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SESSION ONE: PURPOSE VALUE AND PREDICTIVE POWER OF MODELS

Back-to-Basics Understanding Supporting Effective Models & Decisions

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As reservoirs become more complex, timelines are shrinking, and there is pressure to deliver faster. This creates a contradiction: the perceived need for more and more detailed models to manage complexity, versus a demand for speed, which drives the need for simplification.

Capturing basic understanding of reservoir plumbing and impact on flow behaviour is more important than ever. Time and time again teams get bogged down in complexity, sometimes missing scenarios which are important for decisions. Shell is using scaled modelling, with decision quality to address the complexity paradox:

1. Understanding drivers of reservoir performance, decision-critical risks, related uncertainties and differentiating scenarios early

2. Simple tools for credible (benchmarked) forecasts to establish impact.

3. Only build high resolution or “complex” models where decisions cannot be addressed with simple tools.

We present a study of a structurally complex gas field in Australia where main risks are water breakthrough and connectivity. Whilst the structure is the key uncertainty, its complexity requires significant time to construct in 3D.

To deliver a model for rapid decision-making, a back-to- basics approach was employed. Detailed interpretation underpinned a simple map-based evaluation of top reservoir structure, thickness, and fault position. Seismic and well data were used with a global analogue database to define a range of depositional scenarios for the fluvial-deltaic environment and used to derive property maps. Uncertainty of Volume was established using maps. The calculated volumes were used to apply adjustments to the existing dynamic model. Analysis of fault juxtaposition, reservoir connectivity and property heterogeneity was undertaken using adjusted grids.

This approach was faster, allowed for evaluation of uncertainties, provided a robust forecast range, and met objectives in a simple way. Solid understanding of reservoir performance, delineation of potential subsurface scenarios and up-front framing is key to simplify models and answer the right questions.

More than a Database: Insightful Ground Models for Offshore Wind Farms

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The challenge of site characterisation for offshore wind farms is not a lack of data, but ensuring that geological, geophysical and geotechnical information is transformed into understanding that supports project feasibility and engineering decision-making. As offshore wind developments increase in scale and complexity, and the global energy market remains volatile, it is increasingly important that engineering geological models provide targeted insight and minimise uncertainty, not just a data management solution.

Engineering geological practice has long recognised the importance of geological models as more than compilations of data. Drawing upon principles established in onshore practice several decades ago, engineering geological models seek to explain the origin, distribution and behaviour of geological materials and processes, providing a framework within which uncertainty and risk can be understood and minimised. The value and usefulness of a model therefore lies not in its complexity, level of detail or visual sophistication, but in its ability to support engineering solutions.

This presentation will cover the application of engineering geological modelling principles to offshore wind development with examples from real world projects where poor predictions can have real engineering impacts. It will demonstrate the benefits of thorough geological understanding and sound but flexible conceptual models, for integrating costly and time-consuming survey datasets, and extracting maximum value for wind farm developers.

In summary, useful geoscience models are suggested to be those that:

Generate understanding rather than merely collating data,

Provide insights that can be appreciated by relevant stakeholders (specialist or non-specialist),

Facilitate the effective communication of uncertainty, hazard, and risk,

Enable engineering solutions, and

Guide decision-making.

While advances in data acquisition, visualisation and digital modelling continue within geoscience practice, the fundamental requirement remains unchanged: expert geological interpretation grounded in sound conceptual understanding. When done correctly, the offshore engineering geological model exemplifies a useful geoscience model.

Seismic modelling of dolomite bodies in the subsurface: making a geological model useful

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Seismic imaging of the subsurface is critical to the exploitation of hydrocarbon, geothermal resources and minerals, geostorage and geohazard prediction. Despite improvements in seismic image quality and processing, challenges to qualitative and quantitative seismic image interpretation remain in carbonate strata. In particular, it can be difficult to differentiate between limestone and dolomite using seismic reflection data. This often reflects the small size of dolomite bodies, placing them at the margins of seismic resolution. However, the significantly different physical properties of dolomite compared to limestone means that it is important to identify its presence with confidence when planning reservoir development.

In this study, 3D seismic modelling was conducted on a geocellular model of a well-exposed outcrop to bridge this gap in understanding. The models, which contained small (<500m wide) non-stratabound dolomite bodies and thin stratabound dolomitised beds, were used to test the sensitivity of seismic images to dolomite–limestone acoustic impedance, seismic wavelet selection and noise. The non-stratabound dolomite bodies were imaged well, although they were transparent and non-reflective. Conversely, individual stratabound dolomite bodies could not be reliably identified on the seismic models, although their presence could be inferred. Overall, the seismic response was poorer at higher signal-noise ratios and was influenced by the choice of wavelet.

The usefulness of our approach, which seismically modelled a geocellular model of a known outcrop, is that it provides a true representation of both sedimentary strata and their diagenetic overprint. This allowed both geological realism and direct comparison between the outcrop, the geological model and output seismic images. The results are important because the detection of dolomite from seismic reflection data is itself critical to elucidating the spatial relationship between past fluid flow and reaction and present-day porosity. This in turn is critical to improving our ability to predict geological heterogeneity in the subsurface.

How useful are numerical models of volcanic and igneous plumbing systems (VIPS)?

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A common criticism of numerical models in general and of models of volcanic and igneous plumbing systems (VIPS) in particular is that they are oversimplified and do not represent nature accurately. Models are, by definition, simplified representations of reality. Therefore, what is questioned is the degree of simplification and if numerical models remain useful despite a high degree of simplification. The answer depends on what is expected from numerical models. Numerical models can be used to make predictions with possible societal or economic applications, or they can be used to test a scientific hypothesis, and/or to understand a process, which make them useful academically.

The challenge in modelling VIPS is the complexity of the system and the scarcity of data. VIPS are complex multiscale, multicomponent systems that cannot be directly observed. These two aspects (complexity and data scarcity) severely limit our ability to produce deterministic models that are accurate enough to have predictive power. However, assumptions can be made, and simplified models can be built that include basic laws of physics. They are useful to test hypothesis and validate or invalidate conceptual models. For example, in the 2000s, several teams tested numerically the conceptual model of crustal melting being caused by heat transferred from underplating basalt. These teams independently showed that crustal melt production in these specific conditions is very limited and that the conceptual model needs to be revised.

