic Calcare Massiccio Fm and the Corniola Fm. In terms of geometry, the MMFZ is arranged in two left-stepping segments with average attitude of N204°/65° (dip dir/dip).

I mapped (at the 1:500 scale) the sector where the two fault strands overlap and collected data in several different structural stations (Fig.1a). The fault core is ~ 30 m thick while the damage zone reaches ~ 630 m in thickness and hosts synthetic and antithetic extensional faults, strike-slip and thrust faults (Fig.1a). At the intersection between compressional and extensional structures, the volume of cataclasites and loose breccias increases significantly. The geological cross sections provided in this study underly structural complexities due to the linkage of different fault segments and to the inherited compressional-to-extensional tectonic inversion.

Both the structural map of MMFZ overstep sector and the damaged fault zone catalogue represent a valuable data source to (1) investigate scaling laws (e.g., fault length vs. fault zone width) for seismogenic normal fault zones in carbonates, (2) constrain future models of ISRs formation and (3) understand shallow-crustal fluid flow within fault damage zones developed in carbonate rocks.

Investigation of the natural hydrocarbon manifestations and 3D modelling of the Tramutola area (Basilicata)

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Keywords: reservoir, modelling, digital processing.

New technologies have been applied on the area of the southern Apennines. This study is based on the correlation of structures recognized in the field and in wells by means of Petrel© 3D modelling software.

The study area is the in Agri Valley (Basilicata), where the largest European in-shore oil and gas field is present. The Tramutola area is important since 19th century because of the natural hydrocarbon springs which indicated the presence of hydrocarbons in the subsurface and encouraged the first prospecting and oil production in the area in the years 1936 – 1943 (Van Dijk et al., 2012). Wells have been drilled at depth spanning between 200 and 500 m and produced a minor amount of oil from small reservoirs located at shallow depths.

The 3D modelling of the reservoir was studied first through the mapping of wells and infrastructures related to oil extraction activities to verify the bibliographic and cartographic information recovered in the Eni archive. Field activity have been performed to verify the extent of the natural hydrocarbons manifestations, in order to hypothesize oil migration paths.

A field geological study allowed the construction of a detailed geological map in an area of about 7 km^2 at a 1:5.000 scale and a bitumen map (1:2.500 scale) where all the hydrocarbon manifestations on the surface have been mapped. All the main tectonic units of the southern Apennines, represented from top to bottom by the Liguride, the Apennine and the Lagonegro units, have been recognized in the mapped area. The surface geology in combination with the well data allowed the 3D modeling of a 1 km^2 wide area up to a depth of 400 m . The results allowed the identification of the several formation tops and the reconstruction of the deep geometry Tramutola area. It was possible to model different sets of high- and low-angle faults to provide hypotheses on their crosscutting relationships. In particular, the extreme thickness reduction or the absence of the Apennine platform in some portions of the study area, as documented by well data, might be interpreted as due to the presence of a low-angle normal fault.

Even though it was not possible to delimit or identify the extent of the reservoir(s) in the Tramutola area, the application of 3D modelling provided useful constraints for a better understanding of the outcropping structures, whose interpretation has always been controversial. Further analyses could be useful to better understand the origin of the oil springs.

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Analog modeling of large-transport thrust controlled by evaporitic décollements: The sub-Andean Huallaga case study

