Hydraulic Fracture Aperture Determination Using Integration of Stoneley Wave “Pressure Testing” with Electrical Borehole Scans

Brian Hornby
Hornby Geophysical

Brian Hornby leads efforts at Hornby Geophysical Services which focuses on consulting and development of proprietary products for downhole acoustic and elastic wave measurements. Brian achieved his Ph.D. degree at the University of Cambridge in 1995 and has over 40 years’ experience in the industry, beginning with field engineer and then moving to R&D roles. Brian started his career in 1977 as a field engineer with Schlumberger, ending up with research scientist positions in Schlumberger-Doll Research and Schlumberger Cambridge Research labs where he focused on advanced solutions for borehole sonic measurements and Rock Physics solutions. Next in 1996 Brian joined ARCO and then BP with the merger where he was a Senior Geophysical Advisor with a focus on borehole geophysics, including 3D VSP imaging and reservoir monitoring using permanent borehole sensors, including DAS (Distributed Acoustic Sensing). After BP Brian joined Halliburton in 2016 as Chief Scientific Advisor for Acoustics where he led efforts focused on advanced borehole sonic answer products, leaving Halliburton in 2020. Brian’s work experience in both Oil Companies and Oil Service Companies has given him the background and experience needed to successfully drive new technologies to a place where commercial success is achieved.

Abstract

I present a workflow that combines electrical borehole scans and borehole sonic Stoneley wave analysis to accurately estimate the width of hydraulic fractures and provide insights into their extent and connectivity. Electrical borehole scans serve as the primary source of information for fractures intersecting the borehole. They deliver high vertical resolution and provide quantitative data on fracture orientation and morphology. However, these scans only measure at the borehole wall and cannot distinguish between fractures that extend beyond the borehole and those that end near it. On the other hand, Stoneley waves function like low-frequency pressure pulses that test the fractures, determining whether they extend from or terminate near the borehole. A limitation is that the low-frequency Stoneley waves used for fracture evaluation have a lower vertical resolution along the borehole, which means closely spaced fractures may contribute to each Stoneley reflection response. Additionally, significant changes in bedding slowness or borehole enlargements can lead to false positives in Stoneley wave fracture evaluation. To overcome these limitations, we first identify fracture locations and aperture at the borehole wall using borehole image scan analysis, then probe them with low-frequency Stoneley waves. A series of steps decides whether the fracture is conductive away from the well, and whether the electrical borehole scan or Stoneley wave estimated fracture width, or both are used in the result. Anomalous results from either measurement are thrown out. Data collected in well 58-32 in DOE’s FORGE Geothermal test site was examined using this method. The comparison of results was informative – showing in large sections an encouraging overlay of both estimated fracture widths. This suggests the estimated effective width is correct and also that the fractures extend some distance away from the well. Differences were seen with some natural fractures and more commonly drilling induced fractures, the Stoneley wave estimate fracture width was lower, indicating the fractures truncate close to the borehole wall. Other differences were attributed to anomalous results by either technique; there the anomalous result was simply dropped. These learnings led to an improved workflow for determining robust hydraulic fracture width.

Case Study: Integrated Analysis of Electrical Image and Acoustic Stoneley Reflectivity for Assessment of Fracture Fluid Conductance

Eglee Lopez
Halliburton

Eglee Lopez received a B.Sc. in Petroleum Engineering from Universidad de Oriente in Venezuela. She entered the oilfield as a Formation Evaluation Engineer. For the past 23 years she has been working with Open and Cased Hole processing & interpretation and currently working as a Petrophysicists for the Geoscience and Production (G&P) Center of Excellence in Halliburton.

