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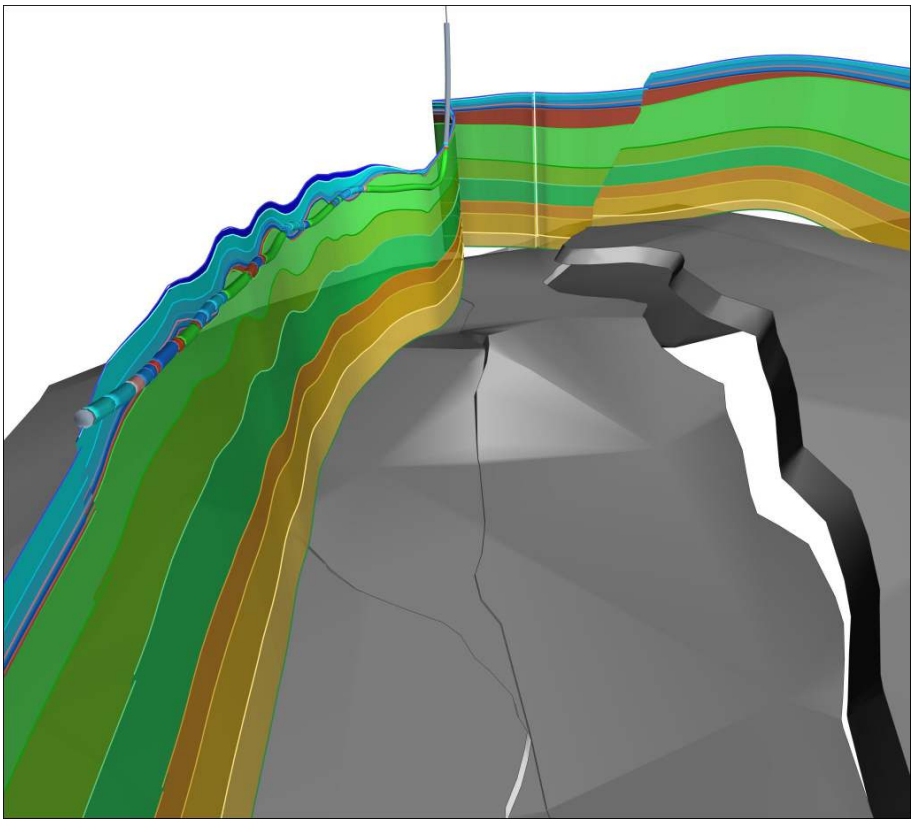
Note

COHIBA User Manual Version 6.0



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Abstract

This user manual describes the COHIBA surface modeling software. It consists of:

Part I	**Introduction:**	Basic ideas and terminology
Part II	**User manual:**	Usage, input data and results
Part III	**Tutorials:**	Special topics such as volumes, simulation and faults
Part IV	**Reference manual:**	Descriptions of all COHIBA model file elements
Part V	**Theory:**	Methods used by COHIBA
Part VI	**Appendix:**	Release notes, known issues, references, list of acronyms, tables and figures, and an index

Advanced topics and technicalities are marked by the warning symbol ⚠ in the right margin. COHIBA model file elements marked by this warning symbol should be used with some care.

The latest version of this document is available at: www.nr.no/COHIBA. For COHIBA support contact Pal.Dahle@nr.no or Ariel.Almendral.Vazque@nr.no.

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The front page shows two fences along well paths on top of a faulted surface on the Valhall carbonate field in the North Sea. The illustration is made by Ingrid Aarnes. We thank Aker BP for permission to publish the illustration.

Keywords	mapping, surfaces, kriging, depth conversion, prediction, deterministic, stochastic simulation, horizontal wells, gross rock volume, spill point, well path uncertainty
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Part I
Introduction

1 What is COHIBA?

COHIBA is a computer program that provides a fast and accurate method for generating a set of deterministic surfaces using prediction, or a set of random realizations of the surfaces using stochastic simulation. COHIBA can use information from:

- Surface observations in wells (well points)
- Horizontal well paths with zone logs
- Travel time maps
- Interval velocity models
- Geological interpretation of depositional thickness
- Spill point depth

COHIBA uses the available data in a consistent manner to minimize the uncertainty. The accuracy is further improved by linking together all surfaces in a consistent multi-layered model.

COHIBA provides two ways of evaluating uncertainty:

- A local depth uncertainty at every surface location can be calculated.
- Stochastic (Monte Carlo)surface realizations can be generated. A set of these span the uncertainty range.

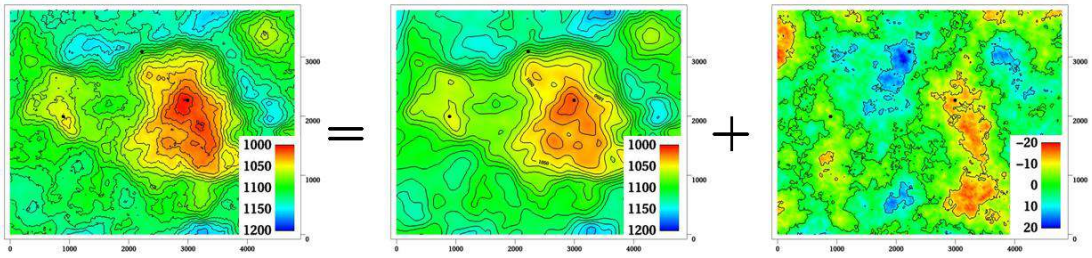
COHIBA can update uncertain well paths to ensure consistency with the surfaces. This is done by modifying the true vertical depth (TVD) values along the well paths.

COHIBA can calculate the volumes between surfaces and hydrocarbon contacts.

1.1 COHIBA basic idea

Surfaces are modeled as a sum of a *trend* and a *residual*. The trend captures the large scale shape of the surface and the residual captures (small) deviations between the trend and the unknown *true* surface. This is illustrated here:

$$\text{Depth} = \text{trend} + \text{residual}$$

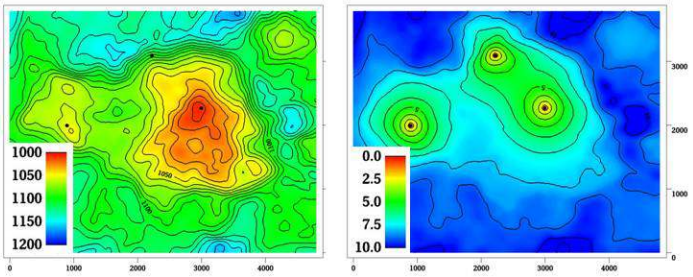


The trend can be a single known map or a linear combination of many known maps. The trend determines the main shape of the surface so the choice of trend maps is very important. The residual is usually small compared to the trend. The residual is specified by a residual uncertainty (standard deviation (SD)) and a spatial continuity determined by a variogram. The residual is in principle unknown and random.

COHIBA will adjust the specified trends to match well data. The remaining difference will be described by the residual. The residual will be irregular and random for stochastic simulation, just like the figure above. For deterministic surfaces, the residual surface is a smooth interpolation of the residuals at the wells. This is illustrated on page 16.

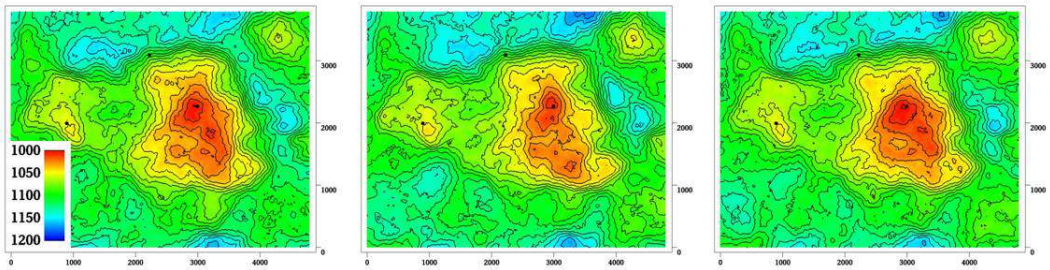
1.2 COHIBA main features

Deterministic surfaces. COHIBA finds the most likely surface given all available data. This is called prediction of surfaces and is typically used for well planning. The prediction uncertainty (SD) can be calculated and displayed as a map. A predicted deterministic surface with corresponding prediction uncertainty is illustrated here:



Note how the prediction uncertainty drops to zero at the three well points.

Stochastic surfaces. COHIBA can generate one or many stochastic realizations that are consistent with all available data. The stochastic realizations are generated using stochastic simulation. Stochastic simulation is sometimes called Monte Carlo simulation. Stochastic realizations are typically used for sensitivity, uncertainty and rock volume studies. Three stochastic simulations are illustrated here:



The average of a large set of stochastic simulations will approximate a deterministic surface obtained using prediction[1]. The SD of a large set of stochastic simulations will approximate the prediction uncertainty.

Stochastic simulated surfaces should look like the true surface. The details are of course not correct since they are unknown and random, but the irregularity should have the same geometric properties as the true surface.

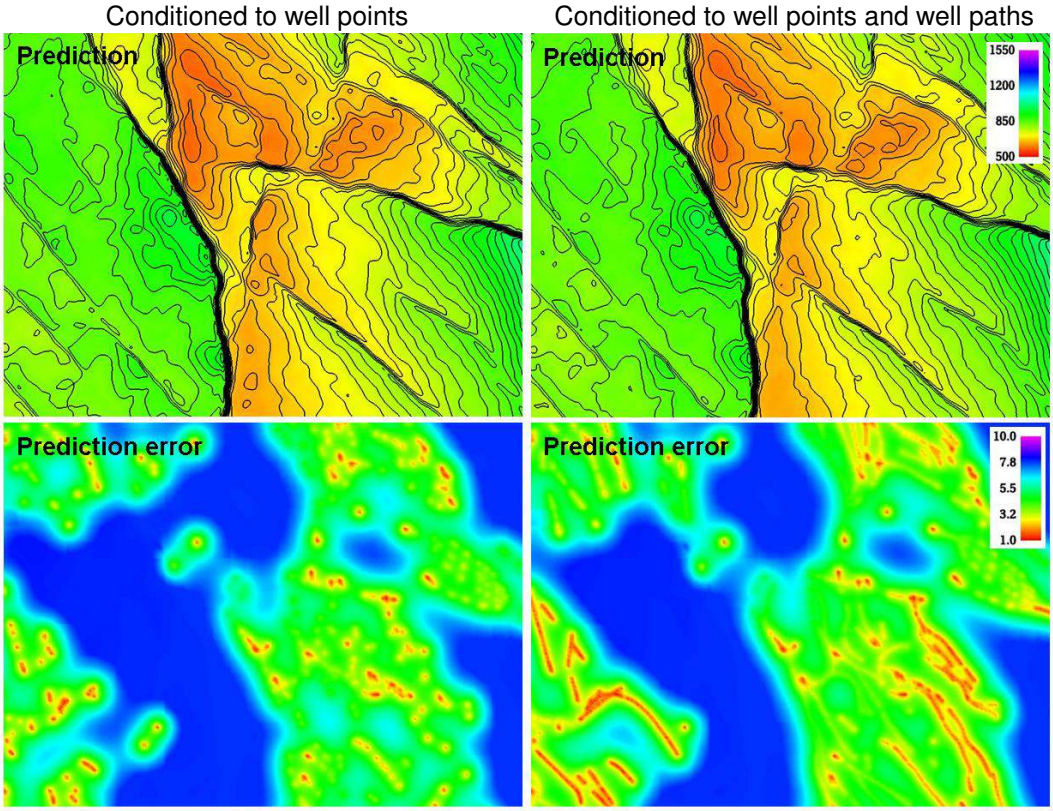
It is impossible to see where the stochastic simulated surfaces are conditioned on well data provided the specified residual is consistent with the well data. That is, the specified residual has a realistic uncertainty. COHIBA provides an estimate of this.

It is common to say that the realizations from stochastic simulations are *equiprobable*. This is true in the sense that they all have probability zero. However, they are not equally *likely*. It is in principle possible to calculate how likely each simulated surface is. The most likely surface is the deterministic surface obtained using prediction. It is irrelevant how likely a simulated surface is. For practical purposes they can be treated as having identical statistical properties.

It is possible to add *acceptance criteria* to the simulated realizations. These are typically related to restrictions on the spill point of the surfaces. If the surface fail to meet the acceptance criteria, the realization is rejected, and new realizations are generated until the acceptance criteria is fulfilled.

1. See Section 19.3 for a discussion on why the average will be different from the deterministic surface.

Horizontal wells. COHIBA ensures that surfaces are correctly positioned according to zone logs in horizontal wells. COHIBA uses an advanced technique where surfaces are conditioned to constraints along the well paths. This ensures correct location of surfaces and reduction of the surface uncertainty along the wells. Here is an example to show the effect of using information from well paths:



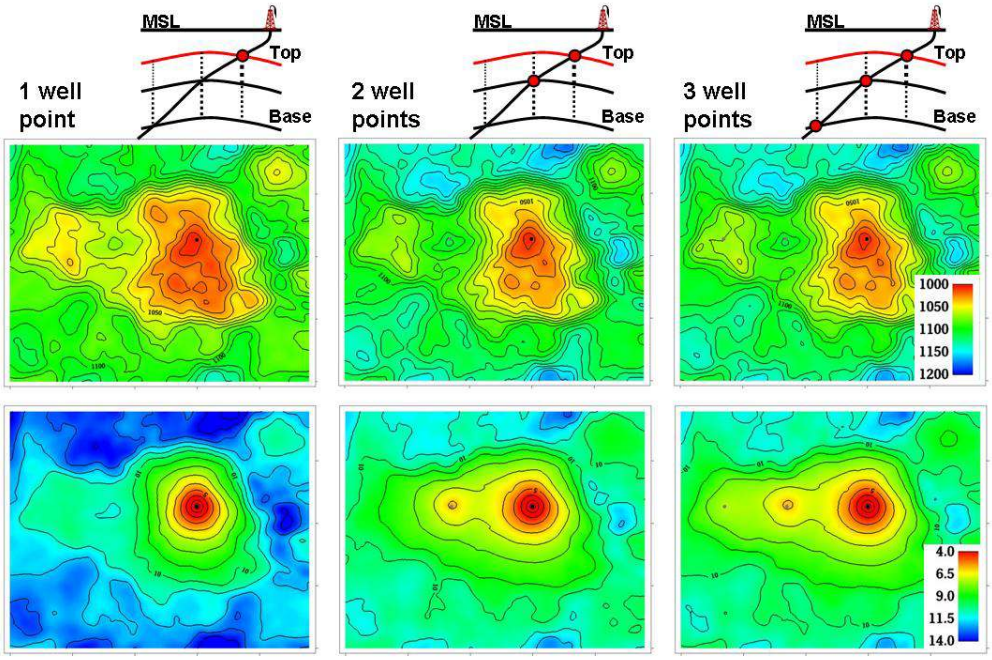
The two upper figures are the deterministic surfaces and the two lower figures are the corresponding prediction uncertainties. The change in the deterministic surfaces are significant and the prediction uncertainty has been significantly reduced along the well paths.

This approach works in complex situations with many surfaces and layers and will ensure correct results even when well paths follow very thin layers.

If a well path TVD uncertainty is specified, then COHIBA will modify the TVD values along the well path to improve consistency and accuracy of well paths and surfaces. As well path TVD uncertainty increases along the well path modifications are typically larger at the well toe than at the well heel. Modifications are done such that well paths remain smooth. This also applies to multilateral wells.

Multi layer models. COHIBA considers models for all surfaces (reflecting and non-reflecting) in a stratigraphic model *simultaneously*. This has two nice implications:

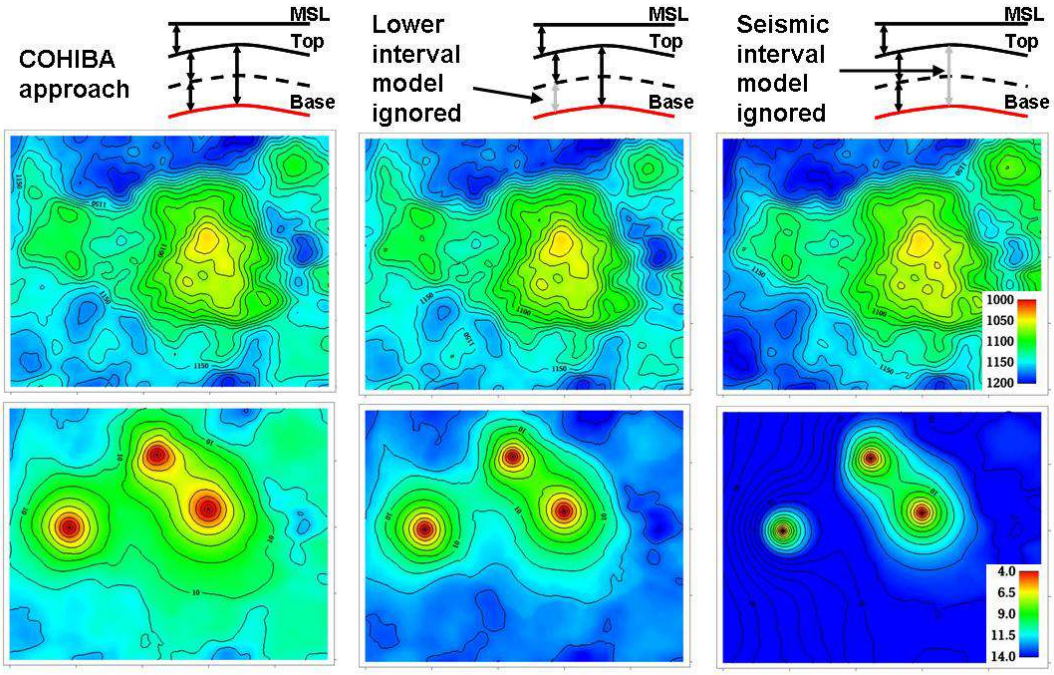
1. A particular surface is constrained by observations from surfaces above and below. This improves precision and reduces the uncertainty. The impact of observations below a surface is illustrated here:



The illustration shows the top surface (and its prediction uncertainty) from a model with three surfaces. This is the red surface in the schematic cross sections above the contoured maps. The three columns show how the deterministic (prediction) surface and prediction uncertainty are modified as a deviated well is drilled into the two lower surfaces. The lateral location of the well points are easily seen on the prediction uncertainty maps. It is clearly seen that the prediction uncertainty is reduced by the observations of deeper surfaces.

2. Sufficient well data are well points and zone logs. Unobserved interval thicknesses in deviating or horizontal wells are not needed.

Ambiguous multi layer models. It is sometimes unclear when it is best to add layers from above or from below. This is solved by specifying multiple models and let COHIBA automatically combine the alternatives so that the precision is optimized. A typical example is a layered reservoir outlined by two accurate seismic reflectors. COHIBA solves this by automatically fitting the layers inside the envelope of seismic reflectors. This is illustrated here:



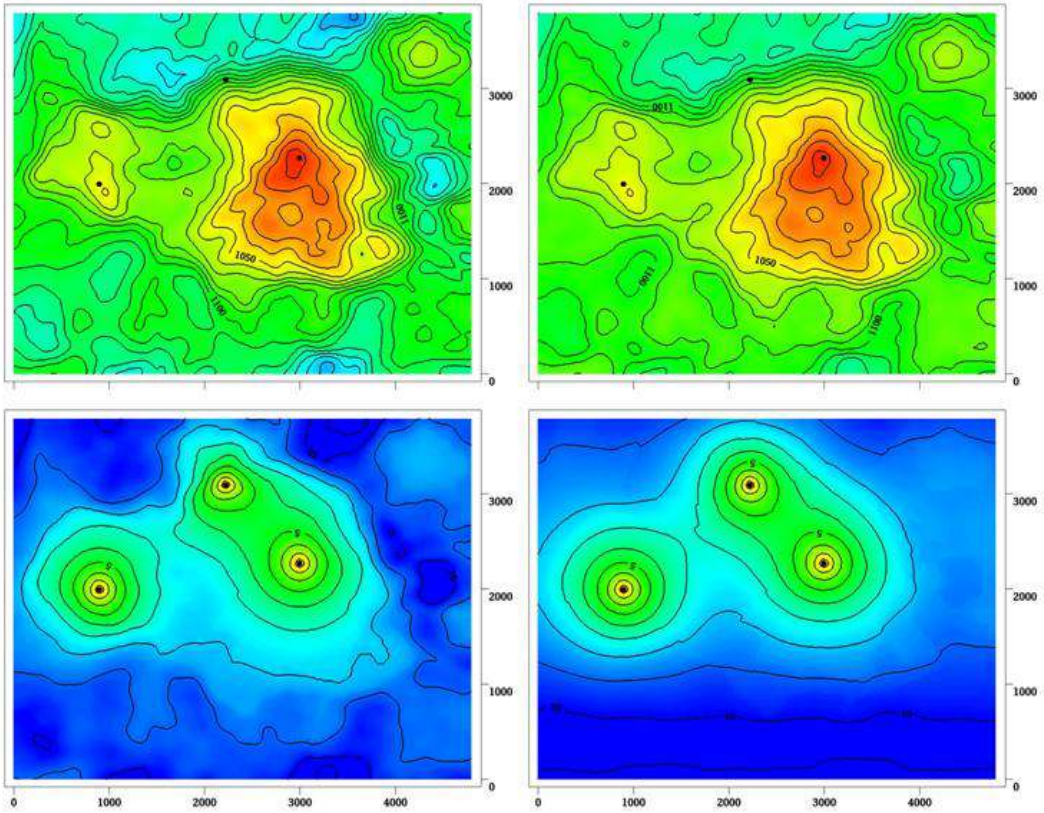
The illustration shows the base surface (and its prediction uncertainty) from a model with three surfaces. This is the red surface in the schematic cross sections above the contoured maps. The top and base surfaces are seismic reflectors. The intermediate surface (dashed line) is not a seismic reflector. The left figures show how COHIBA handles this situation. The two figures in the middle show a typical solution where the model for the lowest layer is ignored. The figures to the right shows what happens if the information from the seismic travel times between the top and base surfaces is ignored.

Section 11 includes a discussion of multiple models.

Depth conversion. Seismic reflectors are described using interpreted travel time maps, often using two-way travel time (TWT) in milliseconds, and an interval velocity model for each interval. The interval velocity model can be fitted to depth observations taking prior information and spatial correlation into account.

Example of two alternative depth conversion models:

$v(x, y) = a + b \cdot t(x, y)$ $v(x, y) = a + b \cdot y$

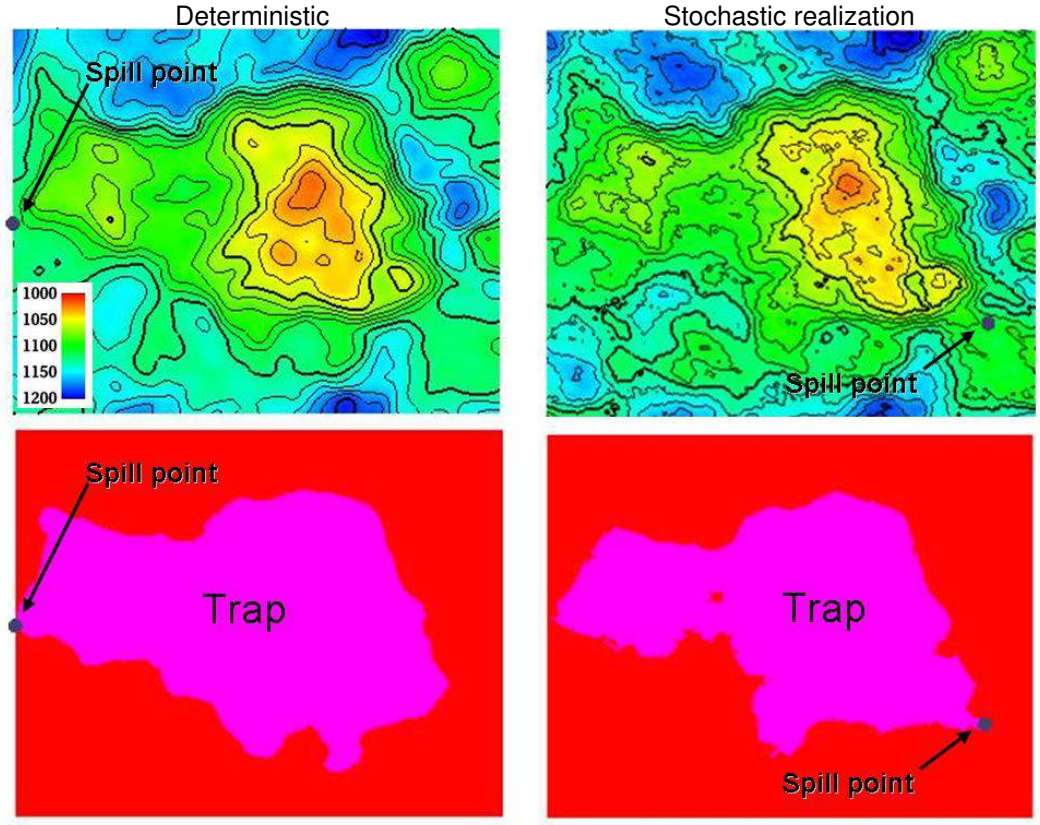


The left deterministic surface and prediction uncertainty are obtained using an interval velocity that increase with the travel time, $t(x, y)$. The right figure shows a result using a north-south interval velocity trend (depend on the y-coordinate). Both interval velocity trends are fitted to the three well points.

Interval velocity maps. Interval velocities from e.g. stacking velocities can be used as the interval velocity model in the depth conversion.

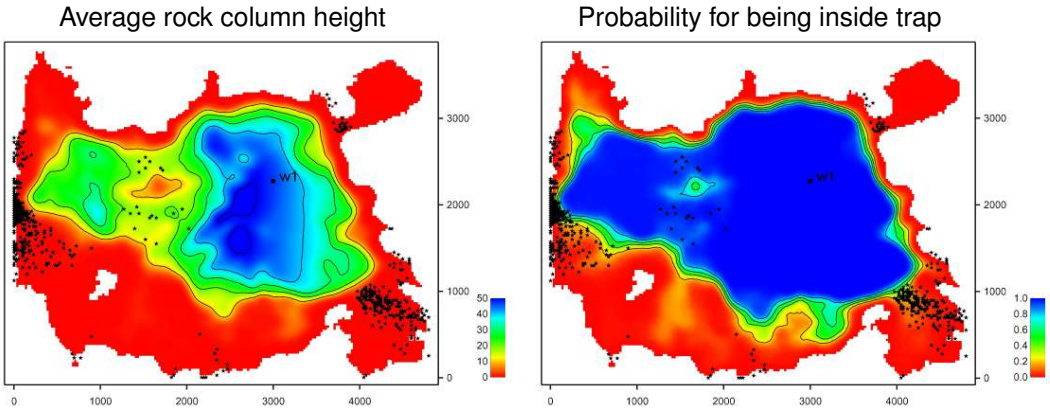
Isochores. Reservoir layers are typically described by smooth isochores or trends. Isochores are fitted to depth observations taking prior information and spatial correlation into account.

Spill point detection. Spill point and the corresponding trapped area can be found for any surface. Spill points can be detected in a single imported surface or on any surface generated by COHIBA. Here is an example of a spill point and the corresponding trap:



The spill point is detected and written to file (x-, y-, and z-coordinate). Also the trapped area can be written to an output grid file. Note that the spill point for the predicted and the simulated surfaces can be quite different.

Volume calculations. The gross rock volume between two surfaces and two hydrocarbon contacts can be calculated. The results are volumes in cubic meters and rock column maps. It is possible to ensure that the hydrocarbon contact is consistent with the spill point and that only trapped or connected volumes are considered. Average maps from multiple stochastic realizations are generated:



These maps are the average of 1000 realizations. The small black dots are the 1000 different spill points. For an extensive discussion of the possibilities see Section 10.

1.3 COHIBA methodology

Deterministic surfaces are obtained using *kriging* for prediction, and stochastic simulation (Monte Carlo) is used for creating alternative realizations. The conditioning data are the well data while seismic data and isochores can be included as trend maps. Kriging with trend maps fitted to well points are called *universal kriging* or *kriging with trends*. COHIBA also offers *Bayesian kriging* which is more robust when few well points are available. For more information on kriging and stochastic simulation see for instance the books by Isaaks and Srivastava (1989), Cressie (1993), Chilés and Delfiner (1999), and Lantuéjoul (2002). COHIBA uses multiple linear regression (see e.g. Weisberg, 1985) to fit the trends to well points. Spatial correlations are taken into account so that the information from closely located well points are given less importance than well points scattered evenly in the area.

Different surfaces are *covariates* so cokriging is used if more than one surface is considered. The interval velocities are also correlated to the surfaces. Therefore surfaces and interval velocities are also covariates.

The residuals (differences between data and trends) are assumed to be *Gaussian random fields* allowing a fast and accurate fast Fourier transform (FFT) stochastic simulation technique. Experience has shown that the Gaussian assumption is reasonable as long as well points are consistent with trends for isochores and interval velocities.

The basic methods for handling several surfaces and intervals simultaneously were developed by Abrahamsen (1993). The extension to handling alternative ways of combining layers to obtain a surface was published by Abrahamsen (2005). The original idea on how to constrain the surfaces to zone logs along well paths was published by Abrahamsen and Benth (2001). COHIBA combines all these ideas into a consistent and robust framework for accurate surface prediction.

Spill point detection can be applied to any surface in the model or to a single imported surface. The algorithm is described in Abrahamsen et al. (2000). The algorithm requires a starting point known to belong to the trap.

Some theoretical details are supplied in Part V.

1.4 COHIBA input data

Depending on the situation, the user can choose to use the following input data:

Well points. Locations of intersections between well paths and surfaces.

- It is possible to specify a well point TVD pick uncertainty. This is the vertical component of the pick (measurement) uncertainty along the well path.

Well paths with zone logs. Well points are extracted and surfaces will be adjusted according to the zone log information. This includes ensuring consistency with horizontal wells.

- It is possible to specify the well path TVD uncertainty. This is the vertical component of the well path *positioning* uncertainty.

Travel time maps. These are interpreted travel time maps for seismic reflectors.

- Uncertainty in the interpreted travel time maps either as a constant value (say 4 ms) or as a map describing the interpretation in different areas.
- Variograms describing the spatial correlation of the uncertainty for each travel time map.

Interval velocity models:

- Interval velocity trend. Typical example is $v(x, y) = a + b \cdot t(x, y)$, where a and b are trend coefficients, and $t(x, y)$ is the seismic travel time at location (x, y). (Any linear function of maps can be used.)
- Interval velocity maps.
- Uncertainty in interval velocities either as a constant value or as a map.
- Variograms describing the spatial correlation of the uncertainty for each interval velocity.

Interval thickness models:

- Interval thickness trend. Any linear trends of coordinates and known maps are possible. For instance: $\Delta z(x, y) = a + b \cdot x + c \cdot y + d \cdot m(x, y)$, where a, b, c, and d are trend coefficients and $m(x, y)$ is any known map.
- Interval thickness trend using an isochore map: $\Delta z(x, y) = a \cdot m(x, y)$, where $m(x, y)$ is a user specified isochore map. Note that pinch outs are possible so $m(x, y)$ can be zero in large areas.
- Uncertainty in interval thickness either as a constant value or as a map.
- Variograms describing the spatial correlation of the uncertainty for each interval thickness.

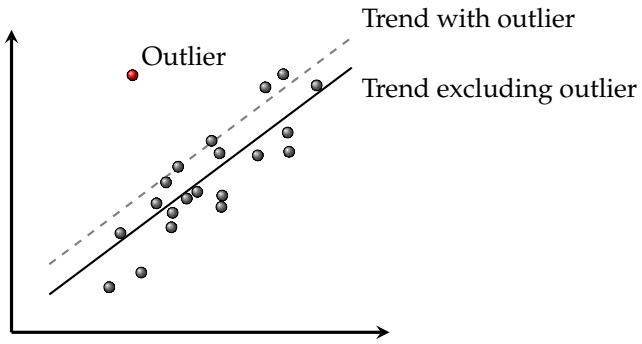
Ordering of surfaces. The surfaces in the model must be ordered according to their depth. This makes it possible to check if well observations are in correct order. Moreover, this ensures that erosion, onlap, and pinch outs, can be handled properly. Free surfaces (Section 13) do not have any ordering.

1.5 Quality control

COHIBA has methods for performing quality control (QC) of the input data. Conflicts and ambiguities in the data are handled automatically and reported, so that actions can be taken when necessary. QC includes:

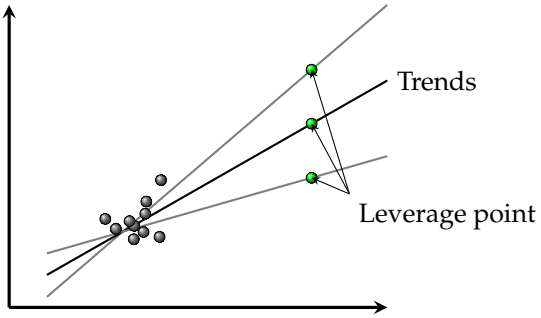
Model conflicts. Well points that are in conflict with the model are flagged. Well points are removed if the conflict may corrupt the results.

- *Outliers*. These are well points that fit the model assumptions poorly. This can be caused by errors in the well data or by inconsistencies between well data and model assumptions. The red point in the following figure could be an outlier:



  Outliers will often have significant impact on the trends and cause "bulls eyes" in surfaces. Outliers are classified as *outlier*, *severe outlier*, *error* or *extreme error* depending on severity. Outliers are tagged, severe outliers are given a well point TVD pick uncertainty, and errors and extreme errors are excluded from all calculations. See Section 18.3.5.1 for details on how outliers are classified.

- *Leverage points*. These are data that *could* be outliers but influence the trend model so strongly that they appear to fit nicely. The following picture shows how a leverage point (the green point) will influence the regression line:



Conflicting observations. A common problem is that two or more well points are at the same location. There are two ways to handle this, depending on the situation:

1. If two well points are identical (same well, same surface, same TVD), only one well point is kept in the calculations.
2. If two well points are identical except for different TVD values they are retained but given a well point TVD pick uncertainty determined by their TVD difference.

Detected outliers, leverage points, and conflicts are flagged for inspection. In severe cases COHIBA removes data that otherwise would corrupt the surfaces. The results from the COHIBA QC are reported in several files. The most important ones are the COHIBA log file and `wellpoints.csv`. The COHIBA output is described in Section 7.

1.6 Robust estimation of trends

The trends are fitted to well points using (generalized) linear regression. Outliers and leverage points may corrupt the fitted trends. Therefore, outliers that are classified as errors or extreme errors are removed prior to the fitting of the trend. This is done in an iterative way: First the trends are fitted using all well points and outliers are classified. Extreme errors are removed one-by-one and the trends are re-fitted to the remaining well points. This is repeated until there are no extreme errors left. Finally, all the remaining well points classified as errors are removed and the trends are re-estimated.

The iterative method of fitting the trends ensures a complete removal of inconsistent data so that trends becomes reasonable. Note that well points classified as errors or extreme errors are also removed from the kriging step where the trends are locally fitted to the well points.

Well points removed from the estimation are flagged and reported. It is recommended to inspect the log files provided by COHIBA to check for errors and inconsistencies. The log files can be read into and analyzed in e.g. Excel..

1.7 Platforms and portability

COHIBA has been developed and tested on 64 bits Linux and Windows. 32 bits operating systems are not supported. We recommend Windows 7 and later and Red Hat Enterprise Linux 5 or later, but Windows XP/Vista and any Linux distribution using kernel 2.6 or newer should work.

In this manual, directory paths are specified using the slash: `/`. On Windows systems the backslash, `\`, is the normal directory separator used in paths. COHIBA will usually accept both alternatives on both platforms. This is slightly dependent om context since Windows usually, but not always, accept both directory separators.

1.8 The name

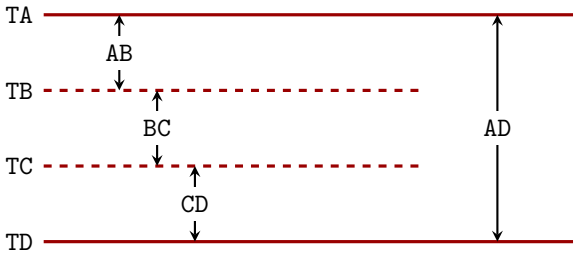
COHIBA is an acronym for **Co**rrelated **H**orizon **I**ntervals and **B**ayesian **A**nalysis. But more important it is a nice word that is easy to remember. Cohiba is also known to be the most luxurious Cuban cigar. The previous versions of COHIBA were called HORIZON.

2 Terminology and concepts

This manual contains a lot of terminology. Some of these concepts, such as *interval*, are commonly used words but they have specific meaning in this document. This section tries to define exactly what is meant when certain words are used in this manual.

Surface. The surfaces in COHIBA are a set of depth surfaces in a specific depth order. The depth may coincide in pinch out situations. Every surface has a unique name used to identify the surface and data that belongs to it. A surface can be a *seismic reflector* with an associated travel time map. Surfaces can be *erosive* to surfaces below, and *onlapped* by surfaces above.

Interval. An interval in COHIBA has a top surface and a base surface. The top and base surfaces are two arbitrary surfaces but they must be in correct depth order (top above base). Any surface can be both a top surface and a base surface in several intervals. A common example is to have one interval spanning the whole reservoir and a set of smaller intervals spanning each individual reservoir zone. This is illustrated here:

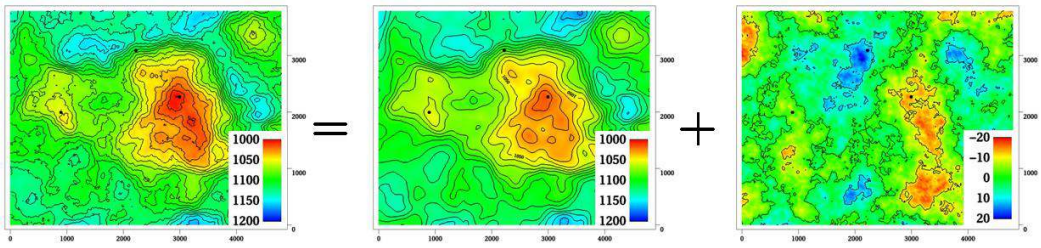


The figure shows a schematic cross section of surfaces (`TA`, `TB`, `TC`, `TD`) and intervals (`AB`, `BC`, `CD`, `AD`). Note that surface `TA` is the top for intervals `AB` and `AD`, and surface `TD` is the base of intervals `AD` and `CD`.

Intervals are the most important building blocks in COHIBA. Surfaces are obtained by adding (or subtracting) the relevant intervals above (or below). The depth to any surface is the sum of interval thicknesses. The user must specify the depth sequence of the surfaces, the top and base surface for each interval, and how to build the interval thickness models. From this information, COHIBA knows how to assemble the intervals to obtain the surfaces in the best possible way.

Model. A model in COHIBA means a *stochastic model* for the intervals and the surfaces. The model is made up of two parts: The trend and the residual. Trends describe large scale behavior whereas the residual describes variations around the trend on a smaller lateral scale (typically less than 2000 m). This is illustrated by the following picture:

Depth = trend + residual



This trend is obtained from a seismic travel time map and a model for the interval velocity trend. The residual is a stochastic simulation of a possible realization of the mismatch between the trend and the real depth to the surface.

Given the model *and* the available data, COHIBA can predict or simulate the depth to surfaces.

Trend. The trend for a thickness can be constructed as a linear combination of known trend maps such as

$$\Delta z = a \cdot 1 + b \cdot x + c \cdot y + d \cdot m(x, y).$$

The three first trend maps, 1, x, and y, are simple, but the last trend map, $m(x, y)$, could for instance include a sedimentological interpretation of the depositional thickness. The values a, b, c, and d are called *trend coefficients*.

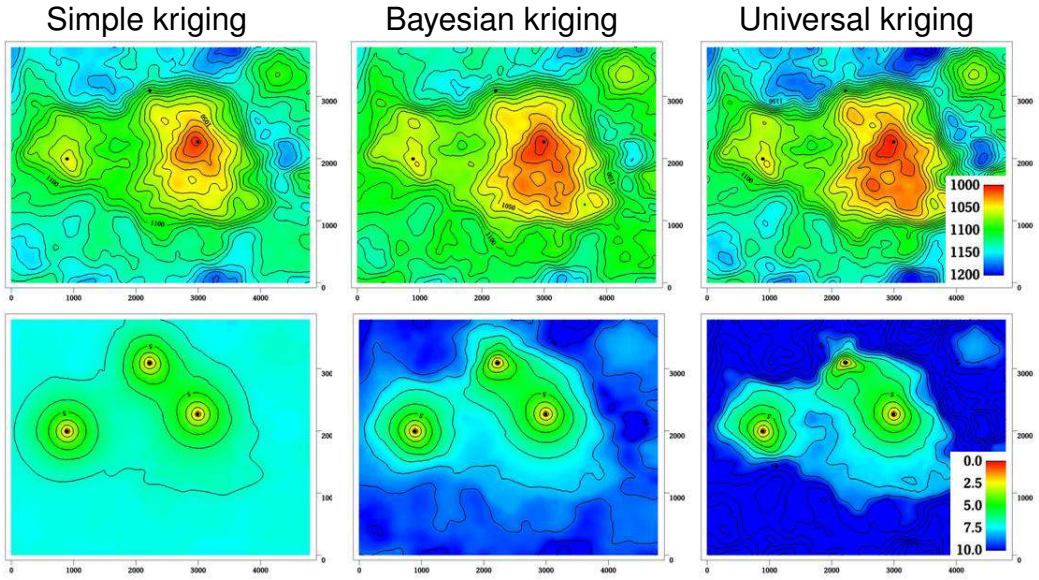
Similarly, interval velocity trends are used in combination with travel time maps for seismic depth conversion.

COHIBA supports any number of trend maps in the linear combination. But, most trends are quite simple and usually contains one or two trend maps.

Trend coefficients. The trend coefficients are assumed to have a Gaussian distribution. COHIBA offers three options of determining the values of the trend coefficients:

1. COHIBA can adjust the trend coefficients to the well points using linear regression by minimizing the generalized least squares (GLS). This is similar to ordinary least squares but it takes into account the variation in precision of the well observations and their spatial clustering. This approach requires that there are enough well points. Otherwise, the estimation might fail or give very uncertain results. This option amounts to using *universal kriging*.
2. The user can specify the trend coefficients. This amounts to *simple kriging*.
3. COHIBA can make a balance between a *prior specification* by the user and the estimates obtained from adapting the trend coefficients to data using linear regression. This is the recommended approach since it handles few (even zero) well points and will approach universal kriging if there is a lot of well points. This approach is called *Bayesian kriging*.

The differences between the three ways of specifying the coefficients and the corresponding kriging types are illustrated here:



The upper row contains the surface depths and the lower row the corresponding prediction uncertainty. There are two trend coefficients in this example that corresponds to surface

depth and surface curvature respectively. There are only three well points in this example and that makes it difficult to estimate the coefficients accurately. In particular the trend coefficient determining the curvature is very uncertain. This is clearly seen on the prediction uncertainty for universal kriging. The opposite extreme is simple kriging where the trend coefficients are assumed to be known. Bayesian kriging is a balance between the two extremes. Universal kriging is unbiased and will perform better with more well points. Simple kriging will adapt locally to additional well points but the trend coefficients initial prior guess will not be modified by additional well points.

The user must specify a prior distribution for the trend coefficients. This amounts to specifying the prior mean values (expectation) and the prior uncertainty (SD) for each trend coefficient. The prior specifications are not used by the universal kriging approach. However, it is very important to always specify reasonable values for the prior mean values because these are used when evaluating depth uncertainties caused by travel time uncertainty and interval velocity uncertainty.

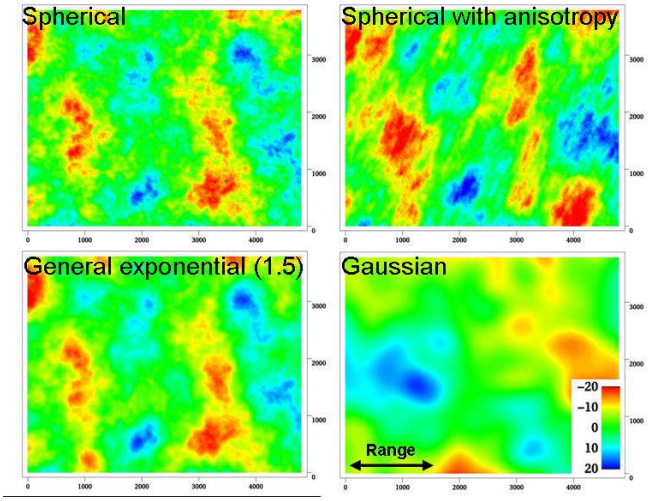
Trend map. The individual trend map(s) must be chosen by the user. This is where the geophysical and geological knowledge enters. Good choices of trend maps will reduce the residual uncertainty and therefore improve precision. The trend maps can be a simple constant (say 200 meters) or complex maps related to geophysical measurements and geological interpretations.

Residual. The residual is added to the trend to capture the difference between the trend and reality. The residual is assumed to be a *Gaussian random field* with known properties that must be specified by the user. The properties include a variogram (spatial correlation function) and an uncertainty (SD). The variogram determines the continuity and smoothness of the residual whereas the uncertainty is a measure of how much we believe in our trend. The uncertainty can be specified by a single value or by a map.

There are three types of residuals used by COHIBA:

1. For seismic reflectors, a *travel time residual* must be specified. This residual describes the interpretation uncertainty. Typical uncertainties are in the range 2–20 msec.
2. For a velocity interval, the *interval velocity residual* must be specified. Typical uncertainties are in the range 10–200 m/s.
3. For a thickness interval, the *thickness residual* must be specified. Typical uncertainties are 0–50 meters. (0 is used for pinch outs.)

Here is four examples of simulated residuals with different spatial smoothness[1]:



1. Some additional examples are found in Section 20.

Depth conversion. The top and base surfaces of some intervals can be seismic reflectors. COHIBA offers the possibility of specifying interval velocities models rather than interval thickness models. COHIBA will depth convert the travel times using the specified interval velocity model for these intervals. Any mixture of interval thickness and interval velocity models is possible.

An interval velocity trend can typically look like

$$v = a \cdot 1 + b \cdot t(x, y).$$

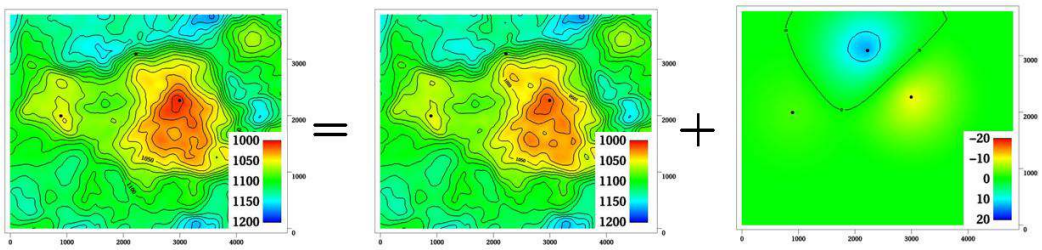
The thickness of the corresponding interval is obtained by multiplying the interval velocity by the travel times for that interval:

$$\Delta z = \Big(a \cdot 1 + b \cdot t(x, y)\Big) \cdot \Delta t(x, y).$$

Prediction. Prediction means to find the *most likely* set of surfaces given the model specifications *and* the data. This is a unique set of surfaces. It is common to call this deterministic surfaces.

A surface model is made of two parts, the trend and the residual. Prediction uses the fitted trend and the interpolated residuals at the well points. This is illustrated here:

Depth = trend + residual



Stochastic simulation. Stochastic simulation is a *stochastic* approach where trend coefficients and residuals are sampled from probability distributions to obtain a *realization*. The realization is *conditioned* to data, that is, the realizations are consistent with all the data. A realization is not unique—using a new random seed provides a new set of surfaces. The average of a large set of realizations will coincide with the deterministic surfaces obtained using prediction.

The stochastic simulation can be thought of as a two step procedure. First, the trend coefficients are drawn stochastically from their estimated distribution and multiplied with the trend maps to form the simulated trend. Then the residuals are drawn stochastically according to their spatially correlated distribution and added to the trends. See illustration on page 13.

Note that the uncertainty from the trends have a global impact whereas the uncertainty in the residual is more local. During this process COHIBA ensures that the result is in correspondence with the well data.

Uncertainty. Uncertainty is a somewhat loose term used to describe lack of knowledge, mismatch between reality and model, and the fact that no observations are exact. All COHIBA input concerning uncertainty is given as *standard deviations* (SD). All output concerning uncertainty is also given as SD.

Well data. There are two types of well data used by COHIBA: *Well points* and *well paths* with a *zone log*. Well points are the intersections between a well path and a surface. Well points can be imported directly from a file. Alternatively, well points can be extracted from a well path (well trajectory) using a zone log. COHIBA will detect all zone transitions and record a well point if the transition is associated with a surface. COHIBA can also ensure that the surfaces are located correctly according to the zone log. This is convenient for horizontal wells.

