

# **Carbonate Petrophysical Rock Typing: Integrating Geological Attributes and Petrophysical Properties while Linking with Dynamic Behavior\***

**Mark Skalinski<sup>1</sup> and Jeroen A. M. Kenter<sup>2</sup>**

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<sup>1</sup>Chevron Energy Technology Company, San Ramon, CA, USA ([mtsk@chevron.com](mailto:mtsk@chevron.com))

<sup>2</sup>Statoil ASA, Sandsli, Norway

## **Abstract**

Carbonate rock typing is critical in distribution of reservoir properties such as permeability and water saturation in the reservoir model. The conventional approach to rock typing is based on textural properties, pore type classification or the application of electro-facies or Flow Zone Indicators. The influence of geological attributes is biased towards depositional properties in case of the use of texture and towards diagenetic attributes when using pore types while electro-facies and FZI are strongly affected by input logs with not well-defined link to geological attributes. The underlying problem is the fact that carbonates are generally strongly modified by diagenetic processes, which influences petrophysical properties to varying degrees. In fact, existing methods have significant gaps in: 1) incorporating diagenetic processes, 2) integrating multi scale and multi-modal pore types 3) accounting for fractures, 4) integrating dynamic data and, 5) lacking the appropriate geostatistical tools to properly distribute Petrophysical Rock Types (PRTs) in the static reservoir model.

## **Introduction**

This workflow addresses these issues in a comprehensive way. The objective of this approach is to determine petro physical rock types, which control the dynamic behavior of the reservoir while optimally linking the geological attributes (depositional and diagenetic as well as their hybrid) and their spatial interrelationships and trends. In the context of this workflow, PRTs are defined as: 1) the category of rocks, which are characterized by specific ranges of petrophysical properties, 2) exhibiting distinct relationships relevant for flow characterization, 3) identified by logging surveys and, linked to geological attributes like primary texture or diagenetic modifications. In this paper, we present an integrated workflow consistent with the PRT definition.

The workflow consists of eight composite and sequential steps, which are represented by a loop-type diagram shown in [Figure 1](#). With progressing field maturity and data scenarios, multiple loops are required to capture reservoir heterogeneity and optimize the representation of the subsurface data ([Figure 1](#)). The final product is the result of Step 8, i.e. 3D static model.

## **Step 1: Data Scenario**

PRT workflows are designed to be applicable to all data scenarios (DS) which are driven by (in order of relevance): 1) well density, 2) logging surveys (vintage and completeness), 3) available core data and, 4) dynamic data. Generally, with field development, the data scenario will change. This progression is shown in [Figure 1](#), where different loops of the workflow represent different data scenarios and reservoir maturity.

## **Step 2: Depositional Rock Typing**

The DRT workflow is designed to test the predictability of unbiased DRTs by logs in order to assess the relative contribution by diagenetic modifiers. This step consists of three sub steps. The Depositional Rock Type (DRT) determination (Step 2.1) requires an unbiased determination of depositional and diagenetic attributes as a function of depth along the cored intervals. These geological attributes allow the generation of a set of DRTs, which represent categories of non-overlapping lithofacies as well as a separate set of diagenetic attributes that may be used later in the workflow to explain the discontinuity between reservoir properties and DRTs. The DRT catalog summary classification (Step 2.2) represents the DRT elements of a depositional model based on core observations and concepts from literature and/or analogs. The DRT catalog includes one or more alternate scenarios that combine DRTs according to geological criteria such as depositional regions, facies belts, etc., to a statistically acceptable number for prediction using logs, generally no more than 15 combined DRT categories. DRT prediction from logs, Step 2.3, requires lumping of the DRTs determined from core. Lumping should follow geological (DRT) associations, generally DRT groupings already made in the DRT catalog. Prediction of DRTs from logs is generally performed using multivariate statistical tools such as Step-wise Discriminant Analysis (SDA) or neural networks combined with deterministic methods.