Abstract
Assessment of fluid conductivity of fractures in interbedded formation types is challenging for resistivity imagers due to non-unique electrical conductivities of fluid and fracture fill, and due to unseen barriers along the fracture face that are beyond the depth of image. For applications such as water disposal, hydrocarbon production, geothermal fluid exchange, or carbon dioxide storage, it is important for image statistics to not only identify the position, size, and orientation of fractures that intersect the wellbore, but also assess the fracture's fluid conductivity. This case study applies a multi-sensor workflow that includes an acoustic 'pressure' wave to assess fracture fluid conductivity in a west Texas well filled with water-based mud. Electrical borehole image logs may misinterpret fractures as open fractures since the high formation resistivity tends to cause borehole images to highlight any conductive materials (such as fine clays) that may be present within the fractures and vugs, which cause potential ambiguity with similar readings from open fractures filled with brine. Borehole image logs can identify fracture features with reasonable confidence as they appear at the borehole wall, but asperities along the fracture face beyond the depth of image may exist that impede fluid flow. Fracture conductivity can only be verified with a pressure test and such a test can be performed with a sonic logging tool that can excite a low frequency (below 1 kHz) monopole (Stoneley) wave mode. In a well drilled with WBM in this field, a micro-resistivity borehole imager and a sonic tool were logged. The Stoneley wave mode 'reflections' are analyzed for their frequency content and inverted to conductivity. The acoustic analysis also has its ambiguities, as the open fractures that connect deep into the formation produce secondary Stoneley waves which appear similar to reflected Stoneley waves caused by near-wellbore acoustic impedance changes (bedding, washouts, concretions). Combined with image analysis, the truly open natural fractures can be characterized and calibrated within a formation while ignoring false or ambiguous signals from individual sensors.

Imaging the Vicinity of a Sub-Horizontal (SH) Drain into the Carbonate Dogger Geothermal Aquifer Using the 3D Far Field (3DFF) Processing of a Dipole Sonic Array Dataset; Results and Perspectives.

Charles Naville
IFPEN

Charles Naville Background: Engineer, Polytechnique-Paris 1973 & ENSPM
Geophysicist in CGG 1977-1989, field assignments in Gabon, USSR, USA, France,
Geophysicist R&D in IFPEN-France, 1990-present.
Surface and borehole seismic acquisition & processing, sonic; method testing
https://www.researchgate.net/profile/Charles-Naville

Abstract
Initially, the dipole sonic array tool was run into the Grigny-GGR5-SH Open Hole (OH) drain to map the reflecting interfaces within the Dogger aquifer and to further improve the geometrical knowledge of the laterally variable porous-permeable geological bodies below and above the sub-horizontal drain. The dipole array sonic tool was pulled to hole bottom by means of a borehole tractor, using a standard wireline cable. Additionally, the 3D FF technique was tested within the lower 200 m cemented Cased Hole in order to assess the sonic imaging quality as a means of seismic prediction below the deviated hole section right before the landing point, so as to inform the drillers about the depth of the first porous beds below top Dogger: such information would therefore eliminate any need for a pilot hole in future geothermal drilling projects in the Dogger reservoir and allow the drillers to plan for an optimal landing angle of the well trajectory impacting the top of Dogger reservoir. In order to fully assess the depth and thickness of the targeted porous beds in the GGR5 borehole, after setting the production casing at the top Dogger, a pilot hole with 65° deviation was first drilled into the Dogger aquifer, then logged and plugged before drilling the 800m sub-horizontal drain.

Running the dipole array sonic tool in and out of the GGR5-SH drain revealed 3 insights:

1. Sh-Sh 3D FF dipole sonic images exhibit clear, 2.5 kHz dominant frequency reflections up to a 35m distance away from the sub-horizontal drain making an angle of at least 3 degrees (to be refined) with the general geological layering.
2. Sh-Sh reflection images cannot be obtained in the GGR5 cemented cased hole section, despite the good cementation generally existing in the 200 m right above casing shoe. Therefore, if the drillers wish to obtain any image prediction of intra-Dogger reservoir BEFORE engaging into the sub-horizontal drilling section, a 3DFF dipole sonic run MUST be carried out in the OH deviated section BEFORE setting the production casing.
3. Sh-Sh reflection images of layered geological contrasts cannot be obtained where the SH drain is parallel to the layering, a well-known unsolvable seismic processing challenge: interfering parallel lines of reflected signals originating either from above or below the borehole, or from parallel