Part II
User manual

3 Getting started

COHIBA is started from the command line with the COHIBA model file as an argument:

```
> cohiba.exe[1] model-file.xml
```

A COHIBA project consists of a COHIBA model file, well data, and a set of trend maps. The COHIBA model file is written using Extensible Markup Language (XML) syntax. We start by running a very simple example, with a constant surface and one well point. We follow the steps:

1. Copy the COHIBA executable to the current directory and create a sub-directory `test/`.
2. Create a file `model-file.xml` in `test/` using the following COHIBA model file:

```
<cohiba>
   <project-settings>
      <project-directory>            test </project-directory>
      <output-grid>
         <format>             roxar binary </format>
         <xstart>                   448300 </xstart>
         <xlength>                    1000 </xlength>
         <ystart>                  6736000 </ystart>
         <ylength>                    3000 </ylength>
         <xinc>                         50 </xinc>
         <yinc>                         50 </yinc>
      </output-grid>
   </project-settings>

   <modelling-settings>
      <mode>                     prediction </mode>
      <kriging-method>             bayesian </kriging-method>
   </modelling-settings>

   <well-data>
      <well-points>
         <files>           wellpoints.dat </files>
      </well-points>
   </well-data>

   <surfaces>
      <!-- Specification of surface TopSurf -->
      <surface>
         <name>                    TopSurf </name>
         <travel-time>
            <value>                      1 </value>
            <variogram>
```

1. Typical names for the COHIBA executable are `cohiba_5.3._Win64_CompanyName.exe` (Windows) or `cohiba_5.3.0_Linux64_RH6_CompanyName` (Linux). These files can of course be renamed.

```
            <type>           spherical </type>
            <range>               3500 </range>
            <SD>                  0.01 </SD>
         </variogram>
      </travel-time>
      <output>
         <depth>                   yes </depth>
         <depth-uncertainty>       yes </depth-uncertainty>
         <depth-trend>             yes </depth-trend>
      </output>
   </surface>
</surfaces>

<interval-models>
   <interval>
      <top>                        MSL </top>
      <base>                   TopSurf </base>
      <interval-type>         velocity </interval-type>
      <trend>
         <coefficient-mean>         1.0 </coefficient-mean>
         <coefficient-SD>           0.1 </coefficient-SD>
         <value>                   1000 </value>
      </trend>
      <variogram>
         <type>           spherical </type>
         <range>               2500 </range>
         <SD>                     5 </SD>
      </variogram>
   </interval>
</interval-models>
</cohiba>
```

3. Create the directory `test/input/` and create a COHIBA well points file called `wellpoints.dat` in `test/input/` with the following content:

   ```
   TopSurf well 448800 6737500 1220 0.0
   ```

4. From the command line type: `cohiba.exe test/model-file.xml`

COHIBA will start by reading the COHIBA model file, `model-file.xml`, and generate output and surfaces according to the specifications. In this case, COHIBA is asked to make a deterministic surface called TopSurf using Bayesian kriging. This will make the surface interpolate the well point with coordinates $(448800, 6737500, 1220)$. Several directories are created under `test/output/`: `surfaces/`, `log-files/`, and `well-points/`. The depth map `d_TopSurf.rxb`, the depth uncertainty map `de_TopSurf.rxb` and the depth trend map `dt_TopSurf.rxb` are written to the directory `surfaces/` using the ROXAR BINARY grid format. Log files are written under `log-files/` and `well-points/` contains ROXAR ATTRIBUTES TEXT files.

In `Section 8: Sampling well trajectories and logs` of the screen output you may find the following table:

```
Interval            Coef    PriorMean     PostMean PostMeanUpd      PriorSD       PostSD    PostSDUpd
-------------------------------------------------------------------------------------------------------
MSL-to-TopSurf         1        1.000        1.217           -        0.100        0.011            -
```

This shows prior and posterior mean and SDs for the trend coefficient. The single data at 1220 m has moved the prior guess at 1000 m to 1217.3 m and the uncertainty has dropped from $0.1 \times 1000\,\mathrm{m} = 100\,\mathrm{m}$ to $0.011 \times 1000\,\mathrm{m} = 11.1\,\mathrm{m}$. This uncertainty should be compared to the residual uncertainties: $0.01\,\mathrm{s} \times 1000\,\mathrm{m/s} = 10\,\mathrm{m}$ (travel time) and $5\,\mathrm{m/s} \times 1\,\mathrm{s} = 5\,\mathrm{m}$ (interval velocity). Combining these gives a total uncertainty of $(10^2\,\mathrm{m}^2 + 5^2\,\mathrm{m}^2)^{1/2} = 11.2\,\mathrm{m}$. This is not a coincidence. A larger residual uncertainty would imply less impact from the well point and a larger posterior SD.

4 COHIBA command line options

The normal way of running COHIBA is with a single COHIBA model file as the argument:

```
> cohiba.exe model-file.xml
```

The COHIBA model file can of course have any name.

4.1 Specifying the random seed

COHIBA offers a few ways of setting the random seed for stochastic simulation. One option is to use the flag `-s`:

```
> cohiba.exe -s 123 model-file.xml
```

where `123` is the random seed. The random seed can also be specified in the random seed file (default is `seed.dat`) or in the COHIBA model file using the `<seed>` element.

4.2 Specifying number of realizations

COHIBA can generate a set of simulated realizations in one run. There are two options for specifying the number of realizations. It can be given in the command line using the `-n` option:

```
> cohiba.exe -n 100 model-file.xml
```

where `100` is the number of realizations. The number of realizations can also be specified in the COHIBA model file using the `<number-of-realizations>` element.

4.3 Spill point detection

COHIBA can find the spill point of a surface using `<spill-point>`. COHIBA also has a special mode where it reads a single surface and reports the spill point:

```
> cohiba.exe -g spillpointgrid.rxb
```

The essential output will look like:

```
      Xstart       Ystart           XSpill       YSpill     ZSpill
-----------------------------------------------------------------
   333092.09   6434195.50        333092.09   6434195.50    1942.75
-----------------------------------------------------------------
```

The input file with an added prefix, `trap_`, is written to file. This file contains ones inside the trap and zeros outside the trap.

The format of the input file is automatically detected. The output file has the same format as the input file. The possible file formats are described in Section 6.2.

The following command line options are available:

Flag: `-g`
Description: Input surface file. Trigger the spill point detection algorithm for a single surface.
Argument: A string specifying the input file name.
Default: No default.

Flag: `-x`
Description: Starting point x-coordinate for the spill point searching algorithm.
Argument: Real
Default: The x-coordinate where the surface has a minimum (highest point in surface).

Flag: `-y`
Description: Starting point y-coordinate for the spill point searching algorithm.
Argument: Real
Default: The y-coordinate where the surface has a minimum (highest point in surface).

Flag: `-m`
Description: Missing as wall flag. See Section 15.4.2.9.1.
Argument: `yes` / `no`.
Default: `yes`

5 The COHIBA model file

The COHIBA model file is an XML file. The file name is typically `model-file.xml`. The basic XML syntax for one *element* is

```
<name attribute = "attribute value">
 argument
</name>
```

where `name` is the name of the element and the `argument` is a value (text, number) or other elements. The attribute is omitted in most cases. Often `argument` contains further elements in a nested structure. Comments in XML starts with `<!--` and ends with `-->`. A comment can not include '`--`' for historical reasons.

The COHIBA model file is divided into six major elements:

```
<project-settings>      ...  </project-settings>
<modelling-settings>    ...  </modelling-settings>
<well-data>             ...  </well-data>
<surfaces>              ...  </surfaces>
<interval-models>       ...  </interval-models>
<volumes>               ...  </volumes>
```

There is a hierarchy of elements belonging to each of these six main elements. The sequence of the elements within a hierarchy is arbitrary[1] but it is recommended to stick to the suggested order to avoid confusion. Figure 5.1 shows an example of the skeleton of a COHIBA model file.

Note that many of the elements can be repeated. E.g. there will be one `<surface>...</surface>` element for every depth surface considered in the model.

A detailed description of all COHIBA model file elements is provided in Section 15. Most elements are optional and default values are provided if the element is omitted.

A list of all the COHIBA model file elements is provided in Section 16.

An extensive example of a COHIBA model file is given in Section 17.

5.1 Editing the COHIBA model file

An XML file is a simple text file and almost any text editor (WordPad, Notepad, Word, Emacs,...) can edit the file. However, the structure of the XML file is easier to read in a more specialized XML editor. For instance the Microsoft XML Notepad 2007 or Notepad++ text editors may be freely downloaded.

5.2 Errors reading the COHIBA model file

COHIBA will detect most spelling and syntax errors in the COHIBA model file. If COHIBA encounters an error corrupting the structure of the XML syntax, then a message will be issued to screen and the COHIBA log file. The message can look like:

```
XML error: ln 287, col 1
```

1. An important exception is the order of surfaces. These *must* be specified in correct stratigraphic order (with the exception of free surfaces, cf. `<free-surface>`) to obtain correct ordering of the generated surfaces.

```
<cohiba>
    <project-settings>
       :
    </project-settings>
    <modelling-settings>
       :
    </modelling-settings>
    <well-data>
       :
    </well-data>
    <surfaces>
        <!-- Surfaces MUST be listed in stratigraphic order -->
        <reference>
           :
        </reference>
        <surface>
           :
        </surface>
       :
    </surfaces>
    <interval-models>
        <interval>
           :
        </interval>
       :
    </interval-models>
    <volumes>
        <volume>
           :
        </volume>
       :
    </volumes>
</cohiba>
```

Figure 5.1. Skeleton of a COHIBA model file.

```
while parsing 'benchmark/model_file.xml'.
Error reading end tag of <project-settings>: found </cohiba>

Fatal error: Could not read XML file
```

In this case, the final tag, `</project-settings>`, was forgotten.

If COHIBA finds an unknown element a message will be issued. It can look like:

```
Error: Unknown tag <variograms> encountered at line 274, column 7.
Select one of: <name>, <top>, <base>, <interval-type>, <trend>, <variogram>,
               <correlations> or <output>
Parsing error on line 264. Missing <variogram> entry under <interval>

Fatal error: Invalid model file.
```

In this case the `<variogram>` element has been misprinted as `<variograms>`. Note that COHIBA suggests the possible supported element names.

6 Files and directories

6.1 File directory structure

COHIBA reads a lot of information from files and writes results to numerous files. It is partly up to the user to organize the input files in a convenient way. Figure 6.1 shows an overview of the recommended directory structure and some input files and Figure 6.2 shows an overview of output files and directories.

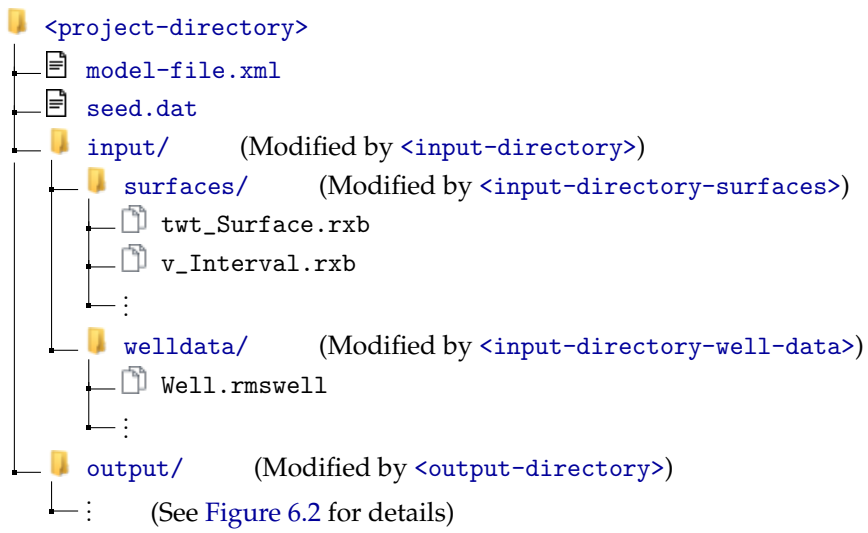


Figure 6.1. Recommended and default directory structure. `Surface`, `Interval`, and `Well` will be replaced by specified surface, interval and well names.

The three top directories can be specified in the COHIBA model file using elements `<project-directory>`, `<input-directory>`, and `<output-directory>`. If a project directory has not been specified by the user, it defaults to the current working directory. The default input directory is `input/` and the default output directory is `output/`.

By default, input surfaces are stored in `surfaces/` and well data in `welldata/` in the `<input-directory>`. The default values for these sub-directories can be overridden using `<input-directory-surfaces>` and `<input-directory-well-data>`.

Results are stored in the directories `log-files/`, `surfaces/`, `spill-points/`, `well-logs/`, `well-points/`, `zonation-points/`, `target-points/`, and `expert/` in the `<output-directory>`. See Figure 6.2 for details. All these output directories and most of the output files have fixed names and can not be modified by the user.

6.2 Surface file formats

COHIBA represents surfaces as regular grids. The following grid file formats are supported:

ROXAR BINARY This is a binary file format that supports rotated grids. File extensions for output is `.rxb`. This is the default format.

ROXAR TEXT This is an ASCII text file format that supports rotated grids. File extensions for output is `.rxt`.

STORM BINARY This is a binary file format that does not support rotated grids. File extensions for output is `.storm`.

ROXAR PATCH BINARY This is a binary file format that supports general surfaces given as overlapping surface patches. This is the format that ROXAR RMS and COHIBA use to exchange surface data for use in the ROXAR RMS structural model.

Constant Allows to define a constant surface value in the COHIBA model file.

ROXAR RMS supports all these grid file formats. Petrel supports ROXAR BINARY and ROXAR TEXT[1].

The input file formats are automatically detected when reading from file. The format detection does not depend on the file extensions.

The output file format and grid dimension are specified by `<output-grid>`.

6.3 Well data file formats

6.3.1 Well log file formats

Well log files contain x-coordinate, y-coordinate, TVD, zone logs and other logs along the well path. COHIBA supports

ROXAR RMS well: This ASCII text format is used for input and output. Output files use the extension `.rmswell`. These output files are only created if well paths are allowed to move.

LAS 2.0 well: This format can be used for input. The Log ASCII Standard (LAS) file format is documented by www.cwls.org/las/. The standard file extension is `.las`.

ROXAR RMS and Petrel supports both file formats[2].

The input well log files are specified using `<files>` under the `<well-log>` element. COHIBA detects the file formats automatically.

6.3.2 Well points file formats

COHIBA supports two well points formats:

ROXAR ATTRIBUTES TEXT: This is a flexible ASCII text format that supports any number of attributes. This file format is recommended for input of well points. This format is used for output using the file extension `.rxat`. This input format is described in Table 6.1.

COHIBA well points: This is an ASCII text format described in Table 6.2. This format can be used for input. This format was used for output using the file extension `.dat`.

Input well points file(s) are specified using the `<well-points>` element. File formats are detected automatically.

6.3.3 CSV-files

These are ASCII text files containing comma-separated-values (CSV) used for output.

The format can be modified using `<csv-file-style>`. Using `fixed with` is convenient when looking at files in normal text editors. It is recommended to choose `comma-separated` (the default) before trying to import files into a spreadsheet[3]. Note that COHIBA uses a dot "." as the decimal mark in numerical values. This require some extra care if the spreadsheet uses a comma "," as the decimal mark.

1. Petrel use the old names Irap classic grid (BINARY/(ASCII)) for ROXAR BINARY and ROXAR TEXT.
2. Petrel uses the old name Irap RMS well (ASCII) for ROXAR RMS WELL.
3. Import of CSV files into Excel is best done from the Data ribbon (Office 2016 and Office 2019).

Typical files are `trend-estimation.csv` and the `wellpoints.csv` that are intended for QC. The file extension is `.csv`.

6.3.4 xyz-files

This is a simple ASCII text file format that contains the x-coordinate, y-coordinate and TVD on each row. The file extension is `.xyz`. All xyz-files are found in the `expert/` directory. The file name will generally explain the content. Typical examples are `zonationpoints-special.xyz` and `targetpoints-Surface.xyz`. These files are numerous and is not written unless `<write-xyz-point-files>` is set to `yes`.

6.3.5 Undefined values

Undefined values are marked by missing codes that differ for various file formats. COHIBA detects and handles missing codes automatically. For ASCII output files, COHIBA uses the missing code `-99999.0` for depths and coordinates and `-999.0` for log values.

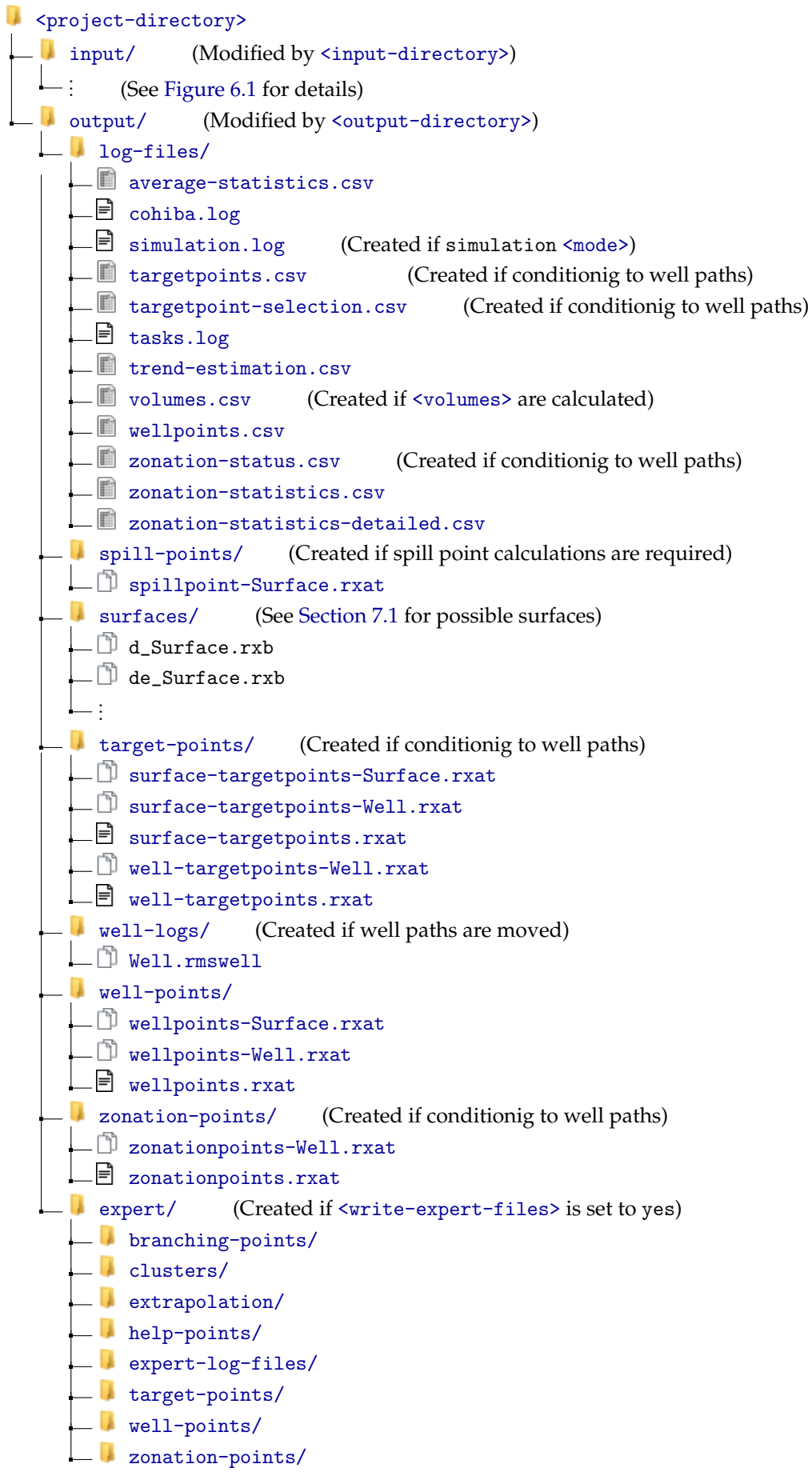


Figure 6.2. Output directory structure. `Surface` and `Well` will be replaced by specified surface and well names.

Table 6.1. The ROXAR ATTRIBUTES TEXT well points file format is an ASCII text file format with one row per well point. The three first columns always specify x-coordinate, y-coordinate and TVD. The next columns are specified in the header by a single line containing attribute type (`String`, `Float`, or `Discrete`) and a text description of the attribute. There can be any number of attributes. The file extension is `.rxat`.

For input files, there *must* be attributes "`String Surface`" and "`String Well`" to identify surface and well names. It is possible to specify well point TVD uncertainty and well path TVD uncertainty. If well path TVD uncertainty is specified there must be a column containing measured depth (MD). See the example below for the correct naming of the attributes. The order of the attributes is arbitrary.

```
Float MD
String Surface
String Well
Float Well point TVD pick uncertainty
Float Well path TVD uncertainty
535045.09  6742547.10  1255.12 1275.12 "Top A" w1  0.00 0.00
535045.09  6742511.36  1383.87 1403.87 "Top B" w1  0.00 0.00
535045.09  6742515.42  1400.23 1420.23 "Top C" w1  0.00 0.00
532273.48  6737634.37  1194.15 1219.15 "Top A" w2  0.00 0.00
532223.72  6737667.37  1284.10 1309.10 "Top B" w2  0.00 0.00
532203.58  6737694.37  1301.15 1326.15 "Top C" w2  0.00 0.00
536393.00  6736356.62  1155.23 1175.23 "Top A" w3  0.00 0.00
536194.01  6736389.87  1255.60 1275.60 "Top B" w3  0.00 0.00
536168.78  6736397.00  1300.75 1320.75 "Top C" w3  0.00 0.00
```

Table 6.2. The COHIBA well points file format use one line for each observation. The two first columns identify the observations by surface name and well name. The next three columns specify the well point coordinates in space, and the last column allows a TVD pick uncertainty (SD). The ordering of the observations is arbitrary and has no effect on the generated surfaces. Lines beginning with a # are treated as comments. The entries can be separated by blanks, tabs or commas. Do not mix comma separated values and white space separated values in the same file.

White space separated (space and/or tabs):

```
#-------------------------------------------------------------
# Surface   Well          x           y       TVD      TVD
# name      name                                   pick SD
#-------------------------------------------------------------
TopA        w1     535045.09  6742547.10  1255.12     0.00
TopB        w1     535045.09  6742511.36  1383.87     0.00
TopC        w1     535045.09  6742515.42  1400.23     0.00
#-------------------------------------------------------------
TopA        w2     532273.48  6737634.37  1194.15     1.00
TopB        w2     532223.72  6737667.37  1284.10     1.00
TopC        w2     532203.58  6737694.37  1301.15     2.00
#-------------------------------------------------------------
TopA        w3     536393.00  6736356.62  1155.23     0.50
TopB        w3     536194.01  6736389.87  1255.60     0.65
TopC        w3     536168.78  6736397.00  1300.75     2.98
#-------------------------------------------------------------
```

Comma separated:

```
#---------------------------------------------------------------------
# Surface    Well              x,           y,      TVD,      TVD
# name       name                                        pick SD
#---------------------------------------------------------------------
Top A,      well 1,     535045.09,  6742547.10,  1255.12,     0.00
Top B,      well 1,     535045.09,  6742511.36,  1383.87,     0.00
Top C,      well 1,     535045.09,  6742515.42,  1400.23,     0.00
#---------------------------------------------------------------------
Top A,      well 2,     532273.48,  6737634.37,  1194.15,     1.00
Top B,      well 2,     532223.72,  6737667.37,  1284.10,     1.00
Top C,      well 2,     532203.58,  6737694.37,  1301.15,     2.00
#---------------------------------------------------------------------
Top A,      well 3,     536393.00,  6736356.62,  1155.23,     0.50
Top B,      well 3,     536194.01,  6736389.87,  1255.60,     0.65
Top C,      well 3,     536168.78,  6736397.00,  1300.75,     2.98
#---------------------------------------------------------------------
```

7 The COHIBA output

COHIBA stores results in the directories `log-files/`, `surfaces/`, `spill-points/`, `well-logs/`, `well-points/`, `zonation-points/`, `target-points/`, and `expert/` in the specified `<output-directory>`. See Figure 6.2 for an overview. Necessary directories are created if they are not already present. COHIBA will overwrite existing files and directories.

The main result of COHIBA are the maps saved in `surfaces/` The log files in `log-files/` contain important information on the quality of the result.

Well data used for generating the surfaces are saved in formats convenient for visualization and QC. The files are stored in directories `well-points/`, `zonation-points/`, and `target-points/`.

The outcome of the spill point detection algorithm is a set of trap surfaces under `surfaces/`, and spill points in `spill-points/`. The `spill-points/` directory is only created when spill points are required.

The `well-logs/` directory contains updated TVD values. This directory is only generated if `<condition-to-well-paths>` and `<allow-wells-to-move>` are both `yes`.

Note that many predefined file names contains the underscore '_'. These are replaced by a dash '-' in this manual[1].

7.1 Output surfaces and maps

All output surfaces (maps) are written to files in the `surfaces/` directory. The file names contain the name of the surface, interval, or reservoir volume that they relate to. A prefix depending on the type of map and a possible trailing text in stochastic simulation `<mode>` is appended to the name. See Table 7.1 for a list of possible output surfaces (maps). Only depth surfaces are generated by default. A few special surfaces (maps), listed in Table 7.2, are written to the `surfaces/` directory when they are calculated.

7.1.1 Multiple realizations from stochastic simulation

By default all realizations are saved to file. A trailing text, `_nnnn`, where `nnnn` is the realization number, is added to the file name. File names could look like:

```
d_TopA_0001.rxb, d_TopA_0002.rxb,..., d_TopA_9999.rxb
trap_TopA_0001.rxb, trap_TopA_0002.rxb,..., trap_TopA_9999.rxb
v_MSL-TopA_0001.rxb, v_MSL-TopA_0002.rxb,..., v_MSL-TopA_9999.rxb
```

Additional digits will be added for realizations beyond realization number 9 999. For instance: `d_TopA_10001.rxb`. The realization number is only added if `<number-of-realizations>` is more than one. Suppressing writing of individual realizations is possible using `<write-realization-maps>`.

Stochastic simulation of multiple realizations trigger the construction of average maps and empirical uncertainty (SD) maps if output for the respective maps are requested. These maps are only made if `<number-of-realizations>` is more than one. These maps are updated and written to file for every finished realization. The average and uncertainty maps get the trailing texts `_mean` and `_SD` in their file names. File names could look like:

1. The reason for using the dash in the file names is that the LaTeX typesetting system used for this manual makes it utterly complicated to generate cross-links in the document containing the underscore.

```
d_TopA_mean.rxb, d_TopA_SD.rxb
trap_TopA_mean.rxb, trap_TopA_SD.rxb
v_MSL-TopA_mean.rxb, v_MSL-TopA_SD.rxb
```

The average depth surface will be similar to the predicted depth surface if the number of realizations is large[2]. If an <acceptance-criteria> apply, there might be a significant difference between the average depth surface and the corresponding predicted depth surface.

2. In principal, the average depth surface will be identical to the predicted depth surface if the number of realizations goes to infinity.

Table 7.1. Output maps found in the `surfaces/` directory. The only maps that are written by default are surface depths.

Map (on/off element)	File prefix	Description
Surfaces:		
<depth>	d_	Deterministic (prediction) or stochastic simulated depth to the surface dependent on the specified <mode>. See Eq. 18.37 (deterministic) or Eq. 19.1 (stochastic simulation).
<depth-trend>	dt_	Similar to <depth> but the residual is omitted. See Eq. 18.23 (deterministic) or Eq. 19.2a (stochastic simulation).
<depth-residual>	dr_	Difference between <depth> and <depth-trend>.
<depth-uncertainty>	de_	Prediction uncertainty (SD) at each point on the surface. No output in stochastic simulation <mode>. See Eq. 18.42a – Eq. 18.42c.
<depth-trend-uncertainty>	dte_	Uncertainty (SD) caused by the uncertainty in trend coefficients. No output in stochastic simulation <mode>. See Eq. 18.24.
<depth-residual-uncertainty>	dre_	Uncertainty (SD) caused by all the residuals in the surface. No output in stochastic simulation <mode>. See Eq. 18.25.
<trap>	trap_	The trap containing the starting point of the spill point calculation. The trap map is 1 if the grid node is inside the trap and 0 otherwise.
Intervals:		
<thickness>	t_	Interval thickness computed as the difference between the two depth surfaces defining the interval (specified in <top> and <base> elements).
<thickness-trend>	tt_	Interval thickness trend computed as the difference between the two depth surface trends defining the interval. See Eq. 18.4.
<thickness-residual>	tr_	Interval thickness residual computed as the difference between <thickness> and <thickness-trend>.
<velocity>	v_	Interval velocity computed as the difference between the two depth surfaces defining the interval divided by the corresponding travel time difference. Unrealistic velocities are removed by smoothing.
<velocity-trend>	vt_	The posterior interval velocity trend. See Eq. 18.48.
Volumes:		
<column-map>	column_	The rock column height in a reservoir. Unit is determined by <z-unit>. See Eq. 9.1 in Section 9.1.

Table 7.2. Special output maps found in the surfaces/ directory. These maps are written when they are calculated.

File prefix	Description
time_truncated_	See <make-time-surfaces-consistent> for details.
Simulated_time_	Stochastic simulated travel time surface. This is the specified <travel-time> plus the simulated travel time residual. See Section 19.2 for details. Only generated in stochastic simulation <mode>. Can be turned off by <write-realization-maps>.
FilteredVelocityTrend_	See <smoothing-factor-velocity-trends> for details.
FilteredSDMap_	See <smoothing-factor-SD-maps> for details.
Unfiltered_v_	See <smoothing-factor-calculated-velocities> for details.
Scaled_	See <scale-isochores-to-seismic-envelopes> for details.
Scaled_SD_	See <weight-isochore-package-above> for details.
Regridded_	These are the input trend maps re-gridded to the resolution of the output maps. These maps are generated when there is a mismatch between the input and output grid resolutions.

7.2 The log files

The log files are written to the `log-files/` directory under the `output/` directory. The log files can be used for QC and inspection of COHIBA results. See Figure 6.2 for a quick overview of the available log files.

7.2.1 The `average-statistics.csv` file

This file is a CSV file containing average statistics for each surface. The columns are explained in Table 7.3.

Table 7.3. Columns in the `average-statistics.csv` file.

Column name	Description
`Surface`	Surface name.
`PriorRes`	Average difference between prior trend and well points (RMSE[a]).
`PostRes`	Average difference between posterior trend and well points (RMSE).
`SpecRes`	Average specified residual uncertainty (SD) at well points (contribution from all specified variograms).
`TotRes`	Total residual. To be removed in future releases.
`RelPriorRes`	Prior residuals divided by specified residual uncertainty.
`RelPostRes`	Posterior residual divided by specified residual uncertainty.
`RelPriorTrendErr`	Relative prior trend error. To be removed in future releases.
`RelPostTrendErr`	Relative posterior trend error. To be removed in future releases.

a. Root mean squared error (RMSE) is the standard estimate for the SD of the residual. It is calculated using RMSE $= \sqrt{\sum_{n=1}^{N} r_n^2/N}$ where $r_n = z_n - \bar{z}_n$ are the residual at well point n.

7.2.2 The COHIBA log file

The name and content of the COHIBA log file is specified in the `<logfile>` element. The default name is `cohiba.log`. An extensive example is given in Section 17.1.

These are the sections in the COHIBA log file:

`Section 1: Model settings`
: Reports the settings in the COHIBA model file. Detail level set by `<model-settings>`.

`Section 2: Loading input data`
: Reports what data has been read from file and possible errors. Detail level set by `<data-loading>`.

`Section 3: Pre-processing input data`
: Detail level set by `<pre-processing>`.

`Section 4: The alternative ways to build each surface`
: Reports what intervals are used to build the surfaces. This includes all alternative models and their weights. See Figure 11.3 for an example of the output.

  Reports how much weight each interval adds to each surface. The weights can be normalized by setting `<normalize-interval-weights-table>` in `<advanced-settings>` to `yes`.

  Detail level set by `<surface-models>`.

`Section 5: Processing well points`
: Reports redundant data and possible merging of duplicate well points. Reports potential conflicts and lists well points that have been removed or given additional uncertainty. Reports on pinch outs. Detail level set by `<well-points>`.

`Section 6: Processing control points for eroded and onlapped surfaces`
Reports possible control points that are needed to constrain eroded and onlapping surfaces at observations of the eroding and onlapped surfaces. Detail level set by `<extra-points>`.

`Section 7: Well branching`
Reports how different well branches (side tracks) are connected into a single multilateral well. The zonation point at the branching is called a *branching point*. COHIBA automatically identifies all branching points. The branching points are used to ensure consistency when moving uncertain wells (see Section 8.5.2). Branching points are always added to the zonation points. Inconsistent zone logs in common sections of side tracks are listed. Detail level set by `<well-branching>`.

`Section 8: Sampling well trajectories and logs`
Reports on processing of well paths with zone logs. Detail level set by `<well-paths>`.

`Section 9: Trend coefficients based on well points`
Reports the estimated values for the trend coefficients in the trends. Detail level set by `<trend-coefficients>`.

`Section 10: Checking specified residual uncertainties`
This is a way of checking that the specification of interval uncertainties are consistent with well points. The specified residual uncertainties are compared to residual uncertainties estimated from well points. This is done by extracting linear combinations[3] of the well points that correspond to observations of the true residual uncertainty.

The specified residual uncertainties for each interval are classified as `OK`, `Low`, `High`, `Too low`, or `Too high`. Especially the two latter classifications is a sign of a wrongly specified residual uncertainty.

The identification of useful linear combinations can be time demanding so the element `<check-specified-residual-uncertainties>` can be used to omit the calculation.

Detail level set by `<residual-uncertainties>`.

`Section 11: Well point QC`
Reports poor matches between well points and trend model. These are classified as outliers or leverage points. Bias in the residuals is reported. Detail level set by `<outliers>`.

`Section 12.x: Conditioning on well points along well paths`
Reports zonation status for zonation points along the well paths and the associated surface help points used to condition surfaces to the well paths. See Table 7.4 for an explanation of the codes used to classify the surface help points. Detail level set by `<well-point-conditioning>`.

`Section 13.x: Finding help points for well path conditioning`
Reports on help points and surface constraints that will be used to ensure correct conditioning to zone logs. See Section 21 for details. Detail level set by `<help-points>`.

`Section 14.x Trend coefficients based on well points and well paths`
Reports the estimated values for the trend coefficients in the trends based on well points *and* well paths. Detail level set by `<trend-coefficients>`.

`Section 15.x: Conditioning surfaces on all available points`
Makes a final report on the quality of the surfaces. Detail level set by `<well-path-conditioning>`.

---

3. It is not always possible to find such linear combinations and the number of linear combinations can be few making the estimates unreliable. The number of such linear combinations are reported. The element `<min-generalized-eigenvalue-for-residual-uncert>` modifies a threshold used for selecting the linear combinations that correspond to the interval.

`Section 16.x: Post process surfaces`
Detail level set by `<post-processing>`.

`Section 17.x: Target point QC`
Detail level set by `<target-point-qc>`.

`Section 18.x: Checking zonation`
Reports possible problems with conditioning surfaces to well paths. Detail level set by `<zonation-checking>`. Table 7.5 contain the various status of help points. This is also written to the file `zonation-status.csv`.

Reports length of correct zonation for each zone. Detailed results are also written to `zonation-statistics.csv` and `zonation-statistics-detailed.csv` in `log-files/`. A log called `Mismatch` reports the TVD mismatch. It is added to the output well log files in the `well-logs/`.

`Section 19.x: Updated well trajectories`
Detail level set by `<well-trajectories>`.

`Section 20.x: Spill points`
Detail level set by `<spill-points>`.

`Section 21.x: Volume calculations`
Detail level set by `<volume-calculations>`.

`Section 22.x: Make and export interval thicknesses and velocities`
Include information about filtering of calculated velocities. Detail level set by `<interval-export>`.

`Section 23.x: Export surfaces`
Reports export of output surfaces. Detail level set by `<surface-export>`.

`Section 24: Timings summary`
Reports the amount of CPU time and real time spent on different operations. Note that the real time can be shorter than the CPU time when using parallel processes. Detail level set by `<timings>`.

`Section 25: Suggested tasks`
This is a task list of possible problems the user should look into. Detail level set by `<tasks>`.

Section 12 – 22 are repeated for every simulated realization. For stochastic simulation `<mode>`, the realization number, and a possible rejection sampling iteration, is added to the section number:

```
*****     Section 15.3.5: Conditioning surfaces on all available points
```

So `15` is the Section number, `3` is the realization number, and `5` is the iteration number. The iteration number is omitted if there are no rejection criteria.

The COHIBA log file is intended for catching problems during execution and for examining the main results. The output to screen is identical to the log file output provided the same detail levels have been specified. The COHIBA log file can be large. The task list is intended to give a quick way to identify possible problems. The task list is also written to `tasks.log`.

More detailed analysis are provided in the files `trend-estimation.csv` and the `wellpoints.csv`.

7.2.3 The `simulation.log` file

This file contains a list of realization number and the random seed used to generate the realization. In case of rejection sampling, the number of rejected realizations are included in the list. This file is only generated in `simulation` `<mode>`.

Table 7.4. Classification of initial zonation status for the well path zonation points and classification of surface help points in `Section 12.x: Conditioning on well points along well paths` in the COHIBA log file and in the file `targetpoint-selection.csv`.

Well path zonation points:		
Column		
`Match`	**Zonation status**	**Explanation**
`Y`	Zonation correct:	Well path zonation point is initially in the correct zone.
`N`	Zonation incorrect:	Well path zonation point is initially in the wrong zone and must be corrected.
`-`	Undefined zonation:	Well path zonation point can not be classified due to crossing surfaces or zero thickness isochores.
Surface help points (`ZoneTop` and `ZoneBase`):		
Column		
`Need`	**Classification**	**Explanation**
`N`	Not needed:	Not needed since the well path point is initially in the correct zone.
`Y`	Needed:	Needed since the well path point is initially in the wrong zone or to close to the surface.
`CY`	Not needed:	Same as `Y` but not needed since neighboring correlated surface help points will ensure correct zonation. The correlation threshold can be modified by `<threshold-for-help-point-deactivation>`.
`XY`	Impossible to use:	This is either because the zone is extremely thin or because a correction requires the surface to move more than 3.09 SDs (see `<t-value-error>`).
`-`	No `ZoneTop` surface:	The top surface is the reference surface (the default is mean sea level (MSL)).

Table 7.5. Classification of final zonation status for the well path zonation points in `Section 18.x: Checking zonation` in the COHIBA log file and in the file `zonation-status.csv`.

Well path zonation points:		
Column		
`Fix`	**Zonation status**	**Explanation**
`-`	Unchanged zonation:	Well path point was initially in correct zone and has ended in the correct zone.
`Y`	Zonation corrected:	Well path point was initially in wrong zone and has ended in the correct zone.
`N`	Correction failed:	Well path point was initially in wrong zone and has not been corrected.
`B`	Broken zonation:	Well path point was initially in correct zone but has ended in a wrong zone.
`F`	Fixable broken zonation:	Well path point was initially in wrong zone and has not been corrected. It might be corrected if COHIBA is allowed to iterate the process by switching on `<minimize-broken-zonation>`.
`X`	Non-correctable zonation:	Well path point was initially in wrong zone and it is impossible to bring it into the correct zone. This is either because the zone is extremely thin or because a correction requires a surface to move more than 3.09 SDs (see `<t-value-error>`).
`U`	Invalid zonation:	There are no valid zonation code at the well path point.
`=`	Undefined zonation:	The zonation code is undefined at the well path point.

7.2.4 The `tasks.log` file

This file contains a task list of possible problems the user should look into. Detail level set by `<tasks>`. This is an extraction of the `Section 25: Suggested tasks` in the COHIBA log file. This file is only generated if there are some suggested tasks.

7.2.5 The `volumes.csv` file

This file is a CSV file giving a list of calculated volumes. It is formatted for easy import into spreadsheets. The file contains volumes from each `<reservoir-name>` and `<area-names>` which is specified in the model file. In case of `simulation <mode>`, the volumes from all realizations are listed. In addition, realization number and seed is included in each row. See Section 9 for more details and an example.

7.2.6 The `trend-estimation.csv` file

This file is a CSV file that contains an analysis of the trend coefficients. There is one line for each trend coefficient. The file is organized in columns described in Table 7.6. Missing or undefined entries are marked by an '–'.

Use the `trend-estimation.csv` file to inspect the quality of the trend coefficient estimates. Trend coefficients with low `UncertRed` might introduce too much uncertainty and could be removed if the t-value (`tEstim` or `tPost`) is small.

7.2.7 The `targetpoint-selection.csv` file

This is a CSV file with the zonation summary in `Section 12.x: Conditioning on well points along well paths` in the COHIBA log file. See Table 7.4 for explanation of classification values.

7.2.8 The `zonation-status.csv` file

These is a CSV file with the zonation summary in `Section 18.x: Checking zonation` in the COHIBA log file. See Table 7.5 for explanation of classification values. This file is only generated if `<condition-to-well-paths>` is set to `yes` (default).

7.2.9 The `zonation-statistics.csv` and `zonation-statistics-detailed.csv` file

These files are CSV files that show the length of correct or incorrect zonation for each well (and zone). The files contains the following columns:

`Well`: Well name
`Zone`: Zone name (only for `zonation-statistics-detailed.csv`)
`Correct`: Length of correct zonation
`Incorrect`: Length of incorrect zonation
`< 1.0`: Length of incorrect zonation that is equal or less than 1.0 (of depth units)
`> 1.0`: Length of incorrect zonation that is more than 1.0 (of depth units)
`Avg miss`: Average TVD miss for the well path points that have incorrect zonation
`Correct (%)`: Correct length / (Correct length + Incorrect length)

These files are only generated if `<condition-to-well-paths>` is set to `yes` (default).

A summary for each zone is shown in `Section 18.x: Checking zonation` in the COHIBA log file.

7.2.10 The `wellpoints.csv` file

This is a CSV file containing an analysis of the well points and how they fit to the surfaces. It also contains a summary of actions taken on well points. There is one line for each well point. See Table 7.7 for a detailed description of the columns.

7.2.10.1 Flags in `wellpoints.csv`

The user should inspect for possible flags. This is an important QC step that may detect serious errors in data and inconsistencies between data and models.

Table 7.6. The `trend-estimation.csv` file. Description of columns. The formulas used are found in Table 18.2.

Tag	Description
`Interval`	Interval name.
`TopSurface`	Name of top surface.
`NumObs`	Number of observations in top surface.
`BaseSurface`	Name of base surface.
`NumObs`	Number of observations in base surface.
`Trend`	The interval often contains more than one trend coefficient. If there are 3 in this interval they will be labeled 1, 2, and 3. The numbering will follow the sequence of the `<trend>` elements.
`PriorMean`	Prior mean value for the trend coefficient. The value is specified by the `<coefficient-mean>` element.
`EstimMean`	Estimated mean value for the trend coefficient. This value is estimated using GLS which amounts to linear regression where the spatial correlation in the well data is accounted for. This value may fail to exist if there are too few data in some of the intervals. It is not calculated if simple kriging is specified.
`PostMean`	Posterior mean value for the trend coefficient. This value is estimated using a Bayesian approach which amounts to a weighting between the prior specification and the GLS estimate. Note that this estimate exist even if the GLS estimate fails to exist. It is not calculated unless Bayesian kriging is specified.
`PostMeanUpd`	Posterior mean value for the trend coefficient estimated using well points *and* information from the zone-logs along the well path.
`SimMean`	Simulated (Monte Carlo) value for the trend coefficient. The simulated values are drawn from the estimated distribution. For simple kriging it will be identical to the value specified in the `<coefficient-mean>` element unless the `<simulate-trend-uncertainty>` element is given the value `yes`. Only calculated in stochastic simulation `<mode>`.
`PriorSD`	Prior SD for the trend coefficient. The value is specified by `<coefficient-SD>`.
`EstimSD`	Estimated SD for the trend coefficient. This value is estimated using GLS. Not calculated if simple kriging is specified.
`PostSD`	Posterior SD for the trend coefficient. This value is estimated using a Bayesian approach. This value will always be less than `PriorSD` and `EstimSD`. Not calculated unless Bayesian kriging is specified.
`PostSDUpd`	Posterior SD for the trend coefficient estimated using well points *and* information from the zone-logs along the well path.
`UncertRed`	For universal kriging: (`PriorSD` – `EstimSD`)/`PriorSD`. For Bayesian kriging: (`PriorSD` – `PostSD`)/`PriorSD`. Uncertainty reduction in percent from the prior specification. Value is always in the range 0 to 100 % for Bayesian kriging. For universal kriging negative values occur when the prior specification is more certain than the estimate. A small (or negative) value signals that well data has minor impact. Consider increasing the prior SD of the trend coefficients if well data has minor impact. Consider using Bayesian kriging if a negative value occurs.
`tPrior`	`|PriorMean|/PriorSD`.
`tEstim`	`|EstimMean|/EstimSD`. A large t-value (> 2) shows that this is an important trend for explaining depth or interval velocity variations according to the well points. A small value (< 1) shows that the well points does not support the existence of such a trend. Consider removing it.
`tPost`	`|PostMean|/PostSD`. See the comments on `tEstim`. Note that the conclusions using this t-value are less significant since these estimates can be heavily influenced by the a priori specifications.

Table 7.7. The `wellpoints.csv` file. Description of columns. File contains one line for each well point. See Table 18.1 for exact formulas.

Column name	Value	Description
`Surface`	Text	Name of surface.
`Well`	Text	Name of well.
`x`	Real	UTM coordinate.
`y`	Real	UTM coordinate.
`TVD`	Real	Observed TVD. (From COHIBA well points file or transitions in zone logs.)
`NewTVD`	Real	Modified TVD if `<allow-wells-to-move>` is set to `yes`.
`DeltaTVD`	Real	Difference between `TVD` and `NewTVD`.
`TravelTime`	Real	Travel times (from `<travel-time>` grids) if `Surface` is a reflector.
`MD`	Real	MD calculated along the well.
`Duplicate`	`Int/-`	Duplicates have the same number. One well point is kept and the rest are removed from calculations.
`Conflict`	`C/-`	Potential conflict with other close well points in same surface. (Slope > 10 %.)
`AddUncertWP`	`U/-`	Uncertainty added to well point because it is close to other well points.
`AddUncertOL`	`U/-`	Uncertainty added to well point because it is a severe outlier.
`Pinchout`	`P/-`	Pinch out. Identical to well point from different surface.
`LevPoint`	`L/-`	Leverage point. Large impact on the trend estimation. Check input values!
`Outlier`	`O`	Outlier. Inspection recommended.
	`U`	Severe outlier. TVD pick uncertainty added. Inspection strongly recommended.
	`S`	Error. Removed from all calculations. Inspection strongly recommended.
	`E`	Extreme error. Removed one-by-one from all calculations. Inspection strongly recommended.
`Deleted`	`B`	Outside grid boundary.
	`P`	Pinch out between other surfaces. Not needed.
	`E`	Specified residual uncertainty is zero.
	`X`	Error or extreme error. (`S` or `E` above.)
	`F`	Close to fault according to fault indicator log.
	`S`	Missing values in trends.
	`R`	Belongs to reference surface. (Uncertainty zero.)
`PriorTrend`	Real	Depth trend using prior trend coefficients. (`-` if universal kriging mode.)
`EstimTrend`	Real	Depth trend using estimated (GLS) trend coefficients. (`-` if too few data or simple kriging.)
`PostTrend`	Real	Depth trend using posterior trend coefficients. (`-` unless Bayesian `<kriging-method>`.)
`SimTrend`	Real	Depth trend using simulated trend coefficients. (`-` unless stochastic simulation `<mode>`.)
`PriorTrendSD`	Real	Prior depth trend uncertainty (SD). (`-` if universal kriging mode.)
`EstimTrendSD`	Real	Estimated depth trend uncertainty (SD). (`-` if too few data or simple kriging.)
`PostTrendSD`	Real	Posterior depth trend uncertainty (SD). (`-` unless Bayesian kriging mode.)
`TrendUncertRed`	Real	Reduction (in %) between prior and posterior uncertainty (SD). (`-` unless Bayesian kriging mode.)
`SpecPickTVD-SD`	Real	Well point TVD pick uncertainty (SD) specified by the user.
`PickTVD-SD`	Real	Well point TVD pick uncertainty (SD) including user specified and automatically added.
`WellTVD-SD`	Real	Well path TVD uncertainty (SD) at well point.
`Residual`	Real	Difference between well point TVD and trend.
`ResidualSD`	Real	Residual depth uncertainty (SD).
`TotSD`	Real	Sum of trend uncertainty and residual uncertainty.
`Mismatch`	Real	Mismatch between observed well point TVD and predicted depth in map. Caused by gridding error and TVD pick uncertainty.
`h`	Real	Used for classifying leverage points. Number between 0 and 1 (Section 18.3.5.1).
`t-value`	Real	Used for outlier classification. `t-value` = |`Residual`|/`ResidualSD`.
`t-Student`	Real	Replaces `t-value` when `h` is available.

When two well points are found to be close, COHIBA checks if there is a potential conflict, that is, the slope between the well points is more than 10 %. A potential conflict is flagged in the `Conflict` column. This typically happens if side tracks have been inconsistently adjusted. A potential conflict might be a serious error and should be checked by the user. A well point can be removed by adding it to the well point file specified in the `<well-points-to-ignore>` element.

COHIBA automatically adds a well point TVD pick uncertainty to all close well points to ensure numerical stability.[4] This is flagged in the `AddUncert` column. The amount of uncertainty added can be found by comparing the columns `TotPickSD` and `PickSD`. The added uncertainty depends on the TVD difference between the potentially conflicting data.

The `LevPoint` flag signals that a particular data point is a leverage point. A leverage point has a very strong influence on the trend coefficients in the trends so these data should be inspected to ensure that they are correct. Leverage points are less likely when there is a lot of data.

Mismatches and conflicts between the trend model and the well points are flagged in the `Outlier` column. If the data had a perfect Gaussian distribution, 5 % of the well points would be classified as outliers. Outliers are classified in four levels depending on severity: *outlier*, *severe outlier*, *error* and *extreme error*. COHIBA adds a well point TVD pick uncertainty to severe outliers, and removes well points that are classified as an error from kriging. Extreme errors are removed from all calculations. COHIBA handles all these situations automatically but it is strongly recommended to look into the reasons for the inconsistency between well points and the trend model.

The final flag in the `Deleted` column shows the well points that have been deleted prior to the trend estimation. There are three situations when well points are removed: Well points outside the grid boundary are not used, well points are a pinch out between other surfaces, and if the specified residual uncertainty (SD) is zero at the well point location.

7.2.10.2 Trend values in `wellpoints.csv`

The trend values, columns `PriorTrend`, `EstimTrend` `PostTrend`, and `SimTrend`, are obtained by evaluating the trends at the well point locations. Some of the trend values might be undefined depending on the `<kriging-method>` and the `<mode>` (`prediction/simulation`).

These values should be compared to the observed TVD in column `TVD`.

7.2.10.3 Trend uncertainty in `wellpoints.csv`

These are given in columns `PriorTrendSD`, `EstimTrendSD` and `PostTrendSD`. These values are obtained by evaluating the impact of the uncertainty in the trend coefficients on the depth uncertainty at the well point locations. Some of these columns may be undefined depending on the `<kriging-method>` and the `<mode>` (`prediction/simulation`). All values are standard deviation (SD).

