ORAL PRESENTATIONS

TUESDAY 06 OCTOBER

SESSION ONE: GEOMECHANICS

Keynote: A nearly 90-year journey of image logs and could we log one on Mars?

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From Noise to Insight: Interpretating Drilling-Induced Damage in Mid- and High-Temperature (150 - 310°C), Conventional Geothermal Systems

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In conventional geothermal development, fluids flowing through existing natural permeability are produced to surface and utilised for energy. Fractures typically dominate economic-scale permeability, and (with rare exceptions) developed geothermal systems are hosted in terrains comprising predominantly volcanic and metamorphic rock types. In mid- and high-temperature geothermal systems (150 - 310°C), thermal stresses at the wellbore wall suppress or eliminate borehole breakout (BHBO) while promoting drilling-induced tensile fracture (DITF) formation. The combined effect of thermal stresses—acting radially along the entire borehole length and locally around fluid loss zones—and rock fabric produces a wide range of atypical DITF morphology and azimuthal wander. Tensile fractures that interact with open natural fractures may indicate favourable permeability conditions. Gaping, off-azimuth tensile fractures occur around major fluid loss zones, presumably driven by localised changes in thermal stress. Natural fractures (and sometimes bed boundaries) appear open only on the tensile sides of the borehole wall or are wider in that area; this challenges the relevance of aperture measurements at the borehole wall for characterising reservoir conditions. These observations of atypical DITF morphology are unsurprising given the well-recognised success of thermal stimulation below the fracture gradient in conventional geothermal resources. Geologically complex, thermally stressed conditions necessitate a nuanced approach to borehole image interpretation; one that captures DITF variability and enables the data filtering required to determine confident azimuths for stress modelling. A growing body of borehole image studies in mid- and high-temperature conventional geothermal systems reveal that stress rotations are the norm, at both the local wellbore scale and the reservoir-scale between wellbores. This finding aligns with geologic and geomechanical studies that highlight the importance of structural complexity and dynamic stress transfer in generating and maintaining economic-scale permeability in conventional geothermal systems.

Borehole Forensics –The Use of LWD Images to Evaluate the Causes of Operational Events and Optimise Drilling Campaigns

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Wells are lost for a variety of reasons that may be related to formation geology, drilling practice or other related factors. However, the root cause is often difficult to detect from standard drilling data since these do not provide a direct view of the wellbore state over time.

LWD images are routinely used to geosteer and evaluate wellbore geology and geomechanics, but are generally neglected for drilling input. LWD acoustic amplitude, transit time and radius images show geological data (bedding and natural faults and fractures) as well as in-situ stress indicators (breakout, drilling-induced tension fractures), bedding plane spalling and mechanical damage caused by drilling equipment and can now be collected while drilling and while running out of hole. Integration of such LWD/POOH image data with drilling dynamic logs (ECD, ROP, WOB, etc) allows forensic examination of wells for improvements to well design. Even when BHAs are lost in hole, real-time data can be interpreted.

In addition to the image logs derived, the acoustic images can be converted to obtain caliper information for hole volume calculation. These time lapse data sets are useful as they allow evaluation of features such as: hole condition changes over time, rock strength from bit-at-rest impressions, scratches and wear to lowside, in-situ stress features that are often absent whilst drilling and grow and evolve over time, and presence of cuttings beds.

Integration of drilling data with written logs of drilling experience can further explain how and when hole damage occurs, allowing changes to operational parameters to be made in a more proactive and informed manner.

In this paper real world examples from Norwegian wells, will be presented to demonstrate that integration of LWD acoustic images and drilling data by experienced interpreters, allows constructive dialogue between Engineers and Geoscientists, reducing uncertainty and leading to improved drilling outcomes.

Borehole Image Applications in real time Deepwater Wireline Operations of Formation Testing and Sidewall Coring

***Anish Kumar*[1]**, *German Garcia*[1], *Adaobi Elekwachi*[1], *Jules El-Khoury*[1], *Andre Bertolini*[1]

1SLB

Since the early days of borehole imaging tool developments, borehole images have been used across the industry for a variety of geological and petrophysical interpretations. Recent developments of borehole imaging tools for non-conductive muds (NCMs) have increased image resolution, borehole coverage and image fidelity, and have brought a far greater ability of interpretation in deepwater operations where wells drilled with NCMs are the norm. These higher quality borehole images for NCMs are finding very relevant application to ongoing operations, such as formation testing and sidewall coring, especially in deep water settings where every operation is crucial and very expensive.

For formation testing operations, such as vertical interference testing or fluid, borehole images provide good guidance for planning the operations for probe or packer placements. It is important to understand where features such as bedding variations, faults or fractures may affect the results of the planned operations. In fact, even during the operations sometimes it is relevant to unravel the behavior of the ongoing test – especially anomalous – by looking at the geology as observed in the borehole images. Similar type of knowledge is also essential for sidewall coring operations. Borehole images provide detailed information about the facies that are to be cored, the variation of the sand and shale depositional characteristics as well as many other diagenetic imprints that might affect sidewall coring plans and operations.

This paper discusses the use of borehole images in deepwater formation testing and sidewall coring operations. Some examples are also discussed. Sometimes the difference between planning with borehole images or choosing not to use borehole images can be the difference between success and failure of very expensive and critical operations. No Operations Managers want expensive failures in their wells. A high quality borehole image can be the ingredient for success.

