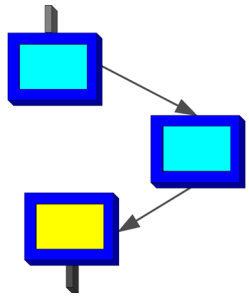


TUTORIAL WORKFLOWS

This section contains:

Rock Physics Models

What's the added value to my interpretation project?

Answer, a rock physics model that:

- Links the petrophysical analysis (ρ-density, P-sonic, and S-sonic logs) and seismic data to yield compatible seismic inversions.
- Enhances your comprehension of the reservoir production characteristics and the underlying geology.
- Provides a consistency check that demands that the elastic constants (*E*, *K*, λ, μ, and ν), minerals, and fluids match well logs and seismic data.
  - V_p, density, and V_s obtained from logs must match the values obtained from the RP model using *K*, μ, and ρ for the minerals and fluids.
  - Synthetic seismic data obtain from impedance and reflectivity curves must match the RP model using *K*, μ, and ρ for the minerals and fluids.
- Generates a P-sonic calculation that you can compare with the P-sonic measurements to check the porosity, minerals, and fluids.
- Computes S-sonic logs if AVO processing is unavailable.
- Uses algorithms to calculate density, V_p acoustic velocity, and V_s shear velocity
- Characterizes your reservoir
  - Model hypothetical fluid substitutions
  - Model impedance logs to create synthetic seismograms and compare these to seismic data.

What are the rock physics model elements?

A rock physics model usually consists of:

- Pore fluids
- Porosity (ϕ)
- Mineral density (ρ), bulk modulus (K), and shear modulus (μ)
- Temperature and pressure
- Density of pore fluids (ρ_{fluid}) and bulk modulus of fluid (K_{fluid})
- Grain and pore structure
- Mineral volume fraction for each mineral type
- Mineral grains for one or more types
- Water saturation (S_w), plus gas/oil ratio (GOR) if needed

Tutorial workflow names

The Fugro-Jason tutorial workflows included with the RPM software are:

- **Starting Point Workflow**—shows how to use basic curves and defined constants to develop basic properties and calculate bulk density, V_p and V_s for a rock physics model.
- **Curve Differences Statistics**—illustrates an approach to determining the RMS (root-mean squared) difference between a measured and a calculated (model) curve. Correlation coefficient and an average bias level are also calculated for the measured and calculated curves.
- **SimpleExpression formulas and logic**—demonstrates how to perform multiple testing logic and evaluate extensive mathematical and rock physics equations.
- **RP Properties for AVO Checks**—provides calculations of acoustic and shear velocities, effective porosity, and Z_p and Z_s impedances. Other elastic constants are computed from velocities and impedances such as:
  - Bulk modulus (K)
  - Shear modulus (μ)
  - Young's modulus (E)
  - Poisson's ratio (ν)
  - Shear modulus/density product ($\mu\rho$) proportional to shear impedance
  - Lamé's constant/density product ($\lambda\rho$) proportional to acoustic impedance
- **Fluid properties to estimate V_s**—uses named constants or PowerLog curves to calculate the fluid (brine, oil, and gas) properties, along with a mean value of each curve.
- **Lithology log construction**—demonstrates building a lithology log based on petrophysical curve values, that can be extended to building a lithology log with rock physics-derived parameters.
- **Gassmann fluid-substitution to predict seismic response**—demonstrates the computation of brine, oil, gas, and fluid properties for existing saturation and new fluid substitution. The results are used with the **GassmannFull** function to predict the acoustic velocity under fluid substitution conditions.

What is a workflow?

A *workflow* is an RPM for PowerLog project that:

- Serves a starting point to develop more complex and customized rock physics models
- Uses PowerLog input curves and named constant values that a user can quickly change
- Reuses different PowerLog projects and wells to achieve multiple project results

Workflows are calculated from input curves belonging to a single PowerLog well project and for limited well depth intervals.

Fugro-Jason provides workflows with RPM for PowerLog software so you:

- Can develop useful computations when you first begin using RPM
- Have an initial starting point to develop your own customized workflows
- Learn some effective development techniques to apply to your own workflows

These workflows illustrate *a single approach* to accomplish a particular rock-physics computation, not necessarily the best way or the only way. You, the geoscience professional, ultimately need to decide that a specific set of workflows is appropriate for the pore fluids, lithology, and goals of your project. The RPM for PowerLog software provides the tools to build your workflow, without a set of rigid constraints or methodology.

This document section describes the tutorial workflows that you can use as a starting point for developing your own reservoir project workflows. Use these examples as models and configure your workflow to meet your specific needs.

Symbols used in rock physics formulas

Table 7. Commonly used symbols in rock physics

Symbol	Name	Purpose
λ	lambda	Lamé's constant ($K - 2\mu/3$)
K	Kappa	bulk modulus
E	Epsilon	Young's modulus
μ	mu	shear modulus (G also used)
ρ	rho	(**1**) density or (**2**) correlation coefficient
φ	phi	porosity
σ	sigma	standard deviation (variance is σ^2)
ν	nu	Poisson's ratio
ω	omega	angular frequency
α	alpha (V_{p0})	(**1**) crack (pore) aspect ratio, (**2**) P-wave velocity along the vertical symmetry axis of a transversely isotropic media, (**3**) mean deviation.
β	beta (V_{s0})	S-wave velocity along the vertical symmetry axis of a transversely isotropic media

Table 7. Commonly used symbols in rock physics (Continued)

Symbol	Name	Purpose
Δ	Delta	Acoustic and shear sonic travel times (measured in μsec/ft.)
M	Mu	P wave modulus ($M = \rho V_p^2$)
Thomsen's anisotropy parameters - relates P-wave and S-wave velocities along the vertical symmetry axis to three phase velocities propagating in the direction of a deviated well.		
γ	gamma	The fractional difference in V_{sh} between the horizontal and vertical directions, and the normalized difference between V_{sh} and V_{sv} in the horizontal propagating S-waves.
δ	delta	Thomsen anisotropy parameter that relates P-wave and S-wave velocities along the vertical symmetry axis to the three phase velocities propagating in the direction of a deviated well.
ε	epsilon	Thomsen anisotropy parameter *for P-wave anisotropy* or the fractional difference in P-wave velocity between the horizontal and vertical directions.

Tutorial workflows overview

Characteristics

These tutorial workflows have several common characteristics:

- Nodes where you *must check for required curve names*, are colored **Red** to denote input curves from a PowerLog well. In these nodes you insert a curve name appropriate for your well or you can insert an appropriate curve alias name.
- Significant rock physics values and workflow flags are defined as named constants and documented in the **Rock and Fluid Properties** and **Constants** software dialog displays.
- Input PowerLog curves, resulting output curves, workflow formulas and RPM functions, and named constants are documented so that you can quickly grasp the workflow essentials.
- Workflow output curves are colored **Blue**.
- Nodes organized in groups, which can be minimized to hide details and show overall workflow organization.

Color schemes

RPM for PowerLog provides you the ability set the color preferences of your workflow elements:

- Node
- Group
- Connection
- Workspace background

Note The color scheme used to document the *Tutorial Workflows* section is described in the next table.

Table 8. Example workflow color scheme

Workflow Element	Color	Color Specification Red: xxx, Green: yyy, Blue: zzz
Workspace (background)		Red: 255, Green: 255, Blue: 192
PowerLog input curves (nodes)		Red: 255, Green: 85, Blue: 0
Computation nodes		Red: 255, Green: 255, Blue: 127
Groups (background)		Red: 255, Green: 170, Blue: 0
Output results (nodes)		Red: 173, Green: 216, Blue: 230
Labels - workflow and constants		Red: 85, Green: 170, Blue: 255
Connections	**Black**	Red: 0, Green: 0, Blue: 0

Starting Point Workflow

The *Starting Point Workflow*[9] helps you get oriented to organizing some of your workflow elements into various groups. In this workflow you calculate a density, V_p, and V_s curve using a number of common petrophysical curves and constants.

Objectives

The *Starting Point Workflow*:

- Calculates density, acoustic velocity, and shear velocity.
- Outputs PowerLog curves to use in the **Curve Differences Statistics** workflow to determine a quantitative measure of the modeling effort's success.
- Illustrates how the elastic moduli from brine, oil, and gas can be calculated using pressure, temperature, and salinity information.
- Shows how to use conditional logic functions to interchange gas and oil properties when computing the final hydrocarbon properties.
- Illustrates simple usage of MixVelocity functions using simple constants for modulus constants and clay velocities.
- Calculates the fluid bulk modulus using Brie's formula (Dvorkin at al. 1999 **[12]**) for patchy saturation.
- Describes and documents named constants to create an easy to use workflow.

9. Many thanks to Mark Sams of Fugro-Jason for developing the initial draft of this workflow.

Computed results

These PowerLog output curves are created when the entire workflow is calculated.

Table 9. Starting Point Workflow - output curves

Node	Curve Name	Type - Units	Description
n17	VpVsmeas	any none	Measured V_p/V_s ratio, calculated from V_p and V_s measured curves
n23	rhocalc	density g/cc	Calculated bulk density
n24	Pvelcalc	p_velocity ft/sec	Calculated acoustic velocity
n25	Svelcalc	s_velocity ft/sec	Calculated shear velocity
n26	Zpcalc	any none	Calculated acoustic impedance
n27	Zscalc	any none	Calculated shear impedance
n28	DTpcalc	p_sonic µsec/ft.	Calculated acoustic sonic
n29	DTscalc	s_sonic µsec/ft.	Calculated shear sonic
n30	VpVscalc	any none	V_p / V_s velocity ratio

Strategies

The key approach to solving this problem involves:

- Using the downhole temperature, pressure information, and named constants with the Fluid/Rock Physics for Brine, Oil, and Gas functions (**BrineRho**, **BrineK**, **GasRho**, **GasK**, **LiveOilRho** and **LIveOilK**).
- Use a conditional logic named constant `Gas_oil_flag` (oil=0, gas=1) to select one set of properties and designate these properties as the HC or hydrocarbon component.
- Specifying a set of clay velocity, density, and modulus constants, along with the clay pore aspect ratio to serve as inputs to the **MixVelocity** functions.
- Combine the brine and hydrocarbon fluid properties, with the clay properties, and use the Volume of wet clay curve as the fractional volume to run each of the MixVelocity functions (**MixVelocityRho**, **MixVelocityVp**, and **MixVelocityVs**).