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The Huallaga Basin is one of the foreland basins of the sub-Andean fold and thrust belt at the northern Peruvian Andes. It shows a particular thin and thick-skinned deformation system with a largeoverthrust, the Chazuta thrust, with more than 40 km displacement detached on Late Permian evaporites. It has been large demonstrated, that salt is a first order controlling factor on structure of fold and thrust belts around the world, well-known as the most effective detachment level for thrusts. Only in particular cases, spectacular large-thrusts with a net slip of 10 km or more happen, (eg. Cotiella and Montsec thrusts in the Pyrenees; Dinar thrust in the Zagros; the Chazuta thrust in the sub-Andean Huallaga basin; or the Salt Range thrust in the Potwar Plateau among others). This kind of structure mainly seems to be controlled by four geological parameters: overburden thickness, salt thickness, syntectonic sedimentation and salt basin geometry. In order to provide insights that will help to shed light over the role that these parameters play on large-transport thrusts formation and evolution, an experimental approach based on scaled physical models has been designed. Moreover, to create more realistic models, the experiments presented here are based on the Chazuta thrust case study. The experimental programme consists on four experiments that have been run in order to understand the effect of each parameter previously detailed. According to the experimental results it is possible to conclude that syntectonic sedimentation, thick salt and a thick overburden are first order parameters that enhance and play a critical role on the formation of large-transport thrusts. It's important to highlight the necessity of coexistence of all these parameters in order to form these structures. The experimental results can be applied to other salt-bearing fold and thrust belts with large transport thrusts.

Integrated gravity and magnetic data analysis in the Val d'Agri area

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Keywords: gravity, magnetic, modelling.

This master thesis was developed during an internship with *Eni Spa – Exploration & Production Division*, concerning 2D gravity and magnetic modelling, and 3D gravity inversion of the Val d'Agri basin (Southern Apennines).

The aim of the work was to obtain a robust 3D model of the area in order to reduce the geological uncertainty in seismic interpretation. For this reason, the use of an integrated multidisciplinary approach was useful, taking advantage of the high vertical resolution of the seismic imaging and from the high lateral resolution of potential field data.

The workflow was divided into three main steps: the first step involved derivative analysis of gravity and magnetic data that allowed the interpretation of several structural trends in the study area. Using the Multiscale Derivative Analysis (*MDA*), a high-resolution boundary-analysis technique, it was possible to enhance the contributions of different depth/extent sources, supposing the large-scale magnetic anomalies produced by deep mafic intrusions, and the local-scale magnetic anomalies produced by magnetic basement wedges. Magnetic basement, indeed, could be reasonably involved in deep thrusting producing wedges tectonically interposed between the Apulian carbonates (thick-skinned model).

The second step consisted of gravity and magnetic 2D modelling constrained by seismic, well and structural data, and integrated with structural lineaments derived from MDA. Moreover, modelling of the top basement geometry was constrained by 3D Euler deconvolution, that provided solutions coherent with the tectonic and geologic setting of the area. This work needed a multidisciplinary approach, modifying the geometry and physical parameters of 2D models, in order to minimize misfit between observed and calculated anomalies.

The third step consisted of 3D initial model construction after interpolating 2D density models. This one represented the initial model of 3D gravity inversion performed by means of a *voxel-based* approach, where the entire volume of the model was inverted after discretizing subsoil with voxels and constraining it with geological and geophysical a-priori information.

In that way, a final robust 3D model was obtained, providing new information in the area without seismic and well data. This model aims at reducing the geological *uncertainty* of the study area and the *risking* related to the rock densities that comes up in the exploration process.

Review of the Early Carboniferous source facies of the North Atlantic

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Keywords: Early Carboniferous; source rocks; lacustrine oil shales; Coals; Torbanites; North Atlantic.

This study reviews and assesses the Early Carboniferous source facies of the conjugate margins of the North Atlantic, specifically those of the British Isles and eastern seaboard of Canada. These Early Carboniferous sources have a long history in being important hydrocarbon resources. The retorting of oil from low maturity oil shales, was widespread in the Midland Valley of Scotland during the 19th century. The sediments exploited are lacustrine derived oil shales, associated Cannel Coals and Torbanites. These lacustrine deposits developed in series of pull-apart basins from dextral movement along major faults north of the Iapetus Suture. A series of such lacustrine influenced basins are noted, Midland Valley of Scotland, Rathlin Basin (Northern Ireland), Deer Lake Basin (Newfoundland) Moncton and Magdalen basins (New Brunswick). These basins experienced various levels of exploration for hydrocarbons.

