A New Workflow to Upscale and Propagate Saturation-Dependent Petrophysical Properties from Wireline Logs to 3-D Geocellular Models*

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Abstract

A new workflow is presented which overcomes one of the more intractable problems of reservoir characterisation: upscaling and propagating saturation-dependent petrophysical properties from sparsely located and sampled 1D wells to every cell in a 3D geocellular reservoir model. Advanced classification techniques are linked with a unique scale-independent parameterisation to implement the new workflow. Such classifications are developed using a Bayesian-based multivariate clustering technique which provides a probabilistic rock typing at each scale. This model is then used to propagate static petrophysical properties away from the locations where they were measured into unsampled regions in either the wellbore or the geocellular model, with these properties then being upscaled using conventional methods. To implement the new workflow, a unique, scale-independent, parameterisation of the petrophysical properties is developed; this being based on the principles of model-prototype hydraulic similitude. Three Characteristic Length Variables (CLVs) are calculated at the fine scale and used to build the Bayesian classification model. After upscaling the static properties, two of the CLVs are used in the probabilistic model to predict the third at the coarser scale, thus facilitating the upscaling of the dynamic properties. An example is presented for a conventional gas reservoir in which both static and dynamic properties are moved from core to the wireline log scale and then to the geocell scale, initially in 1D. The properties are then propagated into all geocells of a 3D geocellular model using the probabilistic model and further analysed.

Introduction

The integration of core data with wireline logs and geocellular models involves volume changes that are both large and complex. The scales of most industry focus are shown in Figure 1, where the total volume change is of the order of 108. Robust and consistent methods are required to effect the necessary changes to the values of petrophysical properties, especially saturation-dependent properties, as they are upscaled through the various volumes. This paper presents advanced classification and propagation (distribution) concepts and workflows that enable such effective upscaling, with a focus on the wireline log and geocell scales.

The requirements, concepts, and implementation methods underpinning the workflow developed to transpose both static and saturation-dependent petrophysical properties rigorously and consistently across the various scale changes are first outlined (full details are in Curtis, 2000 and Curtis et al., 2019a). An example of the use of the workflow is given for an onshore, predominantly siliciclastic, reservoir formation at each of the core plug, wireline log, and geocell scales. A software "plug-in" to a 3D geocellular model is used to populate every cell of the 3D geomodel with both static and dynamic (saturation-dependent) petrophysical properties.

Changing Scales – The Importance of Classification

Classification Schemes based on a Genesis and Scale-based Nomenclature

Classification into lithological groupings is generally treated as a singular concept. However, within the petroleum industry, many forms of Classification are used and these may be usefully categorised into three main groups based on their genesis: Geologically-based Classification, Trace or Log-based Classification, and Properties-based Classification. The development and applicability of the three groups across successive scales is fully described by Curtis et al., 2019a and applied in two other quite different but illustrative examples in Curtis et al., 2019b and Eslinger et al., 2019. Since the objective in this study is to produce appropriately scaled petrophysical properties data at all scales, it is necessary to employ a Classification at each scale which is based on such properties. Thus, the Properties-based Classification schema is adopted here, with the Classifications being called "...types" at all scales. At the scale of the core plug the Classified groups are called Petrotypes, at the wireline log scale Electrotypes, and at the geocell scale, Geotypes. When based on wireline logs alone (with no petrophysical properties data directly involved), the Classified groups are termed Electroclasses (as in the example that follows).

Classification Methodology

Examples of typical Classification outputs based on the use of Bayesian-based Probabilistic Multivariate Clustering Analysis (PMVCA) for three wireline log variables are shown in Figure 2. The seven Electroclasses which were developed are shown at the lower left, colour coded by Lithology. Then from left to right; a 2D projection, a 3D plot, and a pair of 1D traces showing first the crisp assignment (labelled as Beds) along with the cumulative mode probability (CMP) of assignment into each of the Electroclasses at each depth point. The PMVCA algorithm follows the form of Perlovsky (1994) and is used throughout the workflow for Classification at all scales.

Classification and Upscaling of Saturation-dependent Properties (CUSP) Workflow (A Multi-scale Classification-based Workflow for Core-Log-Geocell Integration)

The concepts and definitions that have been presented above have been used to develop a multi-scale workflow to translate petrophysical properties, both static and dynamic, from core plug to log scale and then from log to geocell scale both in 1D and 3D (here the whole core scale is by-passed both for simplicity of illustration and because generally only limited data is available at this scale). This workflow, called for conciseness the Classification and Upscaling of Saturation-dependent Properties workflow, or CUSP, is scale independent, i.e. the same workflow steps are applicable at all scales and across all scale changes. The scale independence also facilitated the coding of the workflow into efficient software.

An outline of the CUSP workflow is shown schematically in Figure 3. First, both static and dynamic petrophysical properties are defined at the core plug scale and Classified as Petrotypes (using the Bayesian PMVCA described above). Then, an established scale-change process, the Classification-Selection-Evaluation-Propagation-Upscaling method, termed CSEPU (Curtis, 2015, Curtis et al., 2019a), is used to translate the Petrotype properties to the Electrotype scale and finally to the Geotype scale, as explained below.

Parameterisation for the CUSP Workflow using Characteristic Length Variables (CLVs)

Hydraulic Similitude and Classification Variables

The CUSP workflow uses purpose designed variables within a Bayesian-based PMVCA to implement the necessary parameterisation, with these variables being the same at each scale (a feature which is vital to the success of the CUSP workflow). Three Characteristic Length Variables (CLVs) were defined by Curtis (2000, 2015) for use in performing Properties-based "…. types" Classification, these being shown in Figure 4. The three CLVs are based on the principles of hydraulic similitude (Hwang, 1981) which ensures an equivalence in behaviour between a model (small/fine scale) and a prototype (large/coarse scale). Hydraulic similitude involves the specification of variables in both the model and prototype which ensure that three constraints are honoured: geometrical similarity, kinematic (flow) similarity, and dynamic (force) similarity. With porous media, these three constraints are implemented by invoking the CLVs: Omega (ω), Kappa (κ), and Eta (η), all of which have the dimension [Length]. (cf. Figure 4).

The CLVs are used in a Bayesian-based PMVCA to first determine probabilistic rock types. Figure 4 (right) shows how the CLVs permit the Classification of rock at any scale (here for two different rock types). A given rock type (e.g. pink) will occupy a defined position in the 3D variable space of ω - κ - η, with a different rock type (blue) occupying a different position in 3D CLV space. The CUSP workflow subsequently uses these purpose-designed CLVs within the same Bayesian-based PMVCA to implement the parameterisation necessary for the Propagation step of the CSEPU-based scale change of the petrophysical properties (as further explained below).

Hydraulic Coarse-scale Homogeneity Assumption and its Corollary

Within petroleum reservoir characterisation practice, use is made of the coarse-scale homogeneity assumption wherein, at any given scale, the unit (coarse) volume, despite being made up of a large number of fine scale volumes, is considered to be homogeneous in respect to its petrophysical properties and flow behaviour. This assumption is also known as the equivalent medium assumption. An important corollary to the assumption, which is used in CUSP, is that any homogeneous volume may be characterised by data taken at a finer scale (provided the finer scale still represents a representative elementary volume). This means that the CLVs of the fine scale volume and the coarse scale volume will be identical. It follows that Classification using CLVs is scale independent and can thus be used both at any scale and across scales to facilitate Upscaling.

Upscaling using CLVs

Consider now that the CSEPU Classification to Upscaling process has been followed and that Upscaled petrophysical properties have been used to develop the same three CLVs at the coarser scale. If the coarse-scale volume, which is also considered to be homogeneous, has values of the CLVs that are identical to those at the fine scale, then by definition the porous material being considered at each scale will have the same hydraulic behaviour. That is, hydraulic similitude will have been achieved between model and prototype, as was shown schematically in Figure 4. The implication of having hydraulically similar homogeneous materials at two different scales (i.e. being identical in CLV space) is that if the properties of the material at one scale are known, then they are also known at the other scale. It is this outcome arising from hydraulic similitude that is the foundation of the CUSP workflow.

