

Tutorial – Petrophysics Module

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Part 1 – Log analysis and processing functions

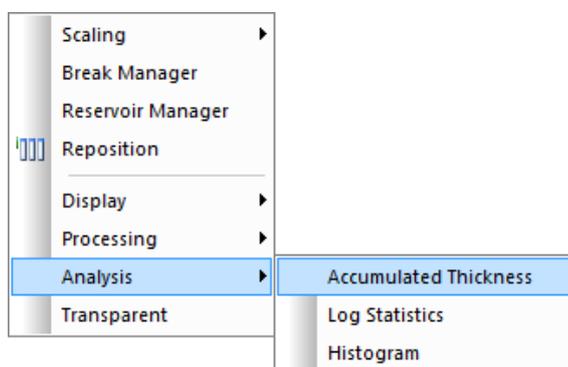
1.1 Log analysis and processing in Cyclolog

CycloLog contains a wide range of functions for analysing and processing log data. Here we describe how to use the more basic functions; the use of some of the more advanced functions is described in the parts that follow.

1.2 Using CycloLog's analysis functions

Under the right-click menu of the log data pane, the following three functions in the **Analysis** menu are found:

- Accumulated thickness
- Log statistics
- Histogram



The **Histogram** function is not discussed here. Refer to the Tutorial – Clustering and Lithology, part 2.

The **Accumulated thickness** function is used to calculate the total thickness of a section where the log value lies in a user-specified range. This function can be used for calculations of, for example, net-to-gross.

In the example on the next pages, the user is interested in the cumulative thickness of sand in the interval between the two markers 4000-4100 and 5000-5100. The user has decided to take a cut-off value of 60 API. The task, then, is to calculate the depth interval for which the value of the GR log is less than 60. To do this:

- Open the log to be analysed (in this case, the GR log).
- Place the cursor on the log, open the right-click menu and select **Analysis → Accumulated thickness**.
- The following dialog box opens:

Accumulated Thickness

Input parameters

Depth
 Break

Top depth: 3200
Bottom depth: 3663,8
Minimum log: 0 } Interval
Cut-off log: 0 } Interval
Maximum log: 150

Analysis results

Accumulated thickness interval 1	0	m	0	%
Accumulated thickness interval 2	410,407	m	88,4678	%

Recalculate Close

- The default depth interval is the entire log: to change this, enter the **Top** and **Bottom** depths of the interval to be analysed.
- Enter the **Cut-off log** value (60 in this example).
- The **Minimum** and **Maximum** log values (here set to 0 and 150) allow the user to exclude any unwanted outlying values.
- Click **Recalculate**. The **Analysis results** box gives the cumulative thickness of the intervals for which the log value is below (interval 1) and above (interval 2) the cut-off value. The results are given both in depth units, and as percentages.

If one or more sets of breaks (see Tutorial – Base Module, part 5) have been defined, it may be easier to specify the interval to be analysed in terms of defined breaks, as follows:

- Open the log to be analysed (in this case, the GR log).
- Place the cursor on the log, open the right-click menu and select **Analysis → Accumulated thickness**.
- At the top of the **Accumulated Thickness** dialog box, click the **Break** button.
- For the breaks that define the **Top** and **Bottom** depths of the interval to be analysed, select the break set and break, as in the example below:

Accumulated Thickness

Input parameters

Depth
 Break

Top depth: Default break set 3308,68 Break 1
Bottom depth: Default break set 3372,18 Break 2

Minimum log: 0 } Interval
Cut-off log: 0 } Interval
Maximum log: 150

Analysis results

Accumulated thickness interval 1 0 m 0 %
Accumulated thickness interval 2 63,6002 m 100,316 %

Recalculate Close

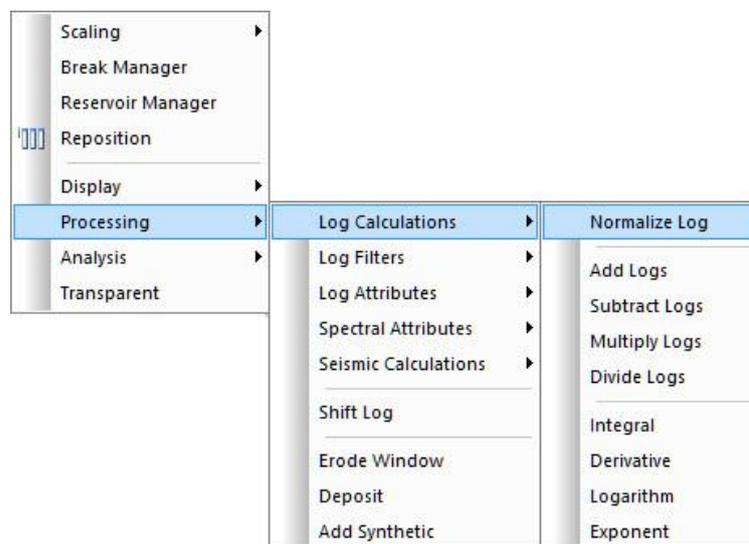
- Click Recalculate, and read the results as described above.

The **Log statistics** function calculates from the minimum and maximum log data values the average, root mean square (RMS), and standard deviation in a user-defined depth interval.

- Open the log to be analysed (in this case, the GR log).
- Place the cursor on the log, open the right-click menu and select **Analysis → Log Statistics**.
- Enter the **Top** and **Bottom Depth** intervals (default = whole log).
- Click **Recalculate**. The statistic results will be
- Note that the calculated values cannot be saved.

1.2 Log calculations

A number of basic mathematical functions are available in Log Calculations. Mathematical operations can be performed for each log Data Pane. The basic mathematical operations available appear in the log data pane right-click menu; select **Processing → Log Calculations**:



All Log Calculation operations can be undone (and redone) using any of the following actions:

- Edit → Undo (Redo); the menu shows the name of the last action
- Undo (Redo) icon on the Standard toolbar
- ALT + backspace

Several successive actions can be undone/redone (the number is more or less unlimited), and CycloLog maintains a separate record of actions for each log data pane. This information is retained, both when you save the project, and also if you close and then re-open the data pane without saving the project.

Normalize Log - Using this option, logs can be normalized as a preparation for e.g., Clustering.

In the **Normalize GR** menu above, **Minimum** and **Maximum** log values are shown. These are the minimum and maximum measured values of a certain property (e.g., GR) that were measured within the depth interval specified further down the menu. Even though different values for the **Minimum** and **Maximum** can be entered, these manual entries are not applied in any calculations.

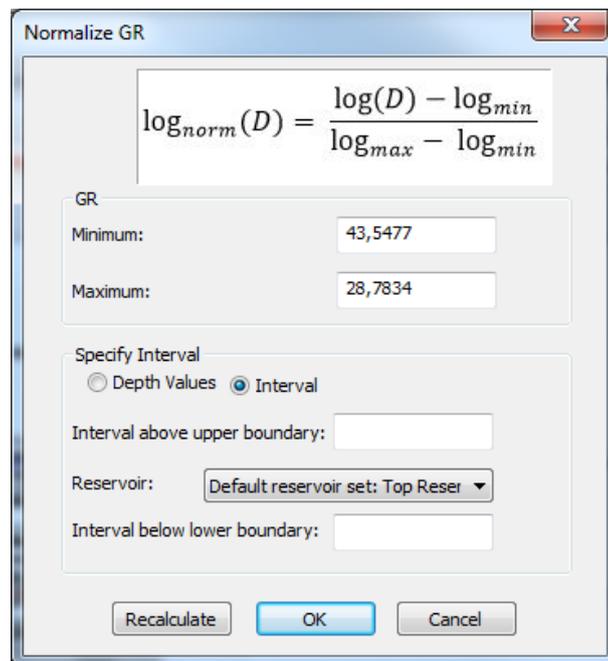
The depth interval that you want to use for normalisation can be specified by:

- Providing depth values for the top and bottom of the interval, or
- Specifying a complete interval (Reservoir) at once.

To provide depth values, check the button **Depth Values**. To specify the top of the interval you want to use for normalisation, either select **Use depth** or **Use break** from the drop-down menu. When **Use break** is selected, an interval can be selected that is added above the break. To specify the bottom of the interval, follow the same workflow as for specifying its top.

When you click **OK**, the normalised log will be saved to the workspace as *norm – <name log>*.

To use a reservoir interval for normalisation, select the button **Interval** and specify a reservoir you defined earlier (see Tutorial – Base Module, part 6). It is optional to add an interval above and below the specified reservoir.



The log value at the Top depth will be used as the minimum for normalisation, the log value at the Bottom will be used as the maximum for normalisation.

Next to normalisation, CycloLog can perform some basic binary mathematical operations on log data. These are launched from the Processing dialog, which is accessed from the log display.

- **Add Logs** (add one log to another).
- **Subtract Logs** (subtract one log from another).
- **Multiply Logs** (multiply one log by another).
- **Divide Logs** (divide one log by another).
- **Integral** (calculate the integral of a log curve).
- **Derivative** (calculate the derivative of a log curve).
- **Logarithm** (calculate the logarithm of all data values in a log).
- **Exponent** (calculate the inverse logarithm of all data values).

These functions are straightforward in their use in CycloLog analysis and will not be further discussed here. They are all launched from the **Processing** menu, which is accessed from the log display right-click menu. In the CycloLog Help manual you can find more details of these functions.

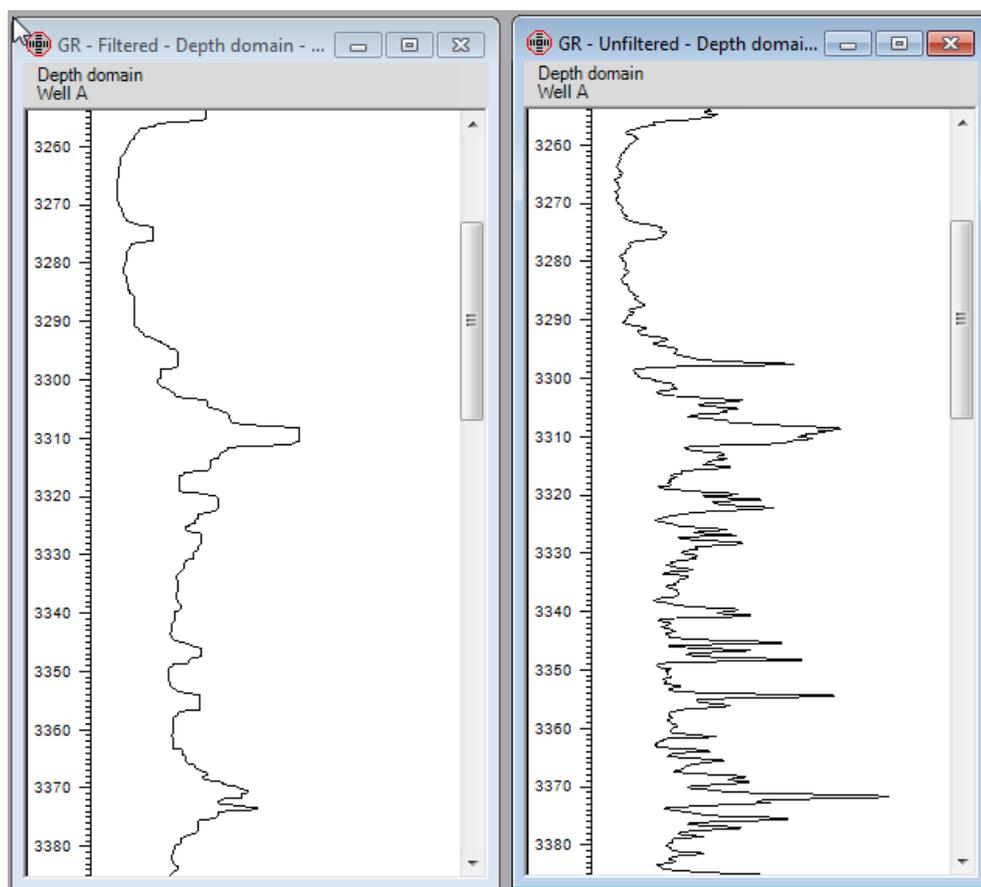
1.4 Log filters

Filtering of log data has a variety of applications, such as smoothing the logs, and enhancing certain wavelengths in the data. Filtering may also be useful in conjunction with frequency analysis (see part 2).

To use log filters, you should first make a duplicate of the log to be processed, in order to keep a copy of the original data.

- Right-click over the name of the log in the workspace.
- Click Duplicate.
- (To move the new log up the list, drag it to the required place in the list.)

- A copy of the log is added to the list in the workspace; double-click on the log to open it.
- Right-click over the log data pane, and select **Processing → Log Filters**.
- Select the type of filter to be used: in the illustrated example, the **Median Filter** was used.
- In the dialog box, enter the length of the window of analysis to be used (5 was used in the example; the default is 3), and click **OK**.
- In the processed log, each log value is now replaced with (in this case) the median of the 5 values in a window centred at that depth.
- All log processing operations, including filtering, can be undone: click the **Undo** button on the Standard toolbar. The Undo operation will apply to the currently active log display pane.
- If you plan to keep the result, rename the processed log: right-click over its name in the workspace, select **Rename**, type the new name, and press the Enter key.