PowerLog input curves

These PowerLog input curves are used to calculate the brine, gas, and oil properties. The water saturation curve is used in the Brie's patchy saturation formula (Brie et al. 1995 [6]) and to compute the density fraction of brine and hydrocarbons. The total porosity and V_{clay} curves are inputs to the **MixVelocity** functions.

Hint For your well, you may need to modify the curve names or replace them with a convenient curve alias name. The curve names in the previous table are from the tutorial `Starting_Point_Workflow` project.

Table 10. Starting Point Workflow - input curves

Node	Curve Name	Type and Units	Description
n0	**SW**	SW none	Water saturation
n1	**PHIT**	porosity none	Total porosity
n2	**VCL**	any none	Volume of Wet Clay
n3	**PRES**	pressure psi	Pressure of formation
n4	**T**	temperature degF	Downhole temperature
n5	**RHOC**	any none	Bulk density - measured
n6	**DT**	p_sonic µsec/ft.	P-sonic measured
n7	**VP**	p_velocity ft/sec	Vp measured
n8	**VS**	s_velocity ft/sec	Vs measured

Named Constants and Mineral Properties

This table displays the named constants, clay properties, grain/clay pore aspect ratios, and the conditional logic switch for gas and oil.

Table 11. Starting Point Workflow - named constants and rock/fluid properties

Name	Value	Units	Used in these workflow nodes
`Brine_salinity`	**150000**	ppm	n9, n10—concentration
`Gas_specific_gravity`	**.07**	none	n11, n12, n13, n14—spec-grav
`Gas_oil_ratio`	**44/5.615**	none	n13, n14—dimensionless Rs
`Oil_api`	**33**	api	n13, n14—oil density
`Gas_oil_flag`	**0 - Gas otherwise Oil**	none	n15, n16—select which hydrocarbon to use in the fluid computations
`Clay_Vs`	**6233.6**	ft/sec	Compute μ_{clay} and K_{clay}
`Clay_Vp`	**13714**	ft/sec	Compute μ_{clay} and K_{clay}
`Grain_aspect_ratio`	**.08**	none	n23, n24, n25—nonclay (Quartz) pore aspect ratio
`Clay_aspect_ratio`	**.05**	none	n23, n24, n25—Clay pore aspect ratio
`Brie_parameter`	**7**	none	n19—patchy saturation computation
`Clay.Mu`	**9.747e9**	N/m^2	n23, n24, n25—clay shear modulus = **MuFromVel** ($V_{s\text{-}clay}$, ρ_{clay})

Table 11. Starting Point Workflow - named constants and rock/fluid properties (Continued)

Name	Value	Units	Used in these workflow nodes
`Clay.K`	**`3.418e10`**	N/m^2	n23, n24, n25—clay bulk modulus = **KFromVel** ($V_{p\text{-}clay}$, $V_{s\text{-}clay}$, ρ_{clay})
`Clay_rho`	**`2.7`**	g/cc	n23, n24, n25—clay density
`Quartz.Mu`	**`4.433e10`**	N/m^2	n23, n24, n25—quartz shear modulus
`Quartz.K`	**`3.789e10`**	N/m^2	n23, n24, n25—quartz bulk modulus
`Quartz.Rho`	**`2.65`**	g/cc	n23, n24, n25—quartz density

Key workflow functions and formulas

The major expressions used in these workflow nodes are:

- **`n9`**—ρ_{brine} = **BrineRho**[10](**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Brine_Salinity)
- **`n10`**—K_{brine} = **BrineK**(**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Brine_Salinity)
- **`n11`**—ρ_{gas} = **GasRho**(**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Gas_specific_gravity, Batzle&Wang)
- **`n12`**—K_{gas} = **GasK**(**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Gas_specific_gravity, Batzle&Wang)
- **`n13`**—ρ_{oil} = **LiveOilRho**(**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Oil_api, Gas_oil_ratio, Gas_specific_gravity, *blank*, Batzle&Wang)
- **`n14`**—K_{oil} = **LiveOilK**(**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Oil_api, Gas_oil_ratio, Gas_specific_gravity, *blank*, Batzle&Wang)
- **`n15`**—K_{HC} = **ConditionalExpression**(Gas_oil_flag, ==, 0, K_{gas} , K_{oil}) [11]
- **`n16`**—ρ_{HC}= **ConditionalExpression**(Gas_oil_flag, ==, 0, ρ_{gas}, ρ_{oil})
- **`n17`**—V_p/V_{smeas} = **VP**$_{curve}$ / **VS**$_{curve}$
- **`n18`**—Density Fraction$_{HC}$= (1 - Gas_spec_gravity) * ρ_{HC}
- **`n19`**—K_{patchy} = (K_{brine} - K_{HC}) * **SW**$_{curve}$ ** Brie_parameter
- **`n20`**—Density Fraction$_{brine}$= **SW**$_{curve}$ * ρ_{brine}
- **`n21`**—ρ_{fluid} = (Density Fraction$_{brine}$ + Density Fraction$_{HC}$)
- **`n22`**—K_{fluid} = (K_{patchy} + K_{HC})

Hint All three MixVelocity functions (**MixVelocityRho**, **MixVelocityVp**, and **MixVelocityVs**) take the same input constants and PowerLog curve names shown.

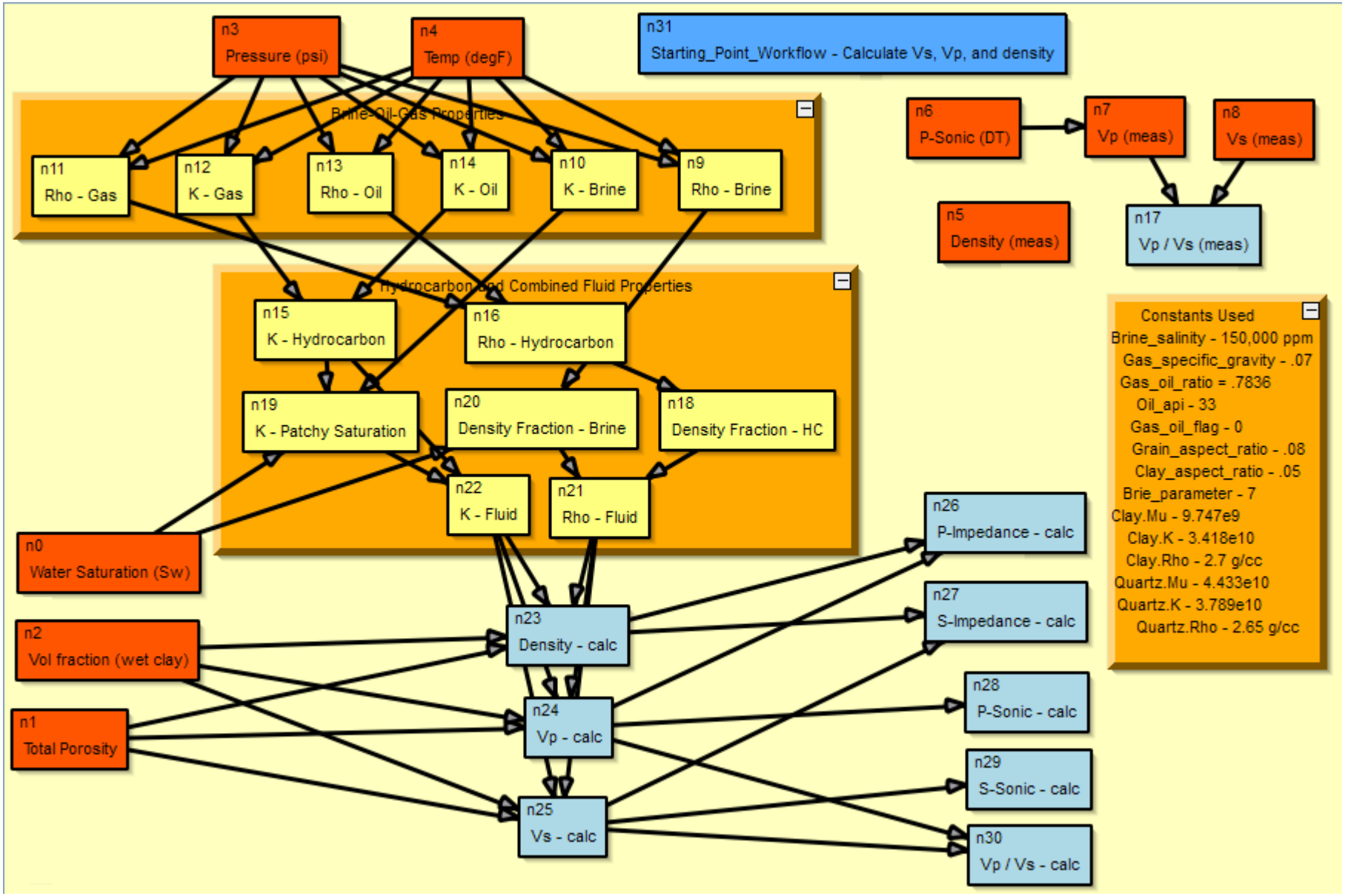
- **`n23`**— **`rhocalc`** = $\rho_{calculated}$ = **MixVelocityRho** (**PHIT**$_{curve}$, **VCL**$_{curve}$, `Quartz.K`, `Clay.K`, `Quartz.Mu`, `Clay.Mu`, `Quartz.Rho`, `Clay.Rho`, `Grain_aspect_ratio`, `Clay_aspect_ratio`, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, K_{fluid}, ρ_{fluid}, XuWhiteApprox)
- **`n24`**— **`Pvelcalc`** = $V_{p\_calculated}$ = **MixVelocityVp** (**PHIT**$_{curve}$, **VCL**$_{curve}$, `Quartz.K`, `Clay.K`, `Quartz.Mu`, `Clay.Mu`, `Quartz.Rho`, `Clay.Rho`, `Grain_aspect_ratio`, `Clay_aspect_ratio`, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, K_{fluid}, ρ_{fluid}, XuWhiteApprox)

10.Name of the RPM rock physics function used for this node. All other nodes use mathematical functions.
11.HC - Denotes hydrocarbon (oil or gas) selected with the **ConditionalExpression** RPM function for K_{HC} and ρ_{HC}.