Endmembers in terms of simplification are the so-called toy models. They are highly idealised and used for understanding processes rather than representing nature. For example, toy models were used to explain how melt extraction and accumulation self-organize, or how the structure of a volcanic plumbing system affects both the duration of volcanic eruptions and the duration of repose periods between eruptions.

SESSION TWO: SIMPLICITY, COMPLEXITY AND FITNESS FOR PURPOSE

Simple Rules, Complex Outcomes: Modelling as a Tool for Discovery in Geoscience

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Geoscience models are often evaluated by their ability to reproduce observations, yet their greatest value may lie in predicting behaviours not yet observed. This contribution explores how both simple and complex models can act as engines of discovery by revealing emergent processes that challenge existing conceptual models, while raising questions about model purpose, conceptual assumptions, and appropriate levels of complexity.

First, we present a deliberately simple theoretical-numerical example (Poulet et al., 2025, Geology), in which minimal process representation produces an unexpected system behaviour not previously identified in analogue or field observations, whereby very small strata dip angles strongly influence density-driven flow in anisotropic rocks. This case highlights how reduced-complexity models can isolate first-order controls, expose implicit assumptions, and guide targeted data acquisition. Here, simplicity does not limit usefulness; rather, it sharpens predictive power by clarifying causality.

Second, we contrast this with a coupled, process-rich model of shear zones (Alevizos et al., 2014, JGR), where the interaction between deformation, thermal evolution, chemical reactions and hydraulic feedbacks generates emergent stick-slip dynamics that cannot be inferred from any individual process. In this context, complexity is essential: it enables the identification of feedback-driven behaviours that would remain invisible in simpler frameworks, but also introduces challenges in interpretation and validation.

Together, these examples illustrate that model usefulness is not a function of fidelity alone, but of how effectively a model interrogates the unknown. Models become most valuable when they (1) explicitly encode and test conceptual hypotheses, (2) reveal gaps in observational datasets, and (3) generate falsifiable predictions that can be pursued experimentally or in the field.

This contribution argues for a reframing of geoscience models from tools of confirmation to engines of discovery, where their predictive capacity is central to their scientific value.

Building the “Right” Models at the Appropriate Scale

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The significant increase in the computing power and software capability available to Development and Production Geologists has led to progressively more fine scale and complex geological models. This increasing level of modeled detail is linked to a fundamental belief that if heterogeneity can be captured in a geologically “realistic” way that history matching will be easier and forecasting will be more robust. It takes significant time to build a finely detailed static model and when project deadlines are tight the focus of the sub-surface team tends to be on a single geological scenario. Uncertainties then tend to be analyzed in the dynamic realm, and do not look outside that one subsurface scenario.

In the period 2015-2018 a study of static modelling practices was undertaken across the Shell portfolio. The long-term aim of the study was to define the model scale required to address specific business decisions and to therefore assist geologists in the building of the “right” suite of models at the appropriate scale.

Since 2018 the modelers in Shell have been on a journey to change the approach to reservoir modeling and uncertainty evaluation. Whilst remaining focused on decisions, there is increased focus on the risks impacting the subsurface and the mitigations for these. This paper will present results of the 2018 study and the current approach to reservoir modeling in Shell.

AvaFan: Designing an analogue modelling project to study autogenic and allogenic processes

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It is widely known that the record of sedimentary systems is steered by autogenic and allogenic signals. This confronts us as geologists with a problem: Without understanding the feedback of autogenic processes and allogenic signals, we cannot establish correct interpretations of the record stored in sedimentary systems.

Here, we present the design of AvaFan: “Allogenic vs Autogenic processes: On the preservation and shredding of environmental signals in submarine fans” - a DFG funded project using analogue modelling to disentangle the influence of autogenic and allogenic signals. AvaFan operates with two main principles: Firstly, we need to understand what the response of our submarine system is to purely autogenetic processes to be able to investigate how allogenic signals modify this response. Secondly, we need to conduct this investigation on a different hierarchal scale than individual runs to introduce an appropriate complexity. The three aims of the project are: 1. First analogue studies on stratal patterns and heavy mineral distributions that are purely produced by self-organizing autogenic processes, 2. Investigation of a wide range of allogenic boundary condition signals cycles building on the insights gained from studies of purely autogenic depositional responses. AvaFan will enable us to pinpoint robust characteristics to identify different allogenic fingerprints. 3. Investigation of heavy mineral and grain size distribution for compositional bodies built by subsequent flows

Experimental setup relies on previous insights from experiments run at the Eurotank facilities, but develops them further and adapts them to the questions at hand. The concept of AvaFan is the combined use of analogue modelling and experimental sediment composition analysis. This approach allows the manipulation of specific boundary conditions, and therefore their influence on the depositional record can be directly quantified without the increased complexity of multiple controlling factors present in natural systems.

When is a geomodel ready to be sent to flow simulation?

Thomas Jerome, *Per Pedersen*

A geomodel is a three-dimensional grid representing the geology of a reservoir. An estimate of the rock characteristics (lithology, porosity…) is calculated in each of its cells, often using geostatistical tools. A geomodel is built at the request of the simulation engineers. They need it to study how fluid will move through the reservoir.

How does one decide that a geomodel is good enough to be sent to flow simulation?

Geostatistics have strong mathematical foundations. Does it mean that using geostatistics per se ensures that a model is good? The author doesn't believe so. Geostatistical tools remain… tools. Using them right is what matter.

Others will say that a geomodel is validated once simulation engineers show that it is able to match engineering data. But are engineers here to validate our geomodel or to validate the geological interpretation of the reservoir?

We believe it is the later and from there comes our answer: a geomodel is ready for flow simulation when the geoscience team confirms that it captures their understanding of the geology. Not because a given algorithm, geostatistical or not, is used. A geomodel misrepresenting the team's geological interpretation should never stand between the geoscientists and the engineers.

What does it mean for the geoscience team?

Firstly, "the algorithm gave us this result" is never a good answer to your team. "We used this algorithm because it allowed us to capture our interpretation" is.