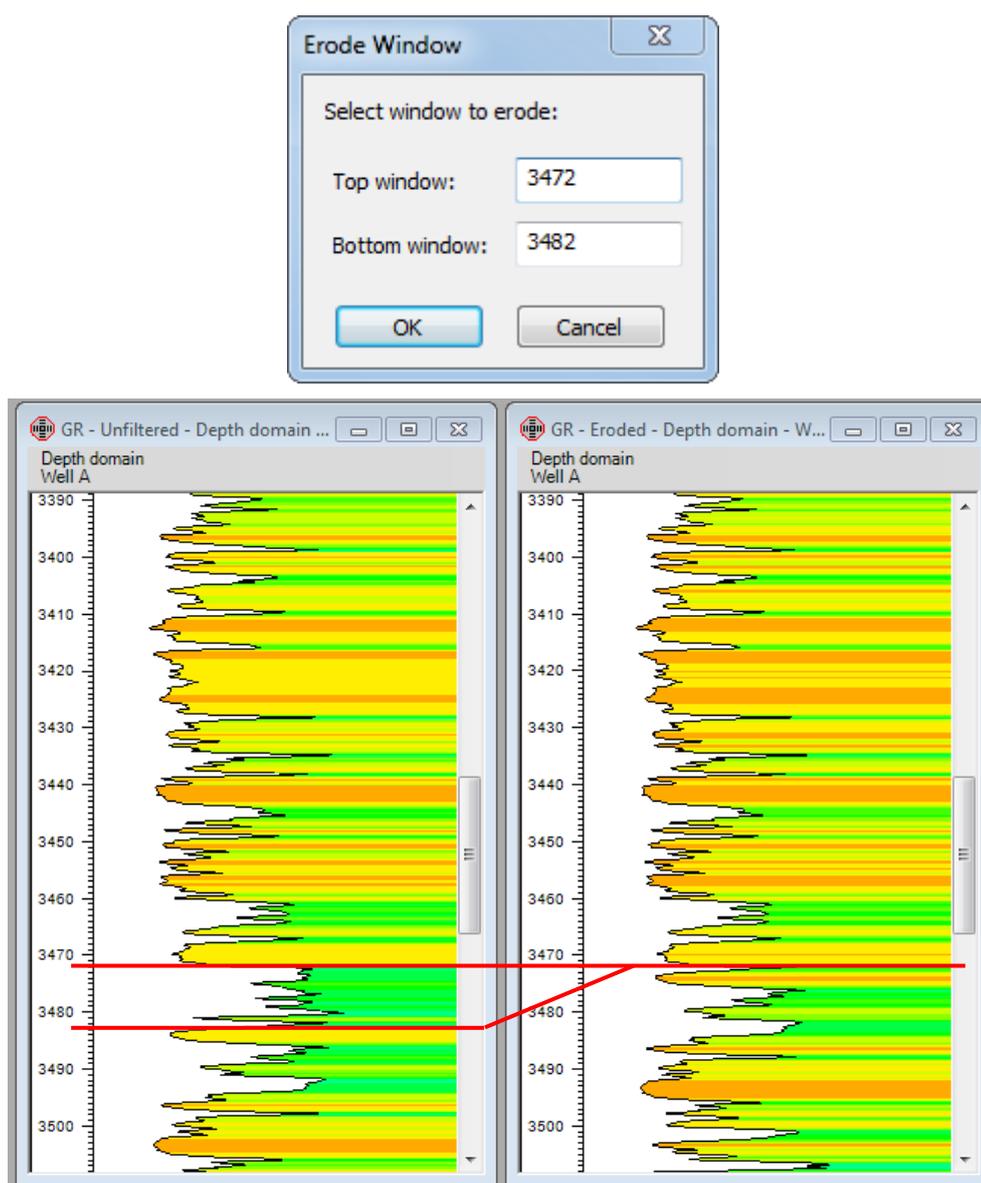
1.5 Using the Erode and Deposit functions

The **Erode** and **Deposit** functions respectively remove section from a log, and add synthetic section to a log. They can be useful for comparing logs from wells in which the succession is similar, but part of the section in one of the wells is missing (because of faulting, say, or non-deposition).

To 'erode' section from a log:

- In case you want to keep both a copy of the original and the newly created log, make a duplicate of the original log.
- Open the duplicate log.
- Right-click over the log data pane, and select **Processing** → **Erode Window**.
- In the dialog box, enter the **Top** and **Bottom** depths of the interval to be removed.
- Click **OK**.
- To undo the ‘erode’ operations, click the **Undo** button on the Standard toolbar. The Undo operation will apply to the currently active log display pane.

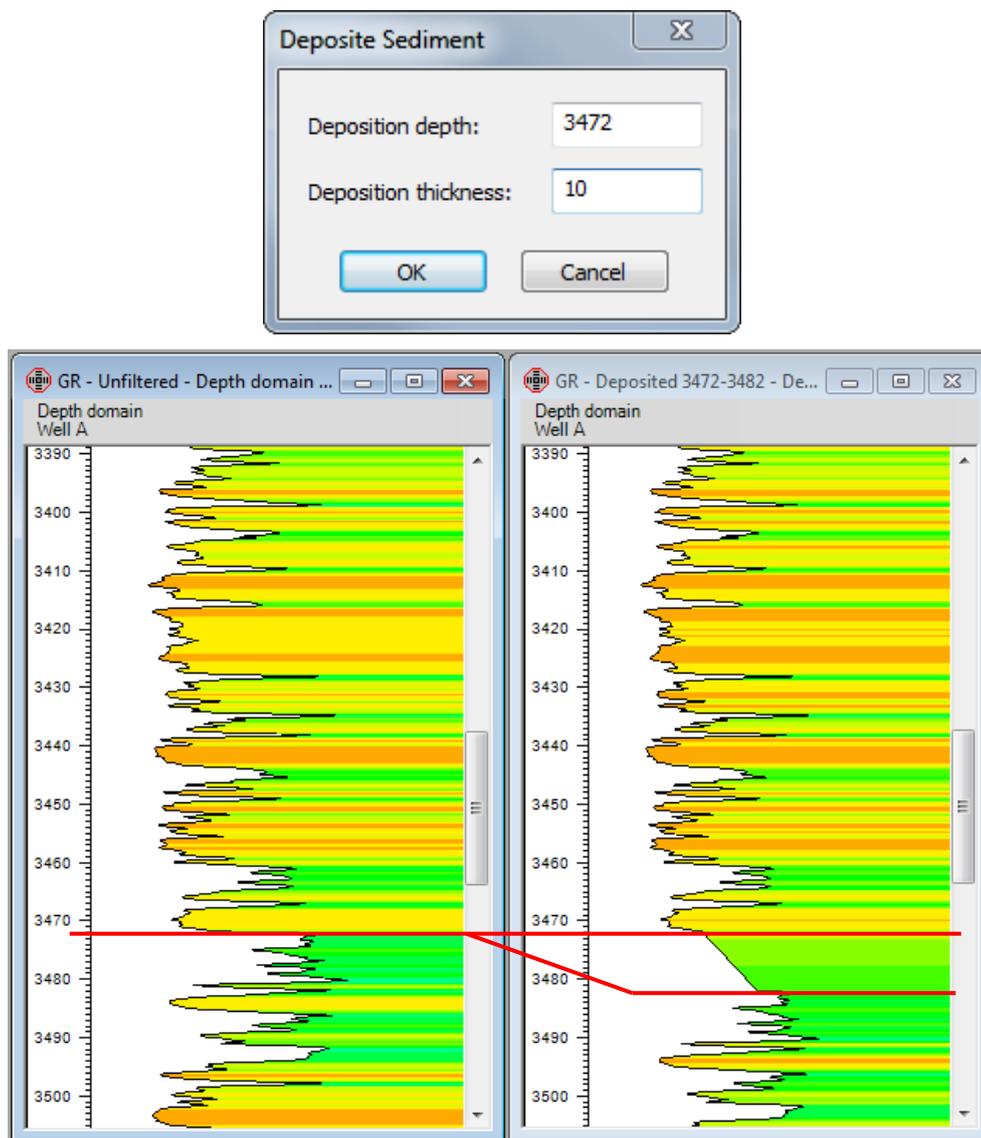
The result is shown below: the shaley interval between 3472m and 3482m has been removed, and the lower part of the log has been moved up to close the gap.



To ‘deposit’ a section within a log:

- In case you want to keep both a copy of the original and the newly created log, make a duplicate of the original log.
- Open the duplicate log.
- Right-click over the log data pane, and select **Processing** → **Deposit**.
- In the dialog box, enter the depth at which section is to be added, and the thickness of the section to be added.
- Click **OK**.
- To undo the 'erode' operations, click the **Undo** button on the Standard toolbar. The Undo operation will apply to the currently active log display pane.

In the example below, 10m of section has been interpolated into the log at a depth of 3472m. Note that this adds 10m to the depths of all data-points below this point.



Part 2 - Log spectral analysis functions

2.1 Log spectral analysis in CycloLog

CycloLog's unique contributions to well log analysis lie in its spectral functions. Spectral analysis exploits methods that are commonly referred to as *time-series analysis*. Time-series (waveform) data have properties of *wavelength (or frequency)*, *amplitude* and *phase*. (Frequency is the inverse of wavelength.) A well log, treated as a composite waveform, has properties of wavelength, amplitude and phase that can be analysed through the methods of spectral analysis.

This approach also underlies the calculation of the PEFA and INPEFA curves, as described in the Tutorial – Base Module, part 3. Indeed, the Prediction Error Filter exploited by PEFA and INPEFA is directly related to the power spectrum calculated using the Maximum Entropy method, as outlined below.

The main purpose of spectral analysis of well log data is the search for stratigraphic cyclicity. In favourable circumstances, stratigraphy may respond to climatic change. An important driver of climate change is the periodic changes in insolation caused by predictable changes in Earth's orbit – the so-called Milankovitch cyclicity. CycloLog has special tools to assist the detection of such cyclicity in log data.

2.2 Introduction to CycloLog's spectral analysis functions

Spectral analysis decomposes a composite waveform into a set of simple sine and cosine waves.

Because the spectral properties of geological data are not constant throughout a well, it is appropriate to use a **sliding-window** approach. This means that the analysis is performed repeatedly for successive, and usually overlapping, 'windows' of the data. The length of the window is typically a few tens of meters (the default value in CycloLog is 40m, though this can be changed by the user). Starting from the bottom, the analysis is performed on the lowest (say) 40m of the data, then the window is moved up (by, say, 1m) and the analysis is repeated, all the way up to the top of the data.

The oldest and most familiar spectral analysis method is Fourier Analysis. The methods available are in CycloLog are:

- Fourier Transform
- Maximum Entropy
- Wavelet (Gabor)
- Wavelet (Modified)
- Walsh Transform

The **Fourier Transform** of a waveform is its exact equivalent *in the frequency domain*. Fourier analysis is appropriate for data – such as radio waves – that can be expected to conform to continuous sine and cosine waves.

The **Maximum Entropy** approach is different and is often referred to as spectral *estimation*. (The *entropy* of a dataset is related to its *information* content.) However, the results can be expressed in the form of a *power spectrum*, in exactly the same way as the results of a Fourier analysis. Thus, the difference of approach need not concern the average user of CycloLog.

- The Maximum Entropy approach is more appropriate to stratigraphic data, (which is much less likely to conform to regular sines and cosines) and we recommend its use in most cases.
- The method is also called MESA (for Maximum Entropy Spectral Anlalysis).

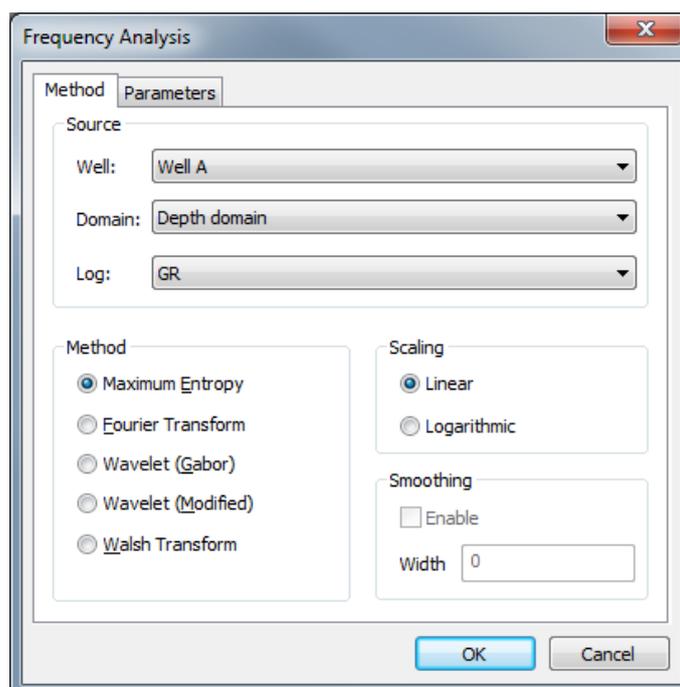
Wavelet approaches to spectral analysis attempt to model the power spectrum at a single point. In practice this is not possible, but the concept is obviously relevant to stratigraphic data, in which the properties can be expected to change abruptly, at hiatuses and boundaries for example. CycloLog includes two different wavelet methods, the details of which (and the differences between them) are not likely to be important to the average user.

The **Walsh Transform** treats the data-series as the composite of a number of square waves, which is a rather different approach to the other methods, and its use is too specialized to be described in detail here. However, the resulting Walsh power spectra are similar to the power spectra from the other methods, and there is no reason why the interested user should not experiment with the method.

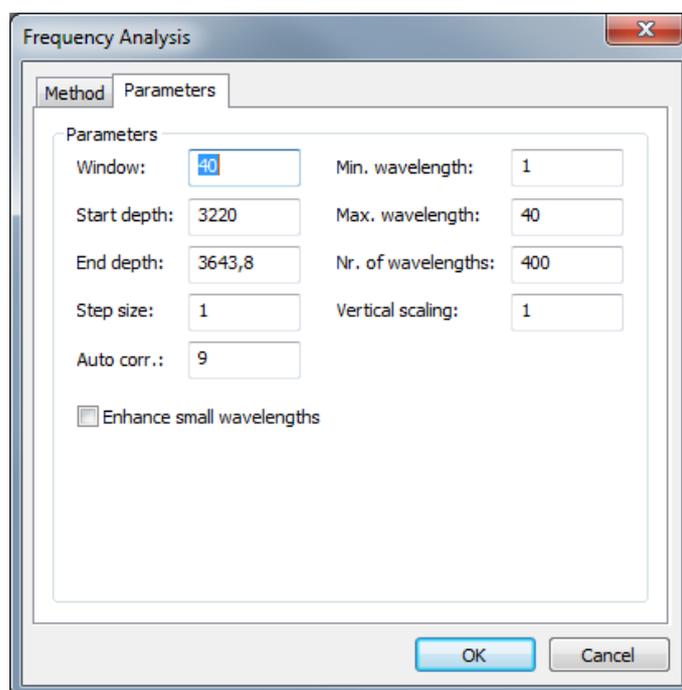
2.3 Using spectral analysis in CycloLog

The use of spectral methods in CycloLog is illustrated here with the Maximum Entropy method, which is the one recommended for general use. While some of the details are different for the other methods, most of the following applies equally to all methods.