The practical importance of the above is that if a CUSP model is constructed (using Bayesian PMVCA) with all three Classification variables at the fine scale, and then if the model is used at the coarse scale with two of these variables as inputs, then the third can be predicted. Since in this prediction at the coarse scale the ω and κ variables are derived from upscaled basic petrophysical properties and the η CLV was originally derived from dynamic properties, then the dynamic properties can be predicted at the coarser scale. Importantly, this applies even when there is no underlying 3D grid to permit their direct calculation. Thus, the predictive Bayesian PMVCA permits the CUSP workflow to be applied, even though the saturation-dependent properties are arrays. How such properties are brought into and used in the workflow is covered in the next section and an example follows.

The CUSP workflow can thus be seen to have several major components. The first is the consistent use of the CSEPU concept to permit rigorous scale changes, which is itself based on a consistent and effective Classification scheme. Another is the widely used concept of an equivalent homogeneous medium, and importantly its corollary, at any scale. This concept is then coupled with the principles of hydraulic similitude to permit petrophysical properties to be predicted using a PMVCA model developed using CLVs with different scale data.

Development of Saturation-dependent Properties at the Coarse Scale in the CUSP Workflow

The development of saturation-dependent properties at the coarser scale is accomplished by first building Representative Pc (Sw) curves at the finer scale, as is shown schematically on the left of Figure 5. The Pc (Sw) curve which best represents the saturation-dependent behaviour of the range of laboratory data of each of four Petrotypes is shown. The purple dot on the Representative Pc (Sw) curve for each Petrotype is termed the CUSP Point (Pc^{CUSP}) and is used to develop the η CLV. Refer to Curtis (2015) and Curtis et al. (2019a) for details.

In the centre of Figure 5, both Petrotypes (core plug scale) and Electrotypes (wireline log scale) are shown in respective schematic vertical depth profiles. A PMVCA model based on the ω, κ, and η CLVs at core plug scale was developed to determine the four Petrotypes shown. The Classification of the Electrotypes was initially based on a PMVCA of the wireline log data. The CSEPU methodology is applied to derive the Upscaled values of the basic (static) petrophysical properties at the wireline log scale. The CUSP workflow then uses these to determine new, Upscaled values of ω and κ for each identified Electrotype. Using the PMVCA model, a value of the capillary-related CLV η is predicted at the Electrotype scale. This is then related, via the CUSP Point, to the Representative Pc (Sw) curve for that rock type and a Pc (Sw) curve reconstructed (back calculated) as is shown on the right side of Figure 5. The method thus practically applies the principle of hydraulic similitude outlined above such that if two homogeneous volumes have the same CLVs, they will have the same hydraulic behaviour, irrespective of scale.

In Figure 5 the CUSP methodology has been illustrated for the case of the core plug to wireline log scale change. The same method can be used for the wireline log to geocell scale change. In this case the basic petrophysical properties are Upscaled across every geocell interval spanning the log to get a value for the Upscaled properties in each blocked well geocell (and thus ultimately a distribution for each Geotype). The Geotypes themselves are developed either in the 1D software or by analysis within 3D geocellular modelling software. As each geocell in a 3D model has a set of basic petrophysical properties (after using classical geostatistics for Propagation), these properties may be turned into CLVs which in turn can be used in the CUSP 3D workflow to predict saturation-dependent properties at the geocell scale.

Case Study

CSEPU-based CUSP Workflow in 1D: Core to Log to Geocells in Blocked Wells

Data from an onshore, predominantly siliciclastic, conventional gas field are used to demonstrate the CUSP workflow. Plots of the logarithm of the ω and κ CLVs are shown at each of the Petrotype, Electrotype, and Geotype scales at left in Figure 6, wherein five Petrotypes (top) have been initially identified by an unsupervised PMVCA of the CLVs. Recall that ω ensures geometric similarity, κ provides kinematic similarity, whilst η ensures force (or here pressure) similarity. The CSEPU Classification to Upscaling methodology and the CUSP workflow are then repeated to move to the Electrotype scale, and then to the Geocell scale. Note that since the unit volume is larger at the Geotype scale, the number of data points is thus reduced, illustrating why a PMVCA approach that can work with sparse data is vital. Figure 6 also shows, at right, Representative Pc (Sw) curves (with bounds) at each scale.

3D Geomodel Construction

To implement the CUSP workflow in 3D it is first a requirement to have a well-constructed 3D geomodel. A relatively simple model of the reservoir was constructed as the objective was to illustrate the application of the CUSP workflow rather than geomodelling intricacies. The structural framework for the model was based on five wells, one of which was used for the prior 1D CUSP-based upscaling (Red well in subsequent figures). Figure 7 shows, at left, a structural cross-sectional view of the five wells of the 3D geomodel, with their areal distribution being shown at right in 3D. The final 3D geocellular model had approximately 650,000 geocells that will require Propagation of Geotypes and petrophysical properties, both basic and saturation-dependent, from just the five wells.

The conventional "facies" model for the 3D geomodel was based on the Geotypes developed from an updated application of the previously outlined CUSP workflow. The five new Geotypes now being used (from a revised PMVCA) are shown in the centre of Figure 8. At the Geotype scale, the CLVs will not be used for Upscaling, but rather to Propagate (distribute) the 1D-derived saturation-dependent properties throughout the full 3D geomodel volume (i.e. into every geocell). A composite view of the Geotypes, in logs, in blocked well geocells, and in two 3D views, is given in Figure 8. Geotypes in the other four wells were predicted from the PMVCA model of CLVs in those wells and these were used in a sequential indicator simulation algorithm (Caers, 2005) to Propagate the Geotypes throughout the 3D model (as shown at right in both plan and sectional views).

The basic petrophysical properties were next Propagated throughout the 3D geomodel, by Geotype, using a co-kriging algorithm. These properties followed the same general trends as is seen for the Geotypes in Figure 8.

CUSP Workflow in 3D: CLVs in 3D

The CUSP workflow has been implemented as a 3D "plug-in" to a standard geomodelling software application. This plug-in works both in the purely 3D setting and by interconnection with the 1D CUSP software. The first step in applying the CUSP workflow is to develop the two CLVs which are based on the basic petrophysical properties at the geocell scale, with these ω and κ values being given in Figure 9. Once ω and κ are determined in every geocell, η can then be predicted from the PMVCA model that was built at the geocell scale in the 1D application. The results for the predicted η CLVs are shown on the left in Figure 10.

CUSP Workflow in 3D: Pc (Sw) and Saturations in 3D

The variable which represents the capillary pressure and from which a full Pc (Sw) can be reconstructed was introduced above, this being Pc^{CUSP}, the CUSP Point. A 3D view of this is shown on the right of Figure 10. An example of the Pc (Sw) curves that have been developed for each geocell can be seen in two different ways in Figure 11. The left-hand plot shows Pc (Sw) curves for Geotype 1 at 150 depths down three vertical pillars of the 3D geomodel, as developed from the predicted η and the calculated CUSP Point in the 3D geomodel. The right-hand plot shows the Depth (Sw) relations for those cells of Geotype 1 in the 12,500 randomly selected geocells, with the Sw value determined from the individual, location specific, Pc (Sw) curve in each geocell. There is very good agreement when viewed across the same capillary pressure range (as shown beneath the two red horizontal lines).

The Depth (Sw) relation for all geocells can be displayed in 3D, as is shown in Figure 12. The 3D view at left shows the water saturation in a slice through the geomodel which dips to and past the Free Water Level (red plane). At right is the same 3D model slice zoomed and with the FWL plane removed to show the detail of the saturation variations with depth. This view clearly shows the influence of the different Geotypes.

Figure 13 then shows a comparison of the resulting Classifications and Depth (Sw) profiles for both the Electrotype (left) and Geotype scales (1D right, 3D centre). The TVDss depth and FWL are the same for both scales. Whilst the differences in rugosity of the saturation profiles with depth are readily apparent, what is also evident is that the major rock type and saturation changes down the profile are preserved in moving to the coarser scale. What needs to be emphasised is that the saturation profiles at both scales have been determined completely independently from conventional wireline resistivity-based analyses. Thus, they serve as an independent check on such analyses whilst offering a view as to the likely uncertainty in either method.