For the Bayesian kriging mode the column `TrendSDRed` is evaluated. It shows

$$(\texttt{PriorTrendSD} - \texttt{PostTrendSD})/\texttt{PriorTrendSD}$$

in percent. The value will be between 0 % and 100 %. A small value indicates that well points has minor impact on the estimated trend in this location. Consider increasing the prior SD of the trend coefficients if well data has minor impact on the trend at many locations.

7.2.10.4 Pick uncertainty in `wellpoints.csv`

Well point TVD pick uncertainty is specified in the last column in the COHIBA well points file. These uncertainties are reported in column `PickSD`. COHIBA adds additional pick uncertainty if potential conflicts are detected. The resulting total pick uncertainty is reported in `TotPickSD`. These are reported as SDs.

4. Well point TVD pick uncertainty is only added if the well point has no initial well pick uncertainty.

The automatically added pick uncertainty (SD) is given by

$$\sqrt{\texttt{TotPickSD}^2 - \texttt{PickSD}^2}.$$

(Variances add linearly.)

7.2.10.5 Residuals and uncertainties in `wellpoints.csv`

The column `Residual` contains the difference between the observed TVD (in `TVD` column) and the trend. The trend depends on the `<kriging-method>` and the `<mode>` (`prediction/simulation`) specified in the COHIBA model file.

The `ResidualSD` column shows the model uncertainty obtained by aggregating the uncertainty in all intervals that are needed to obtain this surface. This include uncertainties in travel time, interval velocity, and interval thickness. All these uncertainties are specified in the `<variogram>` elements.

The `TotPickSD` column contains the total uncertainties and is a combination of `ResidualSD` and the uncertainty in the trend (i.e. `PostTrendSD` with Bayesian kriging mode). Comparing the `TotPickSD` column to the `ResidualSD` column shows if it is the local residual uncertainty or the global trend uncertainty that dominates.

The `Mismatch` column shows the difference between the well point and the prediction obtained by using bilinear interpolation between the four nearest predicted values in the grid. The mismatch is the sum of two factors:

1. A *gridding error* that is proportional to the `Residual` values. The gridding error can be large (several meters) if the residual is large. The gridding error is inevitable unless well points coincide with a grid corner location. See Figure 18.1 for an illustration.
2. Kriging is not a perfect interpolator when well point TVD pick uncertainties are present. Pick uncertainties can be specified in the COHIBA well points file and the pick uncertainties are estimated from the resolution of the zone logs when well points are calculated from zone logs.

The mismatch between well point TVD values and the predicted surface depth is by default removed in the post processing by adjusting the four grid values closest to each well point. This is not done for well points with a significant TVD pick uncertainty (> 1 meter by default). The adjustment of the grid values can be turned off using `<make-surfaces-interpolate-well-points>`.

7.2.10.6 Statistical measures for outliers in `wellpoints.csv`

Leverage points are well points that influence the estimated trend values strongly. A corrupted leverage point might not be identified as an outlier because the estimates adapts to it. The column `h` contains the diagonal elements of what is called the hat matrix. This is a by-product of linear regression and can be used to identify leverage points. It is not available if the linear regression fails. See Section 18.3.5 for details.

The `t` column contains the t-value for each well point:

$$\texttt{t} = |\texttt{Residual}|/\texttt{ResidualSD}.$$

The t-value is used for classifying outliers. Large values indicates that there is a severe mismatch between the well point and trend. Values above 1.96 are flagged as outliers, above 2.57 as uncertain, and values above 3.09 is classified as errors[5]. If the well points had a perfect Gaussian distribution this would occur with a frequency of 5 %, 1 %, and 0.2 % respectively.

5. These thresholds can be modified by the elements `<t-value-outlier>`, `<t-value-severe-outlier>`, and `<t-value-error>`.

The tStud column is similar to t but includes a correction for leverage points. This makes it possible to identify leverage points as outliers even though the trend coefficients have adapted strongly to them.

7.2.11 The targetpoints.csv file

Logs the surface target points used for conditioning on well paths with zone logs. This file is only generated if there are constraints from well paths that COHIBA consider relevant.

7.3 Files in the spill-points/ directory

In addition to the trap output grids written to surfaces/, COHIBA generates a set of files for analyzing the trap(s). These files are written to the directory spill-points/ under the output directory. This directory is only created when spill point calculations are required.

The spillpoint-Surface.rxat file contains the spill points coordinates of surface Surface using the ROXAR ATTRIBUTES TEXT format. For stochastic simulation, the spill point coordinates for each realization is listed on a separate line. The realization number is the only attribute and is called SimulationNumber.

The fillpath-Surface.rxat file contain the set of points on surface Surface visited by the spill point detection algorithm before it terminates. The trail starts at the starting point (of the algorithm) and finish at some boundary point. Possible traps will be seen as clusters of points. This file is only generated when spill points are triggered from command line (see Section 4.3).

7.4 Files in the target-points/ directory

For an explanation of surface target points and well target points see page 200. These files are saved in the target-points/ directory under the specified output directory. The file format is ROXAR ATTRIBUTES TEXT.

There is a *surface* target points file surface-targetpoints.rxat that contains all surface target points. There are also surface target points files for each well and surface that are named surface-targetpoints-Well.rxat and surface-targetpoints-Surface.rxat where Well and Surface is replaced by the well and surface names respectively.

There is one *well* target points file well-targetpoints.rxat that contains all well target points. There is also a well target points file for each well that is named well-targetpoints-Well.rxat where Well is replaced by the well name. These files are only generated if <allow-wells-to-move> is set to yes.

7.5 Files in the well-logs/ directory

Output well logs files are saved in the well-logs/ directory under the specified output directory. The file format is ROXAR RMS WELL. These files can be used to compare the original well logs in the welldata/ in the input/ directory.

There is one well logs file for each well and these are named Well.rmswell where Well is replaced by the well names.

These files are only generated if <write-wells> is yes (default is no) or if <condition-to-well-paths> and <allow-wells-to-move> are both yes. Then the well path TVD uncertainty is taken into account and the TVD values along the well path will be modified to improve consistency with the surfaces. The modified TVD replace the original TVD values in the Well.rmswell output files.

The output well log files are similar to the input well log files. The difference between the input well log files and the output well log files are primarily the modified TVD values. In addition a log called RepositioningDifference is added. This log is the difference between modified TVD

values and original TVD values.

A log called `Mismatch` contain the TVD mismatch. If the zonation is correct the value is 0.0, otherwise the absolute TVD mismatch is given.

COHIBA replaces input well path TVD uncertainty log values that are missing or negative by proper values. The modified logs replace the original well path TVD uncertainty logs by modified (reduced) uncertainty logs in the output well log files.

If `<allow-wells-to-move>` is `yes` and `<wellpath-TVD-SD-log-name>` is not used, a parametric well path TVD uncertainty log is generated. This log is called `Well-path-TVD-SD` when added to the output well logs files.

7.6 Files in the `well-points/` directory

Well point files are saved in the `well-points/` directory under the specified output directory. The file format is ROXAR ATTRIBUTES TEXT. These files can be used to inspect a large number of properties at each well point. The available attributes are described in Table 7.8.

The `wellpoints.rxat` file contains a line for every well point. There are also separate files that only includes well points that belong to a single well or surface. These are named `wellpoints-Well.rxat` and `wellpoints-Surface.rxat` where `Well` and `Surface` are replaced by well and surface names respectively.

These attributes are almost the same as the columns in `wellpoints.csv` that are described in Table 7.7.

7.7 Files in the `zonation-points/` directory

For an explanation of zonation points see Section 21.1. The zonation points files are saved in the `zonation-points/` directory under the specified output directory. The file format is ROXAR ATTRIBUTES TEXT.

The `zonationpoints.rxat` file contain all zonation points along all well paths. There are also files that only include zonation points for each well, named `zonationpoints-Well.rxat` where `Well` is replaced by the well names. Se Table 7.10 for details.

Table 7.8. Well point attributes used in the ROXAR ATTRIBUTES TEXT files wellpoints.rxat, wellpoints-Well.rxat and wellpoints-Surface.rxat.

Attribute name	Type	Description
Original Z-value	Float	TVD input data. Added if <allow-wells-to-move> is yes.
Change in Z-value	Float	TVD adjustment. Added if <allow-wells-to-move> is yes.
Measured depth	Float	MD calculated along the well.
Travel time value	Float	Travel times (from <travel-time> grids).
Surface	String	Name of surface.
Well	String	Name of well.
Fault block	String	Name of fault block (in ROXAR RMS).
Obtained from zone log	Discrete	1 if true and 0 if false.
Point has a duplicate	Discrete	1 if true and 0 if false.
Possibly involved in conflict	Discrete	1 if true and 0 if false.
Close observation uncertainty added	Discrete	1 if true and 0 if false.
Severe outlier uncertainty added	Discrete	1 if true and 0 if false.
Part of pinch-out	Discrete	1 if true and 0 if false.
Leverage point	Discrete	1 if true and 0 if false.
Outlier	Discrete	1 if true and 0 if false.
Deleted	Discrete	1 if true and 0 if false.
Prior trend	Float	Depth trend using prior trend coefficients. ('-' if universal kriging mode.)
Estimated trend	Float	Depth trend using estimated (GLS) trend coefficients. ('-' if too few data or simple kriging.)
Posterior trend	Float	Depth trend using posterior trend coefficients. ('-' unless Bayesian <kriging-method>.)
Simulated trend	Float	Depth trend using simulated trend coefficients. ('-' unless stochastic simulation <mode>.)
Prior trend uncertainty (SD)	Float	Prior depth trend uncertainty. ('-' if universal kriging mode.)
Estimated trend uncertainty (SD)	Float	Estimated depth trend uncertainty. ('-' if too few data or simple kriging.)
Posterior trend uncertainty (SD)	Float	Posterior depth trend uncertainty. ('-' unless Bayesian kriging mode.)
Trend uncertainty reduction	Float	Reduction (in %) between prior and posterior uncertainty. ('-' unless Bayesian kriging mode.)
Well point TVD pick uncertainty specified (SD)	Float	Pick uncertainty specified by the user.
Well point TVD pick uncertainty (SD)	Float	Pick uncertainty including user specified and automatically added.
Well path TVD uncertainty (SD)	Float	Well path TVD uncertainty specified by uncertainty log.
Residual	Float	Difference between TVD and depth trend.
Residual uncertainty (SD)	Float	Residual depth uncertainty.
Total uncertainty (SD)	Float	Sum of depth trend uncertainty and residual depth uncertainty.
Mismatch	Float	Mismatch between observed TVD and predicted depth in map. Caused by gridding error and TVD pick uncertainty.
Leverage point indicator	Float	Used for classifying leverage points. Between 0 and 1.
t-value	Float	t-value = |Residual|/Residual uncertainty. (Used for outlier classification.)
t-Student	Float	Replaces t-value when Leverage point indicator is available.

7.8 The `expert/` directory

There is a large number of possible output files that are saved in the `expert/` directory under the specified output directory. These are only written if `<write-expert-files>` is set to `yes`. The default is `no`. These files are not necessary for normal QC and is mainly intended for special situations such as debugging by developers.

The `expert/` directory contains the sub-directories `branching-points/`, `clusters/`, `expert-log-files/`, `extrapolation/`, `help-points/`, `target-points/`, `well-points/`, and `zonation-points/`.

The content of these are briefly described in the following but note that there might be additional undocumented files and directories in the `expert/` directory. Most of the files however are self-explanatory.

7.8.1 Files in the `branching-points/` directory

This directory contains the file `branching-points.rxat` in the ROXAR ATTRIBUTES TEXT format that lists all branching points detected by COHIBA in the input wells. Branching points are also logged in the `Section 7: Well branching` in COHIBA log file. Normally a multilateral well with n branches will have $n - 1$ branching points. A file could look like:

```
Float MD
Float max-merge-distance
String Wells
533526.21 6744757.27 1559.67  2258.89 0.000 "10/2-X-13_Y1H, 10/2-X-13_Y1HT2"
533483.39 6744772.95 1559.36  2228.49 0.005 "10/2-X-13_Y1H, 10/2-X-13_Y2H, 31/2-X-13_Y1HT2"
533393.44 6744807.11 1558.76  2172.78 0.007 "10/2-X-13_Y1H, 10/2-X-13_Y2H, 10/2-X-13_Y3H, 10/2-X-13_Y1HT2"
```

The maximum merging distance is zero when different branches are sampled identically. This is the normal situation.

7.8.2 Files in the `clusters/` directory

When finding surface target points and help points to replace the surface constraints, these are grouped into clusters. Each cluster is handled separately. See Section 21.4 for details.

The `cluster-Num-wellpoints.xyz` file contains the well points belonging to cluster number `Num`. The `cluster-Num-constraints.xyz` file contains the target points belonging to cluster number `Num`. The file format is xyz-file. These files are only written if `<write-xyz-point-files>` is set to `yes`.

The `cluster-large-mismatch-Num.rxat` and `cluster-large-mismatch-Well.rxat` files contains target points for cluster number `Num` or well `Well` for which there is a large mismatch between the target point depth and the (interpolated) surface value. This mismatch is partly due to the gridding error, but may also indicate numerical problems. Mismatches may arise if clusters are incorrectly treated as independent of each other (ref. `<threshold-for-cluster-merging>`), if clusters become too large (convergence problems), or if a too small neighborhood is used in the final surface conditioning. These files are written using the ROXAR ATTRIBUTES TEXT format.

7.8.3 Files in the `expert-log-files/` directory

The `posterior-correlation-matrix.dat` file contains the posterior correlation matrix between trend coefficients. The diagonal is the posterior uncertainty `PostSD` given in file `trend-estimation.csv`. The sequence follows the sequence in `trend-estimation.csv`. This is an ASCII file.

7.8.4 Files in the `extrapolation/` directory

This directory contains extrapolated

If `<extrapolate-input-surfaces>` is used, then all areas with missing codes in input trends, travel time and SD maps will be replaced by extrapolated values. The extrapolated input maps

can be written to this directory. The file names are the original file names with an additional prefix `extrapolated_`.

In addition, the points used when extrapolating the missing areas are saved in three files with post-fix `_points_control.rxat`, `_points_edges.rxat`, and `_points_stationary.rxat`. These files are written using the ROXAR ATTRIBUTES TEXT format.

7.8.5 Files in the `help-points/` directory

A surface help point is calculated for each surface constraint. The surface help points are used to push or drag surfaces away from selected zonation points along the well paths. Surface help points are only used when making deterministic surfaces in prediction `<mode>`.

The surface help points enters the kriging equations as ordinary well points but they have associated TVD pick uncertainty. Surface help points belonging to the same cluster will have correlated TVD pick uncertainty.

The surface help points are chosen so that the surfaces interpolate the surface target points. Surface target points are the expected location of the (deterministic) surface at the surface constraints. The Data Augmentation Algorithm is used for calculating the surface target points. See Section 21.1 for details.

The `helppoints-Surface.xyz` and `helppoints-Well.xyz` files contains the surface help points that belongs to `Surface` or `Well` respectively. The file format is xyz-file. These files are only written if `<write-xyz-point-files>` is set to `yes`.

7.8.6 Files in the `target-points/` directory

The `targetpoints-Surface.xyz` and `targetpoints-Well.xyz` files contains the surface target points that belongs to `Surface` or `Well`. The file format is xyz-file. These files are only written if `<write-xyz-point-files>` is set to `yes`.

7.8.7 Files in the `well-points/` directory

The `wellpoints-before-processing.dat` file contains all the well points initially considered by COHIBA. It is written as a COHIBA well points file. The well points can be imported from multiple COHIBA well points files and from well paths containing zone logs. The well points specified in the files in the `<well-points-to-ignore>` element are removed from this list.

COHIBA removes unnecessary or corrupt data, and the remaining data after the pre-process is written to the `wellpoints.dat` file using the COHIBA well points file format. This file can be used as input to COHIBA. Note however that it does not contain all information from well paths with zone logs; only the zone transitions are kept.

The excluded well points, the difference between between `wellpoints-before-processing.dat` and `wellpoints.dat`, are collected in the xyz-files `wellpoints-excluded-surface-Surface.xyz`, `wellpoints-excluded-zonelog-Well.xyz`, and `excluded-wellpoints-pointfile-Well.xyz`. The first set of files contains excluded well points belonging to surface `Surface`, the second set of files contains excluded well points extracted from zone logs in well `Well`, and the last set of files contain excluded well points read from COHIBA well points files that belongs to well `Well`.

7.8.8 Files in the `zonation-points/` directory

Zonation points selected from LAS 2.0 well or ROXAR RMS WELL files are chosen at approximately twice the lateral grid spacing.

The `zonationpoints.dat` file contains all zonation points along all wells. The file is an ASCII file with x-coordinate, y-coordinate, TVD and the zone code for each zonation point.

The `zonationpoints-Well.rxat` file contains information about zonation points in `Well` when surfaces have been conditioned to well points only and *not* to surface constraints at the selected

Table 7.9. File naming convention for the `zonation-Status-Well.xyz` files. See Table 7.5 for explanation of zonation status codes.

File name	Zonation status
`zonation-failed-Well.xyz`	N
`zonation-broken-Well.xyz`	B & F
`zonation-noncorrectable-Well.xyz`	X
`zonation-undefined-Well.xyz`	U

zonation points. The files use the ROXAR ATTRIBUTES TEXT. The available attributes are listed in Table 7.10.

Well path points where the zone log is inconsistent with the calculated surfaces are written to a set of xyz-files. These files are only written if `<write-xyz-point-files>` is set to `yes`. These files are named `zonation-Status-Well.xyz` where `Status` is replaced by zonation status type and `Well` is replaced by well names. The status types are explained in Table 7.5 and the file naming conventions are shown in Table 7.9.

The zonation is *non-correctable* if the zonation points are inside a very thin zone or if the surface must be moved more that 3.09 SDs. (See `<t-value-error>`.)

The *failed* and *broken* zonation refers to zonation points where COHIBA is unable to get the zonation correct. Broken zonation means that the zonation at this well point was correct when surfaces were conditioned to well points alone.

The `zonationpoints-special.xyz` file contains the zonation points at the branching points and the zonation points at the edges of zonation. The edges are where zone log values changes from defined to undefined or at the endpoint of wells. See Section 8.5.1 for some illustrations. This is an xyz-file. This file is only written if `<write-xyz-point-files>` is set to `yes`.

Table 7.10. Attributes in the `zonationpoints-Well.rxat` files after the conditioning on well paths.

Attribute name	Type	Description
`Measured Depth`	`Float`	MD at zonation point location.
`Well`	`String`	Name of the well.
`Fault block`	`Discrete`	Fault block number (ROXAR RMS).
`Deactivated point`	`String`	See Table 7.11.
`Branching point`	`Discrete`	1 if a branching point. 0 otherwise.
`Isochore thickness`	`Float`	Isochore thickness at zonation point location.
`Isochore thickness change`	`Float`	Isochore trend thick. at zonation point location.
`Distance to top surface`	`Float`	Distance to top surface from zonation point.
`Change in distance to top surface`	`Float`	Change in dist. to top surface from zonation point.
`Distance to base surface`	`Float`	Distance to base surface from zonation point.
`Change in distance to base surface`	`Float`	Change in dist. to base surface from zonation point.
`Name of true zone`	`String`	Zone name in well at zonation point location.
`True zone`	`Discrete`	Zone number in well at zonation point location.
`Name of calculated zone`	`String`	Zone name in resulting surface model.
`Calculated zone`	`Discrete`	Zone number in resulting surface model.
`Zonation match`	`String`	Match between true and calculated zones? (Table 7.11)
`Zonation corrected with zone log conditioning`	`String`	Was zonation corrected? (See Table 7.11.)

Table 7.11. The possible values for the attributes `Deactivated point`, `Matching zonation` and `Zonation corrected with zone log conditioning` in `zonationpoints-Well.rxat` files.

Attribute name	Description
`Deactivated point`	Details about possibly deactivated zonation point.
`-`	Not deactivated.
`D`	Duplicate of another point.
`F`	Too close to a fault.
`W`	Too close to a well point in another well.
`U`	Associated with undefined surface/interval values.
`Matching zonation`	Initial zonation status. See Table 7.4 for more details.
`Y`	Zonation matches.
`N`	Zonation does not match.
`U`	Zonation status is undefined.
`Zonation corrected...`	Final zonation status. See Table 7.5 for more details.
`-`	Zonation matched without surface help points.
`Y`	Zonation was fixed by surface help points.
`N`	Zonation was not fixed. Unknown why.
`B`	Zonation was broken by introduction of surface help points.
`F`	Zonation was broken but can be fixed by iterations. Use `<minimize-broken-zonation>` to activate.
`X`	Zonation was not fixed because surface help points could not be used.
`U`	Zonation is undefined in either well of surface model.

8 Well data

There are two types of well data used by COHIBA: *Well points* and *well paths with zone logs*. Well points[1] are the intersections between a well path and a surface. The zone logs are a representation of the zonation along the well path.

The preferred approach is to use well paths with zone logs. Then COHIBA detects zone transitions along the well paths and record them as well points. For deviated or horizontal wells, COHIBA ensures that all surfaces are located correctly according to the zonation along the well paths.

The file formats used for importing well data are described in Section 6.3.

8.1 Using well path with zone logs

The ROXAR RMS WELL or LAS 2.0 well formats are used for importing well paths with zone logs.

There is no generic relationship between the surfaces in the COHIBA model and the zones in the zone log. The link between surfaces and zones are made by specifying which zone a surface is directly on top of using the `<top-of-zone>` element. Non-unique zone names are discussed in Section 8.4.5.

The well path with zone log files can contain a series of different logs so the particular zone log we want to use must be chosen using `<zone-log-name>`. Zone logs are numbers (non-negative integers) that must be linked to zone names. For ROXAR RMS WELL files these numbers are linked to zone names in the file header:

```
GM2005a DISC 1 ABOVE 2 DRAUPNE 3 6BC 4 6AC 5 6AM 6 5CC 7 5CM 8 5BC
```

Here `GM2005a` is the zone log name, `DISC` specifies that the log is discrete, and the rest is the list of zone numbers and their associated zone names. The zone numbers must constitute a sequence of non-negative integers that increase by one.

The LAS 2.0 well format does not include the zone names in the header so this must be supplied using `<zone-log-specification>`. This specification is very similar to the header in the ROXAR RMS WELL files but it allows more general zone names.

Note that the zone name specification must be identical for all zone logs. Files with different zone name specification will be discarded. Also note that well names must be unique. An error is reported if there are multiple files with identical well names. This is to avoid reading the same data repeatedly.

8.2 Using fault indicator logs

COHIBA can not distinguish between a zone transition at a surface or a zone transition at a fault. In both cases, the transition will be interpreted as a zone top. This is not correct if the transition is at a fault.

To avoid this situation, we can add *fault indicator logs* to the existing well logs. These logs are discrete and consist of 0's and 1's. A 1 means that we are close to a fault and that COHIBA should ignore zone transitions.

The fault indicator log is properly specified in the header of the ROXAR RMS WELL file as

1. Well points ares sometimes called well picks or well markers.

```
FaultIndicator DISC 0 no 1 yes
```

where the structure is fixed except the label `FaultIndicator`. The fault indicator logs are specified using the `<fault-log-name>` in the `<well-log>` element.

8.3 Close well points

If two or more well points are close they are likely to either carry *redundant* or *conflicting* information. In both cases COHIBA has to modify the well points to avoid numerical instabilities. Depending on the situation, COHIBA will either delete well points or add uncertainties to well points.

Two well points are considered laterally close if their separation in the x- and y-directions are smaller than the corresponding grid cell sizes. Since this measure is linked to the grid resolution, fewer points will be considered close as the resolution increases. For two well points to be considered *close* they must also be close vertically, and the action taken depends on whether the well points belong to the *same* or *different* surfaces.

8.3.1 Identical well points

COHIBA looks for *identical* well points at two different stages in the calculation: When well points and well logs are read from file, and when well points are checked for internal consistency.

1. Upon reading well point files and well log files, identical well points are identified and one is removed. At this stage, well points are regarded as identical if they belong to the same well and same surface, and if their lateral and vertical coordinates are within one centimeter. Such duplicates are typically encountered because a well point file contains repeated information, or because both well point files and well logs are used as input.

2. When well points are checked for internal consistency, COHIBA looks for points that, for all practical purposes, are the same surface observation. In this case, well points are treated as identical if their lateral distance is less than 5.0 meters, and their vertical distance is less than 0.5 meters. The points may belong to different wells. Only one point is used for calculations, but the other point is later reintroduced for logging/visualization purposes and given the same attributes as the point that was kept. The threshold for being considered identical can be controlled by keywords `<max-dxy-for-identical-well-points>` and `<max-dz-for-identical-well-points>`.

If both well points are taken from zone logs or both well points are taken from well points files (Section 6.3.2) COHIBA keep the well point with the lowest specified TVD pick uncertainty. If one well point is from well points file and one well point is from a zone log, the well point from the well points file is kept. Well points files can therefore be used to specify the TVD pick uncertainty of well points extracted from a zone log.

8.3.2 Close well points belonging to different surfaces — pinch outs

If two or more well points belong to different surfaces, they are considered close if they are laterally close and their TVD difference is smaller than one centimeter.

This situation creates a *pinch out*. When pinch outs are encountered, the correlation between all pairs of points are calculated, and if the correlation is larger than 0.999, only the uppermost point is retained.

Well points that are part of a pinch out are flagged by a `P` in the `PinchOut` column of the `wellpoints.csv` file. If the point has been deleted the `P` is given in the `Deleted` column instead.

8.3.3 Close well points belonging to the same surface

If two or more well points belong to the same surface, they are considered close if they are laterally close. They are considered *similar* if the slope between them are less than 10 %, that is, $\Delta z/\Delta xy < 0.1$. They are considered *potentially conflicting* if the slope is larger than 10 %. When two well points are involved in a potential conflict, these points, their lateral and vertical distance as well as their intermediate slope are written to the COHIBA log file, provided the log level is sufficiently high. A well point involved in a potential conflict is also indicated by a `C` in the `Conflict` column of the `wellpoints.csv` file.

To ensure numerical stability and to reflect the actual uncertainty, close well points are assigned a TVD pick uncertainty (SD) given by:

$$\sigma_z = \frac{1}{\sqrt{2}}|\Delta z|. \tag{8.1}$$

If one or both of the well points already have higher TVD pick uncertainties, no action is taken. Well points with increased TVD pick uncertainties are flagged by a `U` in the `AddUncert` column of the `wellpoints.csv` file.

8.3.4 Well points giving model error

If a residual uncertainty is set too low, a diagonal element of the kriging matrix may become small and lead to numerical instabilities. When this happens, COHIBA deletes the well point and reports this by giving an `E` in the `Deleted` column of the `wellpoints.csv` file.

This error is avoided by ensuring that the residual uncertainty is larger than zero.

8.3.5 Well points in undefined areas

Well points become redundant if at least one of the input surfaces (usually a time surface) has an undefined value in one of the four grid nodes around the observation. In such cases the well point is removed. To avoid this, the surface with undefined values should be interpolated or extrapolated in this area.

Well points removed because of undefined values are flagged by `S` in the `Deleted` column of the `wellpoints.csv` file.

The region outside the output grid is also treated as undefined. In this case the well point is flagged by a `B`.

8.4 Extracting well points from zone logs

Consider the 5 zones: `Overburden`, `A`, `B`, `C`, `D`, and refer to the surfaces (transition between zones) as `TA`, `TB`, `TC`, and `TD`. See Figure 8.1.

8.4.1 Simple zonation

If all zones have thicknesses larger than zero, it is straight forward to extract surfaces from zone transitions. The well passing through Figure 8.1 makes the zone transitions `Overburden`→`A`, `A`→`B`, `B`→`C`, and `C`→`D`, and the corresponding well points belongs to surfaces `TA`, `TB`, `TC`, and `TD`. The direction of the transition is irrelevant for the assignment of surfaces. The transition `A`→`B` and `B`→`A` are both observations of surface `TB`.

The zone log values are typically defined at one feet intervals. COHIBA will extract a well point in the middle between the two log values at the transition. Also COHIBA will use a TVD pick uncertainty that is $1/4$ the vertical difference between the two TVD values at the transition.

8.4.2 Zones with pinch outs

If a zone has zero thickness in some area, it is said to have a *pinch out*. When a zone transition is made in a pinch out, two surfaces are observed.

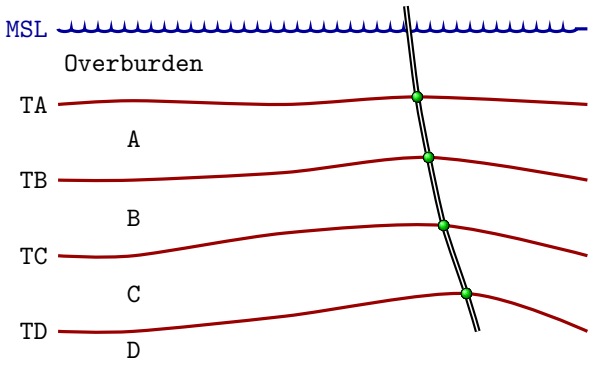


Figure 8.1. Transitions between a simple set of zones. The well points are given as green bullets.

In Figure 8.2, we have depicted a well crossing a set of zones where zone B has zero thickness in an area. The three zone transitions reported in the zone log are above→A, A→C, and C→D. While the former and latter of these transitions refer to surfaces TA and TD respectively, the middle transition is really the joint transition A→B→C, and is consequently an observation of the two surfaces TB and TC.

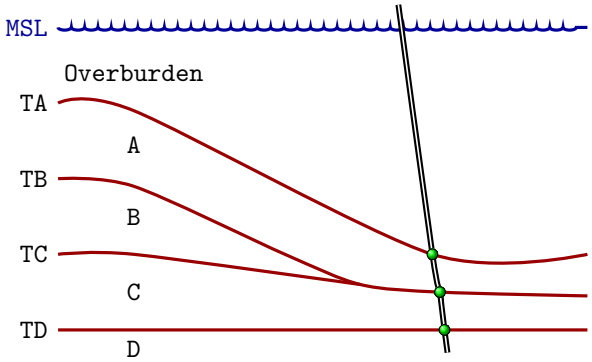


Figure 8.2. Zones with pinch out. The well points are given as green bullets.

A total of 12 different zone transitions may be observed between 5 zones. These are summarized in Table 8.1. Note that the table is symmetric in the "From" and "To" zones.

A well passing through a pinch out is a challenge as two well points get exactly the same coordinates. This may lead to numerical instabilities, requiring one of the observations to be removed. COHIBA is implemented to allow observations of different surfaces to coincide.

8.4.3 Erosive and onlapped surfaces

If we encounter a zone transition of type A→C, it is not always true that this transition may be interpreted as the transition A→B→C. For this relation to hold, surface TB cannot be erosive. If TB *is* erosive, the transition A→C will be an observation of TB alone and *not* TB and TC.

A similar situation occur when there is a surface with onlapping zones/surfaces. This surface is called *onlapped*. The situation is almost identical to the situation with erosion except that erosive surfaces truncate surfaces below whereas onlapped surfaces truncate surfaces above. Note that a surface can be both erosive and onlapped.

In Figure 8.3, we have illustrated a set of zones where the surface TB is erosive. The zone transitions observed in the well, are above→A, A→B, B→C, and C→A. As argued above and illustrated in the figure, the latter of these transitions is an observation of surface TB only. Note how the ero-

Table 8.1. Surfaces observed for different zone transitions.

	To			
From	A	B	C	D
A	—	TB	TB, TC	TB, TC, TD
B	TB	—	TC	TC, TD
C	TB, TC	TC	—	TD
D	TB, TC, TD	TC, TD	TD	—

Table 8.2. Surfaces observed for different zone transitions if surface TB is erosive.

	To			
From	A	B	C	D
A	—	TB	TB	TB
B	TB	—	TC	TC, TD
C	TB	TC	—	TD
D	TB	TC, TD	TD	—

siveness of surface TB, implies that one or more zones may be completely undefined (as opposed to being defined but with zero thickness).

Figure 8.4 illustrates the concept of an onlapped surface. Surface TD is onlapped by zones A, B, and C. As the onlapped surface truncate from below, the zone transition B→D becomes an observation of surface TD only.

In Table 8.2, we have summarized the different zone transitions that may be encountered with zones A, B, C, and D, where surface TB is erosive, and listed what surface-observation each transition corresponds to. The difference between this table and Table 8.1 is that, in all zone transitions involving zone A, only surface TB is observed. This is a result of the erosion. The symmetry in the "From" and "To" zones is maintained, however.

Whether a surface is erosive and/or onlapped or neither of these, is specified by the elements `<erosive>` and `<onlapped>`. When two or more surfaces are erosive, the upper surfaces erode the lower. In COHIBA, an erosive surface will erode an onlapped surface.

8.4.4 Faults

A transition between zones can be caused by a fault rather than a surface. This situation is illustrated in Figure 8.5.

Interpreting a zone transition caused by a fault as a well point could give corrupt results. The well shown in the figure enters from zone A into zone B via the fault. This zone transition is not an observation of TB.

It is impossible to distinguish a transition caused by a fault from an ordinary transition using a zone log alone. Therefore, some extra information must be supplied. This can be done by supplying *ignore points* using the element `<well-points-to-ignore>`. These are well points that should be excluded if found in the zone logs. An alternative is to specify a fault indicator log using the element `<fault-log-name>` in the element `<well-log>`.

8.4.5 Non-unique zone names

A zone log must be expected to contain more zones than those included in the COHIBA model file. Figure 8.6 illustrates a situation with nine zones and surfaces, but only four of these surfaces are of interest; the red surfaces labeled TA, TB, TC, and TD.

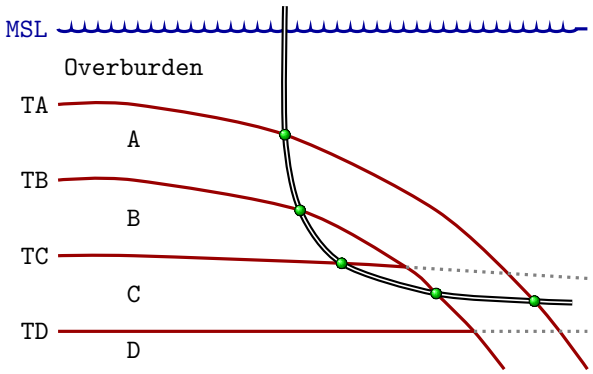


Figure 8.3. Zones where surface TB is erosive. The well points are given as green bullets.

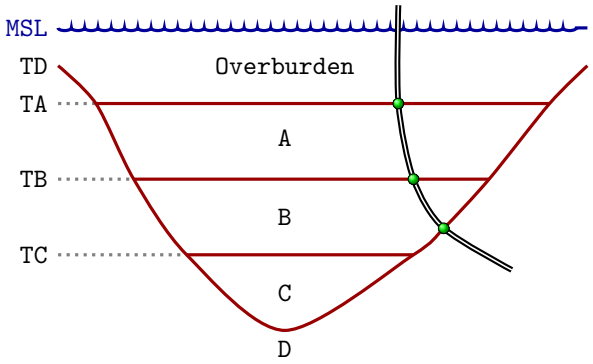


Figure 8.4. Zones where surface TD is onlapped. The well points are given as green bullets.

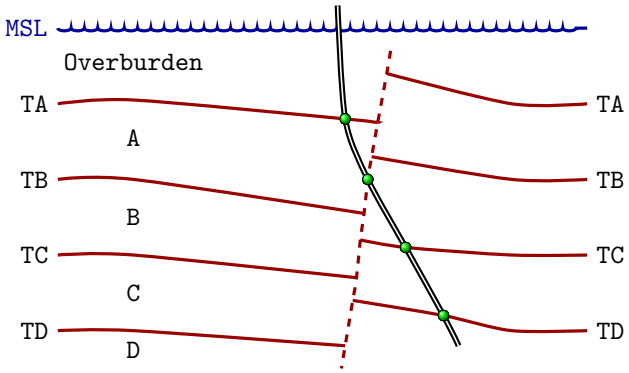


Figure 8.5. A set of faulted zones. The well points are given as green bullets.

To be able to extract the well points for these surfaces COHIBA needs to know the sequence of the surfaces and the name of the zones that are directly below the surface. The COHIBA model file specification use <top-of-zone> to associate a surface name as the top of the zones. The situation in Figure 8.6 could be specified as:

```
<surface>
   <name>        TA         </name>
   <top-of-zone> A, A'      </top-of-zone>
   ...
</surface>
<surface>
```

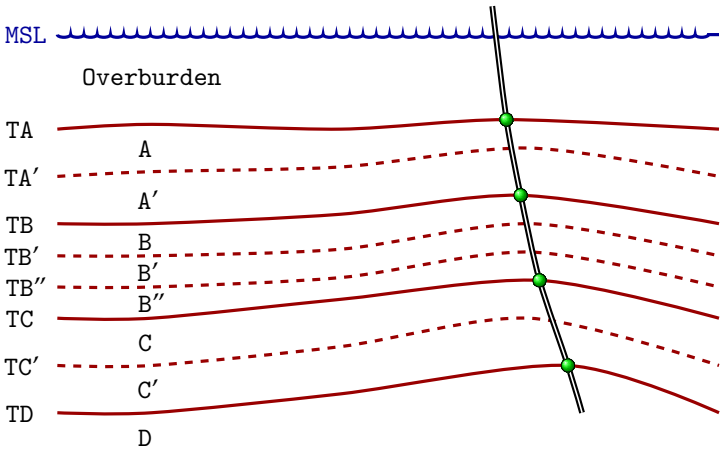


Figure 8.6. A simple set of zones with a zonation finer than the surface model. The well points are given as green bullets.

```
   <name>        TB         </name>
   <top-of-zone> B, B', B'' </top-of-zone>
   ...
</surface>
<surface>
   <name>        TC         </name>
   <top-of-zone> C, C'      </top-of-zone>
   ...
</surface>
<surface>
   <name>        TD         </name>
   <top-of-zone> D          </top-of-zone>
   ...
</surface>
```

It is sufficient to specify only the first zone since we require that zone numbers increase with increasing depth. So it is equivalent and simpler to write:

```
<surface>
   <name>        TA </name>
   <top-of-zone> A  </top-of-zone>
   ...
</surface>
<surface>
   <name>        TB </name>
   <top-of-zone> B  </top-of-zone>
   ...
</surface>
<surface>
   <name>        TC </name>
   <top-of-zone> C  </top-of-zone>
   ...
</surface>
<surface>
   <name>        TD </name>
   <top-of-zone> D  </top-of-zone>
   ...
</surface>
```

This alternative is better since it reduces the risk of introducing errors like typing errors or zonation errors. It requires that zone names are listed in the well-header in the correct depth order. By correct depth order we mean a consecutive increasing sequence of non-negative integers.

Example: Valid zone log:

```
LOGNAME DISC 1 ABOVE 2 A  3 B  4 C  5 D
```

Example: Valid zone log:

```
LOGNAME DISC 1 ABOVE 2 A  3 A'  4 B  5 B'  6 B''  7 C  8 C'  9 D
```

Example: Valid zone log:

```
LOGNAME DISC 10 ABOVE 11 A  12 A'  13 B  14 B'  15 B"  16 C  17 C'  18 D
```

Example: Invalid zone log:

```
LOGNAME DISC 9 ABOVE 11 A  12 A'  13 B  14 B'  15 B"  16 C  17 C'  18 D
```

(The number 10 is missing.)

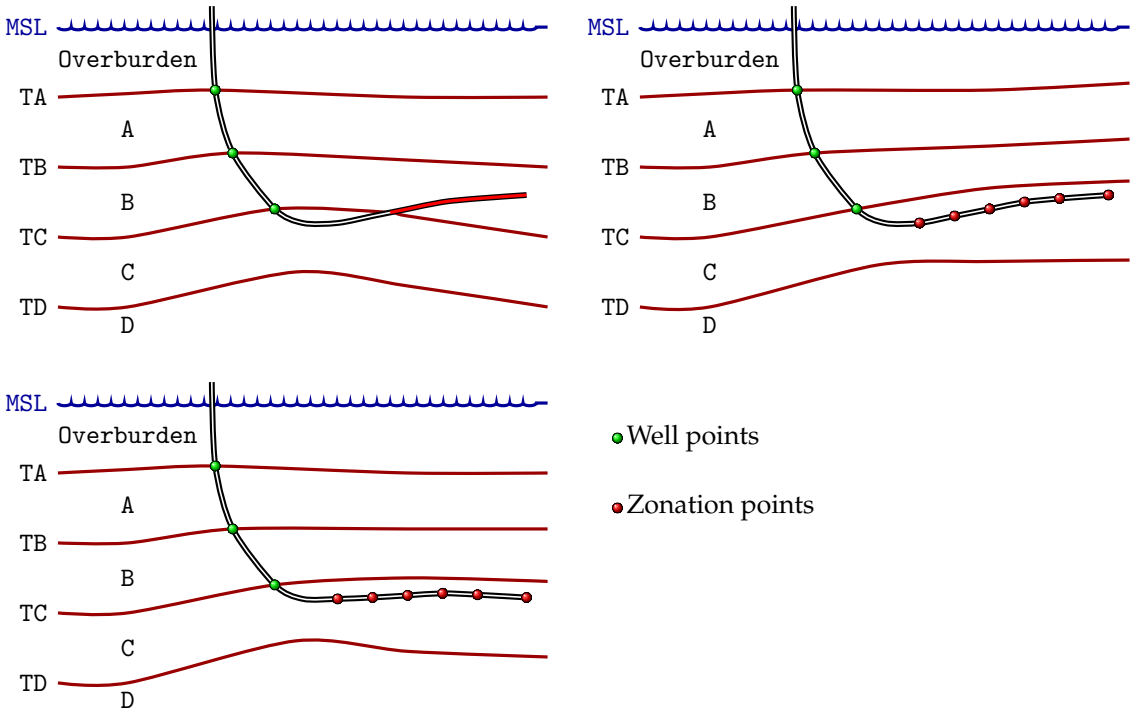


Figure 8.7. In the top left figure a part of the well (colored red) have ended up in the wrong zone. In the top right figure, the surfaces have been modified using surface constraints at selected zonation points along the well. In the lower figure the surfaces *and* the well path have been modified to obtain consistent results. Modifying the well path is possible if a well path TVD uncertainty is specified and `<allow-wells-to-move>` is set to `yes`.

8.5 Horizontal wells

In parts of a well where the well runs parallel to a surface, the well points alone are not enough to guarantee that surfaces are consistent with the zone logs. This is illustrated in the left part of Figure 8.7, where the well is colored red in the region with incorrect zonation.

To avoid that surfaces cross well paths at incorrect locations, COHIBA makes a series of *zonation points* along the well paths and impose surface constraints at selected zonation points when necessary. In the right part of Figure 8.7, six zonation points have have been introduced. Surface constraints at selected zonation points force the surface TC to lie above the well path in accordance with the zone log. The surface constraints do not state explicitly where the surface TC is located, they only force TC to stay above the well. Also note that the other surfaces will also be influenced by the constraints imposed on TC. The bottom figure COHIBA have modified the surfaces *and* the well path. This is possible if there is specified a well path TVD uncertainty and wells are allowed to move (see Section 8.5.2).

COHIBA handles surface constraints from zone logs according to the method developed in Abrahamsen and Benth (2001). Without going into details, the approach boils down to finding some additional surface help points used in the kriging equations. The additional surface help points are chosen so that surfaces are consistent with trends, residuals, well points and surface constraints at selected zonation points. For details see Section 21.

8.5.1 Undefined sections in the zone log

Many zone logs have sections that contain missing codes. This is usually the situation in the upper part of the well path. This is illustrated in Figure 8.8. It is also common that there are sections with undefined zonation in the middle of wells. This is illustrated in Figure 8.9. COHIBA

will add zonation points at the edges of the undefined sections. This includes the endpoints of wells when the zonation extends to the end. This will introduce surface constraints at the edges if these zonation points are among the selected zonation points. See Section 21 for more details on how the zonation points are used to ensure consistency between zone logs and surfaces.

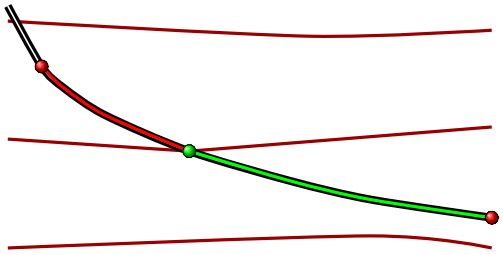


Figure 8.8. Cross section of three surfaces along a well path. A well point is marked by a green dot. Zonation points (red dots) are added at the end of sections with defined zonation. These zonation points may impose necessary surface constraints.

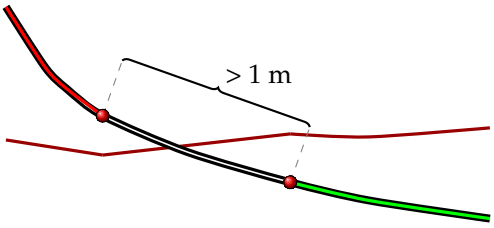


Figure 8.9. Cross section of one surface along a well path. Zonation points (red dots) are added at the edges of the undefined zone log section if the undefined section is long (ΔMD > 1 meter). These zonation points may impose necessary surface constraints.

COHIBA will handle a *short* undefined section as an ordinary zone log transition. That is, the zone log transition introduces a well point. Since the vertical gap could be slightly larger than normal zone log transition, the added well point TVD pick uncertainty[2] is usually larger. This is illustrated in Figure 8.10. The reason for replacing two close constraints by a single well point is to make calculations simpler and faster.

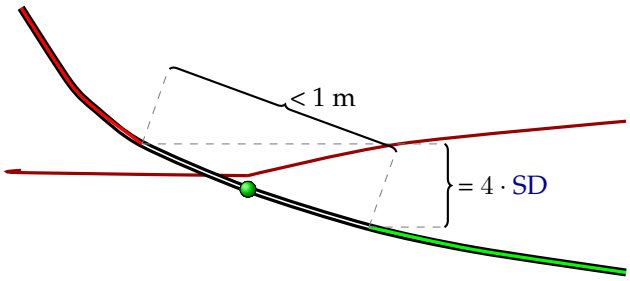


Figure 8.10. Cross section of one surface along a well path. A short (ΔMD ≤ 1 meter) undefined zone log section is replaced by a well point (green dot) at the center with TVD pick uncertainty (SD) equal to $\frac{1}{4}\,\Delta$TVD.

COHIBA considers an undefined section as short if the distance (MD) between the endpoints of the undefined section is less than one meter (default). This distance can be changed using the element `<threshold-for-removing-undefined-well-sections>`.

8.5.2 Well path TVD uncertainty

COHIBA will take into consideration the well path TVD uncertainty if `<allow-wells-to-move>` is set to `yes` (default is `no`). Then, the TVD values along the well paths will be updated so that the they become consistent with the surfaces. Updated TVD values are written to well log files in `well-logs/`. The updating of TVD values along the well path depend on the specified well path TVD uncertainty and the uncertainty of the surfaces constrained by the well path. This is illustrated in Figure 8.7.

2. The SD is 1/4 times the vertical gap (ΔTVD).

The well path TVD uncertainty is specified using `<wellpath-TVD-SD-log-name>`. This TVD uncertainty log must contain positive values and should be monotonically and smoothly increasing along the well paths. Well path TVD uncertainty logs that belong to different branches in the same multilateral well should have the same values along the common sections. COHIBA makes a number of QC checks on the well path TVD uncertainty logs and give warnings if unreasonable or inconsistent values are detected.

The well path TVD uncertainties must be smooth since the drill pipe is rigid. Moreover, the uncertainty must increase along the well path since the survey uncertainties accumulate for geomagnetic and inclination tools[3] along the well path. So the true well path has a tendency to drift away from the measured well path. Figure 8.11 illustrates this behavior. The smoothness is determined by `<wellpath-TVD-SD-range>` that has the default value of 300 meters.

Spatial smoothness and accumulation of survey uncertainty is obtained using a continuous stochastic process known as the *integrated Ornstein-Uhlenbeck process*. Stochastic realizations from the integrated Ornstein-Uhlenbeck process are continuous and smooth (differentiable). There is no direct way of measuring the smoothness since there is no way to observe the difference between the true well path and the measured well path. The default choice of 300 meters for `<wellpath-TVD-SD-range>` has been chosen because it gives reasonable results.

If `<allow-wells-to-move>` is `yes` and `<wellpath-TVD-SD-log-name>` is not used, a parametric well path TVD uncertainty log is generated. The increase in the well path TVD uncertainty can be modified by `<wellpath-TVD-SD-increase-rate>`. The default value is 4 meters for every 1000 meters of lateral distance along the well.

See Section 21.2 for some theoretical details on the integrated Ornstein-Uhlenbeck process.