- **n25— Svelcalc** = $V_{s\_calculated}$ = **MixVelocityVs** (**PHIT**$_{curve}$, **VCL**$_{curve}$, `Quartz.K`, `Clay.K`, `Quartz.Mu`, `Clay.Mu`, `Quartz.Rho`, `Clay.Rho`, `Grain_aspect_ratio`, `Clay_aspect_ratio`, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, *blank*, K_{fluid}, ρ_{fluid}, XuWhiteApprox)

- **n26— Zpcalc** = $Z_{p\_calculated}$ = $V_{p\_calculated}$ * $\rho_{calculated}$
- **n27— Zscalc** = $Z_{s\_calculated}$ = $V_{s\_calculated}$ * $\rho_{calculated}$
- **n28— DTpcalc** = $\Delta t_{p\_calculated}$ = 1000000. / $V_{p\_calculated}$
- **n29— DTscalc** = $\Delta t_{s\_calculated}$ = 1000000. / $V_{s\_calculated}$
- **n30— VpVscalc** = $V_{p}/V_{s\_calculated}$ = $V_{p\_calculated}$ / $V_{s\_calculated}$

Figure 54. Starting Point Workflow



Curve Differences Statistics

The *Curve Differences Statistics* workflow helps you to understand how accurately any calculated curve from a rock physics model workflow approximates the equivalent measured petrophysical log. A correlation value ≥ 0.8 suggests a *strong* correlation, while a value ≤ 0.5 suggests a *weak* correlation. You can use this workflow to assess the calculated results of the *Starting Point Workflow* against the measured well curves:

- Density (ρ)
- V_p (acoustic velocity)
- Shear velocity (V_s)
- V_p / V_s (acoustic / shear) velocity ratio

Objectives

The *Curve Differences Statistics* workflow:

- Provides information about the accuracy of a rock physics model curve calculation.
- Illustrates a workflow building block that can be used interchangeably with any set of measured and calculated curves
- Identifies if the measured and calculated (modeled) curves are strongly correlated, suggesting that the model approximates the measured response.
- Computes a quality control value in the form of the averaged RMS difference percentage between the calculated and measured curves. This value can be compared with other workflow calculations to see if the model error is decreasing or increasing due to parameter or model variations.
- Computes a bias function. A significant average bias function suggests there are unaccounted factors not described by the model.

Computed results

The *Curve Differences Statistics* workflow yields these results for each measured and calculated curves:

- **Error function curve (n2)**—curve stored in PowerLog that can be plotted beside the calculated and measured curves. Node **`n2`** is where you change the name of the output error function curve.
- **RMS Difference Percentage (n7)**—A value that describes the average difference between the calculated and measured curves. This value is the computed as: **`n7`**—RMS Difference Percentage = 100 * Δ_{RMS} / $mean_{meas}$, that is, the root-mean square of the curve difference, normalized by the mean of the measured curve
- **Correlation Coefficient value (n3)**—A value describing the amount of linear correlation between the measured and calculated curve. A correlation value ≥ 0.8 suggests a *strong* correlation, while a value ≤ 0.5 suggests a *weak* correlation.
- **Average Bias Percentage (n10)**—A value equal to the average deviation between the measured and calculated curve.

Strategies

The computations in the *Curve Differences Statistics* workflow are a straightforward usage of the **Correlation**, **Mean**, **Sum**, and **Rms** RPM statistical functions.

You can use the *Curve Differences Statistics* workflow in two ways:

- **Method One**—Change the names of the two input PowerLog curves and the single output curve and rerun the workflow four times with the desired curves. For example, the density, V_p, V_s, and V_p/V_s curves from the **Starting Point Workflow**.
- **Method Two**—Make three identical copies of these workflow nodes. You can then calculate the curve difference statistics for density, V_p, V_s, and V_p/V_s in a single workflow.

Table 12. *Curve Differences Statistics* workflow - curve names

Curve Type	Calculated Curve Node n0	Measured Curve Node n1	Output Error Function Name
Density	`rhocalc`	`RHOC`	`Rhoerr`
Vp	`Pvelcalc`	`VP`	`Vperr`
Vs	`Svelcalc`	`VS`	`Vserr`
Vp/Vs ratio	`VpVsmeas`	`VpVscalc`	`VpVserr`

Input curves

See **Table 12, "Curve Differences Statistics workflow - curve names," on page 95**.

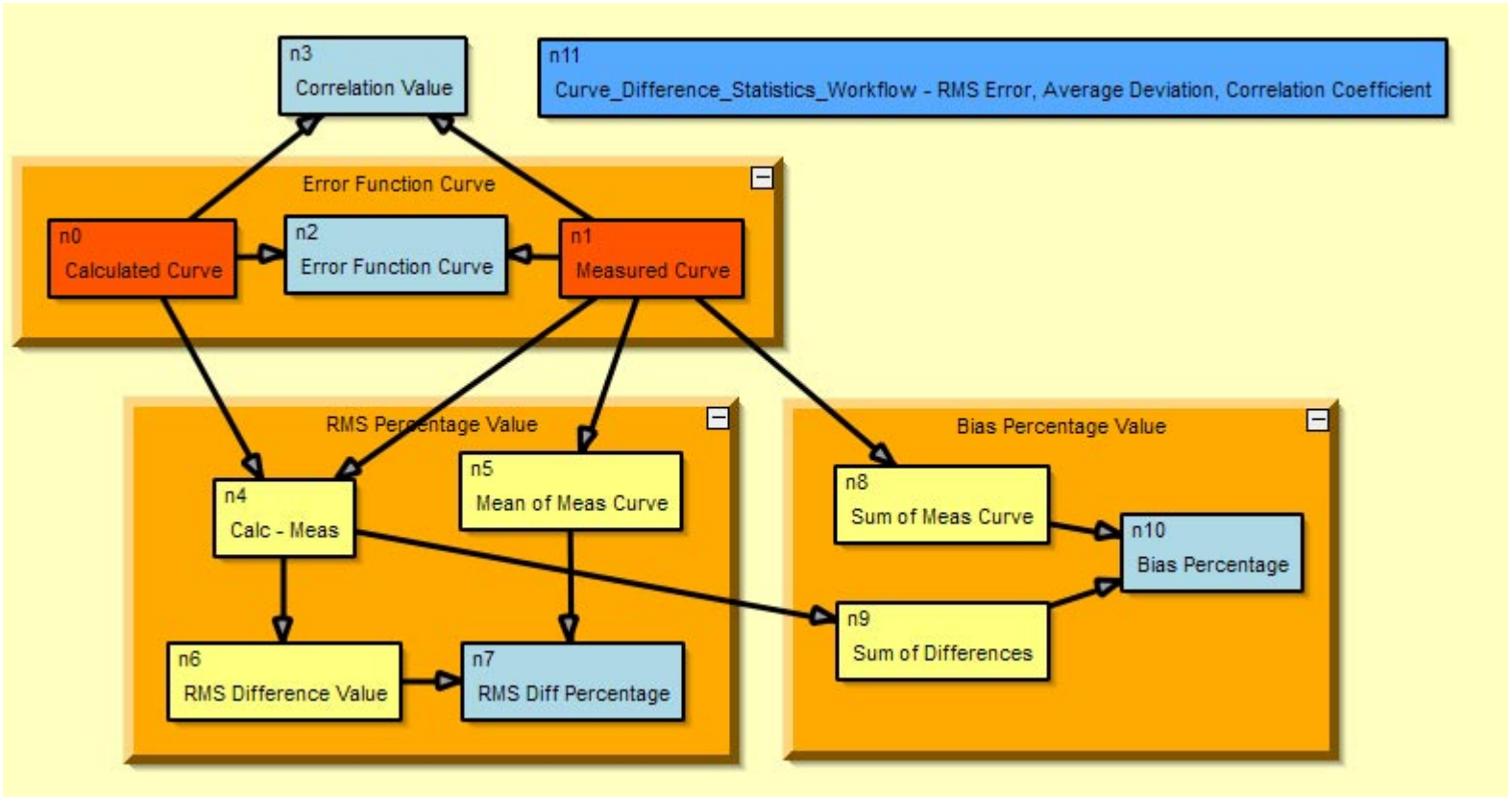
Named constants

The *Curve Differences Statistics* workflow uses no named Constants or Rock and Fluid Properties.

Key workflow functions and formulas

- `n2`—Difference function = $2 * (Meas_{curve} - Calc_{curve}) / (Meas_{curve} + Calc_{curve})$
- `n3`— ρ = **Correlation** $(Meas_{curve} , Calc_{curve})$
  m_{calc} = mean of calculated curve, m_{meas} = mean of measured curve
  σ_{calc} = Standard deviation of calculated, σ_{meas} = Standard deviation of measured
  Correlation Coefficient r =
  $(1/N) * \sum (curve_{meas} - m_{meas})(curve_{calc} - m_{calc}) / \sigma_{meas} * \sigma_{calc}$
- `n4`—$\Delta_{curve} = Meas_{curve} - Calc_{curve}$
- `n5`—$mean_{meas}$ = **Mean**$(Meas_{curve})$
- `n6`— Δ_{RMS} = RMS of curve difference = **Rms**$(Meas_{curve} - Calc_{curve})$
- `n7`—RMS Difference Percentage = $100 * \Delta_{RMS} / mean_{meas}$
- `n8`—$\sum_{meas}$ = **Sum** $(Meas_{curve})$
- `n9`— $\sum_{\Delta curve}$ = **Sum** (Δ_{curve})
- `n10`—Bias Percentage = $100 * \sum_{\Delta curve} / \sum_{meas}$

Figure 55. Curve Differences Statistics workflow



SimpleExpression formulas and logic

This workflow demonstrates some of the computational formulas and sophisticated logic possible with the **SimpleExpression** function in RPM for PowerLog.

Objectives

The *SimpleExpression formulas and logic* workflow demonstrates how to:

- Control the computation sequence using parentheses
- Implement multiple decision logic two ways to determine a:
  - curve that is limited between an minimum and a maximum value
  - lithology coding
  - fluid substitution value
- Implement a rock physics formula not found in RPM
  - Brie's patchy saturation formula
  - $\lambda\rho$ lambda-density product and $\mu\rho$ mu-density product
  - Poisson's ratio[12]
  - Young's modulus

Named Constants

This table displays the named constants, for the *SimpleExpression formulas and logic* workflow.