Conclusions

A workflow has been presented which overcomes one of the more intractable problems of reservoir characterisation: upscaling and propagating saturation-dependent (dynamic) petrophysical properties from sparsely located and sampled 1D wells to every cell in a 3D geocellular reservoir model. Such properties, being array data, can only be propagated from secondary variables using an appropriate and consistent parameterisation. Advanced classification techniques have been linked with a unique scale-independent parameterisation to implement the new workflow.

Classifications were first developed using a Bayesian-based probabilistic multivariate clustering technique which provided a probabilistic rock typing at the core plug scale. The resulting multivariate model is then used to implement the propagation of static petrophysical properties away from regions where they were measured into unsampled regions in either the well or the geocellular model. The propagated properties are then upscaled using conventional methods. The scale-independent parameterisation uses three Characteristic Length Variables (CLVs) which are based on the principles of model-prototype hydraulic similitude. The CLVs are calculated from the static and dynamic petrophysical properties at the fine scale and used to build the classification model. After upscaling the static properties, two of the CLVs are used in the same PMVCA model to predict the third at the coarser scale, thus facilitating the upscaling of the dynamic properties.

An example has been presented for a conventional gas reservoir in which both static and dynamic properties are moved from wireline log scale to the geocell scale in 1D and then into all geocells of a 3D geocellular model. The effects of the homogenisation of the properties at increasing scales is clearly seen in the CLVs derived from each level of upscaled data. The effect is also clearly evident in the capillary pressure curves developed at each scale. Saturation profiles with depth developed from the capillary pressure functions at both the Electrotype and Geotype scales show a very good match, albeit with (as expected) less rugosity at the geocell scale.

The new workflow provides a robust and consistent framework in which to implement the scale changes involved when integrating logs with geocellular models. The adoption of scale-independent CLVs permits consistent classification at any scale. The inherent value of the CLV-based multivariate model is realised when it is used to propagate petrophysical properties into the 3D volume, away from the necessarily limited set of well-derived data points used in their evaluation. The workflow is comprehensive and rigorous in its specification, but simple enough in its application to permit ready use by all disciplines involved in the reservoir characterisation process.

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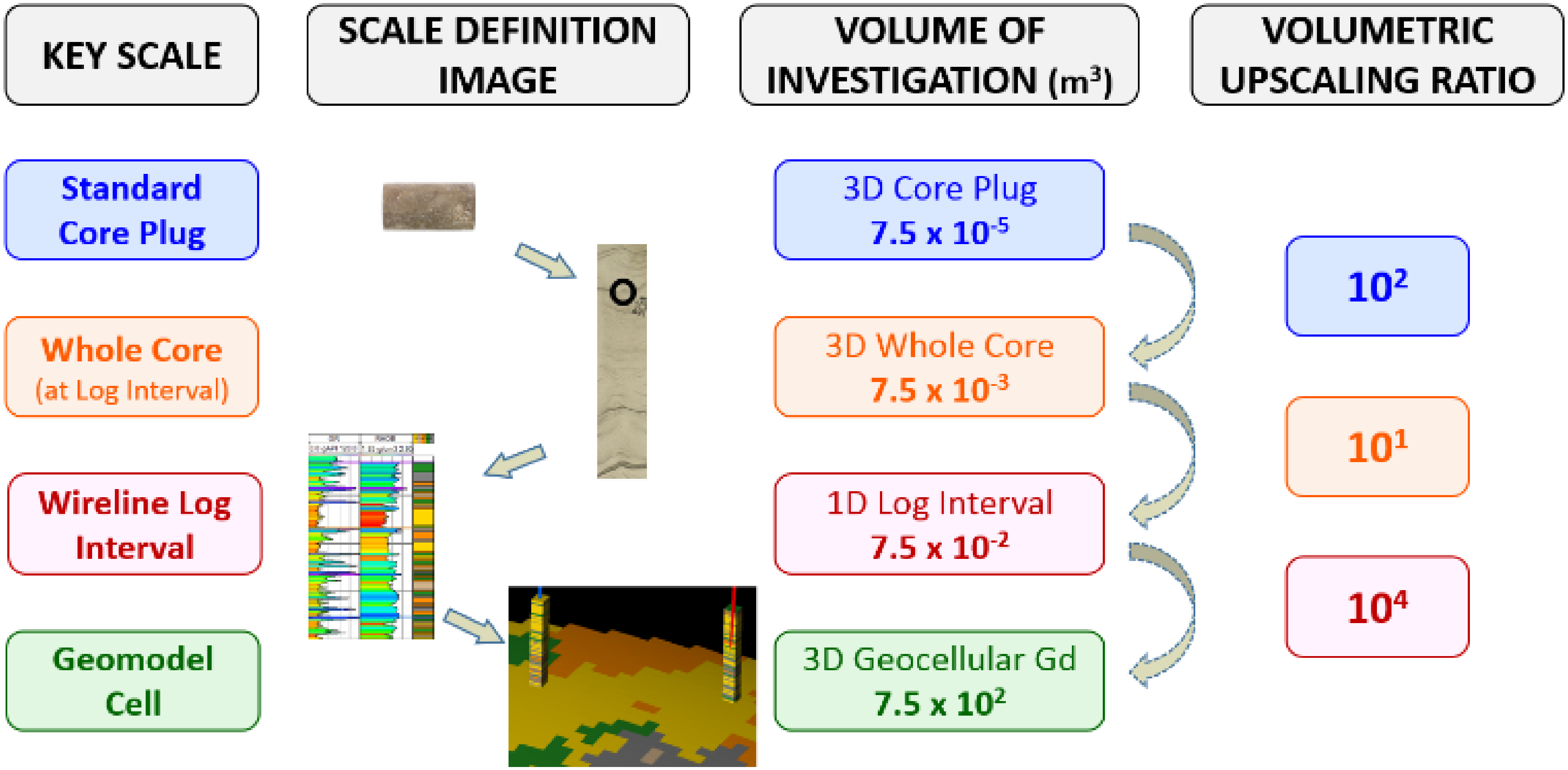

Figure 1. Schematic of Volumetric Upscaling Requirements over Successive Key Scale Changes (after Curtis, 2015).