## **Step 3: Reservoir Typing**

Carbonate reservoirs are highly susceptible to diagenetic processes, which alter their original depositional fabric and petrophysical properties. In addition, fractures can overprint both systems. Since, up to date, relatively little is known of the processes and spatial distribution of fractures, the Nelson (1999) fracture types are a reliable classification of the influence of fractures on the dynamic properties of carbonate reservoirs. Nelson (1999) fracture types were defined on their relative contribution to permeability and porosity and range from “a” to “c”, where “a” defines dominant fracture control while “c” represents dominant matrix control on flow. The process of Reservoir Typing (RT) is the determination of the relative contribution on fluid flow of: 1) the degree of diagenetic modification (DM) of the original depositional rock types (DRTs) and, when present, 2) the Nelson type fractures. To achieve the RT three steps are required. An assessment of conformity between DRTs and flow indicators (Step 3.1) involves a quantitative assessment of conformity between DRTs and flow indicators using porosity-permeability cross plots, Lorenz plots, Production Logs (PLTs), drill stem test data (DSTs) and wire line formation test (WFT) data. In case the result is a high degree of conformity between DRTs and flow indicators, the RT as described above is classified as RT I and the next step (3.2) can be skipped. In this case, present baffles or barriers will be identified or confirmed as DRTs. If there is no conformity the fluid flow is controlled, at least in part, by DM and the following step is needed. The assessment of diagenetic modifiers (Step 3.2) requires core data and descriptions of diagenetic attributes. The result of this step will be assessment of type and degree of diagenetic modifiers,

which should be included in the PRT definition of Step 5, and classification of the RT. Step 3.3 (final reservoir type definition – RT) determines the RT assignment based on the relative contribution of DM and fractures on flow using [Figure 2](#).

#### **Step 4: Pore Typing**

Carbonate petrophysical heterogeneity (flow properties) is generally the result of complex and multi-modal pore systems including fractures. Identification and prediction of pore types is therefore essential for a reliable rock typing in carbonate. Pore typing workflow accounts for different data scenarios depending on availability of core, MICP data and specialty logs data such as NMR or Formation Microscanner (FM). Appropriate pore type identification comes from MICP interpretation. MICP is providing information on pore throat distributions controlling flow in reservoir. MICP derived pore types (IPT) have to be combined with larger scale observations such as vugs and fractures. Specialty logs provide this information. In case of data scenarios lacking MICP measurements but including available representative core an alternative path (B) is to be followed which produces Core Pore Types (CPT). In case of absent NMR and/or FM data pore types (PT) would be defined from IPT (when MICP data available) or CPT. In case when neither core nor NMR/FM data are available, determination of relevant pore types is less reliable or impossible.

#### **Step 5: PRT Definition**

In the context of this workflow, PRTs are defined as: 1) the category of rocks that are characterized by specific ranges of petrophysical properties, 2) exhibiting distinct relationships relevant for flow characterization, 3) identified by logging surveys and, linked to geological attributes like primary texture or diagenetic modifications ([Figure 3](#)). In this critical step, PRTs are defined according to the relative influence of the following attributes: permeability barriers, DRTs, DMs, and pore types. The permeability barrier(s) are either non-reservoir rocks or low-permeability rocks that act as flow barriers or baffles indicated by dynamic data. In summary, PRTs are defined by combining PRT elements such as: “DRT\_pred”, PT, barriers, and other diagenetic modifiers affecting the log response. The definition of PRTs has to take into account the logging data scenario. The PRT definition at the beginning of this paragraph contains the primary criteria used to define PRT from PRT elements. The final PRTs have to conform to all four segments of the definition.

#### **Step 6: PRT Determination in a Multi-well Setting and QC Using Maps**

This step includes the determination of PRTs in all wells using predictive algorithms developed in the previous steps. The resulting well data are mapped across the field and investigated for outliers and possible underlying reasons. Next, spatial trends and relationships between PRTs are extracted. This step is especially critical when RT is higher than I and dominated by diagenetic modification. The PRT determination follows three steps: 6.1) development of algorithms or models for PRT prediction; 6.2) PRT determination; 6.3) QC and trends.

### **Step 7: Dynamic Validation of PRTs**

A quantitative validation of the link between PRTs and available flow indicators is performed by: 1) comparing PRT with PKS data (such as porosity-permeability cross plots and Lorenz plots) and, 2) the comparison of PRTs with dynamic data such as Production Logs (PLTs), Drill stem test data (DSTs) and wire line formation test (WFT) data. The goal of this step is to confirm that PRTs are linked to flow profiles observed in dynamic data. In particular, barriers and flow zones should be correlated to appropriate PRTs. In case the linkage is poor, a look-back to the step 5 is required. If dynamic data are available, the workflow includes the following 3 steps: 7.1) validation of PRTs with core data, 7.2) validation of PRTs with dynamic data and, 7.3) PRT conformance assessment.