High resolution at-bit imaging: Concept, deployment, learning, limitations and way forward

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Borehole imaging has been helping geoscientists through various applications, and the technology evolved from wireline to LWD conveyance for high resolution data. At-bit imaging has recently been introduced with a new measurement, that of axial forces experienced by a stinger element trailing behind the leading cutter in a bit. This brings a unique opportunity where mud-type, mud-wt and hole size don’t matter as the measurement is independent of all these with at-bit acquisition with in-bit sensor.

The idea was conceptualized and lab tested a few years ago; however, image generation with correct orientation is achieved lately and the technology has been put through a rigorous testing against existing established imaging technologies across the globe to assess its applicability against various applications. The early deployment through middle east carbonates to US land to Africa, Europe, Asia and the South America has led to a series of high quality image log acquisition, bettering the gold standard of 0.2” in many cases for vertical resolution, deciphering host of geological features.

Learnings are made to understand the application of technology beyond borehole imaging, into other aspects of subsurface characterization (drilling, mud loss, rock-strength). Also, with LWD or WL images, the time lapse impact on downhole features were studied. Current limitations of the technology in soft formations are discussed with way forward to mitigate these with increased sensitivity. Geological answer products are comparable with established imager, and new answer development is discussed as well.

SESSION THREE: SEDIMENTOLOGY

Palaeowind patterns in the Permian of Europe: adding to palaeogeographies and validating numerical climate models from historical data

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Aeolian sediments allow numerical climate models of the Pangean to be evaluated for wind direction and strength, two key parameters derived from such models. Both Northern and Southern European Permian basins were sites for the accumulation of aeolian dunes. Dipmeters and borehole imaging tools allow the determination of aeolian dune-bedding orientations. Tens of thousands of cross-bedding orientations have been derived from these dune sandstones. Some of these data are in the public domain. Including information from outcrop locations, almost 400 sites in the study area had aeolian dune cross-bedding azimuth data. Palaeocurrent data was in the form of numerical values, azimuths quoted to inter-cardinal values, rose histograms, stereonets, tadpole plots and arrows on maps. For each site, major and minor mean azimuths were recorded and a bulk azimuth plot showed the presence of five azimuth modes, dominated by W and SW modes, with lesser developed NW and E-SE modes and a weak N-NE mode. The occurrence and strength of these modes varied across the study area. Each mode had a spread of azimuth data which overlapped with neighbouring modes. Mode separation was completed by comparing azimuth modes between neighbouring areas. For each mode, mean azimuths were derived across the study area, from which gridded spatial averages were plotted as arrows. These arrows were then compared to published palaeowind directions taken from climate models. The comparison between the climate models and the palaeocurrent data is good. The S and SW modes, the principal trade wind, is seen in all models. The NE trade wind, present in all climate models, is a rare feature in the cross-bedding data. A SE to E mode is seen in some models and is expressed in the palaeocurrent data typically north of the mid North Sea High. One climate model features a NW mode.

Multi-scale Core-to-BHI Reservoir Characterization distinguishes deepwater depositional elements: an example from offshore Suriname

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Integration of borehole image (BHI) and core provides a detailed stratigraphic context critical for characterizing and interpreting deepwater reservoir facies in a frontier basin. Preserving granularity when upscaling to a more field-scale stratigraphic framework remains a challenge. Here we showcase results from an integrated data set linking core to BHI and seismic scale observations from a well in offshore Suriname.

Environment of deposition (EOD) was generated linking stratigraphic architecture to depositional features observed in core (bed set > storey > storey set). Four distinct packages defined by facies association and grain size have been described from base of the core as: sand debrite and overlying shale, sand-prone heterolithics, amalgamated sand beds and thin beds. Abundant lamination and dewatering features were observed throughout the cored interval. Some possible injectites and mudclast-rich sandstones are also observed.

These depositional facies have been extended beyond the cored intervals using high-resolution BHI utilizing a descriptive nomenclature that distinguished between primary strata types. In the reservoir intervals, massive, electrically homogenous amalgamated beds were distinguished from more heterolithic beds. Sandy cross-strata, identified as packages of non-planar or discontinuous interfaces with rapid changes in bed orientation, provided insights into depositional dip direction. Together with mottled debritic textures, these facies helped identify channel margin features and define sediment fairways.

Residual dips from BHI identify multiple domains that dip in the basinward direction with wide scatter. These are interpreted as unconfined splay complex associated with a channel belt. Core and BHI facies, along with the presence of dewatering structure, hybrid beds, and variable dip orientation allow us to define the discrete depositional element of 'crevasse splay complex' for the objective interval, which suggests more unconfined and laterally extensive depositional packages than a channel-levee interpretation. This integrated model was extrapolated to areas without core to ascertain the overall EOD with a focus on differentiating channelized deposits from channel-adjacent unconfined deposits to sweetspot reservoir quality.

