A Successful 4th EAGE Naturally Fractured Reservoir Workshop!

Report on the 4th EAGE Naturally Fractured Reservoir Workshop in Ras Al Khaimah, United Arab Emirates, held on 11-13 February.

Exploration and appraisal aspects of fractured reservoirs

The first EAGE workshop in Ras Al Khaimah was set in motion by Dr. E. Ukar, University of Texas at Austin, who described the importance of diagenesis on fractured reservoirs. She illustrated aspects of synkinematic (crack-seal) and post kinematic cement growth in fractures through a first selection of examples. She evidenced how fault rock properties are influenced by a combination of cataclastic and diagenetic processes during the fault zone evolution.

Using the example of the Andean Formation of Vaca Muerta, she also illustrated how the observation of fracture mineralization can support the evaluation of fracture chronology. Eventually, she used an example in the Tarim Basim to describe deep-origin mineralization in a system including fractures, faults and paleo-karst features. Exploration and appraisal aspects of fractured reservoirs.

The first session of the 4th Naturally Fractured Reservoir Workshop included a diverse selection of both oral and poster presentations. Dr. E. Angerer used diffraction imaging technology as an alternative to classic seismic reflection to enhance the visualization and interpretation of faults in the complexly structured Wisting field (Barents Sea). She introduced the method principles and presented a comparison with legacy data and more recent data ("P. Cable" data). She demonstrated the benefit of the combination of diffraction imaging and P- cable data in enhancing the imaging of small-scale faults and supporting their interpretation.

Dr. G. Bertotti, professor at Delft University of Technology, presented a study on hypogenic karst in carbonate sequences. The purpose was to provide tools to predict the location of cavities as well as input about their dimensions and geometry. An underlying idea was also to transfer these geological bodies into simulators.

He first defined the hypogenic character of caves by specifying the origin of dissolving fluids (CO2 and H2S) and used cave geometry as characteristic criteria. He discussed the effect of cooling in facilitating the dissolution of CaCO3 and precipitation of SiO2. He eventually associated the flow of reactive fluids to the tectonic evolution and introduced the use of chemical dissolution models to model karstic patterns.

Dr. R. Jones, Geospatial Research Limited, introduced his talk on fractures in basement reservoirs with a quick overview of World – Basement fractured reservoirs and their key components. He described these reservoirs as typically dominated by fractures in terms of porosity and permeability. He then described the example of Lancaster field (Rona Ridge East Scotland) in details. He distinguished the respective impacts of faults, fractures and fissures on the porosity and permeability system of the field.

Dr. Juliette Lamarche described a detailed study of fractures across a km-scale anticline overlying a thrust fault in southern France. Due to erosion by a river valley, it was possible to log bedding, joints, veins, stylolite's and small faults along a traverse across the anticline hinge. The anticline was asymmetric, with a near vertical north limb but shallower dipping south limb.

They were able to relate the fractures to four stages of deformation at different positions on the burial history path, and then to predict the relative contribution of fracture porosity to total porosity at different stages of anticline evolution. This varied extensively through time, both due to fracture generation during the active inversion phases, and

cementation of the fractures during the subsidence phases.

Dr. Pascal Richard described a study on the Sabiriyah field in Kuwait. The tectonic settings of the field followed an evolution similar to the outcrops studied on the field trip. The field benefits from a rich dataset (plenty of well and seismic data). It was traditionally interpreted as an unfractured reservoir, but it does contain many transtensional faults of varying lengths. The question is, if it has undergone extension and strike-slip deformation, why does it not contain fractures?

The faults are represented in the reservoir models as single continuous planes, but in reality, they are likely to be segmented, and especially vertically segmented – with displacement being localized onto a single slip surface in the more brittle layers, but more distributed across a wider zone in the intermediate layers. It is also possible to identify cemented fractures in core, and cemented horizons (c. 1m thick) on borehole images. These cemented horizons (representing sedimentary cycle tops) have high permeability. Tracer data also showed high connectivity along the mapped faults.

The inference is that where the faults cross the high permeability cemented layers, they generate a zone of intense fracturing, which act as a high permeability flow path. Reservoir conceptual models were re-evaluated on this basis and included more detailed fault geometry, and the presence of the highly fractured cemented layers to honor these observations.

Vincenzo La Bruna has been working on karst systems in onshore outcrops in Brazil. In particular he is studying the role of faults and fractures, and fluid circulation, in controlling the evolution of the karst systems. He showed examples from 2 basins, the Potiguar basin (with epigenic karst systems) and the Irece basin (with hypogenic karst systems).