direct arrivals lines, cannot be (an ancient “Euclidian” blockage!). However, successive oblique reflections clearly appear after direct arrival and horizontal reflection filtering, evidencing prograding geo-bodies (Figure 1). Vincent et al. recently identified giant subaqueous oolitic and bioclastic dune developed during the regressive phase of the third order sequence Bt3 within the Dogger outcrops of the SE Paris Basin. These subaqueous dunes were so far unknown in the center of the Paris basin where the geothermal drilling takes place; in the quarries, the Bt3 dunes are about 10-15m in height, dipping 10-20° towards NE. The observed oblique reflecting progradations evidenced in the GGR5-SH drain are only 5m high, dipping 9° to NE, and develop in the following Bt4 sequence The 3D FF sonic images cannot establish if the observed oblique reflections would originate from above or from below the horizontal part of the GGR5-SH drain; in the present case, the geological knowledge allows to determine that these dune reflections plausibly originate from above the horizontal drain. The formation material constituting the subaqueous dunes represent potentially porous and permeable bodies of geothermal industrial interest, which internal heterogeneities can be easily resolved by the analysis of outcrop equivalents.

The presented abstract results from the multidisciplinary collaboration of several authors: 3DFF Signal processors from SLB-Netherland, Drillers of GPC-IP/GEOFLUID-France, and various Geologists in IFPEN and Cambridge carbonate-UK

Successful Avoidance of Production Hazards, from Sub-Seismic Faults, on a Multiple Horizontal Well Project in the Permian Basin

Derek Buster
ProdiGeology, Inc.

Derek Buster is the President and CEO of ProdiGeology, Inc., an investment banking advisory company specializing in North American unconventional resources. He was the Petrophysical Advisor for Blackstone Energy Partners portfolio investment at Guidon Energy & Swallowtail Royalties Holdings Corporation. Prior to Guidon, he was a Petrophysicist at Stone Energy Corporation and Apache Corporation working North American shale in the Appalachian Basin, Permian Basin, Alberta Basin, Eagle Ford Basin and several frontier exploration projects in lessor known shale basins. He was a field engineer and geoscientist with Schlumberger & Baker Hughes in the Gulf of Mexico and North America land. He has co-authored several SPE and SPWLA publications related to delivering significant cost savings to operators through leveraging technology as a first adopter.

Abstract
For this case study, a Permian basin operator deployed wireline dipole acoustic shear wave imaging through five stacked cased hole wells to determine the extent and orientation of sub-seismic, water bearing faults prior to completing eight closely spaced horizontal wells. Operator encountered continuous and uncontrollable water flows throughout drilling and casing of the first horizontal well on the multi-well pad. To minimize the risk on $50 million dollars in capital and potential long-term operating expenses associated with excessive water production, cased hole logs were acquired in four additional horizontal wells off-line operations. Acoustic log data was recorded in five of the eight wells from two adjacent drilling pads. Reflected geologic features cutting across these wellbores were correlated with drill breaks, gas influxes, and changes in drilling mud properties which helped identify the geohazard connecting the wells to this large water bearing fault. The faulted zones were left uncompleted and production results indicates the study wells performance exceeded that of neighboring wells in the field on a per completed lateral foot basis. Waveform acquisition was extended in time to expand detection radius away from the wellbore. Advanced processing was performed to bring out acoustic reflections several tens of feet away from the wellbore. Images were exported in orthogonal planes and viewed in earth coordinates to correlate reflective features, in a 3D visualization space, between the adjacent boreholes. Several important observations and conclusions are drawn from this study. Cement quality directly impacts formation wave coupling on monopole data, the lower frequency dipole source did not generate significant casing ring, and generated quality images through intervals with poor cement bond. Direct logging measurement methods resolve observations on drilling reports, and indirect seismic methods lack the resolution required to guide an engineered completion design. Smaller, sub-seismic features are difficult to detect and cause significant operational issues. Operators can leverage higher resolution log data to identify geologic events not resolved by surface seismic data. Deep acoustic wave imaging presents a unique post-drill technology to interrogate, in either open or cased hole condition, the extent of intersecting and non-intersecting geological features proximal to the wellbore. Close well spacing may benefit total recovery, however, a single fault network can impact several wells, thus, geohazard risk is compounded in tight spacing developments. Many operators avoid open hole evaluation services due to the rig time costs and conveyance risks in horizontal sections. These risks are minimized by deploying

acoustic tools in a cased hole environment. Wireline tools can be rigged up from a crane and deployed through the horizontal section on a wireline tractor. In Drilled but Uncompleted (DUC) stage of wells, the casing inside is clean and operational risk is greatly reduced. The offline operation eliminates significant standby costs of drilling rig or fracturing fleet.