Secondly, they need to be ready to explicit their geological interpretation with special attention to be given to connectivity. Geostatistical tools are great at capturing statistics, less at capturing expected connectivity.

Thirdly, and it's the most important point, they need to be ready to push back against a geomodel that simply doesn't capture their interpretation.

This presentation will illustrate those conclusions with a few examples.

Conceptual bias in exploration targeting: an example of adaptive reasoning

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Exploration targeting programs rely heavily on conceptual models to define prospectivity, yet these models inherently prioritise certain observations, processes, and spatial representations over others. This creates a risk of conceptual bias, where prior assumptions constrain how geological systems are interpreted and subsequently explored. While models and priors provide a necessary framework, their limitations become evident when applied to complex real-world systems such as the Yeneena Basin of the Paterson Orogen, NW Australia.

Most Australian basin-hosted Cu systems deviate from classical sediment-hosted stratiform copper models, raising questions about the transferability of established paradigms and the more consequential influence of factors such as age, deformation, and structural complexity. Studies of the Nifty Cu deposit in the Yeneena Basin have captured evolving conceptual models from diagenetic to structural controlled to multi-stage metallogenesis. The evaluation of changing configurations and processes, including metal distribution, basin evolution, and hydrothermal overprinting, as well as their contribution to the development of economic mineralisation within the basin is challenged by the spatial representation of the processes documented at a deposit scale. Recent research through MinEx CRC highlights gaps between observation-based understanding, synthetic modelling, and applied exploration targeting in this region.

Testing and evolving more holistic conceptual models relative to the regional history is therefore critical. Approaches that explicitly interrogate assumptions, incorporate temporal dynamics, and account for cumulative geological processes can help reduce bias and improve targeting outcomes. Emerging methods, including knowledge graph frameworks linked to prospectivity, provide a mechanism to represent and test alternative geological hypotheses in a systematic and adaptive way.

Useful models start and end with geology: Surface-based modelling and simulation for realistic flow

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Building and simulating spatially realistic representations of heterogeneity is a challenging task that is limited by the inflexibility of predefined pillar or cornerpoint grids. Rock types with diverse petrophysical characteristics are 'averaged' within grid cells of arbitrary size and shape, and the continuity and connectivity of baffles, barriers or high-permeability zones is often lost. Because the same areal grid resolution is needed everywhere in the model, large features are over-resolved and small features are under-resolved or omitted. We present a surface-based modelling workflow using grid-free surfaces and adaptive unstructured meshes that allows efficient creation and simulation of realistic geologic models without the limitations of predefined grids.

Surface-based reservoir modelling uses a boundary representation approach. All heterogeneity of interest (structural, stratigraphic, sedimentologic, diagenetic) is modelled by its bounding surfaces, independent of any grid. Smooth surfaces are modelled across scales using a parametric description. These surfaces are efficient to generate and manipulate and allow fast creation of multiple realizations of geometrically realistic reservoir models that contain detail at appropriate scales.

For flow simulation in IC-FERST (open source), a fully unstructured tetrahedral mesh is created that preserves the complex surface architecture. The governing flow equations are solved using a control-volume finite element method. The built-in dynamic mesh optimization algorithm allows the mesh geometry to change between time steps in a numerical solution, while preserving geology. The resulting mesh is optimised for the solution of interest (e.g. phase volume fraction, temperature, salinity, …) and allows computational resources to be allocated more efficiently.

We show this surface-based modelling and simulation approach using examples across different geological settings and different scales, demonstrating that preserving geological heterogeneity from model into simulations is not only useful but essential.

Representative Elementary Volumes: incorporating small scale heterogeneities and their impact on subsurface flow in Geo-models.

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Small scale geological heterogeneities can play significant roles in the sequestration of CO_2, hydrogen storage processes, and geothermal applications. These scales are often not accurately represented in conventional reservoir or field-scale models with grid cell sizes of the order of 10s of meters horizontally and several meters vertically. To effectively capture the impact of small-scale geological heterogeneities on subsurface fluid flow without resorting to computationally expensive and challenging high-resolution models we need a geology-based upscaling methodology. The concept of a Representative Elementary Volume (REV), defined as the minimum volume over which heterogeneous properties can be meaningfully averaged, has been around in geosciences since the early 1970's. Traditionally the REV has been determined using stochastic distributions of porosity and permeability using hundreds of reservoir models, but the application of the REV in reservoir modelling remains quite abstract in the literature.

We introduce a three-dimensional flow-based methodology to determine the REV at any scale and perform a systematic sensitivity analysis between small scale heterogeneities (sub-meter-scale strata) and the REV. Building on these results; an upscaling methodology is proposed. We validate this methodology using a first upscaling step from aeolian laminae scale (sub-meter) to co-set scale (10's of meters) based on an outcrop analogue. The findings show the dimensions of the REV increase non-linearly with bed thickness and have a weak negative correlation to the arithmetic and harmonic means of the permeability. We conclude that the REV-based upscaling method is an effective method that allows us to incorporate the flow impact of small-scale geological heterogeneities in larger scale (reservoir) models.

Don’t Force the Forcing: Useful quantification of basin-scale allogenic controls.

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Stratal stacking geometries reflect the combined autogenic and allogenic processes controlling rates of sediment supply and accommodation creation. Recognising patterns in interpreted stacking geometries remains inherently subjective and prone to bias. Numerical stratigraphic forward modelling demonstrates that organised cyclic patterns can emerge without allogenic forcing, generating pseudo-Milankovitch signals indistinguishable from true allogenic cycles. Conversely, signatures of allogenic forcing are variably preserved across basins and frequently masked by autogenic processes. False positive and false negative interpretations can therefore arise when inferring controlling mechanisms. These results highlight a fundamental limitation of pattern recognition approaches: apparent cyclicity is not diagnostic of its driving mechanism.

Time-independent architectural similarity analysis does not rely on interpreting patterns. Using only sandbody thickness and lateral-extent to quantify recurrence of geometries in a normalised basin-thickness framework detects presence or absence of external forcing independently of local signal heterogeneity, preservation bias, or interpretive assumptions. This reproducible and outcrop-applicable method should be useful to rigorously quantify likely allogenic forcing and allow comparison across basins of different ages, durations, tectonic settings, and potentially even other planets.