To launch any of the spectral methods, go to the main menu bar and select **Analysis → Frequency Analysis**. This opens the Frequency Analysis dialog box:



- In the *Method* tab, check that the correct well and log are selected from the drop-down lists, and select **Maximum Entropy** from the list of Methods.
- In the *Parameters* tab, you have to set some important parameters for the analysis:



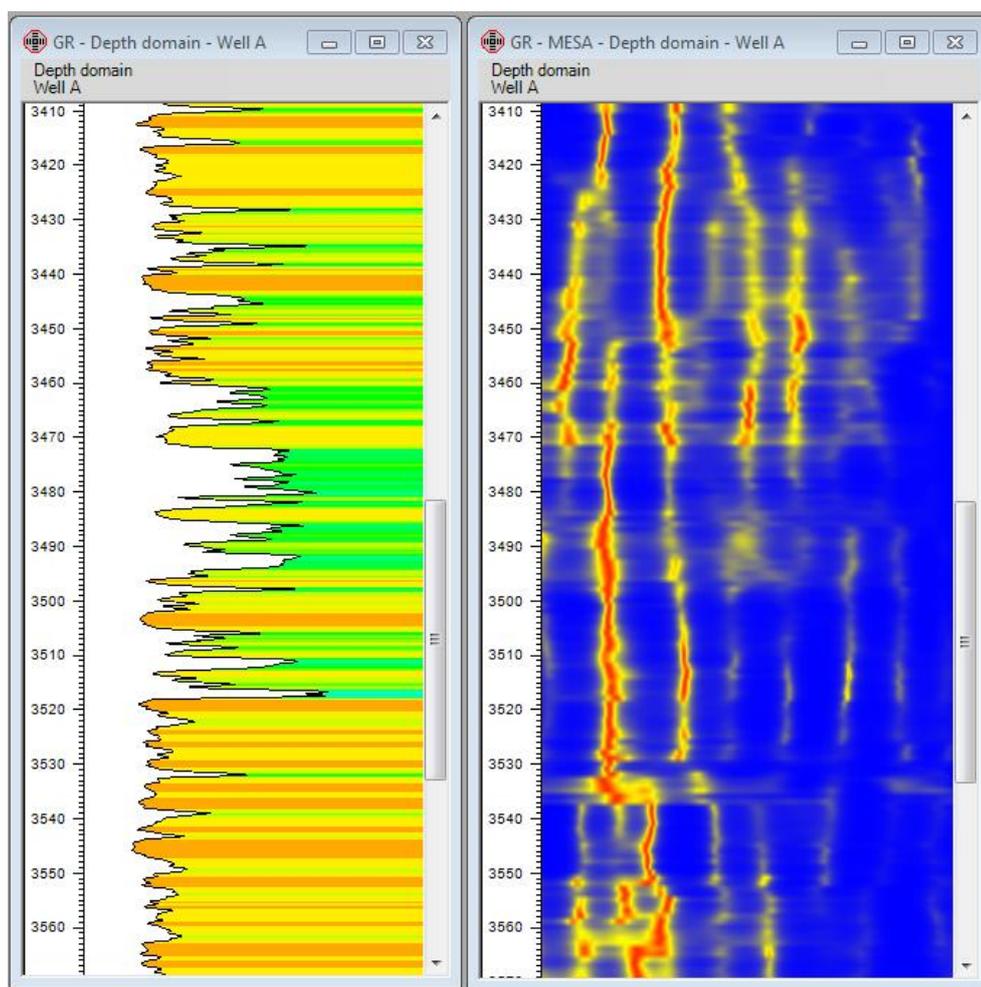
It will be necessary to experiment with the parameters; the following guidelines may help:

- **Window** is the length of the analysis window in depth units: start by using the default value (40m). *(Note: when your data is in feet, use 120ft).*
- The default **Start** and **End depths** include the entire log: change the depths if you wish to analyse only a part of the data.
- The **Step size** is the amount (in depth units) by which the window is moved at each step in the calculation. Start with the default value (1m). *(Note: when your data is in feet, use 3ft).*
- The **Autocorrelation length** should be set to approximately a quarter of the window length. (The default value for window length 40m is 9m.) *(Note: when your data is in feet, use 27ft).*
- The values of **Minimum** and **Maximum Wavelength** define the range of values shown on the horizontal scale of the finished power spectrum. Start with the defaults and adjust to different values if the results are not satisfactory.
- **Vertical scaling** is best kept to the default value of 1.
- In many cases, the power of the smaller wavelengths will be swamped by the large ones: in such cases check the **Enhance small wavelengths** box to correct for this effect.

When all parameters are set, click **OK** in the Frequency Analysis dialog box.

CycloLog runs the spectral analysis, and adds the result to the list of logs in the workspace. The name of the new “log” will be, for example, **GR – MESA**. If you run a second analysis, its name will be **GR – MESA (2)**.

To open the MESA results, double-click on its name in the workspace. The example below shows the result of a MESA analysis (Right pane) on the GR log displayed in the left pane. The vertical axis of the MESA display is depth, and the display scrolls with other logs from the same well.

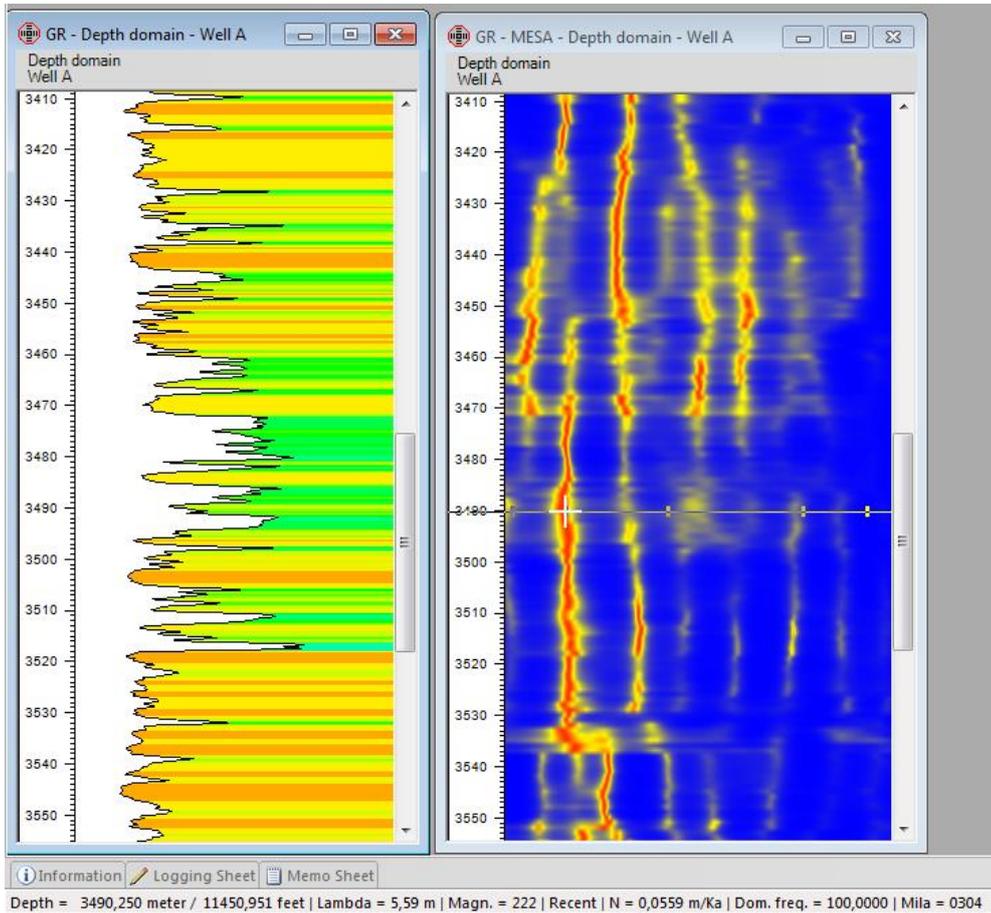


To interpret the results, remember that the method uses a moving window of analysis. The power spectra resulting from analysis of each window are stacked up, such that the *peaks* in successive spectra line up to form *ridges* in the stack. The peaks are coloured to represent their relative height (i.e. amplitude), so that higher spectral ridges appear as brightly coloured *streaks* on the display.

The horizontal scale of the display represents wavelength, decreasing logarithmically from left to right. (Longer wavelengths on the left; shorter wavelengths towards the right.) A vertical streak of bright colour indicates a wavelength that is persistently present through that interval of the log data.

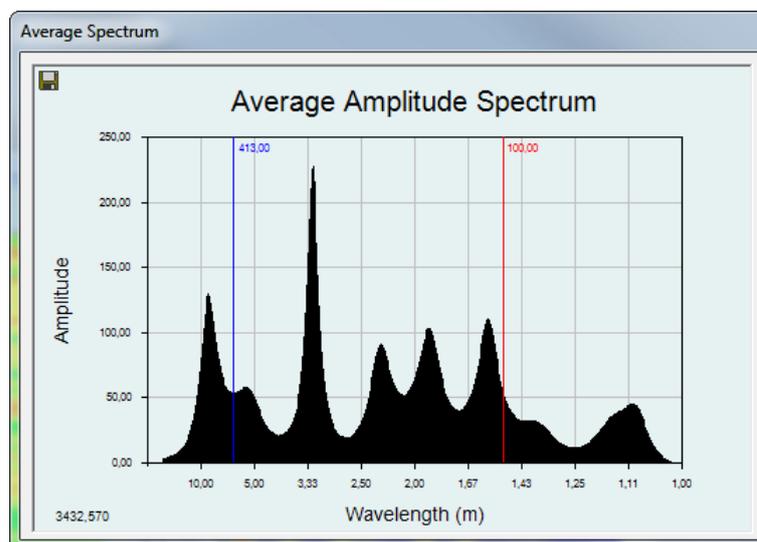
Although no horizontal scale is shown on the display, the wavelength of any peak at any depth can be found by using the cursor, as follows:

- To view the power spectrum at a single depth, move the cursor over the MESA log pane. The cursor changes into a horizontal line with five tick marks:



- Vertical Scale
- Break Manager
- Reservoir Manager
- Analysis Parameters
- Reposition
- Geological Period
- Toggle Average Spectrum
- Smoothing Width
- Pick Depth-Wavelength Curves
- Snap to Maximum
- Generate Time-Depth Curve
- Select Spectrum
- Optimal MilaSum

From this menu, select **Toggle Average Spectrum**.

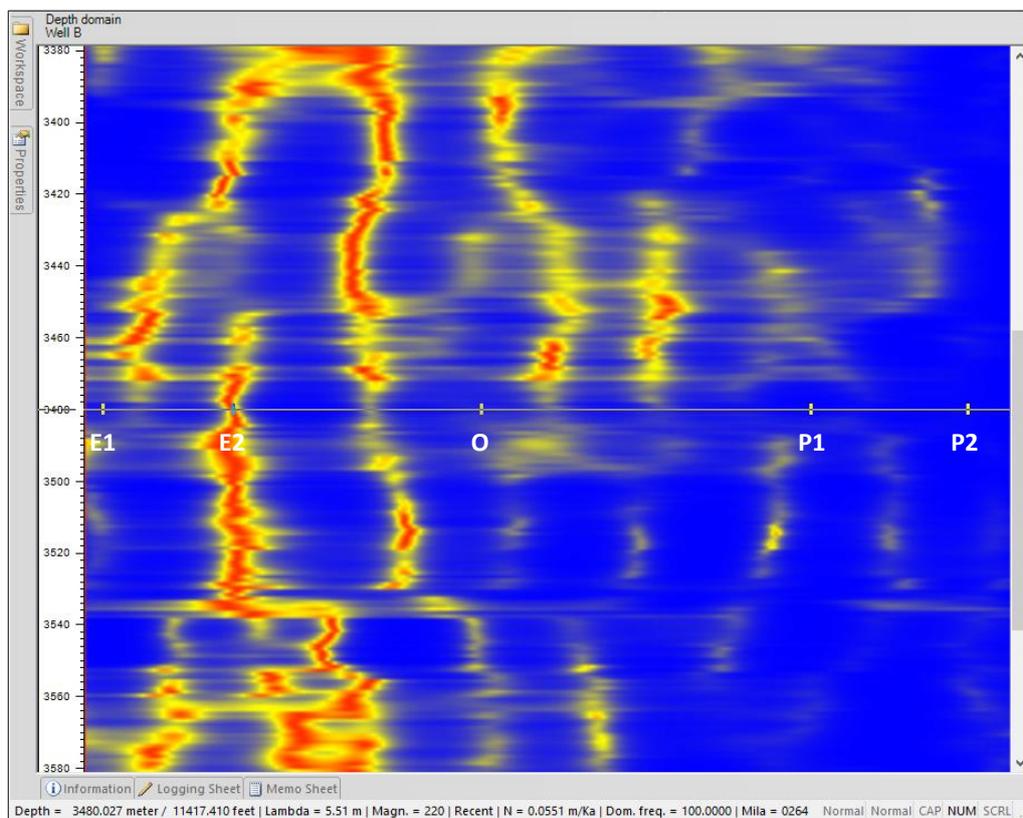


The **Average Spectrum** window opens. This window shows the Average Amplitude Spectrum, or power spectrum, at a single depth point (in the image above, at depth 3432.570m); the spectrum changes as the cursor is moved up and down the GR - MESA data pane.

The **Amplitude** is scaled vertically; the **Wavelength (m)** is shown on the horizontal axis, where it is plotted logarithmically, from higher values on the left, to lower values at the right.

2.4 Interpretation of Milankovitch cycles

The result of a spectral analysis is a breakdown of the data into a set of simple (sine/cosine) waves. Deciding whether or not these have any geological and/or climatic significance is a matter of interpretation.



When the cursor is over the MESA display, it takes the form of a horizontal line with five tick marks, as in the above figure. The relative positions of the ticks represent (in terms of wavelength) the ratios among the principal predicted Milankovitch frequencies. For different Periods, the obliquity and precession cycles vary. For recent times these are:

- E1, long orbital eccentricity cycle: 413ka
- E2, short eccentricity cycle: 100ka
- O, axial obliquity cycle: 41ka
- P1, precession cycle: 23ka
- P2, precession cycle: 19ka

Note that the logarithmic scale makes the 413ka and 100ka tick marks appear closer together than the 23ka and 19ka ticks!

