ABSTRACT: Simplifying fluid-flow physics in conventional reservoirs is convenient by assuming uniform lithology and system-geometry with minimal rock/hydrocarbon interactions. Such simplification restrains mathematical models’ ability to simulate unconventional reservoirs’ actual flow behavior and production performance. Researchers can achieve precise adaption for the physics of fluid flow in porous media if they geometrically characterize the system under study appropriately, and there are minimal interactions indeed. 3D-printed replicas of porous-rock samples obey this criterion. In this work, we used image-processing tools used for creating presentable porous and permeable replicas of different scales and configurations of the petroleum system from lab-scale to field-scale. The workflow of 3D-printed replicas creation is presented for replicas of conventional core samples, naturally and synthetically fractured cores, geological drilling units of multistage fractured horizontal wells, and full-field models, e.g., Norne field in Norway. These samples are ideal for experimentally testing the validity of the analytical or numerical models of oil and gas reservoirs’ characterization. These replicas’ ideality of these results from limited uncertainties of the geometry of the system under study and fluid/rock interactions because of the uniform composition. For validation purposes, 3D-printed replicas with different materials and 3D-printing technologies were created based on a reconstructed image-processed CT scan of their original Berea sandstone. These replicas were tested for storage capacity (porosity) and transport capacity (permeability) and compared with their original sample’s capacities. The matched results proved replicas’ ability to be used in oil and gas laboratory experimental research.

INTRODUCTION

Experimental research in the oil and gas industry is crucial to estimate hydrocarbon reserves and develop optimal exploitation strategies. Fluid-flow and characterization experiments, e.g., core flooding, porosity, permeability, and wettability experiments, are conducted on samples acquired from subsurface reservoirs. Those experiments reflect the subsurface’s fluid/rock interactions, and their results are used to build representative mathematical models, numerical or analytical, to predict reservoirs’ future performance. The effectiveness of potential enhanced oil recovery (EOR) technology is tested experimentally on core samples from the reservoir before the expensive field-implementation. Laboratory experiments are conducted under similar conditions to downhole/reservoir in situ conditions, i.e., injection pressure, reservoir temperature, normal stresses, and fluid composition. Under such conditions, acquired attributes like oil recovery, decline rates, pressure changes, and fluid composition changes enhance understanding the reservoir nature and its response to production mechanisms.

Numerical and analytical models are used to predict reservoirs’ future performance after accurate characterization.

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and validation versus core-scale lab results. The fundamental challenge to validate such models is characterizing rock/fluid interactions for samples with spatially varying rock mineralogy and complex flow geometry. Complicated models have been developed to accurately simulate fluid flow in porous media to its finest complexity scale, i.e., micro- and nanoscale. These models failed to handle complex interactions and/or complex geometries because of the limitations on computational power and the issues of convergence and stability of the mathematical solution. Even the perfect-matching models, among them, have nonquantifiable uncertainties due to the existence of too many controlling variables, e.g., pore network configuration, the physical boundaries of the system, and governing equations’ assumptions. Therefore, geomodelers tend to simplify the system complexities, geometrical and/or compositional, to have usable models for lab- and field-scale systems.

Petrophysical properties’ upscaling is an example of models’ simplification, which eases models’ utilization. Assuming minimal spatial-variabilities and interactions can simulate experiments on samples from conventional reservoirs and generate reliable results. For unconventional reservoirs, such simplifications cannot be trusted where system complexity is non-negligible and controls the system behavior.

3D-printers can effectively create complicated designs with minimal waste and flaws. Wide applications of 3D-printing have been presented recently in fundamental research areas, e.g., multiphase fluid flow, geomechanics, paleontology, and geomorphology. The usage of 3D-printing technology stimulated researchers in the petroleum engineering and geoscience fields. Applications of 3D-printing are signified by its capability to translate virtual models into 3D-printed specimens for experimental research. In this work, 3D-printing technology was used to create ideal porous specimens from the lab- to field-scale petroleum systems to overcome their geometrical and compositional complexity challenges. Image-processing tools were developed for manufacturing physically tangible replicas of petroleum systems based on their reconstructed conceptual models, e.g., a reconstructed core CT scan or seismic field data. The advantages of manufacturing 3D-printed replicas of core samples and full-field models are multifold. These advantages are

(a) Numerical models of experiments, which are conducted on the 3D-printed replicas, have minimal geometrical uncertainties as these models will be created based on the same geometrical mesh that will be used in the 3D-printing process itself.

