Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
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doi: 10.3850/978-981-18-8071-1_P094-cd

On the Relevancy of Systems Thinking in Permanent Plug and Abandonment Regulations in Norway

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More than 2500 production wells on the Norwegian Continental Shelf (NCS) will require permanent Plug and Abandonment (P&A) in the future. For this activity, the Norwegian regulations have, up to recently, adopted a principle of zero well leakage for perpetuity. This principle makes it appropriate to consider wells in isolation and ignore system effects, as any well leakage is unacceptable. The NORSOK D-010 issued in 2021 introduced a shift to this principle, by tolerating low-rate well leakage. Whether it is still appropriate to ignore the system effects has not yet been clarified. This article considers the relevancy and role of systems thinking in Norwegian P&A regulations, where Leveson's STAMP model is used as basis for the analysis. The system-wide effects investigated include well leakage in area perspectives, and whether feedback concerning well leakage is adequate for proper risk management. The analysis point to important system effects. Wells tend to cluster on the NCS, and certain clusters share characteristics associated with an elevated well leakage risk. We argue that a system's approach to P&A is required to properly manage the well leakage risk. The analysis indicates that feedback from well monitoring and well leakage detection fails to verify that the system operates properly, making identification of best technologies and best practices in P&A more difficult. A systems theoretical approach represents a way to strengthen current regulations.

Keywords: Complex systems, Systems perspective, STAMP, P&A, standards, regulations, well leakage risk.

1. Introduction

Managing the risks associated with the increasingly complex systems of modern society is a major challenge. Understanding and managing these risks have been key priorities in previous decades (McDaniel and Driebe, 2006; Helbing, 2013). Models such as System Theoretic Accident Model and Process (STAMP) and the Function Resonance Analysis Model (FRAM) were developed to improve the analysis and management of the risk associated with complex systems. There is broad agreement that adopting a systems perspective has merits. Langdalen et al. (2020a; 2020b investigate the merits of adopting a systems perspective in the analysis of risk.

The focus of this article is to assess whether systems thinking can improve the Norwegian authorities' management of the well leakage risk associated with permanent Plug and Abandonment (P&A) of wells on the Norwegian Continental Shelf (NCS). All wells experience P&A at the end of their productive life. The primary goal of P&A is to install barriers which reseal the reservoir(s) in a manner which permanently prevents the migration of fluids from the reservoir(s) to the outer environment. As of 2015 a total of 2880 wells had been permanently abandoned on the NCS, and a further 2,637 had yet to be permanently abandoned (Khalifeh and Saasen, 2020). The operating companies on the NCS are responsible for carrying out P&A in accordance with the Norwegian petroleum regulations for P&A. These regulations are, however, formulated in a general manner, and refer to the industry standard NORSOK D-010 (2021) for further guidance. This standard is instrumental in interpreting and operationalizing Norwegian P&A regulations, and the 2021 revision of this standard represented a shift in the approach to P&A by abandoning the requirement of zero leakage in acceptance that the current practice of using cement as a barrier material means that the barriers are not impermeable and therefore has a potential for some seepage through them. The Norwegian authorities have the ultimate responsibility for managing the well leakage risk post P&A, as responsible for the regulatory regime which governs P&A (including post P&A well leakage detection), and for supervising the operating companies which carry out P&A. The question is whether Norwegian authorities would benefit from a stronger emphasis on the systems perspective in their management of the well leakage risk post P&A?

Several frameworks attempt to incorporate the systems perspective in risk management. The FRAM method emphasizes scenario analysis, while the STAMP model emphasizes the significance of feedback in complex systems. Feedback is crucial in a regulatory setting, so STAMP is selected for the analysis of the role of systems thinking in P&A in this article.

The article presents systems thinking in Section 2, the P&A context in Section 3, and discuss the applicability of STAMP to Norwegian P&A regulations and practices on in Section 4. Section 5 is the concluding remarks.

2. Systems Thinking

Leveson's STAMP model, presented in "Engineering a Safer World" (2016), is widely recognized as a useful model for understanding and managing the risk associated with complex systems, and the STAMP model emphasizes the importance of feedback channels. According to Leveson, managing the risks associated with the increasingly complex systems we construct today requires a new approach.