Note also that the relative positions of the predicted Milankovitch periods are also shown on the Average Amplitude Spectrum display: see the figure above in part 3.2.

By default, the 100ka tick is selected as the “dominant” frequency: it is distinguished from the others, by having a cross line through it. To change the dominant frequency, see further below.

The **Status Bar** displays the frequency (**Dom. freq.**) and amplitude (**Magn.**) of the power spectrum at the point under the “dominant” tick mark.

The Status Bar also provides two statistics designed to help in the identification of Milankovitch periods:

- **Sedimentation rate:** this is the net accumulation rate implied by the wavelength position corresponding to the position of the “dominant frequency” tick mark on the Milankovitch cursor (**N = 0.0551 m/ka** on the figure above). This assumes, of course, that deposition was continuous and at an unchanging rate, so must be used with care.
- **MilaSum** (“Mila” on the Status Bar) is an arbitrary measure of the quality of the match between the predicted Milankovitch period ratios, and the ratios between the observed peaks, for the current position of the Milankovitch cursor. This statistic should also be used with care, but it may help with choosing between different interpretations.

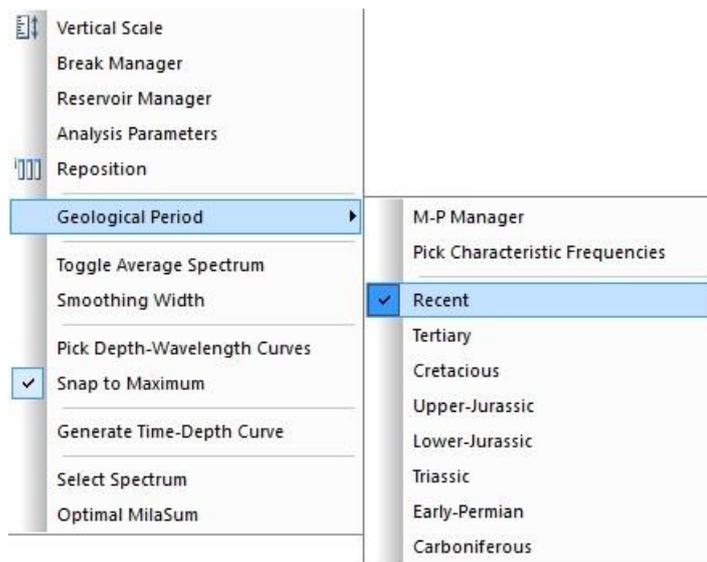
If a full suite of Milankovitch periods is perfectly represented in the stratigraphy, then the corresponding peaks in the MESA spectrum should all lie under one of the ticks on the Milankovitch cursor. Moving the cursor ticks with the mouse should indicate whether or not this is likely. Bear in mind that any interpretation in terms of Milankovitch cycle periods must be consistent with available evidence for the total duration of the succession.

It is very rarely the case that all Milankovitch periods are represented. The user will therefore have to decide, (a) whether any of the spectral wavelengths are likely to represent Milankovitch periods, and, if so, (b) which wavelengths correspond to which of the predicted cycle periods.

2.5 Using the MESA menu

Place the cursor over the GR - MESA data pane and right-click with the mouse to open a menu that contains a number of special functions.

- *Analysis parameters* shows a record of the parameters used to generate the MESA display.
- *Toggle Average Spectrum* was explained above; it can be toggled on/off.
- *Geological Period* (illustrated below). The ratios between the Milankovitch periodicities change through geological time; select the period most appropriate to the data being analysed. (See CycloLog Help for further information.)
- *M-P Manager* (on the *Geological Period* menu). Use this dialog box to change the periodicity selected as “dominant” (default – 100ka).



Part 3 - Advanced log processing functions

3.1 Advanced processing functions in CycloLog

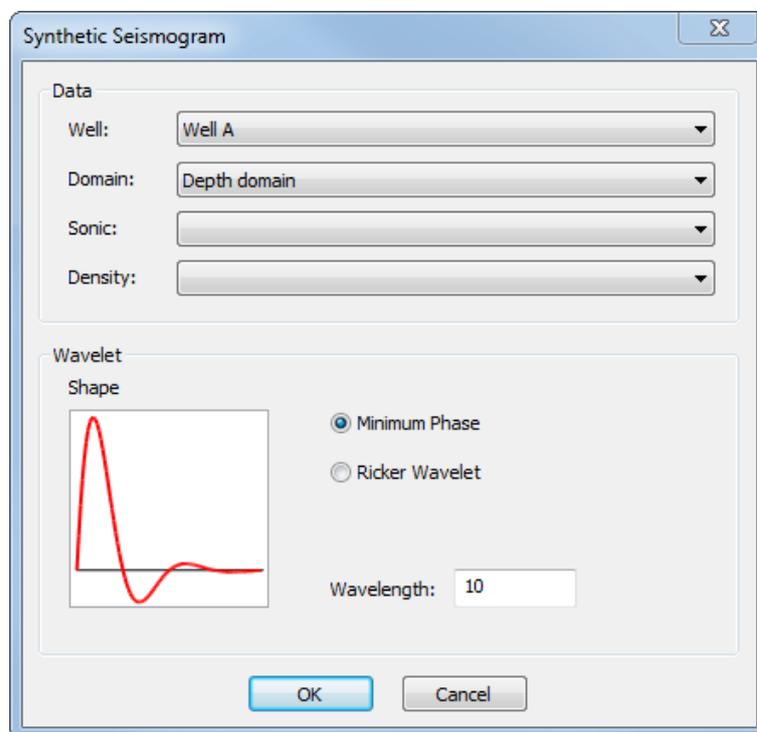
CycloLog has a number of additional/advanced calculation and analysis functions. Introductory instructions for some of these functions are given in this section of the tutorial; others are explained in **CycloLog Help**. The functions covered here are:

- **Synthetic seismogram** – generating simple seismic traces from logs
- **Math Studio** – defining arithmetical combinations of logs
- **Markov Chain Analysis** – analysing patterns of upward change

3.2 Generating synthetic seismograms

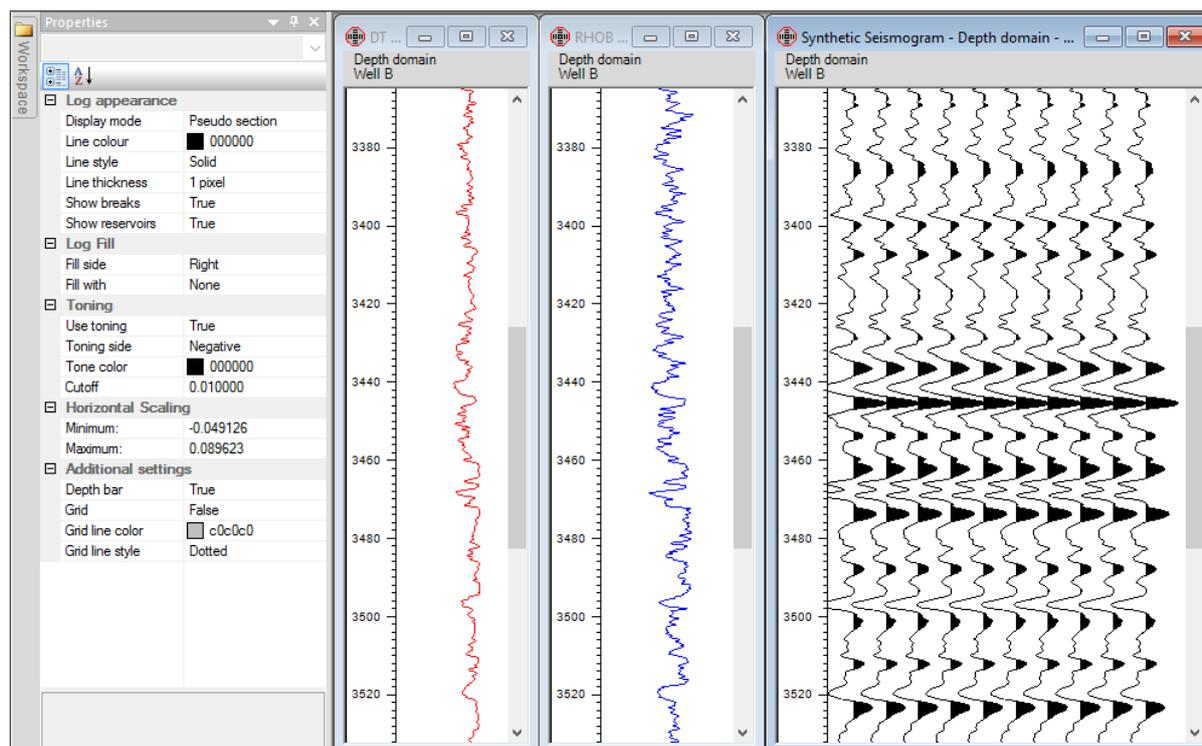
Synthetic seismic traces can be generated in CycloLog, either automatically or manually. The automatic method is described here; the manual method is described in **CycloLog Help**.

- Go to the main menu bar and select **Calculations** → **Synthetic Seismogram**. The following dialog window opens:



- Select the **Well** you wish to calculate a synthetic seismogram. Check the **Domain**.
- From the **Sonic** and **Density** drop-down lists, select the sonic and density logs that you wish to use in the calculation.
- Select a **Wavelet** – *see below for information*.
- Define the **Wavelength** (default = 10m). Click **OK**.

- The Synthetic Seismogram is generated, and added to the workspace.



The above figure shows the synthetic seismogram displayed alongside the sonic and density curves from which it was generated. The display initially shows only a single trace, without toning. This is converted to a multiple trace display (as shown above) as follows:

- Make sure the synthetic seismogram pane is open and the active pane.
- Open the properties pane.
- Under **Log appearance**, set the **Display mode** to **Pseudo section**.
- Under **Toning**, set **Use toning** to **True** and set the **Toning side**, **Tone color** and **Cutoff** value.

Note: Wavelet types available in the Synthetics Seismogram dialog are:

- *Minimum Phase Wavelet*
- *Ricker Wavelet Type 1 (the standard Ricker wavelet)*
- *Ricker Wavelet types 2, 3 and 4 (Ricker wavelets with a more “ringing” character)*

3.3 Using Math Studio

The **Math Studio** consists of a range of calculations that can be performed on logs.

Several basic calculations can be performed without using the Math Studio. Their use was described in part 1.3 of this tutorial, and they are:

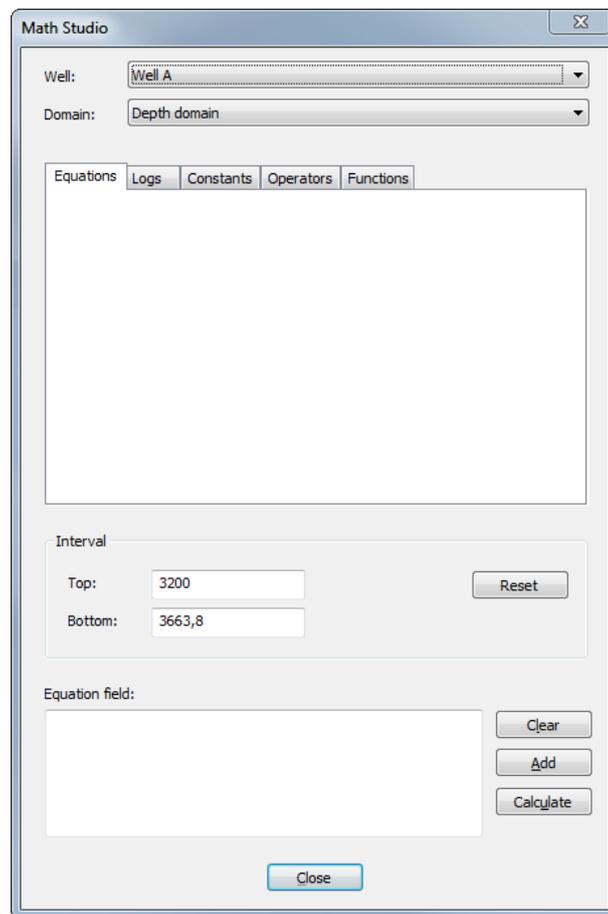
- **Add Logs** (add one log to another)
- **Subtract Logs** (subtract one log from another)
- **Multiply Logs** (multiply one log by another)
- **Divide Logs** (divide one log by another)
- **Integral** (calculate the integral of a log curve)
- **Derivative** (calculate the derivative of a log curve)
- **Logarithm** (calculate the logarithm of all data values in a log)
- **Exponent** (calculate the inverse logarithm of all data values)

For the above calculations, open the log that is to be the subject of the calculation (*suggestion: use a **copy of the log***), right-click over the opened log pane and select **Processing → Log Calculations** and then select the required operation.

For more advanced calculations, use the Math Studio, as follows:

- From the main menu bar select **Tools → Math Studio**.
- The **Math Studio** dialog box opens. It a number of tabs and other features, briefly explained in the following figure below.
- The **Math Studio** is used to set up formulas that will be applied to every depth point in a specified interval.

The formulas can be set up by selecting the logs, the arithmetical operators, various available functions, and a selection of constants, from standard lists.



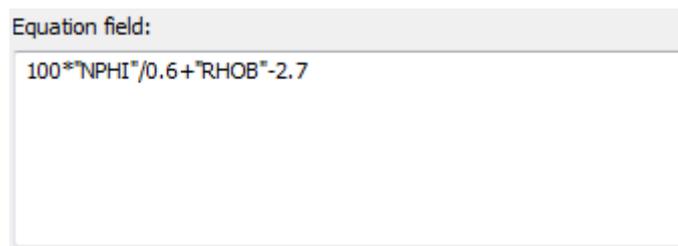
- The **Equations** tab is where you will set up a formula, as in the example described below.
- The **Logs** tab has a list of all the logs of the selected well in the workspace, including logs that you have created such as cluster logs or synthetic seismograms.
- The **Constants** tab lists four basic constants (DZ, PI, ZMAX, and ZMIN).
- The **Operators** tab lists ten basic arithmetical operators (add, subtract etc.).
- The **Functions** tab lists twenty-six more advanced functions, including trigonometrical functions (sine, cosine, etc.), logarithms (natural and base 10), and exponentiation.