3. See for instance the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA).

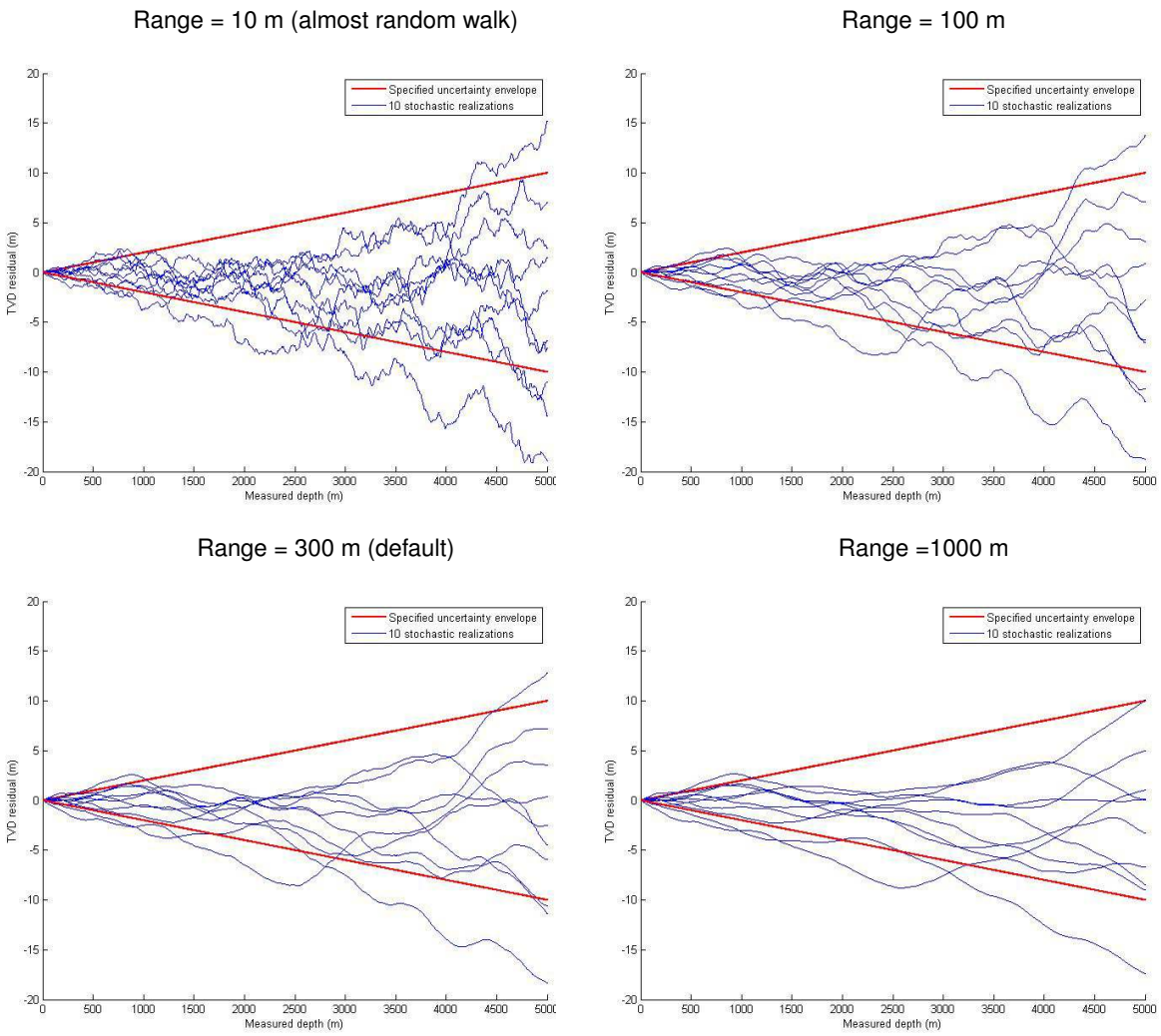
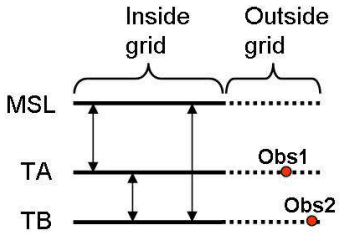


Figure 8.11. Well path TVD uncertainty as a function of MD. The red lines are the TVD uncertainty (± 2 SD) specified by `<wellpath-TVD-SD-log-name>`. The blue lines are simulated realizations of possible TVD residuals, that is, the difference between the true TVD and the measured TVD. The blue lines are realizations of the integrated Ornstein-Uhlenbeck process. The same random seeds have been used in the four different figures so similar curves with varying smoothness can be recognized in the different figures. The smoothness is specified by `<wellpath-TVD-SD-range>`.

8.6 Using well points outside lateral grid

Well points outside the grid definition can be added using the element `<values-outside-grid>` in the `<well-data>` element. At least one value will trigger the estimation of trend coefficients with this new point included in the estimation. Well points outside the lateral grid are not included in kriging. For each of these *outside grid well points* additional information must be provided. The number of `<value>` elements defines the minimum input required for other data types such as interval trend outside grid values, travel time outside grid values and SD outside grid values. If no (X,Y) coordinates are provided, COHIBA will automatically generate large coordinates. If a well-name is omitted, COHIBA generates the name "outside-well".

Example: Given three surfaces: `MSL`, `TA`, and `TB` (both `TA` and `TB` are reflectors) and three intervals: `MSL->TA`, `TA->TB` and `MSL->TB`:

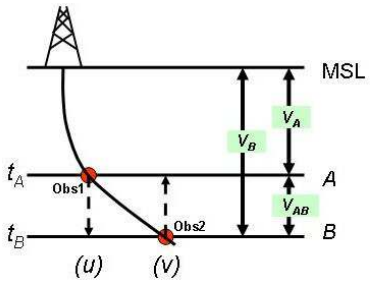


An outside grid well point (`Obs1`) at `TA` and an outside grid well point (`Obs2`) at `TB` require the following input:

Two values for travel time to `TA`
Two values for travel time residual SD for `TA`
Two values for travel time to `TB`
Two values for travel time residual SD for `TB`
Two values for interval velocity trend `MSL->TA`
Two values for interval velocity residual `MSL->TA`
Two values for interval velocity/isochore trend `TA->TB`
Two values for interval velocity/isochore residual `TA->TB`
Two values for interval velocity trend `MSL->TB`
Two values for interval velocity residual `MSL->TB`

This amounts to 20 values in total. If any of the values above are not entered, COHIBA will assume 0 as input, giving meaningless results. The required trend values must be taken at the same lateral location as the well point. This applies whether these extra well points originate from a vertical well or not. A consequence of this is that for a vertical well with one well point at both of two successive surfaces, the same values must be entered twice. Once for the first well point, and once for the second well point. COHIBA cannot assume that the well is vertical, and has no check for this.

A detailed look at the region outside the reservoir is illustrated below.



Following the system given in the list above, when Obs1 is located at u and Obs2 is located at v COHIBA therefore require:

$t_A(u)$ and $t_A(v)$
$\sigma_{t_A}(u)$ and $\sigma_{t_A}(v)$
$t_B(u)$ and $t_B(v)$
$\sigma_{t_B}(u)$ and $\sigma_{t_B}(v)$
$V_A(u)$ and $V_A(v)$
$\sigma_{V_A}(u)$ and $\sigma_{V_A}(v)$
$V_{AB}(u)$ and $V_{AB}(v)$
$\sigma_{V_{AB}}(u)$ and $\sigma_{V_{AB}}(v)$
$V_B(u)$ and $V_B(v)$
$\sigma_{V_B}(u)$ and $\sigma_{V_B}(v)$

Omitting the model dependency of the V_B velocity model would ideally reduce the required input to:

$t_A(u)$ and $t_A(v)$
$\sigma_{t_A}(u)$ and $\sigma_{t_A}(v)$
$t_B(v)$
$\sigma_{t_B}(v)$
$V_A(u)$ and $V_A(v)$
$\sigma_{V_A}(u)$ and $\sigma_{V_A}(v)$
$V_{AB}(v)$
$\sigma_{V_{AB}}(v)$

However, COHIBA has not yet included the functionality of checking for *required data* only. At the time COHIBA reads the COHIBA model file part containing the data for one surface, the information on whether or not it is a coupled model with two or just one possible interval paths to each surface, is not available. Therefore, COHIBA demands that the data is given under the assumption of coupled models. Dummy values for $t_B(u)$ and $\sigma_{t_B}(u)$ must therefore be provided when specifying data for surface B.

The necessary information is provided hierarchically as follows. The `<values-outside-grid>` sections are highlighted in red:

```
<cohiba>
  <project-settings>
     ......
  </project-settings>
  <modelling-settings>
     ......
  </modelling-settings>
  <welldata>
     ......

    <values-outside-grid>
      <value well-name="outside-well" surface-name="TA" x="456000.0" y="6766000.0" stddev="0.1">
         1010
      </value>
      <value surface-name = "TB">
         1040
      </value>
    </values-outside-grid>
     ......
  </welldata>
  <surfaces>
```

```
   <!--Surfaces MUST be listed in stratigraphic order -->
   <reference>
     ......
   </reference>
   <surface>
     <name>   TA    </name>
     ......
      <travel-time>
       ......

       <values-outside-grid>
         <value>  1.01  </value>
         <value>  1.03  </value>
       </values-outside-grid>
       <variogram>
          ......

          <values-outside-grid>
            <value>  0.005  </value>
            <value>  0.005  </value>
          </values-outside-grid>
        </variogram>
     </travel-time>
         ......
   </surface>
    <surface>
     <name>   TB    </name>
     ......
      <travel-time>
       ......

       <values-outside-grid>
         <value>  1.11  </value>
         <value>  1.13  </value>
       </values-outside-grid>
       <variogram>
          ......

          <values-outside-grid>
            <value>  0.005  </value>
            <value>  0.005  </value>
          </values-outside-grid>
        </variogram>
         ......
     </travel-time>
         ......
   </surface>
</surfaces>

<interval-models>
   <interval>
      <name>    MSL-to-TA        </name>
       <trend>
          ....

           <values-outside-grid>
             <value>  2505  </value>
```

```
          <value>  2510  </value>
        </values-outside-grid>
       ....
     </trend>
     <variogram>
         ......

        <values-outside-grid>
          <value>  10.0  </value>
          <value>  15.0  </value>
        </values-outside-grid>
        .....
     </variogram>
   .....
</interval>
<interval>
   <name>    TA-to-TB        </name>
     <trend>
       ....

        <values-outside-grid>
          <value>  32  </value>
          <value>  33  </value>
        </values-outside-grid>
       ....
     </trend>
     <variogram>
       .......

        <values-outside-grid>
          <value>  4.0  </value>
          <value>  5.0  </value>
        </values-outside-grid>
       .......
     </variogram>
   .....
</interval>
<interval>
   <name>    MSL-to-TB        </name>
     <trend>
       ....

        <values-outside-grid>
          <value>  13  </value>
          <value>  14  </value>
        </values-outside-grid>
       ....
     </trend>
     <variogram>
          ......

        <values-outside-grid>
          <value>  12.0  </value>
          <value>  13.0  </value>
        </values-outside-grid>
        ......
     </variogram>
```

```
        .....
      </interval>
    </interval-models>
</cohiba>
```

Part III
Tutorials

9 Volume calculations

COHIBA can calculate the gross rock volume of reservoirs confined between surfaces and hydrocarbon contacts (HCCs). Volume units are cubic meters.

Here is an example of a COHIBA model file specification for calculating the gross rock volumes between the gas oil contact (GOC) and the oil water contact (OWC) in two reservoirs called `Brent Oil` and `Statfjord Oil`:

```
<volumes>
   <volume>
      <reservoir-name>      Brent Oil                </reservoir-name>
      <top-surface>         Top Brent                </top-surface>
      <base-surface>        Base Brent               </base-surface>
      <top-contact>         GOC Brent                </top-contact>
      <base-contact>        OWC Brent                </base-contact>
      <area-file>           brent-segments.roxbin    </area-file>
      <area-names>          0, Central Block,
                            2, East Block,
                            3, West Block            </area-names>
      <only-trapped-volume> yes                      </only-trapped-volume>
      <connected-volume>
         <xstart>           1234567.0                </xstart>
         <ystart>           1234567.0                </ystart>
      </connected-volume>
      <column-map>          yes                      </column-map>
   </volume>
   <volume>
      <reservoir-name>      Statfjord Oil            </reservoir-name>
      <top-surface>         Top Statfjord            </top-surface>
      <base-surface>        Base Statfjord           </base-surface>
      <top-contact>         GOC Statfjord            </top-contact>
      <base-contact>        OWC Statfjord            </base-contact>
      <area-file>           statjord-segments.roxbin </area-file>
      <area-names>          0, Central Block,
                            1, West Block            </area-names>
      <only-trapped-volume> no                       </only-trapped-volume>
      <remove-isolated-volumes-less-than>
                            1000000
      </remove-isolated-volumes-less-than>
      <column-map>          yes                      </column-map>
   </volume>
</volumes>
```

The `<reservoir-name>` is used to identify the volume unit in output files. The surfaces are identified by their `<name>` in their `<surface>` specification. The `<top-surface>` and `<base-surface>` must belong to the stratigraphic framework of ordered surfaces and `<top-contact>` and `<base-contact>` must be free surfaces. The default for `<top-surface>` is the `<reference>` surface (mean sea level (MSL) as default). At least one of `<base-surface>` and `<base-contact>` must be

specified.

The <area-file>[1] is an optional grid with integers called *area numbers*. The <area-file> is used to separate a reservoir into different areas such as fault blocks, license units or national territories. Volumes will be calculated for every non-negative area number present in the <area-file>. The optional <area-names> is used to associate names to the areas. If this option is used only integers that are associated with area names will be included in the volume calculations.

The volumes will be reported in a comma separated file volumes.csv that can be analyzed by Excel or other tools. The volumes.csv could look like:

```
          ,      ,     Brent Oil,   Brent Oil,   Brent Oil, Statfjord Oil, Statfjord Oil
Realization,  seed, Central Block,  East Block,  West Block, Central Block,    West Block
1,           12345,   12562962.10, 23205894.80, 23205894.03,   16562962.11,   17205894.34
2,           12346,    9792432.52, 20201481.70, 25105251.71,   14372851.31,   17504144.28
```

The first row contains <reservoir-name> and the second row contains <area-names>. There will be one row for each simulated realization. Each row contains the realization number, the random seed, and the volumes for that realization. Note that the random seed is incremented by one for each realization[2]. The volumes.csv is updated for every new simulated realization so aborting the execution will not destroy the information accumulated so far.

A map of the rock column heights are calculated and saved to a grid file in surfaces/. A prefix, column_, is added to the <reservoir-name>. So a typical file name reads: column_Brent Oil.roxbin. These maps are by default written to file. The writing of these files can be turned off by <column-map>.

If the <only-trapped-volume> is put to yes, then the spill point for the <top-surface> must be calculated and possible volumes outside the trap will be discarded. This requires that <xstart> and <ystart> in <spill-point> are specified. The <connected-volume> element removes all volumes that are not in contact with the specified starting point, <xstart> and <ystart>. These coordinates could be the starting points, <xstart> and <ystart>, for the <spill-point> of <top-surface> or any other point known to be within the reservoir volume. The element <remove-isolated-volumes-less-than> does a similar job but it only removes connected volumes less than the specified threshold.

If there are different contacts in different sub-areas a separate <volume> specification must be made for each sub-area. The sub-area is selected by associating <area-names> to the area numbers in the <area-file> corresponding to the sub-area. Assume for instance that the Statfjord Central block has its own oil water contact:

```
<volume>
   <reservoir-name> Statfjord Central        </reservoir-name>
   <top-surface>    Top Statfjord            </top-surface>
   <base-surface>   Base Statfjord           </base-surface>
   <top-contact>    GOC Statfjord            </top-contact>
   <base-contact>   OWC Statfjord Central    </base-contact>
   <area-file>      statjord-segments.roxbin </area-file>
   <area-names>     0, Central Block         </area-names>
</volume>
```

In this case the surface OWC Statfjord Central is used as the OWC for the Central Block (area

1. The grid definition of the <area-file> should coincide with the grid definition given in <output-grid>. Otherwise, the area file will be re-sampled onto the output grid and area numbers can be replaced by non-integer averages of the area numbers. Non-integer area numbers are ignored in the volume calculations.
2. This may look strange but two random seeds that only differ by one digit give just as different simulated realizations as any pair of random seeds.

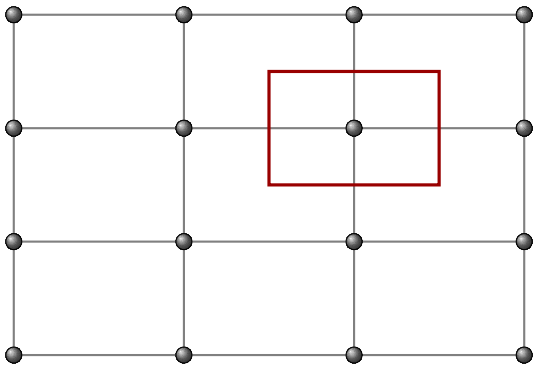


Figure 9.1. The volume within the red rectangle is assigned to the grid node in the center of the red rectangle.

number 0).

9.1 Calculating the volumes

COHIBA represents depth surfaces on regular grids where the grid nodes are assigned depth values. Calculating volumes requires that the surfaces are defined between the grid nodes. The simplest extension is to extend the grid node value to the rectangle centered at the grid node, where the rectangle side lengths are identical to the distances between grid nodes. This is illustrated in Figure 9.1.

The rock column at a grid node is

$$\Delta z = \max\Big(0, \min\big(z_{\text{base}}, z_{\text{base contact}}\big) - \max\big(z_{\text{top}}, z_{\text{top contact}}\big)\Big). \tag{9.1}$$

This is the rock column reported in the `<column-map>`. The rock volume of the column is

$$V = x_{\text{inc}}\, y_{\text{inc}}\, \Delta z, \tag{9.2}$$

where the increments are the distances between grid nodes. The total volume belonging to an area is obtained by summation of the rock volume associated to each grid node belonging to the area. This is the default algorithm for calculating volumes used by COHIBA. Note that volumes are always reported in cubic meters even though the vertical units are feet.

COHIBA also supplies a volume calculation based on bilinear interpolation of the surfaces instead of nearest neighbor interpolation. This is selected using `<volume-calculation-method>`. The two interpolation methods are compared in Figure 18.3. The two methods will give slightly different volumes since the interpolation algorithms are different. The numerical accuracy for the two methods are comparable. The algorithm for bilinear interpolation use algebraic expressions for the volume based on an analytical solution of the volume integral. The rock volume assigned to a grid node is the volume of the four nearest quadrants of the four adjacent cells. This is the volume in the colored rectangles seen in Figure 18.3(a). The rock column reported in the column map is

$$\Delta z = \frac{V}{x_{\text{inc}}\, y_{\text{inc}}}. \tag{9.3}$$

10 Stochastic simulation example

This section illustrates the use of stochastic simulation, rejection sampling, and volume distributions obtained from multiple realizations. The main purpose is to calculate gross rock volume and the spatial distribution of the reservoir. The uncertainty in the volume and the uncertainty in spatial extent of the reservoir is calculated and visualized.

The model consists of the top and bottom surfaces of the reservoir and a horizontal OWC. The reservoir is assumed to be a filled structure so that the OWC is at the depth of the spill point of top reservoir. The gross rock volume above the OWC is calculated. Three wells are included sequentially to mimic an early appraisal situation. Surfaces are only accepted if their spill points are consistent with well observations. A large number of simulated realizations ensures that the uncertainties in the reservoir are captured in the calculated volume distributions. The top reservoir and the three wells are shown in Figure 10.1.

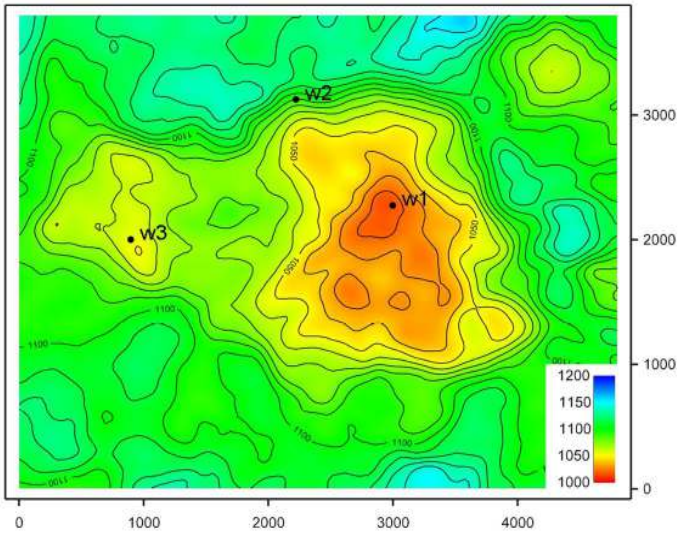


Figure 10.1. Map of top surface. The three wells are labeled `w1`, `w2` and `w3`.

10.1 Acceptance criteria

The volume above the oil water contact is the volume of interest. In this example we assume that the reservoir is a filled structure so that the OWC is located at the depth of the spill point. The OWC surface is conditioned to the spill point of the top surface using `<condition-to-spill-point-at-surface>`.

By including the three wells in Figure 10.2 sequentially, three different cases are defined. In the first case only the first well, `w1`, is included. This well crosses the bottom of the reservoir at a depth of 1063 meters. This well does not enter the water zone so the OWC must be below 1063 meters. In this case the spill point of the top reservoir, and thereof the depth of the OWC, is only accepted if it is below 1063 meters. This is specified by `<spill-point-below>`.

In the next case the second well, `w2`, is included. This well is an appraisal well drilled in the north flank of the main dome. The well crosses top reservoir at 1090 meters and enters the water zone without entering the oil zone. The second case therefore includes a new requirement that the spill

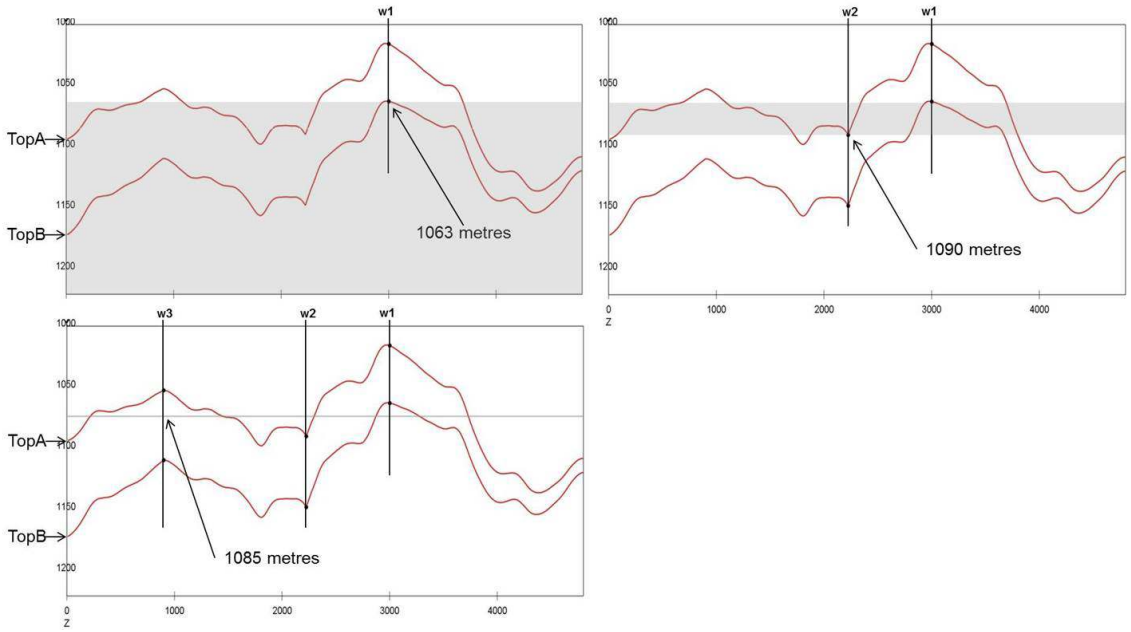


Figure 10.2. Fence diagram through the three wells. The grey areas indicate the acceptable depths for the spill points for the three cases.

point and the OWC must be above 1090 meters. This is specified using `<spill-point-above>`.

The third well, `w3`, is included in the final case. This well crosses the OWC at 1085 meters. The acceptance criteria in the models above can therefore be replaced by a stricter criterion which requires that the spill point must be at 1085 meters depth. This is specified by the `<spill-point-at>`. It is however too restrictive to require the spill point to be at *exactly* this depth, hence an tolerance of ± 0.5 meters is accepted. This is specified by `<spill-point-tolerance>`. The acceptance criteria for the three cases are summarized in Table 10.1 and illustrated by the fence diagrams in Figure 10.2.

Table 10.1. Acceptance criteria for the three cases.

	1 well	**2 wells**	**3 wells**
`<spill-point-below>`:	1063 m	1063 m	1084.5 m
`<spill-point-above>`:		1090 m	1085.5 m

In order for a realization to be accepted, the spill point depth must be within the specified acceptance criteria. If the spill point is not accepted, new samples are drawn until it is; hence giving one realization. The number of iterations is however limited by the `<max-rejection-rate>`. See Section 19.4 for details of rejection sampling.

The reservoir volume is calculated between top surface and base surface, and above the OWC. These three surfaces are specified using `<top-surface>`, `<base-surface>` and `<base-contact>`. See Section 9 for details regarding volume calculation. The volume in each realization is dependent on the simulated surfaces and the depth of the spill point.

In each of the three cases, 1000 realizations have been generated. The number of realizations is specified using `<number-of-realizations>`. Average and empirical standard deviation (SD) surfaces from all realizations are written to file.

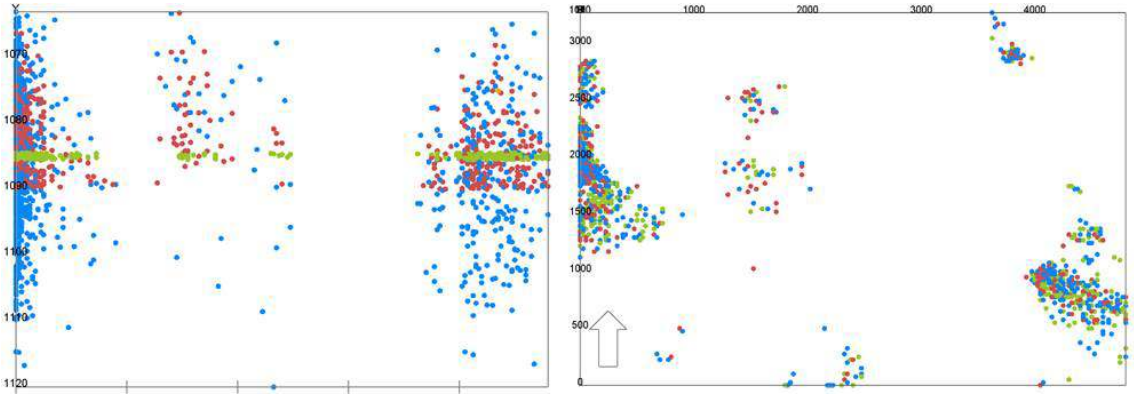


Figure 10.3. Spill points from 1000 realizations with 1, 2 and 3 wells. Left figure is a vertical cross section along the x-direction. The right figure is a top view. Blue spill points are constrained by 1 well, red spill points are constrained by 2 wells, and the green spill points are constrained by 3 wells.

Through this example the results from the stochastic simulations are compared to predictions (best estimate) results. Predictions of the surfaces are made using prediction `<mode>`.

10.2 Results

The rejection rates from the simulations are given in Table 10.2. The acceptance criteria for the case with all three wells are very strict, hence giving a rejection rate of 95 %. The number of samples to be drawn to get 1000 realizations is thus very high, which required a high `<max-rejection-rate>`.

Table 10.2. Rejection rate, average spill point depths and average gross rock volumes based on 1000 simulated realizations. The uncertainties are SDs.

	Rejection rate	**Average spill point depth** (m)	**Average volume** (10^6 m^3)
1 well:	2 %	1086.7 ± 10.4	183.4 ± 32.4
2 wells:	54 %	1083.6 ± 4.8	163.9 ± 25.4
3 wells:	95 %	1085.0 ± 0.3	162.6 ± 15.4

The spill points from all realizations are shown in Figure 10.3. From the right figure it can be seen that the most probable locations for spill are at the west and south-east in the map. The acceptance criteria has not affected the location of the spill points in the x-y plane, as spill points from all three cases seem to be represented in all clusters. The left figure shows that the the depth of the spill points are according to the acceptance criteria. The figure shows very clearly how the acceptance criteria is stricter in the model with 2 wells than with 1 well, and that only depths within an interval of a meter are accepted for the model with 3 wells.

The OWC is set to the spill point depth in each realization. The depth of the OWC will affect the volume in the reservoir, as the volume is only calculated above this contact. In addition, the uncertainties in the simulated surfaces will affect the volume. The calculated volumes from all three cases are summarized in Figure 10.4 and Figure 10.5. Figure 10.4 shows histogram of volume in bins of 8 million cubic meters in addition to cumulative distributions. In Figure 10.5 the minimum, maximum and mean plus/minus one SD is illustrated in a bar plot. The figures show that the spread in volumes decreases as the acceptance criteria gets stricter and the number of wells in the model increases. The average volume is higher in the model with 1 well since there is no lower bound on the spill point and OWC. The average volumes of the models with 2 and 3 wells are in the same order, however the spread is less in the latter, which can be seen by the steeper cumulative curve in Figure 10.4. The SD is also decreasing with stricter acceptance criteria

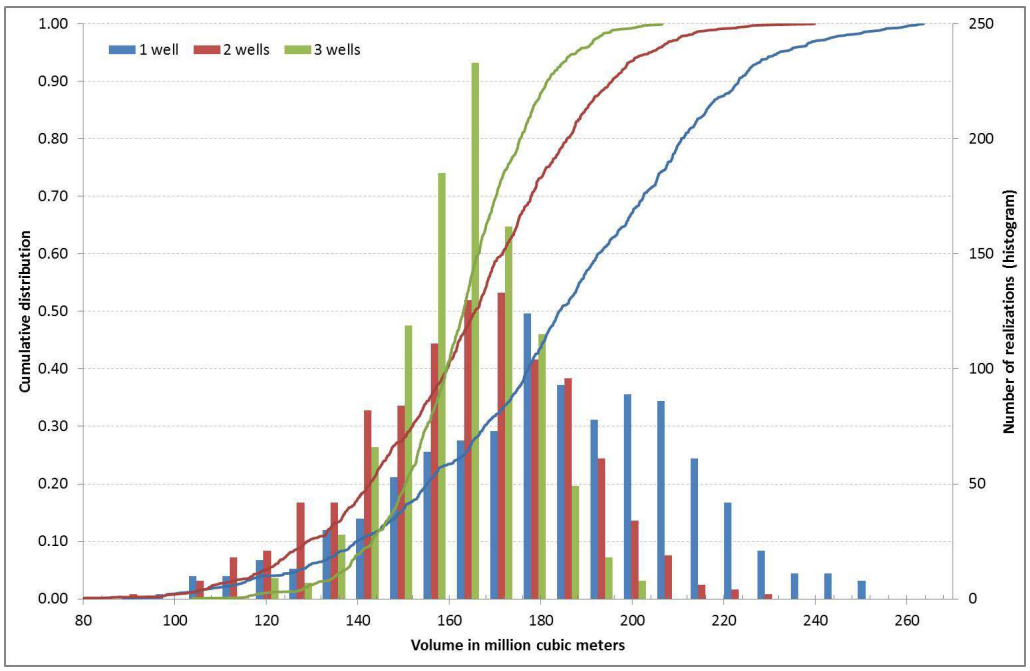


Figure 10.4. Histogram in bins of 8 million cubic meters and cumulative distribution of calculated volumes from 1000 realizations with 1, 2 and 3 wells.

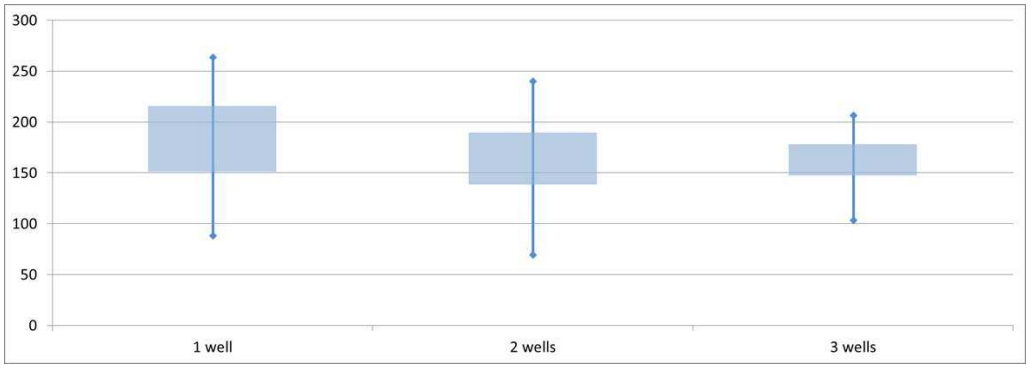


Figure 10.5. Box plot showing statistics of the calculated volumes from 1000 realizations in million cubic meters. The top and bottom of the vertical lines are the maximum and minimum volume. The top and bottom of the rectangle are the average volume plus and minus one SD.

as expected. The average spill point depth and volume with SDs are listed in Table 10.2.

Figure 10.6 shows the empirical mean of all 1000 realizations for the top surface for all three models. The relevant wells are included in the figures. It is not easy to spot much difference between the three cases based on these mean surfaces only. In the same figure the difference between the predicted depth and the empirical mean surfaces are given. These are plotted on a scale where zero difference is white, where predicted depth deeper than the mean is red, and blue is the opposite case. In the model with 1 well the entire map is light blue. This indicates that the mean of the realizations is somewhat deeper than the predicted depth. In the models with 2 and 3 wells however, the mean of the realizations are slightly shallower than the predictions. In these models the surfaces have been lifted to obtain correct spill points. The model with 2 wells has the highest mean surface compared to the prediction. This model has also the most shallow average spill point depth, see Table 10.2. The spill point depth from the predictions are in the order 1092 meters, which is somewhat deeper than the averages from all three simulation

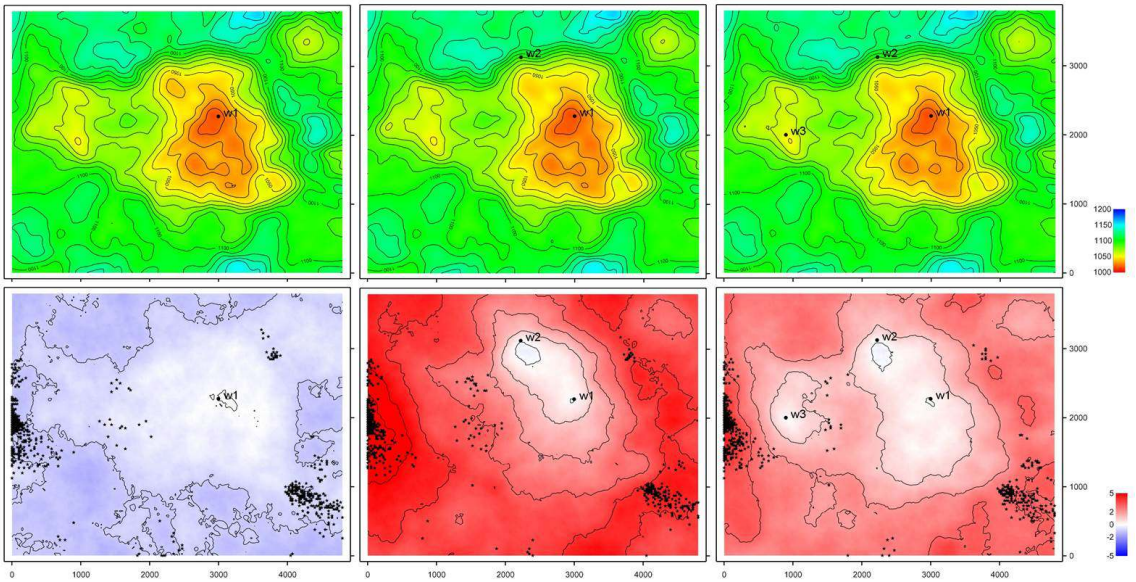


Figure 10.6. At the top are maps of mean surfaces of 1000 realizations with 1 well, 2 wells and 3 wells respectively. They use the same color legend as Figure 10.1. At the bottom are maps of predicted depths minus the mean surfaces. White color indicates no difference, red color shows that the predicted depths are deeper than the mean, and blue indicates the opposite. The spill points from cases with 1, 2 and 3 wells are included in the lower figures.

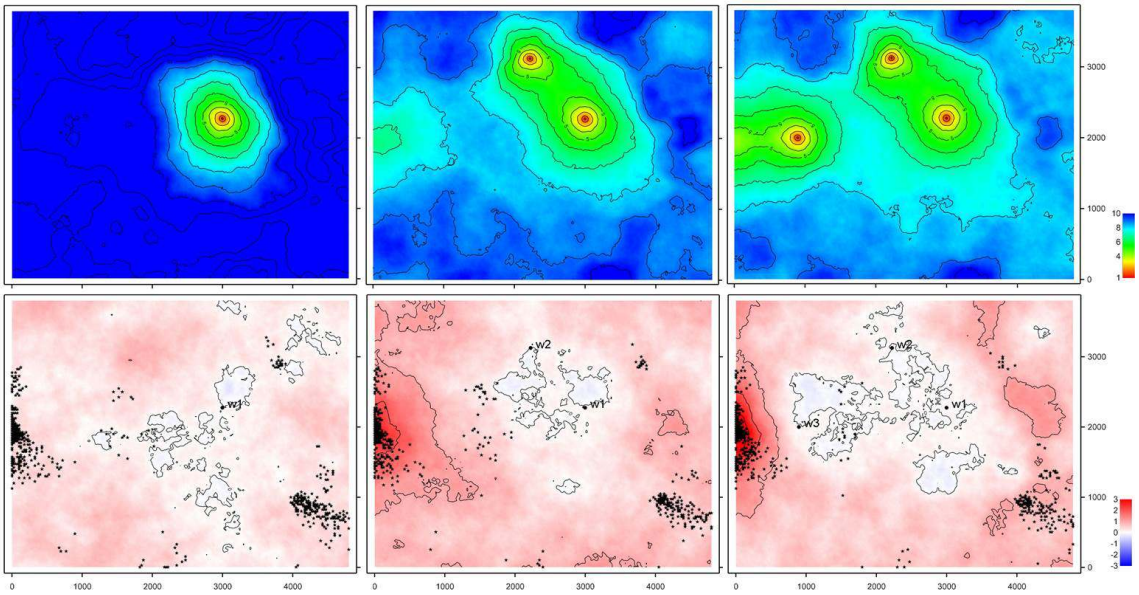


Figure 10.7. Empirical SD maps of 1000 realizations with 1, 2 and 3 wells respectively on top. At the bottom are prediction uncertainty minus SD from the 1000 realizations with 1, 2 and 3 wells. White color means no difference, red means that the depth uncertainty is higher than the empirical SD and blue is the opposite. The spill points from cases with 1, 2 and 3 wells are included in the lower figures.

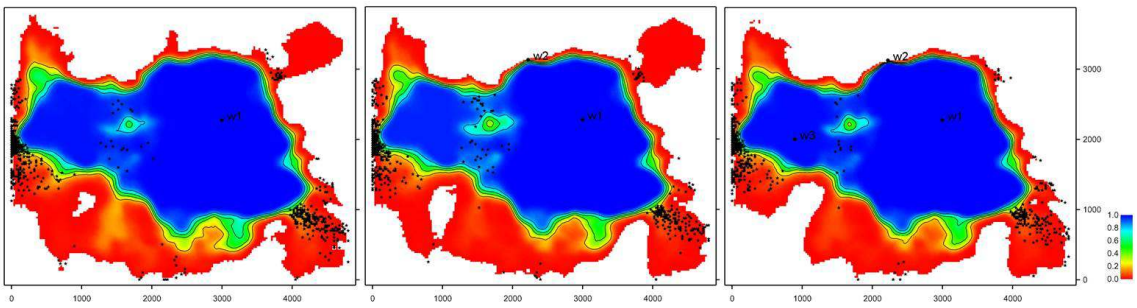


Figure 10.8. Map of probability for being inside the trap. This is the mean trap maps from 1000 realizations from case with 1, 2 and 3 wells respectively.

models.

In Figure 10.7 the empirical SD of the top surface is shown for the three cases. The location of the wells are easily spotted in these figure as the SD is zero at the wells. The SD of the realizations is compared to the prediction uncertainty, and the differences are shown in the figure for all cases. If there were no rejected samples, the prediction uncertainty should be approximately identical to the empirical SD of a large number of simulated realizations. The difference between the prediction uncertainty and the empirical SD therefore gives an indication of the effect of the rejection sampling. Also here we can see a change related to the location of the spill points in the models with 2 and 3 wells. The SD is reduced compared to the prediction uncertainty in the locations of the spill points, especially at west of the map, as the acceptance criteria have limited the variability of the surfaces in these areas.

Figure 10.8 shows the probability for being inside the trap obtained from the average of trap maps from 1000 realizations. This map is written to file by using element `<trap>`. A trap map from one realization is 1 inside the trap and 0 outside; hence the locations with one in the average map are inside the trap of all realizations. The figures show that there is a large variability in the area included in the volume calculation. Some traps have a large area, but about 70–80 % seem to be in the same order. Figure 10.9 includes column maps from the average of 1000 realizations at the top, and predictions at the bottom. These maps can give the volume directly by multiplying the value of each grid cell by the area of the grid cell, and can be written to file by using element `<column-map>`. The volume of the predicted models is in the order of 200 million cubic meters, which is larger than the average from the simulations. This is caused by a deeper spill point in the predicted top surface. This can to some extent be seen from Figure 10.9.

Figure 10.10 shows the empirical SD of the column maps in addition to the average of 1000 realizations. These figures show that the uncertainty in the area of the reservoir is reducing with increasing number of wells and stricter acceptance criteria, especially at west of the map.

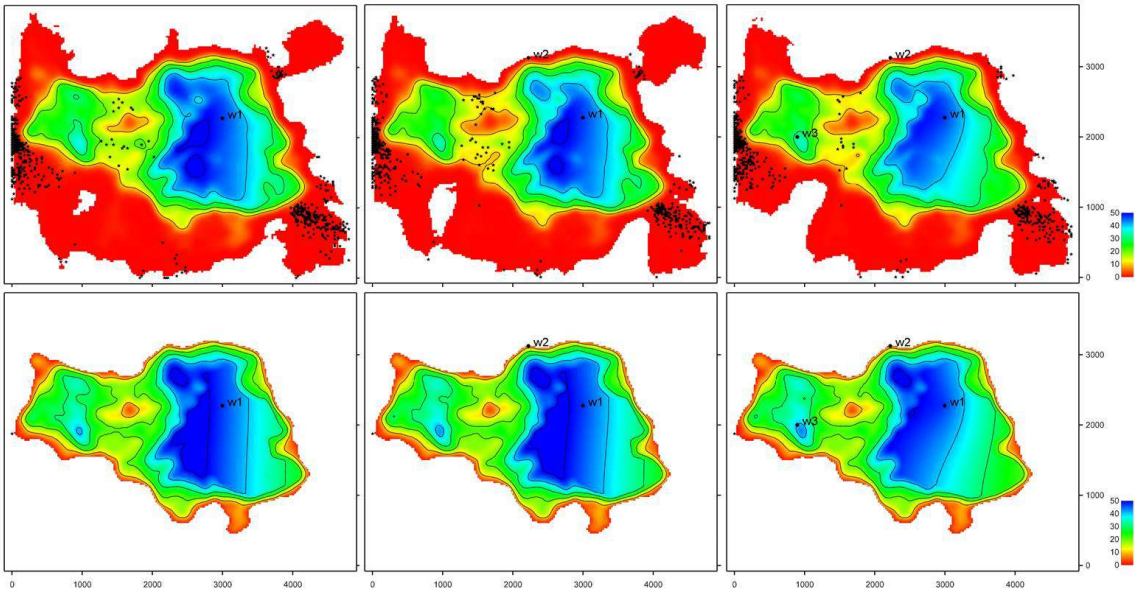


Figure 10.9. At the top; average rock column height map from case with 1, 2 and 3 wells respectively. At the bottom, the rock column height map from predictions with 1, 2 and 3 wells. The relevant wells and spill points are included.

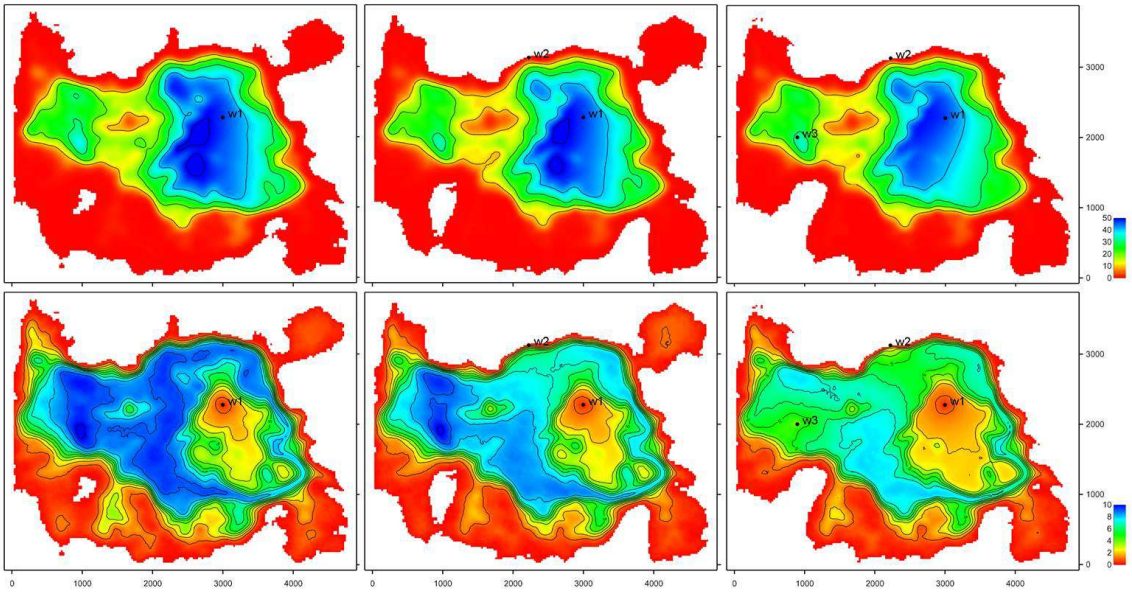


Figure 10.10. At the top; average rock column height map from model with 1, 2 and 3 wells respectively. At the bottom, empirical SD of rock column height map from model with 1, 2 and 3 wells respectively. The relevant wells are included.

11 Multiple models

COHIBA allows the user to specify several alternative ways of combining intervals to obtain a surface. This leads to multiple models that are combined into a unique solution for each surface. This is a unique feature for COHIBA.

Multiple models is a convenient way of squeezing surfaces between envelopes of well defined surfaces such as seismic reflectors. Intervals with large uncertainty are used for absorbing the inconsistencies between the models. Figure 11.1 shows an example.

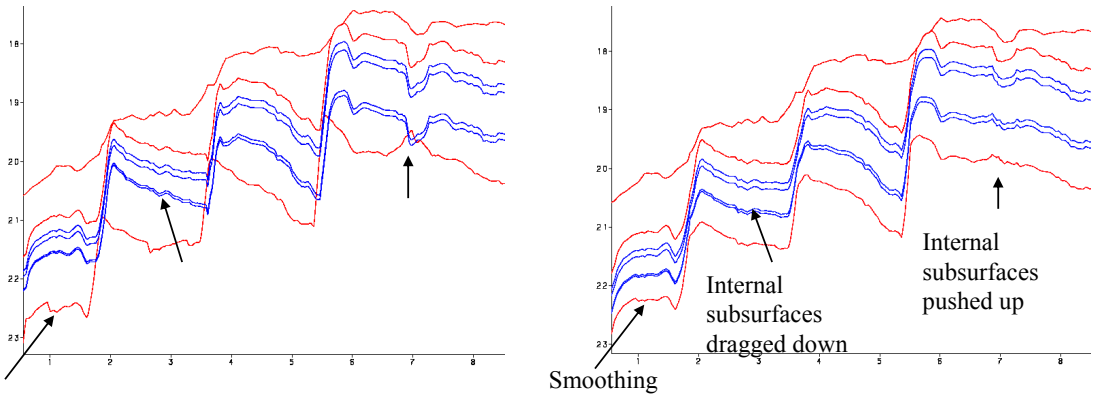


Figure 11.1. Cross section of two alternative ways of combining intervals. The red surfaces are seismic reflectors. The blue surfaces separates the internal zones that are assumed to have constant thickness. The figure to the left shows the surfaces when the internal zones are added to the seismic reflector above. The figure to the right shows the surfaces when COHIBA distributes the internal zones within the two seismic reflectors. We see that the result is a compromise between zones of constant thickness and the shape given by the two seismic reflectors. Note in particular that the seismic reflectors are also affected by the assumption that the zones have constant thickness.

11.1 Example from the Brent Group

Lets be specific and consider the Brent Group in the North Sea with its subdivision into the formations Broom, Rannoch, Etive, Ness and Tarbert. Assume that the top and base of Brent are good seismic reflectors. The crucial information is summarized in Table 11.1.

There are two ways of obtaining the depth to the surfaces below TopBrent. We can either add the isochores to TopBrent or we can find the depth to BaseBrent using depth conversion of the Brent group and add the isochores on top of BaseBrent.

COHIBA will use both approaches and take a weighted average of the two results. These *model weights* are essentially proportional to the inverse of the squared uncertainty (the variance). It is possible to make a quick assessment of the uncertainty of the surfaces and thereby get a rough idea of what the model weights will be.

Table 11.1. The interpretation uncertainty of the travel times are 4 msec. and 8 msec. (two-way travel time (TWT)) for TopBrent and BaseBrent respectively. The interval velocity uncertainty is 10 m/s for the interval down to TopBrent and the interval velocity uncertainty in Brent is 150 m/s. The isochore uncertainty of the individual formations are chosen to be 30 % of the thickness. All uncertainties are SD.

		Time maps		Interval veloc.		Isochore	
Surface	Interval	typical	uncert.	typical	uncert.	typical	uncert.
		(msec. twt)		(m/s)	(m/s)	(m)	(m)
MSL		0	0				
	MSL-Brent			2200	10		
TopBrent		1900	4				
	Tarbert					30	9,0
TopNess							
	Ness					70	21,0
TopEtive							
	Etive			2500	150	30	9,0
TopRannoch							
	Rannoch					50	15,0
TopBroom							
	Broom					5	1,5
BaseBrent		2050	8				

Table 11.2. There are three alternative approaches for obtaining the depth to the surfaces below TopBrent: Adding isochores to TopBrent, adding isochores to BaseBrent, or the COHIBA approach combining both. The arrows indicate how the surfaces are obtained. Red arrows means depth conversion. The values in Table 11.1 were chosen so that the depth values are very similar for all approaches. The uncertainties however, differ significantly. The model weights chosen by COHIBA is seen in the Weight columns for each of the "Building from" approaches.