Testing the influence of allogenic influences (sediment concentration and grain size composition) on sediment transport by turbidity currents and depositional patterns of lobe deposits

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In turbidite systems, allogenic factors, particularly variations in sediment concentration and grain size, play a major role in controlling the evolution of flows and depositional patterns. However, how these factors influence turbidite systems remains poorly understood and limits the accurate interpretation of submarine lobe systems in outcrop. We conducted two series of flume experiments to study the specific impact of sediment concentration and grain size on flow dynamics and depositional patterns of submarine lobes under constant discharge. Series I examines cyclic variations in sediment volume concentration to simulate natural fluctuations in sediment input, while Series II assesses the effects of grain-size variability. Each series consists of five successive runs that produce distinct depositional patterns. The results show that variations in sediment concentration and grain size directly control flow behavior and sediment transport. High sediment concentrations produce thick, high-relief deposits that favor lateral migration over flow stacking. These frequent changes in flow path and depocenter illustrate that allogenic forcing does not steer autogenic signals but rather amplifies their patterns in the deposit. The flow velocity showed no correlation with sediment concentration. In Series II, sand-rich flows create thick, axially centered deposits, whereas silt-rich flows exhibit higher erosion in the channel and channel-lobe transition zone and form thinner, laterally extensive deposits in the basin floor. As the sand/silt ratio increases (Runs 1 to 3), the flow velocity also increases.

Observed thickening and thinning upward trends observed in basin floor deposits do not necessarily indicate changes in sediment supply. These trends rather result from the lateral migration induced by evolving depositional topography. Our observations highlight that sediment concentration and grain size play key roles in the evolution of the flow field and deposition patterns, thus providing a framework for interpreting submarine lobe systems at both the surface and subsurface.

Understanding surface deformation driven by magmatism using scaled analogue models

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The transport of magma within intrusions often generates space by fracturing and folding the host rock. This deformation can displace the free surface by mm to m and can be detected using ground- and satellite- based tools. Such surface displacement data forms a crucial part of volcanic hazard management, providing a proxy for the activity level of volcanic systems and reflecting the underlying magma intrusion depth, location and geometry. However, as it is not possible to make direct observations of intrusions driving surface displacement, we rely on analytical inversion models to estimate intrusion properties and trajectory. Whilst these analytical models have transformed our understanding of volcanic systems, they typically assume simple intrusion geometries (e.g. point-source or spherical) and the host rock is represented by a homogeneous, isotropic, linearly elastic half-space, which cannot capture the complexity of the natural system. Analogue models provide an opportunity to quantify the relationship between growing intrusions and the induced surface deformation in 3D.

To assess the impact of overburden thickness, rigidity and layering on surface displacements induced by dyke-fed sills, we conducted scaled analogue experiments using layered, elastically deforming gelatine as a crustal analogue and water as the magma analogue. Injections were made through the base of the clear-Perspex tank at a constant flux to create a dyke-fed sill at the interface between the layers. The movement of the gelatine surface was tracked by two cameras positioned above the tank using 3D digital image correlation. Increasing overburden thickness decreased the magnitude of surface displacement, agreeing with theoretical solutions from elastic plate theory, whilst increasing overburden rigidity did not decrease the surface displacement magnitude as would be expected. These analogue experiments provide novel insights into the interplay between overburden properties, intrusion geometries and their resulting surface deformation, which is vital for improving volcanic risk estimate accuracy.

Iterative Development of 3D Geological Model for Tunnelling in Heterogenous Quaternary Deposits and Faulted Bedrock: Integrating Ground Investigation, Geophysics, and Legacy Data

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A proposed tunnel in a complex geological setting characterised by heterogeneous Quaternary deposits and variable bedrock conditions, required a three-dimensional (3D) ground model to support design and construction. This study describes the iterative development of a 3D geological model that integrates recent intrusive ground investigation (GI) data and geophysical survey outputs with legacy British Geological Survey (BGS) information.

A key objective was to collate datasets of varying age, resolution and quality into a unified interpretative model. The methodology adopted an incremental approach, whereby stratigraphic complexity was progressively resolved in successive modelling iterations within Leapfrog Works. Early-stage models employed simplified stratigraphic units to establish broad geometrical consistency, followed by refinement through the incorporation of higher-resolution GI data, re-interpretation of borehole logs, and integration of geophysical constraints.

Central to this workflow was the continuous feedback loop between 3D model realisations and borehole log interpretation. Each iteration informed revisions to stratigraphic assignments and correlations, enabling inconsistencies to be identified and resolved systematically. This approach also facilitated the incorporation of geophysical data as both a validation tool and a constraint on subsurface continuity, particularly in areas with sparse borehole coverage. For example, the presence of a potential fault zone within the area of interest was identified by reconciling BGS mapping and regional understanding with seismic imaging and discontinuity logging.

The resulting model demonstrates improved spatial coherence of geological units, enhanced representation of complex glacial sequences, and a transparent audit trail of interpretative decisions. The study highlights the value of iterative modelling in managing uncertainty, refining geological understanding, and producing a defensible ground model suitable for major infrastructure design.

Fracture Prediction from Structure Driven Deep Learning

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Predicting the distribution and intensity of natural fractures remains a major challenge across subsurface applications, including hydrocarbon and mineral exploration, geothermal energy, groundwater, and geological storage. Fractures strongly control fluid flow, storage capacity, and seal integrity, yet direct observations are sparse, scale-limited, and expensive, while seismic data rarely resolve fracture-scale variability. This often leads to oversimplified extrapolations that overlook the geological processes driving fracture development.

We present a modelling strategy integrating process-based geoscience models with data-driven learning. We use ensembles of geomechanical forward structural models—specifically discrete element simulations (CDEM 2D)—to train deep learning algorithms for fracture prediction. These models simulate time-dependent deformation under varying stress regimes, rock properties and geometries, tracking key variables such as strain and stress through geological time. This provides physically consistent outputs reflecting deformation, burial, uplift, and erosion.