To demonstrate how to set up an equation, the following example calculates shale separation from the neutron and density curves, using the formula: $100 * \text{NPHI} / 0.6 + \text{RHOB} - 2.7$. (This formula assumes that NPHI is expressed as a ratio; where NPHI is a percentage, the formula is $\text{NPHI} / 0.6 + \text{RHOB} - 2.7$).

- Go to the **Equations** tab.
- Click in the **Equation field**, at the bottom of the dialog box.
- The following sequence of operations will construct the equation:
- Type **100**.
- Go to the **Operators** tab and double-click on the multiply operator (*). Note that this operator is added to the Equation field.

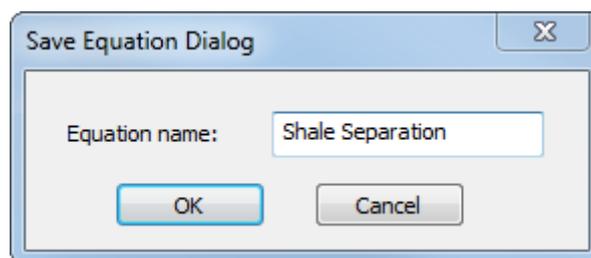
- Go to the **Logs** tab and double-click on the NPHI log.
- Go to the Operators tab and double-click on the add operator (/).
- Type **0.6**.
- Go to the **Operators** tab and double-click on the add operator (+).
- Go to the **Logs** tab and double-click on the RHOB log.
- Go to the **Operators** tab and double-click on the subtract operator (-).
- Type **2.7**.

The full formula now appears in the Equation field, as:

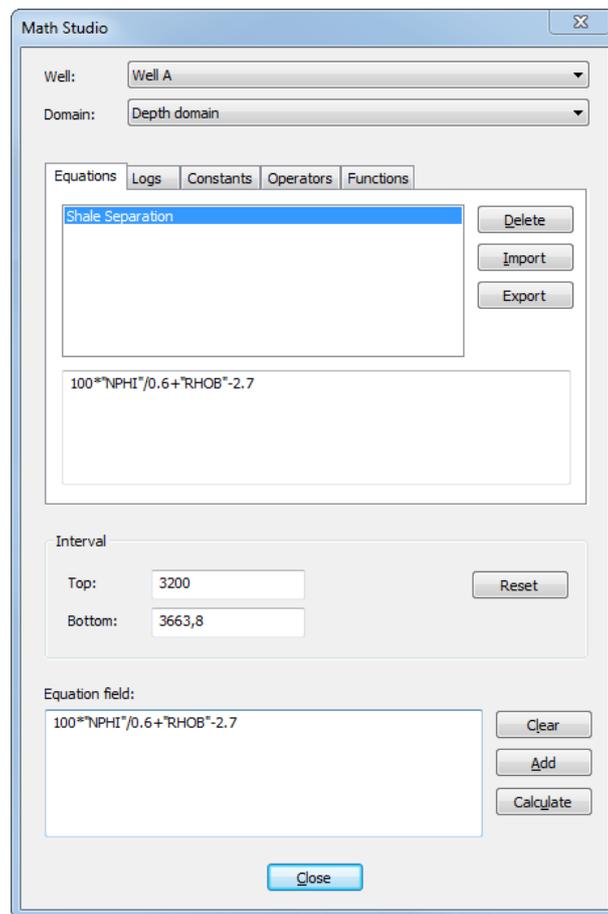


To save this formula:

- Click the **Add** button to open the **Save Equation Dialog** box.
- Type a name for the formula, and click **OK**.



The formula has been saved for future use; it will now appear on the **Equations** tab every time you open the Math Studio.



To apply the formula:

- Check that the correct **Well** is selected at the top of the dialog box.
- Check that the equation is listed in **Equation field** (if not double-click on “Shale separation” in the equation list).
- Change the depth **Interval** if you do not want the formula applied to the entire data set.
- Click **Calculate**.
- CycloLog runs the calculation, and adds the results to the workspace as a new log with the name of the formula (in this case, the new log is called “Shale Separation”).

To save the formula for importing to another CycloLog project:

- Select the formula in the list on the **Equations** tab.
- Click **Export** and give the file a name (e.g., ShaleSeparation).
- The file will be saved as (for example) **ShaleSeparation.equ**.

3.4 Markov Chain Analysis in CycloLog

Markov Chain Analysis in general looks for relationships between the current state of a process and its previous state. In stratigraphy, it is used for testing the relationships between adjacent lithologies in a stratigraphic succession: is the succession of lithologies purely random, or is there some order to the way in which lithologies succeed each other?

No single log has a direct relationship with lithology; it is therefore necessary to start by defining the 'lithologies' that the Markov Chain Analysis will work with. There are several ways to do this, but a good starting point is a Cluster Analysis, as described in Tutorial – Clustering and Lithology, part 1.

The following description of a Markov Chain Analysis in CycloLog is based on the result of the cluster analysis that was used as an example in the Tutorial – Clustering and Lithology, part 1.

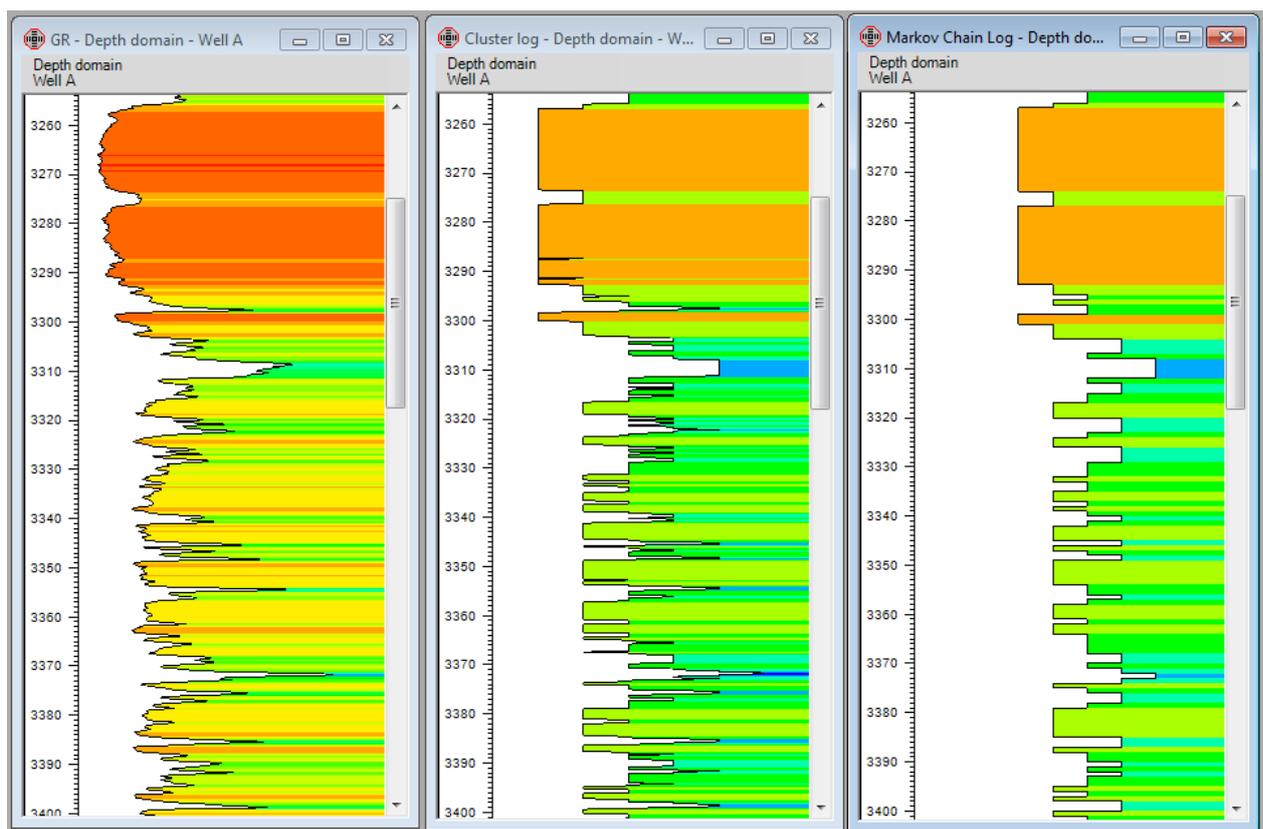
The native clustering was based on the combination of the GR, sonic, neutron and density logs; it defined seven clusters.

- From the main menu bar select **Analysis → Markov Chain Analysis**.
- On the **General** tab of the dialog box, select the **Well** and the **Log** on which the analysis will be based; in the example, this is the *Cluster Log*.
- Define the **Top** and **Bottom** depth interval for the analysis.
- Define the **Step size**; this is the size of the intervals into which the data will be divided into 'lithologies' (1 meter in the example).

The screenshot shows the 'Markov Chain Analysis' dialog box with the 'General' tab selected. The 'Source' section includes dropdown menus for 'Well' (Well A), 'Domain' (Depth domain), and 'Log' (Cluster log). The 'Interval' section has input fields for 'Top' (3200), 'Bottom' (3663,8), and 'Step size' (1). The dialog box has 'OK' and 'Cancel' buttons at the bottom right.

- Now open the **Lithology** tab.

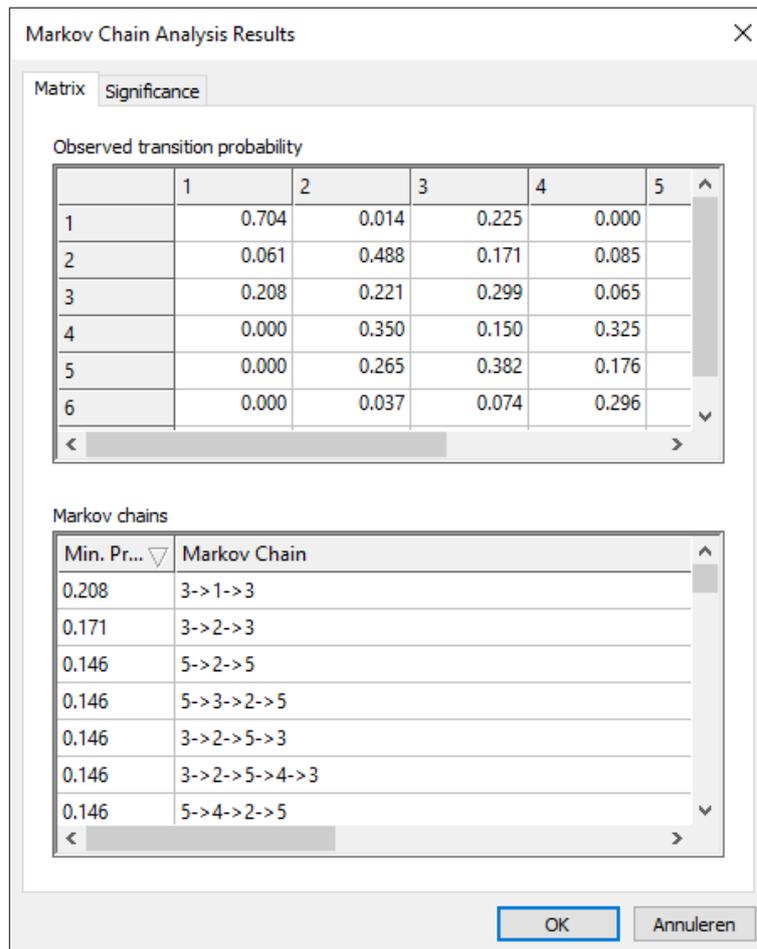
- Accept the default method: **Automatic**. See below concerning the other methods (**Predefined model**, and **Manual**).
- For the log on which the analysis is to be based, identify the **Minimum** and **Maximum** values of the log in the interval to be analysed. (In the example, the clusters are numbered from 0 to 7, so the minimum is 0 and the maximum is 7.)
- Define the **Number of Intervals** (i.e. 'lithologies') into which the data are to be divided (7 in the example). Click **OK**.
- The analysis runs, and a **Markov Chain Log** is added to the list in the workspace. (This depicts the 'lithologies' into which the chosen log has been subdivided for the analysis.)



The figure above shows the Cluster log (middle pane) which was used as the basis for subdivision into lithologies. In the Markov Chain Log (right hand pane), 7 'lithologies' (based on the clusters) are defined in 1m steps. The Markov Chain Analysis categorizes every upward transition, at every 1m step, and counts the resulting transitions.

To view the results of the analysis:

- Open the new Markov Chain Log.
- Right-click over the opened Markov Chain Log pane and select Analysis Results.
- The following Markov Chain Analysis Results dialog box opens:



The analysis categorises and counts every upward transition from one lithology to the next. Note that, because all steps are the same size (1m in the example), many of the upward transitions will be “self-transitions”, at which the lithology stays the same. Based on these counts, the probability of every possible upward transition is calculated; if the data are not random, then some upward transitions will be more likely than others.

The results box presents this information in three parts, two on the **Matrix** tab and one on the **Significance** tab.

On the **Matrix** tab, the table of **Observed transition probabilities** shows the relative probabilities of every possible upward transition. (See the data on the **Significance** tab for the details of these results.) The table should be read from row to column. A few of these results are now discussed, to suggest how the results might be interpreted.

- In the example, lithology 1 is succeeded by itself with a high probability of 0.980. Lithology 1 has the characteristics of e.g. a fine-grained sandstone; the high probability of an upward “self-transition” means that such sandstones are likely to occur in units greater than 1m in thickness.
- Lithologies 3 and 4 have lower probabilities of self-transition, so are more likely to occur in thinner beds.

- Lithology 5 has a high probability (0.382) of upward transition to lithology 3, but zero probability of upward transition to lithology 1.
- Lithology 4 is quite likely (0.350) to be succeeded by lithology 2, but lithology 2 is much less likely (0.085) to be followed by lithology 4.