(b) 3D-printed replicas eliminate the uncertainties of rock/fluid interactions because of the uniform composition of the 3D-printing materials, e.g., plastics or gypsum, which quantifies the interaction with hydrocarbons in the simulation models accurately.

(c) 3D-printed replicas reduce the cost of destructive experiments as these synthetic samples have the advantage of cheap 3D-printing repeatability and preserving expensive original samples.

(d) 3D-printing enables inserting syntactic or natural fractures inside the specimen to simulate fracture-matrix flow physics experimentally.

(e) Unconsolidated rock samples can be 3D-printed to create replicas that can persist firmly extreme pressures during coreflooding experiments.

(f) 3D-printing enables creating a downscaled lab-scale pilot or full-field models that are physically unattainable to acquire from the subsurface to test in the laboratory.

The following cases present image-processing tools and 3D-printing technology capabilities to create and tailor synthetic specimens of cores and downscaled pilot/full-field models in reasonable dimensions for laboratory experiments.

RESULTS AND DISCUSSION

Case 1: 3D-Printing Conventional Cores Using Different Materials and Printing Technologies. A standard commercial Berea sandstone core (1.5 in. in diameter and 2 in. in length) was 3D-printed after building its virtual 3D-printable object (Figure 1). The Berea sample was CT-scanned, and its CT scan was image-processed to segment Berea’s grains/pores into two separate classes. The grain class represented the solid volume to be 3D-printed and create the synthetic replica. The image-processing and segmentation steps are

(a) Adapting the CT scan’s areal and longitudinal resolutions to match the resolution limitations of 3D-printers on object details and reduce processing memory requirements (the adaption process is conducted by upscaling the number of pixels per CT slice along with 3D interpolation to fill the gaps between the CT slices).

(b) Segmenting grain/pore geometrical domains in the scan using a definite grayscale threshold, which separates the pores’ pixels from the grains’ ones.

(c) Meshing the grains’ segmented pixels to construct a 3D continuous object, which can be 3D-printed in a stereolithography format (.stl file).

(d) Slicing the 3D object to a sequence of intersection horizontal-layers to be 3D-printed one by one by the 3D-printer to construct the replica.

(e) 3D-printing the sliced 3D object using different 3D-printing materials and technologies, as shown in Figure 2.

Figure 2 shows the 3D-printed replicas with different printing materials such as common white and transparent plastic PLA (polylactic acid), CPE (co-polyester), ABS (acrylonitrile butadiene styrene), transparent resins, and colored sandstone. Each material has its well-documented mechanical and texture properties. The used material is selected based on the purpose of 3D-printing, the operating conditions of the experiment (pressure and temperature), the complexity of the model, and the maximum required resolution. Five 3D-printers were used with four different 3D-printing technologies, i.e., fused filament fabrication (FFF) (Ultimaker 3D-printer), fused deposition modeling (FDM)
Porosity and permeability are measured and are listed for all samples in Table 1 to compare the original’s static and dynamic properties with 3D-printed replicas’ properties. The measurements show that transparent resins and colored-sandstone replicas have lower hydraulic behavior to their original properties. 3D-printing with plastics (BLA or ABS) resulted in low permeabilities as compared to the original core.

Table 1. Petrophysical Properties for the Original and 3D-Printed Core Samples

| Material            | 3D-printer | por. (%) | perm. (md) |
|---------------------|------------|----------|------------|
| original core       |            | 20       | 100        |
| PLA                 | Stratasys  | 18       | 150        |
| Ultimaker           | 25         | 70        |
| transparent PLA     | Ultimaker  | 26       | 75         |
| transparent CPE     | Ultimaker  | 28       | 80         |
| ABS                 | Ultimaker  | 15       | 60         |
| Prusa I3            |            | 12       | 62         |
| Formlabs            |            | 23       | 96         |
| Sandstone ProJet 660 | 22           | 110      |

The quality of 3D-printing differs from one technology to another and even from one 3D-printer model to another with the same printing technology.31 Porosity and permeability were measured and are listed for all samples in Table 1 to utilize them for another set of experiments. In the next section, resizing a CT scan will be explained to create smaller samples without damaging the original cores.