Table 13. SimpleExpression formulas and logic workflow - named constants

Name	Value	Units	Used in these workflow nodes
`Sonic_min`	**`90`**	µsec/ft.	n3, n5—minimum sonic transit time
`Sonic_max`	**`100`**	µsec/ft.	n3, n5—maximum sonic transit time
`Previous_value`	**`2`**	none	n6, used in n11 and n10—previous lithology log value determination
`Min_clay_volume`	**`.4`**	none	**`n7, n11`**—minimum clay volume for calcareous shale
`Min_coal_volume`	**`.1`**	none	**`n8, n11`**—minimum coal volume for calcareous shale
`Min_quartz_dominates`	**`.5`**	none	**`n9, n11`**—maximum quartz volume for calcareous shale
`Calcareous_shale`	**`1`**	none	**`n10, n11`**—value representing calcareous shale for lithology log
`Vol_clay_max`	**`.2`**	none	**`n12, n17`**—maximum clay volume permitted for fluid substitution
`Phi_effective_min`	**`.05`**	none	**`n14, n17`**—minimum effective porosity required for fluid substitution

12.The Poisson function does perform this calculation.

Table 13. SimpleExpression formulas and logic workflow - named constants (Continued)

Name	Value	Units	Used in these workflow nodes
Sw_new	.2	none	**n15, n17**—new water saturation is for fluid substitution
Z_conversion	92903.4	none	**n23, n24**—converts μρ and λρ to metric

Key workflow functions and formulas

The *SimpleExpression formulas and logic* workflow uses a few nodes and the **SimpleExpression** function to demonstrate each concept listed in the *Objectives*.

Computation Sequence

The *Computational precedence* group (in the workflow) demonstrates the use of parentheses to explicitly control how a complex mathematical expression is evaluated.

Without any parentheses inserted into a **SimpleExpression** function, the computation sequence defaults to trules two through six.

Operator precedence

Priority	Operator Type	Operators	Operator Description
1st	Parenthesis	(or)	Parenthesis control order
2nd	Arithmetic	^ or **	Raising a value to a power
3rd	Arithmetic	* or /	Multiplication and Division
4th	Arithmetic	+ or -	Addition and subtraction
5th	Comparison	< <= > >= = == != <>	Comparison
6th	Conditional	? or :	If-then and Else

Comments For each priority, operators that have the same rank level are evaluated from left to right.

Caution! The conditional operators are evaluated *right to left*.

Comments `( 8 - 2*3 + 3 ) ** 2` evaluates to `8 - 6 + 3 = 5 ** 2 = 25` because the `2*3` multiplication operator has precedence over other arithmetic operators and the parenthesis operator has higher priority than the power (`**`) operator.

Two example nodes make this very clear:

- **n0**— 1 + 2 + 3 * 4 ^ 5 * 6 + 7
  evaluates to
  1 + 2 + 3 * 1024 * 6 + 7
  1 + 2 + 3072 * 6 + 7
  1 + 2 + 18432 + 7 = 18442
- **n1**— (1 + 2) + (3 * 4) ^5 * (6+7)
  evaluates the same expression with parentheses to control the computation
  3 + (12) ^ 5 * (13)
  3 + 248832 * 13
  3 + 3234816 = 3234819

Curve range values limited, two implementations

The *Two curve range implementations* group shows how to limit the values within a PowerLog curve to a range between a minimum and maximum threshold:

- **n3**—all curve values are between the minimum and maximum values. If a curve sample exceeds the maximum, the curve sample is set to maximum threshold. Conversely, if a curve sample is less than the minimum, it is set to the minimum threshold.
- **n5**—uses the **SimpleExpression** to test each curve sample. If the curve sample exceeds either threshold value, the curve sample is set to an undefined value (**UNDEF_POWERLOG**).

Lithology coding decision making

The *Lithology coding decision making* group shows how to group multiple decision criteria into a single SimpleExpression statement and reduce the number of RPM nodes from four to one:

- **n7, n8, n9, and n10**—use the **ConditionalExpression** for each test and then a **SimpleExpression** function to check that all three tests were true.
- **n11**—uses the **SimpleExpression** to perform a boolean AND operation with three separate conditional tests.

The logic for the **n11** node can be diagrammed with each indentation level signifying a subordinate `If-then-else` structure (with PowerLog curves **VCL**, **VCLC**, and **VCLQ**):

```
VCL >= Min_clay_volume
                Then ? VCLC >= Min_coal_volume
                                Then ? VCLQ <= Min_quartz_dominates
                                                Then ? Calcareous_shale
                                                Else : n6
                                Else : n6
                Else : n6
```

Fluid substitution decision making

The *Fluid Substitution decision making* group shows two methods for selecting the appropriate water saturation value, based on clay volume and effective porosity:

- In nodes **n12** through **n16**, the **ConditionalExpression** function is used to decide whether to use the new S_w value or take the existing water saturation value.
- n17—using the **SimpleExpression** compresses the decision making logic to a single node.

The logic for the **n17** node can be diagrammed with each indentation level signifying a subordinate `If-then-else` structure (with PowerLog curves **VCL**, **PHIE**, and **SW**):

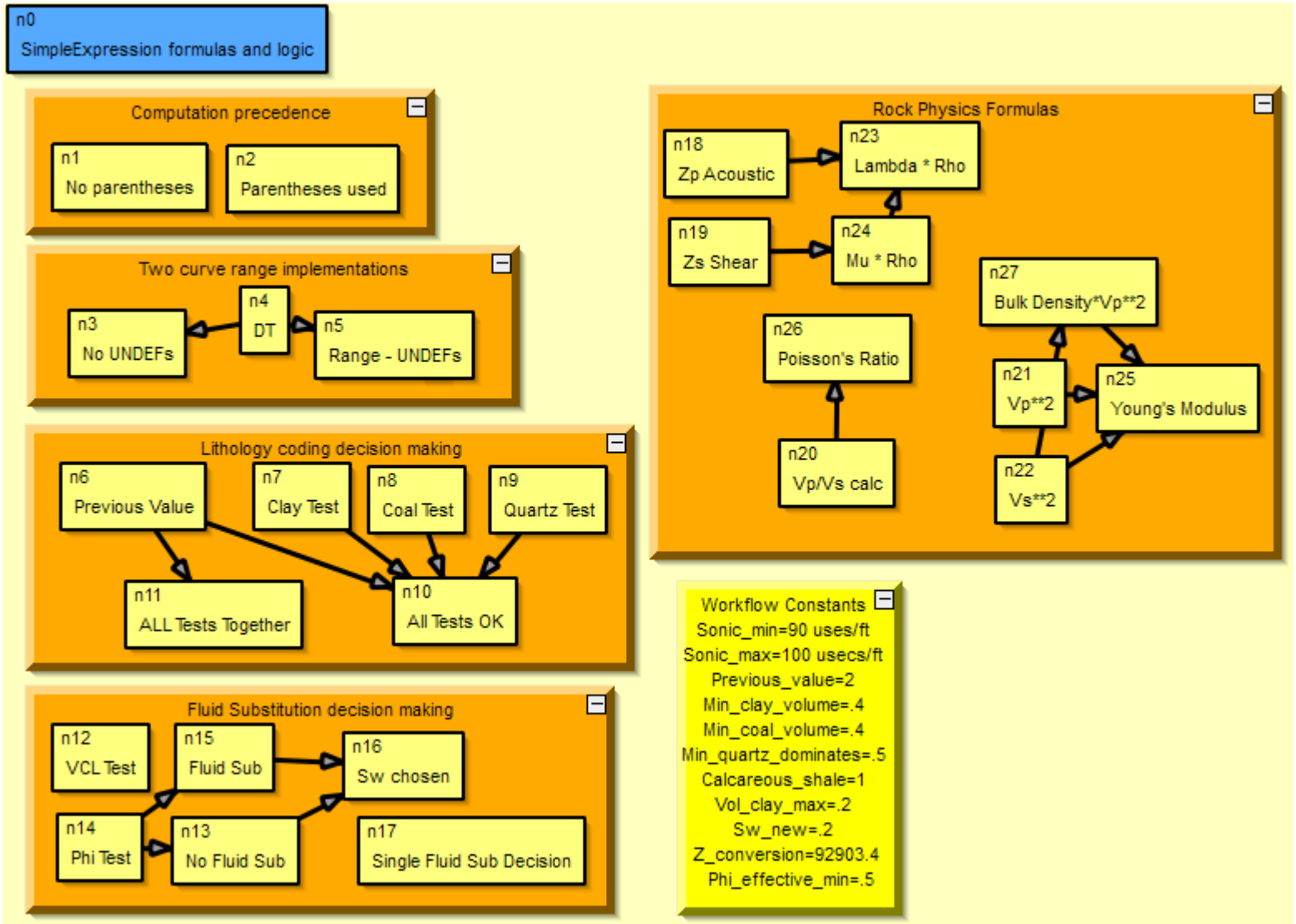
```
VCL < Vol_clay_max
        Then ? PHIE > Phi_effective_min
                        Then ? Sw_new
                        Else : SW
        Else : SW
```

Rock physics formulas

The *Rock Physics Formulas* group implements four expressions for elastic moduli:

- **`Poisson's ratio (n20`** and **`n26)`** — $\nu = (1/2) [(V_p/V_s)^2 - 2] / (V_p/V_s)^2 - 1)$
- $\lambda\rho$ and $\mu\rho$ **`(n18`**, **`n19`**, **`n23`**, and **`n24)`** —
  $\mu\rho = V_s^2\rho^2$ * `Z_Conversion,` where `Z_Conversion` converts to metric units
  $\lambda\rho = V_p^2\rho^2$ * `Z_Conversion` - $2*\mu\rho$
- **`Youngs Modulus (n21`**, **`n22`**, **`n25`**, and **`n27)`** —
  $E = \rho*V_s^2 * [(3*V_p^2 - 4*V_s^2) / (V_p^2 - V_s^2)]$

Figure 56. SimpleExpression formulas and logic workflow



RP Properties for AVO Checks

The *RP Properties for AVO Checks* workflow uses density, acoustic log, and shear velocity log to calculate elastic constants that are useful in checking direct hydrocarbon indicators. Goodway et al. [15] suggested that Lamé's elastic parameters λ and μ, and their products with density, can be useful tools in AVO analysis.