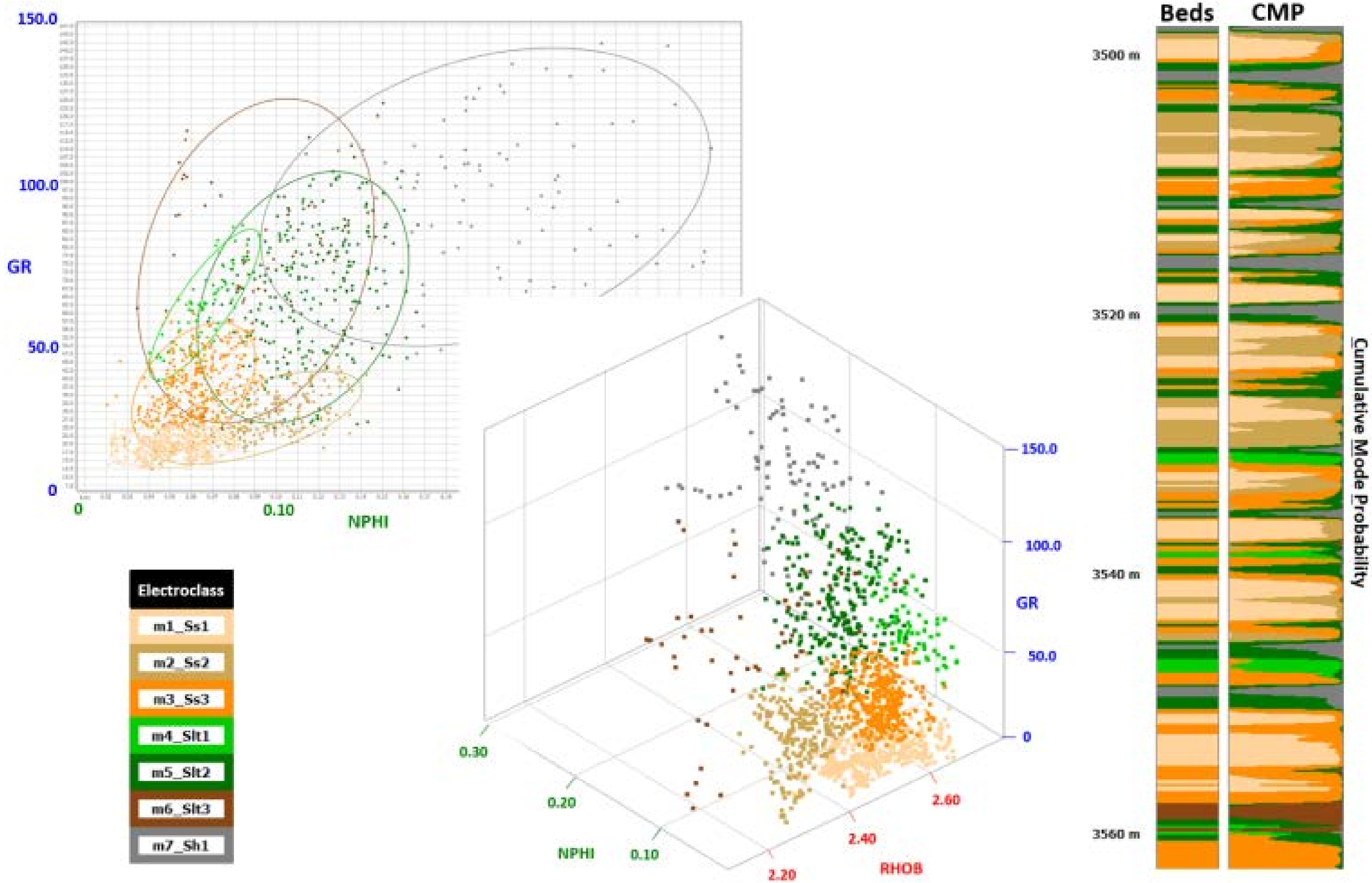

Figure 2. Bayesian-based Probabilistic Multi-variate Clustering Analysis Outputs for a Section of Wireline Log.

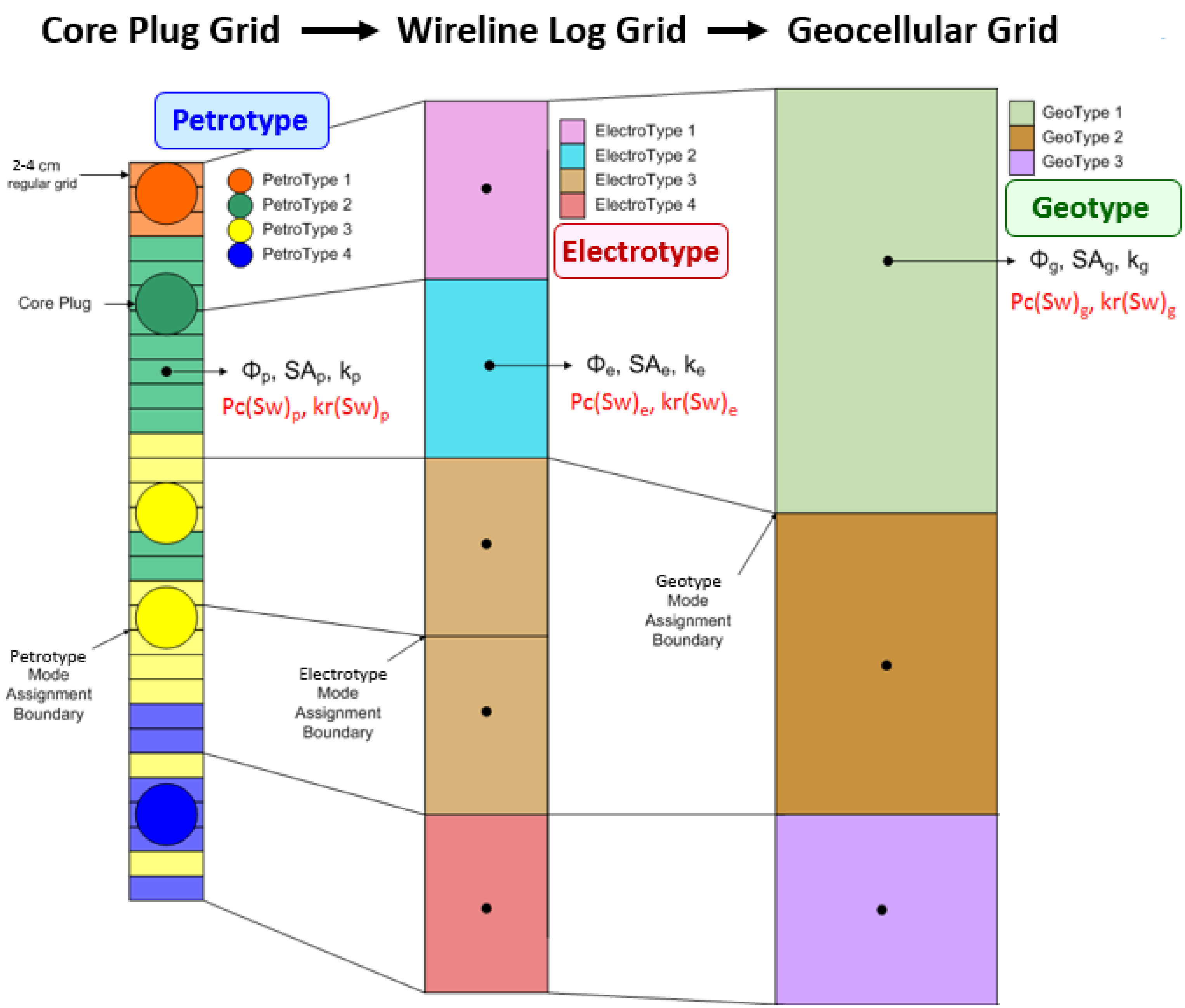

Figure 3. Translation of Petrophysical Properties from Core Plug Scale to Geocell Scale using CSEPU and CUSP (after Curtis, 2015).