Case 2: 3D-Printing Tailored and Resized Core Samples’ Replicas. Nitrogen-adsorption measurement requires samples 1 in. in diameter and 1 in. in length.36,37 In contrast, triaxial geomechanics and transient permeability measurements require samples 1 in. in diameter and 2 in. in length.38 So, the Berea sample 1.5 in. in diameter and 2 in. in length cannot be used to conduct such experiments. Other Berea samples can be acquired to proceed with the experiments, but that will lead to inconsistent results because of the samples’ different pore network structures and mineralogy. The appropriate solution is to resize the sample to the new dimensions. The two possible ways of sample resizing are

(a) Resizing the core mechanically

(b) Resizing the CT scan digitally using image processing and then 3D-printing the new reconstructed object

The mechanical method is not preferred due to the probable damage and the possibility of losing the sample. Therefore, it is preferred to resize the CT scan digitally by image processing. The original CT-scan images/slices can be cropped to resize the sample’s diameter to the required new diameter by trimming the pixels outside the area of interest. As an example, Figure 4 shows a CT slice cropped from 1.5 to 1 in. diameter. On the other hand, resizing the scan in length can be conducted by removing the redundant CT slices from the original scan, as shown in Figure 5a–c. After fitting the CT scan to the desired size, the continuous conceptual models, shown in Figure 5d–f, are reconstructed. Finally, those models are 3D-printed with different materials (colored sandstone, PLA, ABS, resin), as shown in Figure 6. The proposed process saves manual effort, sampling expenditure, and experiments’ time of labwork by providing as many samples as needed with the same printing technology.31 Porosity and permeability are measured and are listed for all samples in Table 1 to explore the importance of the work.
suitable configurations once the original sample’s CT scan is acquired.

Case 3: 3D-Printing Naturally and Synthetically Fractured Core Samples. The flow physics of matrix/fractures is not fully understood yet because of the limited conducted experiments. For instance, naturally fractured rocks are fragile and rupture under the applied friction stresses and heat of the coring process. Another characterization issue, to extensively describe their physics, is referred to the deficiency in describing the matrix/fracture system geometrically. The proposed image-processing methodology can be extended to 3D-print cores with such complex geometry, i.e., cores with natural fissures. 3D-printing facilitates experimental research on naturally fractured samples and makes it possible and more practical. Figure 7 compares synthetic sections produced from Berea sandstone (conventional core; left) and a section 3D-printed from a core, including vugs and fissures (right).

Experimental research on cores with synthetic fractures is essential to study failure modes and flow physics of field-hydraulic fracturing operations. Artificial inclusion of cracks inside the natural core samples is challenging, if impossible. The proposed image-processing workflow enables a precise insertion of synthetic fractures to the CT scan and 3D-print the processed object to study the stress−strain geomechanical behavior, e.g., fatigue planes, during an injection experiment. The steps of the workflow (Figure 8) are

(a) Selecting the CT slices, where the fracture is encompassed intentionally
(b) Overlaying the fracture geometry (aperture, profile, and width) on the CT slices
(c) Removing the pixels of the fracture geometry from the scan set
(d) Constructing the meshed 3D-structure (i.e., *.stl file)
(e) 3D-printing the resulting object with the proper printing material and technology

Case 4: 3D-Printing a Prototype of the Drilling Unit Pilot Model. There is no published literature regarding experimental research on downscaled pilot models. Most feasibility studies on pilots were based on field application or simulation studies. 3D-printing enables creating a tangible pilot model for lab-scale experiments. The printed pilot-replicas can physically study the reactions of stimulated reservoir volumes (SRVs) to any recovery strategy and support analytical/numerical models experimentally. In this section, different models for a multistage-fractured horizontal well (MSFHW) were created from virtual cross sections, including a well-path, porous media, natural fractures, and different hydraulic fracture geometries in the SRV. These models can save ineffective strategies’ field expenditures by facilitating conducting sensitivity experiments for testing different EOR/development plans before implementing them in the field.
Various combinations of a reservoir (homogeneous, naturally fractured, tight, and conventional), well (vertical, horizontal, slanted, and fractured), and hydraulic fractures (transverse, longitudinal, and complex branches) can be geometrically designed. Figure 9 and Table 2 show the steps of generating printable pilot models for four cases with different well/reservoir configurations. The steps are:

