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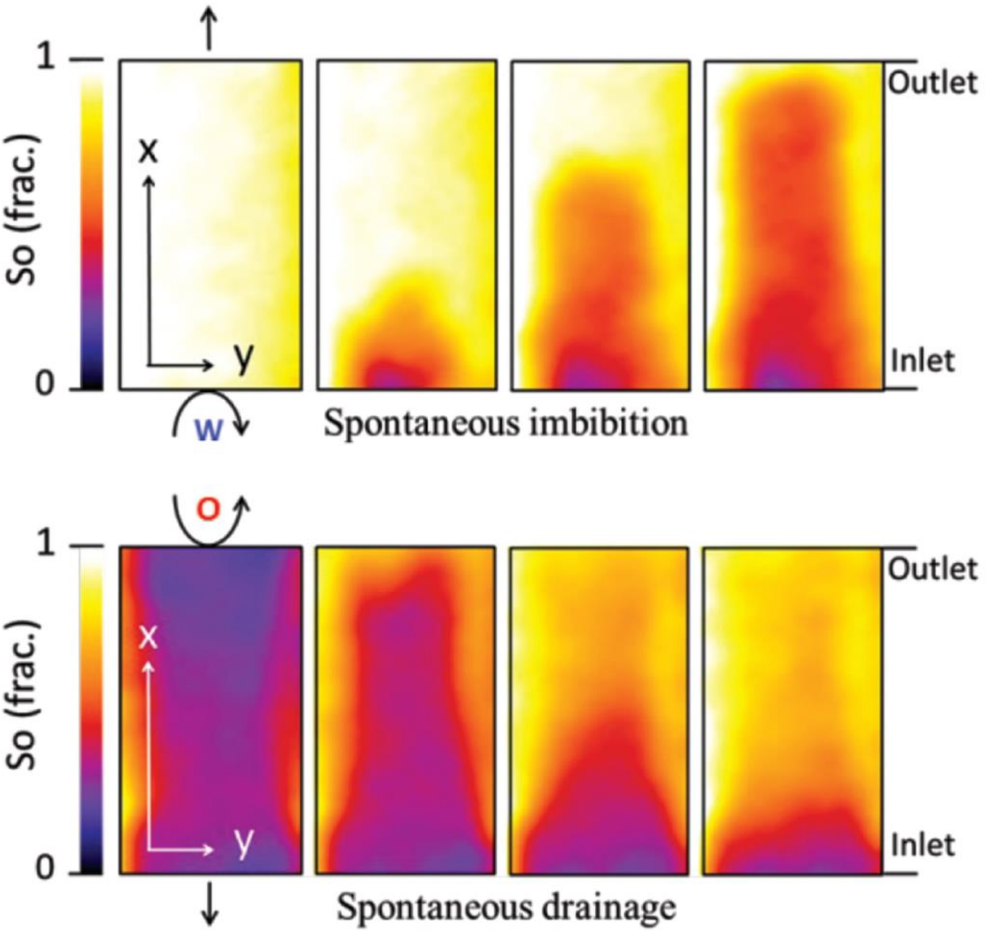

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Title: A Machine-Learning-Based Approach to Assistive Well-Log Correlation

Seth Brazell, Alex Bayeh, Michael Ashby, Darrin Burton. Petrophysics, 60(4): 469 – 479, DOI: SPWLA-2019-v60n4a1. https://www.onepetro.org/journal-paper/SPWLA-2019-v60n4a1

The process of well-log correlation requires significant time and expertise from the interpreter, is often subjective and can be a bottleneck to many subsurface characterization workflows. Algorithmic approaches to well-to-well correlation suffer from the inherent heterogeneity of geophysical measurements in the wellbore, both from a geologic and data-quality perspective.We demonstrate a rigorous and repeatable method for well-log correlation by deploying a correlation tool that leverages a machine learning model for pattern matching between well logs and programmed stratigraphic correlation techniques. A supervised-learning approach was used to train a novel deep convolutional neural network (CNN) architecture using over five million data samples, which were derived from thousands of well logs and expert interpreted correlations. To ensure that a robust pattern-matching model was trained, well logs from several US onshore basins with various tectonic regimes and environments of deposition were used to construct training and validation datasets. The result is a universal model for pattern matching of wireline measurements that can incorporate multiple geophysical-log signals as input data and can be deployed at scale without the need for retraining. Overall, the pattern-matching model was able to achieve a level of accuracy of 96.6% and classification area-under-the curve (AUC) of 0.954 on a separate validation dataset.