Use of Acoustic Far-Field and Borehole Imaging in Reservoir Evaluation and Hydraulic Stimulation Evaluation

Yvegeniy Karpekin
SLB

Yevgeniy Karpekin currently works as Petrophysics and Acoustic Domain Expert in SLB Engineering Center in Sugar Land. He has been with Company for the last 26 years. Started his career as Wireline Field engineer in North Sea, then taking different technical and managerial positions in Wireline and Data and Consulting Services. Last 11 before present assignment worked as Petrophysics and Acoustics Domain Champion in Indonesia, Russia and Central Asia countries. Holds master degree in Geology and Geophysics from Moscow State University.

Abstract
Natural fractures and reservoir structure at a well-scale are studied using high-resolution borehole imaging data and other log information. Abundance of different elements identified on the images complicates the analysis and masks truly prolific fractures. Acoustic far-field imaging data adds additional dimension into the analysis – distance away from a borehole up to 100ft. Tracing fractures that cross a borehole and extend away to a few tens of feet makes a clear filter of prominent and therefore permeable fractures during the interpretation. Two methods complement each other where borehole imaging ensures the accuracy of azimuthal and dip information of fine-scale fractures at borehole intersection, while the acoustic far-field imaging is blind to borehole vicinity and best sees the reflectors starting from several feet away. This feature allows to identify permeable fractures that are plugged by LCM material during drilling and require cleaning and stimulation to achieve optimal well performance in fractured reservoirs. In horizontal wells, acoustic far-field imaging allows to trace several bed-boundaries within a reservoir with high definition compared to a surface seismic. In addition to faults and fractures evaluation, tracing bed-boundaries along horizontal section of adjacent wells and wells of a next pad drilling helps to control position of important structural markers and improve accuracy of reservoir model. Geometric evaluation of hydraulic stimulation of reservoirs is usually limited to vertical and horizontal wells. In the first case, hydraulic fractures cause anisotropic behavior of shear wave log that is analyzed to infer the height and azimuth of a fracture plane. In horizontal wells, micro-seismic technique is used to evaluate stimulated volume. Far-field sonic imaging bridges a gap between these two scenarios in deviated wells and allows to see the vertical extent and azimuth of a vertical hydraulic fracture that extends away from an inclined borehole. This method features the most accurate and visually intuitive interpretation among the different techniques in use today for hydraulic stimulation of a reservoir. We will present different case studies along these subjects and discuss technical details of processing and interpretation methods used to produce those answers.

Integration of Borehole and Acoustic Imaging Improves Trajectories to Increase Production in Lateral Well Campaign

Luis Mendoza
SLB

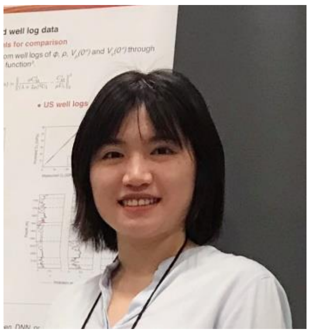
Luis Mendoza got his Geophysics bachelor degree in 2010 from Instituto Politecnico Nacional in Mexico City . He joined SLB in 2011 as Petrophysicist Jr., he developed his career in the measurements processing and interpretation from wireline tools. He got his SLB senior petrophysics nomination in 2021 and currently he works as petrophysics associated domain champion for Mexico and Central America.