(a) Plotting a 2D geometry of a cross section of the system
(b) Segmenting the grayscale solid-domain from the pore's one as followed for segmenting a CT-scan slice
(c) Extruding as many slices as needed to cover the SRV's 3D-volume
(d) Building the continuous conceptual volume to be meshed
(e) 3D-printing the pilot model in proper dimensions for lab-testing

Matrix porosity can be gained from the porosity of the printing material, i.e., sandstone silica/gypsum powder, or by artificial insertion of pore space. This local porosity and permeability should be downcaled from a reservoir-scale to a lab-scale for each volumetric unit. A useful application of 3D-printing pilot models is studying stress changes and their implications, e.g., subsidence and changes of hydraulic fractures' configurations. Basins' subsidence rates have been...
widely investigated for oil and gas reservoirs.\(^{42,43}\) Such studies were not experimentally investigated on a laboratory scale. Downscaled 3D-printed pilot models accommodate specimens to study the impacts of field-scale attributes on the reservoir system. Figure 10 shows a geomechanical model to study in situ stress change effects on the fracture dimensions, validated experimentally with a 3D-printed pilot model in Table 2.

**Case 5: 3D-Printing a Lab-Scale Replica for a Full-Field Model.** 3D-printing also enables full-field studies of production mechanisms and EOR processes on a lab-scale. For any EOR technique, flooding fronts can be physically monitored, streamlines can be tracked and visualized, and sweep efficiency can be quantified experimentally on full-field 3D-printed prototypes. Downscaled static models will be based on 3D-printing porosity, permeability, and boundary transmissibilities, e.g., sealing faults and reservoir limits. The E-Segment of the Norne field, in the Norwegian Sea, the Heidrun oil field, is examined, and its static model is processed from seismic data.\(^{44,45}\) The downscaled static is then 3D-printed by following the workflow summarized below (Figures 11 and 12)

(a) Acquiring the geologic model’s attributes, e.g., reservoir boundaries, porosity, and permeability from seismic data, well logs, etc.
(b) 2D slicing the porosity static model to generate a set of 2D slices to be image-processed, i.e., digitally binarized, as CT scan slices
(c) Cartesian meshing the reservoir’s horizons and surfaces to obtain corner-point nodes to track the outer boundaries of the 3D-printing model accurately
(d) Triangulating the reservoir’s Cartesian mesh, as 3D-printable objects’ surfaces should be defined by triangular facets (see Figure 12)
(e) Resizing the mesh’s global dimensions with a reasonable aspect ratio, as shown in Figure 13 with the 3D-printed E-Segment of the Norne field printed in three different sizes
(f) Geostatistically populating a virtual cloud of 3D solid spheres to generate artificial porosity and permeability inside the printable volume or 3D-printing a solid volume and count on the approximate printing material’s porosity and permeability

### CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Image processing and 3D-printing technology facilitate reconstructing and tailoring specimens for experimental research and modeling validation of fluid-flow physics in petroleum systems. 3D-printed samples reduce the geometrical and lithological uncertainties of real rock samples with quantifiable rock/fluid interactions along with the sizing flexibility. Such simplifications, in subsurface complexities, advance and ease precise analytical/numerical fluid-flow formulations. An image-processing workflow is proposed to create 3D-printable porous and permeable specimens for laboratory experiments in this work. The processing steps were
explained for reconstructing the acquired CT-scan slices by binarizing the grayscale slices and segmenting pores from grains. Cropping and resizing the CT scan are presented as another practical image-processing application that overcame samples’ resizing challenge, i.e., physical damage of mechanical resizing, to fit various experiments’ different size requirements. The ability to re-evaluate matrix/fracture flow physics experimentally is enabled by the image-processing approach of synthetic fracture insertion in a CT scan and 3D-print fractured replicas. The workflow of 3D-printing conventional core samples or synthetically/naturally fractured ones was used to 3D-print full-field models and pilot models of different combinations of well-reservoir configurations. Cases of multi-stage-fractured horizontal wells in naturally fractured SRVs were 3D-printed. Static seismic data and artificial cross sections were treated as CT slices to 3D-print pilot and full-field models. On the 3D-printed models, analytical and numerical models of recovery mechanisms, e.g., EOR, can be tested and validated experimentally. The 3D-printed core samples were created with different materials and printing technologies. The petrophysical properties, i.e., porosity and permeability, of the replicas were measured and matched their original Berea’s properties.
Using 3D Static Model Gridblocks’ Corner Nodes