The use of borehole image logs in distinguishing depositional environments in non-marine carbonate successions

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Borehole image (BHI) logs, like the dipmeter logs that preceded them, provide a means of deriving bedding dip and azimuth. These parameters can be used to discriminate between different depositional environments once structural dip has been removed. During the early years of Pre-Salt exploration in the Santos Basin, Brazil most wells which penetrated the Barra Velha Formation encountered a cyclic succession of thinly bedded (typically < 1 m) carbonates interpreted to represent deposition in a low gradient lake system. As such, these facies lacked any significant depositional dip after structural restoration. However, as more of the basin was mapped positive topographic features with high angle dipping margins were described. Some preferred to interpret these features sedimentologically as carbonate mounds growing on structural highs, whereas others interpreted them as the products of structural inversion. In the former scenario, one would expect the facies succession to be quite different from the cyclic lake successions proven in older cored wells and to show an appreciable depositional dip as suggested by their relief. In the latter, one would expect a cyclic lake facies succession, heavily faulted and fractured due to tectonic inversion, but still lacking depositional relief. When one of these mound-like features was finally drilled, BHI log interpretation proved critical in discriminating between these two hypotheses. Thick (> 100 m) fractured and karstified successions with steep depositional dips (c. 20-40° but locally up to 70°) and distinctive image fabrics were encountered. It therefore became clear that the relief identified by seismic interpretation was depositional. This interpretation was further corroborated by taking whole core from the interval of high depositional dip. BHI logs have proven invaluable in discriminating between lacustrine and spring mound environments as well as constructing plumbing diagrams for Pre-Salt reservoirs.

Advanced Sedimentological and Structural Characterization of Malaysian Petroleum Systems Utilizing Borehole Image Logs

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Malaysia's complex geological framework spans diverse depositional and tectonic environments, driving a robust multi-play petroleum landscape. This review synthesizes key exploration insights from the nation's core sedimentary provinces—the, and Offshore Malay, Penyu, Sarawak and Sabah basins—while demonstrating how borehole image (BHI) logs serve as a critical bridge between sub-seismic rock features and macro-scale reservoir models. As exploration targets shift toward increasingly heterogeneous plays and Carbon Capture and Storage (CCS) initiatives, high-resolution subsurface imaging has become indispensable for characterization.

- In the Malay Basin, BHI logs are vital for identifying thin-bedded, highly heterolithic shaly sands and sandy shales that fall below standard seismic resolution. Image data enables the precise measurement of thin beds and paleocurrent directions, confirming a primary Southeast-trending fluvial system overprinted by Northwest-directed marine transgressions.

- Within the Sarawak Basin (Balingian Province), borehole images differentiate complex Cycle II depositional facies, guiding log analysts through a spectrum of highly bioturbated massive sands, laminated heterolithics, and tight siderite or coal hardgrounds. This facies analysis allows for accurate mapping of geometry transitions from braided sand bars to highly meandering tidal-fluvial channels.

- Offshore Sabah's deepwater plays rely on image logs to distinguish structureless, massive turbidite sands from chaotic Mass Transport Complexes (MTCs/MTDs). BHI data effectively isolates these impermeable slumps and debris flows, reducing structural risk in expensive deepwater wells.

- The Luconian Province exhibits isolated pinnacle reef carbonates where BHI logs provide a distinct advantage. Images characterize extreme reservoir heterogeneity by mapping karstic facies, identifying macroporosity, and isolating the open fracture networks that enhances permeability.

- Unconventional Basement Play, Malay Basin, where the reservoir consists of fractured meta-sediments, borehole images are the primary tool used to determine fracture apertures and orientations, revealing a dominant North-South and subordinate East-West striking network.

Ultimately, these high-resolution sedimentological and structural insights help optimize hydrocarbon production, as well as providing insight in repurposing Malaysia's depleted reservoirs—such as the Kasawari CCUS project, and for future Plug and Abandonment.

How Borehole Images are Used Across the Lifecycle of a Field

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Since the first three-arm “dipmeters” appeared in the 1940’s, our ability to understand the geology local to a well has improved drastically. With current options in both logging-while-drilling (LWD) and post-drill wireline operations, companies have a variety of imaging tools at their disposal to include in formation evaluation programs. These borehole image logs allow us to better characterize our reservoirs (and non-reservoirs) with increased structural, sedimentological, stratigraphic, and stress related information. However, specific questions and needs from these topics may change during the lifecycle of a field. Based on a litany of reasons, from overall petroleum industry considerations to financial particulars of a single project, imaging options may vary between exploration, appraisal, and development phases within a field. For example, during the exploration phase a company may not only want to prove the existence of hydrocarbon but also run image logs to de-risk reservoir quality and refine initial depositional models. Appraisal programs, on the other hand, may be focused on obtaining images to calibrate with a coring program. Once it is time to transition to development, high quality image log interpretations can help inform well completions, drilling trajectories, and production optimization. Each phase within the lifecycle of a field may present opportunities to vary which type of borehole image log (LWD or pad-based tools) is acquired to help answer specific questions. Operators must consider logging cost vs. what the data can be used for and, of course, always be prepared to pivot.

SESSION FOUR: CLASSIFICATION & DELIVERABLES

A Trice Revival: Descriptive Borehole Image Evaluations Using Contemporary Technologies

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Twenty-seven years ago, Robert Trice introduced a morphological terminology applicable to electrical and acoustic borehole image (BHI) evaluations that was meant to standardize interpretations and facilitate communication between different analysts. Arguably, the significance of an objective and repeatable descriptive nomenclature has grown since then, with the commercialization of a range of BHI devices which now encompass logging-while-drilling density images to multi-frequency wireline electrical images, radar and acoustic logs, and helical visible light photographs or circumferential X-ray computed core tomography images.

Trice's criteria, including trace continuity, image fabric, and petrophysical response, still allow analysts to progress from a series of observable characteristics to the application of geological concepts, but the relevance of the methodology requires reassessment to consider standoff and dielectric effects common in modern electrical technologies and the implications of a non-unique scheme in an era when BHI are more routinely evaluated through automated workflows.