From these simulations, we generate training datasets pairing observable structural parameters (e.g., horizon and fault geometries) with geomechanical outputs (e.g., strain metrics used as proxies for fracture density). Deep learning models trained on this synthetic but geologically grounded data learn nonlinear relationships between present-day structures and subsurface fracture likelihood. Once trained, they can be applied directly to interpreted seismic geometries, avoiding the need for computationally expensive simulations for each new case. Tests on unseen synthetic data show good agreement with ground-truth strain fields.

This approach combines the strengths of both methods: forward models ensure geological realism and uncertainty control, while machine learning delivers scalability, speed, and generalisation. It effectively transforms complex, expert-driven modelling workflows into accessible tools for geoscientists. By embedding geological evolution into training data, the method reduces reliance on analogues, supports rapid scenario generation, and enables uncertainty quantification. Ultimately, it demonstrates how coupling geoscience models with machine learning can create reusable predictive tools to improve subsurface decision-making where fractures govern risk and value.

SESSION FOUR: INTEGRATING MODELS AND DEVELOPING NEW APPROACHES

Modelling Risk and Uncertainty using Multipoint Statistics

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Modelling uncertainty typically involves creating multiple equally likely model scenarios, or realisations, which can be used to model the probability density of outcomes. The development of software that enables construction of realisations from Sequential Gaussian Simulation (SGS) was therefore a significant breakthrough. As Multiple Point Statistics (MPS) was promoted as a further development of geostatistical modelling, potentially replacing SGS, the question is asked: how can this be applied to risk and uncertainty modelling? The answer, that it cannot, is not based on questions of meeting stationarity requirements but on its ability to generate equally likely realisations: as presently implemented in software, it cannot do this and MPS is therefore not useful as a tool for creating models designed to investigate risk. Recent work on flume tank experiments may be able to change this and make MPS models useful for risk analysis. Clearly, it is not feasible to run a flume tank experiment for each experiments realisation but, by using mass balance considerations and parameterising the sediment input to the flume tank experiment, Duller, and Straub at University of Liverpool, UK, and Tulane University, USA, have shown how key reservoir architecture can be parameterised to allow equally likely scenarios to be generated for subsequent input to Mont Carlo models, and hence to generate models of probability density for the required outcomes. Whilst this is limited to a subset of sedimentary processes, it is nevertheless a breakthrough in moving risk and uncertainty analysis forward in line with developments in deterministic modelling.

Matching Subsurface Reservoirs to Outcrop Analogues: An Automated Analogue Finder Tool Using Synthetic Well Logs

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The identification of appropriate outcrop analogues for subsurface reservoirs remains a fundamental challenge in subsurface characterization. This study presents a fully automated, data-driven workflow that combines outcrop-derived Synthetic Well Logs (SWLs), with Dynamic Time Warping (DTW) algorithm to identify the most appropriate outcrop analogue for a given input well. Repurposed as an analogue finder, DTW is extended to handle (i) significant unequal-thickness log pairs, (ii) simultaneous multivariate curve alignment, and (iii) normalized distance comparability across log pairs – together yielding a ranked, reproducible list of analogue candidates that answers, the longstanding open question: analogous in what respect? here, in terms of architectural elements Gamma Ray (GR), Sonic (DT), Density (RHOB) and Neutron (NPHI) wireline responses and their expression as vertical stacking patterns at the scale of depositional sequences.

Two models are developed, referred to as M1 and M2. Both run DTW under the same constraints but differ in how the cost matrix is constructed, reflecting two distinct geological assumptions about what makes an appropriate analogue, and each leading the model to ask a different question. M1 asks: if the depositional sequence captured by the SWL was preserved at the same thickness as the given input well, how analogous would the two successions be respectively? M2 instead asks; if the input interval corresponds to only part of the SWL rather than to the full log profile, where within the SWL would the input well interval sit?

The framework is demonstrated through a case study including six outcrops spanning from continental to shallow and deep marine clastic depositional environments. The selected outcrops are; (1) Escanilla-Olson, Spain; (2) Indian Creek, USA; (3) Beacon Hill, UK; (4) Helper Face, USA; (5) Ainsa Quarry, Spain; and (6) Kilkloher Cliff, Ireland. Overall, M1 and M2 results highlight two key well-known challenges in subsurface workflows: first, that wireline can be similar across different depositional environments, being outcrops from environments different to the input ranked highly; and second, the improvement in results obtained after introducing metadata to the models. Essentially, the proposed approach objectively guides analogue selection while supporting the improvement of well log correlation and reservoir model construction.

Integrating Analogue and Geophysical Models: From Qualitative Insight to Quantitative Prediction

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Analogue (sandbox) models provide physically consistent representations of structural evolution but are typically interpreted qualitatively. In contrast, geophysical modelling enables quantitative prediction of seismic observables yet is often limited by uncertainty in subsurface structure and heterogeneity. Bridging these approaches remains a key challenge in developing predictive geoscience models.

A workflow is presented that transforms high-resolution imagery of analogue models into geophysically consistent earth models suitable for wave-equation-based forward modelling and imaging. Digitised cross-sectional photographs are processed using image analysis and machine learning-based segmentation to extract pixel intensities, which are spatially scaled and mapped to impedance perturbations. This approach preserves the structural and textural complexity of the analogue model while enabling efficient and reproducible model construction. The resulting models support direct simulation of seismic wavefields and imaging using methods such as reverse time migration.

The methodology is inherently multi-scale. At basin scale, analogue-derived models enable quantitative testing of acquisition geometries and imaging strategies in complex salt provinces, including assessment of long-offset diving waves for constraining velocity models through full waveform inversion. At reservoir scale, pixel-based filtering provides a mechanism to generate realistic heterogeneity for fluid substitution modelling and time-lapse (4D) seismic analysis.

This scalability links process-based structural evolution directly to application-driven geophysical problems. In complex salt systems relevant to subsurface energy storage, the workflow enables quantitative evaluation of storage monitorability, including the impact of salt inclusions. Understanding the risks associated with salt heterogeneity is critical for both cavern development and monitoring in hydrogen storage, and more broadly for subsurface applications within the Energy Transition.

By preserving realistic structural and textural heterogeneity, this integration converts analogue models into quantitatively testable earth models that support systematic validation of geophysical workflows. The approach provides a robust foundation for reducing uncertainty and delivering more reliable, decision-ready predictions in structurally complex environments.