2.1. *Complex systems, and the risks associated with such systems*

The body of literature concerning complexity and complex systems is voluminous and stems from a wide range of scientific disciplines. There is no widely recognized definition of the term complex system. According Bocarra (2010) "(…) a system is a collection of interacting elements making up a whole (…)" (p. 1). There is however agreement on certain properties which characterize complex systems. According to Bocarra (2010) a key characteristic of complex systems is that they exhibit emergence, and their emergent behaviour does not result from the existence of a central controller. Examples of emergent behaviour include the myriad of geometries found in snowflakes, the intricate interactions found in schools of fish and bird flocks, or a bank run.

Emergent behaviour is a deep scientific topic, but for the purpose of this article the root causes of emergent behaviour are the most important. Emergent behaviour may arise from interdependencies, interconnections, and feedback loops within complex systems. Complex systems can exhibit non-linearity between the variables within the system, and it can even be difficult to establish the cause-and-effect relationships within the system. Another key characteristic is dynamic complexity, where the long-term effect of a change within the system differs from the short-term effect.

The modelling of complex systems is inherently difficult. A key indicator of weak knowledge is that models of the system make uncertain predictions. Managing the risk associated with complex systems is a key challenge going forward, and a wide range of tools have been developed to improve the risk management of such systems. Within engineering Leveson's STAMP model is widely recognized as useful for understanding and managing the risks associated with complex systems.

2.2. *The STAMP model*

Leveson's STAMP model is presented in "Engineering a Safer World" (Leveson, 2016). Leveson identifies and addresses some key challenges associated with highly complex socio-technical systems. These challenges include the increasing pace of technological change, digitalization, systems where cause and effect relationships are non-linear, systems where component interactions are incomprehensible, inadequate communication between humans and machines, and changing regulatory and public views of safety.

In the text Leveson describes challenges associated with highly complex sociotechnical systems, including emergent behaviour. Leveson argues that a new approach, STAMP, is required to ensure that such systems are designed and operate in a safe manner. According to the STAMP model a well-designed system is contingent upon a precise definition of the failure states of the system. The basic building blocks of the STAMP model, as illustrated in Figure 1, are (i) safety constraints, (ii) a hierarchical control structure, and (iii) process models.

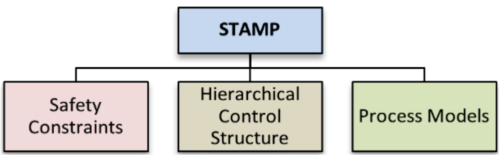

Fig. 1. The basic building blocks of STAMP

Leveson (2016) states that: "(…) emergent properties, such as safety, arise from the interactions among the system components. The emergent properties are controlled by imposing constraints on (…) the components. Safety then becomes a control problem where the goal of the control is to enforce the safety constraints." (p. 75). STAMP's hierarchical control structure implies that safety constraints are imposed on a lower level in the hierarchy and need to be communicated in a clear and precise manner. Similarly operational experience can provide crucial feedback for those responsible for formulating and imposing safety constraints at higher levels in the hierarchy. Feedback channels monitor system performance by collecting operational experience data as seen in Figure 2.

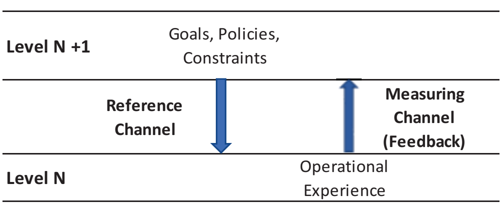

Fig. 2. Communication channels between control levels in STAMP inspired by Leveson (2016), p. 83.

According to Leveson (2016) feedback is a basic part of STAMP, and risk management relies on information flow. Early detection of sub-optimal system performance is crucial, and continual improvement relies on feedback. Selecting appropriate feedback channels is crucial in the system design.

3. P&A Context

Permanent P&A is generally understood as the plugging (installation of cross-sectional permanent barriers) of a well with no intention to re-enter or re-use it. P&A is primarily carried out to prevent the flow of hydrocarbons from reservoirs to the outer environment, and secondarily to prevent flow between reservoirs.