The universal deep CNN is one component of the correlation tool. Algorithmic three-dimensional search logic was constructed around the deep CNN model which determines the optimal correlation and marker propagation pathway. Rules-based criteria have also been applied to the model output ensuring conformance to stratigraphic principles including preserving stratigraphic order and honoring present-day structural trends. We present several examples to highlight the strengths and weaknesses of this machine-learning-based approach to well-log correlation which can be used to efficiently generate high-density datasets for regional exploration, development mapping and reservoir characterization exercises.

一种基于机器学习的辅助测井相关性分析方法

测井相关性分析需要大量的时间和解释人员的专业知识，且通常具有主观性，成为了井筒地球物理表征工作流程的瓶颈。从地质和数据质量的角度，井间相关性分析算法受井筒地球物理测量固有非均质性的影响。我们通过使用一种机器学习的模型，将配套的测井解释成果和地层相互对比，证明了一种严格且可重复的相关性分析方法。使用监督——学习方法训练这种新的深度卷积神经网络（CNN）结构，该结构使用超过 500 万个数据样本。这些样本均来自于数千口测井解释专家的解释

结果。为了确保能够训练出一个稳定可靠的匹配模型，构建训练和验证数据集的样本来自美国多个不同构造形态和沉积环境的陆上盆地。其训练结果为一个普适性的电测数据匹配模式，该模式可以将多个地球物理测井信号作为输入数据，并在不重复训练的情况下将该数据加载至模型中。总体而言，该匹配模型能够在独立的验证数据集上达到 96.6%的准确度和 0.954 的曲线下分类面积。该普适性的深度神经卷积网络（CNN）是相关性工具研究的组成部分。深度神经卷积网络基础上的三维搜索算法的逻辑，确保了相关性的最优以及传播路径的标记。基于规则的标准也应用于模型输出，以确保模型符合地层实际情况，即保证地层层序以及现金构造趋势的客观性。我们提供了几个例子来突出这种基于机器学习的测井相关分析方法的优缺点，并且这种方法可用于高效生成高密度数据集，用于区域勘探、开发绘图和储层特征描述练习。

Total Organic Carbon Characterization Using Neural-Network Analysis of XRF Data

Lateef Owolabi Lawal, Mohamed Mahmoud, Olalekan Saheed Alade, and Abdulazeez Abdulraheem. **Petrophysics, 60(4): 480 – 493, DOI: SPWLA-2019-v60n4a2.** **www.onepetro.org/journal-paper/SPWLA-2019-v60n4a**

The co-occurrence of kerogen and nonkerogen minerals in shale poses a great challenge; most importantly, different scales of measurements and ranges of analytical instruments become the prerequisite for characterization. The traditional shale-characterization technique adopts mineralogical analysis for the inorganic constituent and the total organic carbon (TOC) for the organic matter (kerogen). However, despite modern laboratory analytical techniques, the direct and simultaneous determination of the organic and inorganic constituents of a shale formation may be costly and unrealistic.

Hence, the use of the cost effective and more efficient X-ray fluorescence (XRF) tools for the elemental characterization of shale. The missing TOC problem, typical of well logging analysis, albeit, is a major challenge of this method. The objective of this work is to carry out quantitative analysis and interpretation of geochemical and mineralogical composition for the evaluation of organic rich shale formations using a neural network (NN) with the primary interest to optimize the performance of the XRF technique. For this purpose, a machine-learning artificial neural network (ANN) method has been devised to map easy-to-measure nondestructive XRF data of organic-rich shale to total organic carbon. Subsequently, the developed model, based on the existing dataset, was used to predict missing TOC. In the data-driven ANN model, 70% of the dataset was used for training, 15% for validation and 15% for testing. The accuracy and improvement of the NN model was established based on statistical parameters as performance metric. Furthermore, a quantitative calibration function to map the XRF data to TOC is developed based on the extraction of weights and biases of the NN. The implementation of the proposed calibration function for the calculation of TOC in comparison to the measured TOC was obtained with the coefficient of determination (R2)and mean absolute percentage error (MAPE) of 0.974 and 14.54%, respectively. These results confirm the applicability of the proposed calibration function in facilitating the simultaneous measurement of TOC and elemental concentration of shale for both laboratory and field-scale applications.