In particular, $\lambda*\rho$ is very sensitive to fluids, while $\mu*\rho$ has little variation within the reservoir zone. Smith and Gidlow [35] plotted Castagna and Smith's [9] set of 25 world-wide measurements of P- and S-wave velocities and densities. Cross-plot domain representations of 25 shale/brine sand, shale/gas sand, and gas sand/brine-sand sets using V_s vs. V_p crossplots and $\mu\rho$ vs. $\lambda\rho$ crossplots clearly showed the distinction between gas-sands and non-pay lithologies,

Objectives

The *RP Properties for AVO Checks* workflow:

- Provides standard calculations of V_p and V_s velocities along with the acoustic impedance I = $V_p\rho$ and shear impedance J = $V_s\rho$. for:
  - Corrected acoustic Δt_p, shear Δt_s, and density logs
  - Identify wet sand acoustic Δt_p, shear Δt_s, and density interval
  - Raw acoustic Δt_p, shear Δt_s, and density logs
- Calculate effective porosity based on measured volume of clay
- Calculate elastic moduli for bulk modulus (*K*), shear modulus (μ), Young's modulus (*E*), Poisson's ratio (ν), shear modulus*density product ($\mu\rho$), and Lamé's constant*density product ($\lambda\rho$).
- Illustrate how to restrict the range of a petrophysical curve values so that V_p/V_s ratios are reasonable. Curve values that exceed the range for Δt_s result in V_p/V_s points that are undefined (**UNDEF**).

Computed results

These PowerLog output curves are created when the entire workflow is calculated.

Table 14. RP Properties for AVO Checks Workflow - output curves

Node	Curve Name	Type and Units	Description
n12	Vp	p_velocity ft/sec	Acoustic velocity - corrected
n13	Vs	s_velocity ft/sec	Shear velocity - corrected
n14	VpVscor	any none	V_p/V_s ratio, calculated from V_p and V_s corrected
n16	Zp_cor	any none	Acoustic impedance - corrected
n17	Zs_cor	any none	Shear impedance - corrected
n21	Lithfrac	any none	Lithology fraction
n22	Phi_eff	any none	Effective porosity
n8	Vp_wet	p_velocity ft/sec	Acoustic velocity - wet sand

Table 14. RP Properties for AVO Checks Workflow - output curves (Continued)

Node	Curve Name	Type and Units	Description
n9	Vs_wet	s_velocity ft/sec	Shear velocity - wet sand
n10	Zp_wet	any none	Acoustic impedance - wet sand
n11	Zs_wet	any none	Shear impedance - wet sand
n18	Poisson	any none	Poisson's ratio
n19	MuRho	any none	$\mu\rho$ hydrocarbon indicator
n20	LameRho	any none	$\lambda\rho$ hydrocarbon indicator
n34	E_cor	any N/m^2	Young's modulus - corrected
n35	K_cor	bulk_modulus N/m^2	Bulk modulus - corrected
n36	Mu_cor	shear_modulus N/m^2	Shear modulus - corrected
n39	VpVs_raw	any none	V_p/V_s ratios from raw curves, where Vs was limited to specific range defined by the named constants: `Min_shear_tdel` to `Max_shear_tdel`. V_s values outside this range yield an undefined value for the corresponding V_p/V_s ratio.

PowerLog input curves

These PowerLog input curves are used to calculate the acoustic velocity and impedance, as well as the shear velocity and impedance. This workflow can use the corrected sonic and density logs, plus the raw logs for its V_p/V_s ratio calculations. The corrected density and velocities are used to calculate the three elastic moduli (Young's, bulk, and shear), plus Poisson's ratio and two AVO-related hydrocarbon indicators.

Hint For your well, you may need to modify the curve names or replace them with a convenient curve alias name. The curve names in the this table are from the tutorial *RP_Properties_for_AVO_Checks_Workflow* project.

Table 15. RP Properties for AVO Checks Workflow - input curves

Node	Curve Name	Type and Units	Description
n0	DTC	p_sonic µsec/ft.	P-sonic corrected
n1	RHOC	density g/cc	Density corrected
n2	DTS	s_sonic µsec/ft.	S-sonic corrected
n3	PHIT	porosity none	Total porosity
n4	VCL	any none	Volume of Wet Clay

Table 15. RP Properties for AVO Checks Workflow - input curves (Continued)

Node	Curve Name	Type and Units	Description
n5	DTC	p_sonic µsec/ft.	P-sonic (wet)
n6	RHOC	density g/cc	Density (wet)
n7	DTS	s_sonic µsec/ft.	S-sonic (wet)
n23	DT_raw	p_sonic µsec/ft.	P-sonic (raw) - uncorrected
n25	RHOCraw	density g/cc	Density (raw) - uncorrected
n24	DTS_raw	s_sonic µsec/ft.	S-sonic (raw) - uncorrected

Named Constants

The *RP Properties for AVO Checks* workflow uses these named constants:

- `Convert_Impedance_to_Metric`—92903.4
- `Max_shear_tdel`—300 µsec/ft.
- `Min_shear_tdel`—100 µsec/ft.

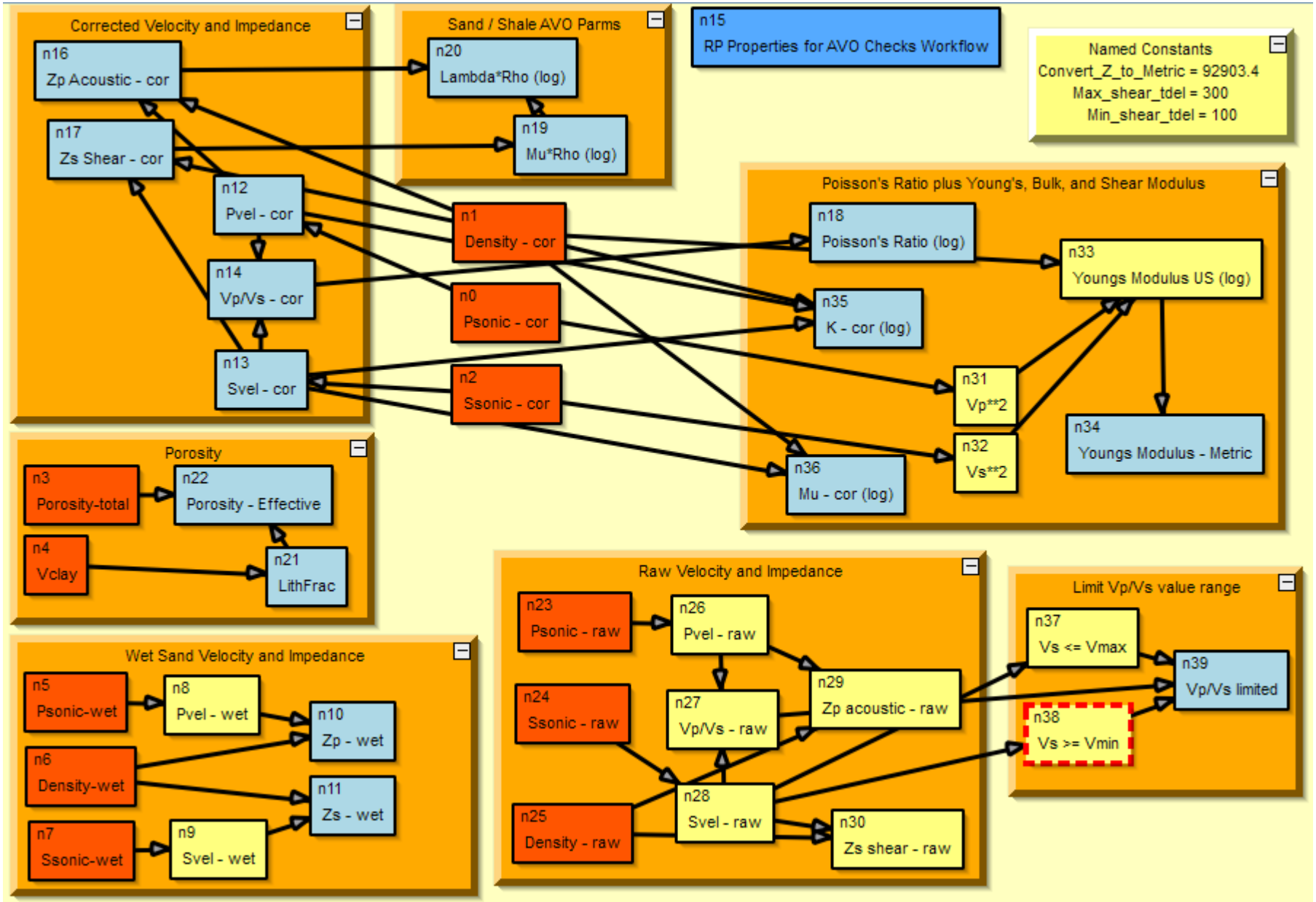
Key workflow functions and formulas

- **n8**, **n9**, **n12**, **n13**, **n26**, **n28**—these workflow nodes implement the simple division to convert a sonic log to the corresponding velocity values using the formula: $Velocity_{x\_curve} = 1000000 / \Delta t_x$, where x = $_p$ (acoustic), x = $_s$ (shear)

- **n10**, **n11**, **n16**, **n17**, **n29**, **n30**—these workflow nodes calculate the acoustic or shear impedance, using the product of the velocity and density curves: $Z_{x\_curve} = Velocity_{x\_curve} * \rho_{curve}$, where x = $_p$ (acoustic), x = $_s$ (shear)

- **n18**—Poisson's ratio computed using $\nu = (1/2) [(V_p/V_s)^2 - 2] / (V_p/V_s)^2 - 1)$
- **n19**—MuRho product = $\mu\rho = V_s^2\rho^2$ * `Convert_Impedance_to_Metric`
- **nn20**—LambdaRho product = $\lambda\rho = V_p^2\rho^2$ * `Convert_Impedance_to_Metric` - $2*\mu\rho$
- **n22**—φ_{eff_curve} = (1 - **Vclay**$_{curve}$) * **PHIT**$_{curve}$
- **n34**—Young's modulus $E = \rho*V_s^2 * [(3*V_p^2 - 4*V_s^2) / (V_p^2 - V_s^2)]$
- **n35**—Bulk modulus K = **KFromVel** (V_p, V_s, ρ)
- **n36**—Shear modulus μ = **MuFromVel** (V_s, ρ)
- **n39**—V_p/V_s measured = V_p/V_s , if `Min_shear_tdel` $\leq \Delta t_s \leq$ `Max_shear_tdel`
  otherwise V_p/V_s measured = **UNDEF_POWERLOG**

Figure 57. RP Properties for AVO Checks workflow



Fluid properties to estimate V_s

The *Fluid properties to estimate Vs* workflow calculates the density and bulk modulus for the subsurface fluids (brine, oil, and gas) as a function of:

- Pressure
- Temperature
- Salinity
- Oil and gas gravity
- Gas oil ratio

Objectives

The *Fluid properties to estimate Vs* workflow shows you:

- How to use conditional logic (named constant and **ConditionalExpression** function) to select between a PowerLog curve and a constant as an input parameter.
- Compute density and bulk modulus using the Brine, Oil, and Gas functions.
- Use named constants as physical parameters and as workflow logic switches.
- Select the oil or gas properties as the dominant hydrocarbon, using the **ConditionalExpression** function.