3.1.*Norwegian P&A regulations*

Norwegian P&A regulations lean more towards function-based than prescriptive. Function-based regulations effectively delegate responsibility from the regulator to the operators responsible for planning and executing the P&A activities. The internal control principle is a cornerstone in Norwegian P&A regulations. The principle state that operators are responsible for ensuring that their activities are in line with the primarily function-based regulations on the NCS. This system is a form of self-regulation and relies on a high level of trust between operators and regulators (Engen et al., 2017)

Current P&A regulations relies on the principle of redundancy by requiring that each well is equipped with a minimum of two well barriers (Khalifeh and Saasen, 2020). Norwegian P&A regulations require that each barrier is verified during P&A, and states that that the wells are permanently abandoned with an eternal perspective. This means that the P&A solution should make consideration for all foreseeable geological and chemical processes such as pressure build-up in the reservoir. The number of barriers installed during P&A depend on the number of reservoirs the well has penetrated. The most common P&A solution on the NCS is to install the prescribed number of barriers by installing cement plugs composed of Portland cement in the wellbore (ibid.). Alternative well barrier materials exist, exemplified by formation as barrier, bismuth, grout, and polymers and composites. (ibid.). A comprehensive review of alternative barrier materials, and their strengths and weaknesses may be found in Khalifeh and Saasen (2020). Post P&A all wells with a potential for flow of hydrocarbons, will be isolated by at least two independent well barriers above the shallowest hydrocarbon reservoir.

The Norwegian Environment Agency (NEA) is tasked with reducing Norwegian greenhouse gas emissions, managing Norwegian nature, and preventing pollution. NEA requires that a field shall be surveyed at specified intervals post decommissioning (NEA, 2020). Such surveys may detect well leakage post P&A, but P&A of wells may take place a long time prior to permanent abandonment of a field. There is no mandatory well monitoring regime which follow directly from the activity of P&A on the NCS at present. Further, it is not clear how a well which experience leakage post P&A will be handled, or by which regulatory agency (NEA, 2021).

3.2. *NORSOK D-010*

The NORSOK D-010 (2021), titled "Well Integrity in drilling and well integrity" provides guidance on how P&A should be carried out according to Norwegian regulations. NORSOK D-010 is not formally a part of the Norwegian Petroleum regulations, but Norwegian P&A regulations refer extensively to the standard for guidance. This gives the NORSOK D-010 (2021) a normative role. The standard is the industry's attempt at interpreting and operationalizing the Norwegian P&A regulations. NORSOK D-010 includes requirements, recommendations and well barrier schematics with examples of acceptable solutions to specific situations (ibid). Prior to 2021 planning for zero leakage post P&A was the ruling principle in NORSOK D-010 (2021). The 2021 revision of NORSOK D-010 explicitly accepts well barrier materials with some permeability, which is in line with the practice of using cement as barrier material. This implies that well leakage from permanently abandoned wells, albeit at very low rates, is acceptable. The impact of NORSOK D-010 (2021) on P&A solutions and practices on the NCS is profound. It states that P&A solutions and practices which deviate from those described in the standard may be acceptable, but the operating company are required to document that alternative solutions comply with regulations.

A key feature of NORSOK D-010 is the emphasis on well leakage, the first order consequence of loss of well integrity. The second order consequences of well leakage are not addressed explicitly in NORSOK D-010.

3.3. *DNVGL-RP-E103*

DNVGL-RP-E103 (2016), being a recommended practice for how to perform risk-based abandonment of offshore wells, states that the well abandonment design should be selected based on well specific data, and an evaluation of the leakage risk associated with each well. According to DNV this evaluation should consider the flow potential of the well, whether valued ecological components are present near the well and how the well fluids are expected to disperse should a leakage occur. An assessment of these factors requires the use of complex models which use environmental data, geological data, and meteorological and oceanic data as input. This approach to P&A is much broader in scope compared to Norwegian P&A regulations and NORSOK D-010 (2021). According to Fanailoo et al. (2017) Norwegian regulatory authorities have accepted P&A solutions which deviate from Norwegian P&A regulations and NORSOK D-010 (2021) supported by DNVGL-RP-E103 (2016). This indicates that Norwegian regulators are open to P&A solutions which deviate from NORSOK D-010, provided that an evaluation of the well leakage risk post P&A is a part of the decision basis. This regulatory practice may be interpreted as a partial admission that a systems perspective has merits in a P&A context.