Making Digital Outcrops FAIR: A Community Platform for Preservation, Discovery, and Collaboration

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Outcrops are irreplaceable records of Earth history and are fundamental to geoscience research, education, and training. Digital outcrop models (DOMs), typically generated from photogrammetry (e.g., UAV, mobile phone) and/or lidar workflows, are commonplace and have transformed the way geoscientists collect and analyse field data. Sufficient and accessible digital dataset preservation and sharing, however, has not kept pace. Many DOMs and related metadata sit on individual or institutional hard drives, are behind paywalls or expired file-share links that make them inaccessible and uncitable, despite significant data collection and analysis costs. Fundamentally, a DOM that cannot be found, accessed, or reused provides little scientific value beyond its original study.

To address this problem directly the cloud-native platform outcrop.io has been developed. The platform is aligned with the Findable, Accessible, Interoperable, and Reusable (FAIR) data principles, and provides a permanent, browser-accessible custodian for 3D digital outcrop data that is designed for interactivity without specialist desktop software. Every uploaded model carries structured, standards-compliant metadata that can be assigned a DOI through an integrated trusted digital repository (e.g., Zenodo) that makes it findable, citable, and archive-quality from the beginning. A versioned interpretation system is integrated into the platform that records annotation layers, labels, and structural measurements with a full audit trail - facilitating re-evaluation of DOMs as geoscientific concepts and techniques advance. Collaboration tools, including peer review workflows, organisation-level reference libraries, and community activity feeds are supported by an AI-powered semantic search layer that facilitates natural-language discovery across outcrop metadata and linked academic literature. Together, these capabilities position outcrop.io as a FAIR-driven community outcrop and digital data infrastructure for the geosciences.

Identifying numerical model limitations from blind inversion of analogue and small-scale experiments

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Numerical models of natural processes, such as lava flows, improve forecasting of hazardous geological events and elucidate the relationships between material properties, system geometry, and dynamics. However, we are often limited in our ability to robustly validate numerical models given the uncertainties in natural systems and processes. Analogue and small-scale laboratory experiments offer the opportunity to validate and calibrate numerical models, but direct comparisons to well-constrained experiments usually require model tuning and refinement which can introduce bias in both parameter selection and confidence in model performance. We invite participants to a community exercise of blind inversion for lava flow models: observations of runout dynamics, but not material properties or flow rates, from experiments using analogue and natural materials at laboratory scale will be distributed to participants for inversion. Numerical models using a variety of parameterizations and assumptions, as well as different inversion methods, will be employed by participants and compared to the real experimental conditions to evaluate both accuracy and evaluations of reported uncertai

Combined controls of basal detachment configuration and shortening rate on the geometry and kinematics of salt-bearing fold-and-thrust belts: New insights from scaled analogue experiments with dynamic digital strain analysis

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Weak evaporitic substrates strongly influence the geometry, kinematics, and strain propagation of fold-and-thrust belts through their dual roles as mechanically weak detachments and mobile viscous source layers. Although previous studies have demonstrated the importance of salt-layer thickness and shortening rate, the coupled effects of shortening rate and salt mobility on deformation styles and thrust-wedge evolution remain poorly constrained. To address this issue, a series of analogue modelling experiments was conducted using frictional and plastic detachments with varying thicknesses and shortening rates. Incremental digital image correlation (DIC) was applied to quantify strain localization, fault activity, and wedge evolution.

All models evolved through forward-propagating deformation sequences accompanied by episodic reactivation of older structures and ultimately developed wedge-shaped thrust systems. However, thrust vergence, wedge taper, structural style, and fault activity varied systematically with detachment properties and shortening rate. Frictional detachments produced steep, narrow wedges dominated by foreland-vergent thrusts, whereas plastic detachments generated broader, lower-taper wedges characterized by variable vergence and more symmetric structural architectures. Increasing detachment thickness enhanced material redistribution and promoted a transition from fault-dominated to fold-dominated deformation. Shortening rate influenced the mobility of the plastic detachment. High shortening rates favored detachment-controlled deformation, whereas low shortening rates enhanced viscous flow, salt redistribution, and the development of salt-related structures.

The experiments further demonstrate that backthrusts are secondary structures that develop during mature stages of wedge growth. Three end-member mechanisms of backthrust formation are identified: (1) accommodation backthrusts derived from active forethrusts, (2) weld-induced backthrusts associated with salt evacuation and welding, and (3) accommodation backthrusts related to breakthrough thrusting in non-welded systems.

The results reveal that shortening rate governs the competition between strain decoupling and salt redistribution, driving a transition from detachment-dominated to flow-dominated deformation. Furthermore, detachment mobility represents a first-order control on thrust vergence by regulating the relative development of forethrusts and backthrusts.

Integrating Conceptual, Physical, and Data-Driven Models for Bypassed Pay Detection and Artificial Lift Diagnostics

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Physics-based and machine-learning models are not competing approaches — they are complementary, and the architecture decisions governing their integration determine whether the resulting model is predictive or merely curve-fitted to training data.

Two integrated modeling frameworks are presented, both targeting mature upstream fields where deterministic petrophysics alone fails to resolve pay ambiguity or production attribution. The first, a Bypassed Pay Platform, chains three model types. A Thomas-Stieber laminated shaly-sand conceptual model defines label legitimacy, eliminating the circular training artifacts that undermine conventional log-based classifiers; a Poupon-Leveaux/Waxman-Smits numerical physics module then quantifies net pay within that constraint; and an RF/XGBoost ensemble classifier resolves residual ambiguity where deterministic physics cannot discriminate. Grouped cross-validation on a 50-well synthetic Eagle Creek field yields ROC-AUC 0.992 ± 0.005. SHAP feature attribution preserves direct linkage to the underlying petrophysical model, and Monte Carlo EMV carries uncertainty through to recompletion economics — making outputs actionable for investment decisions, not just log interpretation.