The area immediately south of the Iapetus Suture within the British Isles has hydrocarbon source facies of Carboniferous age. Late Carboniferous Coal Measures are known sources for many commercial gas discoveries within the East Irish Sea Basin and Corrib gas-field located offshore Western Ireland. Two significant oilfields exist within the East Irish Sea Basin, Douglas and Lennox, each containing around 200 mmbbls STOIIP. These fields are sourced by Early Carboniferous Shales that have an overriding marine character. This region to the south of the Iapetus Suture was subjected to a different tectonic regime relative to that to the north.

These two tectonic settings have more recent counterparts that have been studied to further illustrate the development of source systems that developed during the Early Carboniferous. For the northern area, comparison with the Tertiary lacustrine basins of Sumatra are made. The area to the south is compared to Sumatran fore-arc basins and to the Eastern Mediterranean region.

Using available datasets, the sources and resultant hydrocarbon products from both the lacustrine and marine influenced Early Carboniferous strata of the study area have been compared. Understanding the nature of the sources, their kinetics and differing hydrocarbon products will have impact on exploration efforts in the underexplored Sydney Basin (offshore Newfoundland / Nova Scotia) where Early Carboniferous sources are considered key in the search for oil and gas. Early Carboniferous sources may have been overlooked in the exploration campaigns west of Ireland (north Porcupine, Slyne and Erris Basins) where a Late Carboniferous source provides the only commercial discovery to date.

An assessment of potential Cretaceous source facies in the Orphan Basin

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Keywords: Orphan Basin, OAE's, Cenomanian-Turonian.

The Orphan Basin lies in the North Atlantic, approximately 400 kms to the east-north-east of St. John's, Newfoundland, Canada. It is an underexplored basin which has a total area in excess of 160 000 km^2 with 10 unsuccessful wells drilled. It is currently of high interest to oil companies, recent successful bid amount of Can$621,021,200 (approximately US$475 Million).

Previous exploration campaigns focus the presumption that any oil generated and accumulated from Late Jurassic source rocks. Renewed interest in the basin has turned to the potential for Cretaceous source facies. As there is a paucity of information regarding such sediments from the drilling that has taken place. Wells drilled to date encountered condensed or eroded Cretaceous sections, others on the basin flanks penetrated thicker Cretaceous sections dominated by courser clastics. Information has been put together from adjoining basins, the conjugate margins and particularly from the records of the Ocean Drilling Program (ODP) and its predecessor, the Deep Sea Drilling Project (DSDP).

The rationale of this study was to look at the tectonic evolution of the basin and then, particularly for the Cretaceous, understand the distribution of sedimentary facies across the basin through a series of time slices. These time slices sometimes coincide with those of Ocean Anoxic Events (OAEs), the well-known being Cenomanian-Turonian. Such events have been well recorded in studies carried out by the ODP/DSDP. One of the main objectives of this study has been to integrate these data and then apply finding to the study area. What has become evident is that some of these events may be more appropriate for inclusion into the study than others. For example, the assessment of ODP site 1276, which is the nearest such site to the Orphan Basin, reveals that OAE 2 (Cenomanian-Turonian) yield some very rich and well developed source rocks, as does OAE 1b (Late Aptian/Early Albian), the latter being considered slightly richer in terms of oil generating than the former.

The results of this study have been used in a 1D basin modelling study utilising Novva Software. A number of possible scenarios have been generated and risked as far as possible. To aid the part of the study Nalcor provided depth converted pseudo-well sections in key locations determined from their extensive seismic database.

Geological section across the northern Oman Mountains

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Keywords: cross-section, balanced cross-section.