		Building from TopBrent				Building from BaseBrent				COHIBA		
Surface	Interval		Depth	uncert.	Weight		Depth	uncert.	Weight		Depth	uncert.
			(m)	(m)			(m)	(m)			(m)	(m)
MSL			0	0,0			0	0,0			0	0,0
	MSL-Brent											
TopBrent			2090	10,5			2090	10,5			2090	10,5
	Tarbert											
TopNess			2120	13,8	90,5 %		2123	32,9	9,5 %		2120	13,4
	Ness											
TopEtive			2190	25,1	49,7 %		2193	25,4	50,3 %		2191	18,9
	Etive											
TopRannoch			2220	26,7	42,2 %		2223	23,7	57,8 %		2221	18,7
	Rannoch											
TopBroom			2270	30,6	21,4 %		2273	18,4	78,6 %		2272	16,4
	Broom											
BaseBrent			2275	30,7	21,2 %		2278	18,3	78,8 %		2277	16,4

Table 11.3. Multiple models weights for the Brent example.

	TWT SD	Velocity SD	Weight to BaseBrent	Weight to TopRannoch
Low uncertainty on BaseBrent:	4 msec.	75 m/s	93.5 %	68.5 %
Base case:	8 msec.	150 m/s	78.8 %	57.8 %
High uncertainty on BaseBrent:	16 msec.	300 m/s	48.4 %	35.5 %

Adding all the formations gives the accumulated uncertainty of the Brent interval as:[1]

$$9^2\,\mathrm{m}^2 + 21^2\,\mathrm{m}^2 + 9^2\,\mathrm{m}^2 + 15^2\,\mathrm{m}^2 + 1.5^2\,\mathrm{m}^2 \approx 29^2\,\mathrm{m}^2.$$

The uncertainty of the thickness of the Brent interval using depth conversion is:[2]

$$\left(2500\,\mathrm{m/s} \times \tfrac{8\,\mathrm{msec.}}{2000\,\mathrm{msec./s}}\right)^2 + \left(150\,\mathrm{m/s} \times \tfrac{150\,\mathrm{msec.}}{2000\,\mathrm{msec./s}}\right)^2 = 10^2\,\mathrm{m}^2 + 11.25^2\,\mathrm{m}^2 \approx 15^2\,\mathrm{m}^2.$$

The first term is the contribution from the travel time uncertainty and the second term is the contribution from the interval velocity uncertainty. We see that using depth conversion gives a lower uncertainty (± 15 m) than using the isochore thicknesses (± 29 m) for BaseBrent. The model weights will be:

$$\frac{29^2}{29^2 + 15^2} = 0.79 \quad \text{and} \quad \frac{15^2}{29^2 + 15^2} = 0.21.$$

So the depth conversion approach will contribute 79 % to BaseBrent.

Table 11.2 shows a summary of the uncertainties and the model weights calculated by COHIBA. There are two important observations:

1. The COHIBA approach favor the approach with the smallest uncertainty. We can see a transition where deeper surfaces are more dependent on BaseBrent than the shallower ones.
2. The surface uncertainty obtained by the COHIBA approach is always smaller than the uncertainty using only one of the approaches. This is not a coincidence. COHIBA chooses the model weights so that the uncertainty is minimized.

Multiple models are indirectly specified by the user by specifying two (or more) interval models for one (or more) surfaces. Figure 11.2 shows how this is done for the Brent example.

Figure 11.3 shows how the multiple models and their weights are reported by COHIBA. The model weights are sampled at a few locations in the grid and will usually give different values for `Avg`, `Min`, and `Max`. In this simple example all surfaces and uncertainties are constant giving equal model weights in all grid nodes.

Model weights will *always* sum to one. This will be true for the reported average (`Avg`) value but not true for the reported `Min` and `Max` values. Note that model weights can be negative and even larger than 1 in some rare cases. This is caused by correlations between different models.

11.1.1 The model weights are sensitive to the uncertainty specifications

Since model weights depend on the inverse of the variances, they can change significantly if the uncertainty is changed by a relatively small amount.

Table 11.3 shows what happens to the model weights if we half or double the uncertainties. In the high uncertainty case, the seismic travel times for BaseBrent are no longer favored more than a simple stacking of isochores from TopBrent.

1. All specified uncertainties are assumed independent. Since the individual uncertainties are assumed independent we can simply add the variances (squared SD) to obtain the total variance.
2. We must divide by 2000 msec./s since travel times are TWT in milliseconds.

```
<interval-models>
   <interval>
      <name>            MSL-Brent    </name>
      <top>             MSL          </top>
      <base>            TopBrent     </base>
      <interval-type>   velocity     </interval-type>
      ...
   </interval>
   <interval>
      <name>            Brent        </name>
      <top>             TopBrent     </top>
      <base>            BaseBrent    </base>
      <interval-type>   velocity     </interval-type>
      ...
   </interval>
   <interval>
      <name>            Tarbert      </name>
      <top>             TopBrent     </top>
      <base>            TopNess      </base>
      <interval-type>   thickness    </interval-type>
      ...
   </interval>
   <interval>
      <name>            Ness         </name>
      <top>             TopNess      </top>
      <base>            TopEtive     </base>
      <interval-type>   thickness    </interval-type>
      ...
   </interval>
   <interval>
      <name>            Etive        </name>
      <top>             TopEtive     </top>
      <base>            TopRannoch   </base>
      <interval-type>   thickness    </interval-type>
      ...
   </interval>
   <interval>
      <name>            Rannoch      </name>
      <top>             TopRannoch   </top>
      <base>            TopBroom     </base>
      <interval-type>   thickness    </interval-type>
      ...
   </interval>
   <interval>
      <name>            Broom        </name>
      <top>             TopBroom     </top>
      <base>            BaseBrent    </base>
      <interval-type>   thickness    </interval-type>
      ...
   </interval>
</interval-models>
```

Figure 11.2. The surface names TopBrent and BaseBrent enter the `<top>` and `<base>` elements twice. These double entries makes this a specification of multiple models. The crucial specifications are marked in dark red.

```
                ModelWeights
Surface       Avg    Min    Max    Models
-------------------------------------------------
TopBrent    1.000  1.000  1.000    1: MSL → TopBrent
TopNess     0.905  0.905  0.905    1: MSL → TopBrent → TopNess
            0.095  0.095  0.095    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch → TopEtive → TopNess
TopEtive    0.497  0.497  0.497    1: MSL → TopBrent → TopNess → TopEtive
            0.503  0.503  0.503    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch → TopEtive
TopRannoch  0.422  0.422  0.422    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch
            0.578  0.578  0.578    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch
TopBroom    0.214  0.214  0.214    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch → TopBroom
            0.786  0.786  0.786    2: MSL → TopBrent → BaseBrent → TopBroom
BaseBrent   0.212  0.212  0.212    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch → TopBroom → BaseBrent
            0.788  0.788  0.788    2: MSL → TopBrent → BaseBrent
```

Figure 11.3. The report of the multiple models and their weights for the Brent case found in Section 4: The alternative ways to build each surface in the COHIBA log file. The arrows indicate an interval.

```
                   ModelWeights
Surface          Avg    Min    Max    Models
-----------------------------------------------------------
...
Top_SN_9.3     0.136 -0.084  0.765    1: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_11.3
                                                → Top_SN_11.2 → Top_SN_11.1 → Top_SN_10.4 → Top_SN_10.3
                                                → Top_SN_10.2 → Top_SN_10.1 → Top_SN_9.4 → Top_SN_9.3
               0.014 -0.045  0.079    2: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_11.3
                                                → Top_SN_11.2 → Top_SN_11.1 → Top_SN_10.4 → Top_SN_10.3
                                                → Top_SN_10.2 → Top_SN_10.1 → Top_SN_9.3
               0.050 -0.023  0.141    3: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_11.3
                                                → Top_SN_11.2 → Top_SN_11.1 → Top_SN_10.4 → Top_SN_10.1
                                                → Top_SN_9.4 → Top_SN_9.3
               0.016 -0.032  0.099    4: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_11.3
                                                → Top_SN_11.2 → Top_SN_11.1 → Top_SN_10.4 → Top_SN_10.1
                                                → Top_SN_9.3
               0.266 -0.020  0.722    5: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_10.4
                                                → Top_SN_10.3 → Top_SN_10.2 → Top_SN_10.1 → Top_SN_9.4
                                                → Top_SN_9.3
               0.058 -0.010  0.123    6: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_10.4
                                                → Top_SN_10.3 → Top_SN_10.2 → Top_SN_10.1 → Top_SN_9.3
               0.249  0.022  0.613    7: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_10.4
                                                → Top_SN_10.1 → Top_SN_9.4 → Top_SN_9.3
               0.212  0.002  0.857    8: MSL → Top_Nordland → Top_Hordaland → Top_Balder → BCU → Top_SN_11.4 → Top_SN_10.4
                                                → Top_SN_10.1 → Top_SN_9.3
```

Figure 11.4. A part of Section 4: The alternative ways to build each surface in the COHIBA log file. The arrows indicate an interval. Note that weights can vary significantly when the residual uncertainties varies and that weights can be negative.

11.1.2 Many multiple models and their weights

It is possible to specify many sets of multiple models including alternative zonation and alternative depth conversions. COHIBA will automatically sort out all possible ways of calculating the depth to any surface. This may include a lot of alternatives. Figure 11.4 shows a small piece of logging information taken from COHIBA log file. It shows the eight alternative models for the surface Top_SN_9.3. model weights

Note that the model weights are quite small for several of the alternatives and that they vary a lot in different areas. The deepest surfaces in this particular example can be reached in 128 different ways so the complexity can be significant.

COHIBA calculates the model weights by looking at the uncertainty of each model *and* the correlation between each model. Many models will have a lot of intervals in common. The common parts will make the alternative models correlated.

COHIBA may use a significant amount of CPU time calculating the model weights and the CPU time will increase with the number of alternative models. The calculation of the actual surfaces (stochastic or deterministic) is not sensitive to the number of alternative models.

11.1.3 Some words of advice

Multiple models are very convenient but they can obscure how surfaces are constructed since they combine several alternatives. It can therefore be difficult to understand why a surface gets its shape. A typical effect is that seismic reflectors are modified so that the features seen on the travel time maps are distorted. Figure 11.1 illustrates this quite clearly. The simple reason is that depth conversion is not accurate and alternative approaches to constructing the surface can strongly influence the surface shape. It is all a consequence of the user chosen uncertainties (SD). Small travel time uncertainties and small interval velocity uncertainties will guaranty that features seen in travel time maps are preserved. But small uncertainties are not always realistic.

Be careful when using many small intervals

This may result in unrealistic small uncertainties since adding many small uncertainties result gives a smaller uncertainty than most realize. This is best illustrated by an example.

Let us consider a depth converted interval of 200 meters where the uncertainty (SD) is 20 meters. Now assume that there is a subdivision of this interval into equally thick zones. Further assume that the uncertainty (SD) of the thickness of each zone is 30 %. That is, if there is one zone, the uncertainty is 200 m $\times$ 30 % = 60 m. If there are two equally thick zones they have 100 m $\times$ 30 % = 30 m uncertainty, and if there are three equally thick zones they have uncertainty 66.6 m $\times$ 30 % = 20 m and so on. If the number of zones are N, the accumulated uncertainty for the whole interval becomes

$$\mathrm{Var}\{\Delta Z\} = N \times (30\,\% \times 200\,\mathrm{m}/N)^2. \tag{11.1}$$

This uncertainty must be compared to 20 meters which is the uncertainty obtained using depth conversion. The uncertainty, $\sqrt{\mathrm{Var}\{\Delta Z\}}$, is plotted as a dark blue line in Figure 11.5 and the corresponding model weights given to the depth conversion alternative is plotted as the blue line.

We see that the model weights are 50 % when the accumulated uncertainty is approximately 20 meters. This is the point where it becomes less uncertain to use the subdivision rather than the depth converted interval.

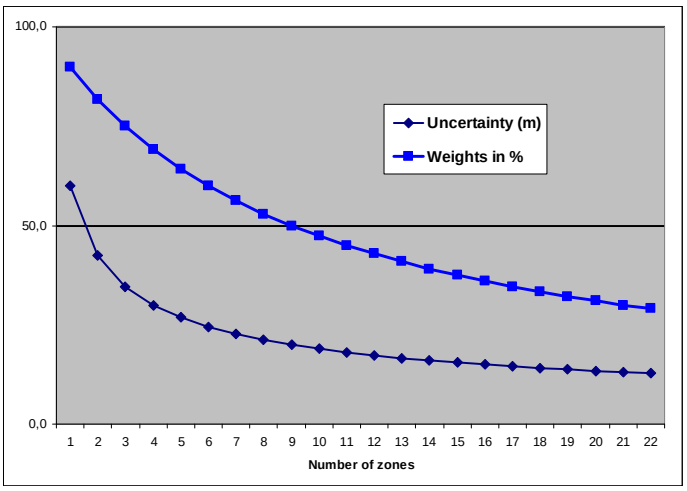


Figure 11.5. Model weights (blue line) as the number of subdivisions of the zone increase. The dark blue line is the accumulated uncertainty (SD) obtained using Eq. 11.1.

Small uncertainties are drowned by bigger uncertainties

Since accumulated uncertainties (SD) are obtained by summing the squares (the variances), small uncertainties are totally dominated by larger uncertainties. Here are a few examples:

$$10^2\,\mathrm{m}^2 + 1^2\,\mathrm{m}^2 \approx 10.05^2\,\mathrm{m}^2$$
$$10^2\,\mathrm{m}^2 + 2^2\,\mathrm{m}^2 \approx 10.2^2\,\mathrm{m}^2$$
$$10^2\,\mathrm{m}^2 + 5^2\,\mathrm{m}^2 \approx 11.2^2\,\mathrm{m}^2$$
$$10^2\,\mathrm{m}^2 + 10^2\,\mathrm{m}^2 \approx 14.1^2\,\mathrm{m}^2.$$

Multiple models with no well data

It is quite common in large models that there are little or no well data for a few surfaces. This could give warnings like this:

```
WARNING: The average thickness between depth trend surfaces 'Top_SN_3.4' and 'Top_SN_3.3' is negative (-6.61).
        Probable cause: Conflict between multiple models for one or both surfaces.
```

11.1.4 Pre-adjusting the standard deviations of isochores

COHIBA has a pre-processing option that can scale the uncertainties in isochore packages to approximately achieve a specified model weight. This feature can be activated by using the element `<weight-isochore-package-above>`, specified on the reflector surface directly below an isochore package. If the model consists of several isochore packages, then each one can be scaled according to an individual model weight.

Using the Brent Group as an example, one can scale the uncertainties of all isochores between the reflectors TopBrent and BaseBrent. Specifying a weight of 0.15 on BaseBrent gives the model weights shown in Figure 11.6, which can be compared with the original weights in Figure 11.3. A weight below 0.5 means that the isochores gets less weight than the velocity model (or depth converted thickness model).

The algorithm starts by extracting a covariance matrix $\mathbf{C}$ for all model paths down to BaseBrent. The matrix is approximated by using the average of all covariance matrices at all the grid nodes. Hence, the model weights will in general not be exactly equal to the value specified by `<weight-isochore-package-above>` (except when all trends are constant values, as is the case in the Brent Group example).

```
                ModelWeights
Surface       Avg    Min    Max    Models
-------------------------------------------------------
TopBrent    1.000  1.000  1.000    1: MSL → TopBrent
TopNess     0.904  0.904  0.905    1: MSL → TopBrent → TopNess
            0.096  0.096  0.096    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch → TopEtive → TopNess
TopEtive    0.460  0.460  0.460    1: MSL → TopBrent → TopNess → TopEtive
            0.540  0.540  0.540    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch → TopEtive
TopRannoch  0.379  0.379  0.379    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch
            0.621  0.621  0.621    2: MSL → TopBrent → BaseBrent → TopBroom → TopRannoch
TopBroom    0.152  0.152  0.152    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch → TopBroom
            0.848  0.848  0.848    2: MSL → TopBrent → BaseBrent → TopBroom
BaseBrent   0.150  0.150  0.150    1: MSL → TopBrent → TopNess → TopEtive → TopRannoch → TopBroom → BaseBrent
            0.850  0.850  0.850    2: MSL → TopBrent → BaseBrent
```

Figure 11.6. The report of the multiple models and their weights for the Brent case, after scaling the isochore package between TopBrent and BaseBrent.

11.1.5 Undefined areas in multiple models

By default, COHIBA returns an undefined depth value if any input map value (trend, travel time, or residual SD) is missing. Despite missing values in some input maps, often one or several of the multiple models are completely specified and could provide reliable depth values. It is therefore provided a simple solution that will give depth values everywhere. Missing input map values can be replaced by extrapolated values using `<extrapolate-input-surfaces>` in `<pre-process-surfaces>`. This will guarantee that all the multiple models are properly defined everywhere. The replacement of missing values by extrapolated values in the input maps are normally not as reliable as defined input values. Multiple models containing extrapolated values will therefore be given lower weight. This is done by increasing the residual SD in areas with extrapolated input map values.

12 Faults

COHIBA 6.0 handles faults when used together with ROXAR RMS. This is done by handling each fault segment semi-independently and extend surfaces beyond the fault blocks. ROXAR RMS imports the overlapping surfaces and cuts and glues the patches together into a consistent structural model with faults and surfaces.

When COHIBA runs without ROXAR RMS, faults must be handled differently. COHIBA does not model faults directly. However, the underlying data used for describing faults, the travel time maps, are handled by COHIBA. So faulted seismic reflectors will give faulted surfaces[1]. The vertical component of the uncertainty of the fault position will depend on the travel time uncertainty and the interval velocity uncertainty. The vertical component of the uncertainty is close to the real uncertainty for low angle faults. The uncertainty will be underestimated for vertical and high angle faults.

COHIBA has a few features that ensure that many normal faults are handled.

1. COHIBA assumes that the uncertainties to the travel times from different surfaces are independent. This is normally a good approximation, but it is unrealistic when two seismic reflectors are very close or coinciding. So COHIBA automatically adjust the travel time uncertainties so that close or coinciding seismic reflectors gets correlated (dependent) residuals. This is both realistic and gives zero uncertainty for the zero thickness between coinciding seismic reflectors along fault planes. This feature can be turned off using the element `<correlate-close-reflectors>`.

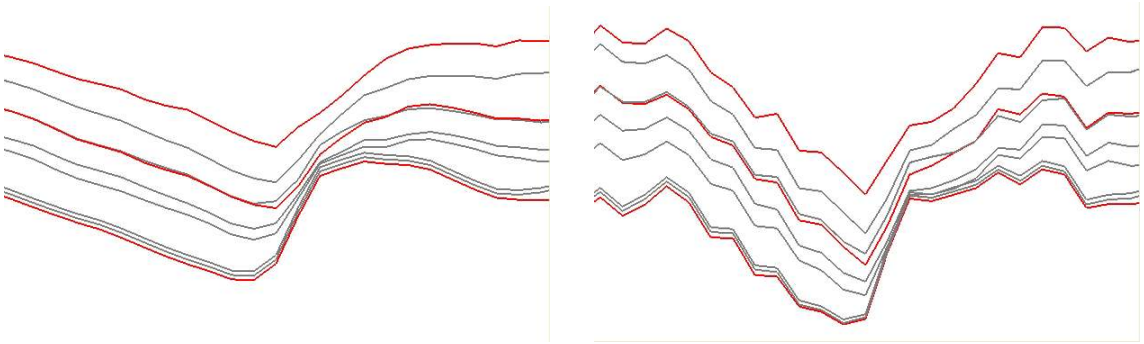
2. The zone thickness trends will in general disagree with the trends obtained from seismic depth conversion. This is solved by combining multiple models. If two seismic reflectors coincide, the thickness uncertainty between the seismic reflectors now becomes zero. This guarantees that the depth conversion alternative for the lower seismic reflector gets model weight 1 and other model alternatives get zero weight. However, the intermediate (non-reflecting) surfaces will not be perfectly squeezed in between the two coinciding seismic reflectors. This is solved if seismic reflectors behave as erosive surfaces *and* onlapped surfaces. The seismic reflectors will then cut away any parts of the intermediate surfaces that are not in between the two seismic reflectors. This is the default but it can be overruled by using `<treat-reflectors-as-eroding-and-onlapped>`.

   Note that this only affects the post processing of surfaces, not the extraction of well points. If a seismic reflector is eroding and/or onlapped, then use the elements `<erosive>` and `<onlapped>`.

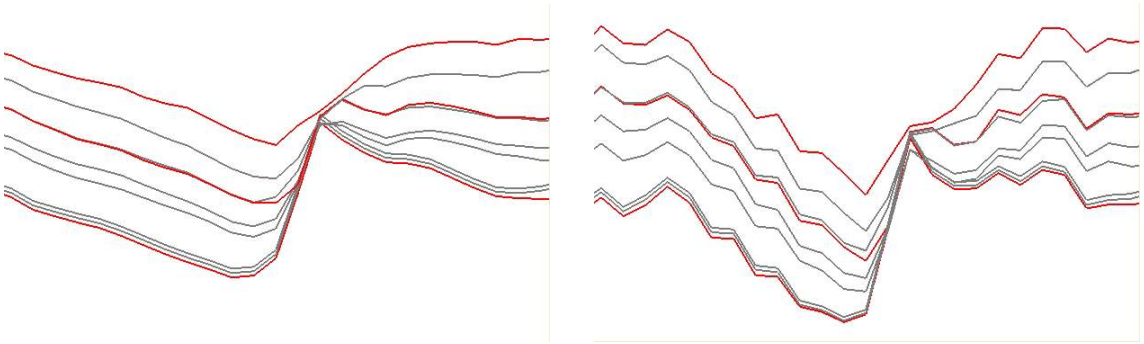
These features are illustrated in Figure 12.1.

1. Only normal faults can be represented by travel time maps so reverse faults must be approximated by vertical faults.

Original COHIBA model. Interval thickness models open the fault defined by the seismic reflectors:



Introducing correlated travel time uncertainty
(Turn off using element `<correlate-close-reflectors>`):



Introducing eroding and onlapped seismic reflectors
(Turn off using element `<treat-reflectors-as-eroding-and-onlapped>`):

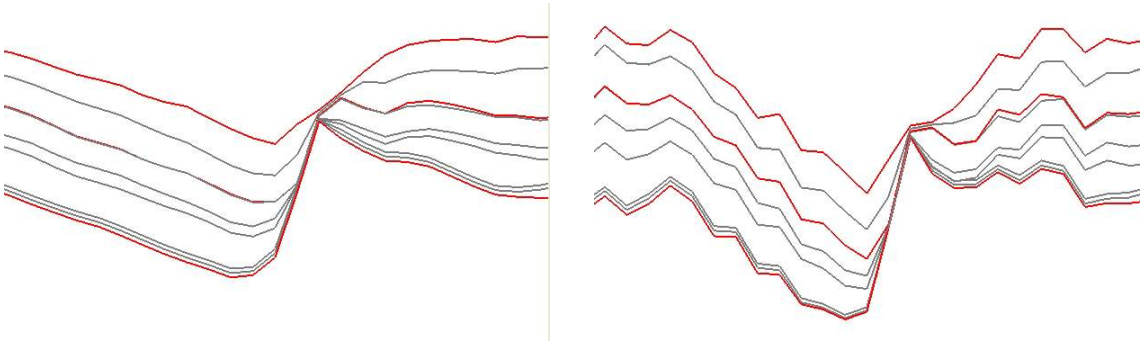


Figure 12.1. Cross section of a fault. Seismic reflectors are red. Deterministic (prediction) in the left column and one stochastic realization in the right column.

13 Free surfaces

A free surface is a surface that does not belong to the ordered sequence of surfaces that define the stratigraphy. A free surface may cut through other surfaces. Typical examples are hydrocarbon contacts (HCCs) and faults.

A surface is specified as *free* using `<free-surface>`. Free surfaces are handled by COHIBA like any other surface except from situations where the correct ordering is needed. Free surfaces are listed after other surfaces.

Since a free surface has no particular order it can not erode other surfaces and it can not be onlapped. Erosion rules specified by `<erosive>` and `<onlapped>` are therefore ignored. A free surface will not be eroded by other surfaces and it will not lap onto other surfaces.

Since a free surface is not a boundary for a stratigraphic zone it is not meaningful to associate it with a `<top-of-zone>`. Therefore, zone logs can not be used to specify well points for free surfaces. Well points for free surfaces must be specified by well point files using `<files>` under `<well-points>`.

13.1 Linking free surfaces to other surfaces

Free surfaces can be linked to any surface using the `<top>` and `<base>` under `<interval>`. This can be utilized in various ways.

13.1.1 Control other surfaces using a flat spot

A flat spot is an almost horizontal gas oil contact (GOC) or gas water contact (GWC) that gives a strong seismic reflection. The seismic travel time to a flat spot will therefore have a very low uncertainty, say ± 1 msec.[1] It is possible to form velocity intervals between the flat spot and other reflecting surfaces. This might reduce the uncertainty in the other reflecting surfaces. Note that it is possible and meaningful to make velocity intervals that have negative thickness and negative interval travel times.

13.1.2 Control other surfaces using a HCC

A HCC is almost horizontal provided the fluids are in gravitational equilibrium. This can be used to reduce and calibrate the well path true vertical depth (TVD) uncertainties.

The SD of the well path TVD uncertainty can be specified in the COHIBA well points files (Table 6.2) or using a well path TVD uncertainty log using `<wellpath-TVD-SD-log-name>`. The *correlation* between well points is determined by the `<wellpath-TVD-SD-range>`.

13.1.2.1 Linking a HCC to spill points

A free surface can be linked directly to the spill point of a different surface using `<condition-to-spill-point-at-surface>`. This is meant to be used for modeling a HCC for a filled structure. The `<name>` of the free surface can be used as the `<base-contact>` in volume calculations. This makes it possible to find the volume of a filled structure with an unknown spill point. This approach should be used in combination with `<only-trapped-volume>`. See Section 9.

1. The travel time uncertainty in areas outside the flat spot should be set to a high value, say 50 msec.

14 Correlated intervals

NEW in 6.0

Consider the two alternative ways of modeling surfaces illustrated in Figure 14.1. The left illustration is the standard approach where deeper surfaces are obtained by adding deeper intervals. The right hand illustration shows another common approach where surfaces are attached directly to the reference surface (MSL in this case). The first approach gives correlated surfaces whereas the second approach gives uncorrelated surfaces since intervals are uncorrelated.

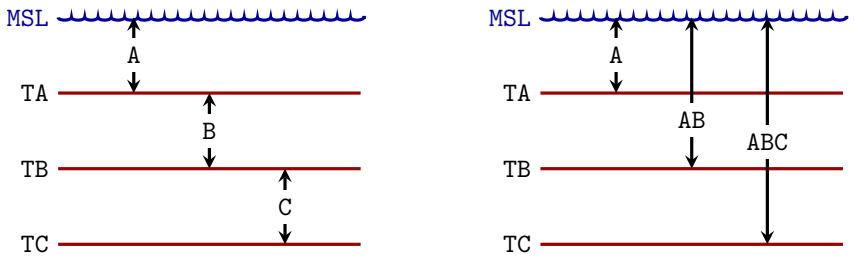


Figure 14.1. Three surfaces, TA, TB and TC obtained by adding deeper intervals (left) or by attaching them directly to the reference surface MSL.

Uncorrelated surfaces may cause a significant uncertainty in the thickness between surfaces and undesired crossing between surfaces can easily happen. One possible solution is to combine both approaches illustrated in Figure 14.1 by using multiple models.

An alternative approach is to introduce correlations between different intervals. This is done by correlating the interval thickness or velocity residuals and by correlating the *prior* interval trend coefficients. This is triggered by using <common-top-for-correlated-intervals> under <reference> and <surface>. All intervals that have the common surface as <top> will be correlated[1]. The correlation between two intervals is high if the average thickness of the intervals is similar and drops to zero if there is a large difference in the average thickness.

Note that correlating the trend coefficients applies to the prior distribution and these correlations can be modified when these are conditioned to well data.

14.1 Calculating correlations

Consider the model illustrated on the right hand side of Figure 14.1. The thickness intervals are modeled as (Eq. 18.4)

$$\Delta Z_{\mathtt{A}}(\mathbf{x}) = \boldsymbol{\beta}_{\mathtt{A}} \cdot \mathbf{f}_{\mathtt{A}}(\mathbf{x}) \quad + \Delta\epsilon_{\mathtt{A}}(\mathbf{x})$$

$$\Delta Z_{\mathtt{AB}}(\mathbf{x}) = \boldsymbol{\beta}_{\mathtt{AB}} \cdot \mathbf{f}_{\mathtt{AB}}(\mathbf{x}) \quad + \Delta\epsilon_{\mathtt{AB}}(\mathbf{x})$$

$$\Delta Z_{\mathtt{ABC}}(\mathbf{x}) = \boldsymbol{\beta}_{\mathtt{ABC}} \cdot \mathbf{f}_{\mathtt{ABC}}(\mathbf{x}) + \Delta\epsilon_{\mathtt{ABC}}(\mathbf{x}),$$

where the normal assumption is that interval trend coefficients from different intervals are uncorrelated (e.g. $\mathrm{Cov}\{\boldsymbol{\beta}_{\mathtt{A}}, \boldsymbol{\beta}_{\mathtt{AB}}\} = 0$) and that interval residuals are uncorrelated (e.g. $\mathrm{Cov}\{\Delta\epsilon_{\mathtt{A}}(\mathbf{x}), \Delta\epsilon_{\mathtt{ABC}}(\mathbf{x})\} = 0$). Also, coefficients are assumed uncorrelated with any residual. This implies, for this model, that any pair of depth surfaces are uncorrelated.

1. The intervals must be of the same <interval-type>, that is, thickness or velocity.

The challenge is to find a reasonable correlation between the interval trend coefficients and between the interval residuals that would introduce correlation between the surfaces.

One possibility is to assume that surfaces that are near are highly correlated, that is, intervals with the same thickness with a common reference surface should be highly correlated. Consider the prior average thickness of an interval, e.g. $\overline{\Delta Z}_{\mathtt{A}} = \boldsymbol{\beta}_{\mathtt{A}} \cdot \bar{\mathbf{f}}_{\mathtt{A}}$, where $\boldsymbol{\beta}_{\mathtt{A}}$ are the prior coefficients specified by <coefficient-mean> and $\bar{\mathbf{f}}_{\mathtt{A}}$ is the average trend functions. The average is taken over the whole modeling area.

The correlation between any pair of prior coefficients in intervals A and AB are modeled as

$$\text{(14.1)} \qquad \operatorname{Corr}\{\beta_{\mathtt{A}i}, \beta_{\mathtt{AB}j}\} = \exp\left(-3\left(\frac{\left\|\overline{\Delta Z}_{\mathtt{A}} - \overline{\Delta Z}_{\mathtt{AB}}\right\|}{R}\right)^{p}\right); \qquad R > 0 \quad \text{and} \quad 0 < p \le 2$$

and the correlation between the interval residuals in A and AB are modeled as

$$\text{(14.2)} \quad \operatorname{Corr}\{\Delta\epsilon_{\mathtt{A}}(\mathbf{x}), \Delta\epsilon_{\mathtt{AB}}(\mathbf{x})\} = \exp\left(-3\left(\frac{\left\|\overline{\Delta Z}_{\mathtt{A}} - \overline{\Delta Z}_{\mathtt{AB}}\right\|}{R'}\right)^{p'}\right); \qquad R' > 0 \quad \text{and} \quad 0 < p' \le 2,$$

where R and R' are the thickness difference where correlations are almost zero[2], and the powers p and p' determine the shape of the general exponential correlation functions. Note that these formulas give a single correlation number for each pair or correlated intervals. In the example illustrated in Figure 14.1 there are three pair-combinations (A-AB, A-ABC, and AB-ABC) so the formulas give three correlations between trend coefficients and three correlations between residuals.

The four parameters in Eq. 14.1 and Eq. 14.2 can be modified by four elements in <correlated-intervals> in <model-settings>: <correlated-intervals-trend-range>, <correlated-intervals-trend-power>, <correlated-intervals-residual-range>, and <correlated-intervals-residual-power>. The default range, R, is 100 meters and the default power, p, is 1 that corresponds to an exponential correlation function.

In simulation <mode> the correlated interval residual fields are drawn correlated by default. The correlation between the drawn residual fields can be removed with the help of <correlated-intervals-simulation>. This is not recommended since it introduces an inconsistency.

14.2 Correlating the trend coefficients using thickness ratios

If we stick to the assumption that the trend coefficients from the intervals A, B and C are uncorrelated we get

$$\operatorname{Cov}\left\{\boldsymbol{\beta}_{\mathtt{A}} \cdot \bar{\mathbf{f}}_{\mathtt{A}}, \boldsymbol{\beta}_{\mathtt{AB}} \cdot \bar{\mathbf{f}}_{\mathtt{AB}} - \boldsymbol{\beta}_{\mathtt{A}} \cdot \bar{\mathbf{f}}_{\mathtt{A}}\right\} = \operatorname{Cov}\left\{\boldsymbol{\beta}_{\mathtt{A}} \cdot \bar{\mathbf{f}}_{\mathtt{A}}, \boldsymbol{\beta}_{\mathtt{B}} \cdot \bar{\mathbf{f}}_{\mathtt{B}}\right\} = 0$$

which is equivalent to

$$\bar{\mathbf{f}}'_{\mathtt{A}} \operatorname{Cov}\left\{\boldsymbol{\beta}'_{\mathtt{A}}, \boldsymbol{\beta}_{\mathtt{AB}}\right\} \bar{\mathbf{f}}_{\mathtt{AB}} = \bar{\mathbf{f}}'_{\mathtt{A}}(\mathbf{x}) \operatorname{Var}\{\boldsymbol{\beta}_{\mathtt{A}}\} \bar{\mathbf{f}}_{\mathtt{A}}(\mathbf{x}).$$

The unknown in this equation is the correlations between coefficients from different intervals in $\operatorname{Cov}\left\{\boldsymbol{\beta}'_{\mathtt{A}}, \boldsymbol{\beta}_{\mathtt{AB}}\right\}$. This is still not solvable because the number of unknown correlations are larger than this single equation[3] can determine. For the simplest situation with only one trend coefficient for each interval, such as $\beta_{\mathtt{A}} \bar{f}_{\mathtt{A}}$, this simplifies to

$$\text{(14.3)} \qquad \operatorname{Corr}\{\beta_{\mathtt{A}}, \beta_{\mathtt{AB}}\} = \frac{\operatorname{SD}\{\beta_{\mathtt{A}}\}}{\operatorname{SD}\{\beta_{\mathtt{AB}}\}} \frac{\bar{f}_{\mathtt{A}}}{\bar{f}_{\mathtt{AB}}}.$$

The important observation is that the correlation is proportional to the thickness ratio $\bar{f}_{\mathtt{A}} / \bar{f}_{\mathtt{AB}}$.

2. $e^{-3} \approx 0.05$.
3. The right hand side is a single number.

This can be generalized to situations with several trend coefficients by assuming a single common correlation for all pairs of coefficients from different intervals: This idea is used to introduce correlations between trend coefficients from different intervals in the prior covariance matrix (Eq. 18.20). This is activated with the <correlated-intervals-ratios-for-trends>.

Note that Eq. 14.3 does not guarantee that the resulting covariance matrix becomes positive definite. This is handled by reducing correlations towards zero until the prior covariance matrix becomes valid.

14.3 Example

Below are specifications that make the intervals in the right hand side in Figure 14.1 correlated.

```
<model-settings>
   <!-- This is not necessary, default values are provided:  -->
   <correlated-intervals>
      <correlated-intervals-residual-range>      200 </correlated-intervals-residual-range>
      <correlated-intervals-ratios-for-trends>   yes </correlated-intervals-ratios-for-trends>
   </correlated-intervals>
</model-settings>

<surfaces>
   <reference>
      <name>                                     MSL </name>
      <!-- This triggers correlating intervals:  -->
      <common-top-for-correlated-intervals>      yes </common-top-for-correlated-intervals>
      ...
   </reference>
   <surface>
      <name>                                     TA  </name>
      ...
   </surface>
   <surface>
      <name>                                     TB  </name>
      ...
   </surface>
   <surface>
      <name>                                     TC  </name>
      ...
   </surface>
</surfaces>

<interval-models>
   <interval>
      <name>                                     A   </name>
      <top>                                      MSL </top>
      <base>                                     TA  </base>
      ...
   </interval>
   <interval>
      <name>                                     AB  </name>
      <top>                                      MSL </top>
      <base>                                     TB  </base>
      ...
   </interval>
      <name>                                     ABC </name>
      <top>                                      MSL </top>
```

```
      <base>                                    TC  </base>
      ...
   </interval>
</interval-models>
```

Part IV
Reference manual

15 COHIBA model file elements

The COHIBA model file is an Extensible Markup Language (XML) file and has the following structure:[1]

```
<cohiba>
    <project-settings>
        :
    </project-settings>
    <modelling-settings>
        :
    </modelling-settings>
    <well-data>
        :
    </well-data>
    <surfaces>
        <reference>
            :
        </reference>
        <surface>
            :
        </surface>
        :
    </surfaces>
    <interval-models>
        <interval>
            :
        </interval>
        :
    </interval-models>
    <volumes>
        <volume>
            :
        </volume>
        :
    </volumes>
</cohiba>
```

A complete list of all COHIBA model file elements is found in Section 16. All the elements are explained in detail in the following.

<cohiba> (required)

Description: Wrapper for all other elements of the COHIBA model file. This is called the root element in XML jargon.
Argument: The six main elements in the COHIBA model file.
Default: No default.

1. Any XML file should contain an initial line `<?xml version="1.0" encoding="UTF-8" ?>` to identify the XML version and the character encoding.

15.1 <project-settings> (required)

Description: General settings such as file name conventions, measurement units, and definition of project coordinate system.
Argument: Wrapper for elements.
Default: No default.

15.1.1 <project-title>

Description: A COHIBA project title.
Argument: String.
Default: Empty string.

15.1.2 <project-description>

Description: Detailed description of the project.
Argument: String.
Default: Empty string.

15.1.3 <seed>

Description: Sets the random seed for the random number generator[2] used in stochastic simulations. The argument is either a file name containing a random seed or a random seed. Any positive integer is accepted as a random seed. The random seed file is located in the directory specified in <project-directory>. The default name of the random seed file is `seed.dat`. When running a stochastic simulation, a new random seed is always written to the random seed file at the end of the stochastic simulation. A new file will be created if it does not exist. The new seed is the old seed plus one.

It is possible to set the random seed using `-s` on the command line (Section 4.1). This has precedence over random seeds specified in the COHIBA model file or a random seed file.

If the random seed is unspecified and the random seed file does not exist, an automatic random seed will be generated based on the system clock.

Argument: File name or positive integer less than or equal to $2^{64} - 1 = 18\,446\,744\,073\,709\,551\,615 \approx 1.8 \times 10^{19}$ (C++ unsigned long long int).
Default: `seed.dat`
Example: Specify a random seed:

```
<seed>  123  </seed>
```

Example: Specify a random seed file:

```
<seed>  myseed.dat  </seed>
```

Example: Specify a random seed on the command line:
`> cohiba.exe -s 123 model-file.xml`.

15.1.4 <project-directory>

Description: A relative or absolute path to a COHIBA project. If a relative path is used, COHIBA must be executed from the directory the relative path refers to.
Argument: A valid path to a directory.
Default: Current directory (. in Linux).
Example: Relative path:

```
<project-directory>  my-cohiba-project/ </project-directory>
```

Example: Absolute path:

2. COHIBA uses the Mersenne Twister MT19937-64.

```
<project-directory>  /path/to/projects/my-cohiba-project/ </project-directory>
```

15.1.5 <input-directory>

Description: Relative or absolute path to all COHIBA input. The relative path is relative to the project directory.
Argument: A valid path to a directory.
Default: input/
Example: Relative path:

```
<input-directory>  my-input/ </input-directory>
```

Example: Absolute path (can be to any location):

```
<input-directory>
   /path/to/projects/my-cohiba-project/my input/
</input-directory>
```

15.1.6 <input-directory-surfaces>

Description: Path to input surfaces. The path is relative to the input directory specified with <input-directory>.
Argument: A valid path to a directory.
Default: surfaces/. If <input-directory> has been specified, the default is ./. See Section 6.1 for more information.
Example:

```
<input-directory-surfaces>   surfaces_50x50/   </input-directory-surfaces>
```

15.1.7 <input-directory-well-data>

Description: Path to well data input. The path is relative to the input directory specified with <input-directory>.
Argument: A valid path to a directory
Default: welldata/. If <input-directory> has been specified, the default is ./. See Section 6.1 for more information.
Example:

```
<input-directory-well-data>   wells/   </input-directory-well-data>
```

15.1.8 <output-directory>

Description: Relative or absolute path to the COHIBA output directories. These are described in Section 7 and are created if they do not exist prior to execution of COHIBA.
Argument: A valid path to a directory.
Default: output/.
Example: Relative path:

```
<output-directory>   my-output/   </output-directory>
```

Example: Absolute path:

```
<output-directory>
   /path/to/projects/my-cohiba-project/my-output/
</output-directory>
```

Example: Absolute path can be to any location:

```
<output-directory>   /path/to/my-output/    </output-directory>
```

Table 15.1. Measurement units. The defaults are SI units.

Properties	Arguments	Unit	Modified by
Lateral distance:	`m`	meter	`<xyz-unit>`

Surface depth, TVD, MD, interval, thickness, and rock column height:	`m`
	`ft`
	`U.S. feet`
		meter
		feet
		U.S. (survey) feet
			`<z-unit>`
			`<xyz-unit>`

Travel time:	`s` `ms`	second millisecond	`<time-unit>`
One-way or two-way travel time:	`yes / no`		`<two-way-time>`
Seismic interval velocity:	`m` `ft`	meters per second feet per second[a]	`<z-unit>` `<xyz-unit>`
Volume	m^3	cubic meters	

a. If vertical depth is measured in feet.

15.1.9 `<number-of-threads>`

Description: Specifies the number of threads (parallel processes on a CPU) that will be used when computing in parallel[3]. The possibilities are:

$$\begin{aligned} n > 0: &\quad \text{Number of threads} = \min(n, max) \\ n = 0: &\quad \text{Number of threads} = max \\ n < 0: &\quad \text{Number of threads} = \max\big(1, (max - |n|)\big), \end{aligned}$$

where *max* is the maximum number of threads available[4]. The usual maximum number of threads are 2 to 8 for laptops, 4 to 16 for desktops, and possibly a lot more for servers. We recommend to use the maximum number of threads on laptops and desktops. The actual number of threads used are reported in the COHIBA log file as:

```
Threads in use                                  : 7 / 8
```

where, in this case, 7 threads out of a maximum of 8 threads have been used.

Argument: Integer.
Default: `0` (Use all available threads.)
Example: Use at most four threads (processors):

```
<number-of-threads>  4 </number-of-threads>
```

Example: Save one thread (processor) for other use:

```
<number-of-threads> -1 </number-of-threads>
```

15.1.10 `<measurement-units>`

Description: Wrapper for specifying measurement units. See Table 15.1 for available units.
Argument: Elements for each unit type.
Default: Void.

3. The kriging operations, estimation of residual uncertainty and the data loading is computed in parallel. The kriging computations usually take 90–95 % of the CPU time. Tests have shown that the efficiency of running the kriging operations in parallel depends on the problem. We have seen perfect scaling in some cases but not in all. Many Intel CPUs supports hyper-threading. This means that there can be two threads on each physical CPU core. Our experience is that the kriging calculations has no benefit from the additional hyper-threads because each core is fully occupied by a single thread.
4. COHIBA uses the OpenMP API for parallelization..

15.1.10.1 <z-unit>

Description: Unit for surface depth, TVD, MD, interval thickness, and rock column height. This unit is used for well data, output surfaces, interval thicknesses and column maps. Options are meters, feet or U.S. (survey) feet. Seismic interval velocity will be measured in feet per second if feet is chosen. Conversion factors are: $1\,\text{ft} = 0.3048\,\text{m}$ and $1\,\text{U.S. (survey) ft} = 1200/3937\,\text{m} = 0.304800609601219\,\text{m}$. . Cannot be used in combination with <xyz-unit>.

Argument: m / ft / U.S. ft

Default: m

15.1.10.2 <xyz-unit>

Description: Unit for the same quantities as in <z-unit>, as well as lateral length. Cannot be used in combination with <z-unit>.

Argument: m / ft / U.S. ft

Default: m

15.1.10.3 <time-unit>

Description: Unit of time. Seconds or milliseconds.

Argument: s / ms

Default: s

15.1.10.4 <two-way-time>

Description: A flag controlling whether the input time grids are given in one-way or two-way travel time (TWT). (The default is one-way.)

Argument: yes / no

Default: no

15.1.11 <output-grid> (required)

Description: Container for elements specifying grid dimensions and grid resolution for the output grids.[5] The dimensions can be read from a grid file using <read-from-file> or be specified using the elements <xinc>, <xlength>, <yinc>, and <ylength>. The number of grid nodes are calculated using

$$n_x = x_{\text{length}}/x_{\text{inc}} + 1 \quad \text{and} \quad n_y = y_{\text{length}}/y_{\text{inc}} + 1. \tag{15.1}$$

The rotation of the grids is specified using <grid-azimuth>. See Figure 15.1 for an overview.

Argument: Elements specifying the grid dimensions.

Default: No default.

15.1.11.1 <format>

Description: Output format. See Section 6.2 for possible file formats.

Argument: roxar binary / roxar text / storm

Default: roxar binary

15.1.11.2 <read-from-file>

Description: Use the specified grid file to define the dimension and resolution of the output grids. Valid arguments are any surface file in the input directory or a surface file with full path. The file format is either ROXAR BINARY, ROXAR TEXT or STORM BINARY. The file format is automatically detected.

Argument: Surface file name.

Default: No default.

Example: Reads grid definition from file dS_IsochoreA.storm in the default input directory:

5. Input grids can have different formats, resolutions, and dimensions. Input grids will be regridded to match the output grid dimension and resolution. Regridding is done by bilinear interpolation, see Section 18.6.1.

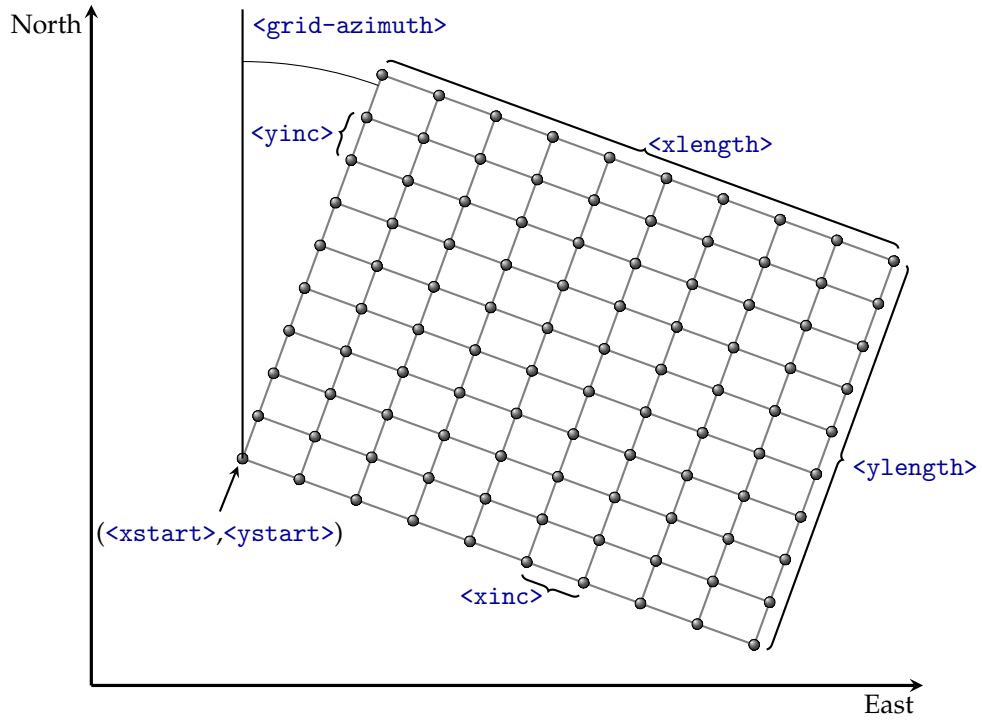


Figure 15.1. Elements used to specify the output grid definition: <grid-azimuth>, <xinc>, <yinc>, <xlength>, <ylength>, <xstart> and <ystart>. Note that using <read-from-file> is simpler. The surfaces are defined at the grid nodes (gray bullets). COHIBA uses bilinear interpolation (Section 18.6.1) to approximate the surfaces inside the rectangles.

```
<output-grid>
   <format>         roxar binary       </format>
   <read-from-file> dS_IsochoreA.storm </read-from-file>
</output-grid>
```

Note that the file format of `dS_IsochoreA.storm` may differ from the specified output format. If the <format> element is omitted, the output format is set equal to that of `dS_IsochoreA.storm`.

15.1.11.3 <xstart>

Description: X-coordinate at reference point. (Typically the lower left corner of the grid.) See Figure 15.1.
Argument: Real.
Default: No default.

15.1.11.4 <ystart>

Description: Y-coordinate at reference point. (Typically the lower left corner of the grid.) See Figure 15.1.
Argument: Real.
Default: No default.

15.1.11.5 <xinc>

Description: X-increment. Size of grid cell in x-direction. See Figure 15.1.
Argument: Positive real.
Default: No default.

15.1.11.6 <yinc>

Description: Y-increment. Size of grid cell in y-direction. See Figure 15.1.
Argument: Positive real.
Default: No default.

15.1.11.7 <xlength>

Description: Length of grid in the x-direction. See Figure 15.1.
Argument: Positive real.
Default: No default.

15.1.11.8 <ylength>

Description: Length of grid in the y-direction. See Figure 15.1.
Argument: Positive real.
Default: No default.

15.1.11.9 <grid-azimuth>

Description: Azimuth angle for rotated grids. Angle is measured clockwise from north in degrees (360°). The center of the rotation is the reference point set by <xstart> and <ystart>. See Figure 15.1.

Note that this option only works for files using the ROXAR BINARY and ROXAR TEXT grid formats (see Section 6.2).
Argument: Real.
Default: 0.0
Example: Grids rotated 15° clockwise from north:

```
<output-grid>
   <format>  roxar binary </format>
   <xstart>           0.0 </xstart>
   <xlength>       5000.0 </xlength>
   <ystart>           0.0 </ystart>
   <ylength>      10000.0 </ylength>
   <xinc>           100.0 </xinc>
   <yinc>           100.0 </yinc>
   <grid-azimuth>    15.0 </grid-azimuth>
</output-grid>
```

15.1.12 <messages>

Description: Wrapper for elements specifying logging output levels to log file and screen. Available logging levels are:

0: No messages reported.
1: Errors reported.
2: Warnings reported.
3: Information messages reported. (Default)
4: Detailed information reported.
5: Very detailed information reported (mainly for debugging purposes).