利用神经网络分析 X 射线荧光数据的有机碳含量表征

页岩中干酪根和非干酪根矿物的共存给页岩的表征带来巨大的挑战；其关键在于，测量尺度与分析仪器的范围是有效表征的前提。传统的页岩表征技术采用无机矿物分析测量非有机质组分、采用有机碳含量表征有机质（干酪根）。然而，尽管现代实验室分析技术能够测定页岩组分中的有机和无机组分，但费用昂贵、不易大规模推广。因此，使用成本较低和效率更高的 X 射线荧光数据对页岩进行元素表征。然而，常规测井分析中 TOC 的缺失问题是该方法面临的主要挑战。本研究的目的在于利用神经网络（NN）对富含有机质页岩地层进行地球化学和矿物学成分的定量分析和解释，以优化 XRF 技术的性能。基于这样的目的，设计了一种机器学习人工神经网络（ANN）方法，将富有机页岩中易测、无损的 XRF 数据映射到总有机碳。随后，基于现有数据集开发的模型被用于预测损失的 TOC 含量。在数据驱动的人工神经网络模型中，70%的数据集用于培训，15%用于验证，15%用于测试。以统计参数作为性能指标，建立了神经网络模型的精度和改进方法。此外，在提取神经网络权值和偏差的基础上，建立了将 xrf 数据映射到 TOC 的定量标定函数。计算总有机碳的校准函数与实际测量总有机碳含量相交会，相关系数（r^2）和平均绝对百分比误差（mape）分别为 0.974%和 14.54%。该结果验证了校准模型实际应用的可行性，能够在实验室和现场实现页岩总有机碳和各类元素的测量。

The Compressibility Factor (Z) of Shale Gas at the Core Scale

Huy Tran, A. Sakhaee-Pour. Petrophysics, 60(4): 494 – 506, DOI: SPWLA-2019-v60n4a3. www.onepetro.org/journal-paper/SPWLA-2019-v60n4a3

The compressibility factor (Z) of a gas inside a nanosize conduit depends on the conduit's characteristic size, in contrast to wide conduits whose dimensions have no effect on the gas compressibility. Nanofluidics, which is a field of study concerned with the fluid flow in nanosize conduits, can quantify the gas compressibility factor in a simple topology, such as a uniform tube with a circular cross section, but it is not apparent how those results are relevant to a complex pore space in the matrix of a shale at the core scale. This study determines the compressibility factor of a shale gas by accounting for the effective connectivity of the pore space at the core scale. We use effective pore-throat and pore-body sizes, which are interpreted using an acyclic pore model applied to the core-scale measurements and not high-resolution images. Eleven shale formations whose data are available in the literature are investigated (Bakken, Barnett, Eagle Ford, Haynesville, Marcellus, Monterey, New Albany, Niobrara, Utica, Wolfcamp, and Woodford). The results, which have applications in developing realistic models based on petrophysical measurements, show the compressibility factor (Z) of the shale formation at the core scale as a function of gas pressure.

岩心尺度页岩气的压缩因子（Z）研究

纳米尺度空间中页岩气压缩因子（Z）取决于通道的尺寸，而尺寸较大孔隙空间对气体的压缩性无影响。纳米流体学专指针对纳米级空间中流体的流动进行研究，可以在简单的拓扑结构中量化气体压缩因子，例如具有圆形横截面的均匀孔隙。但是，在岩心尺度下，上述研究结果与页岩基质中复杂孔隙空间之间的相关性并不明显。该研究通过计算岩心尺度下孔隙空间的有效连通性确定页岩气的压缩因子。我们使用有效的孔喉、孔隙体尺寸，该结果来源于岩心尺度测量不可循环模型，而非高分辨率的图像。11 个页岩地层资料（Bakken、Barnett、Eagle Ford、Haynesville、Marcellus、Monterey、New Albany、Niobrara、Utica、Wolfcamp 和 Woodford）参与研究。研究结果表明，岩心尺度下页岩地层的压缩因子（Z）与气体压力呈函数关系，可用于建立基于岩石物理实验的实际模型。