4. Analysis Based on the STAMP Model

We propose that from the perspective of the Norwegian authorities the process of ensuring that wells have been, and continues to be, permanently abandoned in a responsible manner should be treated as a complex system. There are several arguments for categorizing P&A on the NCS as a complex system. The severity of the consequences of well leakage depends in part on the ambient levels of hydrocarbon contamination, and the vulnerability of local ecosystems. Ecosystems are, generally, considered complex systems, and proper management of the well leakage risk associated with P&A incorporates assessing the potential impact of well leakage on local ecosystems. In the case of well leakage post P&A, climate gases may ultimately reach the atmosphere and contribute to global warming.

Proper management of the well leakage risk involves an understanding of the global warming potential of well leakage post P&A. These are just two examples which illustrate the complexities of managing the well leakage risk post P&A. We argue that ensuring that well P&A is carried out in a responsible manner on the NCS can be characterized as managing a complex system.

Considering the management of P&A on the NCS as a complex system, the STAMP model has been used as a basis for the evaluation of how Norwegian authorities govern P&A on the NCS. Through regulations and regulatory practices Norwegian authorities define the goal for P&A activities on the NCS, the constraints operators face while carrying out P&A, and the feedback operating companies on the NCS are required to present the authorities with prior to, during, and post P&A. The focus of the evaluation is whether goals and constraints for P&A on the NCS properly account for system effects, and whether existing feedback channels enables Norwegian authorities to monitor systems operations.

The discussion evaluates the potential impact of adopting more of a systems perspective in the governance of P&A in Norwegian waters. Based on the evaluation five key issues with a high impact on P&A have been selected. Sections 4.1. and 4.2. investigate whether the safety constraints, (P&A regulations) are fit for purpose. Section 4.3. investigate whether the feedback channels within the hierarchical control structure, ensure proper monitoring of system performance. Section 4.4. investigates whether the system failure states are properly defined. Section 4.5. investigates whether the Norwegian authorities' (implicit) goal for P&A is the most appropriate.

4.1. *Area effects of well clustering*

A dilemma of current P&A regulations and practices on the NCS from a systems perspective is related to geographical areas with large well clusters. It may be argued that the effect of the recommendations, requirements, and examples of acceptable solutions in NORSOK D-010 (2021) resembles that of prescriptive regulations. The NORSOK D-010 does not address that the expected aggregated well leakage in an area depend, in part, on the well count in the area.

In the 2021 revision of NORSOK D-010 (2021) well leakage, albeit at a very low rate, is acceptable (as some permeability is allowed). The current regulations do not explicitly address the potential impact of low-rate leakage from a high number of wells in a confined geographical area. The actual impact on local ecosystems of well leakage post P&A will depend on the ambient contamination, the aggregated hydrocarbon contamination of the marine environment from all other hydrocarbon sources. These sources include natural seepage, produced water, accidental hydrocarbon discharges, shallow gas leakage from wells, discharges from drill cuttings, leakages from pipes and flanges, and well leakage post P&A from neighbouring wells.

Leakage through permeable well barriers is not the only scenario which may lead to well leakage post P&A. The likelihood of all other well leakage scenarios in an area will presumably also increase with the number of wells in the area, all other factors being equal. The major field developments on the NCS have large well inventories, but current P&A regulations do not explicitly address the elevated leakage risk in these areas. It may be argued that the elevated well leakage risk and the elevated expected cumulative well leakage rate post P&A in regions with a high well density should be addressed in P&A regulations and standards.

One may argue that current regulations and practices are sufficiently stringent to ensure an acceptable level of well leakage risk post P&A in areas with a high well density. This would, however, indicate that current P&A regulations and practices may be too stringent in areas where the well density is low. The result may be that the resources set aside for P&A is allocated amongst the fields in an inefficient manner.

To summarize, the rationale for arguing that area effects are important in P&A is that the impact of well leakage for local ecosystems is contingent upon the hydrocarbon contamination from all other sources. In an area with a high number of wells, the ambient level of contamination is, in part, contingent upon the well leakage rate from neighbouring wells. This is not properly addressed in current P&A regulations.