The output information accumulate so that level 5 includes everything reported on level 4 an so on everything reported on level 4 and so on.
Argument: Elements specifying output to log file and screen.
Default: Void.

15.1.12.1 `<logfile>`

Description: Wrapper for elements describing the output to the COHIBA log file. The log file is written to the `log-files/` directory, under the output directory.
Argument: Elements specifying output to the COHIBA log file.
Default: Void.

15.1.12.1.1 `<name>`

Description: A string describing the name of the COHIBA log file.
Argument: String.
Default: `cohiba.log`

15.1.12.1.2 `<detail-level>`

Description: Wrapper for elements specifying the level of detail in the COHIBA log file. Each element can be set individually.
Argument: The elements corresponding to the different sections of the log file.
Default: Void.

15.1.12.1.2.1 `<overall>`

Description: Level of detail in output to the COHIBA log file. The levels are:

0. **Off:** No logging at all.
1. **Severe:** Only errors are reported.
2. **Warning:** Errors and warnings are reported.
3. **Low:** Important information messages are also reported. (Default)
4. **Medium:** Detailed information messages are reported.
5. **High:** Even some debugging messages are reported.

Note that the COHIBA log file can be very large when using the two highest levels. This level can be overruled within each output section mentioned below. See Section 7.2.2 for a brief explanation of each section.
Argument: 0 – 5
Default: 3

15.1.12.1.2.2 `<model-settings>`

Description: Level of detail in model settings output.
Section title: `Section 1: Model settings`
Argument: 0 – 5
Default: 3

15.1.12.1.2.3 `<data-loading>`

Description: Level of detail in reporting data loading.
Section title: `Section 2: Loading input data`
Argument: 0 – 5
Default: 3

15.1.12.1.2.4 `<pre-processing>`

Description: Level of detail in reporting pre-processing of input data.
Section title: `Section 3: Pre-processing input data`
Argument: 0 – 5

Default: 3

15.1.12.1.2.5 <surface-models>

Description: Level of detail in reporting of surface models and possible multiple models for surfaces. See Figure 11.3 for an example of the output. There is no output if this level is less than 3.
Section title: `Section 4: The alternative ways to build each surface`
Argument: 0 – 5
Default: 3

15.1.12.1.2.6 <well-points>

Description: Level of detail in reporting the processing of well points.
Section title: `Section 5: Processing well points`
Argument: 0 – 5
Default: 3

15.1.12.1.2.7 <extra-points>

Description: Level of detail in reporting the processing control points for eroded and onlapping surfaces.
Section title: `Section 6: Processing control points for eroded and onlapped surfaces`
Argument: 0 – 5
Default: 3

15.1.12.1.2.8 <well-branching>

Description: Level of detail in reporting of how different well branches are connected into a single multilateral well.
Section title: `Section 7: Well branching`
Argument: 0 – 5
Default: 3

15.1.12.1.2.9 <well-paths>

Description: Level of detail in reporting the processing of zone logs along well paths.
Section title: `Section 8: Sampling well trajectories and logs`
Argument: 0 – 5
Default: 3

15.1.12.1.2.10 <trend-coefficients>

Description: Level of detail in reporting trend coefficients.
Section title: `Section 9: Trend coefficients based on well points`
Section title: `Section 14.x Trend coefficients based on well points and well paths`
Argument: 0 – 5
Default: 3

15.1.12.1.2.11 <residual-uncertainties>

Description: Level of detail in reporting match between specified and observed residual uncertainties.
Section title: `Section 10: Checking specified residual uncertainties`

Argument: 0 – 5
Default: 3

15.1.12.1.2.12 <outliers>

Description: Level of detail in reporting match between well points and trend models.
Section title: `Section 11: Well point QC`
Argument: 0 – 5
Default: 3

15.1.12.1.2.13 <well-point-conditioning>

Description: Level of detail in reporting of errors in conditioning (kriging).
Section title: `Section 12.x: Conditioning on well points along well paths`
Argument: 0 – 5
Default: 3

15.1.12.1.2.14 <help-points>

Description: Level of detail in reporting of searching for surface help points sampled along the well paths.
Section title: `Section 13.x: Finding help points for well path conditioning`
Argument: 0 – 5
Default: 3

15.1.12.1.2.15 <well-path-conditioning>

Description: Level of detail in reporting of errors from well points sampled along well path.
Section title: `Section 15.x: Conditioning surfaces on all available points`
Argument: 0 – 5
Default: 3

15.1.12.1.2.16 <post-processing>

Description: Level of detail in report post processing. The post processing handles erosion, onlapping, pinch outs, and gridding mismatches.
Section title: `Section 16.x: Post process surfaces`
Argument: 0 – 5
Default: 3

15.1.12.1.2.17 <target-point-qc>

Description: Level of detail in report target point quality control (QC).
Section title: `Section 17.x: Target point QC`
Argument: 0 – 5
Default: 3

15.1.12.1.2.18 <zonation-checking>

Description: Level of detail in report on checking zonation.
Section title: `Section 18.x: Checking zonation`
Argument: 0 – 5
Default: 3

15.1.12.1.2.19 <well-trajectories>

Description: Level of detail in report on updated well trajectories.
Section title: Section 19.x: Updated well trajectories
Argument: 0 – 5
Default: 3

15.1.12.1.2.20 <spill-points>

Description: Level of detail in report on spill point detection.
Section title: Section 20.x: Spill points
Argument: 0 – 5
Default: 3

15.1.12.1.2.21 <volume-calculations>

Description: Level of detail in report on volume calculations.
Section title: Section 21.x: Volume calculations
Argument: 0 – 5
Default: 3

15.1.12.1.2.22 <interval-export>

Description: Level of detail in report on interval export.
Section title: Section 22.x: Make and export interval thicknesses and velocities
Argument: 0 – 5
Default: 3

15.1.12.1.2.23 <surface-export>

Description: Level of detail in report on surface export.
Section title: Section 23.x: Export surfaces
Argument: 0 – 5
Default: 3

15.1.12.1.2.24 <timings>

Description: Level of detail in report on CPU time usage.
Section title: Section 24: Timings summary
Argument: 0 – 5
Default: 3

15.1.12.1.2.25 <tasks>

Description: Level of detail in report on tasks.
Section title: Section 25: Suggested tasks
Argument: 0 – 5
Default: 3

15.1.12.2 <screen>

Description: Wrapper for elements describing the output to screen (monitor).
Argument: Elements specifying output to screen.
Default: Void.

15.1.12.2.1 <detail-level>

Description: Wrapper for elements specifying the level of detail in the output logging to screen. Each element can be set in the same way as the output levels for the COHIBA log file.
Argument: Elements corresponding to the different sections of logging. See the sub-elements of <detail-level> for the COHIBA log file for details.
Default: Void.

15.1.13 <write-expert-files>

Description: This option makes COHIBA generate the expert/ directory with its subdirectories that contain numerous output files meant for QC and error checking. This output is mainly used by the COHIBA developers. See Figure 6.1 for the name of the subdirectories.
Argument: yes / no
Default: no

15.1.14 <additional-output-control>

Description: Wrapper for output control related to intermediate results and formatting in general.
Argument: Elements specifying format settings or which output to generate.
Default: Void.

15.1.14.1 <write-all-logfiles>

Description: This option makes it possible to suppress writing of log-files for well points, average statistics, trend estimation and surface help points. It is primarily intended to avoid writing a lot of files when generating multiple realizations when using stochastic simulation <mode>.
Argument: yes / no
Default: yes

15.1.14.2 <write-realization-maps>

Description: Turns on or off the writing of maps to file for individual simulated realizations. See Table 7.1 for a list of possible maps. Average and empirical SD maps are not affected. Choosing no may save a lot of disc space.

The realization numbers are added to the standard file names:

```
d_TopA_0001.rxb, d_TopA_0002.rxb,...
trap_TopA_0001.rxb, trap_TopA_0002.rxb,...
v_MSL-TopA_0001.rxb, v_MSL-TopA_0002.rxb,...
```

Additional digits will be added for realizations beyond realization number 9 999.

This option has no consequence for prediction <mode>.
Argument: yes / no
Default: yes

15.1.14.3 <write-xyz-point-files>

Description: COHIBA can write a lot of xyz-point files (extension .xyz). These files are potentially numerous and not always needed so they are by default not written. The export of these files are triggered by choosing yes
Argument: yes / no
Default: no

15.1.14.4 <write-scaled-input-isochores>

Description: COHIBA can pre-process input isochores and scale them to fit seismic envelopes (see <scale-isochores-to-seismic-envelopes>). Export of these scaled isochores are triggered

by choosing yes. Exported isochores are prefixed with Scaled_.
Argument: yes / no
Default: no

15.1.14.5 <write-scaled-input-SD-isochores>

Description: COHIBA can pre-process input isochore uncertainties and scale them relative to the seismic envelope (see <weight-isochore-package-above>). Export of these scaled isochore uncertainties are triggered by choosing yes. Exported isochore uncertainties are prefixed with Scaled_SD_.
Argument: yes / no
Default: no

15.1.14.6 <write-filtered-velocity-trends>

Description: Smoothed velocity trends (see <smoothing-factor-velocity-trends>) may be exported by setting this value to yes.
Argument: yes / no
Default: no

15.1.14.7 <write-filtered-SD-maps>

Description: Smoothed uncertainty maps (see <smoothing-factor-SD-maps>) may be exported by setting this value to yes.
Argument: yes / no
Default: no

15.1.14.8 <write-regridded-input-maps>

Description: Input maps that are regridded to fit the output grid as described in Section 18.6.1 may be exported by setting this value to yes. Exported maps are prefixed with Regridded_.
Argument: yes / no
Default: no

15.1.14.9 <write-unfiltered-output-velocities>

Description: Calculated velocities are smoothed according to the value of <smoothing-factor-calculated-velocities>. The non-smoothed velocities may be exported by setting this value to yes. Exported maps are prefixed with Unfiltered_v_.
Argument: yes / no
Default: no

15.1.14.10 <write-wells>

Description: Wells with zone logs are written to well-logs/.
Argument: yes / no
Default: no (yes if <allow-wells-to-move> is set to yes.)

15.1.14.11 <prefix-for-log-files>

Description: Specification of prefix for *all* log files.
Argument: String.
Default: Empty string

15.1.14.12 <csv-file-style>

Description: Choose possible styles (file formats) used for comma-separated-values (CSV) files (extension .csv). For import into spreadsheets it is recommended to use any of the character-separated formats such as comma-separated. In the character-separated formats all other white space characters between values are removed so the files are hard to read in normal

text editors. The `fixed width` option can be readably visualized in any text editor but is not recommended for importing into spreadsheets.

Argument: `comma-separated` / `semicolon-separated` / `tab-separated` / `fixed width`
Default: `comma-separated`

15.2 <modelling-settings>

Description: Wrapper for elements determining the methods and algorithms used.
Argument: Elements specifying overall modeling settings.
Default: No default.

15.2.1 <mode>

Description: The default mode is `prediction`, that is, to generate a deterministic set of most likely surfaces using *kriging*.

Stochastic realizations are generated if `simulation` is chosen. The number of stochastic realizations are chosen by <number-of-realizations>.

The `estimation` mode gives the possibility to run through the initial estimation of the trend coefficients without entering the more time consuming generation of surfaces.

Argument: `prediction` / `simulation` / `estimation`
Default: `prediction`

15.2.2 <kriging-method>

Description: The three available kriging methods to be used. *Simple kriging* assumes no uncertainty on the trend coefficients. *Universal Kriging* assumes the trend coefficients are unknown and fits them to well data. This method fails if there are too few well data. *Bayesian Kriging* assumes the trend coefficients are partly known (expectation and SD specified) and adapts the trend coefficients to well data. This method is robust and works for any number of well data. If there is a lot of well data, Bayesian kriging will be very similar to universal kriging. Note that this will also affect stochastic simulation.
See Part V for more details.

Argument: `simple` / `bayesian` / `universal`
Default: `bayesian`

15.2.3 <number-of-realizations>

Description: Number of realizations for stochastic simulation <mode>.
Argument: Positive integer.
Default: 1

15.2.4 <condition-to-well-paths>

Description: Starts a method that move surfaces so that they are in correspondence with the zonation points. The algorithm will make surface constraints at zonation points when needed to ensure consistency between zonation points and surfaces. If speed is critical set the value to `no`.

Argument: `yes` / `no`
Default: `yes`

15.2.5 <allow-wells-to-move>

Description: This gives COHIBA the possibility of taking into account the well path TVD uncertainty. The consequence is that the TVD values are updated along the well path to make wells consistent with the surfaces. This flag is only relevant if <condition-to-well-paths> is set to `yes` (default). The well path TVD uncertainty can be specified by <wellpath-TVD-SD-log-name>. If <wellpath-TVD-SD-log-name> is not specified a parametric well path TVD uncertainty log is automatically generated. The magnitude of the automatically generated uncertainty log can be adjusted using <wellpath-TVD-SD-increase-rate>. The updated TVD values are written to `well-logs/`. See Section 7.5.

Argument: yes / no
Default: no

15.2.6 <check-specified-residual-uncertainties>

Description: Turns on or off the estimation of residual uncertainty. This can be a time consuming calculation and is not necessary when the specified residual uncertainties are considered correct. This calculation use parallel processes if COHIBA uses more than one thread. See <number-of-threads> for details.
Argument: yes / no
Default: yes

15.2.7 <minimize-broken-zonation>

Description: COHIBA selects and use a set of zonation points along the well paths to constrain the surfaces. See Section 21 for details. In certain cases, the selected zonation points are insufficient to ensure that all zonation points along the well paths are consistent with the surfaces. In particular, some of the selected zonation points may cause some non-selected zonation points to become inconsistent. These are called *broken zonation points*. The number of broken zonation points are reported in 'Section 18.x: Checking zonation' in the COHIBA log file. Choosing Yes tells COHIBA to add the broken zonation points to the selected zonation points and repeat the process of conditioning surfaces to the well data. Note that each iteration will increase the execution time significantly. The maximum number of iterations is set by <max-iterations-to-avoid-broken-zonation>.
Argument: yes / no
Default: no

15.2.8 <distance-between-zonation-points>

Description: The well paths are sampled at approximately equidistant locations along the well path. The distance between zonation points are measured along the path (that is MD) in meters. The default distance between zonation points is two times the grid resolution.

Choosing a small distance between zonation points will increase CPU time without necessarily increasing precision in results. Choosing a large distance between zonation points may reduce CPU time at the cost of reduced precision.
Argument: The sampling distance along well paths in meters.
Default: $2\min(\texttt{xinc}, \texttt{yinc})$ (See Figure 15.1.)

15.2.9 <add-uncertainty-to-severe-outliers>

Description: Well point TVD pick uncertainty is by default added to well points if they are classified as severe outliers. Choose no to avoid adding this pick uncertainty. The threshold for classification of severe outliers is set by <t-value-severe-outlier>.
Argument: yes / no
Default: yes if <include-all-well-points-in-kriging> is specified to no, otherwise no.

15.2.10 <include-all-well-points-in-kriging>

Description: All well points that are classified as error or extreme error are excluded from all calculations. Choosing yes includes such well points in the kriging step. The threshold for classifying a well point or well path constraint as an error or extreme error is set by <t-value-error> and <t-value-extreme-error>.
Argument: yes / no
Default: no

15.2.11 <simulate-trend-uncertainty>

Description: This flag has only effect in stochastic simulation <mode> and if simple kriging has been specified. If yes is specified, the trend coefficients will be drawn from the prior specification. This option can be used to specify exactly the SD on the trend coefficients used during stochastic simulation.
Argument: yes / no
Default: no

15.2.12 <pre-process-surfaces>

Description: Wrapper for elements controlling pre-processing of surfaces.
Argument: Elements controlling pre-processing.
Default: Void.

15.2.12.1 <make-time-surfaces-consistent>

Description: When turned on (yes), COHIBA makes seismic reflectors consistent by letting the upper travel times erode the deeper travel times. Truncated time surface maps are written to files prefixed by time_truncated_.

Warning: Note that this *should not* be turned on if air interpretations are intentionally used. Any air interpretation will be removed if this option is turned on.
Argument: yes / no
Default: no

15.2.12.2 <scale-isochores-to-seismic-envelopes>

Description: When both seismic reflectors and isochores are given as input to COHIBA, there is no guarantee that they are consistent. Isochore packages may, for instance, be too large and force faults to open up. For this not to happen, the isochore uncertainties have to be smaller than the reflector uncertainties in the fault region. Alternatively, the isochores should be pre-adjusted to the seismic envelope. Choosing yes for this element, COHIBA will scale all isochores in an isochore package with a factor

$$f(x,y) = \frac{\text{seismic envelope thickness } (x,y)}{\text{isochore package thickness } (x,y)} \tag{15.2}$$

The scaled isochores can be exported using <write-scaled-input-isochores>. If the seismic envelope consist of depth surfaces (no travel times given) then <reflector> must be set to yes for this option to have any effect.
Argument: yes / no
Default: no

15.2.12.3 <extrapolate-input-surfaces>

Description: Areas with missing codes in input trend maps, travel time and SD maps will be replaced by extrapolated values. This has the consequence that output surfaces will be defined everywhere. There are two alternative extrapolation methods, kriging and inverse-distance-interpolation that are specified by <extrapolation-method>. See Figure 15.2 for an example using default values. The extrapolated maps are written to extrapolation/ if <write-expert-files> is set to yes.

Extrapolating values introduces uncertainty in the extrapolated areas. This is handled by locally increasing the SD values of relevant residual maps. The increase depends on distance to known trend values. The maximum increase is <extrapolation-SD-factor> times the local SD value. Note that this applies to travel time residuals, thickness residuals and interval

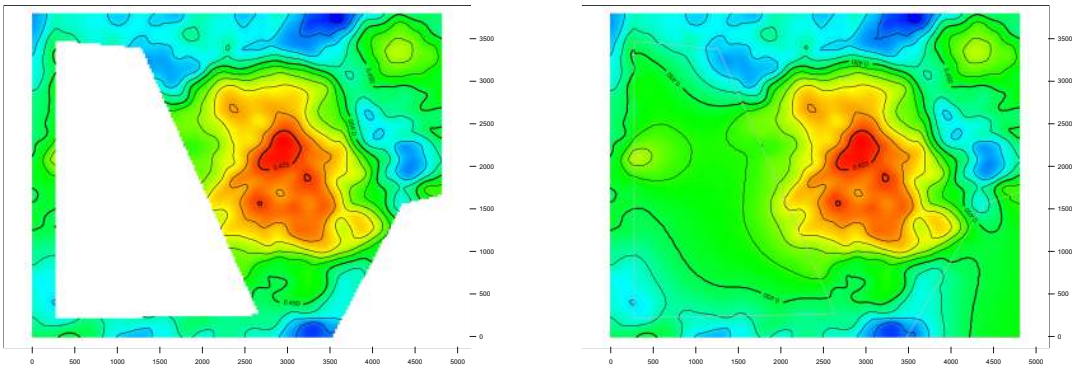


Figure 15.2. Original travel time map to the left with missing areas. Extrapolated travel time map to the right. The default extrapolation method (kriging with 1000 m range) has been used.

velocity residuals individually.

In the situation where there are multiple models for any surface, the huge residual uncertainties in the extrapolated areas will effectively make non-extrapolated trend models dominate totally. This is the way it is intended to be.

Argument: Turns on input surface extrapolation. Container for optional elements controlling extrapolation method.

Default: Void.

Example: Just turning on extrapolation:

```
<extrapolate-input-surfaces> </extrapolate-input-surfaces>
```

Example: Turning on extrapolation and reducing kriging range to 500 meters:

```
<extrapolate-input-surfaces>
      <extrapolation-kriging-range>     500     </extrapolation-kriging-range>
</extrapolate-input-surfaces>
```

15.2.12.3.1 `<extrapolation-method>`

Description: Choosing among the `kriging` or `inverse-distance-weighting` methods for extrapolation. Kriging uses an general exponential correlation function with power 1.5. The range is specified using `<extrapolation-kriging-range>`. Inverse distance weighting (Wikipedia) is controlled by a power parameter that can be modified by `<extrapolation-inverse-distance-weighting-power>`.

Argument: `kriging` / `inverse-distance-weighting`

Default: `kriging`

15.2.12.3.2 `<extrapolation-kriging-thinning-correlation>`

Description: The number of points along the edge of an undefined area is large. To speed up kriging, it is possible to remove highly correlated points. The thinning removes points that correlated above this correlation threshold.

Argument: Real in $[0, 1]$

Default: 0.9

15.2.12.3.3 `<extrapolation-kriging-range>`

Description: Variogram range in kriging extrapolation method.

Argument: Positive real (in meters)

Default: 1000

15.2.12.3.4 `<extrapolation-inverse-distance-weighting-power>`

Description: The inverse distance weighting extrapolation method is controlled by a *power parameter* (see Wikipedia).
Argument: Positive real
Default: 2.0

15.2.12.3.5 `<extrapolation-SD-factor>`

Description: The increase in residual uncertainty maps are calculated using the kriging prediction error σ^* in Eq. 18.42a with unit variance. The increased SD value is SD $\cdot\,(1 + c\,\sigma^*)$, where c is the specified factor. The Gaussian correlation function and range given by `<extrapolation-kriging-range>` is used. See Figure 15.3 for an illustration.
Argument: Non-negative real
Default: 10

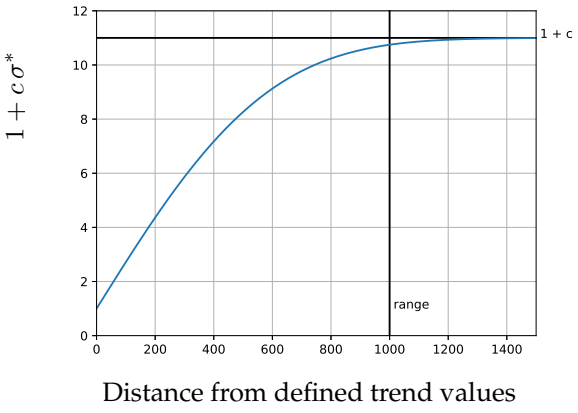


Figure 15.3. Increase in residual SD in areas with extrapolated trend maps. The default value $c = 10$ is used in the figure. The SD increases until it reaches the range given by `<extrapolation-kriging-range>` where it flattens at $1 + c$ times the original local SD value. The factor c is specified by `<extrapolation-SD-factor>`.

15.2.12.4 `<smoothing-factor-velocity-trends>`

Description: Sometimes the input velocity trend maps contains large fluctuations or irregularities. Smoothing the maps on input will in such situations give more realistic velocity trends by filtering out high frequencies. This factor decides how much smoothing is performed. 0 means no smoothing, leaving the input map unchanged. 1 means full smoothing giving a constant (the mean). If input maps show a low-frequent behaviour, even quite high values of the smoothing factor will keep the maps unchanged. After the smoothing, a check is performed to decide if smoothing makes a significant impact.[6] If the impact is small the smoothing is

6. This is done as follows:
a) Make the smoothed velocity trend: $\bar{v}(x, y)$.
b) Find the residual: $r(x, y) = v(x, y) - \bar{v}(x, y)$.
c) Find minimum and maximum residual: $r_{\min} = \min r(x, y)$ and $r_{\max} = \max r(x, y)$.
d) Find the smoothed velocities at these two locations: $\bar{v}_{\min}$ and $\bar{v}_{\max}$.
e) Find the span of values: $\bar{v}_{\text{span}} = \bar{v}_{\max} - \bar{v}_{\min}$.
f) Calculate $t_{\min} = |r_{\min}/\bar{v}_{\min}|$ and $t_{\max} = |r_{\max}/\bar{v}_{\max}|$.
g) Calculate $u_{\min} = |r_{\min}/\bar{v}_{\text{span}}|$ and $u_{\max} = |r_{\max}/\bar{v}_{\text{span}}|$.
The smoothed trend is used if $t > 0.01$ and $u > 0.1$. The t's and the u's measure if the smoothing makes a noticeable change relative to the value of trend and relative to the range of values in the trend respectively.

dropped. Modified trend maps are written to file with prefix `FilteredVelocityTrend_`.

Argument: Real in [0, 1].

Default: `0.5`

15.2.12.5 `<smoothing-factor-SD-maps>`

Description: Sometimes the SD maps contains spikes and sharp edges that may cause artifacts in the final maps. Smoothing the maps by filtering out high frequencies will usually improve results. This factor decides how much smoothing is performed. 0 means no smoothing, leaving the input map unchanged. 1 means full smoothing giving a constant (the mean). If input maps show a low-frequent behaviour, even quite high values of the smoothing factor will keep the maps unchanged. After the smoothing, a check is performed to decide if smoothing makes a significant impact. See the discussion in the footnote to `<smoothing-factor-velocity-trends>`. If the impact is small the smoothing is dropped. Modified trend maps are written to file with prefix `FilteredSDMap_`.

Argument: Real in [0, 1].

Default: `0.8`

15.2.13 `<post-process-surfaces>`

Description: Wrapper for elements controlling post-processing of surfaces. This includes truncating surfaces due to erosion and onlapping, pinch outs and removal of gridding mismatches.

Argument: Elements controlling pre-processing.

Default: Void.

15.2.13.1 `<erode-and-onlap>`

Description: Choosing `no` overrides all input flags related to `<erosive>` and `<onlapped>` surfaces. Default is to truncate all surfaces by the erosive and onlapped surfaces. This also applies to output trends.

This has no effect on free surfaces since they can not erode or be onlapped.

Argument: `yes` / `no`

Default: `yes`

15.2.13.2 `<treat-reflectors-as-eroding-and-onlapped>`

Description: Will ensure that seismic reflectors truncate other surfaces. See Figure 12.1 for an example. This will only affect the post processing and not the extraction of well points from zone logs. If `<erode-and-onlap>` is set to `no`, this has no effect. The individual elements `<erosive>` and `<onlapped>` for each seismic reflector will be overruled by this setting. A surface is a reflector if it has a specified `<travel-time>` or it is explicitly specified to be a `<reflector>`.

This has no effect on free surfaces since they can not erode or be onlapped.

Argument: `yes` / `no`

Default: `yes`

15.2.13.3 `<make-average-of-crossing-surfaces>`

Description: Post-process surfaces to produce a sequence of stratigraphically correct surfaces. Negative thickness will be removed and replaced by a zero thickness interval — a pinch out. This algorithm does not take into account well observations. The default is to remove all negative thicknesses.

Argument: `yes` / `no`

Default: `yes`

15.2.13.4 <make-surfaces-interpolate-well-points>

Description: Kriging is a perfect interpolator but the regular gridding of the surfaces introduce a systematic smoothing of the bulls eye at the well point. This introduces a gridding error away from the grid nodes. By choosing yes the gridding mismatch at the well points is removed. (See Section 18.6.) This is done by adjusting the four grid values closest to a well point to ensure perfect bilinear interpolation. Since different well points may share common grid values all modifications are treated simultaneously. The algorithm minimizes the sum of all adjustments.

The removal of the gridding mismatch for well points are treated simultaneously with the removal of gridding mismatch along well paths.
See <allow-small-surface-adjustment-at-zonation-points>.

The gridding mismatch at a well point is only removed if a few conditions are met:

- The well point is not an outlier.
- The well point uncertainty is less than 1 meter (default). The default value can be modified using <max-SD-for-well-points-interpolation>.
- The residual, observation minus trend, is less than the value specified by <max-residual-for-well-points-interpolation>. (Default is 999 meters.) This gives a possibility to avoid some rare occasions that gives large spikes in the surfaces.
- If two well points are close, the surface can get spikes caused by a steep gradient between the well points. The maximum allowed gradient can be set using <max-gradient-for-surface-adjustment>. (Default is 100.)

Argument: yes / no
Default: yes

15.2.13.5 <allow-small-surface-adjustment-at-zonation-points>

Description: Removes gridding mismatch along well paths. The gridding mismatch has the same cause and is removed in the same way as gridding mismatches for well points. See <make-surfaces-interpolate-well-points> for details. The adjustment of surfaces to remove the gridding mismatch for well paths are consistent with the removal of gridding mismatch for well points. The value set by <max-gradient-for-surface-adjustment> affects the removal of gridding mismatches at zonation points and well points.

The gridding mismatch at a zonation point is only removed if one of these conditions are met:

1. If a zonation point is less than 1 meter (default) on the *wrong* side of a surface. The default value can be modified using <max-residual-for-adjustment-at-zonation-points>.
2. If a zonation point is *closer* than 0.5 meter (default) to the surface. The default value can be modified using <min-distance-from-surface-to-zonation-points>.

The surface grid nodes are modified such that the surface becomes exactly 0.5 meter (default) away from the well path at the zonation points. This distance is modified by <min-distance-from-surface-to-zonation-points>.

Argument: yes / no
Default: yes

15.2.13.6 <set-eroded-nodes-to-undefined>

Description: Eroded areas is set to undefined (missing code) if value is yes. If <erode-and-onlap> is set to no, this has no effect. See Figure 15.4.
Argument: yes / no

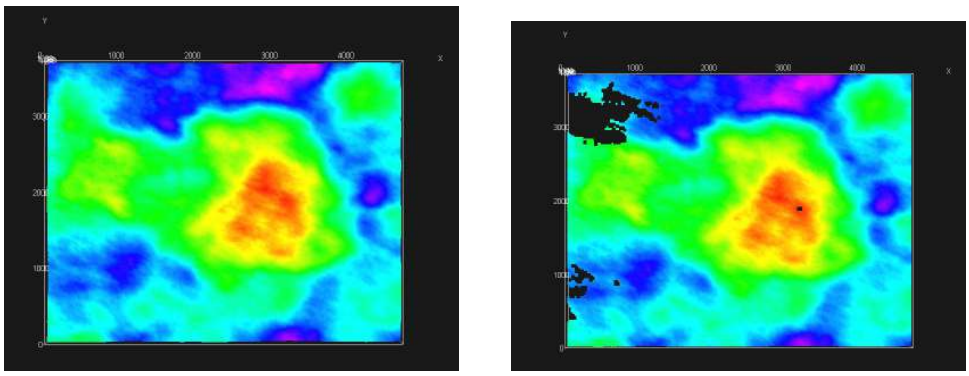


Figure 15.4. Original surface to the left (default). To the right is `<set-eroded-nodes-to-undefined>` set to `yes`.

Default: `no`

15.2.13.7 `<smoothing-factor-calculated-velocities>`

Description: Interval velocities are calculated as $v = \Delta z/\Delta t$. This might give unrealistic results for very short travel times, Δt. Unrealistic velocities are replaced by a smoothing process if `<smoothing-factor-calculated-velocities>` is set to a positive value. This means that the high frequencies in the calculated velocity maps are filtered out. Low value gives little smoothing with 0.0 leaving the velocities unchanged, while higher values gives much smoothing, with 1.0 leaving a constant velocity (the mean). A suggested value if smoothing is desired is 0.5.

Argument: Real between 0 and 1.

Default: `0.0`

15.2.14 `<correlated-intervals>`

NEW in 6.0

Description: Wrapper for elements controlling correlating intervals. The correlations are calculated based on the difference in the *prior* average thickness of the intervals for every pair of intervals sharing a `<common-top-for-correlated-intervals>`. All the correlated intervals must be either `thickness` or `velocity` `<interval-type>`. Both prior trend coefficients and interval residuals become correlated. For details see Section 14.

Argument: Elements controlling linking of intervals.

Default: Void.

15.2.14.1 `<correlated-intervals-residual-range>`

NEW in 6.0

Description: Correlation between interval residuals depend on the average thickness difference when they share a `<common-top-for-correlated-intervals>`. If the thickness difference is bigger than this parameter the intervals are practically uncorrelated. See Eq. 14.2.

Argument: Non-negative real (meters).

Default: `100.0`

15.2.14.2 `<correlated-intervals-residual-power>`

NEW in 6.0

Description: See Eq. 14.2.

Argument: Non-negative real less than 2.0.

Default: `1.0`

15.2.14.3 `<correlated-intervals-simulation>`

NEW in 6.0

Description: The residual fields drawn for each interval will be correlated using the correlation matrix calculated for the residuals. Changing this to `no` introduces an inconsistency. See

Section 14.
Argument: `yes` / `no`.
Default: `yes`

15.2.14.4 <correlated-intervals-trend-range>

NEW in 6.0

Description: Correlation between prior interval coefficients depend on the average interval thickness difference when they share a <common-top-for-correlated-intervals>. If the thickness difference is bigger than this parameter the intervals are practically uncorrelated. See Eq. 14.1.
Argument: Non-negative real (meters).
Default: `100.0`

15.2.14.5 <correlated-intervals-trend-power>

NEW in 6.0

Description: See Eq. 14.1.
Argument: Non-negative real less than 2.0.
Default: `1.0`

15.2.14.6 <correlated-intervals-ratios-for-trends>

NEW in 6.0

Description: The prior trend coefficients for any two linked intervals `A` and `B` are correlated with a function of the ratios $\Delta Z_{\mathtt{TB}}/\Delta Z_{\mathtt{TB}}$, where the $\Delta Z_{\mathtt{A}}$ and $\Delta Z_{\mathtt{B}}$ are the prior thicknesses of the intervals `A` and `B` respectively. See Section 14.2.
Argument: `yes` / `no`.
Default: `no`

15.2.15 <advanced-settings>

Description: Wrapper for elements controlling algorithms. Don't touch it if you don't mean it.
Argument: Elements controlling algorithms.
Default: Void.

15.2.15.1 <max-rejection-rate>

Description: This is the maximum rejection rate for rejection sampling during stochastic simulation. The default, 0.9, gives at worst a 90 % rejection rate. The stochastic simulation is aborted if COHIBA estimates that the rejection rate is larger than the specified maximum rejection rate. The rejection rate is estimated during the initial iterations. If the stochastic simulation is aborted due to large rejection rates, the <acceptance-criteria> must be relaxed or the maximum rejection rate must be increased. See Section 19.4 for more details.
Argument: Real in $\langle 0, 1]$.
Default: 0.9

15.2.15.2 <model-weight-resolution>

Description: This option makes it possible to calculate model weights (Section 11) once and to save them for later use when running multiple realizations. This may reduce CPU times. It is also possible to calculate the model weights on a coarser grid in order to save memory.

Choosing `0` (default) means that model weights are calculated at full resolution and must be recalculated for every realization.
Choosing `1` means that model weights are calculated at full resolution and that they will be saved and reused if multiple realizations are generated.
Choosing any $n > 1$ means that the weights are calculated at every n^{th} grid node in each direction. Model weights in between the calculated weights are obtained by bilinear interpo-

lation. Model weights will be saved and reused if multiple realizations are generated.

If $n > 0$ and the <number-of-realizations> is more than 1 in stochastic simulation <mode>, then model weights will be saved for later use. The memory usage is proportional to $1/n^2$. We recommend to use $n > 1$ when there is many alternative models. Choosing a large n will reduce the spatial accuracy of the model weights.

We recommend to use 5 for fast simulation. We recommend to use the default for prediction and ordinary simulation since the gain in speed normally is small.

Argument: Non-negative integer.
Default: 0

15.2.15.3 <max-SD-for-well-points-interpolation>

Description: Gridding mismatches at a well point is removed if the uncertainty (SD) is less than this value. Has only effect if <make-surfaces-interpolate-well-points> is yes.
Argument: Positive real (meters).
Default: 1.0

15.2.15.4 <max-residual-for-well-points-interpolation>

Description: Gridding mismatches at a well point is removed if the residual is less than this value. The value can be set to a smaller value (say 10) to avoid spikes in the surfaces. Has only effect if <make-surfaces-interpolate-well-points> is yes.
Argument: Positive real (meters).
Default: 999.0

15.2.15.5 <max-gradient-for-surface-adjustment>

Description: Gridding mismatches at a well point or zonation point is removed if the gradient between the point and another point is less than this value. The value can be set to a smaller value (say 10) to avoid spikes in the surfaces. Has only effect if <make-surfaces-interpolate-well-points> or <allow-small-surface-adjustment-at-zonation-points> are yes.
Argument: Positive real.
Default: 100.0

15.2.15.6 <max-residual-for-adjustment-at-zonation-points>

Description: Gridding mismatches at a zonation point is removed if the zonation point is less than 1 meter (default) on the *wrong* side of a surface. Increasing this value will increase the number of grid nodes that are modified. It has only effect if <allow-small-surface-adjustment-at-zonation-points> is yes.
Argument: Positive real (meters).
Default: 1.0

15.2.15.7 <min-distance-from-surface-to-zonation-points>

Description: The distance between a well path and a surface will never be smaller than this value. Also gridding mismatches at a zonation point is removed if the zonation point is closer to a surface than 0.5 meters (default). Increasing this value will increase the number of grid nodes that are modified. It has only effect if <allow-small-surface-adjustment-at-zonation-points> is yes.
Argument: Positive real (meters).
Default: 0.5

15.2.15.8 <allow-zonation-points-near-faults>

Description: Allow zonation points also where the fault indicator log indicates a fault.
Argument: yes / no
Default: no

15.2.15.9 <base-help-points-on-simulated-surfaces>

Description: When doing simulations, the target points may be based on the simulated surfaces instead of the predicted ones. This reduce the probability of wells crossing surfaces in wrong locations.
Argument: yes / no
Default: no

15.2.15.10 <solver-for-weights>

Description: Specifies the method used for solving the linear equation system that gives the model weights. The conjugate gradient method is significantly faster than the Cholesky decomposition if there are many model weights. The two methods can give slightly different results since the linear equation system can be (very) rank deficient.
Argument: conjugate-gradient / cholesky
Default: conjugate-gradient

15.2.15.11 <max-iterations-to-avoid-broken-zonation>

Description: This option has only an effect if <minimize-broken-zonation> is set to yes. Choosing an integer $N > 1$ allows COHIBA to repeat the kriging N times. At each new iteration broken zonation points from the previous iteration is added to the selected zonation points. Note that each iteration will increase the execution time significantly. Setting <minimize-broken-zonation> to no is equivalent to selecting 1.
Argument: Positive integer.
Default: 3

15.2.15.12 <correlate-close-reflectors>

Description: COHIBA assumes that all residuals are uncorrelated. This assumption fails for seismic reflectors that are near or coinciding. Then the uncertainty in the two time residuals are highly correlated. Turning this flag on makes COHIBA automatically modify the correlation between travel time residuals. See an example in Figure 12.1.

The correlations are increased towards 1 when seismic reflectors are closer than $\sigma_{t_1} + \sigma_{t_2}$, that is, the sum of the SDs of the two travel time residuals. The correlation is set to $\rho = \max\big(0, [1 - \frac{|\Delta t|}{\sigma_{t_1}+\sigma_{t_2}}]\big)$. So correlations becomes 1 if $\Delta t = 0$. Also the SD of the deepest surface is set to $\min\big(\sigma_{t_2}, \frac{|\Delta t|}{2}\big)$ to avoid crossing surfaces.

This option does not affect reflectors that are free surfaces (see <free-surface>).
Argument: yes / no
Default: yes

15.2.15.13 <max-obs-direct-estim-trend-coef>

Description: When the number of well points is smaller than this threshold, the posterior trend coefficients and covariance matrix are calculated using Eq. 18.21a and Eq. 18.21b. If the number of well points is larger than this, expressions Eq. 18.22a and Eq. 18.22b are used. This only applies when <kriging-method> is bayesian. See Section 18.3.2 for details.
Argument: Positive integer.
Default: 200

15.2.15.14 <max-obs-GLS-approx-trend-coef>

Description: When the number of well points is more than this threshold the non-zero covariances are ignored when estimating trend coefficients. This amounts to replacing the generalized least squares (GLS) estimates (Eq. 18.18a and Eq. 18.18b) by the weighted least squares (WLS) estimates (Eq. 18.19a and Eq. 18.19b). The WLS approximation can handle a lot of well points. This applies when <kriging-method> is `universal` or `bayesian`. See Section 18.3.1 for details.

Argument: Positive integer.

Default: `2000`

15.2.15.15 <max-obs-GLS-approx-extreme-outliers>

Description: When trend coefficients are calculated, well points classified as extreme errors (see <t-value-extreme-error>) are removed one at a time, and after each removal updated trend coefficients are calculated. To save time, we estimate the trend coefficients using the WLS approximation when there are more than 1000 well points available and remove as many extreme outliers as possible. When no more outliers are found, we recalculate trend coefficients using the GLS vs WLS approximation (if there are less than 2000 well points available) and continue to remove extreme errors. The element <max-obs-GLS-approx-extreme-outliers> gives maximum number of well points that can be available in a calculation before the WLS approximation is used to remove extreme outliers.

Argument: Positive integer.

Default: `1000`

15.2.15.16 <max-obs-update-trend-coef-using-well-paths>

Description: The trend coefficients are not adjusted to fit horizontal well paths *if* the number of well points are more than this value. This saves a lot of CPU time. The idea is that the trend coefficients are estimated with sufficient accuracy when the number of well points exceed this limit.

Argument: Positive integer.

Default: `200`

15.2.15.17 <threshold-for-trace-clustering>

Description: The constraints from each well path are grouped in correlated clusters (see Section 21.4). This element specifies the threshold for the correlations. Specifying a low correlation means that all constraints are probably grouped into one cluster. Specifying a high value means that constraints must be strongly correlated to be grouped. Ideally all constraints should be handled simultaneously, but small clusters are important to obtain fast performance.

Argument: Real in [0, 1].

Default: `0.1`

15.2.15.18 <threshold-for-cluster-merging>

Description: The correlated clusters (see Section 21.4) are merged if any pair of constraints have a correlation larger than this threshold. A small value will cause all clusters to be merged. A large value will avoid any merging of clusters. Some merging is needed if well paths are near.

Argument: Real in [0, 1].

Default: `0.2`

15.2.15.19 <threshold-for-well-point-cluster-inclusion>

Description: COHIBA estimate the correlation between well points and surface constraints for all well points that are within one range of the constraints and include these points in the well-

cluster (see Section 21.4) if the correlation is larger than this threshold. All well points within one range are included if the threshold is 0.0. Increasing this value will reduce the cluster size at the expense of introducing possible inaccuracies. Note that filtering based on this correlation threshold is only done if the number of well points within one range is above 200.

Argument: Real in [0, 1].
Default: `0.1`

15.2.15.20 `<threshold-for-removing-undefined-well-sections>`

Description: A well point replaces a zone transition in and undefined section if the undefined section is shorter than this distance (MD). The well point is located in the middle of the endpoints of the undefined sections. A well point TVD pick uncertainty will be added. The pick uncertainty (SD) 1/4 of the difference of the TVD values at the end points of the undefined section.

If the undefined section in a zone transition is longer than this distance, then the transition will be represented as two inequality constraints, one at each endpoint. See Section 8.5.1 for some illustrations.

Argument: Positive real (meters).
Default: `1.0`

15.2.15.21 `<threshold-for-help-point-deactivation>`

Description: COHIBA keeps those *target points* (see page 200) that impose the strongest restrictions on the surfaces and deactivate those that are highly correlated to the strongest restrictions. Choosing 1 means that no surface target points will be deactivated while choosing a low value (< 0.5) means that many target points will be deactivated. Note however that deactivated zonation points might be used in later iterations if `<minimize-broken-zonation>` is set to `yes` (Default). Choosing a small value will reduce the number of target points and thereby reduce the CPU time.

Argument: Real in [0, 1].
Default: `0.8`

15.2.15.22 `<threshold-for-special-help-point-deactivation>`

Description: Similar to `<threshold-for-help-point-deactivation>`, but now applied to special sample points. These are help points connected to zonation points at the end of the well, or where the zone log goes from defined to undefined.

Argument: Real in [0, 1].
Default: `0.997`

15.2.15.23 `<threshold-for-high-correlation-wp-wp>`

NEW in 6.0

Description: Threshold for marking highly correlated well points from the same well. Only one of the two well points is kept for calculations, while the other is deleted. The point that is kept is flagged as a pinch out point.

Argument: Real in [0, 1].
Default: `0.999`

15.2.15.24 `<threshold-for-high-correlation-wp-ip>`

NEW in 6.0

Description: Threshold for removing inequality points that are highly correlated with a well point.

Argument: Real in [0, 1].
Default: `0.999`

15.2.15.25 `<threshold-for-high-correlation-wp-ep>`

NEW in 6.0

Description: Threshold for removing extra points that are highly correlated with a well point.

Argument: Real in [0, 1].
Default: `0.995`

15.2.15.26 `<min-isochore-thickness>`

Description: COHIBA will not impose surface constraints at selected zonation points along well paths for zones thinner than this threshold.
Argument: Positive real (meters).
Default: `0.1`

15.2.15.27 `<threshold-for-mild-error>`

Description: COHIBA will classify a mismatch between a well path and a surface according to this threshold. Only affects reporting.
Argument: Positive real. Length unit in meters.
Default: `1.0`

15.2.15.28 `<t-value-outlier>`

Description: Threshold for flagging well point as *outlier*. 5 % of the well points will be classified as outliers if they follow a Gaussian distribution.
Argument: Positive real.
Default: `1.95996` (see e.g. Wikipedia).

15.2.15.29 `<t-value-severe-outlier>`

Description: Threshold for flagging well point as a *severe outlier*. A well point TVD pick uncertainty is added unless `<add-uncertainty-to-severe-outliers>` is set to `no`. 1 % of the well points will be classified as uncertain if they follow a Gaussian distribution.
Argument: Positive real.
Default: `2.57583` (see e.g. Wikipedia).

15.2.15.30 `<t-value-error>`

Description: Threshold for flagging a well point or a well path constraint as an *error*. A well point or well path constraint classified as an error will be removed from all calculations unless `<include-all-well-points-in-kriging>` is set to `yes`. 0.2 % of the observations will be classified as an error if they follow a Gaussian distribution.
Argument: Positive real.
Default: `3.09023` (see e.g. Wikipedia).

15.2.15.31 `<t-value-extreme-error>`

Description: Threshold for flagging a well point or a well path constraint as an *extreme error*. These well points are removed and the trends re-fitted. The procedure will be iterated until all extreme errors have been removed. A well point or well path constraint classified as an extreme error will be is removed from all calculations unless `<include-all-well-points-in-kriging>` is set to `yes`. 0.01 % of the observations will be classified as extreme errors if they follow a Gaussian distribution.
Argument: Positive real.
Default: `3.8906` (see e.g. Wikipedia).

15.2.15.32 `<t-value-first-help-point>`

Description: A zonation point is close to a surface if it is closer than `<t-value-first-help-point>` times the prediction uncertainty. A close zonation point gives a surface constraint used when conditioning to zone logs. See Step 3 on page 199 for more details.
Argument: Positive real.
Default: `2.0`

15.2.15.33 <t-value-second-help-point>

Description: A close zonation point and its associated surface constraint might cause the neighboring surface to violate the zonation point. Therefore, surface constraints usually come in pairs. See Step 3 on page 199 for more details. If the zonation point is closer to the second surface than <t-value-second-help-point> times the prediction uncertainty, then this surface constraint is also used.

Argument: Positive real.

Default: `2.5`

15.2.15.34 <max-generalized-eigenvalue-for-inequality-points>

Description: When calculating the surface help points, the inverse of the matrix $(C^{i|e} - \Sigma^i)$ goes into the formulas. This matrix is not always positive definite since Σ^i is obtained empirically from a set of 256 drawn realizations and Monte Carlo noise will introduce small errors. This is corrected by truncating some eigenvalues. The specified number gives this truncation limit such that eigenvalues are above this limit.

Argument: Real value less than 1.0.

Default: `0.9`

15.2.15.35 <max-dxy-for-identical-well-points>

Description: If two well points on the same surface are close enough, they will be treated as equal. This keyword is used to change the largest lateral distance two well points can have before they are treated as different well points.

Argument: Positive real (meters).

Default: `5.0`

15.2.15.36 <max-dz-for-identical-well-points>

Description: If two well points on the same surface are close enough, they will be treated as equal. This keyword is used to change the largest vertical distance two well points can have before they are treated as different well points.

Argument: Positive real (meters).

Default: `0.5`

15.2.15.37 <max-slope-before-possible-conflict>

Description: If two well points are close, uncertainty is added. If the slope between the well points (calculated as dxy/dz) are too large, the points are flagged as possibly in conflict. This keyword can be used to alter this sensitivity.

Argument: Positive real.

Default: `0.1`

15.2.15.38 <min-SD-close-well-points>

Description: If there are two well points belonging to the same surface within a grid-cell distance they are required to have a minimum uncertainty. This keyword can be used to change this minimum uncertainty.

Argument: Positive real (meters).

Default: `0.01`

15.2.15.39 <threshold-for-conditioning-in-neighbourhood>

Description: Controls the use of neighborhoods in the kriging algorithm. If the number of well points is larger than this number, kriging is performed in overlapping rectangular subsets. This algorithm runs fast and gives a good approximation. If there appears rectangular

patches in the output grids, consider increasing this number.

It is recommended to keep this number low since each rectangular subset is run in parallel processes.