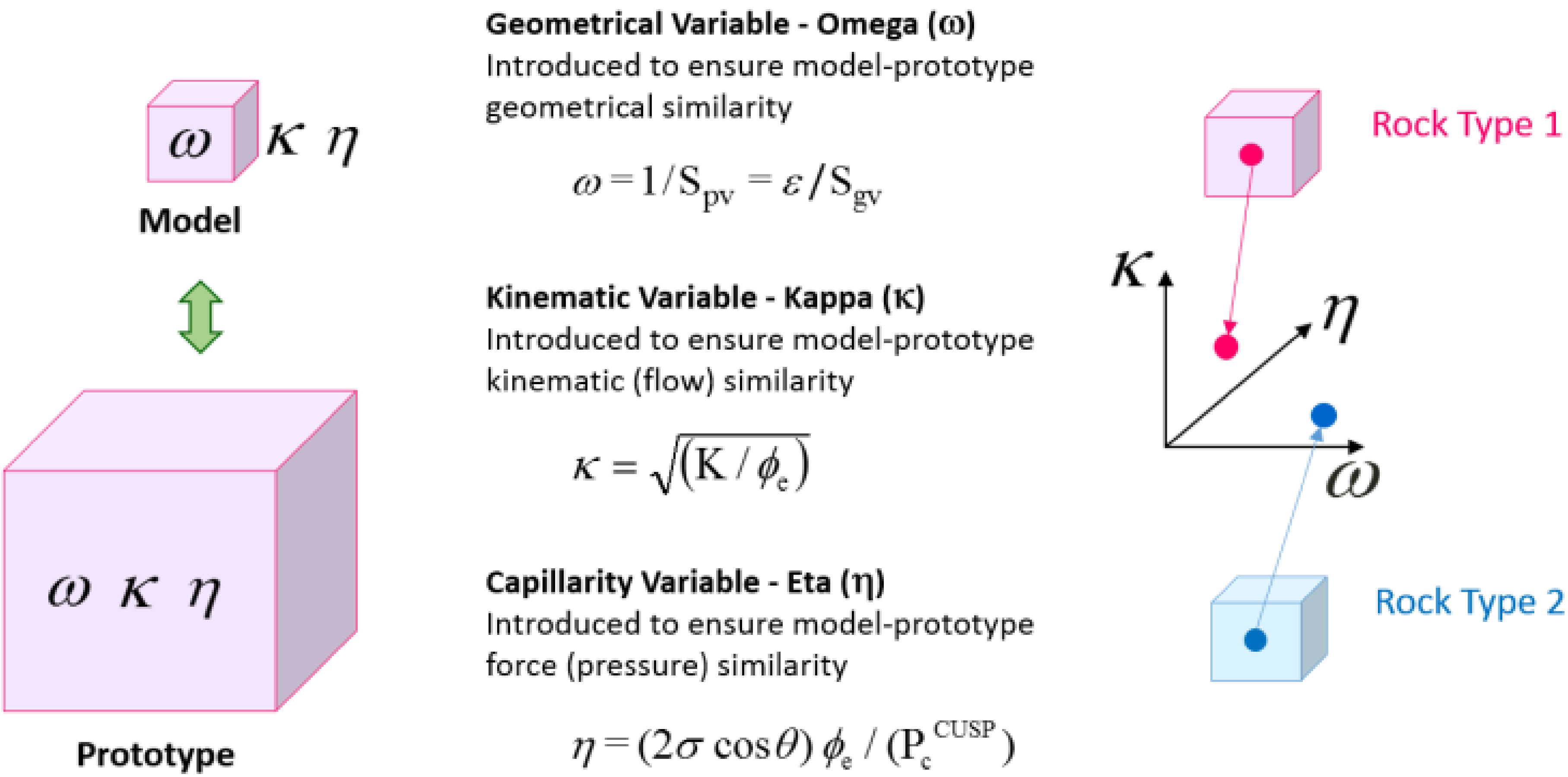

Figure 4. Characteristic Length Variables (CLVs) Defined to Ensure Hydraulic Similitude in the CUSP Workflow (see Curtis, 2000 and Curtis et al., 2019a for details of the equations and nomenclature).

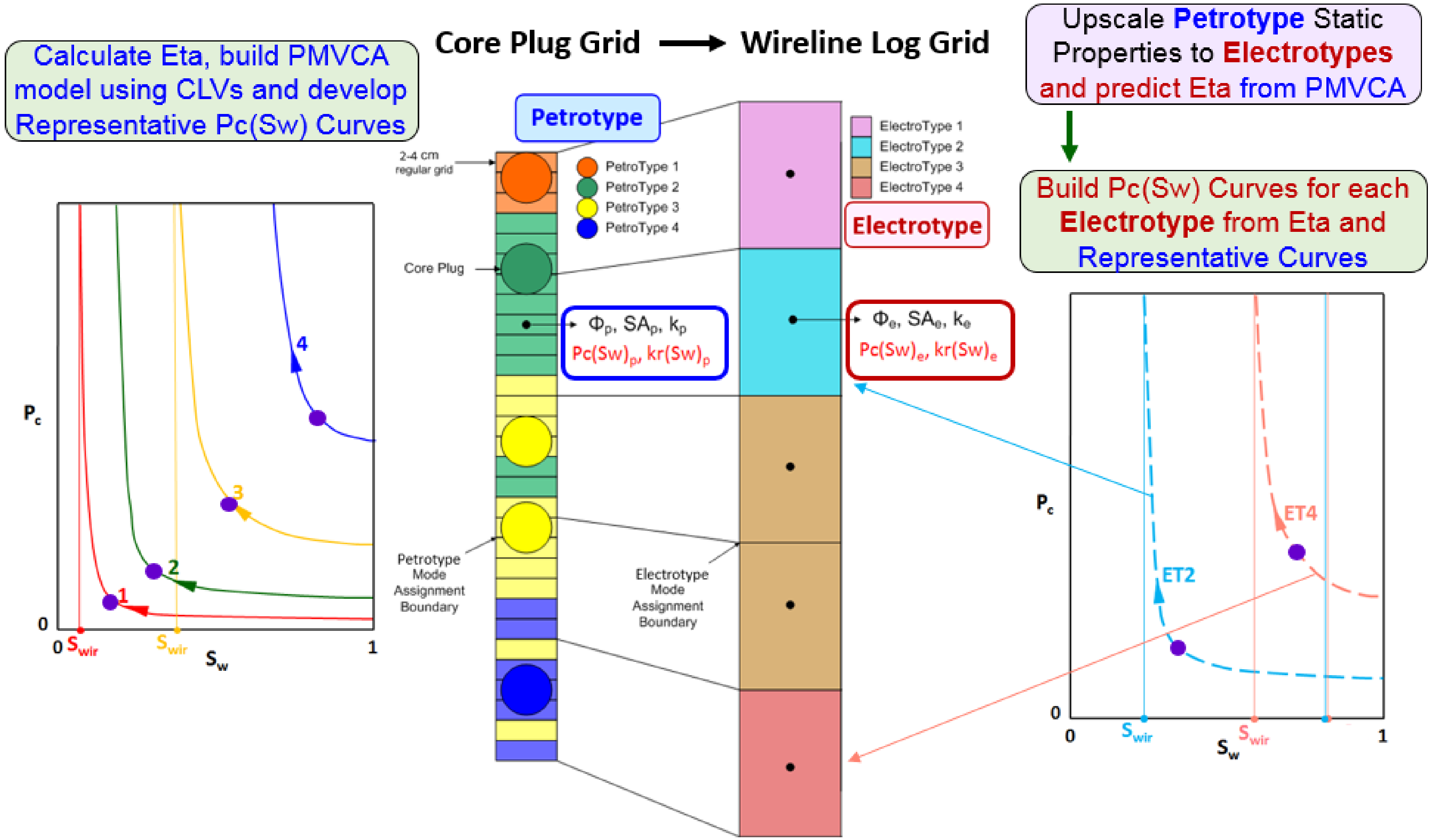

Figure 5. Workflow to Develop Coarse Scale Saturation-dependent Properties using the CUSP Workflow (after Curtis, 2015).