Oman is a relevant hydrocarbon province, and most of the resources are contained in the Lower Cretaceous carbonates of the Autochthonous Unit. Therefore, for a successful exploration, it is necessary to understand the deep structure of this unit. Hence, the aim of this study is the comprehension of the deep structures through a balanced cross-section constrained by available subsurface information and through a forward model. The study area is in the northern part of the Oman Mountains; this NW-SE-oriented belt, formed in mid-Cretaceous time, due to the closure of the ancient ocean and the consequent obduction of oceanic crust onto the Arabian continental margin. Obduction, thrusting and folding led to a stack of four units, from the highest to lowest: Semail, Haybi, Hawasina, and Sumeini. These units lie structurally above the Arabian continental margin or Autochtonous Unit, also covered by syn-nappe and post-nappe sequences. During Tertiary, renewed thrusting and folding phases affect the post-nappe succession causing the developing of some unconformities.

The geological section was balanced with an excellent result with an error minor than 1% and together with the forward model shows a thrusting propagation from NE to SW, as well as the SW-vergence thrusts. Shortening measured along the section is 10 km, and most of it occurs through the three main thrusts. The study area is also affected by two different deformation styles: one thin-skinned, in the syn-nappe succession, affecting also the post-nappe unit, and one thick-skinned, affecting the Autochthonous Unit. Along the section, the bottom of the post-nappe succession is much more deformed than the Autochthonous, due to the deformation in the syn- nappe sediments and this is evidenced by unconformities identified in the post-nappe sequence. For a well-addressed hydrocarbons exploration, it is essential to understand the different deformation between the outcropping post-nappe sequence and the deep pre-nappe succession.

Diagenesis of Aptian sandstones from the Espírito Santo Basin, and implications for the South Atlantic Pre-salt paleoclimatic conditions

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Keywords: sandstones, diagenesis, pre-salt, paleoclimate.

The sandstones of the Mucuri Member from the Mariricu Formation (Aptian) were deposited at the margin of the extensive lacustrine system where voluminous Pre-salt carbonate reservoirs were formed. Their detrital composition, which is extremely immature and rich in feldspars, micas and heavy minerals, reflects provenance from plutonic terrains uplifted during the preceding rift stage. First cycle sediments were eroded under dry climate, rapidly transported, and deposited by alluvial and short, ephemeral fluvial streams systems. Limited wave reworking promoted enrichment of micas, mainly biotite, in the marginal lacustrine deposits. Intense eodiagenetic processes resulted from the interaction of the primary mineralogy with diluted meteoric water or lacustrine alkaline fluids. The distribution of these fluids varied dynamically, as a response to climate variations and lake level changes. Authigenic kaolinite cement was formed in sandstones affected by meteoric waters, while calcite and smectitic clays precipitated by the percolation of lacustrine alkaline fluids. The reaction of detrital feldspars with meteoric waters promoted their dissolution and/or kaolinization, while their interaction with alkaline fluids caused replacement by smectites, authigenic K- feldspar and carbonates, particularly calcite. Biotite grains were expanded and replaced by kaolinite, vermiculite and siderite under influence of meteoric fluids, or by smectite, pyrite, calcite and dolomite in reactions with alkaline fluids. Muscovite grains were expanded and kaolinized. Heavy minerals were dissolved and replaced by TiO2 and kaolinite under meteoric conditions, or smectite, calcite and dolomite under alkaline conditions. Garnets, the most abundant heavy minerals, were dissolved and replaced by kaolinite, smectite and carbonates. The intense diagenesis altered the sandstones essential detrital composition, and their chemical composition. Cementation and compaction affected intensely the porosity and permeability of the Mucuri sandstones, controlling their quality as oil reservoirs. The lacustrine system was recharged episodically and at a limited scale by meteoric water and alluvial sediments. Such a limited supply is not compatible with the oscillations observed at lake level, suggesting that other water sources were replenishing the large lake system. The characterization of the Mucuri sandstones eodiagenetic processes is important to expand the understanding of the paleoenvironmental conditions prevailing at the margins of the lacustrine system where the extensive Pre-salt Aptian carbonate reservoirs were formed.