Based on these transition probabilities, the **Markov chains** box on the **Matrix** tab shows the possible upward **chains** of lithological states, in decreasing order of their probability. Each such chain is a “cycle” in that it starts and finishes with the same lithology. In the example, there is a large number of possible chains, indicating that there is no one dominant cyclic or repetitive pattern. Looking at the first few in the example, and taking the Cluster Matrix of the Cluster Log analysis results into account (see below):

- The chain 3 > 1 > 3 occurs with the highest probability. Lithologies 1 and 3 both have low GR values, so this chain expresses the moderate probability of switching between sandstones with slightly higher and slightly lower GR values.
- The next three chains are 3 > 2 > 3 with probability 0.171; and 5 > 3 > 2 > 5 (0.146). They represent variations on transitions among lithologies with mid- to high-range GR values.
- The following two chains contain rather more abrupt transitions: 5 > 2 > 5 (0.146); and 5 > 4 > 2 > 5 (0.146). Lithologies 2 and 5 are considerably more different in their GR values.

Part 4 - Basic petrophysical functions

4.1 Petrophysical functions in CycloLog

CycloLog includes a number of basic petrophysical functions. Introductory instructions for these are given in this section of the tutorial. Functions covered here are:

- Porosity calculation
- Porosity calibration using core measurements
- Permeability calculation
- Water saturation calculation
- Water resistivity calculation
- Creating a petrophysical summary report

4.2 Porosity calculation

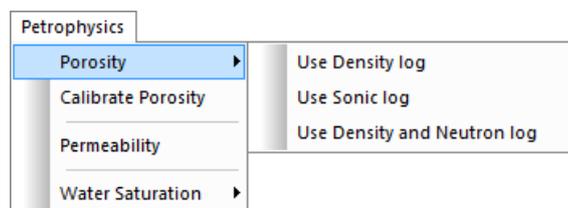
In CycloLog, there are three different ways for calculating porosity estimations, starting from the following logs:

- Density log
- Sonic log
- Density and neutron logs

You may wish to use more than one of these methods, depending on which logs are available, and to compare the results.

All three options are selected from the **Porosity** menu:

- Go to the main menu bar and select: **Petrophysics** → **Porosity**.
- Move the cursor to the **Porosity** item you wish to use.
- Select the required method.



4.3 Porosity calculation from a density log

Calculation of porosity (ϕ_{density}) from a density log uses the following formula:

$$\phi_{\text{density}} = (\rho_{\text{matrix}} - \rho_{\text{bulk}}) / (\rho_{\text{matrix}} - \rho_{\text{fluid}})$$

where,

- ρ_{matrix} = matrix (or grain) density
- ρ_{bulk} = bulk density as measured by the logging tool
- ρ_{fluid} = density of fluid

As long as we can provide numbers for the matrix density (ρ_{matrix}) and the fluid density (ρ_{fluid}), this formula will give the porosity (in fraction between 0.0 and 1.0) from the density log (ρ_{bulk}).

If the lithology of the matrix is known, use the following standard density values (in g/cm³):

Sandstone (quartz)	2.648
Limestone (calcite)	2.710
Dolomite	2.850
Gypsum	2.351
Anhydrite	2.977
Halite	2.032

For the fluid density, use 1.0 g/cm³ for freshwater, and 1.1 g/cm³ for brine.

Alternatively, the matrix density can be obtained directly from the log data, as explained below.

To start the calculation:

- From the main menu bar, select: **Petrophysics → Porosity**;
- Then select **Use Density Log**.
- The following dialog box opens:

Calculate porosity using the density

$$\varphi_{den} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Select the density log

Well:

Domain:

Density:

Interval

Top:

Bottom:

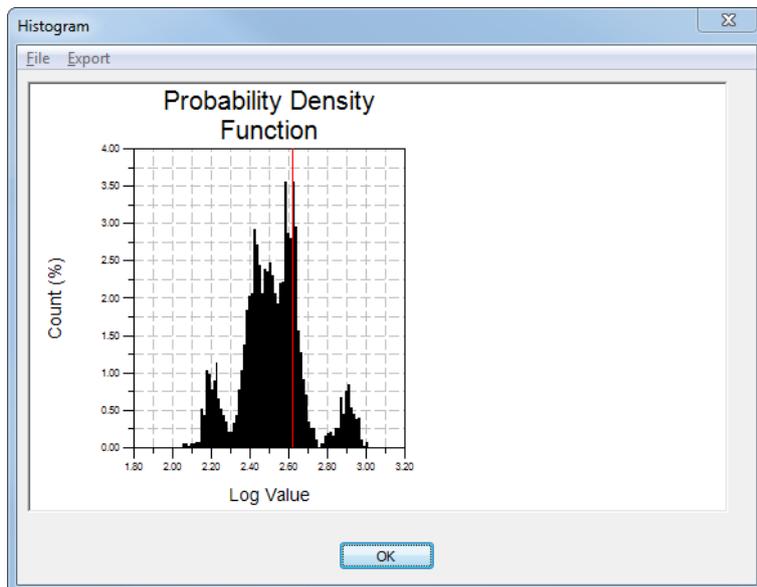
Density parameters

Matrix density:

Fluid density:

OK Cancel

- Check that the correct **Well** is selected.
- Select the required density log from the drop-down list.
- Specify the **Top** and **Bottom** depth interval over which the porosity is to be calculated.
- Enter the **Fluid density** (in g/cm³). See above.
- **EITHER** enter the **Matrix density** (if known).
- **OR** average the **Matrix density** from the data as follows:
 - Click on the **Histogram** icon next to the **Matrix density** box.
 - Hold the cursor over the value regarded as representing the appropriate density value, and click once with the left mouse button
 - A vertical red line marks the currently selected value.
 - Click **OK** to enter this value into the **Matrix density** box in the **Calculate porosity** dialog box.
- Click **OK** to run the porosity calculation.



CycloLog runs the calculation and creates a new log called **Porosity <logname>** (here: RHOB) that is saved to the workspace.

4.4 Porosity calculation from density and neutron logs

The second method available in CycloLog calculates porosity (in %) from a combination of a density and a neutron log. The combined porosity (ϕ_{N-D}) is calculated as the root-mean-square of the porosities from the density and neutron logs separately:

$$\phi_{N-D} = ((\phi_N^2 + \phi_D^2) / 2)^{1/2}$$

If the lithology of the matrix is known, use the following standard density values (in g/cm³):

Sandstone (quartz)	2.648
Limestone (calcite)	2.710
Dolomite	2.850
Gypsum	2.351
Anhydrite	2.977
Halite	2.032

For the fluid density, use 1.0 g/cm³ for freshwater, and 1.1 g/cm³ for brine.

Alternatively, the matrix density can be obtained directly from the log data, as explained below.

To start the calculation:

- From the main menu bar, select: **Petrophysics → Porosity**.
- Then select **Use Density and Neutron Log**.
- The following dialog box opens:

- Check that the correct **Well** is selected.
- Select the required **Density** log from the drop-down list.
- Select the required **Neutron** log from the drop-down list.
- Specify the **Top** and **Bottom** depth interval over which the porosity is to be calculated.
- Enter the **Fluid density** (in g/cm³).
- **EITHER** enter the **Matrix density** (if known).
- **OR** average the **Matrix density** from the data as follows:
 - Click on the **Histogram** icon next to the **Matrix density** box.

- Hold the cursor over the value regarded as representing the appropriate density value, and click once with the left mouse button.
- A vertical red line marks the currently selected value.
- Click **OK** to enter this value into the **Matrix density** box in the **Calculate porosity** dialogue box.
- Click **OK** to run the porosity calculation.

CycloLog runs the calculation and creates a new log called **Porosity <logname>** (here: RHOB-NPHI). This log is added to the workspace tree.

4.5 Porosity calculation from a sonic log

Porosity (ϕ_{sonic}) may also be calculated from a sonic log if no density log is available, although the results may be less reliable. The calculation is based on the following formula:

$$\phi_{\text{sonic}} = (\Delta t_{\text{log}} - \Delta t_{\text{matrix}}) / (\Delta t_{\text{fluid}} - \Delta t_{\text{matrix}})$$

where,

- Δt_{log} = sonic log value (interval transit time)
- Δt_{matrix} = interval transit time for the matrix
- Δt_{fluid} = interval transit time for the fluid

Given values for the interval transit time in the matrix and the pore fluid, this formula allows us to calculate sonic porosity from the values of the sonic log.

If the lithology of the matrix is known, you may be able to use one of the following standard values (in $\mu\text{s}/\text{ft}$) for Δt_{matrix} :

Sandstones (quartz)	55.5 – 51.0
Limestone (calcite)	53 – 47.6
Dolomite	43.5
Gypsum	52 – 53
Anhydrite	50
Halite	67.0

For the fluid interval transit time, use 189 $\mu\text{s}/\text{ft}$ for freshwater-based mud, or 185 $\mu\text{s}/\text{ft}$ for saltwater-based mud.

Alternatively, the matrix interval transit time can be obtained directly from the log data, as explained below.

To start the calculation:

- From the main menu bar, select: **Petrophysics** → **Porosity**.
- Then select **Use Sonic Log**.
- The following dialog box opens:

Calculate porosity using the sonic

$$\varphi_{sonic} = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

Select the sonic log

Well:

Domain:

Sonic:

Interval

Top:

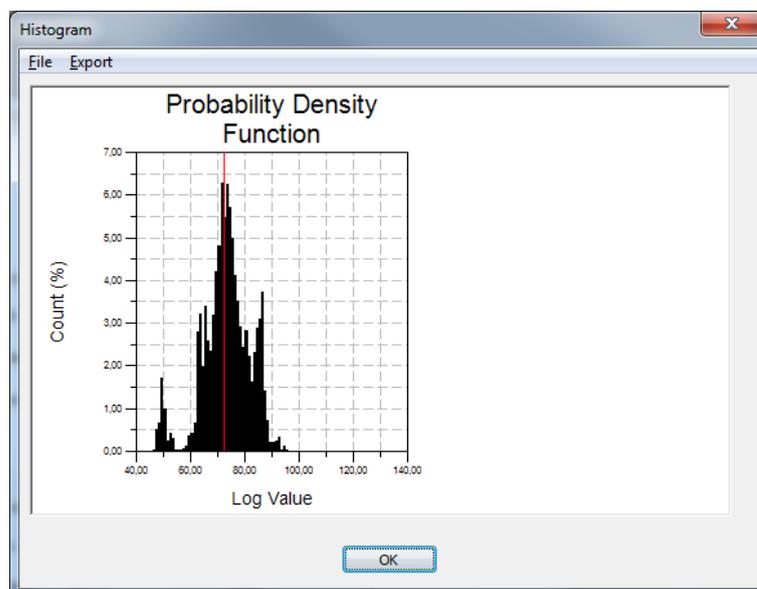
Bottom:

Sonic interval transit time

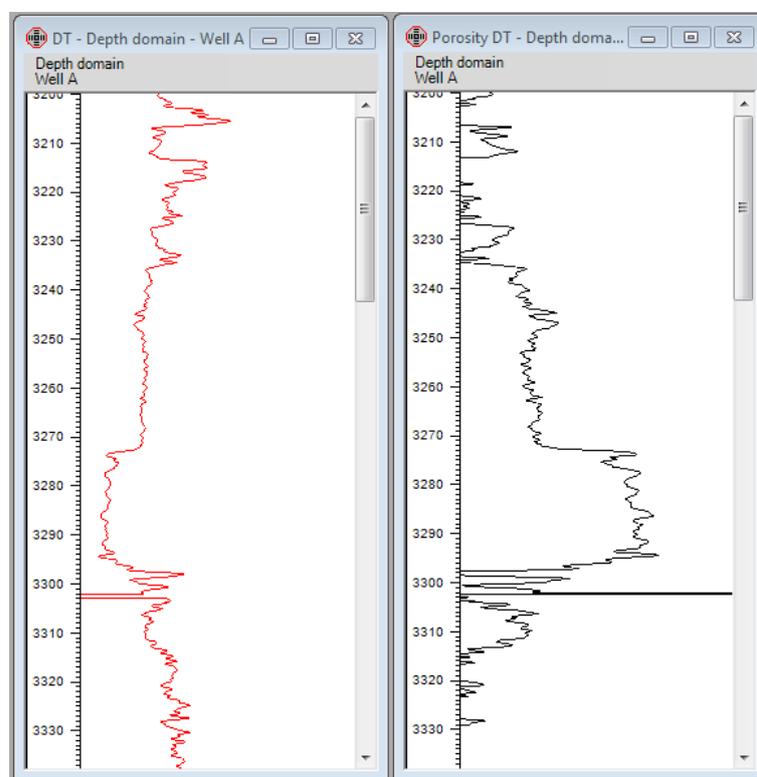
Matrix: 

Fluid:

- Check that the correct **Well** is selected.
- Select the required **Sonic** log from the drop-down list.
- Specify the **Top** and **Bottom** depth interval over which the porosity is to be calculated.
- Enter the **Fluid interval transit time** (in $\mu\text{s}/\text{ft}$);
- **EITHER** enter the **Matrix interval transit time** (if known).
- **OR** average the **Matrix interval transit time** from the data as follows:
 - Click on the Histogram icon next to the Matrix interval transit time box.
 - Hold the cursor over the peak regarded as representing the appropriate sonic value, and click once with the left mouse button.
 - A vertical red line marks the currently selected value.
 - Click OK to enter this value into the Matrix interval transit time box in the Calculate porosity dialog box;
- Click **OK** to run the porosity calculation.



CycloLog runs the calculation and creates a new log called Porosity <logname> (here: DT). This log is shown in the following illustration beside the original sonic (DT) log:



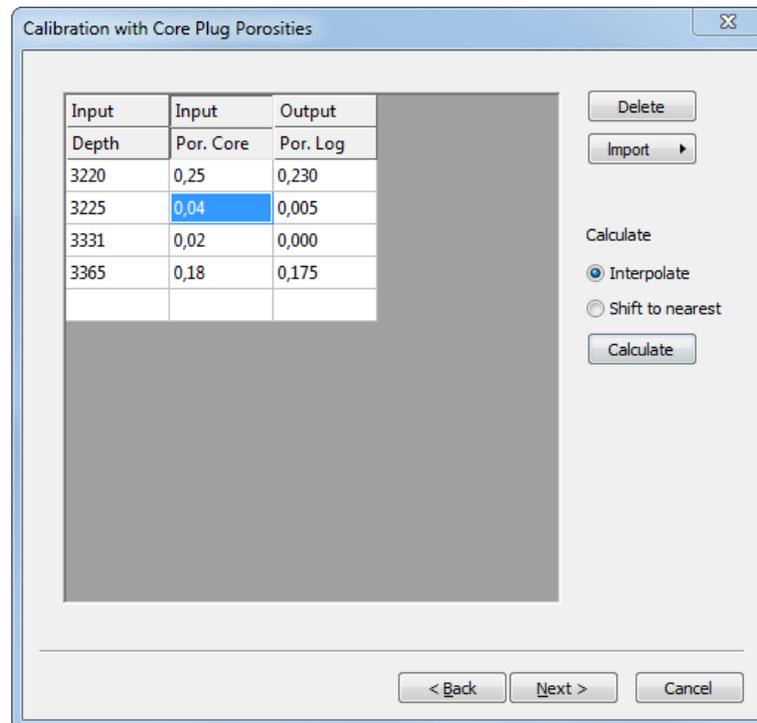
4.6 Porosity calibration

If direct porosity measurements are available (from core samples, for example), these can be used to calibrate a log-derived porosity curve.