Computed results

These PowerLog output curves are created when the entire workflow is calculated. Additionally, when a PowerLog curve is selected for use, the mean value of the calculated curves is also determined in the workflow.

Hint If you do not want to add the mean calculation nodes to your workflow, you can use the **F8** (Calculate workflow) command to calculate the workflow. Once it finishes, you can place the mouse on each of the Curve Nodes in the next table. For each node, the function is shown in a tool tip and the node output curve name, mean value, and number of defined samples is displayed in the status bar. See **Figure: 87, 'Status bar", on page 146**.

Table 16. Fluid properties to estimate Vs workflow - output curves

Curve Nodes	Curve Name	Mean Nodes	Type and Units	Description
`n7`	`Salinity`	`n12`	salinity ppm	Salinity input
`n13`	`D_brine`	`n21`	density g/cc	Density of brine
`n14`	`K_brine`	`n22`	modulus N/m^2	Bulk modulus of brine
`n15`	`Den_gas`	`n23`	density g/cc	Density of gas
`n16`	`K_gas`	`n24`	modulus N/m^2	Bulk modulus of gas
`n17`	`Den_oil`	`n25`	density g/cc	Density of oil
`n18`	`K_oil`	`n26`	modulus N/m^2	Bulk modulus of oil
`n19`	`Den_hydr`	`n27`	density g/cc	Selected hydrocarbon density
`n20`	`K_hydr`	`n28`	modulus N/m^2	Selected hydrocarbon bulk modulus

PowerLog input curves

These six PowerLog input curves are used to compute the density and bulk modulus of the fluid properties.

Hint For your well, you may need to modify the curve names or replace them with a convenient curve alias name. The curve names in the this table are from the tutorial *Fluid_properties_to_estimate_Vs* project.

Table 17. Fluid properties to estimate Vs workflow - input curves

Node	Curve Name	Type and Units	Description
n0	**PRES**	pressure psi	Pressure of formation
n1	**T**	temperature degF	Downhole temperature
n2	**Sal**	salinity ppm	Brine salinity
n3	**API**	oil api	Oil gravity
n4	**SPEC**	any api	Gas specific gravity
n5	**GOR**	any none	Gas oil ratio

Named constants

The named constants for the *Fluid properties to estimate Vs* workflow consists of two groups; one set for physical fluid properties and the other to control the workflow computations.

Table 18. Fluid properties to estimate Vs workflow - named constants

Constant Name	Value	Units	Used in nodes
Salinity_brine	**72000**	ppm	**n7**
Oil_gravity	**43**	api	**n8**
Gas_specific_gravity	**.65**	none	**n10**
Gas_oil_ratio	**15000**	none	**n11**
Constant Name used as conditional logic flag	**Value**	**Units**	**Used in nodes**
Salinity_LogOrConstant	1 = Log, else constant	none	**n7**
Oil_grav_LogOrConstant	1 = Log, else constant	none	**n8**
Gas_grav_LogOrConstant	1 = Log, else constant	none	**n10**
GasOilRatio_LogOrConstant	1 = Log, else constant	none	**n11**
Hydrocarbon_gasoil_select	0 = Gas, otherwise oil	none	**n19, n20**

Key workflow functions and formulas

Most of the functions used in the *Fluid properties to estimate Vs* workflow, are the Brine, Oil, and Gas functions (see online help from each of the workflow nodes).

The **ConditionalExpression** function:

- Selects between a PowerLog curve and a constant value for salinity, oil gravity, gas specific gravity, and the gas-oil ratio inputs.
- Selects between the computed oil and gas constants (hydrocarbon density and bulk modulus) for this workflow calculation.

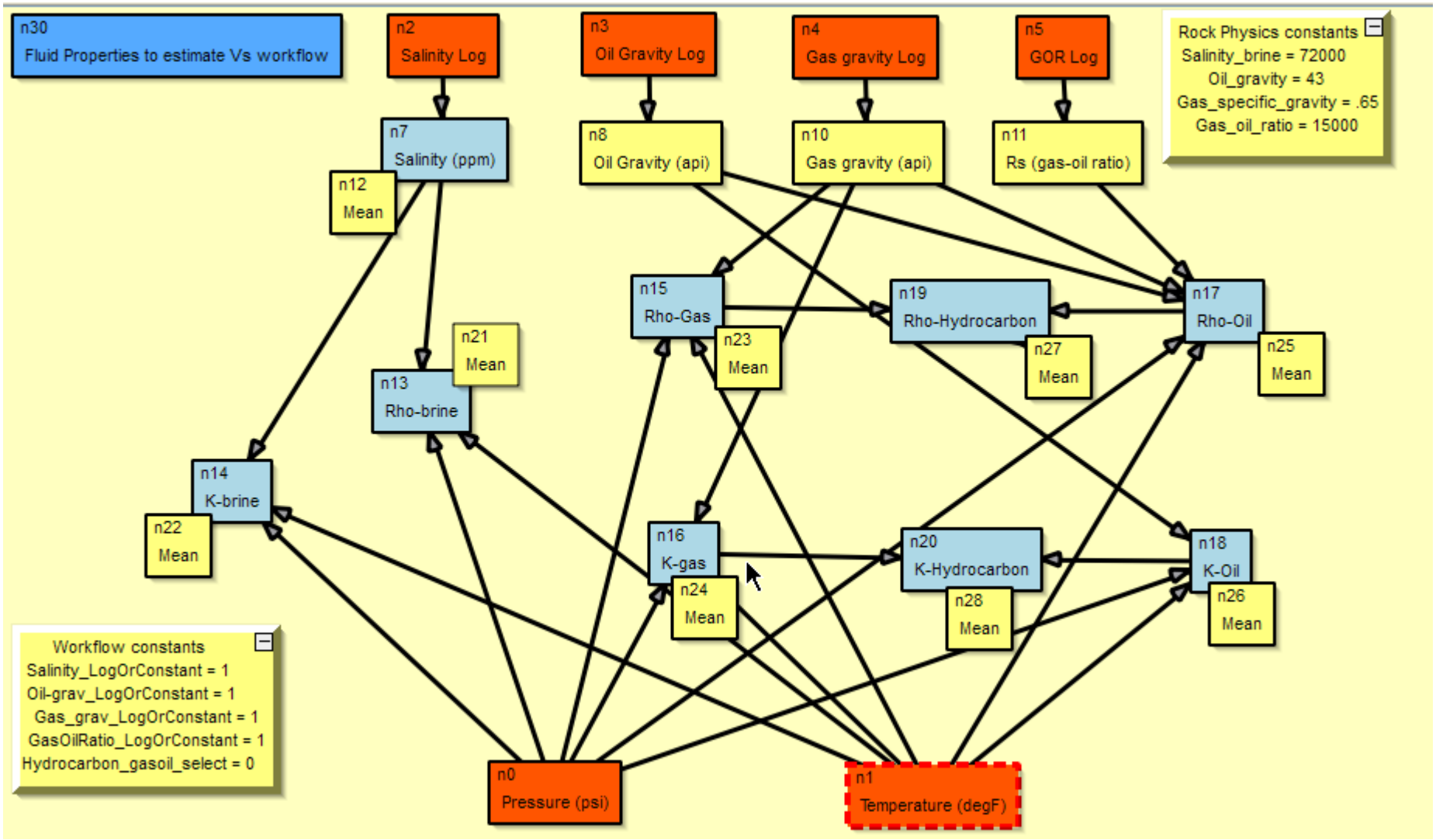
The Brine, Oil, and Gas functions used in this workflow are:

- **n13**—ρ_{brine} = **BrineRho** (**Pressure, Temp, salinitiy**)
- **n14**—K_{brine} = **BrineK** (**Pressure, Temp, salinitiy**)
- **n15**—ρ_{gas} = **GasRho** (**Pressure, Temp, spec, Batzle&Wang**)
- **n16**—K_{gas} = **GasK** (**Pressure, Temp, spec, Batzle&Wang**)
- **n17**—ρ_{oil} = **LiveOilRho** (**Pressure**, **Temp**, **oil_api**, **Rs**, **spec**, *blank*, **Batzle&Wang**)
- **n18**—K_{oil} = **DeadOilK** (**Pressure, Temp, oil_api, Batzle&Wang**)

The general form for the Conditional logic that selects a curve or constant is:
if (**curvename_LogOrConstant == 1**) then **Curve**, else **Constant**

The form for the Conditional logic that selects gas or oil is:
if (Hydrocarbon_gasoil_select **== 0**) then **Gas**, else **Oil**

Figure 58. Fluid properties to estimate Vs workflow



Lithology log construction

Petrophysicists construct lithology logs using many combinations of measured logs to infer geology and potential production zones. This RPM for PowerLog workflow uses six input PowerLog curves to construct a lithology coding log.

Objectives

The *Lithology log construction* workflow:

- Illustrates how a lithology log can be constructed by replacing petrophysical log measurements with rock physics parameters.
- Describes how to use name constants and RPM functions to define complex logical expressions.

Computed results

The *Lithology log construction* workflow result is a single PowerLog curve (`LITHTYPE, N26`) with lithology coding. The values are coded in the **Table 20, "Lithology log construction workflow - named constants," on page 111**.

- 0 = shale (default)
- 1 = calcareous shale
- 2 = limestone
- 3 = coal
- 4 = sand
- 5 = gas sand

PowerLog input curves

Hint For your well, you may need to modify the curve names or replace them with a convenient curve alias name. The curve names in the this table are from the tutorial `Lithology_log_construction_workflow` project.