Gridblocks’ Faces Triangulation

3D-Printable .STL Geometry

To boost the benefits of the technology of 3D-printing in oil and gas industry research, it is highly recommended that the 3D-printers’ manufacturers develop their technology to

(a) Reduce resolution limitations to facilitate 3D-printing tight rocks with smaller pore throats
(b) Increase physical-dimensions’ limitations to enable 3D-printing full-field models with larger dimensions
(c) Adapt 3D-printers to print with natural materials, e.g., sandstone grains, not only with synthetic ones
(d) Enable multimaterial printing in which an actual hydrocarbon material can be implanted inside the model
(e) Increase the mechanical stability of the 3D-printing materials to hold extreme conditions of high pressure and temperature
(f) Increase the chemical stability of the printing materials to avoid any interaction with the used experimental fluids

Figure 12. Triangulation of Cartesian corner nodes of the static model to generate the 3D-printable .STL geometry for a full-field model, e.g., the E-Segment of the Norne field in the North Sea.

Figure 13. 3D-printing the meshed geometry of the E-Segment of the Norne field in the North Sea in three different sizes.

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Notes
The authors declare no competing financial interest.

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REFERENCES

(1) Head, D.; Vanorio, T. Effects of Changes in Rock Micro-structures on Permeability: 3-D Printing Investigation. Geophys. Res. Lett. 2016, 43, 7494–7502.
(2) Torsøe, O.; Abtahi, M. Experimental Reservoir Engineering Laboratory Workbook; Norwegian University of Science and Technology 2003.
(3) Abou-Kassem, J. H.; Ali, S. M. F.; Islam, M. R. Chapter 1 - Introduction; Abou-Kassem, J. H., Ali, S. M. F., Islam, M. R. B. T.-P. R. S., Eds.; Gulf Publishing Company, 2006; pp. 1–6. DOI: 10.1016/B978-0-9765113-6-6.50007-1.
(4) Lake, L. W. Enhanced Oil Recovery; Prentice Hall, 1989.
(5) Fanchi, J. R. Principles of Applied Reservoir Simulation; Elsevier Science, 2005.
(6) Sinha, S. P. Numerical Simulation To Design and Analyze Pressure-Transient Tests in a Shaly, Interbedded Reservoir. SPE Middle East Oil and Gas Show and Conference; Society Petroleum Engineers 2005, 93491-MS.
(7) Blunt, M. J.; Bijeljic, B.; Dong, H.; Gharbi, O.; Iglauer, S.; Mostaghimi, P.; Paluszny, A.; Pentland, C. Pore-Scale Imaging and Modelling. Adv. Water Resour. 2013, 51, 197–216.
(8) Deglint, H. J.; Clarkson, C. R.; Ghanizadeh, A.; DeBuhr, C.; Wood, J. M. Comparison of Micro- and Macro-Wettability Measurements and Evaluation of Micro-Scale Imbibition Rates for Unconventional Reservoirs: Implications for Modeling Multiphase Flow at the Micro-Scale. J. Nat. Gas Sci. Eng. 2019, 62, 38–67.
(9) Hahn, B. H.; Valentine, D. T. Introduction to Numerical Methods. Essent. MATLAB Eng. Sci. 2017, 295–323.
(10) Mohaghegh, S. D. Data-Driven Reservoir Modeling: Top-down Modeling (TDM) : A Paradigm Shift in Reservoir Modeling, the Art and Science of Building Reservoir Models Based on Field Measurements; Society of Petroleum Engineers, 2017.
(11) Kalbar, M.; Perez, G.; Chopra, A. Applied Geostatistics for Reservoir Characterization; Society of Petroleum Engineers, 2002.
(12) Luo, H.; Delshad, M.; Pope, G. A.; Mohanty, K. K. Scaling up the Interplay of Fingering and Channeling for Unstable Water/Polymer Floods in Viscous-Oil Reservoirs. J. Pet. Sci. Eng. 2018, 165, 332–346.
(13) Pankaj, P. Characterizing Well Spacing, Well Stacking, and Well Completion Optimization in the Permian Basin: An Improved and Efficient Workflow Using Cloud-Based Computing. SPE/AAPG/SEG Unconventional Resources Technology Conference. Unconventional Resources Technology Conference: Houston, Texas, USA 2018, p 29. DOI: 10.15530/URTEC-2018-2876482.