These concepts are explored by presenting outcrop observations from Devonian-aged fluvial sequences at Llansteffan, U.K., and manually-derived, core calibrated BHI interpretations from aeolian and lacustrine carbonate settings. In each case, the evaluation workflow advanced by (1) using descriptive field methodologies or (2) the log-based observational criteria defined by Trice to distinguish between the primary depositional fabrics, facies architecture, structure, and the interpreted environment of deposition.

Results confirm the suitability of Trice's methodology and demonstrate that the non-unique morphological classification scheme continues to provide a useful framework for multi-disciplinary well evaluations. Importantly, direct observations derived using different petrophysical techniques from logs or core are appropriate for (1) automated classification workflows that do not force geological concepts (2) knowledge transfer, and (3) the eventual evaluation of borehole-scale geology that can be upscaled to the environment of deposition and used to constrain subsurface uncertainty in static and dynamic reservoir models.

Keynote: Use and interpretation of borehole image logs in geothermal systems: geology, alteration, structures, borehole conditions, and stress

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Tracking characteristics of permeable zones and unusual drilling-induced features in New Zealand high-temperature geothermal reservoirs with borehole images

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Geothermal energy in Aotearoa New Zealand generates over 20% of the country's electricity and direct heat, with expansion planned. Most geothermal electricity is produced in Te Ahi Tupua, a densely faulted rift within the active volcanic arc of the Taupō Volcanic Zone. Geothermal reservoirs are typically hotter than 250°C and naturally fractured, however permeability remains complex and challenging to target for production and reinjection.

Interpretation of borehole images acquired since 2010, together with pressure, temperature and spinner velocity (PTS) logs, indicates that most permeable zones are controlled by fractures, although these exhibit varied characteristics. We present examples from volcanic and metamorphic basement reservoirs. At the Tauhara Geothermal Field, major permeable zones are often associated with reservoir-scale faults or fracture clusters. Minor permeable zones are linked to fracture clusters or fractures distributed over broader intervals. In some minor feed zones, absence of visible fractures suggests that fluid flow is not controlled by local fracture networks. Conversely, many fractures with similar characteristics occur outside permeable zones.

Drilling-induced features provide direct constraints on in-situ stress orientations and magnitudes. Cooling during drilling in a normal faulting regime results in numerous drilling-induced tensile and petal-centreline fractures, and few breakouts. In addition, we hypothesise that many unusual features arise from the interactions between drilling processes and complex rock properties, including texture, mechanical anisotropy, natural fractures and veins, fault density, thermal stress, and variations in hydrothermal alteration. These features that require further investigation show promise for refining stress and permeability models critical for drilling stable and productive geothermal wells, key to optimising conventional, superhot and enhanced geothermal systems.

Borehole image interpretation has already improved well targeting strategies during drilling campaigns and refined geothermal system conceptual models. Integrating results with other structural datasets enhances seismic hazard models, thereby improving preparedness for communities and industry.

Engineering applications of Borehole Images: the next 100 years?

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Borehole images have been used extensively within the oil industry for decades, with well-developed workflows aiding interpretation and understand of a range of complex geological problems.

With technology advances and the development of slim hole optical and acoustic televiewers, borehole images are increasingly used within ground investigation and engineering applications. Data from which can reveal in situ stress directions, geomechanical information and provide invaluable insight into geohazard recognition and interpretation.

Despite this, borehole images are often underutilised within engineering applications, due to a lack of understanding and deployment of developed oil industry workflows.

Using data from the Glasgow Geothermal Observatory - a test case for shallow mine geothermal heating, this study demonstrates the use of image logs to better constrain ground models and provide valuable information on fault and fracture characteristics, contamination pathways and void detection; conditions which are difficult to assess using traditional engineering datasets.

Analysis of the borehole image logs reveal the structural dip of the bedding planes, fault and fracture orientations, maximum horizontal stress (SHmax) trends and geomechanical property variations of the rocks encountered. Geohazards are often readily identifiable within the images, with evidence of mine workings and collapse, voids and other man-made features.

This study highlights how data from image logs can better constrain rock mass properties as well as provide vital data to aid in the engineering assessment of anthropogenic and geological hazards. Data which can provide invaluable insight into ground conditions, reducing risk and improving engineering design.

Geological and stress field analysis from WL and LWD borehole image logs – Reservoir characterisation for a geothermal field in Germany

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More than 30 years of exploration established borehole image (BHI) workflows generally relevant for reservoir characterisation independent from the fluid type. Results relate to structural geology, depositional environment, and stress field. Geothermal fluids are typically produced from matrix or vuggy porosity and through fault and fracture zones. BHI analyses locate productive intervals and quantify vuggy and fracture porosity. Drilling-induced fractures and breakout help to constrain the stress tensor, its orientation and magnitudes, vital for optimising well path with respect to drainage/flow and hole stability.

A recent geothermal prospect was explored in S-Germany. With temperatures of >200°C, BHI logging switched from WL in the main hole to LWD in the sidetrack, both measuring electrical resistivity. The analysis of BHI logs revealed several changes of structural dip across rotated fault blocks and a distinct fracture network. It turned out that deformation within the targeted fault zone in terms of bedding tilt is more complex than originally anticipated from seismic. The main well drilled into the major fault zone and encountered several wide-open faults and fractures. The sidetrack was deviated slightly away from the major fault zone and revealed a smaller degree of deformation, accommodated by several antithetic faults. Fracture zones formed after the major tilting event(s) and could be linked to the recent stress field.