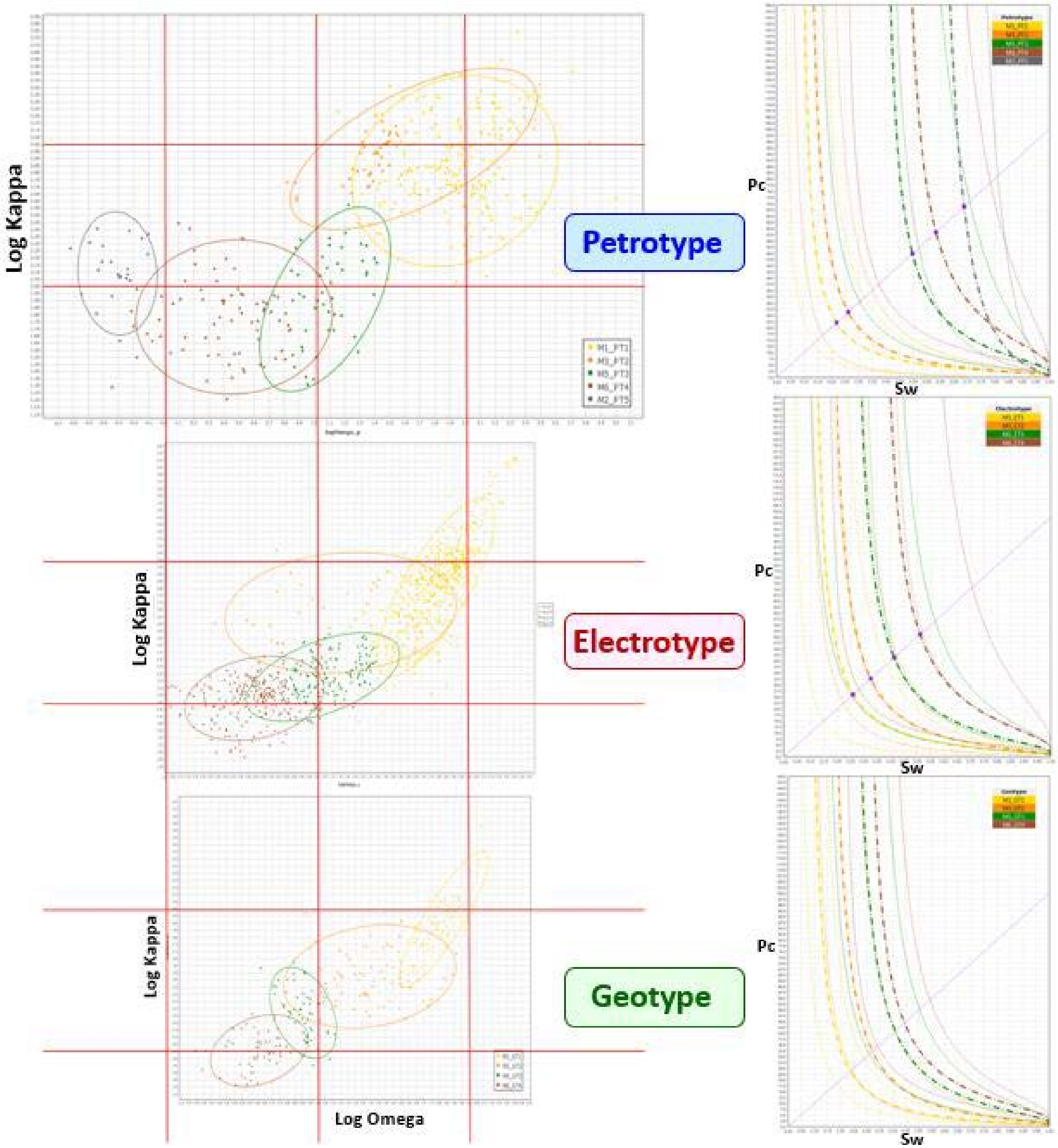

Figure 6. Comparison of CUSP CLVs (ω and κ) (left) and Representative Pc (Sw) Curves (dashed lines) at Three Different Scales (right).

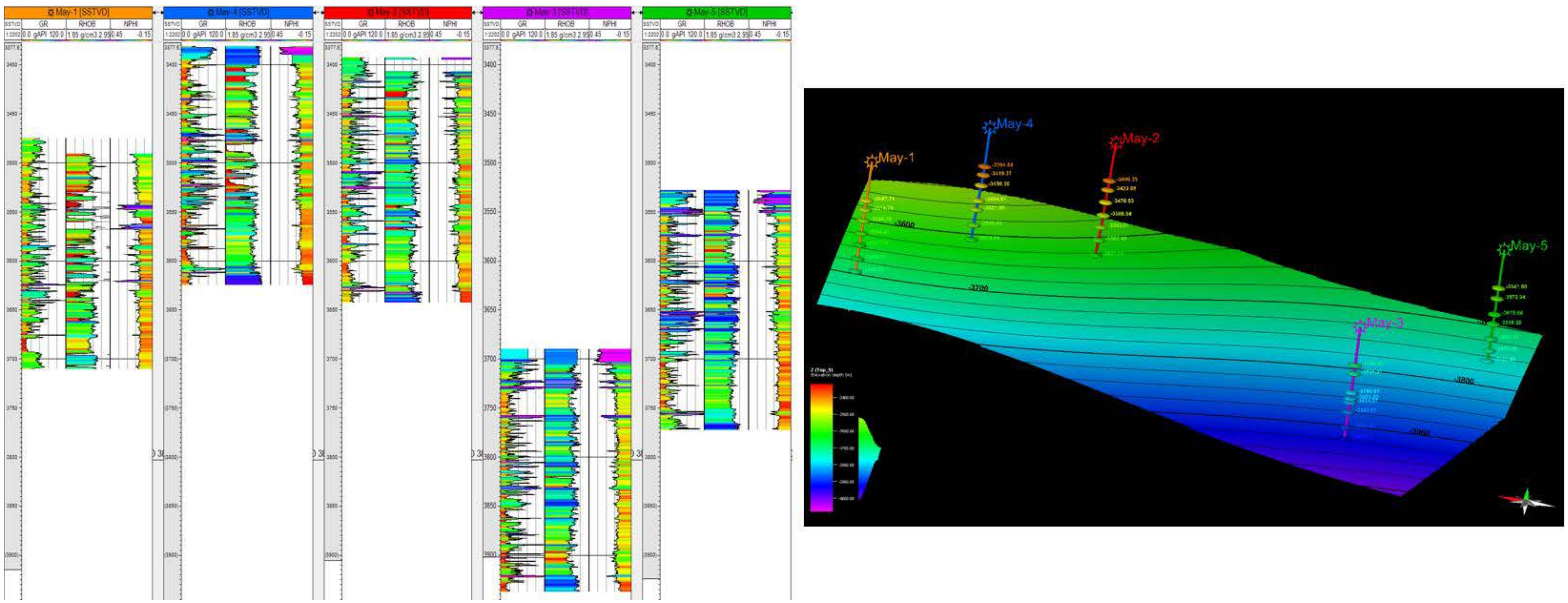

Figure 7. Structural Cross-sectional 2D Views of Five Wells of the 3D Geomodel and their Areal Distribution in 3D. The three Wireline Log Tracks are Gamma Ray (GR), Density (RHOB), and Neutron Porosity (NPHI), each independently shaded by relative magnitude. (The GR and RHOB curves of the Red well are replicated in the first two tracks of the next figure).