### **Step 8: PRT Distribution and Spatial Validation**

This step comprises the completion of the spatial interrelation rules and trends for PRTs extracted in Step 6. Those rules and trends will be used as soft constraints (probability maps) and in designing training images or variograms for the distribution of PRTs in 3D models. The distribution method is also a function of RT and data scenario. In other words, spatial patterns of - and interrelationships between - PRTs are controlled by the relative contribution of depositional versus diagenetic processes (Figure 2). In case RT equals 1, PRTs and flow are controlled by DRTs. In addition to RT, also the data density controls the choice of methods to distribute PRTs in the static model. With increasing density of data, the spatial trends are driven by well control rather than concepts. Multiple Point Statistics (MPS) is suggested as the best geostatistical tool to honor trends of - and spatial interrelationships among - PRTs. An example of PRT definition and distribution using MPS is shown in Figure 4. High resolution and quality 3D seismic data can be used as soft constraint for PRTs, especially for green fields or intermediate fields where well density is not capturing spatial heterogeneity. The following four steps are included in the PRT distribution and spatial validation process: 8.1) determination of PRT trends and spatial interrelationships; 8.2) determination of optimal geostatistical method; 8.3.1) in case stochastic, analyze variogram lengths, generate PRT probability cube and run PRT distribution; 8.3.2) in case MPS, design TI, generate PRT probability cube and run PRT distribution; 8.4) QC and evaluation PRT distribution and, if needed, loop back.

#### **Tengiz Example (Figure 4)**

The Tengiz Field is unique since several of the PRTs, though diagenetically modified, still mostly follow primary spatial trends, PRTs 1 and -3, while others have trends that are the result of diagenetic processes and have spatial trends that truncate the SSF and change within cycles. The interesting observation is that the timing of those diagenetic processes played a crucial role: PRT 1 and -3 were modified early and formed baffles with reduced porosity and permeability bordering cycles or “containers” that were later overprinted by corrosion, mostly in the center of the platform, and cementation towards the northeastern and eastern sectors of the field where calcite and bitumen cements occluded porosity. These trends, partially based on detailed diagenetic studies and core and log observations, provide juxtaposition rules and guidelines that were used for multiple point statistical analyses and simulation of the PRTs, and subsequently porosity and permeability across the field.

### **First Eocene example (Figure 5)**

The First Eocene reservoir at Wafra field consists of dolomitized subtidal packstone and grainstone deposited under arid or semi-arid conditions of a shallow, very gently dipping restricted ramp environment. The shallowing-upward cycles are capped by mud-dominated tidal flat facies, which are followed or replaced by evaporites level indicating occasionally hyper-saline lagoons and sabkhas. DRTs were described in 12 cored wells indicating eight DRTs, which were further lumped to three to allow reliable prediction from logs. Three lumped DRTs were: 1) evaporites, 2) tidal flat caps including algal dominated grainstone and, 3) packstone and subtidal packstone. Due to extensive dolomitization, formation of anhydrite nodules and dissolution processes, the reservoir type is classified as hybrid (RT II). Pore types were initially defined from MICP clustering and complemented by vugs prediction from NMR and FMI logs. PRT were defined by combining log-predicted DRT's with pore types and evaporites volumes determined by Multimin analysis. PRTs were then calculated in all logged wells penetrating the First Eocene in Wafra Field. The resulting PRTs at the wells were then analyzed in map – and cross section view to unravel their spatial trends and relationships, necessary to construct training images and distribute them in 3D model using Multi Point Statistics. Distribution of permeability by PRT-driven cloud transforms helped to construct robust static model. PRTs also assisted in a more reliable determination of Sw using PRT driven saturation height functions.

**DS = Data Scenario**  
**DRT = Determined DRT**  
**DM = Diagenetic Modification**  
**RT = Reservoir Type**  
**PT = Pore Type**  
**PRT = Petrophysical Rock Type**  
**SR = Spatial Rules**

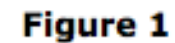


Figure 1. Sequential and Progressive PRT Workflow.