Abstract

Production performance in tight carbonate reservoirs depend greatly on the presence of natural fractures, they significantly impact permeability of the reservoir improving fluid flow to the subsurface. The area of study, discovered in 1920's, is located northeastern onshore Mexico, where many long-history production fields are located. In this cretaceous low porosity carbonate depleated reservoir in the Tampico-Misantla basin the impregnated thicknesses ranges around 150 meters; therefore, a well trajectory intersecting as many fractures as possible is the best development strategy. Typically, fracture characterization was performed well-centric in a vertical pilot well, by integrating borehole images with conventional Stoneley waveform reflections and acoustic anisotropy analyses, however the results are limited to only few centimeters into the formation. A novel acoustic imaging identifies dip and azimuth deep into the formation for reflectors created by acoustic impedance contrast. The technique applies similar-to-seismic waveform filters, a semi-automatic time pick and event localization by combining ray tracing with 3D slowness time coherency analysis taking advantage of the longitudinal and azimuthal receivers of advanced sonic logging tool. The result is a 3D structural map of the reflectors. Additionally, acoustic images provide the appropriate values for migration workflow to be used further in characterization. In this project three vertical wells were strategically located; borehole images and azimuthal acoustic waveforms were acquired. Applying novel acoustic imaging technique structural interpretation and understanding of natural fractures distribution near the borehole wall and far into the reservoir was achieved, mapping fracture distribution up to 40mts around the pilot well even if those fractures were not intercepted by pilot well, resulting in a reservoir-centric field development strategy. Integration of structure and fractures around the borehole combined with the far field acoustic image allowed from a vertical pilot well select the best interval to land the horizontal well to intersect the highest fracture density far from pilot. The fractures in this reservoir at borehole scale are typically layer bound; with the integration of 3D far field sonic imaging the uncertainty of fracture propagation beyond the borehole deep into the reservoir was discarded. Allowing identification of intervals with better lateral continuity fractures to construct the most suitable trajectory for horizontal well design. In addition, this integration of information was used to produce a 3D structural map of the reservoir. As a result of the drilling campaign the field production growth objective for this mature field has been surpassed, being one of the newly horizontal wells the highest field producer.

Enhancing Automatic Facies Classification of Brazilian Pre-salt Acoustic Image Logs with SwinV2-Unet: Leveraging Transfer Learning and Confident Learning

Nan You
Purdue



Nan You recently joined the AI team at Aramco Research Center in Houston in late September. Before that, she worked as a Postdoctoral Researcher in the Department of Earth, Atmospheric, and Planetary Sciences at Purdue University for one and a half years. She earned her Ph.D. degree in Geophysics from the National University of Singapore in 2021. Her main interest lies in developing ML-based interpretation methods for digital rocks, lab measurements, and well logs to enhance reservoir characterization**.**

Abstract
Borehole image logs play a vital role in accurately characterizing hydrocarbon reservoirs by providing critical structural, textural, and lithological information. This is particularly important in heterogeneous and anisotropic carbonate formations, such as those in the Brazilian pre-salt region. Manual interpretation of these complex and diverse image logs remains the industry standard, despite its drawbacks of being time-consuming, laborintensive, subjective, and non-repeatable. Recent advancements in machine learning offer promising solutions for automating the interpretation process. However, previous attempts to train deep neural networks (DNNs) for facies identification have faced difficulties in generalizing to new data due to limited labeled data and the inherent complexity and diversity of image logs. Additionally, human errors in manual labels further hinder the performance of trained models. To address the aforementioned challenges, we propose a series of enhancements to optimize the performance of DNN-based facies classification. First, we adopt a cutting-edge DNN known as SwinV2-Unet (Cao et al., 2023) for depthwise facies classification. This model is a pure Transformer that integrates the advanced shifted-window-based multi-head self-attention mechanisms with the powerful U-Net structure. This combination empowers the SwinV2-Unet to learn local-global semantic features efficiently. Second, we propose a refined training procedure that combines transfer learning and confident learning algorithms. Transfer learning is leveraged to mitigate overfitting, caused by limited labeled data, by utilizing the pre-trained weights of the Swin-Transformer-V2 model from the extensive ImageNet-1k database. Additionally, the confident learning algorithm (Northcutt et al., 2021) is utilized to identify and prune human label errors by estimating the joint distribution between the noisy manual labels and actual labels. Our training workflow encompasses two rounds of training using the k-fold cross-validation algorithm, wherein the labeled dataset is divided into five folds, and each fold serves as the test set in turn during the five iterations. The lengths of the test folds range from 366.6 meters to 374.4 meters.
The detailed training workflow is as follows.