(14) Ishutov, S.; Jobe, T. D.; Zhang, S.; Gonzalez, M.; Agar, S. M.; Hasiuk, F. J.; Watson, F.; Geiger, S.; Mackay, E.; Chalaturnyk, R. Three-Dimensional Printing for Geoscience: Fundamental Research, Education, and Applications for the Petroleum Industry. Am. Assoc. Pet. Geol. Bull. 2018, 102, 1–26.

(15) Watson, F.; Maes, J.; Geiger, S.; Mackay, E.; Singleton, M.; McGravie, T.; Anouillh, T.; Jobe, T. D.; Zhang, S.; Agar, S.; Ishutov, S.; Hasiuk, F. Comparison of Flow and Transport Experiments on 3D Printed Micromodels with Direct Numerical Simulations. Transp. Porous Media 2019, 129, 449–466.

(16) Bacher, M.; Schwen, A.; Koestel, J. Three-Dimensional Printing of Macro pore Networks of an Undisturbed Soil Sample. Vadose Zone J. 2015, 14, 1.

(17) Ishutov, S.; Hasiuk, F. J. 3D Printing Berea Sandstone: Testing a New Tool for Petrophysical Analysis of Reservoirs. Petrophysics 2017, 58, 592–602.

(18) Ishutov, S.; Hasiuk, F. J.; Fullner, S. M.; Buono, A. S.; Gray, J. N.; Harding, C. Resurrection of a Reservoir Sandstone from Tomographic Data Using Three-Dimensional Printing. Am. Assoc. Pet. Geol. Bull. 2017, 101, 1425–1443.

(19) Jiang, C.; Zhao, G.-F. A Preliminary Study of 3D Printing on Rock Mechanics. Rock Mech. Rock Eng. 2015, 48, 1041–1050.

(20) Bourke, M.; Viles, H.; Nicolli, J.; Lyew-Ayee, P.; Ghent, R.; Holmlund, J. Innovative Applications of Laser Scanning and Rapid Prototype Printing to Rock Breakdown Experiments. Earth Surf. Process. Landforms 2008, 33, 1614–1621.

(21) Hasiuk, F.; Harding, C. Touchable Topography: 3D Printing Elevation Data and Structural Models to Overcome the Issue of Scale. Geol. Today 2016, 32, 16–20.

(22) Berman, B. 3-D Printing: The New Industrial Revolution. Bus. Horiz. 2012, 55, 155–162.

(23) Almetwally, A. G.; Jabbari, H. CT-Scan Image Processing for Accurate Pore Network Modeling and Core Samples 3D Printing: Polynomial Interpolation & Geostatistical QC. 53rd U.S. Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association: New York City, New York 2019, p 8.

(24) Almetwally, A. G.; Jabbari, H. Development of Novel Workflow to Replicate Pore Network of Porous Core Samples through 3D Printing Technology. 53rd U.S. Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association: New York City, New York 2019, p 8.

(25) Hasiuk, F. J.; Florea, L. J.; Sukop, M. C. Three-Dimensional Printing: Transformative Technology for Experimental Groundwater Research. Groundwater 2016, 54, 157–158.

(26) I lowu, N. A.; Nardi, C.; Long, H.; Varlout, T.; Øren, P.-E. Effects of Segmentation and Skeletonization Algorithms on Pore Networks and Predicted Multiphase-Transport Properties of Reservoir-Rock Samples. SPE Reserv. Eval. Eng. 2014, 17, 473–483.

(27) Bose, S.; Vahabzadeh, S.; Bandopadhyay, A. Bone Tissue Engineering Using 3D Printing. Mater. Today 2013, 16, 496–504.

(28) Gao, W.; Zhang, Y.; Ramanujan, D.; Ramani, K.; Chen, Y.; Williams, C. B.; Wang, C. C. L.; Shin, Y. C.; Zhang, S.; Zavattieri, P. D. The Status, Challenges, and Future of Additive Manufacturing in Engineering. Comput. Des. 2015, 69, 65–89.

