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Mega Giga Pore Segmentation in acoustic data image borehole

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Abstract Summary

The characterization of porosity in Brazilian pre-salt carbonate reservoirs poses significant challenges due to the complexity of large-scale pore (Mega Giga Pores - MGphi) structures, such as caves, vugs, and enlarged fractures. These features are difficult to represent in conventional geological models because of the lack of reliable data. There are methods proposes the use of borehole image logs combined with image processing techniques to quantify the morphological properties of such features. Metrics such as area, perimeter, internal length, and diameter were extracted, allowing the morphological classification of pores (de Jesus et al., 2019) Victor (2017).

Given the large volume of data and the time consuming manual analysis required by experts, the use of automation tools and artificial intelligence techniques, particularly deep learning neural networks, emerges as a promising approach. These models are capable of identifying complex patterns at multiple scales and making accurate predictions in significantly reduced time. The results show that the proposed method achieves Dice coefficients up to 99% on blind samples, with inference completed in minutes, an expressive gain compared to the days or weeks required by specialists. This method significantly improves geological reservoir modeling and the understanding of pore connectivity, supporting strategic decision-making in oil field development.

Introduction

The analysis of porosity in pre-salt carbonate reservoirs involves the thorough evaluation of a massive volume of data derived from borehole image logs. The article (Dias et al., 2020) highlights that for each drilled well, thousands of images must be carefully inspected by specialists, which requires an extremely long time in addition to specific technical knowledge. This process, traditionally manual, can take weeks or even months, especially when attempting to characterize complex structures such as vugs, caves, and enlarged fractures, whose geometry varies significantly throughout the reservoir. The morphology of these structures directly influences the connectivity of the porous medium and, consequently, the dynamic properties of the reservoir, such as productivity and fluid injection behavior. In this context, the need for rapid and standardized characterization becomes increasingly evident. The use of automation and computational analysis tools, particularly those based on Artificial Intelligence (AI) algorithms combined with digital image processing techniques, emerges as a promising solution (Dias et al., 2020).

Deep learning tools based on images have proven increasingly effective in the characterization of geological formations, especially when compared to traditional methods or classical image processing and statistical algorithms. Deep learning models are extremely effective in detecting subtle and non-linear spatial patterns in borehole images because they do not require manual definition of criteria — they automatically learn these features during training. Models can be trained to identify features across multiple scales, from small structures to large caves, which is challenging for conventional algorithms. These networks can maintain spatial consistency when handling different image resolutions, which is essential for characterizing porosity. Over time, models can be refined with new data, becoming more accurate as they learn from actual field results (e.g., other logs obtained from different tools used in the well), making deep learning highly adaptable (de Jesus et al., 2024; de Oliveira et al., 2022; Dias et al., 2020).

These tools are able to predict MGphi formations by extracting key morphological metrics in a fraction of the time that a specialist would take. In addition to improving efficiency, automation reduces the subjectivity of interpretation and enables the integration of large volumes of data into more representative geological models. Automated algorithms do not replace specialists but rather enhance their analytical capacity, making it possible to apply this knowledge in a timely manner for strategic decision making in field development (de Jesus et al., 2016, 2024; de Oliveira et al., 2022).

The developed technique contributes to improving the understanding and representativeness of porosity scales, honoring the complexity of the structures generated by karstification processes. Additionally, new workflows have been developed to incorporate pore diameters into the geological modeling of reservoirs. In a second step, the distinct properties of each porous medium could be represented in models using fluid dynamics equations (Bom et al., 2021; de Jesus et al., 2016).

In this work, we propose a Deep Learning Classification pipeline that learns from ultrasonic image data and infers the presence or not of MGphi. We use borehole data from one well in the pre-salt region of Brazil to train our model. We separate a part of it to serve as a blind test sample.

Method

Our architecture of choice is a U-net, which features a distinctive U-shaped encoder-decoder architecture specifically designed to perform well with small training datasets. It comprises four encoder blocks on the left and four decoder blocks on the right. The encoder processes the input image through multiple convolutional layers to extract meaningful features. The decoder then upsamples these feature maps using transposed convolutions and integrates information from earlier layers through skip connections. This process results in a segmentation mask as the final output of the network (dos Anjos et al., 2022).

We develop the U-Net supervised Machine Learning (ML) scheme where the goal is to predict the label associated with a given input: background or MGPhi. We preprocessed the images by applying a 32x32 sliding window and normalizing the acoustic data to $[0, 1]$. Sliding windows with only background were removed from the training set to speed up the process.