1. Initialize the SwinV2-Unet with the pre-trained SwinV2-T weights from ImageNet-1K in each training session.
2. Train the initial SwinV2-Unet on the noisy manually labeled dataset using k-fold crossvalidation algorithm to get out-of-sample predictions on all samples.

3. Estimate the joint distribution between the noisy labels and the true labels based on out-of-sample predictions and the noisy labels.
4. Rank and prune label errors
5. Train and evaluate the final SwinV2-Unet on the cleaned dataset using k-fold crossvalidation algorithm, providing an unbiased assessment of the DNN's generalizability.

Our approach yields an impressive average accuracy of 89% and an unprecedentedly high macro F1 score of 0.90 for the test folds. This surpasses the 68% classification accuracy and 0.68 macro F1 score obtained by the previous state-of-the-art Facies-Unet (You et al., 2023) under the same conditions. Through an ablation study comparing Facies-Unet and our SwinV2-Unet, with the macro F1 score as the evaluation metric, we investigate the contribution of different operations. The results show that the substitution of U-Net with SwinV2-Unet, the inclusion of transfer learning, and the utilization of confident learning techniques improve the macro F1 score by 0.02, 0.08, and 0.12, respectively. Therefore, the modifications implemented in this study are proven to be highly effective. Furthermore, compared to the manual labeling approach, our final facies classification model exhibits superior performance in terms of efficiency, consistency, and resolution. It also provides reliable predictions for low-quality uncertain image log sections, offering valuable guidance for geologists to make better judgments about the facies. In summary, we have developed a robust end-to-end facies classification model that exhibits high accuracy, efficiency, and generalizability when applied to image logs from the Brazilian pre-salt region, contributing to the field of automatic facies classification significantly.

An Integrated New Workflow Leveraging Lateral Heterogeneity, and its Effect on Hydraulic Stimulation

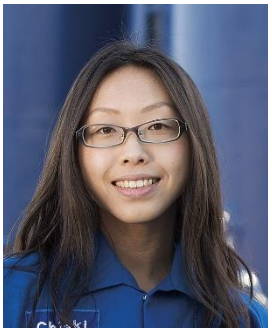
Elia Haddad
SLB

Elia Haddad is the Geology Domain Champion for America Land under the Reservoir Performance Division. He is based out of Houston, Texas. Elia oversees all the western globe as the geology champion, helping different operators across US Land, Canada and South America to tackle and solve different geological complexities to assess their reservoirs accurately and efficiently. Elia has 20+ years of experience in the upstream oil and gas industry in borehole geology, structural geology, and sedimentology. He studied special geology and Graduated from Helwan University in Egypt. He started his professional career within the oil and gas industry as a borehole geologist with SLB Egypt. He did contribute to numerous field exploration development plans within significant petroleum provinces in the Middle East (offshore Nile Delta) and the unconventional petroleum systems in North America within Canada and United States. Published many papers about the sedimentological aspects of different reservoir types and how it can help with the reservoir delineation and how to apply new technology imaging techniques for lateral wells in North America unconventional.

Abstract
Hydraulic stimulation remains one of the most challenging parts of any unconventional reservoir's life cycle. Plenty of assumptions have been analyzed and taken into consideration during the last decade with the evolution of different technologies, as far as tracing fluids away from the well, measuring fracture heights using microseismic events all the way to fiber technologies, monitoring the well beat by beat. This plethora of technologies helped a lot decipher many unknowns and solve an abundant amount of parameters used for modeling. Nevertheless, all of these technologies address the 'after-effect," which explains why the well behaved in a certain way. Understanding the well behavior and adjusting different scenarios along the horizontal well would enhance the well productivity and overall efficiency before stimulation. A newly designed workflow to acquire high-resolution logs in the lateral bringing back the geological aspect and the lateral heterogeneity recorded from various logs, including borehole image, 3D far Field data from sonic tools and lithology from spectroscopy data. The data is used to build a more comprehensive 3D structural model with discrete fracture network honoring the actual fracture distribution and fracture length, permitting to identify different scenarios of the well behavior from stimulation. Local structural complexity and sub-seismic faults observed from image logs and sonic data are all added to the model pushing a more realistic picture to the near and far space from wellbore. A fit for purpose approach delivered to our operators, tailoring a more robust stimulation design not based solely on the geometry but more into the job details covering proppant volume, pump rates, and schedules. Based on sensitivity analysis, different scenarios targeting different solutions from specific operator objectives.