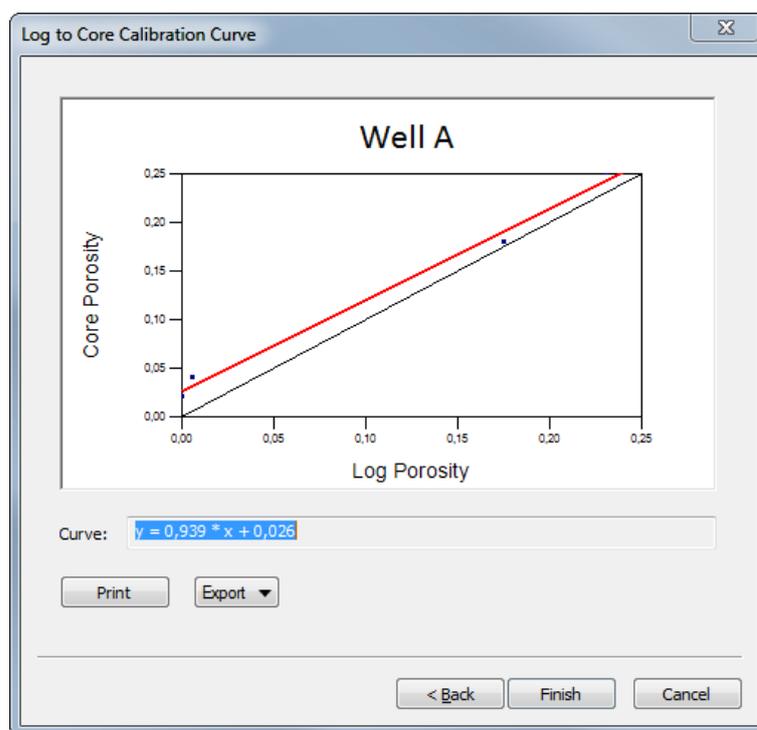
Suppose that the following porosities have been measured on a core of the selected well, at the given depths:

<i>Depth</i>	<i>Porosity</i>
3220m	0.25
3225m	0.04
3331m	0.02
3365m	0.18

- From the main menu bar, select **Petrophysics** → **Calibrate Porosity**.
- In the dialog box that opens, select **Well** and **Porosity** log to be calibrated. Click **Next**.
- The **Calibration with Core Plug Porosities** dialog box opens:



- Enter the **Depths** and core porosity measurements (**Por. Core**) in the first and second columns.
- *(Alternatively, if you have the values in a table like the one above, copy it to the clipboard, and click the **Import** button to paste the values into the dialog box).*
- Click **Calculate**, and CycloLog enters the porosity values from the selected log.
- *(You can choose either to **Interpolate** between the values at the nearest depths, or **Shift to nearest**, to use the log value at the nearest available depth).*
- Click **Next**.
- A graph of **Core Porosity** against **Log Porosity** opens, in which the black line represents a reference line when no calibration is needed, and the red line shows the relationship as calibrated with the core porosity measurements.
- The regression equation for the calibrated relationship is shown.
- Use the **Print** and **Export** buttons to print the graph, or to export it as an image file.



- If the graph is acceptable, click **Finish** to apply the calibration to all the points in the porosity log.
- The calibrated log is saved in the workspace as (for example) **Porosity RHOB-calibrated**.

4.7 Permeability calculation

Calculation of permeability in CycloLog requires (1) a porosity log, and (2) some core permeability measurements.

The steps are the same as for **Calibrate Porosity**, above. That is:

- From the main menu bar, select **Petrophysics → Permeability**.
- In the **Calculate Permeability** dialog, select the porosity log to be used (and the **Top** and **Bottom** depth interval, if relevant).
- Click **Next**.
- In the **Permeability** dialog box, enter the **Depth** and **Permeability** values for each available core permeability measurement.
- Click **Calculate** to find the corresponding log porosity values.
- Click **Next**.
- The graph and regression equation show the resulting relationship between core permeability and log porosity: if this is acceptable, click **Finish**.
- CycloLog applies the equation to all log values (in the specified depth interval) and creates a new log called, for example, **Permeability from Porosity RHOB-NPHI**.

4.8 Water saturation calculation

Calculation of water saturation in CycloLog requires (1) a porosity log, and (2) the formation resistivity curve (or a deep resistivity log).

To run a water saturation calculation:

- From the main menu bar, select Petrophysics → Water Saturation → Water Saturation.
- The Calculate Water Saturation dialog box opens:

Calculate Water Saturation

$$S_w^n = \frac{a R_w}{\phi^m R_f}$$

Input logs

Well: Well A

Domain: Depth domain

Formation resistivity: ILD

Porosity: Porosity DT

Interval

Top: 3200

Bottom: 3663,8

Calculation parameters

Tortuosity factor: 0,62

Cementation exponent: 2,15

Water resistivity: 0

Saturation exponent: 2

OK Cancel

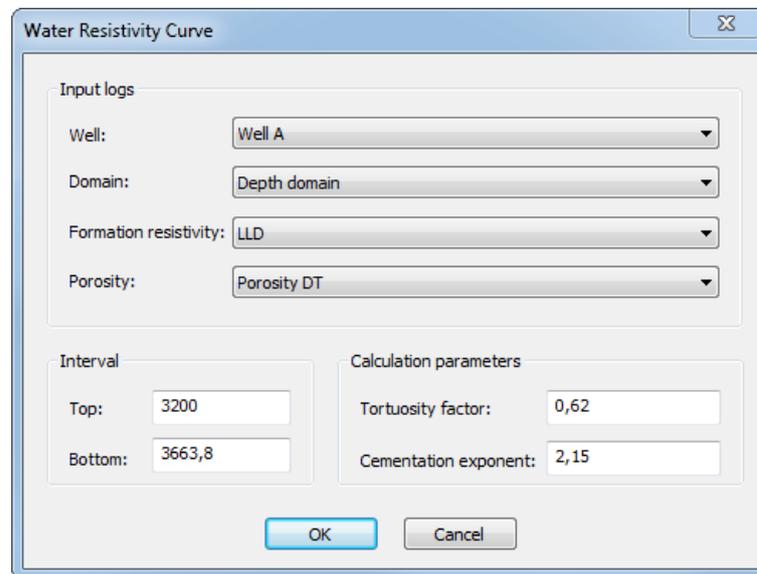
- The box shows the formula used to calculate water saturation.
- Under **Input logs**, select the **Well**, its **Domain**, the **Formation resistivity** log and the **Porosity** log to be used.
- Under **Interval**, enter the **Top** and **Bottom** depths of the interval of calculation.
- Add a non-zero value for the **Water resistivity**.
- Either accept the default values for the **Tortuosity factor**, **Cementation exponent**, and **Saturation exponent**, or enter your preferred values.
- Click **OK**.
- CycloLog calculates the new log, and saves it in the workspace as **Water Saturation Curve**.

4.9 Water resistivity calculation

Calculation of water resistivity in CycloLog requires (1) a porosity log, and (2) the formation resistivity curve (or a deep resistivity log).

To run a water saturation calculation:

- From the main menu bar, select **Petrophysics** → **Water Saturation** → **Water Resistivity Curve**.
- The **Water Resistivity Curve** dialog box opens:



- Under **Input logs**, select the **Well**, its **Domain**, the **Formation resistivity** log and the **Porosity** log to be used.
- Under **Interval**, enter the **Top** and **Bottom** depths of the interval of calculation.
- Either accept the default values for the **Tortuosity factor**, and **Cementation exponent**, or enter your preferred values.
- Click **OK**;
- CycloLog calculates the new log and saves it in the workspace as **Water Resistivity Curve**.

4.10 Generate petrophysical report

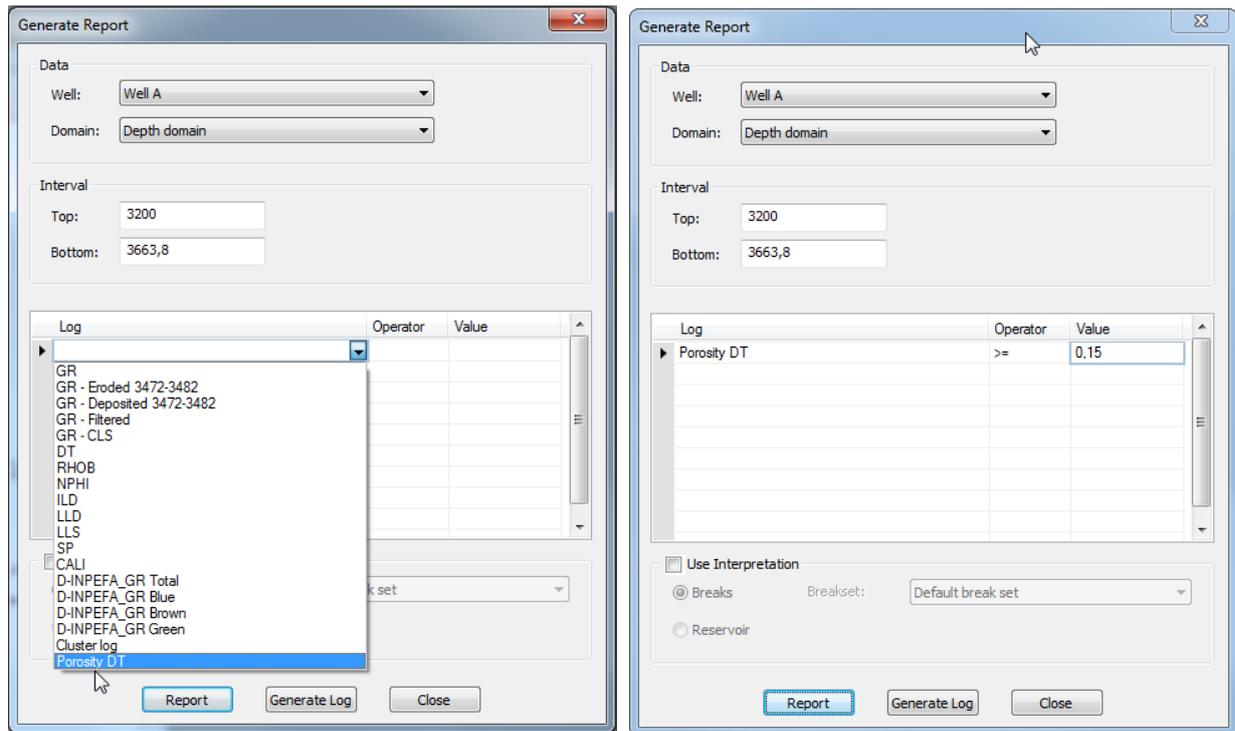
The **Petrophysical Report** function in CycloLog can be used to generate a simple N/G report, or other similar types of report.

The report can be generated for a total interval, or the total interval can be subdivided, the subdivisions being based on a pre-defined set of either **Breaks** (see Tutorial – Base Module, part 5), or **Reservoirs** (see Tutorial – Base Module, part 6).

To generate a **Petrophysical Report**:

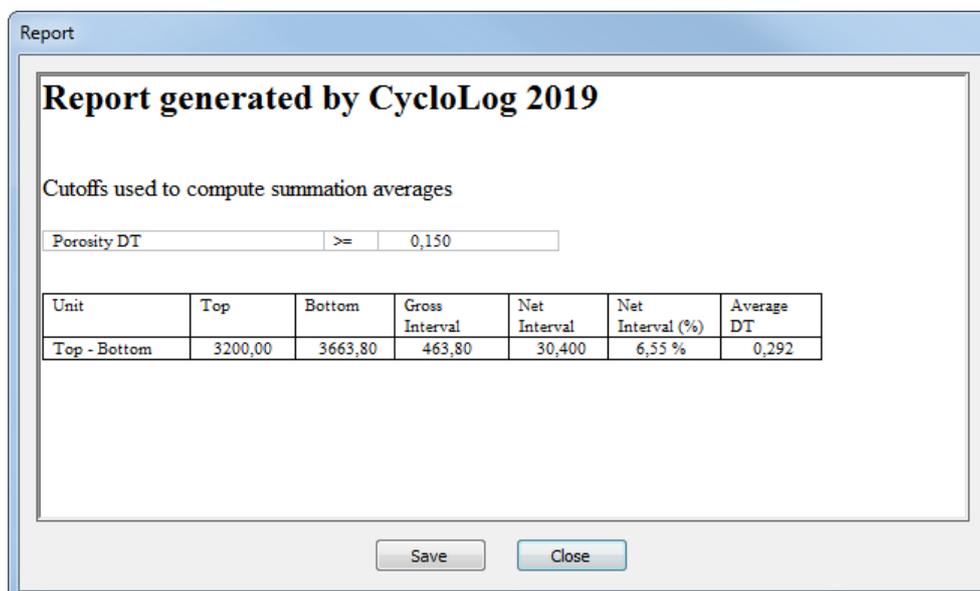
- Go to the main menu bar and select: **Analysis** → **Report**.

- The **Generate Report** dialog box opens:



In the example above, the analysis will look for all depths in the **Porosity DT** log for which the value is greater than or equal to 15.