4.2. *Well clusters sharing well characteristics indicative of an elevated well leakage risk*

Wells within a field often share key well characteristics, and this is an issue which may benefit from a systems perspective. These characteristics include reservoir temperature, reservoir pressure, well depth, the concentration of the highly corrosive gas H_2S and the less corrosive gas CO_2 in the reservoir fluids, reservoir compaction and subsidence, inadequate or missing well logs, the presence of shallow gas pockets close to the well bores, the properties of the formation surrounding the well bore, and whether the formation surrounding the wellbore include sections of creeping shale to name some (Vrålstad et al., 2019). These well characteristics may be shared by all, or most of the wells in a field. Current P&A regulations and practices do not address all well characteristics which are associated with an elevated well leakage risk. Major field developments on the NCS may have a high number of co-located wells which share well characteristics associated with an elevated well leakage risk post P&A.

One may again argue that current regulations and practices are sufficiently stringent to ensure an acceptable level of well leakage risk in these fields. This implies that current P&A regulations and practices may be too stringent in fields where the shared well characteristics are not associated with an elevated well leakage risk.

To summarize, current P&A regulations and practices do not fully address area effects associated with an elevated well leakage risk. The result may be an inefficient allocation of resources within P&A in Norwegian waters.

4.3. *Feedback channels – well monitoring and well leakage detection post P&A*

The focus here is on feedback channels for well leakage post P&A. Leveson (2016) state that feedback channels include audits, performance assessments, incident and accident investigations, and reporting systems designed to register and address anomalies.

Disregarding cost, current technologies allow for continuous leakage monitoring of permanently abandoned wells on the NCS. If a potential well leakage has been detected, it can be verified, and the leakage rate can be determined. Samples of the well fluids can then be collected for analysis to determine whether the well release shallow gas, or gas from the deep reservoir.

So, what is status quo in well leakage detection and follow-up post P&A in Norwegian waters? Extensive documentation is collected prior to and during P&A. Part of the P&A process is to verify that the barriers are acceptable. NORSOK D-010 (2021) describes these well barrier verification procedures. But which types of feedback channels can inform on the performance of NCS well barriers post P&A?

At present Norwegian P&A regulations do not require well leakage monitoring or surveillance post P&A. There are certain regulations and practices which has a chance of detecting well leakage post P&A for certain wells, but these regulations do not encompass all wells. A brief review of current practices in well leakage detection is in order. It is prudent to distinguish between well leakage consisting primarily of natural gas, and well leakage where the crude oil fraction of the released fluids is significant. Post P&A leakage of crude oil will result in the formation of oil slicks on the sea surface, provided the leakage rate is sufficiently high. These oil slicks can be detected visually through satellite imagery. The regions of the NCS with operating fields are routinely monitored for oil slicks using satellite imagery. This does, however, not include decommissioned fields or regions with permanently abandoned exploration wells in fields which have not yet been developed. Post decommissioning Norwegian regulations require visual surveys of abandoned installations, and the collection of water and sediments samples at prescribed intervals. The visual surveys of abandoned fields are, however, not aimed specifically at well leakage detection, and the mandatory water and sediment samples are all collected at a significant distance from the location of the permanently abandoned wells (NEA 2020; 2021). The governmentally funded Mareano project use multi beam echo sounder to collect data which can detect hydrocarbon seepage in Norwegian waters. These seepages are predominantly natural, but some seepages are co-located with permanently abandoned wells (Thorsnes, 2021). Seepages on the NCS which are co-located with wells are also discussed in Vielstädte et al. (2015). According to NEA (2021) it is not clear how Norwegian regulators should react to indications that a well may be experiencing well leakage post P&A. It should be noted that the release of hydrocarbons near a permanently abandoned well may be the result of natural seepage, well-induced leakage of shallow gas, or well induced leakage of hydrocarbons from a deep reservoir. Indications of well leakage can be verified through visual observation, the leakage rate can be measured, and collection and analysis of a samples of the released hydrocarbons can determine whether the hydrocarbons originate from a shallow gas reservoir or a deep reservoir. How Norwegian regulators react to data which indicate that a well is experiencing leakage post P&A is not public knowledge. In their 2021 report the Norwegian Environment Agency recognizes the need for more strict requirements regarding monitoring and surveillance of permanently abandoned wells in geographical areas where the prevalence of shallow gas pockets is high (NEA, 2021). According to NEA (2021) technologies for well leakage surveillance and monitoring post P&A exist and are warranted when the cost is not grossly disproportionate to the benefits.