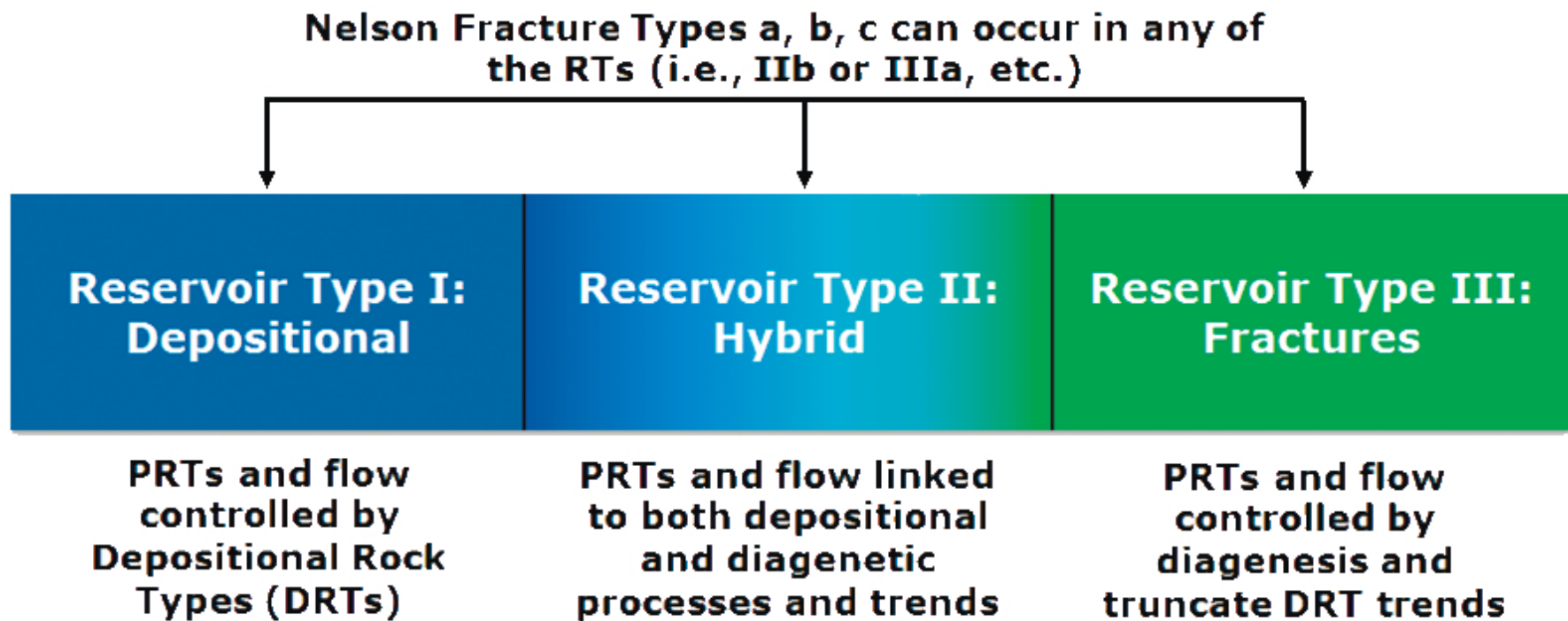


Figure 2. Fracture types vs. reservoir types.