Mesozoic stretching and tectonic evolution of the Briançonnais

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Keywords: Backstripping – Tectonic Subsidence – Rifted margins.

During the Mesozoic, the relative movement of African and Eurasia plates caused the opening of the Tethys oceanic basin. The rifting phase is well charted by the stratigraphic sequence of Western Alps, which provide an exceptional record of continental margin evolution. The Briançonnais domain occupies a pivotal place for examining and testing various rifting models. This domain classically contains a remarkably uniform succession of very shallow-water carbonates of Triassic age. These units are strongly eroded with locally deep-penetrating palaeokarst systems – the extent of which values between different sectors (now contained in different Alpine thrust sheets). The erosion surface is variably capped by Middle-Jurassic shallow-water carbonates or by non-deposition before passing abruptly up into deep-water "ammonitico rosso" or radiolarites and thin deep-water limestones. Here we show that the back-stripped Mesozoic tectonic evolution of the Briançonnais block can be applied to investigate models of lithospheric stretching. Applying the Airy correction, we found that the Triassic is characterised by a constant tectonic subsidence rate of 17 m/Ma. If this is the result of "post-rift" thermal re-equilibration of upper mantle after late Palaeozoic rifting, this rift phase occurred with a stretching factor of c 1.3-1.4. The subsidence of more than 3000m during Bathonian-Callovian stages are too rapid to be explained by thermal re-equilibration: it suggests substantial crustal thinning. Our results demonstrate that a uniform stretching model is not able to explain the Jurassic isostatic movement of the Briançonnais domain. Moreover, comparison of Alpine rifted margin with ION-1000 seismic line of East Indian margin shows very close affinity between magma-poor rifted margins.

This study represents a starting point for more sophisticated and developed numerical models, to explain rapid vertical movements in hyper-extended continental margins.

Unlocking New Room of Production in Brown Field; Integration of Geological Data Conditioned 3D Reservoir Modelling of Lower Senonian Matulla Formation, Ras Budran Field, East Central Gulf of Suez

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Keywords: Brown Field; 3D Reservoir Modelling; Lower Senonian Matulla Formation; Ras Budran Field; East Central Gulf of Suez.

The Late Cretaceous deposits are well developed through-out Egypt. This is due to a transgression phase associated with the subsidence caused by the neo-Tethyan rift event that took place across the northern margin of Africa, resulting in a period of dominantly marine deposits in the Gulf of Suez. The Late Cretaceous Nezzazat Group represents the Cenomanian, Turonian and clastic sediments of the Lower Senonian. The Nezzazat Group has been divided into four formations namely, from base to top, the Raha Formation, the Abu Qada Formation, the Wata Formation and the Matulla Formation. The Cenomanian Raha and the Lower Senonian Matulla formations are the most important clastic sequence in the Nezzazat Group because they provide the highest net reservoir thickness and the highest net/gross ratio. This study emphasis on Matulla formation located in the eastern part of the Gulf of Suez. The three stratigraphic surface sections (Wadi Sudr, Wadi Matulla and Gabal Nezzazat) which represent the exposed Coniacian-Santonian sediments in Sinai are used for correlating Matulla sediments of Ras Budran field. Cutting description, petrographic examination, log behaviors, biostratigraphy with outcrops are used to identify the reservoir characteristics, lithology, facies environment logs and subdivide the Matulla formation into three units. The lower unit is believed to be the main reservoir where it consists mainly of sands with shale and sandy carbonates, while the other units are mainly carbonate with some streaks of shale and sand. Reservoir modeling is an effective technique that assists in reservoir management as decisions concerning development and depletion of hydrocarbon reserves, So It was essential to model the Matulla reservoir as accurately as possible in order to better evaluate, calculate the reserves and to determine the most effective way of recovering as much of the petroleum economically as possible. All available data on Matulla formation are used to build the reservoir structure model, lithofacies, porosity, permeability and water saturation models which are the main parameters that describe the reservoirs and provide information on effective evaluation of the need to develop the oil potentiality of the reservoir. This study has shown the effectiveness of; 1) the integration of geological data to evaluate and subdivide Matulla formation into three units. 2) Lithology and facies environment interpretation which helped in defining the nature of deposition of Matulla formation. 3) The 3D reservoir modeling technology as a tool for adequate understanding of the spatial distribution of property and in addition evaluating the unlocked new reservoir areas of Matulla formation which have to be drilled to investigate and exploit the un-drained oil. 4) This study led to adding a new room of production and additional reserves to Ras Budran field.