The second framework, the Niger Delta Gas Lift Optimizer (ND-GLO), employs a Physics-Informed Neural Network architecture that couples a reservoir subnet (Jones-Blount-Glaze IPR) with a surface subnet (H_2S corrosion kinetics), and is joined by a disentanglement regulariser that enforces causal separation between formation decline and equipment degradation signatures. The key departure from standard hybrid modeling is that physics-data consistency is imposed at every training step, not applied post hoc. MC Dropout provides calibrated epistemic uncertainty, enabling probabilistic attribution of production loss to reservoir or facilities causes — a distinction with direct consequences for NOC workover and maintenance planning.

Both frameworks share a common logic: conceptual geology constrains what labels are physically admissible, numerical physics bounds the solution space, and machine learning resolves what remains ambiguous. Applied across analogous NOC portfolios, this three-tier structure offers a practical architecture for mature field redevelopment where data volume is high but interpretive confidence is low.

Rapid Reservoir Modelling: Sketch-based geological modelling with flow diagnostics

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Sketch-based geological modelling with flow diagnostics is an interactive and intuitive prototyping approach to quickly build geomodels and generate quantitative results to evaluate volumetrics and flow behaviour. This approach allows users to rapidly test the sensitivity of model outputs to different geological concepts and uncertain parameters, and informs selection of geological concepts, scales and resolutions to be investigated in more detailed models. Here we apply the sketching and prototyping approach to different aspects of geological modelling and use in geoscience and engineering projects.

Rapid Reservoir Modelling (RRM) is a free open-source sketch-based geological modelling tool with an intuitive interface that allows users to rapidly sketch geological models in 3D (open source). Geological models that capture the essence of heterogeneity of interest and related uncertainty can be created within minutes. Geological operators ensure correct truncation relationships between these 3D surfaces by the modelling engine. Flow diagnostics then computes key indicators of predicted flow and storage behaviour within seconds.

Example use cases will be discussed, including:

(1) Capturing uncertainty in geological concepts cannot be achieved by changing a numerical variable but can be varied easily by sketching the different concepts, such as lateral connectivity, continuity and geometry of geological heterogeneities that act as flow barriers and pathways. Capturing multiple different concepts in conventional modelling approaches is time-consuming and in practice not often carried out.

(2) Sketching of mini-models and hierarchical models to derive effective properties. Calculated effective properties can then be used to populated models sketched at larger scale. Sketching is free of existing restrictive templates and realistic subsurface models can be generated easily.

(3) Training of geoscientists and engineers to investigate the impact of geological interpretations on storage and flow without prior geomodelling expertise.

Shifting paradigms or just shifting dogma? Small actions and paths to mineral discovery

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Paradigm shifts are given exalted status in science, and with good reason. They represent a transition from a prior period of stagnation, limited scientific advancement, and adherence to the status quo, to a period where the overturning of a dominant view occurs, a flood of new hypotheses is generated, and establishment figures are supplanted by a new corps of scientists. As in the previous description, paradigm shifts occur in our collective consciousness as dramatic events. Science offers many famous examples from geoscience, including the transition from continental drift to plate tectonics and the recognition that Earth systems are non-linear, dynamic, and stochastic, rather than predictable and deterministic. However, the generally agreed-upon thesis is that paradigm shifts simply mean looking at the same information in a different way. Much progress has been made without the need for paradigm shifts, yet they occur when information is viewed from a different perspective. While not as dramatic, such events nonetheless occur in impactful ways in the geosciences, often giving rise to mineral discoveries or the development of new technologies. This presentation is an examination of exploration decisions made in the context of theories of truth: correspondence, coherence and pragmatic. We will explore what encourages conceptual change, ranging from commercial forces to human curiosity and dissatisfaction with conventional thought. Examples from exploration geoscience tell a story of mineral discoveries made when small actions were inspired by fundamental shifts in concepts, leading to deeper investigation of geological processes and systems.

SANDBOX MODELLING OF THRUST RELATED GEOMETRIES IN DUNGA GALI-KUZA GALI AREA, SOUTHERN HAZARA BASIN LESSER HIMALAYAS, PAKISTAN.

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The investigated area is located near western flank of Hazara Kashmir Syntaxis in Hazara Basin, northwest Himalayas, Pakistan and bounded by Nathia Gali Thrust and Main Boundary Thrust from north and south respectively. The sedimentary rocks units from Precambrian to Tertiary make the stratigraphic framework of Hazara Basin. A major synclinorium is present in the Hazara Basin which is divided into two synclinal complexes; Dunga/Kuza Gali synclinorium in the south and/or Nawanshahar in the north. This research work focused on Dunga/Kuza Gali synclinorium. An analogue modelling technique was used to investigate the developments of structural elements in study area. For this purpose, an apparatus named Sandbox model was built up. The model was scaled geologically, kinematically and dynamically to compare the results with real time data. Different materials were

layered with different colors to make the stratigraphy. Model was used to check the behaviour of deformation of rock units under forces and to calculate the total shortening. Different faults were developed during experiment and the total calculated average shortening is 28%. The interpreted results

show that the study area lies in the compressional regime.

Spatio-temporal analysis of hydro-climatic vulnerability in the Mandoto watershed (Madagascar): impacts on water resources within a One Health framework

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Hydro-climatic vulnerability represents a critical challenge in semi-tropical regions, where climate variability strongly affects water availability and public health. The Mandoto district, in the Vakinankaratra region, located between the central highlands and the coastal areas of the Morondava sedimentary basin, exemplifies the challenges faced by rural Malagasy communities. Increasing pressure on water resources in this area is closely linked to environmental and health risks. This study analyzes the spatio-temporal dynamics of hydro-climatic vulnerability in the Mandoto watershed from 2020 to 2025, integrating impacts on water resources and human health using a One Health approach. A multi-source methodology was employed, combining hydro-climatic and hydrological data, health data and indicators from the national DHIS2 system, and the identification of hydro-climatic anomalies and seasonal variability at the watershed scale. Geographic information systems were used to map water resource vulnerability and explore correlations with health indicators. Spatio-temporal statistical methods assessed relationships between hydro-climatic variability and water-related diseases, focusing on diarrheal diseases and malaria, major public health concerns in Madagascar. Results reveal pronounced spatial and temporal variability in hydro-climatic conditions. Monthly rainfall ranged from 100 to 350 mm during the wet season and 5 to 50 mm during the dry season. Rising temperatures increased water evaporation and plant transpiration, reducing surface water availability and generating periods of water stress. Intensified runoff accelerated soil erosion and the transport of sediments and nutrients to rivers, altering turbidity and water chemistry. Topographic and geological factors, including steep slopes and the presence of crystalline bedrock or sedimentary zones, influenced runoff velocity and groundwater storage capacity. Deforestation and subsistence agriculture further reduced the watershed's natural resilience to climatic shocks. Significant correlations were observed between precipitation variability and water-related disease incidence. Annual diarrheal cases ranged from 263 to 526, while malaria cases fluctuated between 13,296 and 14,613. Rural areas reliant on surface water were the most vulnerable. The integration of hydro-climatic thresholds enabled the development of an early-warning framework linking climate variability, water resource vulnerability, and eco-health risks. This study provides crucial insights into the interactions between hydro-climatic variability, water resource vulnerability, and public health in semi-tropical contexts. By integrating environmental and health data within a One Health framework, the findings provide a scientific basis for enhancing sustainable water management and strengthening climate-resilient health monitoring systems. The approach is potentially transferable to other African watersheds facing similar hydro-climatic pressures, supporting improved water security and public health resilience under changing climatic conditions.