To summarize, the quantity and the quality of the data which indicate whether a well is leaking post P&A are insufficient. Leveson (2016) states that proper feedback channels are a prerequisite for a well-functioning system. Well leakage detection is crucial feedback in P&A. This should be addressed going forward.

4.4. *Are system failure states properly defined?*

Hydrocarbon seepage which is co-located with a permanently abandoned well may either be natural seepage, or well induced leakage from a shallow or deep reservoir. At present only well induced leakage from the deep reservoir is considered well leakage post P&A. A shallow gas seep which is co-located with a permanently abandoned well could, arguably, also be considered well leakage post P&A if the seepage is likely to be drilling-induced. This issue has received considerable attention from Norwegian regulators in recent years. The primary objective of P&A is to ensure that well fluids from the deep reservoir do not migrate to the outer environment through the well bore. The migration path of shallow gas seepages which are co-located with wells may, at least in part, be the wellbore or drilling-induced cracks and fissures in the formation surrounding the wellbore. Natural seepages are, however, known to be prevalent in the vicinity of field developments, and have historically been a key indicator for promising exploration blocks. Further evidence is required to confidently categorize shallow gas seeps which are co-located with permanently abandoned wells as shallow gas well leakage.

The relevant authority should clarify how to address shallow gas seepages when they are co-located with permanently abandoned wells. Failure states should be formulated in a clear and precise manner (Leveson, 2016), and that is arguably not the case for well leakage post P&A.

4.5. *Minimizing well leakage or minimizing the consequences of well leakage?*

The primary goal of Norwegian P&A regulations may be interpreted as minimizing well leakage post P&A. A fair question is whether a more appropriate goal in P&A would be to minimize the second order consequences of well leakage, such as the consequences of well leakage for personnel safety, the environment, and the climate. If so, the Norwegian P&A regulations, and by extension the NORSOK D-010 standard, should shift their focus towards the second order consequences of well leakage.

DNVGL (2016) argues that well abandonment designs should be selected based on each well's characteristics and an evaluation of the leakage risk associated with each well. The multitude of variables which influence the well leakage risk are not explicitly implemented in Norwegian P&A regulations at present. It may prove difficult to develop regulations and standards which account for the key variables which influence the well leakage risk post P&A. It should however be feasible to develop more flexible regulations and standards. At present the most common P&A solution is to install well barriers composed of Portland cement of a prescribed length (Vrålstad et al., 2019). This is a possible solution to a specific situation presented in the well barrier schematics within NORSOK D-010 (2021). DNVGL (2016) is one initiative aimed at making the allocation of the resources set aside for P&A more efficient. The well specific leakage risk varies broadly among the wells in Norwegian waters, and a transition towards more tailor-made P&A solutions may lead to considerable reductions in the well leakage risk and/or the cost of P&A.

5. Conclusions

There is broad agreement that proper management of the risks associated with complex systems represents a major challenge. We argue that, from the Norwegian authorities' perspective, managing the post P&A well leakage risk on the NCS is the management of a complex system. Our analysis of current regulations and practices for P&A in Norwegian waters indicate that adopting more of a systems perspective would be beneficial. An emphasis on the area-specific well leakage risk rather than the well specific well leakage risk would presumably lead to a more efficient allocation of the resources set aside for P&A. A more precise definition of well leakage, the primary failure state of the system, would also be beneficial. Our analysis indicates that the current feedback channels within the system are insufficient. An improved regime for post P&A leakage detection through well monitoring and/or surveillance would provide crucial data on the status of NCS wells post P&A. Continual improvement processes rely on adequate feedback concerning the performance of the existing permanent well barriers on the NCS. Norwegian regulators have, supported by the guideline DNVGL-RP-E103 (2016) for risk-based abandonment of offshore wells, accepted P&A solutions which deviate from NORSOK D-010. This indicates that Norwegian authorities are open to new approaches to P&A. We suggest that Norwegian authorities should give more weight to the system's perspective in P&A going forward.

Acknowledgement
This work has been funded by the Research Council of Norway through the Petromaks2 Research Program, project no. 295173.

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