To limit mud losses the mud weight was keep as low as possible, leading to the formation of breakout, however drilling-induced fractures formed as well. These provide an excellent data base for constraining the stress tensor, keeping in mind the impact of drilling operations. In the shallower parts of the reservoir the vertical stress dominates. Downwards, within stiffer formations, the stress regime changes towards transitional strike-slip. The changes in stress magnitudes are associated with a systematic rotation of principal stress axes across fault zones.

Facies-Based 3D Modeling of Boron Mineralization in Colemanite Deposits Using Lateral Well Petrophysical and Image Logs

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Boron is a critically important metal having several unique properties that sometimes occurs in evaporite minerals. Boron mineralization in colemanite deposits is often associated with nodular facies within evaporitic–lacustrine sequences, yet their lateral continuity and spatial distribution remain difficult to predict in subsurface exploration. In this study, we present a workflow integrating high-resolution image log interpretation from a lateral well with petrophysical analysis and 3D facies modeling to constrain the occurrence of Boron-bearing intervals.

For petrophysical interpretation, an exotic suite of minerals identified in drill cuttings was incorporated into a simultaneous multimineral solver based on modeled endpoint responses, with an aim to identify colemanite-bearing intervals. Results were then compared to textural facies extracted directly from the high-definition borehole images.

Based on the borehole images, facies were classified into three main groups: nodular, laminated, and massive. The nodular facies, characterized by irregular resistive textures, was identified as the primary Boron host by comparing to the petrophysical analysis.

The resulting model delineates discrete nodular pods and stratiform layers within the colemanite sequence, providing predictive insight into Boron prospectivity beyond the wellbore. It captures the distribution, continuity, and clustering of nodular units and gives clear stratigraphic context to the placement of the wellbore. This facies-based approach reduces uncertainty in targeting mineralized zones, supports volumetric resource estimation, and improves drilling efficiency in subsequent wells.

This case study highlights the value of an efficient data-gathering platform for the evaluation of lateral wells for industrial mineral exploration in a complex geologic environment. It specifically demonstrates the value of integrating image-log facies interpretation with advanced petrophysical techniques and 3D geostatistical modeling as a robust exploration tool for boron exploration. Although this specific workflow is designed for boron, its’ main components are broadly applicable to other heterogeneous deposits where mineralization is facies-controlled and core coverage is limited.

Integrated High-Resolution Characterization of Clay-Rich Formations Using Borehole Imaging, Core Data, and Machine Learning: Applications in Switzerland's Exploration for a Deep Geological Repository for Radioactive Waste

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The radioactive waste of Switzerland's nuclear power plants, research and medical applications will be deposited in a deep geological repository. The identification of a safe disposal site in Switzerland is governed by the Swiss Sectoral Plan for Deep Geological Repositories, which requires a comprehensive characterization of the subsurface, including structural architecture, formation composition and characteristics. The Mid-Jurassic Opalinus Clay in northern Switzerland has been selected as host rock and its over- and underlying confining units add additional safety barriers for the safe storage of radioactive waste. For the assessment and selection of a suitable site, 9 scientific boreholes were drilled and >6 km of core retrieved, complemented by extensive laboratory analyses alongside a full suite of wireline logs and borehole imaging data.

Despite such a comprehensive suite of materials and their datasets, a major challenge, in particular in clay-rich units and formations such as the Opalinus Clay, is the characterization of thin beds at centimetric scale, which cannot be resolved by conventional wireline logs due to their limited vertical resolution. As a consequence, an integrated workflow combing borehole imaging tools with Multi-Sensor Core Logger measurements and standard petrophysical logs has been developed to generate high-resolution petrophysical property curves. The novel workflow successfully characterizes bed heterogeneities down to only 2-3 cm which are generally not resolved by standard-resolution interpretations. Validation against core properties, such as XRD mineralogy and porosity, shows very good agreement, although calibration accuracy is influenced by depth-matching uncertainties and sampling-scale effects.

To further enhance petrophysical characterization for high resolution profiles, an image-based approach being developed using core images, FMI and computer vision. A transfer learning strategy based on convolutional neural networks was employed, first trained for lithological classification and subsequently fine-tuned for mineralogical regression. Preliminary results already demonstrate robust prediction of mineralogical trends and highlight the potential of image-based methods for complementing efficiently traditional core and log analysis workflows.

Both approaches demonstrate the potential of borehole image data to enhance conventional borehole data interpretation methodologies for detailed rock characterization.

SESSION SIX: STRUCTURE

The use of muon tomography in geological imaging

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Muon radiography, ("muography") is a technique which exploits the behaviour of cosmic ray muons generated in the upper atmosphere as they pass through underground structures. Muons are an abundant and free source of highly-penetrating particles which lose energy when interacting with materials, enabling non-invasive and non-contact imaging similar to medical x-ray computed tomography.

The presentation will focus on two topics relevant to this meeting. The first will discuss a project completed in Norway, in 2023 where the world's first application of muography to CCS took place. The instrumentation used in this campaign will be described and a 3D visualisation of the imaged CO2 plume will be presented alongside a comparison with co-deployed 4D seismic imaging.