He showed how fracture zones can form flow corridors for fluids that then generate the karst, and that bed-parallel stylolite's often control the development of vuggy porosity. However, cave roofs are often composed of siliciclastic units that can form seals or flow barriers. The surface drainage pattern also relates to the karst system – areas where there is no surface drainage indicate subsurface drainage through the karst.

He developed a conceptual model for karst development where a fracture zone develops along the crest of an anticline; hydrothermal fluids then flow up through the fractures, dissolve the calcite and create the karst system.

The oral presentations were followed with 6 poster presentations. The poster session was designed to ensure maximum exposure for all the posters. The poster presenters therefore gave a brief (2-3 minute) oral introduction to their posters, with 1-2 slides, before the session. During the session, attendees were asked to choose a poster to start with, and then a bell was rung at 10-minute intervals to encourage attendees to move on to the next poster. In this way, attendees would have time to visit every poster. The poster session was split in two, with 5 posters presented in the morning and 4 in the afternoon.

Oral Posters featured on 12 February 2020 were:

NFR08: Theresa Schrockenfuchs described a study of highly deformed thrust sheets of flysch, cut by normal, reverse and strike-slip faults which made seismic imaging very difficult. They were targeting a glauconitic sandstone within the flysch. The seismic data was reprocessed using CBM, CRS and ant-tracking, but best results were obtained from the HAC algorithm in Petrel. The interpretation was constrained with dipmeter data, which was used to identify faults and missing section.

NFR09: Renata Araujo was looking at the control of stratigraphy on karst formation. She had taken strat logs in 4 locations, measuring porosity, permeability and UCS (using a Schmidt hammer). She logged karstification and stylolitisation in the different layers – vuggy porosity often forms along bed-parallel stylolites.

NFR10: Vincenzo La Bruna discussed the relationship between karstification in the Irece Basin (described in his previous talk), a compressive basin with thrust faults, and in the offshore pre-salt, formed in an extensional environment. He planned to take samples of the cements for geochemical analysis to establish timing of karst formation.

NFR11: Sylvain Luby described a study of faults and lineaments in eastern Egypt, mapped from satellite images at multiple scales for outcrop to regional scale. They had run automated statistical processing of lengths and orientations of the fractures using Matlab, to suggest a fractal relationship of faults of different scales.

NFR12: Rubson Maia investigated the evolution of karst systems onshore Brazil. He showed that rivers

flow towards the centre of the basin, and karstification becomes more intense downstream, so that we can see the evolution of the karst from isolated dolines, to gorges, until the drainage becomes fully subterranean.

NFR13: Cayo Pontes mapped the shapes in detail (in 3D) of 4 karst-derived cave systems in Brazil. The cave geometry can be directly related to the geometry of the fracture network – e.g. a single fracture set gives a system of parallel aligned caves, whereas two fracture sets give a network of orthogonal caves.

NFR19: Ricardo Inama described syndepositional fractures in a platform carbonate in northern Italy. The outcrop comprised a steep-sided and flat-topped plateau with very good exposure, which was mapped by drone at 5-7cm resolution. This gave both cross-section and plan view data, on which he was able to identify small-offset syn-sedimentary faults with bed thickening, fractures delineating dm- to m-scale collapse zones, and fractures with sedimentary infilling. The next stage is to examine the links between fractures and sedimentary fractures, and tectonic reactivation of synsedimentary fractures.

NFR20: Juliette Lamarche investigated filed classification of fracture corridors. Based on numerous outcrop examples, she found extreme variability in the morphology and geometry of the corridors, sometimes even within the same corridor, over a distance of 10s of metres. A method based on fracture clustering analysis was also proposed to support a more objective identification of fracture corridors from scanlines.

NFR23: Weiwei Zhu introduced a method of automatically interpreting a fracture network from aerial or satellite photos. This consisted of 2 stages – first a neural net was used to classify all pixels in the image as either fractures or non-fractures, then an algorithm was created to convert the pixelated image into a vector network.

Recent and future developments in Fracture Geology

The second session of the workshop began on the afternoon of the 12th of February 2020 as Yasmin Bouzida presented a multi-scale fracture characterization workflow integrating data from core, borehole image log, Dipole Deep Shear Wave Imaging and seismic to better to optimize the impact of natural fractures on production with regard to well placement and completion/hydraulic fracturing. The workflow has also been coupled with a geomechanical study of critically stressed fractures.