Table 19. Lithology log construction workflow - input curves

Node	Curve Name	Type and Units	Description
`n0`	`VCLC`	any none	Volume of **calcite** relative to total volume (correct shale velocity)
`n1`	`VCOA`	any none	Volume of **coal** relative to total volume
`n2`	`VCL`	any none	Volume of **clay** relative to total volume
`n3`	`VQUA`	any none	Volume of **quartz** relative to total volume
`n4`	`PIGE`	any none	Effective porosity minus irreducible water
`n5`	`Sw`	Sw none	Water saturation

Named constants

The *Lithology log construction* workflow uses two sets of named constants; one to specify the decision making constants and another to implement the lithology coding.

Table 20. Lithology log construction workflow - named constants

Lithology coding constants	Value	Units	Used in nodes
Shale_lith	0	n/a	none
Calcareous_shale_lith	1	n/a	n20
Limestone_lith	2	n/a	n15
Coal_lith	3	n/a	n16
Sand_lith	4	n/a	n23
GasSand_lith	5	n/a	n26
Conditional logic constants	**Value**	**Units**	**Used in nodes**
Min_calcite_volume	.45	none	n15
Min_coal_dominates	.5	none	n16
Min_clay_volume	.4	none	n17
Min_coal_volume	.1	none	n18
Min_quartz_dominates	.5	none	n19
Min_quartz_volume	.45	none	n21
Min_porosity_effective	.08	none	n22
Max_Sw_gassand	.7	none	n25

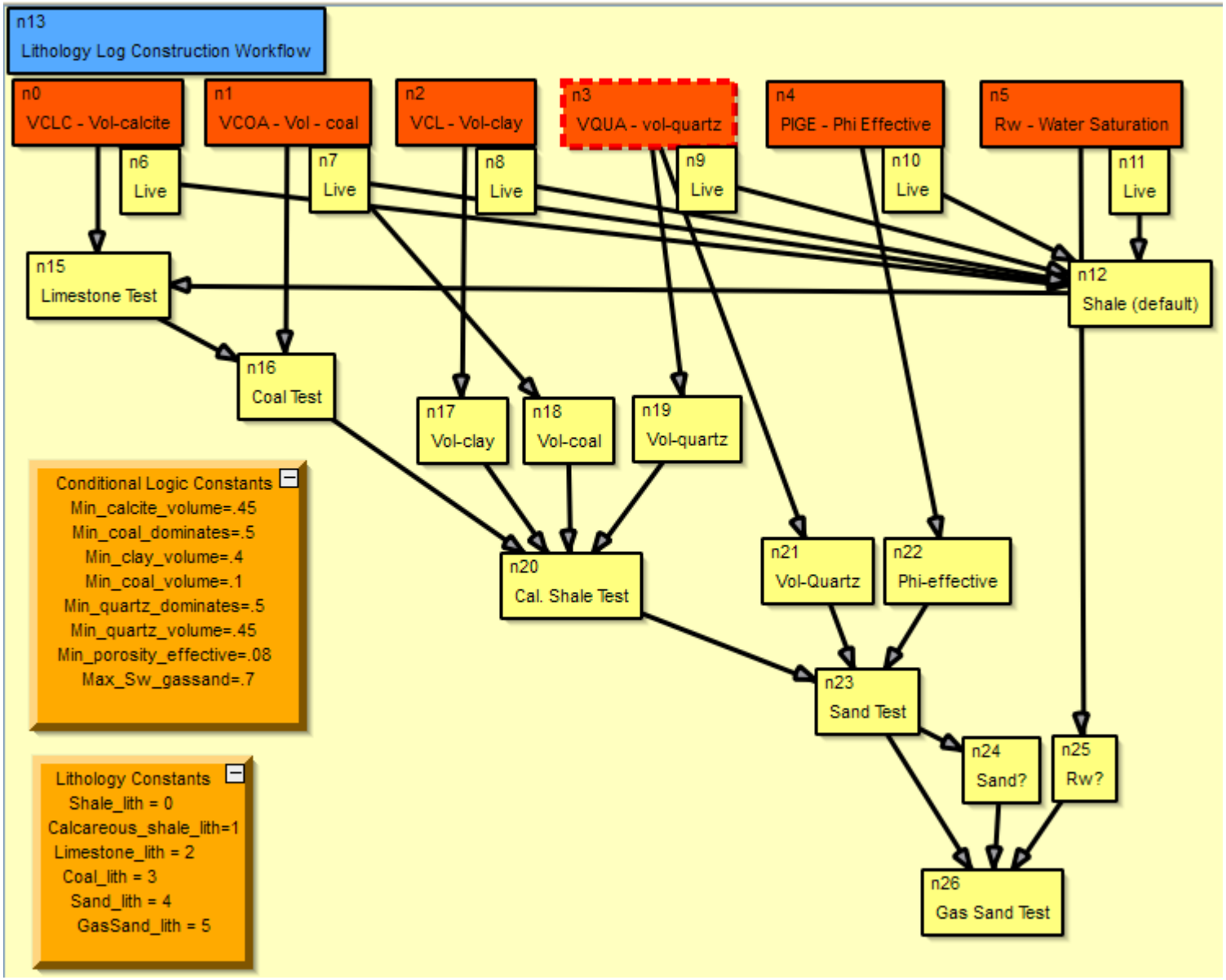
Throughout the conditional logic nodes in the *Lithology log construction* workflow, these values are used. If you want to extend these indicators, create additional named constants similar to the ones in the previous table.

Key workflow functions and formulas

Within these workflow nodes you can use either the **ConditionalExpression** or **SimpleExpression** functions to implement the decision logic. When multiple conditions must be combined (nodes **n17**, **n18**, and **n19**), set the output of each separate condition equal to 1 and test to see that all conditions (node **n20**) are true:

- **n12**— If (all curve samples not UNDEF) then **LITHTYPE** = **Shale_lith**, else **UNDEF**
- **n15**— If ($Vol_{calcite} \geq$ Min_calcite_volume) then **LITHTYPE** = Limestone_lith
- **n16**— If ($Vol_{coal} \geq$ Min_coal_dominates) then **LITHTYPE** = Coal_lith
- **n17, n18, n19, n20**— If ($Vol_{clay} \geq$ Min_clay_volume) AND ($Vol_{coal} \geq$ Min_coal_volume) AND ($Vol_{quartz} \leq$ Min_clay_volume) then **LITHTYPE** = Calcareous_shale_lith
- **n21, n22, n23**— If ($Vol_{quartz} \geq$ Min_quartz_volume) AND (**PIGE** ≥ Min_porosity_effective) then **LITHTYPE** = Sand_lith
- **n24, n25, n26**— If (**LITHTYPE** = Sand_lith) AND ($R_w \leq$ Max_Sw_gassand) then **LITHTYPE** = GasSand_lith

Figure 59. Lithology log construction workflow



Gassmann fluid-substitution to predict seismic response

The *Gassmann fluid-substitution to predict seismic response* workflow performs a hydrocarbon fluid substitution for the original brine in reservoir rocks so that the resulting velocity change can predict the seismic response of oil or gas in a reservoir. The S_w measured in the logs describes the original fluid composition.

Fluid substitution criteria

The workflow dynamically determines whether to perform the fluid substitution:

- For rocks with good porosity and low clay content (reservoir rocks), you perform a fluid substitution that reduces S_w to a lower level, thus increasing the hydrocarbon content.
- For rocks that do not meet the porosity and clay content criteria (non-reservoir rocks), the original S_w log is retained and no fluid substitution takes place.

The cutoff for wet clay content (V_{clay}) in good reservoirs is found in named constant, **`Vol_clay_max`**. The V_{clay} maximum is initially set at 0.20, but can be adjusted.The cutoff for effective porosity (**`PHIE`**) in good reservoirs is found in the named constant **`Phi_effective_max`**. You can change the value (effective porosity maximum = 0.05) by editing the named constant.

Thus rocks with V_{clay} < 0.2 and **`PHIE`**$_{curve}$ >0.05 are considered reservoir rocks and fluid substitution is performed in these rocks. S_w in these rocks becomes 0.20, instead of the initial value in the S_w curve. The replacement value for S_w is set in the named constant **`Sw_new`**, and can be adjusted.

Fluid substitution overview

PowerLog Pressure and Temperature logs are used in the Brine, Gas, and Oil Properties group to compute the properties of the individual fluids in the borehole.

The properties of the original combined fluid are computed in the **`Combined Fluid Properties (OLD)`** group. The Water Saturation (S_{w_old}) node inputs the S_w curve from PowerLog, which determines the S_w prior to any fluid replacement. Brie's formula for patchy saturation is used to compute the bulk modulus and density of the combined fluid in the **`Brie's Formula (OLD)`** group. The empirical Brie parameter (set to one) can be adjusted as the named constant `Brie_oldfluid_parameter`.

Next, the we compute the elastic parameters for a new fluid (brine in the original fluid replaced by hydrocarbons), but only in rocks with good porosity and low clay content. The selection of rocks with good porosity and low clay content (good reservoir rocks) takes place in the **`Fluid Substitution Criteria Check`** group. PowerLog for effective porosity, bulk density, (wet) clay content, and velocities are found in the **`Gassmann Inputs`** group.

The new S_w (the replacement value in reservoir rocks, the old value in all other rocks) is computed in the **`SwFluid Sub`** node in the **`Combined Fluid Properties (NEW)`** group. The bulk modulus and density of the replacement fluid are computed in this group just like the **`Combined Fluid Properties (OLD)`** group. Brie's patchy saturation formula in the **`Brie's Formula (NEW)`** group is used again. The Brie parameter is again set to one in the named constant `Brie_newfluid_parameter`.

The bulk modulus for the solid matrix is computed from a weighting of the *K* for clay (in the K_{clay} Fraction node) and the *K* for quartz (in the **`Kquartz`** Fraction node). Bulk modulus values for the minerals can be changed by using the **Rock and FLuid Properties** dialog.

Results from workflow

Finally, the Gassmann substitution, using the fluid parameters for the substituted fluid (which differ only in the reservoir rocks) is computed in the **`Gassmann FluidSub`** node. The rock density with the new fluid, P-sonic travel time, acoustic velocity (**GassmannFull** function), and impedance are calculated in the final workflow nodes.

Data consistency issues

Caution! There is sometimes a data-consistency issue with **GassmannFull** function in the **`Gassmann FluidSub`** node if input logs for the original rock (before the fluid substitution) are not sufficiently consistent with the relationship: $K = V_p^2 * \rho - 4/3*\mu$, where $\mu = V_s^2 * \rho$ and V_p, V_s, and ρ are calculated from log petrophysical analysis.