Secondly, a programme of simulations addressing the application of muography to safeguarding of geological repositories for long-term nuclear waste disposal will be discussed. These studies combine Monte Carlo simulations with ray-tracing techniques to model muon trajectories, allowing for accurate predictions of detection rates across different geological safety and safeguarding scenarios. Detailed geological data from an analogue nuclear disposal facility - the Grimsel Test site in Switzerland - were used as a framework for the simulations.

Results will be presented from different simulation scenarios which pose potential problems in safety and safeguarding long-term nuclear disposal and storage sites. The scenarios included the determination of unknown voiding and karstic features, the presence of undocumented fault zones and incomplete backfill post emplacement. Whilst simulated in context of nuclear waste emplacement and final disposal the results are of generic relevance to understanding these and similar geological features.

Finally we will summarise the evidence presented that muography offers significant advantages for geological monitoring emphasising potential benefits including non-invasive monitoring, long-term stability assessment, scalable detector deployment and sensitivity to changes in overburden density as a result of effects such as water ingress.

Sub-seismic faults matter

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Borehole image logs are an integrator log between core-scale analyses and seismic-scale visualizations. Manual fault mapping focuses on large-offset seismic scale faults. Advances in automatic or user-driven fault detection have begun to detail smaller offset fault confidence and should be validated using fault damage zones from image logs to create confidence in the data. An example is a well where seismically no faults were thought to be intersected, where at the image log scale 7 fault zones were identified that could be seen in the seismic, once the data proved they were there.

Structural interpreters often see challenging image log response over structurally complicated intervals. Poor response is due to structural features, drilling challenges, mudcake buildup and more. Specific steps include quality-control, understanding the various petrophysics in the tools, resolution, processing, and ultimately identification of structural picks including travel time, amplitude, conductivity, density, and cementation uniquely related to the dataset available. Multiple user disciplines need to be involved; skillsets take time to develop to determine what the data is saying. Faults seen along with borehole shape changes between downlog and uplog runs highlight the potential active nature of these faults in the subsurface. This can be flagged as a risk for wellbore collapse or shearing which leads to reduced access to the reservoir.

Integrating all three scales over the lifetime of a field is unique every time. Exploration to production drilling campaigns vary, so core, image log tool physics, tool resolution, mud type, seismic line density, and quality vary. Need for rapid decision making vs. the length of time for a full image log analysis is very different. Integrating learnings and long-term dynamic response is a desirable end goal. The key takeaway is that wells are expensive so if you have image log data - it needs to be used.

Multiscale analysis of the Paleocene to Oligocene sequences in the central part of the Llanos Basin in Colombia

Allan Cifuentes*[1]*, *Wilson Gil, Alexis Rosero and Lenin Bueno*

1LPS

In the central part of the Llanos Basin in Colombia, a multiscale characterization was conducted of the primary Paleocene and Oligocene reservoirs and secondary Upper Cretaceous reservoirs tested in recent discoveries in the Toritos, Saltador, and Zorzal fields, which have a time-to-market of just days, maximizing the acquisition of conventional LWD and borehole images (BHI), as well as improving the positioning of new wells.

Flow units and their petrophysical properties are controlled by the presence of NNE-SSW paleohighs and their relationship to multiple migration events of the foreland basin flexure, which led to the reactivation of ancient structures and the coexistence of different sedimentary environments in this geographic area, defined through the correlation between core and BHI, where physical and biogenic sedimentary structures, facies associations, and paleocurrent are identified as kinematic indicators of drainage evolution, which are directly proportional to the distribution of tractive facies and the geometry of geobodies.

Structural domain of the Paleocene reservoir is preserved in the areas adjacent to the overlying incised valleys, consistent with the structural dip identified in BHI, despite the absence of the Paleocene seismic reflector below the incision. A direct drilling of this reflector would generate a reservoir contour map with structural lows beneath the incised valleys, which would lead to the omission of possible truncation points and even part of the reservoir.

Finally, conventional logs at the Paleocene-Cretaceous boundary suggest the presence of a single massive sand. However, BHI analysis allowed for the identification of the juxtaposition of two distinct levels: the Upper Cretaceous sands exhibit well-developed porosity and high bioturbation, but with low pore connectivity; in contrast, the Paleocene sands show better connectivity as porosity increases. From a petrophysical standpoint, this corresponds to two separate flow units, with an LKO reaching the unconformity boundary that was previously interpreted as OWC.

LWD image data – the great under-used resource

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Logging-while-drilling (LWD) imaging tools are commonly run in deviated wells for geosteering purposes; often they are then disregarded because of a perception that they are not 'high resolution' enough to warrant further interpretation. This neglects a potentially rich, already-purchased, data source for geological understanding of the sub-surface that may have been gathered routinely across most wells in an asset.

Even lower resolution LWD data such as density images are orders of magnitude more detailed than seismic. They may be acquired over several kilometres per well. When they are integrated between different wells and, better yet, with contextual data such as seismic or deep resistivity curtains, the combination significantly increases their value for constraining geometric relationships across well to field scales and hence reduce uncertainty within geomodels.

Furthermore, technological advances in LWD imaging mean that high resolution acoustic and resistivity tools are now commonly available and can provide extremely detailed geological information for formation evaluation and understanding reservoir behaviour. These can be interpreted in their own right, but they can also (as with wireline images) be used to guide the interpretation of lower resolution images in offset wells, by providing a reference against which less well defined textures can be judged. This can allow some aspects of formation character to be assessed using the lower resolution images and trends to be analysed on a field scale where multiple wells can be integrated.