- Specify the **Top** and **Bottom** depth interval for the analysis.
- Click a row under the column **Log**, to reveal a drop-down list.
- Select the log you wish to analyse.
- Click under **Operator** and select the operator to be used (>=, meaning **greater-than-or-equal-to**, in the example illustrated).
- Under **Value**, enter the target value (0,15 in the example).
- Click **Report**.
- The following window opens:



This shows the results of the analysis: for the specified depth interval, the criterion **Porosity \geq 15%** is satisfied in 30.4m out of the total of 463.8m, with an average N/G of 0.0655 in the net interval.

- Click **Save** to save these results to a file, then
- Click **Close** to close the report window.

The **Generate Report** dialog also offers a **Generate Log** button. This generates a simple log in which the value 1 indicates that the condition (e.g., Porosity \geq 15%) is satisfied at that depth, and 0 indicates that it is not satisfied. The log is added to the workspace, and is called **Report Log**.

This log can be used, for example, to colour a GR log to show the intervals in which the porosity is greater than 15%. (Open the GR log, open the properties pane, under **Log Fill** select **Fill with**. Select **Log** and then select the **Report Log** in the dropdown menu).

Part 5 - Total Organic Carbon (TOC)

5.1 TOC calculation method in CycloLog

The Total Organic Carbon (TOC) curve is calculated in CycloLog based on the method as described in Passey *et al.* (2009). This method, the $\Delta \log R$ technique, applies the overlaying of a porosity log on a resistivity curve. In their paper, a combination of the transit-time curve (sonic, in $\mu\text{sec}/\text{ft}$) and resistivity curve (in ohm) is used.

The following log combinations can be used in CycloLog:

- resistivity – sonic
- resistivity – neutron
- resistivity – density

Note that each log must be specified in the following units:

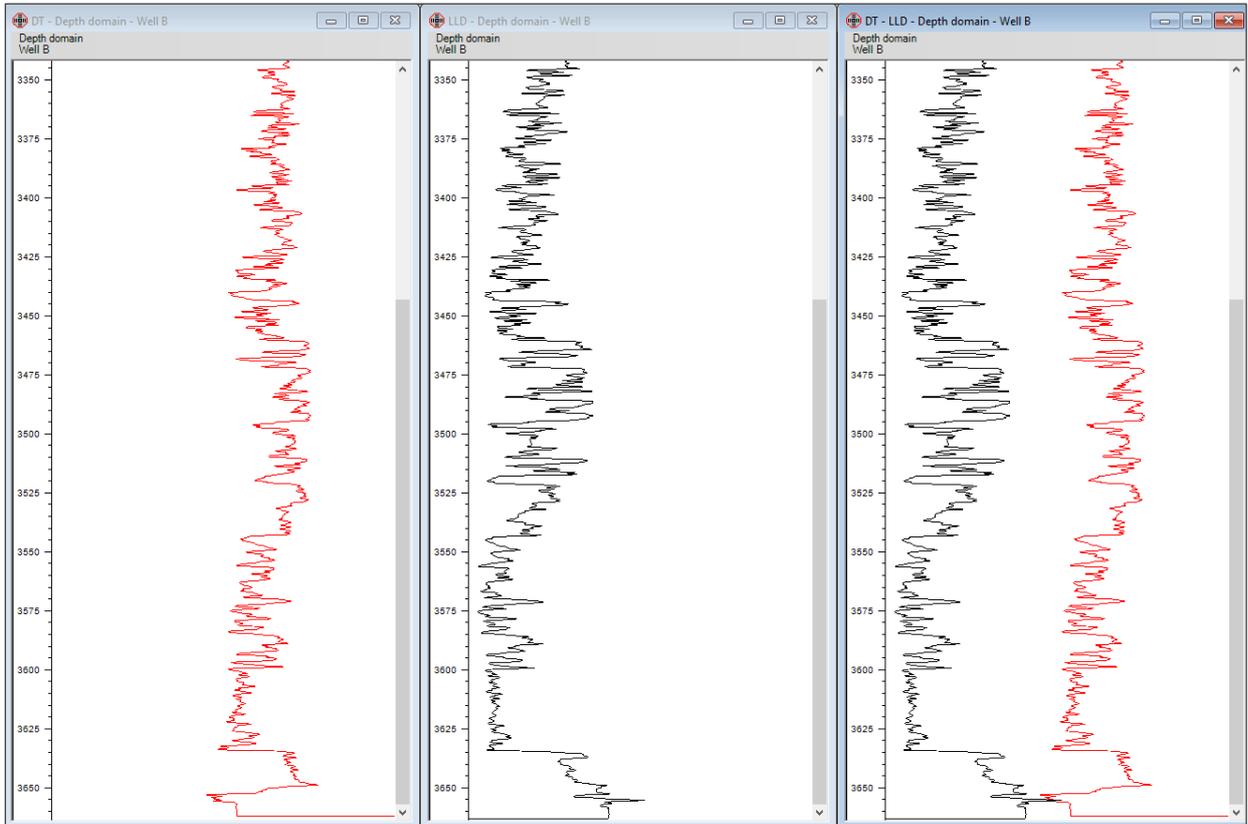
- Resistivity : ohm
- Sonic : $\mu\text{sec}/\text{ft}$
- Neutron : V/V (0-100)
- Density : g/cm^3

5.2 TOC workflow in CycloLog

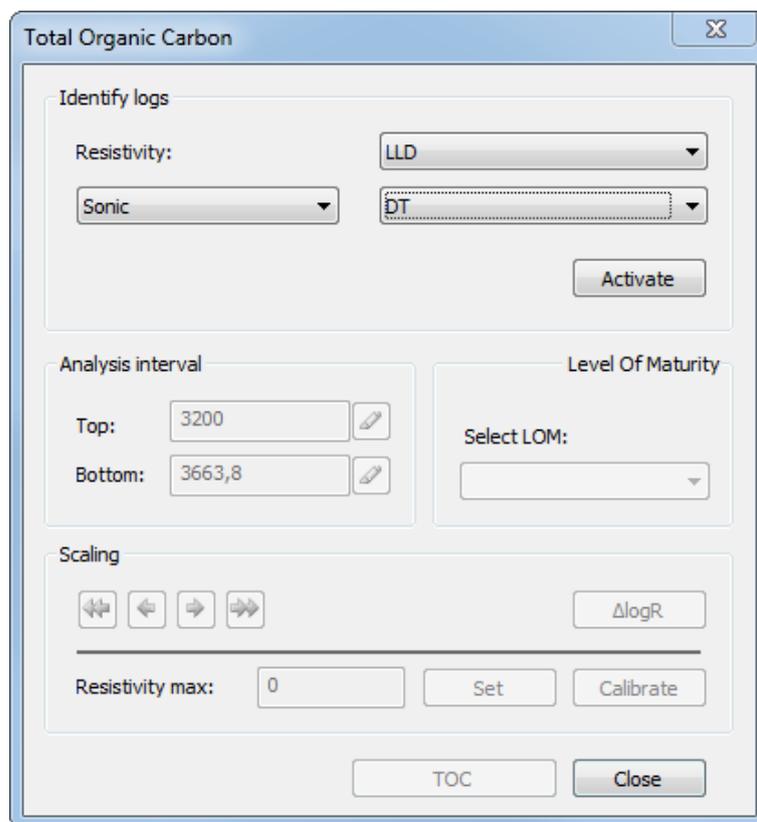
In this workflow, the resistivity and the sonic curves are used to calculate the TOC content in a well. The curves will be overlain and baselined in a fine-grained, 'non-source', rock interval. With the baseline established, organic-rich intervals can be recognised by separation of the two curves, which is the $\Delta \log R$. The $\Delta \log R$ is linearly related to TOC and is a function of maturity. Therefore, the maturity (in level of organic metamorphism units, LOM) is needed. If the LOM value is not known, it can be derived from measured vitrinite reflectance values (Hood *et al.*, 1975). The well should be subdivided into several intervals, if multiple (and different) levels of maturity are present.

To determine TOC, start with displaying the resistivity and the sonic curve in an overlay pane:

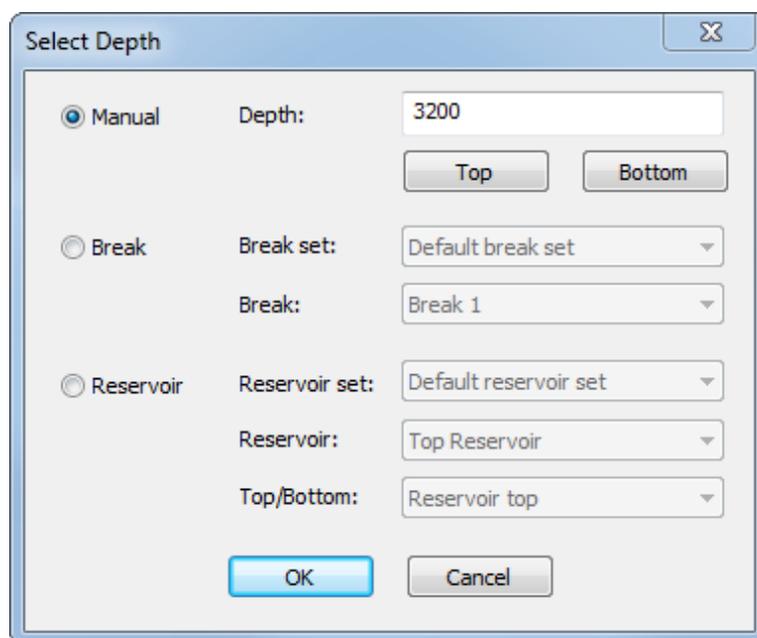
- In the main menu bar, select **View** → **Log Overlay**.
- Select from the **Log Overlay View** dialogue box the logs to be displayed: the **resistivity** and **sonic** logs.



- Right-click over the overlay pane and select **Analysis** → **Total Organic Carbon**. The Total Organic Carbon dialog window appears, showing four input fields.
- In the **Identify logs**, select the logs as used in the overlay pane: in the topmost input field select the **Resistivity** curve. In the lower left hand input field select one of the three log families (Sonic, Density, or Neutron), in this example the **Sonic** log, then select the corresponding curve in the right hand input field.



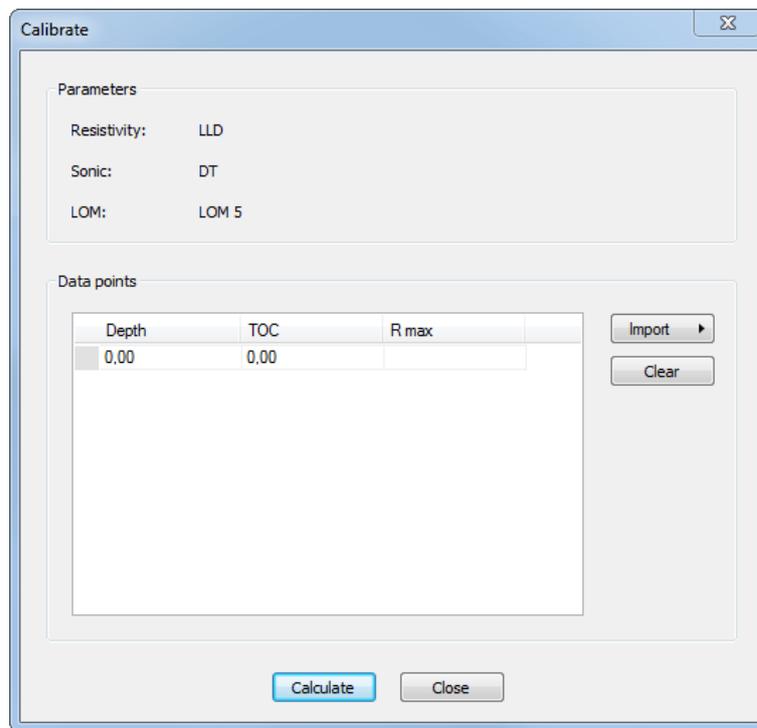
- Click on the **Activate** button.
- In the **Analysis Interval** field, click on each of the edit buttons next to the **Top** and **Bottom** input fields. The **Select Depth** dialog window appears.
- In this dialog window, three options for selecting the depth interval are available:



- In the **Manual** option, enter a **Depth** or click on the **Top** or **Bottom** button.
- The **Break** option allows you to select a depth interval delineated by breaks. When a **Break set** is selected, all breaks within the set are listed in the menu below. Choose the desired **Break**.
- The **Reservoir** option allows you to select the top or bottom of a reservoir interval. When a **Reservoir set** is selected, all reservoirs within the set are listed in the menu below. Choose the desired **Reservoir**. In the **Top/Bottom** selection field, choose the Reservoir top or bottom for the desired depth interval.
- After you have finished with the depth interval selection, click on the **OK** button.
- Prior to the **Scaling**, go to the **Level Of Maturity** field and a value in the **Select LOM** field.

In the **Scaling** field, you can calculate the TOC curve. This can be done in two ways:

- The first way uses a calibration interval from the two overlay curves. In an interval where the two curves overlay, it is assumed that this is a non-organic clay rich interval, and is used to calibrate the TOC calculation:
 - Use the green arrow buttons to shift the two curves over each other.
 - Click the **Δ log R** button, the separation between the two curves is calculated and added to the workspace.
 - Click the **TOC** button, the level of maturity is used to convert the separation between the two curves into a TOC curve which is added to the workspace.
- The second way uses TOC measurements for calibrating the TOC curve:
 - Click on the **Calibrate** button. The **Calibrate** window appears where you can import the measured TOC data points.
 - Click the **Calculate** button in the Calibrate window. The scaling value for the resistivity curve is calculated. Close the window.
 - Back in the Scaling box in the Total Organic Carbon window, determine an average resistivity scaling value and fill this value in the **Resistivity max** field.
 - Click on the **Set** button. The scaling of the curves in the overlay pane is adjusted according to your settings.
 - Click the **Δ log R** button, the separation between the two curves is calculated and added to the workspace.
 - Click the **TOC** button, the selected level of maturity is used to convert the separation between the two curves into a TOC curve.



References

Hood, A., Gutjahr, C. C. M., and Heacock, R. I., 1975. Organic metamorphism and the generation of petroleum: AAPG Bulletin. V. 59, No. 6, P 986-996.

Passey, O. R., Creaney, S., Kulla, J. B., Moretti, F. J., and Stroud, J. D., 1990. A practical model for organic richness from porosity and resistivity logs: AAPG Bulletin. V. 74, No. 12, P 1777-1794.