Dr. R. Jones presented a multi scale outcrop fracture study at Ras Al Khaimah integrating laboratory-based micro-tomography, traditional fieldwork, and digital 3D data (Lidar) and its impact on P32 and fracture porosity estimates.

Dr. T. Schröckenfuchs described a workflow to integrate drill cuttings into the characterization of micro fractures in basement rocks. Drill cutting are selected in specific zones of interest (through PTA, BHI etc.) and in order to answer key questions. The selected samples are analyzed through thin sections with a polarized-light microscope, X-ray diffraction and X-ray fluorescence to obtain the bulk mineralogical composition and geochemistry. This analysis enables to define the most fractured type of rock (granite) the best reservoir zones (breccias and cataclasis zones), a micro fracture network connected with secondary leached feldspar grains. The method is however limited with the mud additives which can pollute the samples.

Dr. M. Welch in his contribution presented a further development of the code he has developed to predict the distribution of fracture networks in reservoir rocks through a (mono layer) geomechanically driven DFN modeling of typical fracture outcrops. Discussing three case studies, Nash Point, Pegwell Bay and Robin Hood's Bay, Welch addresses key issues such as the fracture spacing, local stress variations, changes in direction and fracture propagation velocities. A very interesting paper providing tools to predict patterns of distributed fracturing in the subsurface.

Mr. R. Inama has presented an impressive and very accurate 3D model of the Lastoni de Formin platform, one of the Early Triassic flat-topped platforms of the Dolomites (N Italy) obtained by drone photogrammetry. One of the most interesting results is the quantification of the increase of layer thickness towards the margin of the platform as a consequence of differential compaction of underlying basin sediments. Fractures, often with syn-sedimentary infill, developed parallel to the platform margin, and then are partially reactivated during the strike-slip Alpine tectonic phase.

From static fracture models to dynamic simulation: what matters?

The second and final day off the workshop began with a keynote address by Dr. A. Lavenu, ADNOC Offshore, providing an overview focused on diffuse

fractures. From outcrop characterization to subsurface data integration. Development of diffuse fractures during early burial or uplift. One of the key questions posed by the audience to A. Lavenu is, 'what are diffuse fractures, how do they develop and what is their impact on flow and how do we integrate diffuse fracturs in static? dynamic models?', and A. Lavenu's feedback noted, there is no single way to model them but to also not disregard them.

Dr. A. Lavenu's keynote address, built an opening for the final session of the workshop focused on static fracture models to dynamic simulation and what matters. To kick start the afternoon were presentations discussing the novel ways to decipher field performance in an NFR carbonate field, role of basement inherited structural network on heat distribution and flow pathways in rift basis, investigation of modeling options for numerical simulation of fractured and karstified reservoirs and interplay of heat transport and fracture aperture in fractured reservoirs.

Mr. P. Olivier from Petroleum Development Oman, kick started the final day with a presentation on a novel way to decipher field performance in NFR carbonate field; Discussing the characterization of the reservoir using an integrated approach with pressure, Borehole image data and production data. Evidence of baffles created by reservoir property variations in line with depositional model and the presenter finally covered Matrix and fracture properties calibrated using history match.

Role of basement inherited structural network on heat distribution and flow pathways in rift basins presented by C. Bossenec, Université de Lorraine, discussed how heat flow and fluid pathways in Rhine Graben reconstructed using reservoir faults, fracture characterization at various scales in integrating mapping, core and geochemical fluid characterization. She closed the presentation on imbricated scale of faults and fractures, sedimentologic and lithologic control on fracture types.

Sensitivity analysis for different simulation methodology and contrast off permeability between matrix and karsts. Single porosity single permeability and dual porosity dual permeability show similar result when matrix has high permeability – bigger differences.

Dr. Machado did a structural model Matrix + fractures + Karsts, then a numerical model with assumptions testing 3 models: single porosity single permeability, dual porosity dual permeability A (split between matrix, and fractures and karst) and dual porosity dual permeability B (split between matrix and karst, and fractures), and the summary indicated that single porosity single permeability is more optimistic.

Sensitivity analysis of fracture network geometry and matrix permeability contrast on heat transport. With the largest permeability contrast, the fracture geometry has higher impact. Fracture aperture will strongly control shortcut between producer and injector.