Practical Approach to Derive Wettability Index by NMR in Core Analysis Experiments

Wim Looyestijn. Petrophysics, 60(4): 507 – 513, DOI: SPWLA-2019-v60n4a4. www.onepetro.org/journal-paper/SPWLA-2019-v60n4a4

Wettability is a crucial factor for the dynamic properties of oil reservoirs. Early recognition of the wettability condition of a recovery may have a significant impact on the development options and of the expected recovery factor. NMR relaxation times of pore fluids are dependent on the wetting through surface relaxation, and are thus known to contain this valuable information. This paper describes an easy-to-implement and reliable procedure to calculate a quantitative wettability index from standard NMR measurements, such as can be made in conjunction with SCAL experiments. The interpretation is fully auditable, and therefore suitable to be part of a standard protocol.

岩心分析核磁共振实验确定润湿性指数的实用方法

润湿性是影响油藏动态特性的关键因素。早期研究认识到润湿性条件会对开发方案选择以及预期采收率系数产生重大影响。孔隙流体的弛豫时间受润湿表面驰豫的影响，进而其包含有大量关于润湿的有价值信息。本文介绍了一种基于标准核磁测量定量计算润湿指数的易实施、可靠的方法，例如可于岩心 SCAL 实验相结合。解释方法完全具有可行性，因此可作为标准规范的一部分。

In-Situ Investigation of Aging Protocol Effect on Relative Permeability Measurements

Using High-Throughput Experimentation Methods

Matthieu Mascle, Souhail Youssef, Hervé Deschamps, Olga Vizika. **Petrophysics, 60(4): 514 – 524, DOI:**

SPWLA-2019-v60n4a5. www.onepetro.org/journal-paper/SPWLA-2019-v60n4a5

Relative permeabilities are a first-order parameter to consider when describing multiphase flows in porous media. Among many other parameters, the core wettability controls the fluids repartition in the porous media at pore scale, strongly affecting how the fluids can be displaced (i.e., their relative permeabilities). As the initial wettability of cores sampling a reservoir is rarely preserved, classical SCAL measurements (such as relative permeabilities) may not reflect the rock properties at reservoir conditions.

This original core wettability may be restored in a process referred as ‘core aging’.
It is generally done by injecting the core with the reservoir fluids (brine and crude-oil) to equilibrate the rock surface with respect to the oil and brine components. Here, we investigated the effect of two aging protocols (static and dynamic) on wettability restoration, and characterize the aging using oil/water relative permeabilities measured on the core after aging. The two aging protocols were applied on a set of initially strongly water-wet outcrop sandstone samples (Bentheimer). The relative permeabilities were measured using the steady-state method and a state-of-the-art experimental setup (CAL-X) based on X-ray radiographies. The setup is equipped with an X-ray radiography facility, enabling monitoring of 2D local saturations in real time and thus giving access to fluid flow paths during the flooding. The relative permeability curves of aged samples show clear differences when compared to water-wet relative permeabilities, hence. suggesting that the wettability has been effectively altered. However, the two aging protocols were unable to produce the same results. The dynamic aging has led to an inversion of the original relative permeability curves asymmetry, suggesting a strongly oilwet system, whereas the static aging protocol has altered the wettability to a lesser extent. The differences can be explained by analyzing 2D saturation maps. In the case of dynamic aging we observed a homogeneous distribution of fluid saturation during fractional flow. In contrast, the static protocol results in heterogeneous flow paths, confirming that this protocol did not uniformly alter the wettability of the sample and generates a patchier mixed-wettability system.