New Findings of Geological History with Volcanic Rock from Borehole Image and Integrated Log Analysis in Hokkaido, Japan

Chiaki Morelli
SLB



Chiaki Morelli is a senior borehole geologist with SLB based in Nagaoka, Japan. She joined SLB in 2007 and has been leading and involving various types of borehole image tools, reservoirs and purposes of analysis such as oil and gas in sandstone and volcanic rock, methane hydrate, geothermal, hydrothermal, CCS, earthquake and scientific research, mainly in Japan. She holds a MSc in organic geochemistry from Hirosaki University in Japan.

Abstract
Tenpoku Seiho Oki-1 (TSO-1) wildcat well was drilled at offshore Hokkaido, Japan in 2021. LWD data (GR, resistivity, neutron, density, sonic), WL data (natural & spectral GRs, SP, borehole image) and side wall core samples were acquired in this well. As a wildcat well, the drilling plan was thoroughly prepared based on the pre-job study, then the operation was conducted safely by monitoring LWD real-time sonic data. Based on the acquired data and core samples, the volcanic rock existence is revealed underneath of the upper clastic rock which has not observed at surrounding wells. In this case study, we conducted geological, petrophysical and geomechanics analysis to understand newly found volcanic rock formation. Geological analysis included dip and facies (Image Facies) was conducted using the high-resolution resistivity borehole image data. The upper clastic zone was classified into 4 facies (Mudstone, Siltstone, Sandstone and Conglomerate) and the lower volcanic zone was divided into 3 major groups (Volcanic clastic, Tuff and Lava) and then classified into 11 facies (tf-Mst, tf-Sst, tf-Congl., Tuff, Lapilli tuff, Breccia tuff, Dolerite, Basalt, Mixed basalt, Basalt-Andesite, Andesite) which are well correlated with machine-learning based facies (ML Facies) and multicomponent inversion analysis (ELAN) results from petrophysical analysis, and show a good match with core samples as well. Seismic data suggested a major normal fault existence at the upper clastic zone. The borehole image does not show a clear fault dip. However, it exhibits messy textures and the bed boundary dip azimuth change at that interval. Additionally, 1D mechanical earth model from geomechanics analysis supported normal fault stress regime in this well. Paleocurrent result from the cross-bedding dip suggested west to east direction, which indicates the clastic sediments were supplied from the Eurasian Continent direction before expansion of the Sea of Japan. The lower volcanic zone (1200m interval) estimated to correspond with the Early Cretaceous Rebun-Kabato Belt from the core analysis results, and at least 19 times volcanic activities were identified from Image Facies result which can be divided into three big volcanic activity cycles, (I) mainly basaltic, very high volcanic active period, (II) more andesitic, high volcanic active period, (III) including dolerite, volcanic active convergence period. From this case study, we figured out the geological history at the TSO-1 area where there used to be a lack of geological information.