From inertial routing to preserved stratigraphy: Assessing pyDeltaRCM's ability to model fluvial architectures

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Fluvial deposits are inherently difficult to characterize due to limited outcrop preservation and sparse observational data. Process-based numerical models provide a controlled and repeatable framework for relating fluvial morphodynamics to resulting stratigraphic architectures. Yet, balancing computational efficiency with process fidelity remains a key challenge for predictive reconstruction of geologically consistent fluvial deposits at reach scale. Here, we assess the pyDeltaRCM framework (Moodie et al., 2021), originally developed for deltaic environments, for its ability to simulate meandering dynamics in purely fluvial settings. The model inherently employs a simplified two-sediment-class representation. We implement modified boundary conditions and parameterizations to represent an erodible floodplain domain and conduct a one-at-a-time sensitivity analysis across 25 simulations. Six governing parameters, including initial velocity, water depth, bedload fraction, sediment concentration, erodibility and slope, are varied by ±20-40% relative to baseline values. Model behaviour shows strong sensitivity to slope and sediment supply conditions, with important implications for geological realism. Sustained meandering emerges only under hyper-gentle slopes, typically below ~10-4, where inertial routing dominates over gravitational forcings, enabling self-organized channel migration without the need for external upstream perturbations. As slopes increase beyond ~1.5x10-4, gravitational forcing suppresses lateral mobility, resulting in persistently straight channels irrespective of parameter interactions. Although discrepancies remain with expected scaling relationships, such as wavelength-to-width ratios, the model reproducibly generates key depositional elements, including lateral point-bar accretion, oxbow channel, cutoff bars, and mud-plug formation. Together, these results highlight both the capability and limitations of pyDeltaRCM for simulating fluvial stratigraphic architectures in meandering systems, demonstrating that plausible depositional elements can emerge despite simplified hydrodynamics and sediment transport. The framework has the potential to simulate transitions across depositional environments (from fluvial to deltaic) within a unified modelling approach. As such, it offers a basis for generating geologically informed priors that can support statistical and machine-learning methods in subsurface modelling.

Modelling magma ascent – a quantitative analogue setup

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Analogue models are useful for understanding geological processes as they allow large-scale behaviours to be scaled down so they can be controlled and observed within the laboratory. Gelatine is commonly used as a crustal analogue, due to its transparency and ability to deform elastically, with photoelasticity making strain-induced stress fields visible through polarised light. Consequently, gelatine is commonly used within volcanology to investigate the physics of magmatic intrusion within the crust, as subsurface processes cannot be observed directly in nature. Such setups can be scaled to nature by adjusting the governing parameters (e.g. the Young's Modulus of the gelatine) and conducting appropriate dimensional analysis to identify the controlling dimensionless numbers (e.g. Reynolds number for defining magma flow regimes).

In this study, we present an analogue setup using a transparent, gelatine solid as a homogeneous elastic crust injected from below by fluids of different properties representing diverse magma compositions typical of continental settings. Two CCD cameras placed above the experiment measure the vertical and lateral surface displacements created by the intrusion, as a penny-shaped experimental dyke grows. Polarised light is used to infer the evolving stress field within the gelatine, recorded by an HD camera positioned at the side of the tank. These experiments measure the 3D intrusion geometry, tip velocity, extent of surface deformation and rate, and relate these to the gelatine's evolving internal stress field. Upscaling measurements of the model surface deformation to natural systems enables direct comparison with GPS and InSAR observations, which are widely used to monitor ground deformation associated with magmatic intrusions and play a key role in eruption forecasting. Results from this experimental setup could therefore have important implications for interpreting surface signals of magma ascent, and deepen our understanding of subsurface processes, and through engagement with volcano observatories, help to improve eruption forecasting capabilities.

Check your footsteps - a model can only be useful when it honours the available data

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Congratulations! You have made the model or model suite. Nothing better for the modeller than to enjoy the sight of their finished creation. But for it to be useful, it must honour all the available data. There is a second round - of model validation.

First, Static Consistency. Does the structural envelope still look like the input information – often seismic? Are any well trajectories or cliff transects in the right place with respect to geological boundaries? Do reservoir properties away from hard control such as wells vary in accordance with any independent data such as seismic or resistivity surveys? Many of these questions can be addressed by a close the loop exercise when the input data is recreated from the model and compared to the original dataset.

There is also the matter of Geological Consistency – comparing the model against the conceptual models drawn to encapsulate the geological understanding of the system. Is the structural envelope geometrically and kinematically valid? Does the distribution of facies and/or reservoir properties reflect the input depositional and diagenetic concepts? Are the baffles and barriers to flow (if relevant) geologically reasonable? And did the inevitable upscaling retain the key characteristics required for predictive work?

Finally, the matter of Dynamic Consistency. If there is dynamic information such as flow, pressure or 4D seismic behaviour available, can the model be used to reproduce that behaviour? The exercise of history matching can result in significant refinement or change to the model. This also provides a second close the loop, where the output of a dynamic simulator is transformed into seismic or pressure data at given time steps and compared to the originals.

Only then, modeller, is your work useful.