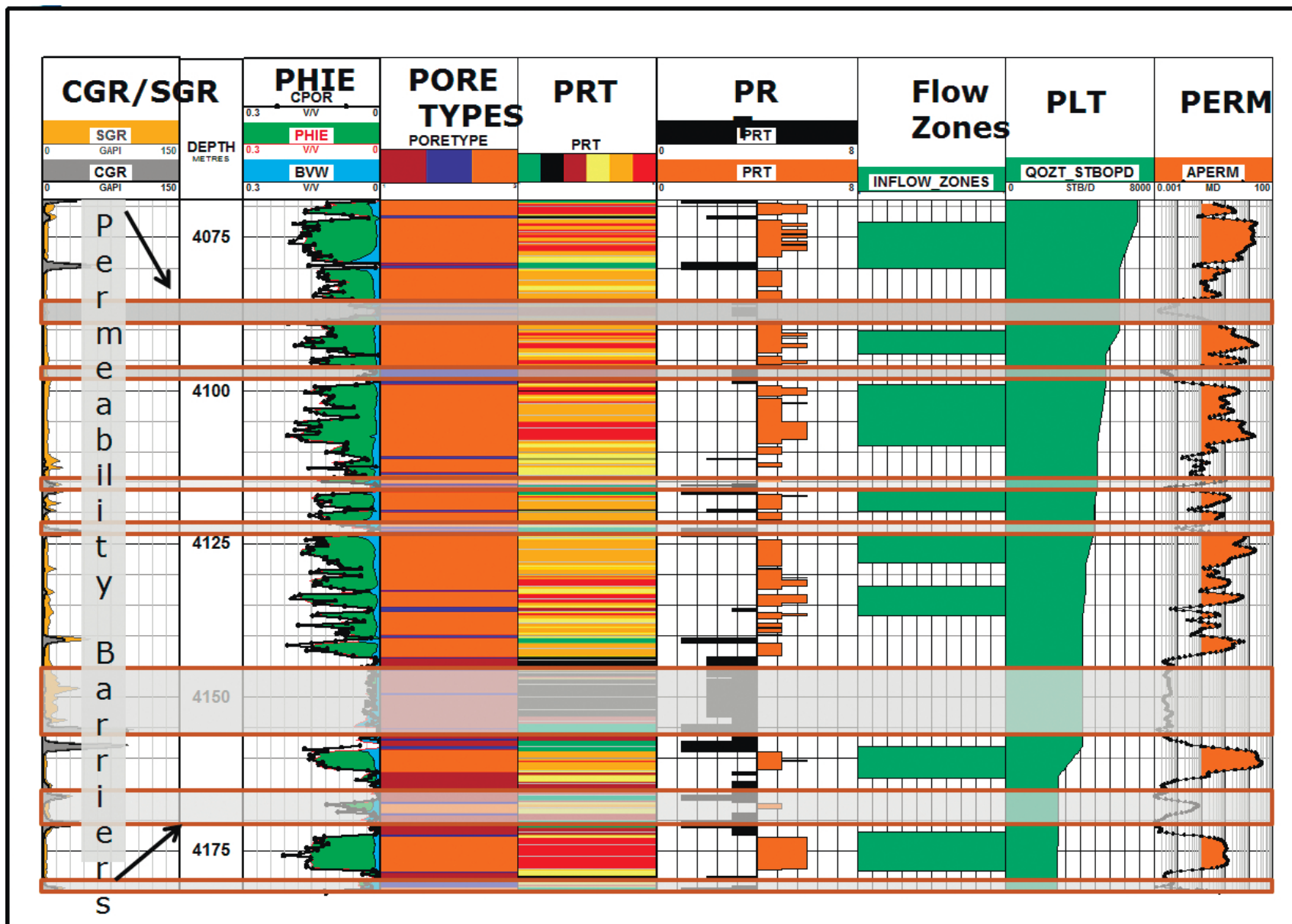


Figure 3. PRT example characterized by specific ranges of petrophysical properties.



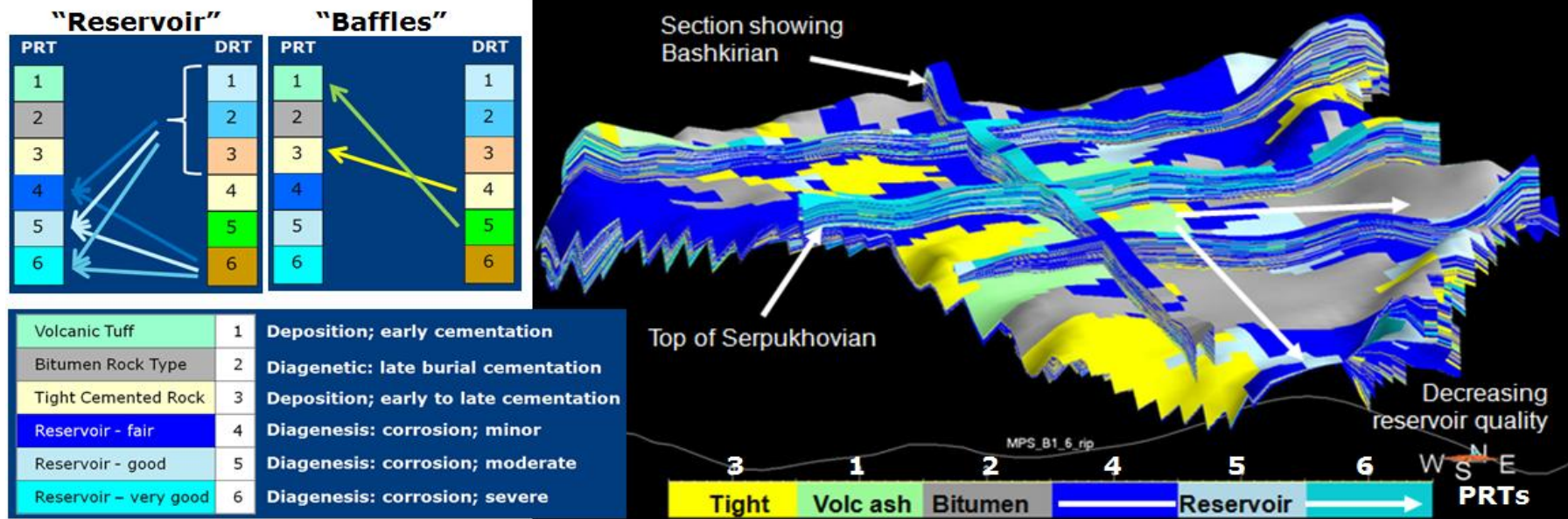


Figure 4. An example of PRT definition and distribution using MPS.