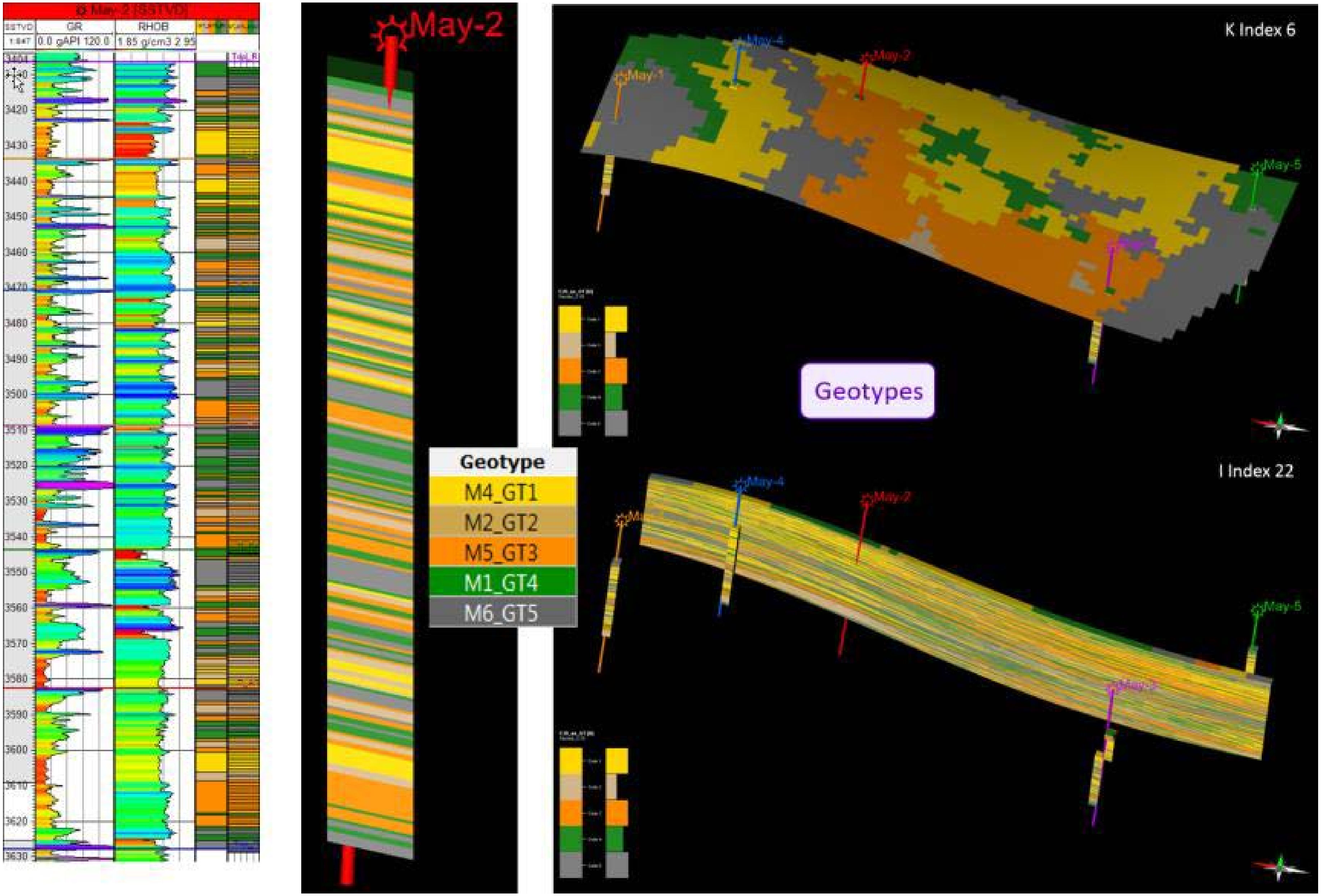

Figure 8. Five Geotypes (defined centre) in Red Well at Log Scale (left, with logs), as a Blocked Well (middle), and in 3D (right).

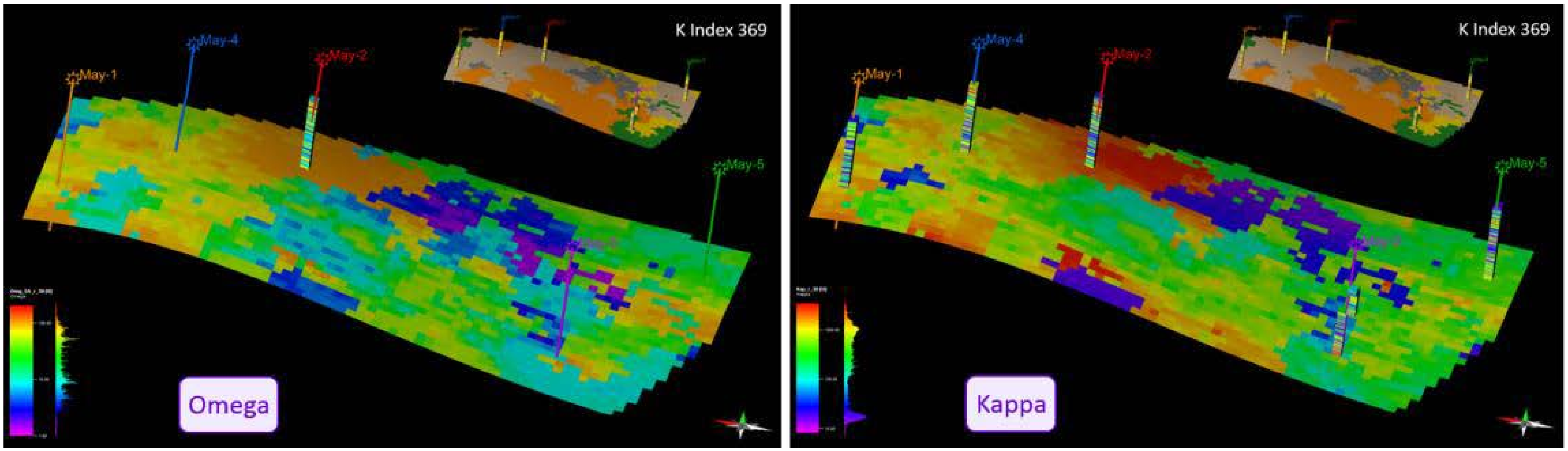

Figure 9. 3D views of the ω and κ CLVs (foreground) and related Geotypes (rear) within the 3D Geomodel.

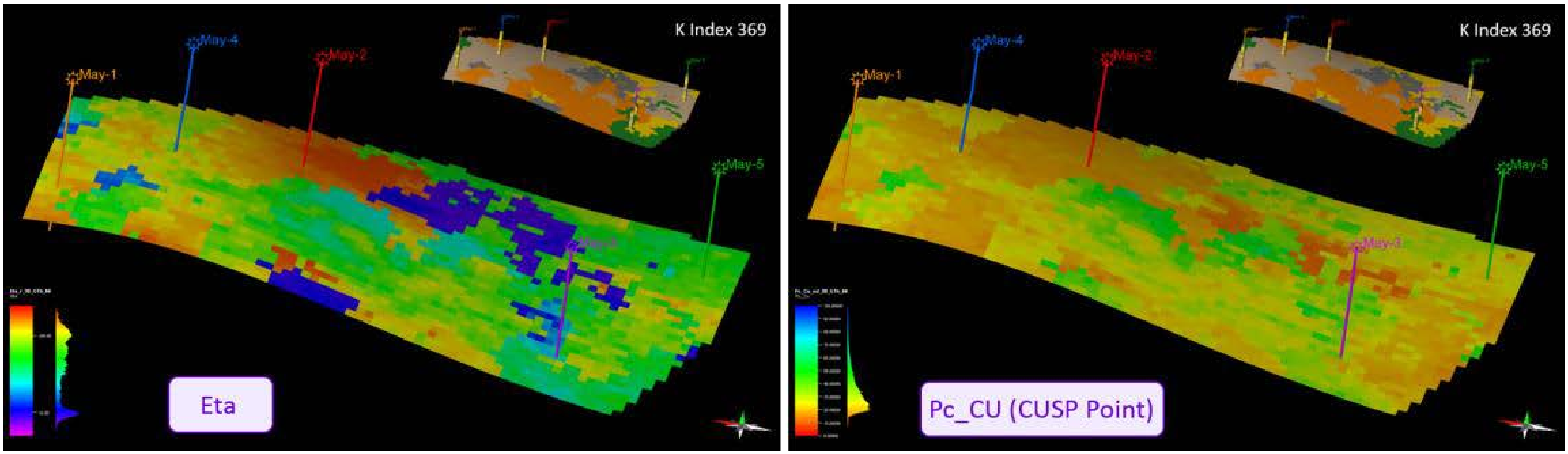

Figure 10. 3D views of the η CLVs and the Pc^{CUSP} variable (foreground) and related Geotypes (rear) within the 3D Geomodel.