Bulk modulus *K* is independent of the input parameters for the densities and bulk and shear moduli of the mineral and fluid constituents of the rock-physics model. But *K* and the constituents of the model are used together in the Gassmann formula to calculate the bulk modulus of the rock with the initial fluid removed (the dry frame), and with a replacement fluid.

Problems in the Gassmann calculation can occur if the rock-physics model chosen is not consistent with the ρ, V_p, and V_s data from the logs (in other words, if the model just is not a good match for the rocks in the well), or if the log ρ and velocity data are not internally consistent. If such inconsistencies are present, the **GassmannFull** function displays error messages and stops before producing an output curve.

These parameter conditions produce error messages:

- $K \leq 0$, produces the error "`Input bulk modulus illegal`"
- K_{dry} (the bulk modulus of the rock frame without fluid), calculated from Gassmann's formula using $K \leq 0$, or greater than *K* for the mineral members, produces the error "`Calculated empty frame modulus illegal`".

Objectives

The *Gassmann fluid-substitution to predict seismic response* workflow:

- Dynamically tests V_{cl} to see if the clay content is too high and ensures the effective porosity exceeds a minimum level before performing a fluid substitution at each log depth.
- Uses Brie's formula to compute the bulk modulus (*K*) and density (ρ) of the combined fluid for the brine in reservoir rocks. It independently use's Brie's formula for patchy saturation again to compute *K* and ρ for the oil or gas replacement.

Computed results

The *Gassmann fluid-substitution to predict seismic response* workflow results permit you to predict appropriate seismic velocities and impedance.

Table 21. Gassmann fluid-substitution to predict seismic response workflow - output curves

Curve Nodes	Curve Name	Type and Units	Description
n30	SW_NEW	Sw none	Water saturation curve - taking into account the new fluid substitution
n36	Den_fsub	density g/cc	Bulk density with replacement fluid
n37	Vp_fsub	P-velocity ft/sec	Velocity for hydrocarbon substitution
n38	Sonic_fs	p_sonic µsec/ft.	Δt_p for hydrocarbon substitution
n39	Zp_fsub	any none	Acoustic impedance

Strategies

To perform the fluid substitution effectively:

- Elastic properties (bulk modulus and density) of the original fluid, composed of brine (plus some gas or oil) are computed.
- A **Gas/Oil** conditional logic named constant group to chooses gas or oil (oil may contain gas) in the original fluid.
- Elastic parameters for a new fluid (much of the brine in the original fluid is replaced by hydrocarbons) are computed for rocks with good porosity and low clay content.
- The cutoffs for V_{clay} and φ_{eff} porosity are defined; V_{clay} cutoff is initially = 0.20 and the initial value for the **PHIE** cutoff = 0.05.
- The new S_w (the replacement value in reservoir rocks, the old value in all other rocks) is computed in the **SwFluid Sub** node.
- The bulk modulus for the solid matrix is computed from a weighting of the *K* for clay.
- The Gassmann substitution, using the fluid parameters for the substituted fluid (which differ in the reservoir rocks), is done in the **Gassmann FluidSub** node.

PowerLog input curves

These PowerLog input curves are used to calculate the brine, gas, and oil properties. The water saturation curve is used in the Brie's patchy saturation formula and to compute the density fraction of brine and hydrocarbons. The total porosity and V_{clay} curves are inputs to the fluid substitution and $K_{mineral}$ groups.

Hint For your well, you may need to modify the curve names or replace them with a convenient curve alias. The curve names in the previous table are from the tutorial **Gassmann_fluid_substitution_predict_seismic_response** project.

Table 22. Gassmann fluid-substitution to predict seismic response workflow - input curves

Node	Curve Name	Type and Units	Description
n1	PRES	pressure psi	Pressure of formation
n2	T	temperature degF	Downhole temperature
n3	SW	Sw none	Water saturation

Table 22. Gassmann fluid-substitution to predict seismic response workflow - input curves

Node	Curve Name	Type and Units	Description
n4	**PHIE**	porosity none	Effective Porosity
n5	**VCL**	any none	Volume fraction of clay relative to total volume
n6	**RHOC**	any none	Bulk density - measured
n7	**Vpcalcr**	p_velocity ft/sec	Vp log
n8	**Vscalcr**	s_velocity ft/sec	Vs log

Named Constants and Mineral Properties

This table displays the named constants, clay and quartz bulk modulus, and the conditional logic switch (**Gas_oil_selection**) for gas and oil.

Table 23. Gassmann fluid-substitution to predict seismic response workflow - named constant and rock/fluid properties

Name	Value	Units	Used in these workflow nodes
Brine_salinity	**150000**	ppm	**n13**, **n14**—concentration in ppm
Gas_specific_grav	**.07**	none	**n9**, **n10**, **n11**, **n12**— Gas spec-grav
Gas_oil_ratio	**44**	none	GOR (Gas Oil Ratio)
GOR_conversion	**5.615**	none	Factor compute dimensionless Rs
Oil_API	**33**	api	**n11**, **n12**—oil density
Gas_oil_selection	**0 - Gas else Oil**	none	**n18**, **n19**—select which hydrocarbon to use in the fluid computations
Brie_oldfluid_parameter	**1**	none	**n24**—Brie exponent for old fluid patchy saturation computation
Brie_newfluid_parameter	**1**	none	**n34**—Brie exponent for new fluid patchy saturation computation
Phi_effective_min	**.05**	none	**n22**—minimum porosity needed for fluid substitution
Vol_clay_max	**7**	none	**nxx**, **nxx**—maximum clay volume allowed for fluid substitution
Rs_dimensionless	**7.83615**	none	**n11**, **n12**—GOR dimensionless value
Sw_new	**.2**	none	**n21**—**Sw** replacement value
Clay.K	**2.091e10**	N/m^2	**n15**—clay bulk modulus
Quartz.K	**3.789e10**	N/m^2	**n16**—quartz bulk modulus

Key workflow functions and formulas

- **n09**—ρ_{gas} = **GasRho**[13] (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Gas_specific_grav, Batzle&Wang)
- **n10**—K_{gas} = **GasK** (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Gas_specific_grav, Batzle&Wang)
- **n11**—ρ_{oil} = **LiveOilRho** (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Oil_API, Rs_dimensionless, Gas_specific_grav, *blank*, Batzle&Wang)
- **n12**—K_{oil} = **LiveOilK** (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Oil_API, Rs_dimensionless, Gas_specific_grav, *blank*, Batzle&Wang)
- **n13**—K_{brine} = **BrineK** (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Brine_salinity)
- **n14**—ρ_{brine} = **BrineRho** (**Pres**sure$_{curve}$, **T**emperature$_{curve}$, Brine_salinity)
- **n15**—K_{clay_frac} = V_{cl} * **Clay.K**
- **n16**—K_{quartz_frac} = (1-V_{cl}) * **Quartz.K**
- **n17**—Kmineral = K_{clay_frac} + K_{quartz_frac}
- **n18**—K_{HC} = **ConditionalExpression**(Gas_oil_selection, ==, 0, K_{gas} , K_{oil}) [14]
- **n19**—ρ_{HC}= **ConditionalExpression**(Gas_oil_selection, ==, 0, ρ_{gas}, ρ_{oil})
- **n20**—$\rho_{Brine\_frac\_(old)}$ = ρ_{brine} * **SW**$_{curve}$
- **n21**—V_{clay} test = **ConditionalExpression**(V_{cl_curve}, <, **Vol_clay_max**, 1, 0)
- **n22**—φ_{eff} test = **ConditionalExpression**($\varphi_{eff\ \_curve}$, >, Phi_effective_min, V_{clay} test, 0)
- **n23**—$\rho_{HC\_frac\_(old)}$ = ρ_{HC} * (1 - **SW**$_{curve}$)
- **n24**—$K_{Brie\_(old)}$= (K_{brine} - K_{HC}) * **SW**$_{curve}$ ** Brie_oldfluid_parameter
- **n26**—No Fluid Sub = (1 - φ_{eff} test)* **SW**$_{curve}$ [*use S_w old*]
- **n27**—Fluid Sub = (φ_{eff} test)*Sw_new [*use S_w new*]
- **n28**—$\rho_{fluid\_(old)}$ = $\rho_{HC\_frac(old)}$ + $\rho_{Brine\_frac\_(old)}$
- **n29**—$K_{fluid\_(old)}$ = K_{HC} + $K_{Brie\_(old)}$
- **n30**—**SW_NEW**$_{curve}$ = $S_{w\_FluidSub}$ = Fluid Sub + No Fluid Sub
- **n31**—$\rho_{Brine\_Frac\_(new)}$ = $S_{w\_FluidSub}$ * ρ_{Brine}
- **n32**—$\rho_{HC\_Frac\_(new)}$ = (1 - $S_{w\_FluidSub}$) * ρ_{Brine}
- **n33**—$\rho_{Fluid\_(new)}$ = $\rho_{Brine\_Frac\_(new)}$ + $\rho_{HC\_Frac\_(new)}$
- **n34**—$K_{Brie\_(new)}$ = (K_{brine} - K_{HC}) * **SW**$_{curve}$ ** Brie_newfluid_parameter
- **n35**—$K_{Fluid\_(new)}$ = $K_{Brie\_(new)}$ + K_{HC}
- **n36**—**Den_fsub**$_{curve}$ = ρ_{Fsub} = RHOC$_{curve}$ + φ_{eff} * ($\rho_{Fluid\_(new)}$ - $\rho_{Fluid\_(old)}$)
- **n37**—**Vp_fsub**$_{curve}$ = **GassmannFull** (Vp$_{curve}$, Vs$_{curve}$, RHOC$_{curve}$, φ_{eff}, $K_{Fluid\_(new)}$, $\rho_{Fluid\_(new)}$, $K_{mineral}$, $K_{Fluid\_(old)}$, $\rho_{Fluid\_(old)}$)
- **n38**—**Sonic_fs**$_{curve}$ = Psonic - Fsub = 1000000. / **Vp_fsub**$_{curve}$
- **n39**—**Zp_fsub**$_{curve}$ = **Vp_fsub**$_{curve}$ * **Den_fsub**$_{curve}$

13.Name of the RPM rock physics function used for this node.
14.HC - Denotes hydrocarbon (oil or gas) selected with the **ConditionalExpression** RPM function for K_{HC} and ρ_{HC}.

Figure 60. Gassmann fluid-substitution to predict seismic response