Example case studies will be presented from the Norwegian Continental Shelf, where LWD images have been integrated between wells and with complimentary data to assist with deciphering the large scale geometry of lithological bodies, and where high resolution LWD acoustic image data were used to semi-quantitively analyse features which could affect reservoir performance, or inform drilling and completion strategies in often complex reservoir situations.

Segmented borehole image log evaluations provide guiding model parameters: a Wilcox Formation example, Gulf of America

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We present a borehole image (BHI) workflow to characterize intra-lobe mudstone architecture within Paleocene Lower Wilcox basin-floor lobe turbidites, southern Alaminos Canyon, Gulf of America, where subsurface control is limited to a small cluster of wells. Mudstone spatial distribution and stacking patterns are used to assess vertical baffle continuity and distinguish intra- from interlobe-scale elements.

First, we analyze BHI-derived bed-boundary orientations to determine original stratigraphic bed geometry. Aggregated across many beds, these measurements constrain lobe-scale depositional orientation, yielding a data-driven stratigraphic scaffolding that parameterizes process-based geomorphic forward simulations of turbidite channel-mouth lobes scaled to the Lower Wilcox system — providing the geometric framework within which mudstone architecture is evaluated.

Second, we use image-derived electrofacies to isolate mudstone intervals and, combined with openhole logs and core, build a statistical distribution of mudstone thicknesses. This distribution, combined with literature analog constraints on mudstone geometries and forward-model output, is used to generate geologically reasonable mudstone architecture scenarios. Scenario testing provides quantitative estimates of intra-lobe mudstone architecture — intervals not implicitly characterized by the asset. It also better constrains the true lateral scale of inter-lobe mudstones, which are explicitly characterized, improving confidence in their areal extent.

Together, these two BHI-driven workflows demonstrate how image log data can extend well beyond structural interpretation to inform depositional geometry, stratigraphic architecture, and dynamic modeling in data-sparse deepwater settings.

Augmentation, automation, and beyond: design considerations for leveraging computer vision in borehole image processing

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This talk provides practical guidance for the implementation of computer vision (CV) models using examples from borehole televiewer data processing. While the underlying mathematics behind CV systems are complex, how these models behave is not. They rely on training data to learn to recognize patterns in ways that are broadly analogous to how humans learn. Structura, a televiewer processing platform developed for mining and geotechnical applications serves as the running example. Structura combines several CV applications: segmentation models for fracture and structural picking on optical and acoustic televiewer (OTV/ATV) imagery, classification models for structure type, and a regression model that predicts rock strength grades; the design trade-offs behind each will be used to ground the discussion.

The primary advantage of CV workflows is their ability to recognize patterns across varying inputs. Borehole wall conditions and geological settings vary widely. To perform successfully in these variable conditions, CV models require large, diverse, and representative training datasets to learn from. These models are not omniscient; like humans, they require context to make their predictions. As such, the input data for CV require thoughtful and deliberate design.

Some context cannot be encoded into the input data (such as geological unit or borehole scale information). Robust workflows can pair CV models with post-processing that reintroduces that context, such as reinforcing individual bedding classifications by testing for parallel fabric across an interval. When repetitive processing tasks can be automated, more time can be spent thinking critically about the information being presented. Additionally, machine learning systems allow for entirely new analytical capabilities, such as predicting rock strength grades from acoustic televiewer data.

POSTER PRESENTATIONS

Deep Learning for Automatic Facies Identification of Borehole Image Logs in Carbonate Environments

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Characterizing and predicting sub-seismic heterogeneity in carbonate reservoirs remains challenging due to the complex interplay of depositional, diagenetic, and structural processes that govern reservoir quality. Borehole image (BHI) logs provide valuable insights into this heterogeneity by enabling the identification of distinct facies, particularly when calibrated with core images. However, their interpretation has traditionally relied on time-consuming manual approaches that are costly and inherently subjective. This often results in only a small fraction of available BHI data being analyzed, leaving substantial information underutilized.

To address these challenges, a workflow based on a supervised deep learning approach is developed for automated facies recognition from BHIs, enabling rapid, consistent, and systematic evaluation of large image datasets.

The workflow comprises: (1) definition of a scale-consistent, texture-based facies scheme (e.g., massive, laminated, vuggy, disrupted) that preserves the intent of core-based descriptions while remaining resolvable at BHI resolution, (2) creation of a curated, representative training dataset of BHI images paired with facies labels generated in a dedicated labelling application, supporting both full-coverage and pad-based images and calibrated with core images where possible; (3) data augmentation using synthetically generated BHIs to improve model robustness; (4) supervised training and validation of the deep-learning model using BHI segments of a given thickness; and (5) development of an application that automatically preprocess new BHI images and applies the deep-learning model to generate first-pass interpretations along depth in previously uninterpreted intervals. The application allows geoscientists to quality control, edit, and export the finalized facies logs for integration in other software platforms.

The workflow has been successfully applied in multiple studies, enabling more consistent interpretations and faster turnaround time across a range of BHI types and geological settings. The quality-controlled BHI facies interpretation improved understanding of reservoir quality and heterogeneity, demonstrating the value of the approach for carbonate reservoir characterization.