Outcrop-scale fracture analysis of tight, well-bedded, Lower Cretaceous limestones, Monte Alpi (southern Italy)

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Keywords: Fractured carbonate; Discrete Fracture Network modelling Hydraulic properties; Fracture porosity Equivalent permeability.

On a global scale, ca. 50% of natural oil and gas reserves are hosted in carbonate rocks. Commonly, both fluid storage and flow properties of these rocks are often dependent upon nature, geometry intensity and connectivity of the fracture network that crosscut them. In order to evaluate the hydraulic properties of tight carbonate matrices crosscut by either a diffuse or a localize deformation, this study focuses on the limestones exposed at the Monte Alpi, southern Italy, which pertain to the Inner Apulian Platform. By combining field and laboratory analyses, we present the results of outcrop-scale structural analysis, micro-scale petrographic analysis of representative limestone samples, and DFN modeling. The goal is to compute the amount of both fracture porosity and equivalent permeability of outcrop-scale, geocellular volumes crosscut by Strata Bound fractures (SB), which represent the limestones cropping out away from major fault zones, and also by Non Strata Bound fractures (NSB) as documented in the study fault damage zone. The study limestones are characterized by a wide spectrum of calcareous facies, from mudstones to grainstones, which were deposited in moderate water energy environment. Results of field structural analysis are consistent with SB fractures being characterized by a Poissonian distribution, forming not clustered configurations within the individual limestone beds. There, bed interfaces are hence interpreted as mechanical interfaces that inhibited the vertical propagation of mode I fractures, joints, which form two cross-orthogonal, bed-perpendicular sets that developed, more or less, at the same time due to a stress-state transition mechanism. Within the fault damage zones, NSB fractures offset up to a few cm the individual bed interfaces, forming a conjugate system sub-parallel to the main slip surfaces. Results of Discrete Fracture Network modelling of geocellular volumes representative of the surveyed outcrops show that the fault damage zone form the main repository for underground fluids, in which NSB fractures act as main control on fracture porosity, and determine almost isotropic horizontal fluid flow properties. This study highlights therefore the importance of studying surface structural analogues, which may provide useful information for the management and development of subsurface fractured carbonate reservoirs.

Lateral compositional variations in the upper Jurassic source rock in the southwestern Barents Sea – an organic or inorganic disclosure

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Keywords: source rock, high-value gamma-ray spikes, uranium.

Prominent high-value gamma-ray spikes in the maximum flooding surfaces of the Upper Jurassic Alge Member of the Hekkingen Formation display an uncommon stratigraphic and regional variation in the southwestern Barents Sea (Marín, personal communication, October 15, 2018). The variation in the gamma-ray spikes indicates compositional variation in the Alge Member, thus, challenging the common perception that the Upper Jurassic source rock is a homogenous succession of black shale. The purpose of this study is to identify the compositional variations in the source rock that causes the high-value gamma-ray spikes in the Alge Member. And by comparing the lateral compositional changes in the Alge Member – be able to develop an improved understanding of the depositional environment and the paleogeography in the area during deposition. The organic composition of the member is determined by geochemical analysis and maceral analysis, whereas mineral analysis and X-ray diffraction of the clay fraction reveals the inorganic composition. In addition, seismic reflection data, well logs and sedimentary core logs are used to compare the composition and variations in the depositional setting of the Alge Member in the southwestern Barents Sea.