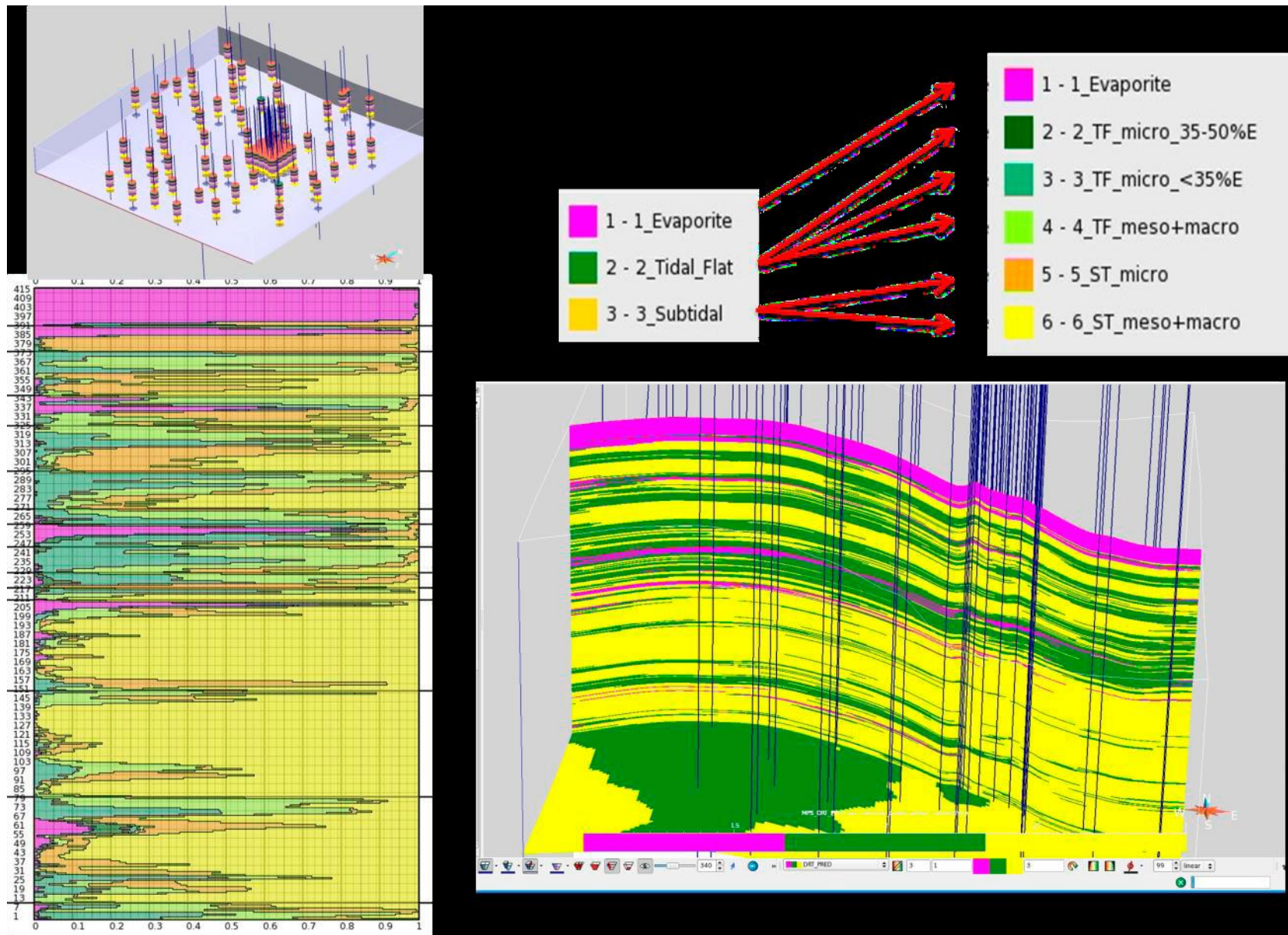


Figure 5. The First Eocene reservoir at Wafra field using spatial trends and relationships to construct training images and distribute them in 3D model using Multi Point Statistics.