Challenges of Fracture and Foliation Interpretation from ultrasonic and micro resistivity images in Large-Diameter Geothermal Wells

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Challenges of Fracture and Foliation Interpretation from ultrasonic and micro resistivity images in Large Diameter Geothermal Wells
Structural characterization in high temperature geothermal wells is challenging due to extreme downhole conditions, heterogeneous lithologies, and the presence of multiple foliation generations with varying orientations and overprinting relationships. These complexities make it difficult to distinguish true geological fabrics from drilling enhanced features. This study evaluates the performance of ultrasonic and micro resistivity wireline imaging acquired in a 12.25 inch geothermal borehole to improve fracture and foliation interpretation in a highly fractured reservoir.
The large borehole diameter and irregular wellbore geometry reduce image resolution and tool to formation contact, complicating the identification of natural fractures, foliation planes, drilling induced tensile fractures (DITFs), and breakouts. Ultrasonic imaging provides full azimuth coverage but lacks the resolution needed for fine scale features, while micro resistivity imaging offers higher detail but suffers from limited pad contact and partial circumferential coverage. By integrating both imaging datasets with caliper measurements, we enhance confidence in identifying structural features and stress related failures. The insights gained support improved targeting of permeable fracture zones and better reservoir connectivity in future well placement.

Increasing Operational Efficiency in Micro-fracking Decisions through Automated Breakout Detection from Ultrasonic Borehole Images; A Machine Learning-Based Approach

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Accurate estimation of in-situ stress orientation is a critical requirement for the effective design and execution of micro-fracturing operations. Borehole breakouts, which develop as stress-induced compressive failures of the borehole wall, are widely recognized as reliable indicators of the horizontal stress direction. Ultrasonic borehole imaging tools provide high-resolution measurements that enable the identification of these features. However, conventional breakout interpretation from ultrasonic images is typically performed manually, making the process time-consuming and challenging to scale across large datasets and multiple wells. These limitations hinder efficient application of breakout analysis within operational workflows.

This study presents a machine learning–based workflow for automated breakout detection and azimuth estimation from ultrasonic borehole images. The proposed approach aims to improve operational efficiency and ensure repeatable and consistent breakout interpretation while preserving geological and geomechanical relevance. By automating breakout identification and orientation analysis, the workflow provides a practical and reliable input for stress characterization and micro-fracturing decision-making.

Borehole Images to Fracture Intelligence: A GenAI-Based Quicklook Reporting Workflow

Srijita Das[1]

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Borehole image logs provide critical insights into subsurface geomechanics by identifying bedding dips, natural fractures, drilling-induced fractures, and borehole breakouts. These features help determine the orientation of the present-day stress regime, particularly the maximum horizontal stress (SHmax). In fractured reservoirs, the relationship between fracture strike direction and SHmax orientation offers a first-order understanding of likely fracture propagation pathways during hydraulic fracturing operations. Zones where natural fractures are favorably oriented with respect to the in-situ stress field are more likely to enhance fracture connectivity, permeability, and stimulation efficiency.

This project proposes an AI-assisted workflow that integrates borehole image interpretation, dip analysis, and stress orientation data to generate automated "fracture propagation quality zones" along the wellbore. Using predefined geological and geomechanical logic, the system assigns QC flags ranging from high fracture propagation potential to poor propagation zones. Parameters such as fracture density, fracture orientation, breakout-induced stress direction, and structural dip consistency are combined into a rule-based scoring model.

A Generative AI interface enables the interpreter to interact with the workflow using natural language instead of complex coding or software scripting. By simply providing borehole image data (LAS/XML), processed interpretations, and reporting templates, the system can automatically generate quick-look reports summarizing stress orientation, fracture behavior, sweet spots, and completion-quality intervals. The workflow aims to significantly reduce interpretation time while maintaining consistency and scalability across assets.

This concept has applications in both conventional and unconventional reservoirs, particularly for rapid reservoir characterization, hydraulic fracturing planning, well placement optimization, and geomechanical screening during field development studies.

Borehole Images: The High-Resolution Lens into Unconventional Reservoir Complexity

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Borehole image logging has become one of the most powerful reservoir characterization tools in the unconventional energy industry, particularly in shale plays such as the Permian Basin, Eagle Ford, and Vaca Muerta formations. Unlike conventional wireline logs that provide averaged formation responses, borehole images deliver high-resolution, formation-scale details that allow direct visualization of geological and geomechanical features critical for reservoir development and completion design.

Modern BHI interpretation enables detailed fracture complexity characterization by identifying natural fractures, induced fractures, fracture intensity, orientation, and connectivity. These parameters are essential for understanding hydraulic fracture behavior and optimizing stimulation strategies. In addition, BHI-derived sand count and laminated facies identification provide a more accurate understanding of reservoir quality and brittleness distribution compared to conventional petrophysical methods.

Dip analysis generated from borehole images offers structurally meaningful and visually consumable interpretations not only for geologists but also for drilling and completion engineers, improving interdisciplinary decision-making. Furthermore, advanced workflows integrating borehole image data with acoustic and density measurements enable the generation of high-resolution UCS (Unconfined Compressive Strength) images and continuous mechanical property profiling along the wellbore. This provides a level of vertical detail and heterogeneity mapping that cannot be achieved using standard logs alone.

The integration of geological textures, structural interpretation, and geomechanical properties from BHI creates a comprehensive framework for sweet-spot identification, well placement optimization, stage design, and completion efficiency evaluation. As unconventional reservoirs become increasingly complex, borehole imaging continues to bridge the gap between geology, geomechanics, and production engineering by delivering actionable insights at a resolution unmatched by any other subsurface logging technology.