Argument: Positive integer.
Default: `1`

15.2.15.40 `<preprocess-range-factor-for-neighbourhood>`

Description: Determines data neighborhood size as the fraction of the range in the pre-processing step. The well points in the neighborhood is used to find the prediction and prediction uncertainty at the zonation points along the well paths. See the second step in Section 21.1 for some explanation.
Argument: Positive real.
Default: `1.5`

15.2.15.41 `<min-range-factor-for-neighbourhood>`

Description: Minimum data neighborhood size as the fraction of the range.
Argument: Positive real.
Default: `1.0`

15.2.15.42 `<max-range-factor-for-neighbourhood>`

Description: Maximum data neighborhood size as the fraction of the range.
Argument: Positive real.
Default: `2.0`

15.2.15.43 `<target-number-of-data-in-neighbourhood>`

Description: If the number of well points within the rectangle determined by `<min-range-factor-for-neighbourhood>` is less than this number, the rectangular neighborhood will be expanded until this number is obtained. However, the rectangle will never exceed the size given by `<max-range-factor-for-neighbourhood>`. Note that the default value, `0`, means that the rectangular neighborhood always remains at the size determined by `<min-range-factor-for-neighbourhood>`.
Argument: Non-negative integer.
Default: `0`

15.2.15.44 `<min-generalized-eigenvalue-for-residual-uncert>`

Description: This is a threshold that determines how many linear combinations of well points that are used when estimating the residual uncertainties. A large value (close to 1) will reject most linear combinations unless they perfectly match the corresponding interval thickness. A small value (close to 0) will include almost all linear combinations and the estimates will approach the overall estimate that blends all intervals.
Argument: Real in [0,1].
Default: `0.5`

15.2.15.45 `<volume-calculation-method>`

Description: Calculating volumes require that the surface is defined between grid nodes. Two interpolation techniques are supplied. We recommend the default because the `bilinear` option has not been rigorously tested. See Section 9.1 for details.
Argument: `nearest-neighbor` / `bilinear`
Default: `nearest-neighbor`

15.2.15.46 <keep-all-pinchout-points>

Description: Controls how well points are extracted from zone logs in a pinchout-situation. Setting this flag to no means that only one of the well points well be kept. Note that even though all the pinch out points are kept, some might be deleted later due to high correlation between well points. The threshold for this deletion can be adjusted using <threshold-for-high-correlation-wp-wp>.

Argument: yes / no

Default: yes

15.2.15.47 <normalize-interval-weights-table>

Description: Normalize all rows in the table of total weight of intervals used when building surfaces, showed in the COHIBA log file under Section 4: The alternative ways to build each surface. This table is only showed if the detail level of <surface-models> is at least 4.

Argument: yes / no

Default: no

15.2.15.48 <check-zonation-in-branching-wells>

Description: Report if the zone logs in two side tracks is different in more than 1 % of the length (MD) in their common section. The results are summarized in Section 7: Well branching and COHIBA will produce a warning and issue a task. The test ignores undefined values.

Argument: yes / no

Default: yes

15.2.15.49 <add-uncertainty-to-close-observations>

Description: Well point TVD pick uncertainty is by default added to well points that lie close to other well points on the same surface (see Section 8.3.3 for details). Choose no to avoid adding this pick uncertainty.

Argument: yes / no

Default: yes

15.3 <well-data>

Description: Wrapper for <well-log>, <well-points>, <values-outside-grid> and <well-points-to-ignore> elements.

Argument: Any number of <well-log>, <well-points>, and <well-points-to-ignore> elements

Default: No default.

Example: See Section 15.3.6 for a complete example.

15.3.1 <wellpath-TVD-SD-range>

Description: Specifies a range in meters along the well path that determines the range (stiffness) of the well path TVD uncertainty. See Section 8.5.2 for details and illustrations. The SD of the well path TVD uncertainty is determined by <wellpath-TVD-SD-log-name> or <wellpath-TVD-SD-increase-rate> when using <well-log>. For <well-points> the SDs are specified in the well point <files>.

Argument: Positive real (meters.)

Default: 300.0

15.3.2 <well-log>

Description: A wrapper for elements describing zone logs and fault indicator logs.

Argument: Elements specifying the zone log or fault indicator log along well paths.

Default: No default.

15.3.2.1 <files>

Description: The well log files to be imported. This element may be repeated in order to import different well log files in different locations (directories). Multiple well log files are separated by a comma. The file formats are detected automatically. See Section 8 for available well log file formats.

The well names must be unique. Two files with identical well names will cause an error.

Argument: Any valid path relative to <input-directory>. Wild cards (*) are supported.

Default: Empty string.

Example: One file:

```
<files> wells/31-2_K-11H.w </files>
```

Example: Three files:

```
<files> wells/W1.rms, wells/W2.rms, wells/W3.las </files>
```

Example: All files in directory:

```
<files> wells/* </files>
```

15.3.2.2 <zone-log-specification>

Description: The zone log specification is a set of integers (non-negative in consecutive order) and associated zone names separated by commas. See Section 8.1 for more details. This specification is necessary when reading LAS 2.0 well log files. It is not needed for ROXAR RMS WELL files since they include the zone log specification in the header. For LAS 2.0 well files the zone name can include any (ASCII) character (including space) except for commas. The zone name can not include spaces if used with ROXAR RMS WELL files. Note that files with a different zone name specification will be discarded.

Argument: A comma separated list.

Default: Empty string.

Example: Reading two LAS 2.0 well files and one ROXAR RMS WELL file:

```
<well-log>
   <zone-log-specification>
                    1, ABOVE, 2, DRAUPNE, 3, 6BC, 4, 6AC, 5, 6AM, 6, 5CC
```

```
    </zone-log-specification>
    <zone-log-name>    GM2005a                  </zone-log-name>
    <files>            w1.las, w2.las, w3.rms   </files>
  </well-log>
```

15.3.2.3 <zone-log-specification-file>

Description: See <zone-log-specification> for details. This element has the same purpose as <zone-log-specification> but the zone log specification is read from an ASCII file rather than from the COHIBA model file. In the ASCII file there is one line entry for each zone, and this entry consists of a comma separated zone number and zone name.

Argument: A string.

Default: Empty string.

Example: Reading two LAS 2.0 well files and one ROXAR RMS WELL file:

```
<well-log>
   <zone-log-specification-file>
                      zone-log-specification.txt
   </zone-log-specification-file>
   <zone-log-name>    GM2005a                  </zone-log-name>
   <files>            w1.las, w2.las, w3.rms   </files>
</well-log>
```

The specification file which is placed in the same directory as the well data may look like:

```
0, Nordaland Gr
1, Hordaland Gr
2, Zone TOP CHALK
```

15.3.2.4 <zone-log-name>

Description: Zone log identifier. A file may contain several zone logs and this element is used to select the correct one. Currently, only one zone log can be specified.

Argument: A string.

Default: Empty string.

Example: `<zone-log-name> GM2005a </zone-log-name>`

Example: `<zone-log-name> ZonesSnorre </zone-log-name>`

15.3.2.5 <fault-log-name>

Description: Specifies the name of the fault indicator log. A 1 in the fault indicator log means that it is near a fault and a 0 means that it is far away from a fault.

Argument: A string.

Default: Empty string.

Example: `<fault-log-name> FaultIndicator </fault-log-name>`

15.3.2.6 <MD-log-name>

Description: Specifies the name of the MD log. COHIBA will try to estimate MD values if this log is not specified. The MD values are primarily used in the various COHIBA log files to simplify identification of well points.

Argument: A string.

Default: Empty string.

Example: `<MD-log-name> MD </MD-log-name>`

15.3.2.7 <wellpoint-TVD-pick-SD-log-name>

Description: Specifies the name of the log describing the well pick TVD uncertainty (SD). The units are determined by <z-unit>. If the specified TVD uncertainty log in a well is missing, the

uncertainty is assumed to be zero for this well.

Argument: A string.
Default: Empty string.
Example: `<wellpoint-TVD-pick-SD-log-name> PickSD </wellpoint-TVD-pick-SD-log-name>`

15.3.2.8 <wellpath-TVD-SD-log-name>

Description: Specifies the name of the log describing the well path TVD uncertainty (SD). The units are determined by <z-unit>. If the specified TVD uncertainty log in a well is missing, the uncertainty is assumed to be zero for this well. The well path TVD uncertainty is smooth and correlated along the well path. The smoothness is determined by <wellpath-TVD-SD-range>. See Section 8.5.2 and in particular Figure 8.11 for more details.

It is possible to use automatically generated TVD uncertainty logs. This is done when <allow-wells-to-move> is yes and <wellpath-TVD-SD-log-name> is not used. The magnitude of the automatically generated TVD uncertainty log can be modified using <wellpath-TVD-SD-increase-rate>.

The well path TVD uncertainty log should in principle be monotonically increasing since positioning survey uncertainties accumulate along the well path. COHIBA will accept any log values but it is highly recommended to use uncertainty logs that are monotonically increasing with few and small exceptions. A large reduction in uncertainty along the well may cause unexpected results. Also note that TVD uncertainty logs that belong to different branches in the same multilateral well *should* have consistent uncertainty logs. COHIBA makes a number of QC checks on the well path TVD uncertainty logs and give warnings if unreasonable or inconsistent values are detected.

The use of the well path TVD uncertainty depends on <condition-to-well-paths> and <allow-wells-to-move>. If both of these are yes, then surfaces *and* the TVD logs will be updated to make a consistent set of surfaces and well paths. New updated TVD values are written to well-logs/.

If both <condition-to-well-paths> and <allow-wells-to-move> are set to no, then the well path TVD uncertainty is assigned to the TVD values at well points.

Argument: A string.
Default: Empty string.
Example: `<wellpath-TVD-SD-log-name> PosSurvTVDUncert </wellpath-TVD-SD-log-name>`

15.3.2.9 <wellpath-TVD-SD-increase-rate>

Description: If <allow-wells-to-move> is yes and <wellpath-TVD-SD-log-name> is not used, a parametric well path TVD uncertainty log is generated. The uncertainty log increases proportional to the *lateral* distance of the well. The increase rate is by default 4 mm per meter. This amounts to an increase of 4 meters SD for every 1000 meters along a horizontal section. See Eq. 21.6 for details.

Argument: Positive real (meters SD per meter lateral component of MD.)
Default: 0.005

15.3.2.10 <tops-as-mean-values>

Description: COHIBA supports two methods for extracting the well points from the zone log:

1. The mean value of the position of the two points in the zone transition. This is the default and is selected with argument yes. A well point TVD pick uncertainty (SD) equal to $|z1 - z2|/4$ is added to the well point. The typical logging distance is one foot which is approximately 30 cm. The SD will then be approximately 7.5 cm.
2. The last (along the well path) point in the zone transition. This is selected with argument

no.

The method chosen affects *all* well log files imported in <files>.

Argument: yes / no
Default: yes

15.3.2.11 <first-log-entry-as-top>

Description: In the LAS 2.0 well format, the first zone top is often given by a zone log transition from −999 to 0 as seawater is not treated as a zone. Choosing yes will ensure that such transition will be recorded as a zone top.

Argument: yes / no
Default: no

15.3.2.12 <TVD-values-are-negative>

NEW in 6.0

Description: In the LAS 2.0 well format TVD values below MSL could be positive or negative. Choose yes if the LAS 2.0 well use negative TVD values below MSL. This has no effect on ROXAR RMS wells.

Argument: yes / no
Default: no

15.3.3 <well-points>

Description: Wrapper for elements specifying well points. The <well-points> element can be used to add additional well points to the well points extracted from zone logs.

If well path TVD uncertainty is present in the well point files, then the uncertainty is assumed to be correlated along the well path. The correlation depend on the specified <wellpath-TVD-SD-range>.

Argument: Elements <files>,
Default: No default.

15.3.3.1 <files>

Description: Specification of the COHIBA well points file (s) to be imported. This element can be repeated in order to import files in different locations. See Table 6.2 on page 30 for details on the file format. Repeating files by accident will not affect the final result since duplicate well points are removed.

Argument: Any valid path relative to <input-directory>. Wild cards (*) are supported.
Default: Empty string.
Example: <files> mywellpoints/* </files>

15.3.4 <well-points-to-ignore>

Description: Wrapper for <files> elements that specify well points that should be discarded.
Argument: <files> elements.
Default: No default.

15.3.4.1 <files>

Description: The well points that should be excluded if found in the zone logs. This element can be repeated in order to import different files in different locations. See Table 6.2 on page 30 for details on file format.

Any valid path relative to <input-directory>. Wild cards (*) are supported.
Default: Empty string.
Example: <files> ignorepoints/* </files>

15.3.5 <values-outside-grid>

Description: Wrapper for <value> elements which specify the TVD and coordinates of the well point outside the grid. Each <value> element defines one well point.
Argument: <value> elements.
Default: Empty.

15.3.5.1 <value well-name="" surface-name="" x="" y="" SD="">

Description: A TVD value associated to the <well-data> element.
Attribute: **well-name** The name of the well associated to this observation.
Attribute value: String
Attribute default: "outside-well"
Attribute: **surface-name** The name of the surface associated to this observation.
Attribute value: String.
Attribute default: Empty string.
Attribute: **x** The X coordinate
Attribute value: Real
Attribute default: Largest machine real
Attribute: **y** The Y coordinate
Attribute value: Real
Attribute default: Largest machine real
Attribute: **SD** The SD
Attribute value: Real
Attribute default: 0.0
Argument: Real.
Default: No default.
Example: <value surface-name = top> 1105.01 </value>

15.3.6 Example of <well-data> specification

```
<well-data>
   <well-log>
      <zone-log-name>             GM2005a                  </zone-log-name>
      <wellpath-TVD-SD-log-name>  TVDUncertainty           </wellpath-TVD-SD-log-name>
      <tops-as-mean-values>       yes                      </tops-as-mean-values>
      <files>                     ../welldata/*.rxb        </files>
   </well-log>
   <well-points>
      <files>                     ../welldata/new_point.dat  </files>
   </well-points>
</well-data>
```

15.4 <surfaces> (required)

Description: Wrapper for <reference> and <surface> elements in stratigraphic order. Free surfaces (see <free-surface>) can be in arbitrary order. A valid model must contain at least one surface different from the reference surface. The surfaces must be defined in a common rectangular output grid specified in the <output-grid> element.

Argument: A <reference> element and <surface> elements in correct depth order.

Default: No default.

15.4.1 <reference>

Description: Wrapper for elements specifying the reference surface. This is typically MSL. There can only be one <reference> element. COHIBA assumes that depth values and travel time values increase with increasing depth. Reference depth and travel time values can be negative.

Note that there will always exist a datum (horizontal plane) that defines zero depth. The reference surface, well points, and the output surfaces are defined relative to this datum. The datum is often MSL but any horizontal plane can be used.

Argument: Elements specifying the reference surface.

Default: A flat surface at zero depth having zero travel times. (See default values below)

15.4.1.1 <name>

Description: Name of reference surface.

Argument: String.

Default: MSL

Example:
```
<name> Mean Sea Level </name>
```

15.4.1.2 <depth>

Description: Depth at the reference surface relative MSL.

Argument: A real number or a grid file.

Default: 0.0

15.4.1.3 <common-top-for-correlated-intervals>

NEW in 6.0

Description: Correlate all trend coefficients and residuals for the intervals that have this surface as the <top> surface. For this option to have any effect, there need to be at least two such intervals, and they must all be of the same <interval-type>. The correlations are automatically calculated, see Section 14 for details. This flag can be also set under <surface>.

Argument: yes / no.

Default: no

15.4.1.4 <travel-time>

Description: Seismic travel time at the reference surface.

Argument: A real number or a grid file.

Default: 0.0

15.4.2 <surface> (required)

Description: Wrapper for elements specifying a single surface. This element is repeated for every surface (except the reference) in the model. Important: The surface elements must be in stratigraphic order.

Argument: Elements specifying the surface.

Default: No default.

15.4.2.1 `<name>` (required)

Description: A *unique* name for the surface. The name is used for identifying data in the COHIBA well points file and for identifying top and base of an `<interval>` and a `<volume>`. All output surface files concerning this surface will include this name.

Argument: String.

Default: No default.

Example:
```
<name> Top Brent </name>
```

15.4.2.2 `<top-of-zone>`

Description: This defines a mapping of zone log transition to the surface. If zone numbers increase with increasing depth, it is sufficient to specify the first zone name below *this surface*. Otherwise, all zone names below this surface and above the next surface must be specified. For details see Section 8.4.5.

This element has no use if the surface is a `<free-surface>`.

Argument: A sequence of zone names separated by a comma.

Default: Empty if no zone log is specified, otherwise it is required.

Example: Zone `A` is directly below the surface:
```
<top-of-zone> A </top-of-zone>
```

Example: Multiple zones between this surface and the next deeper surface:
```
<top-of-zone> A, B, C </top-of-zone>
```
The two zones `B` and `C` can normally be dropped (see Section 8.4.5).

15.4.2.3 `<erosive>`

Description: A flag controlling whether the surface is erosive or not. This affects the extraction of well points from zone logs *and* post processing. Erosiveness in the post processing for all surfaces may be turned off using the element `<erode-and-onlap>`.

A `<free-surface>` can not be erosive so this element has no effect for free surfaces.

Argument: `yes / no`

Default: `no`

15.4.2.4 `<onlapped>`

Description: A flag controlling whether this surface is going to be onlapped by surfaces above. An onlapped surface can be eroded by a surface above. This affects the extraction of well points from zone logs *and* post processing. To override the post processing for all surfaces use the element `<erode-and-onlap>`.

A `<free-surface>` can not be onlapped so this element has no effect for free surfaces.

Argument: `yes / no`

Default: `yes`

15.4.2.5 `<free-surface>`

Description: A flag controlling whether this surface is free or not. A surface is considered free if it is not part of the stratigraphy, typically, a fault or a HCC. See Section 13 for more details. This flag affects the extraction of well points from zone logs since a free surface is not associated to any zone. So `<top-of-zone>` have no meaning for a free surface. Well points belonging to a free surface must therefore be specified using `<well-points>`. All surfaces (ordinary and free) are conditioned to all well points, including well points on free surfaces. Free surfaces can be connected to other surfaces through intervals, and they can also be reflectors. Free surfaces are reported after the set of stratigraphically ordered surfaces, following the order

in which they appear in the COHIBA model file.

Travel time residuals for free surfaces are never assumed to be correlated to other travel time residuals so that <correlate-close-reflectors> will not affect free surfaces.

Free surfaces can not erode and they can not be onlapped. Free surfaces are not eroded by other surfaces and they will not onlap other surfaces.

Argument: yes / no
Default: no

15.4.2.6 <reflector>

Description: Surfaces with travel time maps are automatically considered reflectors. For reflectors given in depth, no direct association can be made, and this element has to be used. This will have effect if <scale-isochores-to-seismic-envelopes>, <treat-reflectors-as-eroding-and-onlapped> or <weight-isochore-package-above> have been activated.
Argument: yes / no
Default: yes if <travel-time> is specified, no otherwise

15.4.2.7 <common-top-for-correlated-intervals>

NEW in 6.0

Description: Correlate all trend coefficients and residuals for the intervals that have this surface as the <top> surface. For this option to have any effect, there need to be at least two such intervals, and they must all be of the same <interval-type>. The correlations are automatically calculated, see Section 14 for details. This flag can be also set under <reference>.
Argument: yes / no.
Default: no

15.4.2.8 <travel-time>

Description: Specification of the grid containing the travel times for the seismic reflector. If this element is used, this surface automatically becomes a seismic reflector.
Argument: Elements specifying the travel time.
Default: No default.

15.4.2.8.1 <value>

Description: The travel time values.
Argument: File name or constant. See Section 6.2 for possible file formats.
Default: 0.0.

15.4.2.8.2 <values-outside-grid>

Description: Wrapper for <value> elements which specify the travel time values. Each <value> element is in one-to-one correspondence with one well point outside the grid in <values-outside-grid> of <well-data>.
Argument: <value> elements.
Default: One <value> with value 0.0 for each <value> given in <values-outside-grid> from <well-data>.

15.4.2.8.2.1 <value>

Description: A travel time value for a well point outside the grid.
Argument: Real.

Default: No default.
Example: `<value> 0.1 </value>`

15.4.2.8.3 `<variogram>`

Description: Wrapper for elements specifying the travel time residual. The residual models the interpretation uncertainty in the travel time. It is specified by the SD and the variogram (spatial correlation function). Typical values for the SD is 4 – 20 msec. TWT.
The available variograms are found in Table 15.2.
Argument: Elements specifying the travel time uncertainty.
Default: Default values for child elements.

Table 15.2. Supported variogram types in COHIBA. Variograms, $\gamma(x)$, are closely linked to correlation functions, $\rho(x)$ by $\gamma(x) = \sigma^2(1 - \rho(x))$, where σ is SD and the ratio $x = r/R$ is the distance r divided by the `<range>`, R. See Section 20 for some illustrations of simulated realizations and e.g. Section 4 in Abrahamsen (1997) for mathematical details..

`<type>`	**Correlation function**	
`constant`	$\rho(x) = 1$	
`white noise`	$\rho(x) = 1$	if $x = 0$, 0 otherwise
`exponential`	$\rho(x) = \exp(-3\,x)$	
`gaussian`	$\rho(x) = \exp(-3\,x^2)$	
`generalized exponential`[a]	$\rho(x) = \exp(-3\,x^p)$,	$0 < p \leq 2$
`spherical2`	$\rho(x) = 1 - \frac{2}{\pi}(x\sqrt{1-x^2} + \arcsin x)$	if $x < 1$, 0 otherwise
`spherical`	$\rho(x) = 1 - \frac{3}{2}x + \frac{1}{2}x^3$	if $x < 1$, 0 otherwise
`spherical5`	$\rho(x) = 1 - \frac{15}{8}x + \frac{5}{4}x^3 - \frac{3}{8}x^5$	if $x < 1$, 0 otherwise
`rational quadratic`[b]	$\rho(x) = 1/(1 + \text{scale} \times x^2)^p$,	$p > 0$
`damped sine`	$\rho(x) = \sin \pi x / \pi x$	
`matern32`[c]	$\rho(x) = e^{-s}(1 + s)$	$s = 4.7\,x$
`matern52`[c]	$\rho(x) = e^{-s}(1 + s + \frac{1}{3}s^2)$	$s = 5.9\,x$
`matern72`[c]	$\rho(x) = e^{-s}(1 + s + \frac{2}{5}s^2 + \frac{1}{15}s^3)$	$s = 6.9\,x$
`matern92`[c]	$\rho(x) = e^{-s}(1 + s + \frac{2}{7}s^2 + \frac{3}{21}s^3 + \frac{4}{105}s^4)$	$s = 7.7\,x$

a. We recommend to use $p \leq 1.5$ for `generalized exponential`. A higher value of p can give under- and overshooting.
b. The scale is chosen such that $\rho(1) = 0.05$. For comparison $\rho(1) = 0.0498$ for the exponential variograms.
c. Simulated realizations using `matern32` are differentiable, using `matern52` are two times differentiable and so on. See Wikipedia for details on the Matérn covariance functions. The scaling factor of s is chosen so that $\rho(1) = 0.05$.

15.4.2.8.3.1 `<type>`

Description: The type of variogram.
Argument: The variograms in Table 15.2.
Default: `spherical`

15.4.2.8.3.2 `<range>`

Description: The variogram range parallel to the azimuth direction. (North-south direction by default)
Argument: Non-negative (meters).
Default: `1000.0`

15.4.2.8.3.3 <subrange>

Description: The variogram subrange. Variogram range perpendicular to the azimuth direction. (East-west direction by default.)
Argument: Non-negative real (meters).
Default: Value of <range>.

15.4.2.8.3.4 <azimuth>

Description: The variogram azimuth. Angle is measured clockwise from north. Units are degrees (full circle is $360°$). Any input angle is possible but a warning is issued if angle is outside $[-360°, 360°]$.
Argument: Real.
Default: 0.0

15.4.2.8.3.5 <SD>

Description: The SD (square root of sill) in meters.
Argument: SD as a constant or a grid file name, or elements <relative> and <minimum>. See Section 6.2 for possible file formats.
Default: 1.0
Example: Constant SD:

```
<SD> 0.001 </SD>
```

Example: SD given by a surface grid file:

```
<SD> sd_TopA.rxb </SD>
```

Example: Relative SD:

```
<SD>
   <relative> 0.1 </relative>
   <minimum>  1.0 </minimum>
</SD>
```

15.4.2.8.3.5.1 <relative>

Description: The SD relative to the travel time specified in <value>.
Argument: Positive real.
Default: 0.1

15.4.2.8.3.5.2 <minimum>

Description: Minimum SD. This has only effect if <relative> has been used.
Argument: Non-negative real (meters).
Default: 0.0

15.4.2.8.3.6 <power>

Description: The variogram power, p. Only used for the generalized exponential variogram and the rational quadratic variogram. See Table 15.2. We recommend to use $p \leq 1.5$ for the generalized exponential variogram to avoid serious under- and overshooting. Choosing p above 10 for the rational quadratic variogram is almost identical to a gaussian variogram.
Argument: Non-negative real. Can not exceed 2.0 for generalized exponential.
Default: 1.0

15.4.2.8.3.7 <values-outside-grid>

Description: Wrapper for <value> elements which specify the travel time residual values. Each <value> element is in one-to-one correspondence with one well point outside the grid in <values-outside-grid> of <well-data>.

Argument: <value> elements.

Default: One <value> with value 0.0 for each <value> given in <values-outside-grid> from <well-data>.

15.4.2.8.3.7.1 <value>

Description: A travel time residual value at the well point outside the grid.

Argument: Real.

Default: No default.

Example: <value> 0.001 </value>

15.4.2.9 <spill-point>

Description: This element triggers the detection of the spill point of the surface. The corresponding trapped area can be written to a map using <trap>.

Wrapper for elements <missing-as-wall>, <xstart> and <ystart> that controls the search for the spill point and the corresponding trap. The starting point for the search algorithm can be anywhere inside the trap. It is recommended to choose a starting point that is known to belong to the trap such as a discovery well or a producing well. If the starting point is outside a trap the algorithm will fail. If the algorithm fails, the output trap map will contain zeros and the file spillpoint-Surface.rxat with spill point coordinates will contain undefined areas.

Note that a depth surface can contain multiple traps. Only the trap containing the starting point will be found.

The spill point is calculated after post processing of the surfaces.

Argument: Elements specifying starting point and how to handle undefined areas.

Default: Void

15.4.2.9.1 <missing-as-wall>

Description: Determines how the spill point search algorithm handles undefined areas (missing code) in the surface maps. The undefined area can either be considered as a wall or as a sink. If undefined areas act as a wall (yes), the trap can not spill into undefined areas and the spill point search stops when the map boundary is found. If the undefined areas are considered as a sink (no), the spill point search algorithm stops when it encounters the map boundary or undefined areas that are in contact with the map boundary.

Argument: yes / no

Default: no

15.4.2.9.2 <xstart>

Description: Starting point x-coordinate for the spill point searching algorithm. The starting point for the search algorithm can be anywhere inside the trap. It is recommended to choose a starting point that is known to belong to the trap such as a discovery well or a producing well.

Argument: Real.

Default: No default.

15.4.2.9.3 <ystart>

Description: Starting point y-coordinate for the spill point searching algorithm. The starting point for the search algorithm can be anywhere inside the trap. It is recommended to choose a starting point that is known to belong to the trap such as a discovery well or a producing well.
Argument: Real.
Default: No default.

15.4.2.10 <acceptance-criteria>

Description: Wrapper for elements specifying acceptance criteria used for rejection sampling in stochastic simulation. The acceptance criteria only apply when simulating surfaces. It is possible to have several acceptance criteria for each surface.

If the rejection criteria are strict, a large number of simulated realizations might be necessary to obtain a single accepted realization. All surfaces will be discarded if one acceptance criterion fails. If the acceptance criteria is very strict the <max-rejection-rate> must be increased.

The acceptance criteria are checked after post processing of the surfaces.
Argument: Elements describing acceptance criteria.
Default: Void.

15.4.2.10.1 <spill-point-above>

Description: The surface is accepted if the spill point is above a constant or above the specified surface at the spill point coordinates. The surface can be specified as any of the surfaces specified in <surfaces> or it can be read from a file. This criteria requires that <xstart> and <ystart> in <spill-point> are specified.
Argument: Constant, surface <name>, or a file name. See Section 6.2 for possible file formats.
Default: Void.

15.4.2.10.2 <spill-point-below>

Description: The surface is accepted if the spill point is below a constant or below the specified surface at the spill point coordinates. The surface can be specified as any of the surfaces specified in <surfaces> or it can be read from a file. This criteria requires that <xstart> and <ystart> in <spill-point> are specified.
Argument: Constant, surface <name>, or a file name. See Section 6.2 for possible file formats.
Default: Void.

15.4.2.10.3 <spill-point-at>

Description: The surface is accepted if the spill point is at a constant or at the specified surface at the spill point coordinate. The surface can be specified as any of the surfaces specified in <surfaces> or it can be read from a file. This criteria requires that <xstart> and <ystart> in <spill-point> are specified.

This is a strict criterion so by default a plus minus one meter tolerance is assumed. This tolerance can be modified by <spill-point-tolerance>.
Argument: Constant, surface <name>, or a file name. See Section 6.2 for possible file formats.
Default: Void.

15.4.2.10.4 <spill-point-tolerance>

Description: The tolerance for accepting criterion <spill-point-at>. This tolerance applies on both sides so 1 meter means that the spill point will be accepted within a two meter depth window. If this value becomes too small then it is highly unlikely to obtain a simulated realization that will be accepted. So there is a trade off between speed and precision.
Argument: Positive real (meters).
Default: 1.0

15.4.2.10.5 <trap-larger-than>

Description: The surface is accepted if the trap is larger than the specified area in square meters. This criteria requires that <xstart> and <ystart> in <spill-point> are specified.

Argument: Positive real (meter^2).
Default: 1.0

15.4.2.11 <condition-to-spill-point-at-surface>

Description: The surface is translated vertically so that its depth matches the depth of the specified surface at the specified surface's spill point. This makes it possible to use this translated surface as the <base-contact> for a filled structure in a <volume> calculation.

This element can only be used for a <free-surface>. This criteria requires that <xstart> and <ystart> in <spill-point> for the specified surface are specified.

We recommend that this surface do not have any well points, and do not link to other surfaces since the translation to fit the spill point will not take into account well points nor the relations to other surfaces.
Argument: Surface <name>.
Default: Void

15.4.2.12 <weight-isochore-package-above>

Description: Pre-adjust the standard deviation of each isochore in the isochore package directly above the surface, relative to the seismic envelope. The scaling will be done so that the weight of the model path that use the isochore package will be (approximately) the number that is specified. A specified weight of 0.5 corresponds to equal weight for the isochore package and the velocity model (or depth converted thickness model). A value close to 0 gives less weight to the isochores, meaning that the seismic envelope will dominate. See Section 11.1.4 for details.

The scaled isochore uncertainties can be exported using <write-scaled-input-SD-isochores>. If the seismic envelope consist of depth surfaces (no travel times given) then <reflector> must be set to yes for this option to have any effect.
Argument: Real in [0, 1].
Default: No default.

15.4.2.13 <output>

Description: Wrapper for elements specifying if a particular map is written to file. The file names are described in Table 7.1.
Argument: Elements for each grid type.
Default: Void

15.4.2.13.1 <depth>

Description: The output depth surface.
Argument: `yes` / `no`.
Default: `yes`

15.4.2.13.2 <depth-uncertainty>

Description: The output depth prediction uncertainty (SD) surface. Note that turning this on will increase the CPU time.
Argument: `yes` / `no`.
Default: `no`

15.4.2.13.3 <depth-trend>

Description: The output depth trend surface.
Argument: `yes` / `no`.
Default: `no`

15.4.2.13.4 <depth-trend-uncertainty>

Description: The output depth trend uncertainty (SD) surface.
Argument: `yes` / `no`.
Default: `no`

15.4.2.13.5 <depth-residual>

Description: The output depth residual surface.
Argument: `yes` / `no`.
Default: `no`

15.4.2.13.6 <depth-residual-uncertainty>

Description: The output *unconditional* depth residual uncertainty (SD) surface.
Argument: `yes` / `no`.
Default: `no`

15.4.2.13.7 <trap>

Description: The output trap surface associated to a spill point. This criteria requires that <xstart> and <ystart> in <spill-point> are specified.
Argument: `yes` / `no`.
Default: `no`

15.4.3 Example of <surface> specification

```
<surface>
   <name>                    TopA          </name>
   <top-of-zone>             IsochoreA     </top-of-zone>
   <erosive>                 yes           </erosive>
   <onlapped>                no            </onlapped>
   <spill-point>
      <missing-as-wall>      yes           </missing-as-wall>
      <xstart>                342292.0     </xstart>
      <ystart>               4263452.0     </ystart>
   </spill-point>
```

```
<output>
   <depth>                    yes            </depth>
   <depth-trend>              yes            </depth-trend>
   <depth-uncertainty>        yes            </depth-uncertainty>
   <depth-trend-uncertainty>  yes            </depth-trend-uncertainty>
   <depth-residual>           yes            </depth-residual>
   <trap>                     yes            </trap>
</output>
<travel-time>
   <value>                    T_TopA.rxb     </value>
   <variogram>
      <type>                  spherical      </type>
      <range>                 1000           </range>
      <subrange>              2000           </subrange>
      <azimuth>                 45           </azimuth>
      <SD>                    sd_TopA.rxb    </SD>
   </variogram>
</travel-time>
</surface>
```

15.5 <interval-models> (required)

Description: Wrapper for <interval> elements. Each <interval> element links two arbitrary surfaces by describing the thickness or the interval velocity (depth conversion) between them. The intervals usually link two adjacent surfaces but it is possible to link surfaces having several surfaces (and intervals) between them. A single surface can be top and base in several intervals so that there are multiple ways of obtaining the depth to a surface.

Argument: <interval> elements.

Default: No default.

15.5.1 <interval> (required)

Description: Wrapper for elements describing the interval. There are two types of intervals: Thickness intervals and velocity intervals. The latter is used to describe the interval velocity between two seismic reflectors. This element is repeated for each interval model between two surfaces.

Argument: Elements describing the interval.

Default: No default.

15.5.1.1 <name>

Description: An interval name. All output concerning this interval will use this name.

Argument: String.

Default: A string made from the names of the top and base surfaces concatenated by -to-.

Example: The specification:

```
<interval>
   <top>    BCU       </top>
   <base>   TopBrent   </base>
   ...
</interval>
```

would give the default name: BCU-to-TopBrent.

15.5.1.2 <top> (required)

Description: The surface defining the top of the interval. Top and base surfaces must be different.

Argument: An existing surface name.

Default: No default.

15.5.1.3 <base> (required)

Description: The surface defining the base of the interval. Top and base surfaces must be different.

Argument: An existing surface name.

Default: No default.

15.5.1.4 <interval-type> (required)

Description: For thickness intervals, the trends describe the thickness, and for velocity intervals, the trends describe interval velocity. Velocity intervals require that the top and base surfaces of the interval are seismic reflectors.

Argument: thickness / velocity.

Default: No default.

15.5.1.5 <trend>

Description: Wrapper for a single interval thickness/velocity trend map and interval trend coefficient. An interval (thickness or velocity) may contain a sum of several interval trend maps so this element may be repeated any number of times.

Argument: Elements describing a interval trend map and its interval trend coefficient.

Default: Void.

Example: An isochore map multiplied by a coefficient with default value 1.0 and a 15 % uncertainty:

```
<trend>
   <value>       S_IsochoreB.roxbin </value>
   <relative-SD> 0.15               </relative-SD>
</trend>
```

Example: An isochore map multiplied by a coefficient with mean 1.07 and uncertainty (SD) 0.05:

```
<trend>
   <value>            S_IsochoreB.roxbin </value>
   <coefficient-mean> 1.07               </coefficient-mean>
   <coefficient-SD>   0.05               </coefficient-SD>
</trend>
```

15.5.1.5.1 <coefficient-mean>

Description: Prior mean value (expectation) of interval trend coefficient. The interval trend coefficient is multiplied by the value specified in element <value> below to obtain the interval thickness/velocity trend. When possible, we recommend to drop this element and thereby use the default value of 1.

Argument: Real.

Default: 1.0

15.5.1.5.2 <coefficient-SD>

Description: Prior uncertainty (SD) of interval trend coefficient. When possible, we recommend to drop this element and use <relative-SD> instead. Do not use this in combination with <relative-SD>.

Argument: Non-negative real.

Default: 0.0

15.5.1.5.3 <relative-SD>

Description: Prior relative uncertainty (SD) of interval trend coefficient. Do not use this element in combination with <coefficient-SD>.

Argument: Non-negative real (measured in proportion of the coefficient, not in percent).

Default: 0.0

15.5.1.5.4 <value>

Description: A interval trend map (grid) or a constant. This trend map is multiplied by its corresponding interval trend coefficient.

An input trend map is regridded if the dimension and resolution does not match the <output-grid>.

Argument: File name or constant. See Section 6.2 for possible file formats.

Default: 1.0

15.5.1.5.5 <values-outside-grid>

Description: Wrapper for <value> elements which specify the trend values. Each <value> element is in one-to-one correspondence with one well point outside the grid in <values-outside-grid> of <well-data>.

Argument: <value> elements.

Default: One <value> with value 0.0 for each <value> given in <values-outside-grid> from <well-data>.

15.5.1.5.5.1 <value>

Description: A trend value associated to the well point outside the grid.
Argument: Real.
Default: No default.
Example: <value> 1105.01 </value>

15.5.1.6 <correlations>

Description: Correlations between interval trend coefficients.
Argument: A sequence of arguments <cp-q>, where p and q (p different from q) refers to the order of the trend coefficients within this <interval> element. Make sure that the values entered define a proper correlation matrix, that is, a symmetric positive definite (SPD) matrix.
Default: 0.0 (no correlations).
Example: Correlation matrix for 3 trend coefficients:

```
<correlations>
  <c1-2> 0.01  </c1-2>
  <c1-3> 0.03  </c1-3>
  <c2-3> 0.002 </c2-3>
</correlations>
```

15.5.1.6.1 <cp-q>

Description: Prior correlations between trend coefficients p and q. The numbering is according to the order of appearance in the list of trends, starting at 1. Indices exceeding the maximum number of trends will be ignored.
Argument: Real in $[-1, 1]$.
Default: 0.0

15.5.1.7 <variogram> (required)

Description: Wrapper for elements specifying the interval uncertainty, that is, interval thickness residual or interval velocity residual. The residual is the *unknown* difference between the true interval thickness/velocity and interval thickness/velocity trend. It is specified by the variogram (spatial correlation function) and SD.
Argument: Elements specifying the interval thickness or interval velocity residual.
Default: No default.

15.5.1.7.1 <type>

Description: The type of interval residual variogram.
Argument: The variograms in Table 15.2.
Default: spherical

15.5.1.7.2 <range>

Description: The interval residual variogram range parallel to the azimuth direction. (North-south direction by default)
Argument: Non-negative real (meters).
Default: 1000.0

15.5.1.7.3 <subrange>

Description: The interval residual variogram subrange. Variogram range perpendicular to the azimuth direction. (East-west direction by default.)
Argument: Non-negative real (meters).
Default: Value of <range>.

15.5.1.7.4 <azimuth>

Description: The interval residual variogram azimuth. Angle is measured clockwise from north. Units are degrees (full circle is 360°). Any input angle is possible but a warning is issued if angle is outside $[-360°, 360°]$.
Argument: Real.
Default: 0.0

15.5.1.7.5 <SD>

Description: The interval residual SD (square root of sill).
Argument: SD as a constant or a grid file name, or elements <relative> and <minimum>. See Section 6.2 for possible file formats.
Default: 1.0
Example: Constant SD:

```
<SD> 0.001 </SD>
```

Example: SD given by a surface grid file:

```
<SD> sd_IntervalAB.rxb </SD>
```

Example: Relative SD:

```
<SD>
   <relative> 0.10 </relative>
   <minimum>  1.00 </minimum>
</SD>
```

15.5.1.7.5.1 <relative>

Description: The SD relative to the thicknesses or interval velocities specified in the interval <trend>.
Argument: Positive real.
Default: 0.1

15.5.1.7.5.2 <minimum>

Description: Minimum SD. This has only effect if <relative> has been used.
Argument: Non-negative real.
Default: 0.0

15.5.1.7.6 <power>

Description: The interval residual variogram power, p. Only used for the variograms generalized exponential and rational quadratic (see Table 15.2).
Argument: Positive real. Can not exceed 2.0 for generalized exponential.
Default: 1.0

15.5.1.7.7 <values-outside-grid>

Description: Wrapper for <value> elements which specify the interval thickness/velocity residual values. Each <value> element is in one-to-one correspondence with one well point outside the grid in <values-outside-grid> of <well-data>.
Argument: <value> elements.
Default: One <value> with value 0.0 for each <value> given in <values-outside-grid> from <well-data>.

15.5.1.7.7.1 <value>

Description: A interval thickness/velocity residual value at the well point outside the grid.
Argument: Real.
Default: No default.
Example: <value> 0.001 </value>

15.5.1.8 <output>

Description: Wrapper for elements specifying if a map (grid) should be written to file.
Argument: Elements for each map.
Default: Void.

15.5.1.8.1 <thickness>

Description: The thickness of the interval, i.e., the difference between top and base depth surfaces.
Argument: yes / no
Default: no

15.5.1.8.2 <thickness-trend>

Description: The thickness trend of the interval, i.e., the difference between the top trend and the base trend surfaces.
Argument: yes / no
Default: no

15.5.1.8.3 <thickness-residual>

Description: The difference between the thickness and the thickness trend of the interval.
Argument: yes / no
Default: no

15.5.1.8.4 <velocity>

Description: The output interval velocity, i.e., the interval thickness divided by the time difference.
Argument: yes / no
Default: no

15.5.1.8.5 <velocity-trend>

Description: The posterior interval velocity trend.
Argument: yes / no
Default: no

15.5.2 Example of <interval> specification

```
<interval>
   <name>                MSL-to-TopA          </name>
```

```
   <top>                  MSL                 </top>
   <base>                 TopA                </base>
   <interval-type>        velocity            </interval-type>
   <trend>
      <coefficient-mean>  2500                </coefficient-mean>
      <coefficient-SD>     200                </coefficient-SD>
      <value>                1                </value>
   </trend>
   <trend>
      <coefficient-mean>  25.0                </coefficient-mean>
      <coefficient-SD>    12.5                </coefficient-SD>
      <value>             v-overburden.rxb    </value>
   </trend>
   <correlations>
      <c1-2>              0.9                 </c1-2>
   </correlations>
   <variogram>
      <type>              spherical           </type>
      <range>             1000                </range>
      <subrange>          2000                </subrange>
      <azimuth>             45                </azimuth>
      <SD>
         <relative>       0.05                </relative>
      </SD>
   </variogram>
   <output>
      <thickness>         yes                 </thickness>
      <thickness-trend>   yes                 </thickness-trend>
      <velocity>          yes                 </velocity>
   </output>
</interval>
```

15.6 <volumes>

Description: Wrapper for elements describing the gross rock volume of one or more reservoirs. Volumes are reported as cubic meters. See Section 9 for details and an example.
Argument: <volume> elements.
Default: No default.

15.6.1 <volume>

Description: Wrapper for elements describing the surfaces outlining one reservoir unit. There is an option for assigning the volume to different areas (segment, license, political boundary, etc.) using <area-names>.
Argument: Elements describing the volume of a reservoir unit.
Default: No default.

15.6.1.1 <reservoir-name>

Description: The name of the reservoir unit. This name is required. This name is used for reporting to volumes.csv.
Argument: String
Default: No default.
Example: <reservoir-name> Upper Brent </reservoir-name>

15.6.1.2 <top-surface>

Description: The name of the top surface of a reservoir, usually the base of the reservoir caprock.
Argument: Surface <name>.
Default: The name of the <reference> surface.

15.6.1.3 <base-surface>

Description: The name of the base surface of a reservoir. Note that either this surface or the <base-contact> must be specified.
Argument: Surface <name>.
Default: No default.

15.6.1.4 <top-contact>

Description: Optional name of the top HCC of a (oil) reservoir. This is usually the GOC. This surface must be a free surface (Section 13).
Argument: Surface <name>.
Default: No default.

15.6.1.5 <base-contact>

Description: Optional name of the base HCC of a reservoir. This is the oil water contact (OWC) for oil reservoirs and the GWC or GOC for gas reservoirs. This surface must be a free surface (Section 13). Note that either this surface or the <base-surface> must be specified.
Argument: Surface <name>.
Default: No default.

15.6.1.6 <area-file>

Description: File with a unique area number (integer) for every area (segment, license, political territory, etc.) of interest. The area numbers are represented as real numbers with decimal point ($-1.0, 0.0, 1.0, 2.0, \ldots$). Volumes will be recorded separately for every non-negative area number presented in the grid. Areas with negative area numbers are ignored. Non-integer area numbers are ignored.

Areas are by default named by the area number. Other names can be supplied using

<area-names>.

The area file *must* include the whole <output-grid> and the grid nodes *must* match the grid nodes of the output grid. We recommend to use exactly the grid format of the <output-grid>. See Section 6.2 for possible file formats.

Argument: File name.
Default: No default.

15.6.1.7 <area-names>

Description: Used to associate the area numbers in the <area-file> by names. If <area-names> is used then only area numbers that are associated with area names will be included in the volume calculations.
Argument: Comma separated list with alternating area number and area name.
Default: No default.
Example:

```
<area-names>
    0, Central Block, 2, East Block, 3, West Block
<area-names>
```

15.6.1.8 <only-trapped-volume>

Description: If yes, then the spill point for the <top-surface> will be calculated and possible volumes outside the trap will be discarded. This option requires that <xstart> and <ystart> in <spill-point> are specified.

This option should be used in combination with <condition-to-spill-point-at-surface> for <base-contact>. This ensures that the base contact is consistent with the spill point depth.

In some situations the trap might be split into disconnected volumes by the <base-surface>. The disconnected volumes can be removed using <connected-volume>.

Argument: yes / no
Default: no

15.6.1.9 <remove-isolated-volumes-less-than>

Description: Small pockets of rock volume is removed from the rock column map before the volumes are calculated.
Nothing is removed if the minimum volume is zero.
Argument: Minimum volume (cubic meters).
Default: 1000000 (one million cubic meters).

15.6.1.10 <connected-volume>

Description: Only a single connected volume in the rock column map is kept. The connected volume must include the coordinates specified by <xstart> and <ystart>.
Argument: The coordinates to a point inside the connected volume.
Default: No default.
Example:

```
<connected-volume>
    <xstart>  314680.00 </xstart>
    <ystart> 7348210.00 </ystart>
</connected-volume>
```

15.6.1.10.1 <xstart>

Description: X-coordinate to a point inside the connected volume. This could typically be the starting point, <xstart>, of the <spill-point> algorithm.
Argument: Real.
Default: No default.

15.6.1.10.2 <ystart>

Description: Y-coordinate to a point inside the connected volume. This could typically be the starting point, <ystart>, of the <spill-point> algorithm.
Argument: Real.
Default: No default.