The ground truth data used for the supervised training was generated from the histogram segmentation of the amplitude image and manual adjustments made by interpreters. Through an image log segmentation tool, the amplitude image histogram is segmented into multiple ranges of values (see details in (de Jesus et al., 2024).

Semantic segmentation aims to determine whether a pixel belongs to the object. As a result, this problem could be characterized as a binary classification problem at the pixel level. In practice, each class present in the dataset is transformed into a numeric value, and the network is optimized using a binary entropy loss `eq:beloss`:

$$BEloss = -(y \log(p) + (1 - y) \log(1 - p)) \tag{1}$$

where y is a binary indicator (0 or 1) for the class label and p is the predicted probability by the network (dos Anjos et al., 2022).

Results

The blind test set was used to evaluate the performance of the U-net. We applied the same preprocessing as in the training set, and defined a threshold of 0.5 to distinguish between background and MGPhi. The dice coefficient for the test set is 99%. An example of segmentation is shown in Figure 1.

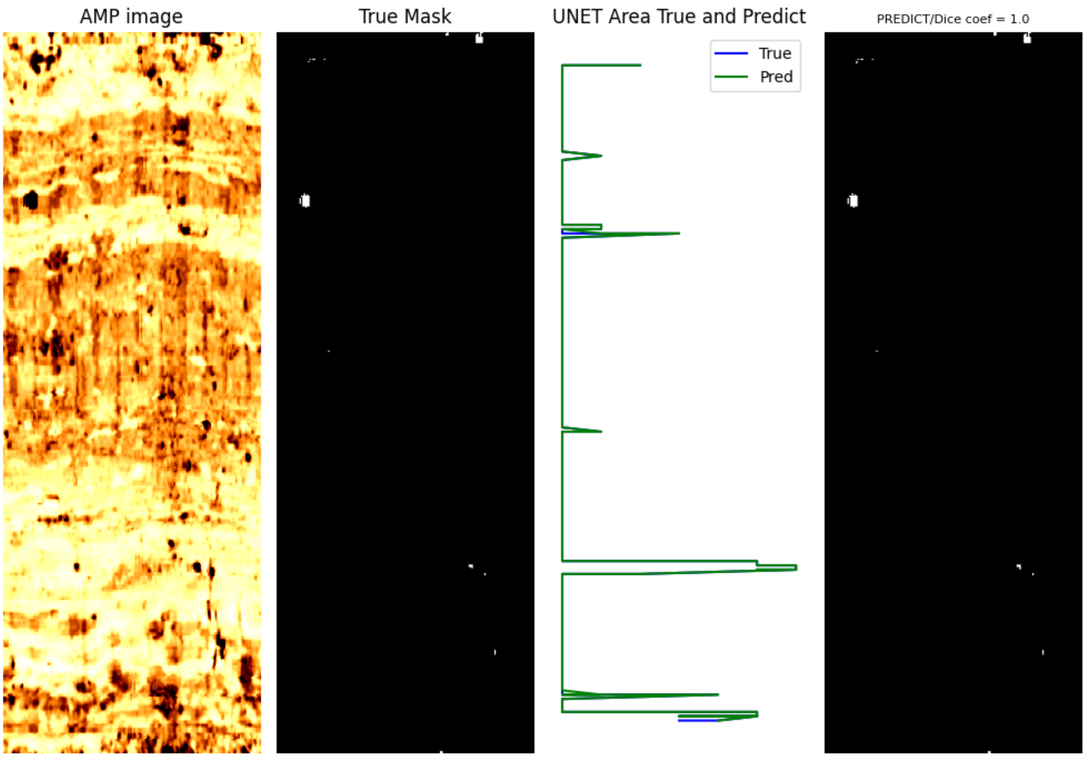

Figure 1: The figures from left to right is AMP image input (from acoustics amplitude using custom range color map), True Masks binary MGphi used to create second input, compare curve of area x depth true and predict and finally result of U-Net model predicted.

Conclusions

In this paper, a U-Net method for finding MGphi in borehole acoustic image logs is described. To verify and evaluate the method, we used a set of real log well data that Petrobras/Waid owned privately and that included a drilled well with the MGphi regions. The quantitative metrics and model predictions highlight the quality of the results. Even with sparse training data, the suggested technique produced encouraging results, with good segmentation metrics and visual outcomes that corroborated the numerical ones. From this, it can be concluded that the offered method can help experts identify possible MGphi in well log image data. The interpretation procedure should then be optimized to reduce costs and the length of the reservoir interpretation. We suggest using transit time details together with the input amplitude data in further study, and also test loss functions that the learning from hard examples in order to improve detection.

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