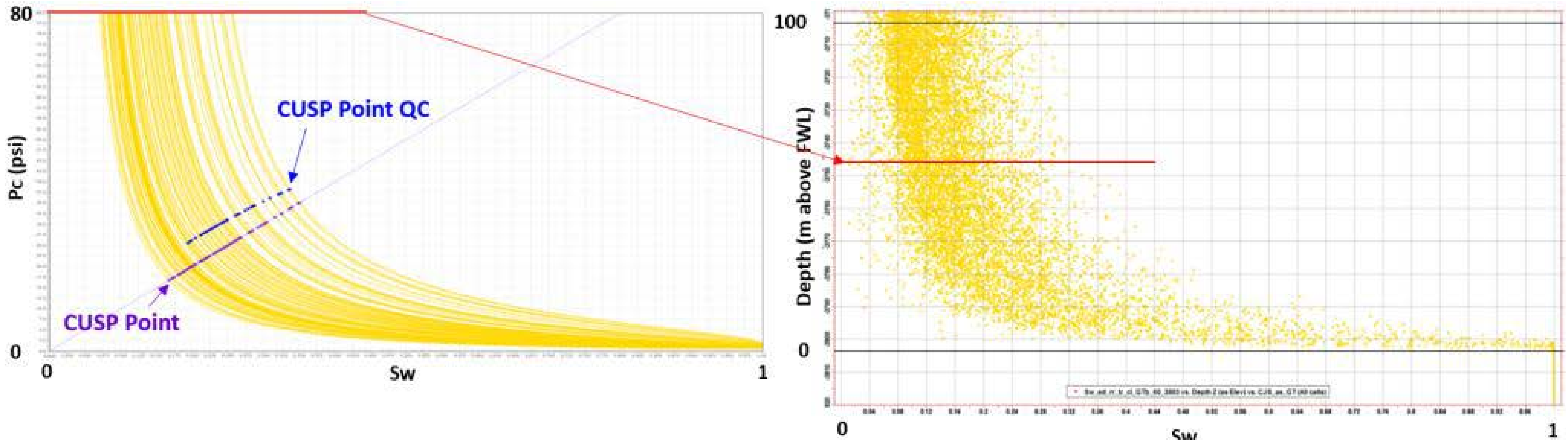

Figure 11. Pc (Sw) Curves for Geotype 1 from three Vertical Pillars (left) and from Sw in Each Cell of the 3D Geomodel.

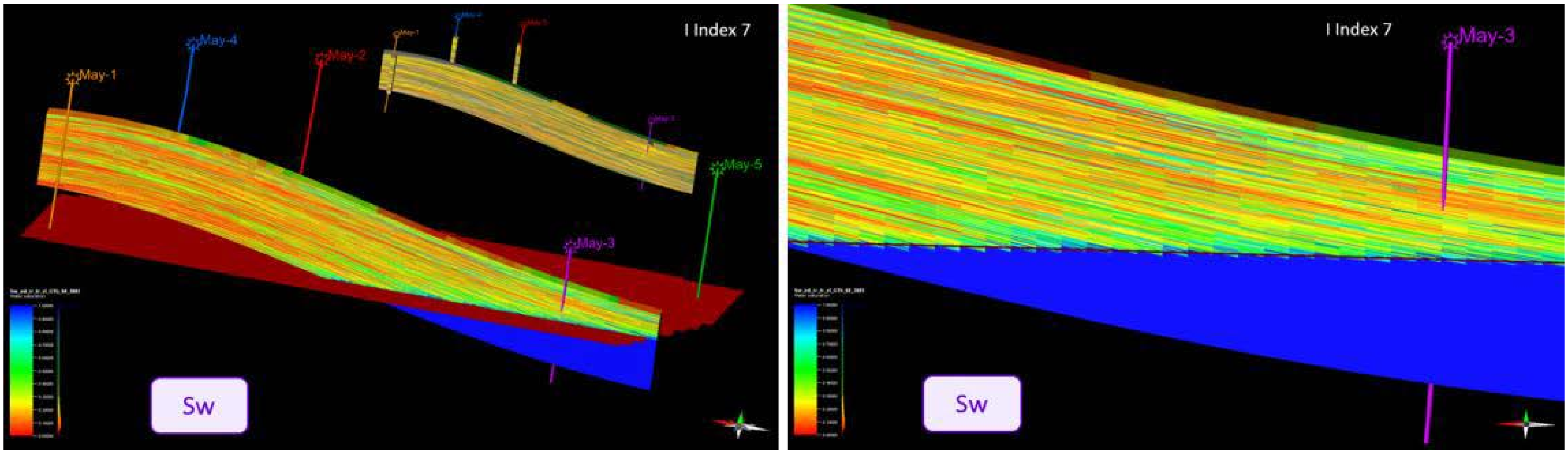

Figure 12. 3D view of the Sw (left foreground) and related Geotypes (rear), and Sw Detail near the Free Water Level

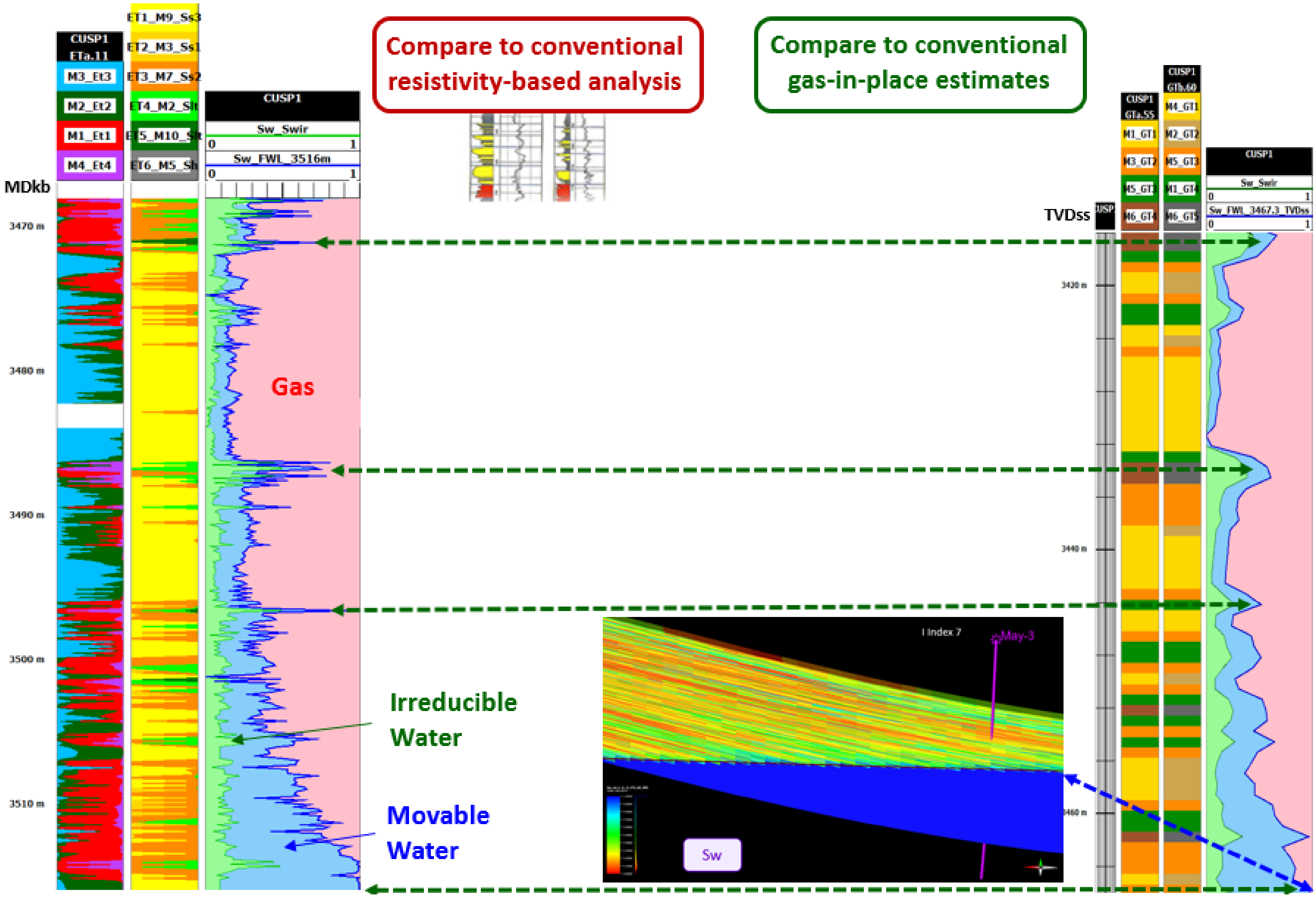

Figure 13. Comparisons at the Electrotype scale (left) and Geotype scale (right) of Rock Type Classifications and Depth (Sw) Profiles. Tracks 1 and 2 are Electrotypes at left and Geotypes at right, whilst Track 3 shows Saturations. Green dashed lines are at the same depth on a TVDss datum.