The studied compositional elements of the Alge Member show no correlation to the high-value gamma-ray spike. West and northwest of the Loppa High, the Alge Member is characterized by a lack of prominent high-value gamma- ray spikes, a wedge-shaped geometry observed in seismic data and the presence of gravity flow deposits interpreted in a core. These observations reveal that the deposition of the member was influenced by the ongoing rifting and uplift of the western Loppa High, suggesting that the Alge Member was deposited in deep water environment with no input of oxic water in this western part (Figure 1). Whereas, in the Hammerfest Basin and in the area eastward toward and surrounding the Nordkapp Basin, the Alge Member experienced a low energy deposition in hypoxic to anoxic bottom conditions.

The study shows that high-value gamma-ray spikes are present when the Alge Member has been deposited in a hypoxic to an anoxic environment. Moreover, the high-value gamma-ray spikes correlate to the uranium content in the black shale, thus, indicating that the prominent gamma-ray spikes develop under the same conditions that are required for uranium to precipitate in sediments. This study could be used to reconstruct the development of the anoxic zone in the southwestern Barents Sea during the deposition of the Alge Member.

Modeling dynamic behavior of fracture corridors from time lapse Electrical Resistivity Tomography (ERT) experiments. Application to the Calvisson Quarry (SE France)

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Keywords: fractured reservoirs; outcrop analogue; mechanostratigraphy; ERT; dynamic behavior.

In naturally fractured reservoirs studies, outcrop analogues are used to understand the genesis, geometry, properties and distribution of fractures in relation to scale and mechanostratigraphy, *i.e.* the static aspect of the fracture network. However, in subsurface reservoirs, it is the dynamic aspects which matter, *i.e.* the flow network. Yet the relationships between fractures and flow networks is hardly predictable.

The aim of this study is to present a simple method to understand the contribution of different fracture scales to flow through time lapse ERT profiles. This concept is applied in the Calvisson quarry (SE France) located on the western border of the Camargue Basin (SE- France). The quarry exposes Hauterivian marly limestones deposited in the South East Basin. Those deposits are affected by diffuse fracture network and several fracture corridors, at the scale of a reservoir simulation cell. There, we acquired several 2D ERT profiles at a dry / relatively dry periods and during three days (at 24/48/72 hours), after a heavy rainfall. The purpose of those acquisitions is to determine how the fracture network is electrically responding to the water saturation and its variation. We also measured the resistivity at sample scale to understand the upscaling effects. Based on structural and LIDAR survey, calibrated with a scanline measurements of fracture density, we realized a 3D structural model of the horizon and fracture corridors pattern. Then, we define a relationship between resistivity/conductivity, saturation and permeability. The goal of this, is to populate a 3D model of the quarry in fractures (DFN) and in dynamic properties. We develop a plug-in for Gocad software suite (geomodeler) especially for this purpose.

Simulating the permeability of multi scale fracture networks, from continuous ERT surveys, is a promising approach to quantify the partitioned contribution to the fluid flow of diffuse versus clustered fractures at reservoir scale. The results will help to understand the fracture heterogeneity and multi-scale pattern while simulating fluid flow in models of naturally fractured reservoirs.

Provenance on the Lange-Lysing megasequences on the Dønna Terrace: focus on stratigraphic variability and lateral sandbody connectivity

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Keywords: Traditional provenance methods, single grain U-Pb, and hafnium isotope analysis, stratigraphic and lateral variability.