(29) Roebeck, K. 3D Printing: High-Impact Emerging Technology - What You Need to Know Definitions, Adoptions, Impact, Benefits, Maturity, Vendors; Tehbo, 2011.

(30) Kim, H.; Park, E.; Kim, S.; Park, B.; Kim, N.; Lee, S. Experimental Study on Mechanical Properties of Single- and Dual-Material 3D Printed Products. Procedia Manuf. 2017, 10, 887–897.

(31) Redwood, B.; Schoffer, F.; Garret, B. The 3D Printing Handbook: Technologies, Design and Applications; 3D Hubs 2017.

(32) Hwa, L. C.; Rajoo, S.; Noor, A. M.; Ahmad, N.; Uday, M. B. Recent Advances in 3D Printing of Porous Ceramics: A Review. Curr. Opin. Solid State Mater. Sci. 2017, 21, 323–347.

(33) Evans, B. Practical 3D Printers: The Science and Art of 3D Printing, 1st ed.; Apress: USA, 2012.

(34) Almetwally, A. G.; Jabbari, H. Experimental Investigation of 3D Printed Rock Samples Replicas. J. Nat. Gas Sci. Eng. 2020, 76, 103192.

(35) Almetwally, A. G.; Jabbari, H. Finite-Difference Simulation of Coreflooding Based on a Reconstructed CT Scan; Modeling Transient Oscillating and Pulse Decay Permeability Experiment. J. Pet. Sci. Eng. 2020, 192, 107260.

(36) Brunauer, S.; Emmett, P. H.; Teller, E. Adsorption of Gases in Multimolecular Layers. J. Am. Chem. Soc. 1938, 60, 309–319.

(37) Sing, K. W. S. Adsorption Methods for the Characterization of Porous Materials. Adv. Colloid Interface Sci. 1998, 76–77, 3–11.

(38) Abdelmalek, B.; Karpyn, Z. T.; Liu, S.; Yoon, H.; Dewers, T. Gas Permeability Measurements from Pressure Pulse Decay Laboratory Data Using Pseudo-Pressure and Pseudo-Time Transforms. J. Pet. Explor. Prod. Technol. 2018, 8, 839–847.

(39) Bisdorff, K.; Gauthier, B. D. M.; Bertotti, G.; Hardebol, N. J. Calibrating Discrete Fracture-Network Models with a Carbonate Three-Dimensional Outcrop Fracture Network: Implications for Naturally Fractured Reservoir Modeling. Am. Assoc. Pet. Geol. Bull. 2014, 98, 1351–1376.

(40) Salmachi, A.; Dunlop, E.; Rajabi, M.; Yarmohammadzadeoosi, Z.; Begg, S. Investigation of Permeability Change in Ultradeep Coal Seams Using Time-Lapse Pressure Transient Analysis: A Pilot Project in the Cooper Basin, Australia. Am. Assoc. Pet. Geol. Bull. 2019, 103, 91–107.

(41) Sneider, R. M.; Sneider, J. S. Abstract: New Oil In Old Places. Am. Assoc. Pet. Geol. Bull. 1999, 83 (2). DOI: 10.1306/E4FD4765-1732-11D7-865000102C1865D.

(42) Sarr, A.-C.; Husson, L.; Sepulcre, P.; Pastier, A.-M.; Pedoja, K.; Elliot, M.; Arias-Ruiz, C.; Solihuddin, T.; Aribowo, S.; Susilohadi. Subsiding Sundaland: REPLY. Geology 2019, 47, e470–e470.

(43) Fernandez, N.; Hudec, M. R.; Jackson, C. A.-L.; Dooley, T. P.; Duffy, O. B. The Competition for Salt and Kinematic Interactions between Minibasins during Density-Driven Subsidence: Observations from Numerical Models. Pet. Geosci. 2019, 3.

(44) Maleki, M.; Davolio, A.; Schozer, D. J. Qualitative Time-Lapse Seismic Interpretation of Norne Field to Assess Challenges of 4D Seismic Attributes. Lead. Edge 2018, 37, 754–762.

(45) Suman, A.; Mukerji, T. Sensitivity Study of Rock-Physics Parameters for Modeling Time-Lapse Seismic Response of Norne Field. Geophysics 2013, 78, D511–D523.