Geothermal Reservoir Characterization via Stress Field Analysis of Borehole Image and Sonic Logs

Bernd Ruehlicke
Eriksfiord

Bernd Ruehlicke (Current President SPWLA-Houston chapter, SPWLA Distinguished Speaker 2021-22). Bernd Ruehlicke is president of Eriksfiord Inc., part of the Eriksfiord group. Bernd worked at Z&S Geologi AS in Stavanger, where he built interpretation modules in RECALL. At PGS and Landmark, he built the interface between the Petrobank (Oracle) database and RECALL, and worked as Dev-Lead on R&D projects such as the Java DecisionSpace® platform. Bernd is the domain expert for image logs and geomechanics in the Eriksfiord group. He holds a BS in Computer Science and MS in Mathematics from Aarhus University in Denmark and an MBA from the University of Houston. He likes strong coffee and Eigenvectors and has been searching for big prime numbers far too long

Abstract
Borehole image logs (BHI) represent an excellent data source for a detailed geological characterization of the subsurface. Based on extensive experience gathered during the past 30 years of oil and gas exploration established workflows provide results generally relevant for reservoir characterization and also for geothermal reservoirs, as well as CO2 storage. Main results from BHI analysis relate to structural geology, depositional environment, as well as the current stress field. As geothermal fluids are typically produced from matrix or vuggy porosity and through fault and fracture zones the BHI is used to e.g. locate productive intervals and to quantify vuggy and fracture porosity; i.e. the BHI provides essential input for a detailed reservoir characterization. In addition, the current stress field (orientation and magnitude) can be determined and applied to optimize well path. Matrix and vuggy porosity reservoirs are characterized from BHI through an image facies subdivision. Image textures are interpreted with respect to depositional environment, e.g. karstified zones or reefal complexes. These can then be correlated to seismic scale features in order to identify sweet spots for well placement. In a similar manner the structural BHI analysis provides a correlation and calibration of structural dip and fault/fracture zones with seismic data. Furthermore, fracture density and aperture are calculated and used to locate high-permeability zones. The BHI analysis of stress related features such as drilling-induced fractures and breakout were used to determine the stress field orientation and magnitudes. Below figure is an example from a deviated well with drilling-induced fractures. Having the full stress tensor relative fracture permeability was used to optimize well path with respect to fracture orientation while taking into account borehole stability (i.e. mud weight and well path). Critical input for such an along-well evaluation are elastic rock properties, e.g. Young's modulus, Poisson's ratio, which are calculated from compressional and shear velocity. It is therefore important to use adequate fullwave sonic tools to secure best possible rock parameters critical for the geomechanical analyses. The presented results from geothermal wells in western Europe will demonstrate the value of stress analysis using BHI for geothermal exploration.

Minimum Horizontal Stress Sharpening

Elia Haddad
SLB

Elia Haddad is the Geology Domain Champion for America Land under the Reservoir Performance Division. He is based out of Houston, Texas. Elia oversees all the western globe as the geology champion, helping different operators across US Land, Canada and South America to tackle and solve different geological complexities to assess their reservoirs accurately and efficiently. Elia has 20+ years of experience in the upstream oil and gas industry in borehole geology, structural geology, and sedimentology. He studied special geology and Graduated from Helwan University in Egypt. He started his professional career within the oil and gas industry as a borehole geologist with SLB Egypt. He did contribute to numerous field exploration development plans within significant petroleum provinces in the Middle East (offshore Nile Delta) and the unconventional petroleum systems in North America within Canada and United States. Published many papers about the sedimentological aspects of different reservoir types and how it can help with the reservoir delineation and how to apply new technology imaging techniques for lateral wells in North America unconventional.

Abstract
One of the most established workflows to understand the effect of laminations in the rock mechanical properties and stresses is using the dipole sonic data to solve for the anisotropic effect of the properties at the resolution of the sonic tool (2ft). Borehole measurements of higher resolution, clearly reveal the true nature of these thin-bedded reservoirs with laminae on the scale of inches and below. It is therefore clear that to characterize the high-resolution mechanical properties of these reservoirs, borehole images provide a unique opportunity to resolve this high-resolution stratigraphic and mechanical variability at layer scale. This work proposes a novel methodology for evaluating thin-bedded reservoirs through the integration of existing anisotropic mechanical properties and stresses from the acoustic measurements and borehole images. The method will introduce high-resolution, quantitative outputs (generated from the electrical contrast of thin bed laminae), a “sharpened” minimum horizontal stress gradient and also a stress image that will honor the depositional facies; introducing mechanical facies with quantitative values that can be extracted all around and along the wellbore.