Stratigraphic variability and consistency within the Lange-Lysing megasequences are established by provenance study. Lateral connectivity within the megasequences presents inconclusive result from traditional provenance methods, apart from single grain isotope analysis. A relation between stratigraphic variability and lateral reservoir quality development, with marginal-marine to the basinfloor gross depositional environment have been established by a change in provenance development. The Cenomanian to Coniacian-Turonian Lange-Lysing megasequences is located on the Dønna Terrace in the Norwegian Sea. Provenance study using traditional provenance methods such as petrography, whole-rock geochemistry, and single grain U-Pb and hafnium isotope analysis, combined with stratigraphy were used to test the validity of correlation within the megasequences. The variation of weathering and recycling pattern, different tectonic setting combined with trace element ratios, reveals significant contrasts within the stratigraphy of the megasequences. The marginal-marine to upper slope reveals a stratigraphic consistency by none to a low degree of sediment recycling combined with a narrower age spectrum of 350-1850 Ma. Provenance development of the marginal-marine unravels a difference in reservoir quality; however, good reservoir quality decreases towards the basinfloor gross depositional environment. The basinfloor to lower slope gross depositional environment show overall bad reservoir quality, however, there are variations within the sandbodies from bad to good reservoir quality pointing to stratigraphic variability. A decrease in reservoir quality has defined a lateral rationale association between the marginal-marine towards the lower slope. Four main sediment transportation directions from seven provenance regions were deduced by frequent (350-1850 Ma), and subordinate (90-300 Ma and 2000-3300 Ma) U-Pb zircon age spectra and are relating to the Western Gneiss Region, Lofoten-Vesterålen and the West-Troms Basement Complex. Combining subordinate juvenile Phanerozoic (90- 350 Ma) and older Archean ages (2500-3300 Ma), with other studies, suggests the origin of the sediments are derived from provenance regions such as the High Arctic Large Igneous Province, Spitsbergen, and Novaya Zemlya in the Barents Sea, including the Varangerfjorden. The lack of a juvenile Phanerozoic and a late Proterozoic U-Pb zircon age spectrum, with a significant Archean component, responds to provenance signatures originating from the northern Greenland region. U-Pb zircon dating results are supported by the hafnium isotope analysis pointing to protosources from the same regions. Finally, this study emphasizes the importance of incorporating provenance methods, and stresses the use of U-Pb and hafnium isotope analysis, in order to comprehend the stratigraphic variability to unravel complex turbidite systems and predict the lateral extent.

Structural and depositional evolution of the Lower Cretaceous in the Danish Feda Graben Area – an analysis based on 3D seismic data

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Keywords: 3D seismic data; Lower Cretaceous; Danish Feda Graben; Structural and depositional evolution.

The Central Graben is part of a failed Mesozoic rift system located in the central North Sea basin. The first extensional tectonic phase in the Danish North Sea was initiated in Late-Paleozoic, continued to Late-Jurassic times and was followed by Late-Cretaceous lateral tectonic shortening resulting in basin inversion. Inversion structures superimposed onto Mesozoic extensional graben systems is a prominent feature in the Danish Central Graben. These structures are of interest in particular with respect to hydrocarbon prospectivity, since a large part of the plays in the Danish Central Graben are associated with inverted structures.

The Feda Graben is a Mesozoic fault-bounded basin in the NW part of the Danish Central Graben and experienced Late Cretaceous inversion, affecting especially the Lower Cretaceous, which reaches thicknesses of up to 1km. Deposition of the Lower Cretaceous units in the Feda Graben was primarily controlled by a major NE dipping fault bounding the Feda Graben to the SW against the Inge High. This normal fault experienced reverse reactivation during the inversion phase, causing the formation of anticlinal folds in the Lower Cretaceous units parallel to the fault. The inversion also controlled smaller scale faulting reaching the base of the Lower Cretaceous unit.

The inversion is generally interpreted as being due to crustal deformation in connection with Alpine tectonism. However, the presence of Zechstein salt has been documented from work in the Norwegian sector, and it also has a major presence in the southern Danish Central Graben. Still, the interaction between inversion- and salt tectonics has yet to be fully investigated

In this study we present an analysis of the structural and depositional evolution of the Feda Graben based on 3D seismic attribute mapping, compare the old tectonic models from the ‘80s with new models and suggest a link between distribution and deformation of Zechstein salt and the inversion structures in the Central Graben in particular the Feda Graben.

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