老化过程对相对渗透率原位测量的影响研究

相对渗透率是描述多孔介质中多相流动时要考虑的一阶参数。在许多其它参数中，岩心润湿性控制着孔隙尺度下多孔介质中流体的重新分配，这对流体的置换方式（即它们的相对渗透性）有很大影响。由于储层岩心取样过程难以保护岩心的初始润湿性，特殊的

岩心实验测量（如相对渗透率）可能无法反映储层条件下的岩石性质。岩心的地层原位条件下的润湿性可通过“岩心老化”进行恢复。通常通过向岩心注入储层流体（盐水和原油）使得岩心表面油和盐水成分达到平。论文研究了静态和动态两种老化方案对润湿性恢复的影响，并利用老化后岩心测量油/水相对渗透率表征老化。这两种老化方案应运用于一组初始强水湿露头砂岩样品（Bentheimer）。利用稳态法和基于 X 射线照相的最先进实验装置（Cal-X）测量了相对渗透率。该装置配备有 X 射线照相设备，能够实时监测二维局部饱和度，进而观测驱替过程中流体流动的路径。老化后样品的相对渗透率曲线与初始强水润湿样品的相对渗透率相比，表现出了明显的差异，表明润湿性在老化后已被有效地改变。然而，这两个老化实验，无法得到相同的相对渗透率测量结果。动态老化导致原始相对渗透率曲线不对称性的反转，暗示润湿性为强油润湿。相比于动态老化，静态老化对润湿性的改变较小。这种差异可以通过分析二维饱和度图加以解释。在动态老化的情况下，我们观察到一个均匀分布的流体饱和度。反之，静态老化导致了不均匀的流动路径，证实了该老化过程并没有均匀的改变样品润湿性，使得样品润湿性为混合润湿。

Novel Coupling Smart Water-CO2 Flooding for Sandstone Reservoirs

Hasan N. Al-Saedi, Ralph E. Flori. **Petrophysics, 60(4): 525 – 535, DOI: SPWLA-2019-v60n4a6.** **www.onepetro.org/journal-paper/SPWLA-2019-v60n4a6**

CO2 flooding is an environmentally friendly and cost-effective EOR technique that can be used to unlock residual oil from oil reservoirs. Smart water is any water that is engineered by manipulating the ionic composition, regardless of the resulting salinity of the water. One CO2 flooding mechanism is wettability alteration, which meets with the main smart water flooding function. Injecting CO2 alone increases the likelihood of an early breakthrough and gravity override problems, which have already been solved using water-alternating-gas (WAG) using regular water. WAG is an emerging enhanced oil recovery process designed to enhance sweep efficiency during gas flooding. In this study, we propose a new method to improve oil recovery via synergistically smart brine with CO2. This new method takes advantage of the relative strengths of both processes. We hypothesized that brine depleted in NaCl provides more oil recovery. We also determined that depleting NaCl in brine is not the end of the story; diluting divalent cations/anions in the brine depleted in NaCl provides higher oil recovery. Injecting smart brine depleted in NaCl with diluted Ca2+ and CO2 resulted in a high oil recovery percentage among the other scenarios. Thus, the above water design was applied as a WAG in three cycles, which resulted in a much higher oil recovery of 24.5% of the OOIP. This improved heavy-oil recovery is a surprising and promising result. The spontaneous imbibition agreed with the oil-recovery results. This study sheds light on how manipulating ions in the water used in WAG can significantly enhance oil recovery.

砂岩储层新型耦合智能水-二氧化碳驱油

二氧化碳驱是一种环境友好、经济高效、可用于油藏剩余油开采的提高采收率技术。所谓智能水，即不考虑最终矿化度，通过调控离子组成而形成的水溶液。二氧化碳驱油的机理之一为改变岩石润湿性，这与智能水驱油的主要作用是一致的。仅使用二氧化碳驱油使突破过早和重力超覆可能性增加的问题已经通过水（常规水）气交替注入技术得以解决。WAG 是一种新兴的提高采收率工艺，旨在提高气驱的波及效率。本研究中，我们利用了两种驱替方法各自的相对优势，提出了一种通过二氧化碳气体与智能水协同作用来提高采收率的新方法。我们认为去除水中的氯化钠可以提高采收率，并且水中氯化钠去除后仍有办法提高采收率，即稀释已去除氯化钠水溶液中的二价阳离子/阴离子；在所有的方案里，使用稀释 Ca^{2+}和 CO^{2-}的智能去氯化钠盐水得到的采收率最高。在 WAG 工艺的三个循环中使用了上述智能水，基于原始石油地质储量的稠油采收率提升了 24.5%，这是一令人惊讶和充满希望的结果。自发渗吸与采收率结果一致。本项研究揭示了 WAG 工艺中所用智能水显著提高原油采收率的机理。