In order to average the k, temperature_ceramics_flow => change continuously in the system and testing the hole in connectivity on flow is linked to fracture aperture; Performance when spacing and flow rate increase.

To create an interval between the two sessions, were the final 3 poster presenters of the 4th EAGE Naturally Fractured Reservoir Workshop.

Oral Posters featured on 13 February 2020 were:

NFR29 – Dr. Stephan Matthai, University of Melbourne, discussed simulation of fracture matrix transfer at the saturation front.

NFR30 – Karla Olvera Carranza, Saudi Aramco described the interplay between fracture apertures and critical stressed in a naturally fractured carbonate reservoir in Saudi Arabia.

NFR31 – Michal Kepinski illustrated and had a discussion on critically stressed fractures and their contribution to flow – coal bed methane case study.

The last session of this workshop chaired by Dr. L. Bazalgette, PDO and Dr. T. Finkbeiner was kicked off with a presentation by PDO's Chadia Volery who discussed a challenging gas-oil-gravity-drainage (GOGD) field development in a heterogeneous and fractured reservoir of the Lower Cretaceous Shuaiba formation that is characterized by a very thin oil column of only 50m – 60m in height. A deeper understanding and optimized management of production is achieved through an integrated approach that involves reprocessed seismic data (for highly improved structural information), advanced well log data acquisition (such as borehole image and spectral noise logs), and dynamic events in the reservoir (e.g., losses during drilling, water and gas production).

Analyzing this data reveals a complex geoplumbing of this reservoir dominated by some of the existing fracture networks. These results serve as calibration data to guide geoscientists and reservoir engineers alike for optimized reservoir management strategies. This includes the optimization of injector and producer well design to avoid gas shortcuts and the use of aquifer pump-off wells to control the vertical position of the oil rim with regards to the location of producer wells.

Alejandro Cardona from King Abdullah University of Science and Technology (KAUST) delivered the second presentation with a focus on developing a so-called Implicit Joint-Continuum Model that couples fracture mechanics with hydraulics. This model transforms global stresses into local stresses that act on the fracture plane. A constitutive model then computes fracture displacements from these local stresses. The coupling between mechanical and hydraulic models uses a set of constitutive equations that satisfy asymptotic states for transmissivity at initial and infinite conditions. The model includes geometrical characteristics of the fracture surfaces such as roughness (fracture aperture variability due to asperities) and matedness (geometrical fit between opposite fracture surfaces). It is validated against analytical solutions and then utilized to investigate the permeability evolution of a fractured rock mass with two conjugate fracture sets. Through the comparison with a real case example in the North Sea, the results reveal intriguing transmissivity directionalities often observed in reservoirs that are difficult to predict with standard reservoir simulator approaches.

Finally, ADNOC's Olivier Pippi presented an interesting field case from offshore Abu Dhabi where the Late Cretaceous Thamama reservoirs is developed. An abundance of static and dynamic data provide a novel way to better understand the role of diffuse fracture sets when it comes to fluid flow in this carbonate reservoir. The data sets include core, well-log and pressure transient analyses. This enables the identification of typical well responses and on this basis of field sectors dominated by matrix, diffuse fractures and conductive faults. This characterization allows both geoscientists and reservoir engineers to decipher how fluids flow through diffuse fractures and eventually connect into main reservoir fault zones. This understanding provides input for improved flow models that can be verified with seismic attribute data. Furthermore, accurate values of horizontal permeability within the matrix, diffuse fractures and also fault corridors of the reservoir deliver more robust reservoir simulation results.

4th EAGE Naturally Fractured Reservoir Fieldtrip

The 4th EAGE Naturally Fractured Reservoir Field Trip: Seeing the (seismically) invisible in outcrops: faults, fracture corridors and distributed fractures was a 1-Day excursion that took place in the foothills of the Northern Emirates Mountains where the lack of vegetation and recent tectonics allow for outstanding exposures!

The excursion focused on fracture corridors, faults and distributed fractures, on their origin, spatial distribution and how these are implemented in geomodelling workflows.

EAGE would like to take this opportunity to thank the two field leaders who made this fieldtrip a success and all participants for their active participation!

Dr. Giovanni Bertotti with Delft University of Technology and Mr. Raffik Lazar with GeomodL International.

EAGE would like to thank the technical committee for a successful workshop in Ras Al Khaimah and would further like to also thank ENI for their generous contribution as the Platinum Sponsor.