15.6.1.11 <column-map>

Description: If yes, then a map of the rock column height of the reservoir is written to a grid file in surfaces/.
Argument: yes / no
Default: yes

16 List of all elements

<cohiba> *(required)*
<project-settings> *(required)*
· <project-title>
· <project-description>
· <seed>
· <project-directory>
· <input-directory>
· <input-directory-surfaces>
· <input-directory-well-data>
· <output-directory>
· <number-of-threads> ⚠
· <measurement-units>
· · <z-unit>
· · <xyz-unit>
· · <time-unit>
· · <two-way-time>
· <output-grid> *(required)*
· · <format>
· · <read-from-file>
· · <xstart>
· · <ystart>
· · <xinc>
· · <yinc>
· · <xlength>
· · <ylength>
· · <grid-azimuth>
· <messages>
· · <logfile>
· · · <name>
· · · <detail-level>
· · · · <overall>
· · · · <model-settings>
· · · · <data-loading>
· · · · <pre-processing>
· · · · <surface-models>
· · · · <well-points>
· · · · <extra-points>
· · · · <well-branching>
· · · · <well-paths>
· · · · <trend-coefficients>
· · · · <residual-uncertainties>
· · · · <outliers>
· · · · <well-point-conditioning>
· · · · <help-points>
· · · · <well-path-conditioning>

```
        <post-processing>
        <target-point-qc>
        <zonation-checking>
        <well-trajectories>
        <spill-points>
        <volume-calculations>
        <interval-export>
        <surface-export>
        <timings>
        <tasks>
    <screen>
        <detail-level>
<write-expert-files>
<additional-output-control>
    <write-all-logfiles>
    <write-realization-maps>
    <write-xyz-point-files>
    <write-scaled-input-isochores>
    <write-scaled-input-SD-isochores>
    <write-filtered-velocity-trends>
    <write-filtered-SD-maps>
    <write-regridded-input-maps>
    <write-unfiltered-output-velocities>
    <write-wells>
    <prefix-for-log-files>
    <csv-file-style>
```

<modelling-settings>
· <mode>
· <kriging-method>
· <number-of-realizations>
· <condition-to-well-paths>
· <allow-wells-to-move>
· <check-specified-residual-uncertainties>
· <minimize-broken-zonation>
· <distance-between-zonation-points> ⚠
· <add-uncertainty-to-severe-outliers> ⚠
· <include-all-well-points-in-kriging> ⚠
· <simulate-trend-uncertainty> ⚠
· <pre-process-surfaces>
· · <make-time-surfaces-consistent>
· · <scale-isochores-to-seismic-envelopes>
· · <extrapolate-input-surfaces>
· · · <extrapolation-method> ⚠
· · · <extrapolation-kriging-thinning-correlation> ⚠
· · · <extrapolation-kriging-range> ⚠
· · · <extrapolation-inverse-distance-weighting-power> ⚠
· · · <extrapolation-SD-factor> ⚠
· · <smoothing-factor-velocity-trends> ⚠
· · <smoothing-factor-SD-maps> ⚠
· <post-process-surfaces>
· · <erode-and-onlap>
· · <treat-reflectors-as-eroding-and-onlapped>
· · <make-average-of-crossing-surfaces>
· · <make-surfaces-interpolate-well-points>
· · <allow-small-surface-adjustment-at-zonation-points>
· · <set-eroded-nodes-to-undefined>
· · <smoothing-factor-calculated-velocities> ⚠
· <correlated-intervals> ⚠ NEW in 6.0
· · <correlated-intervals-residual-range> ⚠ NEW in 6.0
· · <correlated-intervals-residual-power> ⚠ NEW in 6.0
· · <correlated-intervals-simulation> ⚠ NEW in 6.0
· · <correlated-intervals-trend-range> ⚠ NEW in 6.0
· · <correlated-intervals-trend-power> ⚠ NEW in 6.0
· · <correlated-intervals-ratios-for-trends> ⚠ NEW in 6.0
· <advanced-settings> ⚠
· · <max-rejection-rate> ⚠
· · <model-weight-resolution> ⚠
· · <max-SD-for-well-points-interpolation> ⚠
· · <max-residual-for-well-points-interpolation> ⚠
· · <max-gradient-for-surface-adjustment> ⚠
· · <max-residual-for-adjustment-at-zonation-points> ⚠
· · <min-distance-from-surface-to-zonation-points> ⚠
· · <allow-zonation-points-near-faults> ⚠
· · <base-help-points-on-simulated-surfaces> ⚠
· · <solver-for-weights> ⚠
· · <max-iterations-to-avoid-broken-zonation> ⚠
· · <correlate-close-reflectors> ⚠
· · <max-obs-direct-estim-trend-coef> ⚠

- <max-obs-GLS-approx-trend-coef> ⚠
- <max-obs-GLS-approx-extreme-outliers> ⚠
- <max-obs-update-trend-coef-using-well-paths> ⚠
- <threshold-for-trace-clustering> ⚠
- <threshold-for-cluster-merging> ⚠
- <threshold-for-well-point-cluster-inclusion> ⚠
- <threshold-for-removing-undefined-well-sections> ⚠
- <threshold-for-help-point-deactivation> ⚠
- <threshold-for-special-help-point-deactivation> ⚠
- <threshold-for-high-correlation-wp-wp> ⚠ NEW in 6.0
- <threshold-for-high-correlation-wp-ip> ⚠ NEW in 6.0
- <threshold-for-high-correlation-wp-ep> ⚠ NEW in 6.0
- <min-isochore-thickness> ⚠
- <threshold-for-mild-error> ⚠
- <t-value-outlier> ⚠
- <t-value-severe-outlier> ⚠
- <t-value-error> ⚠
- <t-value-extreme-error> ⚠
- <t-value-first-help-point> ⚠
- <t-value-second-help-point> ⚠
- <max-generalized-eigenvalue-for-inequality-points> ⚠
- <max-dxy-for-identical-well-points> ⚠
- <max-dz-for-identical-well-points> ⚠
- <max-slope-before-possible-conflict> ⚠
- <min-SD-close-well-points> ⚠
- <threshold-for-conditioning-in-neighbourhood> ⚠
- <preprocess-range-factor-for-neighbourhood> ⚠
- <min-range-factor-for-neighbourhood> ⚠
- <max-range-factor-for-neighbourhood> ⚠
- <target-number-of-data-in-neighbourhood> ⚠
- <min-generalized-eigenvalue-for-residual-uncert> ⚠
- <volume-calculation-method> ⚠
- <keep-all-pinchout-points> ⚠
- <normalize-interval-weights-table> ⚠
- <check-zonation-in-branching-wells> ⚠
- <add-uncertainty-to-close-observations> ⚠

```
<well-data>
·   <wellpath-TVD-SD-range>
·   <well-log>
·   ·   <files>
·   ·   <zone-log-specification>
·   ·   <zone-log-specification-file>
·   ·   <zone-log-name>
·   ·   <fault-log-name>
·   ·   <MD-log-name>
·   ·   <wellpoint-TVD-pick-SD-log-name>
·   ·   <wellpath-TVD-SD-log-name>
·   ·   <wellpath-TVD-SD-increase-rate>
·   ·   <tops-as-mean-values>
·   ·   <first-log-entry-as-top>
·   ·   <TVD-values-are-negative>  NEW in 6.0
·   <well-points>
·   ·   <files>
·   <well-points-to-ignore>
·   ·   <files>
·   <values-outside-grid> ⚠
·   ·   <value well-name="""" surface-name="""" x="""" y="""" SD="""">  ⚠
```

```
<surfaces> (required)
·   <reference>
·   ·   <name>
·   ·   <depth>
·   ·   <common-top-for-correlated-intervals> ⚠ NEW in 6.0
·   ·   <travel-time>
·   <surface> (required)
·   ·   <name> (required)
·   ·   <top-of-zone>
·   ·   <erosive>
·   ·   <onlapped>
·   ·   <free-surface>
·   ·   <reflector>
·   ·   <common-top-for-correlated-intervals> ⚠ NEW in 6.0
·   ·   <travel-time>
·   ·   ·   <value>
·   ·   ·   <values-outside-grid> ⚠
·   ·   ·   ·   <value> ⚠
·   ·   ·   <variogram>
·   ·   ·   ·   <type>
·   ·   ·   ·   <range>
·   ·   ·   ·   <subrange>
·   ·   ·   ·   <azimuth>
·   ·   ·   ·   <SD>
·   ·   ·   ·   ·   <relative>
·   ·   ·   ·   ·   <minimum>
·   ·   ·   ·   <power>
·   ·   ·   ·   <values-outside-grid> ⚠
·   ·   ·   ·   ·   <value> ⚠
·   ·   <spill-point>
·   ·   ·   <missing-as-wall>
·   ·   ·   <xstart>
·   ·   ·   <ystart>
·   ·   <acceptance-criteria>
·   ·   ·   <spill-point-above>
·   ·   ·   <spill-point-below>
·   ·   ·   <spill-point-at>
·   ·   ·   <spill-point-tolerance>
·   ·   ·   <trap-larger-than>
·   ·   <condition-to-spill-point-at-surface>
·   ·   <weight-isochore-package-above> ⚠
·   ·   <output>
·   ·   ·   <depth>
·   ·   ·   <depth-uncertainty>
·   ·   ·   <depth-trend>
·   ·   ·   <depth-trend-uncertainty>
·   ·   ·   <depth-residual>
·   ·   ·   <depth-residual-uncertainty>
·   ·   ·   <trap>
```

<interval-models> *(required)*
· <interval> *(required)*
· · <name>
· · <top> *(required)*
· · <base> *(required)*
· · <interval-type> *(required)*
· · <trend>
· · · <coefficient-mean>
· · · <coefficient-SD>
· · · <relative-SD>
· · · <value>
· · · <values-outside-grid> ⚠
· · · · <value> ⚠
· · <correlations> ⚠
· · · <cp-q> ⚠
· · <variogram> *(required)*
· · · <type>
· · · <range>
· · · <subrange>
· · · <azimuth>
· · · <SD>
· · · · <relative>
· · · · <minimum>
· · · <power>
· · · <values-outside-grid> ⚠
· · · · <value> ⚠
· · <output>
· · · <thickness>
· · · <thickness-trend>
· · · <thickness-residual>
· · · <velocity>
· · · <velocity-trend>

```
<volumes>
·   <volume>
·   ·   <reservoir-name>
·   ·   <top-surface>
·   ·   <base-surface>
·   ·   <top-contact>
·   ·   <base-contact>
·   ·   <area-file>
·   ·   <area-names>
·   ·   <only-trapped-volume>
·   ·   <remove-isolated-volumes-less-than>
·   ·   <connected-volume>
·   ·   ·   <xstart>
·   ·   ·   <ystart>
·   ·   <column-map>
```

17 COHIBA model file example

See Section 17.1 for the COHIBA log file generated from this example.

```
<?xml version="1.0" encoding="utf-8"?>
<cohiba>
  <project-settings>
    <project-title>       Synthetic Vilje                       </project-title>
    <project-description> This example has two crossing wells  </project-description>

    <project-directory> 23_syntetic-vilje-crossing-wells-meter </project-directory>

    <additional-output-control>
      <csv-file-style>      fixed width                              </csv-file-style>
    </additional-output-control>
    <messages>
      <logfile>
        <detail-level>
          <overall> 4 </overall>
        </detail-level>
      </logfile>
      <screen>
        <detail-level>
          <overall> 4 </overall>
        </detail-level>
      </screen>
    </messages>

    <measurement-units>
      <z-unit>               m  </z-unit>
      <time-unit>            ms </time-unit>
      <two-way-time>         no </two-way-time>
    </measurement-units>

    <output-grid>
      <xstart>              0.0 </xstart>
      <ystart>              0.0 </ystart>
      <xlength>          4800.0 </xlength>
      <ylength>          3800.0 </ylength>
      <xinc>               50.0 </xinc>
      <yinc>               50.0 </yinc>
      <format>      roxar text  </format>
    </output-grid>
  </project-settings>

  <modelling-settings>
    <mode>                     prediction </mode>
    <kriging-method>           bayesian   </kriging-method>
    <condition-to-well-paths>  yes        </condition-to-well-paths>
    <check-specified-residual-uncertainties>           yes </check-specified-residual-uncertainties>
    <post-process-surfaces>
      <make-surfaces-interpolate-well-points>           no </make-surfaces-interpolate-well-points>
```

```
      <allow-small-surface-adjustment-at-sample-points> no </allow-small-surface-adjustment-at-sample-points>
    </post-process-surfaces>
  </modelling-settings>

  <well-data>
    <well-log>
      <zone-log-name>        PD2011       </zone-log-name>
      <files>                w1.rmswell   </files>
      <files>                w4.rmswell   </files>
    </well-log>
    <well-points>
      <files>       synthetic_markers.dat </files>
    </well-points>
  </well-data>

  <surfaces>
<!--Surfaces must be listed in stratigraphic order -->
    <reference>
      <name>                 MSL               </name>
      <depth>                0                 </depth>
    </reference>

    <surface>
      <name>                 TopA              </name>
      <erosive>              no                </erosive>
      <onlapped>             no                </onlapped>
      <top-of-zone>          A                 </top-of-zone>
      <output>
        <depth>              yes               </depth>
        <depth-trend>        yes               </depth-trend>
        <depth-error>        yes               </depth-error>
        <depth-trend-error>  yes               </depth-trend-error>
        <depth-residual>     yes               </depth-residual>
      </output>
      <travel-time>
        <value>              T_TopA.storm      </value>
        <variogram>
          <type>             spherical         </type>
          <range>            1000              </range>
          <subrange>         2000              </subrange>
          <azimuth>          20.00             </azimuth>
          <SD>               2.0               </SD>
        </variogram>
      </travel-time>
    </surface>

    <surface>
      <name>                 TopB              </name>
      <erosive>              no                </erosive>
      <onlapped>             no                </onlapped>
      <top-of-zone>          B                 </top-of-zone>
      <output>
        <depth>              yes               </depth>
        <depth-trend>        yes               </depth-trend>
        <depth-error>        yes               </depth-error>
        <depth-trend-error>  yes               </depth-trend-error>
        <depth-residual>     yes               </depth-residual>
```

```
    </output>
  </surface>

  <surface>
    <name>                TopC              </name>
    <erosive>             no                </erosive>
    <onlapped>            no                </onlapped>
    <top-of-zone>         C                 </top-of-zone>
    <output>
      <depth>             yes               </depth>
      <depth-trend>       yes               </depth-trend>
      <depth-error>       yes               </depth-error>
      <depth-trend-error> yes               </depth-trend-error>
      <depth-residual>    yes               </depth-residual>
    </output>
  </surface>
</surfaces>

<interval-models>
  <interval>
    <name>                MSL-to-TopA       </name>
    <top>                 MSL               </top>
    <base>                TopA              </base>
    <interval-type>       velocity          </interval-type>
    <trend>
      <coefficient-mean>  1.00              </coefficient-mean>
      <coefficient-SD>    0.08              </coefficient-SD>
      <value>             2500              </value>
    </trend>
    <trend>
      <relative-SD>       0.50              </relative-SD>
      <value>             Vcorr.storm       </value>
    </trend>
    <variogram>
      <type>              spherical         </type>
      <range>             1000              </range>
      <subrange>          2000              </subrange>
      <azimuth>           20.00             </azimuth>
      <SD>                10.00             </SD>
    </variogram>
    <output>
      <velocity>          yes               </velocity>
    </output>
  </interval>

  <interval>
    <name>                TopA-to-TopB      </name>
    <top>                 TopA              </top>
    <base>                TopB              </base>
    <interval-type>       thickness         </interval-type>
    <trend>
      <relative-SD>       0.2               </relative-SD>
      <value>             S_IsochoreA.storm </value>
    </trend>
    <variogram>
      <type>              spherical         </type>
      <range>             1000              </range>
```

```
        <subrange>          2000              </subrange>
        <azimuth>           20.00             </azimuth>
        <SD>                10.00             </SD>
      </variogram>
    </interval>

    <interval>
      <name>                TopB-to-TopC      </name>
      <top>                 TopB              </top>
      <base>                TopC              </base>
      <interval-type>       thickness         </interval-type>
      <trend>
        <relative-SD>       0.2               </relative-SD>
        <value>             S_IsochoreB.storm </value>
      </trend>
      <variogram>
        <type>              spherical         </type>
        <range>             1000              </range>
        <subrange>          2000              </subrange>
        <azimuth>           20.00             </azimuth>
        <SD>                 9.00             </SD>
      </variogram>
    </interval>
  </interval-models>
</cohiba>
```

17.1 COHIBA log file example

The following COHIBA log file was generating using the COHIBA model file in Section 17.

```
*************************************************************************************************
*****                                                                                       *****
*****                                  C O H I B A  -  6.1.0 beta                           *****
*****                                                                                       *****
*****                          Copyright (c) 2018 by Norsk Regnesentral                     *****
*****                                                                                       *****
*************************************************************************************************

License expiration                          : 365 days
Licensed to                                 : Norsk Regnesentral

Log written by                              : SYSTEM
Date and time                               : Wed Jul 31 13:27:10 2019
Host                                        : --unknown--
Threads in use                              : 4 / 4

*************************************************************************************************
*****     Section 1: Model settings                                                         *****
*************************************************************************************************

Model file                                  : 23_syntetic-vilje-crossing-wells-meter/modelfile.xml

Project title                               : Synthetic Vilje
Project description                         : This example has two crossing wells

Project directory                           : C:\Jenkins\workspace\COHIBA_DEVELOP_WIN7_VS2015\test_suite\23_syntetic-v
Input directory for surfaces                : input\surfaces
Input directory for well data               : input\welldata
Output directory                            : output

Modelling mode                              : prediction
Conditioning method                         : Bayesian kriging
Condition to well paths                     : yes
Allow wells to move                         : no
Check specified residual uncertainties      : yes
Iterate to minimize amount of broken zonation  : no
Add uncertainty to severe outliers          : yes
Include all well points in kriging          : no

Pre-process surfaces:
   Make time surfaces consistent            : no
   Smooth velocity trends if needed         : yes
   Smooth standard deviation maps if needed : yes
   Scale isochores to fit seismic envelopes : no
   Extrapolation of input surfaces          : no

Post-process surfaces:
   Treat reflectors as eroding and onlapped : yes
   Set eroded nodes to undefined            : no
   Truncate against erosive/onlapped surfaces  : yes
   Make average of crossing surfaces        : yes
   Make surfaces interpolate well points    : no
   Allow small surface adj. at zonation points : no
   Smooth calculated velocities             : no

Additional output control:
   Also write point files using XYZ format  : no
   Include all logfiles if simulation       : yes
   Surface and interval realization output  : yes
   Export scaled input isochores            : no
   Export scaled input std grid isochores   : no
   Export filtered velocity trends          : no
```

```
   Export filtered standard deviation maps     : no
   Export regridded input maps                 : no
   Export unfiltered output velocity           : no
   Export wells                                : no
   Delimiter type used for CSV log files       : fixed width
Well logs:
   Zone log name                               : PD2011
   File names                                  : w1.rmswell; w4.rmswell
   Interpret first log entry as zone top       : no
   Find zone tops as mean values               : yes

Well points:
   File names                                  : synthetic_markers.dat

Output grid:
   format                                      : roxar text
   xstart  (rot. point)                        :        0.00
   ystart  (rot. point)                        :        0.00
   azimuth                                     :        0.00
   xinc                                        :       50.00
   yinc                                        :       50.00
   nx                                          :          97
   ny                                          :          77

Measurement types:
   Depth                                       : True vertical depth (TVD)
   Time                                        : One-way time (OWT)

Measurement units:
   Lateral distance                            : m
   Depth                                       : m
   Time                                        : ms
   Velocity                                    : m/s

Reference surface:
   Name                                        : MSL
   Depth                                       : 0.00
   Time                                        : 0.00


Surface              TravelTime      Variogram [ Type        Range  Subr. Power  Azimuth          SD ]
-------------------------------------------------------------------------------------------------------
MSL                        0.0000                -             -     -      -        -            -
TopA                 T_TopA.storm                spherical    1000  2000     -     20.00      2.0000

Surface              Erosive  Onlapped  Reflector  Free   IsoWeight  ComRefSurf  TopOfZones
-------------------------------------------------------------------------------------------
MSL                  no       no        yes        no     -          no          -
TopA                 no       no        yes        no     -          no          A
TopB                 no       no        no         no     -          no          B
TopC                 no       no        no         no     -          no          C

Surface output       Depth    Trend    Residual  DepthUncert TrendUncert ResidualUncert Trap
-----------------------------------------------------------------------------------------
MSL                  yes      no       no        no          no          no             no
TopA                 yes      yes      yes       yes         yes         no             no
TopB                 yes      yes      yes       yes         yes         no             no
TopC                 yes      yes      yes       yes         yes         no             no

Interval        Trend [   Mean        SD              Value]   Variogram [ Type        Range  Subr. Power  Azimuth
-------------------------------------------------------------------------------------------------------------------
MSL-to-TopA             1.0000    0.0800           2500.00                spherical    1000  2000     -     20.00     10
MSL-to-TopA             1.0000    0.5000  Vcorr.storm                     spherical    1000  2000     -     20.00     10
TopA-to-TopB            1.0000    0.2000  S_IsochoreA.storm               spherical    1000  2000     -     20.00     10
TopB-to-TopC            1.0000    0.2000  S_IsochoreB.storm               spherical    1000  2000     -     20.00      9
```

```
Interval                TopSurface   BaseSurface    Type
-------------------------------------------------------------
MSL-to-TopA             MSL          TopA           velocity
TopA-to-TopB            TopA         TopB           thickness
TopB-to-TopC            TopB         TopC           thickness

Interval output         Thickness  ThicknessTrend  Residual  Velocity  VelocityTrend
-----------------------------------------------------------------------------------
MSL-to-TopA             no         no              no        yes       no
TopA-to-TopB            no         no              no        no        no
TopB-to-TopC            no         no              no        no        no

*****************************************************************************************************
*****     Section 2: Loading input data                                                        *****
*****************************************************************************************************

The specification for zone log 'PD2011' is taken from the well 'w1'

Well points are extracted between the following groups of zones:

ZoneTop    Erosive/Onlapped       ZoneNum  SubZones
---------------------------------------------------------
MSL           no  / no               0     ( Above )
TopA          no  / no               1     ( A )
TopB          no  / no               2     ( B )
TopC          no  / no               3     ( C )


                                                                                                  Zones
Well                    MD           x           y      TVD  Block  WellTVD-SD  PickTVD-SD  Fault   Upper/Lower  ZoneTop
-------------------------------------------------------------------------------------------------------------------------
w4                  1210.80     2602.51     1840.00  1039.18      -        0.00        0.05     no      0 / 1        1
w4                  1955.85     3347.51     1840.01  1045.01      -        0.00        0.00     no      1 / 2        2
w4                  1960.85     3352.50     1840.00  1045.00      -        0.00        0.00     no      1 / 2        2
w4                  2110.85     3502.50     1840.00  1045.00      -        0.00        0.00     no      0 / 1        1

w4                  : Number of zone tops :     4


                                                                                                  Zones
Well                    MD           x           y      TVD  Block  WellTVD-SD  PickTVD-SD  Fault   Upper/Lower  ZoneTop
-------------------------------------------------------------------------------------------------------------------------
w1                  1078.69     3001.00     2272.50  1015.81      -        0.00        0.40     no      0 / 1        1
w1                  1755.85     3001.00     1597.50  1042.16      -        0.00        0.08     no      1 / 2        2
w1                  2053.97     3001.00     1300.00  1061.00      -        0.00        0.00     no      2 / 3        3
w1                  2103.99     3001.00     1250.00  1062.00      -        0.00        0.00     no      2 / 3        3
w1                  2286.52     3001.00     1067.50  1059.96      -        0.00        0.02     no      1 / 2        2
w1                  2366.52     3001.00      987.50  1059.00      -        0.00        0.00     no      0 / 1        1

w1                  : Number of zone tops :     6


Valid wells                                 :        2
     1 : w1
     2 : w4

Number of zone tops found in logs           :       10

Well points read from file 'C:\Jenkins\workspace\COHIBA_DEVELOP_WIN7_VS2015\test_suite\23_syntetic-vilje-crossing-wells-m


Well points added                           :        6
Duplicate well points                       :        0
Total number of well points                 :       16
```

```
Finished loading well point files.

Wells added from point file(s)              :        2
     3 : w2
     4 : w3

No well points have been assigned measured depth (MD) from well logs.

No well points from points file were marked as close to a fault.

No well points were assigned uncertainties from well logs.

Well points read from zone logs/well point files (before processing in COHIBA):
```

Surface	Well	MD	x	y	TVD	Block	WellTVD-SD	PickTVD-SD
TopA	w1	1078.69	3001.00	2272.50	1015.81	-	0.00	0.40
TopB	w1	1755.85	3001.00	1597.50	1042.16	-	0.00	0.08
TopC	w1	2053.97	3001.00	1300.00	1061.00	-	0.00	0.00
TopC	w1	2103.99	3001.00	1250.00	1062.00	-	0.00	0.00
TopB	w1	2286.52	3001.00	1067.50	1059.96	-	0.00	0.02
TopA	w1	2366.52	3001.00	987.50	1059.00	-	0.00	0.00
TopA	w4	1210.80	2602.51	1840.00	1039.18	-	0.00	0.05
TopB	w4	1955.85	3347.51	1840.01	1045.01	-	0.00	0.00
TopB	w4	1960.85	3352.50	1840.00	1045.00	-	0.00	0.00
TopA	w4	2110.85	3502.50	1840.00	1045.00	-	0.00	0.00
TopA	w2	-	900.00	2001.00	1052.50	-	0.00	0.00
TopB	w2	-	900.00	2001.00	1072.63	-	0.00	0.00
TopC	w2	-	900.00	2001.00	1109.46	-	0.00	0.00
TopA	w3	-	2225.00	3101.00	1085.21	-	0.00	0.00
TopB	w3	-	2225.00	3101.00	1115.44	-	0.00	0.00
TopC	w3	-	2225.00	3101.00	1143.62	-	0.00	0.00

	Time map nodes		Time SD map nodes	
Surface	Defined	Undefined	Defined	Undefined
TopA	7469 (100.00%)	0 (0.00%)	7469 (100.00%)	0 (0.00%)

		Interval trend map nodes		Interval SD map nodes	
Interval	Trend	Defined	Undefined	Defined	Undefined
MSL-to-TopA	1	7469 (100.00%)	0 (0.00%)	7469 (100.00%)	0 (0.00%)
MSL-to-TopA	2	7469 (100.00%)	0 (0.00%)	7469 (100.00%)	0 (0.00%)
TopA-to-TopB	1	7469 (100.00%)	0 (0.00%)	7469 (100.00%)	0 (0.00%)
TopB-to-TopC	1	7469 (100.00%)	0 (0.00%)	7469 (100.00%)	0 (0.00%)

	Time map				Time SD map			
Surface	Avg	SD	Min	Max	Avg	SD	Min	Max
TopA	447.71	9.78	422.24	471.19	2.00	0.00	2.00	2.00

		Interval trend map				Interval SD map			
Interval	Trend	Avg	SD	Min	Max	Avg	SD	Min	Max
MSL-to-TopA	1	2500.00	0.00	2500.00	2500.00	10.00	0.00	10.00	10.00
MSL-to-TopA	2	0.07	9.78	-25.39	23.56	10.00	0.00	10.00	10.00
TopA-to-TopB	1	17.06	7.03	5.00	29.12	10.00	0.00	10.00	10.00
TopB-to-TopC	1	23.09	10.55	5.00	41.17	9.00	0.00	9.00	9.00

```
Memory usage for grids
----------------------
Memory needed to hold all input grids              ( 11) :    0.6 MB
```

```
Memory needed to hold all output grids             ( 15) :    0.9 MB
Total memory usage needed for grids                       :    1.5 MB

****************************************************************************************************
*****     Section 3: Pre-processing input data                                                 *****
****************************************************************************************************

Converting time grid and time standard deviation grid for surface MSL into seconds.
Converting time grid and time standard deviation grid for surface TopA into seconds.

Crossing time surfaces are allowed.

Time surface residuals of close reflectors are not correlated.

Difference between input velocity trend and filtered velocity trends:

Interval          Trend       Minimum    Maximum    Average         SD     Smooth
------------------------------------------------------------------------------
MSL-to-TopA           1         0.000      0.000      0.000      0.000         no
MSL-to-TopA           2        -0.794      0.863      0.002      0.156         no

Difference between standard deviation maps given as input and filtered standard deviation maps:

Interval                      Minimum    Maximum    Average         SD     Smooth
------------------------------------------------------------------------------
MSL-to-TopA                     0.000      0.000      0.000      0.000         no
TopA-to-TopB                    0.000      0.000      0.000      0.000         no
TopB-to-TopC                    0.000      0.000      0.000      0.000         no

Extrapolation of input surfaces is not activated.

Scaling of isochores to fit seismic envelopes is not activated.

Scaling of isochore standard deviations is not activated.

****************************************************************************************************
*****     Section 4: The alternative ways to build each surface                                *****
****************************************************************************************************

                    Model weights
Surface     Avg     SD    Min    Max    Models
-----------------------------------------------------
TopA      1.000  0.000  0.000  1.000    1: MSL -> TopA
TopB      1.000  0.000  0.000  1.000    1: MSL -> TopA -> TopB
TopC      1.000  0.000  0.000  1.000    1: MSL -> TopA -> TopB -> TopC

                     Depth uncertainty (SD)
Surface         Avg         SD        Min        Max    Models
-------------------------------------------------------------------
TopA          6.728      0.080      0.000      6.896    1: MSL -> TopA
TopB         12.053      0.044      0.000     12.147    1: MSL -> TopA -> TopB
TopC         15.042      0.035      0.000     15.118    1: MSL -> TopA -> TopB -> TopC

Total weight of intervals used when building the surface (average):

Surface     MSL-to-TopA  TopA-to-TopB  TopB-to-TopC
-------------------------------------------------
TopA              1.000             -             -
TopB              1.000         1.000             -
TopC              1.000         1.000         1.000

****************************************************************************************************
*****     Section 5: Processing well points                                                    *****
****************************************************************************************************
```

```
Processing close points belonging to the same surface and different wells.

Identifying points that will be treated as duplicates (identical points).

Maximum lateral distance for considering well points identical  :    5.0
Maximum vertical distance for considering well points identical :    0.5

The following well points have been identified as identical. One is kept for calculations, both are
used for visualization. If both well points are taken from zone logs or both taken from a well point
file, the observation with the lowest pick uncertainty is kept. Otherwise the well point taken from
the well point file is kept.

Surface         Well 1            MD          x          y      TVD  Block    Well 2            MD          x
-------------------------------------------------------------------------------------------------------------------
TopB            w4          1955.85     3347.51    1840.01  1045.01      -    w4          1960.85     3352.50     1840

Number of duplicate points deleted                  :        1
Number of well points left for calculation          :       15

Identifying points that are close but not in conflict (slope < 0.1). Uncertainty will be added :

Surface         Well 1            MD          x          y      TVD  Block    Well 2            MD          x
-------------------------------------------------------------------------------------------------------------------
TopC            w1          2053.97     3001.00    1300.00  1061.00      -    w1          2103.99     3001.00     1250

Number of point pairs otherwise too close           :        1

The following well points have been given increased uncertainty (due to proximity to another point):

                                                                                                PickTVD-SD
Surface          Well             MD          x          y      TVD  Block  WellTVD-SD    Old    New
-------------------------------------------------------------------------------------------------------
TopC             w1         2053.97     3001.00    1300.00  1061.00      -        0.00   0.00   0.71
TopC             w1         2103.99     3001.00    1250.00  1062.00      -        0.00   0.00   0.71

Number of well points with increased uncertainty    :        2

Number of well points before processing             :       16
Well points available for conditioning              :       15

Surfaces                WellPoints
-----------------------------------
TopA                            6
TopB                            5
TopC                            4
-----------------------------------
Total                          15

*************************************************************************************************
*****     Section 6: Processing control points for eroded and onlapped surfaces               *****
*************************************************************************************************

Nothing to do here when there are no extra control points available.

*************************************************************************************************
*****     Section 7: Well branching                                                           *****
*************************************************************************************************

No wells are branched.

*************************************************************************************************
*****     Section 8: Sampling well trajectories and logs                                      *****
*************************************************************************************************

Sampling well paths at 50.0 intervals giving zonation points.
```

```
w1                  : Zonation points   (after/before)              (    25/   293)
w4                  : Zonation points   (after/before)              (    24/   271)

Number of zonation points available                          :      564
Number of zonation points selected                           :       49

Removing zonation points outside output grid boundaries.

All zonation points are inside the output grid.

No constraints are chosen for zonation points that are close to faults.

No zonation points are marked as close to a fault.

All zonation points are sufficiently distant to the well points.

Removing zonation points associated with undefined surface/interval values.

No zonation points are associated with undefined surface/interval values.

*************************************************************************************************
*****     Section 9: Trend coefficients based on well points                                *****
*************************************************************************************************

Computing a-posteriori coefficients using exact formulas.

                                                                                  Trend coefficients
Interval            PriorMeanValue         Coef    PriorMean   PriorSD     PostMean    PostSD   PostMeanUpd   PostUpdSD
-------------------------------------------------------------------------------------------------------------------
MSL-to-TopA         2500.0000              1       1.000       0.080       0.972       0.003          -           -
MSL-to-TopA         0.075                  2       1.000       0.500       1.020       0.426          -           -
TopA-to-TopB        17.058                 1       1.000       0.200       1.025       0.163          -           -
TopB-to-TopC        23.086                 1       1.000       0.200       1.043       0.142          -           -


*************************************************************************************************
*****     Section 10: Checking specified residual uncertainties                             *****
*************************************************************************************************

 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Total number of well points      : 15
Number of well points available  : 15

                Specified/Obs    95% AcceptanceRange     NumberOf    Specified
Interval         Uncertainty    LowerLimit UpperLimit   WellPoints  Uncertainty
-------------------------------------------------------------------------------
MSL-to-TopA              -             -          -           -              -
TopA-to-TopB         1.443         0.624      2.453           5             OK
TopB-to-TopC         5.210         0.566      3.729           3       Too high
-------------------------------------------------------------------------------
Overall              1.528         0.739      1.548          15           High

Consider reducing the prior residual uncertainty for interval 'TopB-to-TopC'

*************************************************************************************************
*****     Section 11: Well point quality control                                            *****
*************************************************************************************************

No leverage points found.

No outliers found.
```

```
                                        Residual
Surface           WellPoints         Bias       SD
-------------------------------------------------
TopA                       6         0.18     5.05
TopB                       5         0.57     9.98
TopC                       4        -0.07    12.30

                                        Residual
Well              WellPoints         Bias       SD
-------------------------------------------------
w1                         6        -7.21     7.95
w4                         3         2.87     3.74
w2                         3        -2.32     3.20
w3                         3        15.11    16.38

*************************************************************************************************
*****     Section 12: Conditioning on well points along well paths                          *****
*************************************************************************************************

In the pre-processing for conditioning to well paths:  1.66% of the grid nodes will be active.

Trends
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
Residuals
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Deleting surface constraints that are redundant due to correlation with
well points (Del-1) and/or other surface constraints (Del-2)

Del-1 / Del-2 / Left / Total :    0 /   32 /  18 /  50

w1                  : Zonation points in wrong zone/total number of points         5/    25
w4                  : Zonation points in wrong zone/total number of points         4/    24

Summary             : Zonation points in wrong zone/total number of points         9/    49

*************************************************************************************************
*****     Section 13: Finding help points for well path conditioning                        *****
*************************************************************************************************

Grouping surface constraints
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Merging clusters ...

Distribution of surface constraints in clusters:

Cluster size    Count   Frequency
---------------------------------
   1-   5           4      80.00%
   6-  10           1      20.00%
  11-  20           0       0.00%
  21-  50           0       0.00%
  51- 100           0       0.00%
 101- 200           0       0.00%
 201- 500           0       0.00%
 501-1000           0       0.00%
1001-2000           0       0.00%
2001-5000           0       0.00%
```

```
5000+               0       0.00%
---------------------------------
Total               5     100.00%

Largest cluster has 10 surface constraints and 15 well points

Calculating surface constraints
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

Calculating surface conditioning points from surface target points

Number of well points                  :       15
Number of help points                  :       18
Total number of conditioning points    :       33

*****************************************************************************************************
*****     Section 14: Trend coefficients based on well points and well paths                    *****
*****************************************************************************************************

                                                                                  Trend coefficients
Interval            PriorMeanValue         Coef    PriorMean   PriorSD     PostMean    PostSD   PostMeanUpd   PostUpdSD
-----------------------------------------------------------------------------------------------------------------------
MSL-to-TopA         2500.0000              1       1.000       0.080       0.972       0.003       0.972       0.003
MSL-to-TopA         0.075                  2       1.000       0.500       1.020       0.426       1.020       0.426
TopA-to-TopB        17.058                 1       1.000       0.200       1.025       0.163       1.025       0.163
TopB-to-TopC        23.086                 1       1.000       0.200       1.043       0.142       1.043       0.142


*****************************************************************************************************
*****     Section 15: Conditioning surfaces on all available points                             *****
*****************************************************************************************************

Trends
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
Residuals
 0%       20%       40%       60%       80%       100%
 |    |    |    |    |    |    |    |    |    |    |
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

*****************************************************************************************************
*****     Section 16: Post-process surfaces                                                     *****
*****************************************************************************************************

Treating reflector depth trends as erosive and onlapped surfaces. The
tables below give the number of grid nodes moved by a reflector.

No erosion truncations performed.

No onlap truncations performed.

The total number of grid nodes that have been moved on each surface.

Truncating surface        Erosive   Onlapped   Reflector   Moved nodes
-------------------------------------------------------------------
TopA                        no         no        yes            0
TopB                        no         no         no            0
TopC                        no         no         no            0

Treating reflector depths as erosive and onlapped surfaces. The
tables below give the number of grid nodes moved by a reflector.
```

No erosion truncations performed.

No onlap truncations performed.

The total number of grid nodes that have been moved on each surface.

Truncating surface	Erosive	Onlapped	Reflector	Moved nodes
TopA	no	no	yes	0
TopB	no	no	no	0
TopC	no	no	no	0

****
***** Section 17: Target point quality control *****
****

Mismatch between target point depths and actual surface values. A part
of the mismatch is due to gridding errors. This error is roughly equal
to the numbers given in the average mismatch column.

Surface	Points	Minimum	Maximum	Bias	Average	SD
TopA	4	-0.19	0.11	-0.06	0.11	0.06
TopB	10	-0.35	1.15	0.29	0.36	0.36
TopC	4	-0.09	0.79	0.34	0.38	0.30

For 1 target point(s), the mismatch between the predicted and the observed
surface value is large. This suggests that the model is poor in that are:

Cluster	Well	Surface	Mismatch
0	w4	TopB	1.15
Average			1.15

****
***** Section 18: Checking zonation *****
****

The table(s) below give zonation status at zonation point locations. The letters
used in the 'Fix' column are explained at the end of the section.

At the medium log-level (4) we log all wells with erroneous zonation status. At
the high log-level we also include wells for which the zone log conditioning
corrected the zonation.

Below, 'unchanged zonation' refers to zonation points that had correct zonation
after conditioning to well points only and for which the zonation is still correct.

Final zonation status at zonation points		< 1.0	> 1.0	Total
Number of zonation points with unchanged zonation	(-) :			40
Number of zonation points with zonation corrected	(Y) :			9
Number of zonation points for which correction failed	(N) :	0	0	0
Number of zonation points with broken zonation	(B) :	0	0	0
Number of zonation points with fixable broken zonation	(F) :	0	0	0
Number of zonation points with incorrectable zonation	(X) :	0	0	0
Number of zonation points with undefined zonation	(U) :			0
Number of zonation points with no zone information	(=) :			0
Total number of zonation points	:			49

Final zonation status for wells:

```
Number of wells with correct zonation after pre-processing:      0
Number of wells with zonation corrected by conditioning   :      2
Number of wells with correct zonation                     :            2
Number of wells with incorrect zonation  < 1.0            :      0
Number of wells with incorrect zonation  > 1.0            :      0
Number of wells with undefined zonation                   :      0
Number of wells with zonation problems                    :            0
-------------------------------------------------------------------------
Total number of wells                                     :            2

Length of correct zonation for each well:

Well                        Correct    Incorrect      < 1.0      > 1.0      Undef    Avg miss       Correct
-------------------------------------------------------------------------------------------------------------
w1                           1470.8         25.0       25.0          -          -         0.1         98.3%
w4                           1375.9         10.0        5.0        5.0          -         0.7         99.3%
-------------------------------------------------------------------------------------------------------------
Total                        2846.7         35.0       30.0        5.0          -         0.2         98.8%
-------------------------------------------------------------------------------------------------------------

Length of correct zonation summed over all wells:

Zone                        Correct    Incorrect      < 1.0      > 1.0      Undef    Avg miss       Correct
-------------------------------------------------------------------------------------------------------------
Above                         688.8          5.0        5.0          -          -         0.1         99.3%
A                            1652.2            -          -          -          -           -        100.0%
B                             480.6          5.0          -        5.0          -         1.3         99.0%
C                              25.0         25.0       25.0          -          -         0.1         50.0%
-------------------------------------------------------------------------------------------------------------
Total                        2846.7         35.0       30.0        5.0          -         0.2         98.8%
-------------------------------------------------------------------------------------------------------------

*************************************************************************************************************
*****     Section 19: Updated well trajectories                                                         *****
*************************************************************************************************************

Nothing to do here when wells are not allowed to move and wells are not exported.

*************************************************************************************************************
*****     Section 20: Spill points                                                                      *****
*************************************************************************************************************

No spill point detection has been requested.

*************************************************************************************************************
*****     Section 21: Volume calculations                                                               *****
*************************************************************************************************************

No volume calculations have been requested.

*************************************************************************************************************
*****     Section 22: Make and export interval thickness maps and velocities                            *****
*************************************************************************************************************

No interval maps exported.

Interval velocities are calculated differently depending on the interval thickness (dt):
  dt < 1.00 ms : Use posterior trend
  dt > 9.00 ms : Use v = dz/dt
  In between  : Use an arctan weight of the two above approaches

Number of unsmoothed velocity trends exported     :  0
Number of smoothed velocity trends exported       :  1
Number of unsmoothed velocity maps exported       :  0
Number of smoothed velocity maps exported         :  0
```

```
*****************************************************************************************************
*****     Section 23: Export surfaces                                                           *****
*****************************************************************************************************

Number of depth surfaces exported                      :  3
Number of depth uncertainty surfaces exported          :  3
Number of depth residual surfaces exported             :  3
Number of depth residual uncertainty surfaces exported :  0
Number of depth trend surfaces exported                :  3
Number of depth trend uncertainty surfaces exported    :  3
Number of trap surfaces exported                       :  0

*****************************************************************************************************
*****     Section 24: Timings summary                                                           *****
*****************************************************************************************************

Section                                        CPU Time/s            Real Time/s
-----------------------------------------------------------------------------
Loading input data                      0.03     1.63%         1.00    50.00%
Regridding input data                   0.01     0.34%         0.00     0.00%
Pre-processing                          0.01     0.28%         0.00     0.00%
Checking residual uncertainties         0.00     0.11%         0.00     0.00%
Preparing prediction along well paths   0.00     0.06%         0.00     0.00%
Define conditioning regions             0.00     0.11%         0.00     0.00%
Predicting surfaces along well paths    0.01     0.67%         0.00     0.00%
Finding help point clusters             0.00     0.11%         0.00     0.00%
Finding help point probability dist.    1.20    67.23%         1.00    50.00%
Preparing prediction                    0.00     0.06%         0.00     0.00%
Predicting surfaces                     0.22    12.29%         0.00     0.00%
Post-processing                         0.00     0.06%         0.00     0.00%
Calculate zonation statistics           0.01     0.45%         0.00     0.00%
Calculate average statistics            0.00     0.11%         0.00     0.00%
Spill point calculations                0.00     0.06%         0.00     0.00%
Writing files                           0.29    16.50%         0.00     0.00%
-----------------------------------------------------------------------------
Total                                   1.78   100.00%         2.00   100.00%

*****************************************************************************************************
*****     Section 25: Suggested tasks                                                           *****
*****************************************************************************************************

 1. The keyword <allow-small-surface-adjustment-at-sample-points> is obsolete and will be removed in a future
    release. Please use the new keyword <allow-small-surface-adjustment-at-zonation-points>.
 2. A change of specified residual uncertainty has been suggested. See residual uncertainty section.

Total CPU  time used by COHIBA:     1.78 s
Total real time used in COHIBA:     2.00 s
```

Part V
Theory

18 Prediction of surfaces

18.1 Surfaces and intervals

The basic assumption made by COHIBA is that any depth surface is obtained by adding intervals specified by <interval> elements. So the fundamental building blocks are the intervals. The link between surfaces and intervals is made by the <top> and <base> elements that associate the top and base surfaces of an interval. COHIBA will automatically assemble the necessary intervals to obtain any surface. COHIBA is very flexible when it comes to combining intervals to obtain surfaces. An illustration is shown on page 13 and an extensive example is given in Section 11. Any combination of surfaces and intervals is possible as long as three requirements are fulfilled:

1. At least one of the intervals must have the <reference> surface as its <top> surface.
2. In every interval, the <top> surface must be above the <base> surface[1].
3. The specification can not be cyclical. That means that a surface can not be obtained by adding an interval that has itself as <top>.

These three requirements guarantees a consistent specification that links any surface to the <reference> surface by adding (or subtracting) intervals.

COHIBA requires a strict ordering of surfaces entering the stratigraphic framework. The ordering is the order the <surface> elements appear in the COHIBA model file. The ordering is used for several purposes:

- Obtain correct truncation caused by <erosive> and <onlapped> properties.
- Correct interpretation of zone logs.
- Automatic change of sign when an interval contributes with a negative thickness to a surface. This happens when intervals are added on top of deeper surfaces.

The strict ordering does not apply to surfaces that are specified as free surfaces (Section 13).

The intervals have no specific order and any surface can be the <top> and <base> of several intervals.

18.2 Stochastic model for surfaces and intervals

The number of intervals defined in the model is denoted I and the number of surfaces are denoted L. There might be more intervals than surfaces so $I \geq L$. To simplify the notation we introduce the set of all intervals that contribute to surface l by $\mathcal{I}^l$. The depth to surface l is obtained by adding[2] the thicknesses of all intervals, i, that belongs to the set $\mathcal{I}^l$:

$$Z^l(\mathbf{x}) = z^{\text{ref.}}(\mathbf{x}) + \sum_{i \in \mathcal{I}^l} \Delta Z_i(\mathbf{x}), \qquad \mathbf{x} \in \mathbb{R}^2. \tag{18.1}$$

The reference surface, $z^{\text{ref.}}(\mathbf{x})$, is usually MSL but can be replaced by an arbitrary reference surface using <reference>. In the following we will assume that $z^{\text{ref.}}(\mathbf{x}) = 0$ to simplify the notation.

The thickness of interval i is modeled as

$$\Delta Z_i(\mathbf{x}) = \Delta m_i(\mathbf{x}) + \Delta \epsilon_i(\mathbf{x}), \tag{18.2}$$

1. This is not a necessary requirement if one of the surfaces is a free surface since free surfaces don't have any ordering (Section 13).
2. Or subtracting if intervals are added on top of deeper surfaces. We omit this to simplify the notation in this section. COHIBA will of course take proper care of possible negative signs.

where $\Delta m_i(\mathbf{x})$ is the *interval thickness trend* and $\Delta\epsilon_i(\mathbf{x})$ is the *interval thickness residual*. The interval thickness residual is modeled as a zero mean *Gaussian random field* (Abrahamsen, 1997) specified by the correlation function, $\rho(h)$, and the standard deviation (SD), $\sigma_i(\mathbf{x})$, so that

$$\mathrm{E}\{\Delta\epsilon_i(\mathbf{x})\} = 0, \tag{18.3a}$$

$$\mathrm{Var}\{\Delta\epsilon_i(\mathbf{x})\} = \sigma_i^2(\mathbf{x}), \tag{18.3b}$$

$$\mathrm{Cov}\{\Delta\epsilon_i(\mathbf{x}), \Delta\epsilon_j(\mathbf{y})\} = \delta_{ij}\,\sigma_i(\mathbf{x})\,\sigma_j(\mathbf{y})\,\rho(\|\mathbf{x}-\mathbf{y}\|). \tag{18.3c}$$

Interval thickness residuals from different intervals are assumed independent. This is obtained by the Kronecker delta[3] in Eq. 18.3c. The SD, $\sigma_i(h)$, is specified by `<SD>` and the correlation function, $\rho_i(h)$, is specified by the `<variogram>` element.

The interval thickness trend for interval i, is a linear combinations of P_i known trend maps, $f_{i,p}(\mathbf{x})$:[4]

$$\Delta m_i(\mathbf{x}) = \sum_{p=1}^{P_i} \beta_{i,p}\, f_{i,p}(\mathbf{x}). \tag{18.4}$$

These trend maps are typically constants, isochore maps, or any map used to model the thickness of interval i. The specification of the known trend maps is done by repeated use of the `<value>` in the wrapper element `<trend>`. To simplify, we organize the P_i known trend maps for interval i as a vector $\mathbf{f}_i{}'(\mathbf{x}) = [f_{i,1}(\mathbf{x}), \ldots, f_{i,P_i}(\mathbf{x})]$ so that Eq. 18.4 can be written

$$\Delta m_i(\mathbf{x}) = \mathbf{f}_i{}'(\mathbf{x}) \cdot \boldsymbol{\beta}_i. \tag{18.5}$$

Using this notation we can write the depth to a surface as

$$Z^l(\mathbf{x}) = m^l(\mathbf{x}) + \epsilon^l(\mathbf{x}), \tag{18.6}$$

where

$$m^l(\mathbf{x}) = \sum_{i\in\mathcal{I}^l} \mathbf{f}_i{}'(\mathbf{x}) \cdot \boldsymbol{\beta}_i \tag{18.7}$$

$$\epsilon^l(\mathbf{x}) = \sum_{i\in\mathcal{I}^l} \Delta\epsilon_i(\mathbf{x}). \tag{18.8}$$

These are called the *depth trend* and the *depth residual* respectively. The depth residual is a sum of Gaussian random fields and is therefore also a Gaussian random field.

To further simplify the notation, consider all trend maps and corresponding trend coefficients for all I intervals organized as two vectors:

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{f}_1(\mathbf{x}) \\ \vdots \\ \mathbf{f}_I(\mathbf{x}) \end{bmatrix}, \qquad \boldsymbol{\beta} = \begin{bmatrix} \boldsymbol{\beta}_1 \\ \vdots \\ \boldsymbol{\beta}_I \end{bmatrix}. \tag{18.9}$$

These vectors contain all the trend maps and all the trend coefficients belonging to all the I intervals so the size of these vectors are $P = \sum_{i=1}^{I} P_i$.

We can now write Eq. 18.6 as

$$Z^l(\mathbf{x}) = \mathbf{f}^{l\prime}(\mathbf{x}) \cdot \boldsymbol{\beta} + \epsilon^l(\mathbf{x}), \tag{18.10}$$

where trend maps in $\mathbf{f}_i(\mathbf{x})$ are replaced by zeros when they belong to intervals that does *not* contribute to surface l. That is, $\mathbf{f}_i(\mathbf{x}) = \mathbf{0}$ in $\mathbf{f}^l$ if $i \notin \mathcal{I}^l$.

3. Kronecker delta: $\delta_{ii} = 1$ and $\delta_{ij} = 0$ for $i \neq j$.
4. The trend coefficients $\beta_{i,1}, \beta_{i,2}, \beta_{i,3}, \ldots$ are labeled by italic letters $a, b, c, \ldots$ in log files and in most parts of this manual.

18.3 Estimating the trend coefficients

All the TVD values at the well points from all the L surfaces can be organized in a column vector:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^1 \\ \vdots \\ \mathbf{Z}^L \end{bmatrix}, \tag{18.11}$$

where $\mathbf{Z}^{l'} = [Z^l(\mathbf{x}_1^l), \ldots, Z^l(\mathbf{x}_{N^l}^l)]$ is a column vector of the N^l TVD observations of the depth to surface l. So $\mathbf{Z}$ is a vector of dimension $N = \sum_{l=1}^{L} N^l$.

Similarly we can organize all the P trend map values at the N well points as a $N \times P$ dimensional *design matrix*[5]

$$\mathbf{F} = \begin{bmatrix} \mathbf{F}^1 \\ \vdots \\ \mathbf{F}^L \end{bmatrix}, \tag{18.12}$$

that is build up by $N^l \times P$ dimensional sub-matrices for each surface:

$$\mathbf{F}^l = \begin{bmatrix} \mathbf{f}^{l'}(\mathbf{x}_1^l) \\ \vdots \\ \mathbf{f}^{l'}(\mathbf{x}_{N^l}^l) \end{bmatrix}. \tag{18.13}$$

Using this notation we can write Eq. 18.10 for all the observed TVD values as

$$\mathbf{Z} = \mathbf{F}\boldsymbol{\beta} + \boldsymbol{\epsilon}, \tag{18.14}$$

where the residual vector, $\boldsymbol{\epsilon}$, is organized in the same sequence as the vector, $\mathbf{Z}$. Eq. 18.14 is recognized as a standard linear regression problem for the trend coefficients $\boldsymbol{\beta}$ with correlated residuals.

18.3.1 Linear regression

The standard estimate for the coefficients, $\boldsymbol{\beta}$, in a linear regression model such as Eq. 18.14 can be found in any textbook on (multiple) linear regression as the ordinary least squares (OLS) solution:

$$\widehat{\boldsymbol{\beta}}_{\text{OLS}} = \left(\mathbf{F}'\,\mathbf{F}\right)^{-1}\mathbf{F}'\,\mathbf{Z} \tag{18.15a}$$

$$\widehat{\boldsymbol{\Sigma}}_{\text{OLS}} = \sigma^2\left(\mathbf{F}'\,\mathbf{F}\right)^{-1}, \tag{18.15b}$$

where $\text{Var}\{\epsilon_i\} = \sigma^2$ is assumed constant and independent for *all* TVD values. This is not a reasonable assumption in this case since surface depths are highly correlated.

According to equations Eq. 18.3c and Eq. 18.8 the covariance between two surface depths are

$$\begin{aligned} \text{Cov}\{Z^l(\mathbf{x}), Z^k(\mathbf{y})\} &= \text{Cov}\{\epsilon^l(\mathbf{x}), \epsilon^k(\mathbf{y})\} \\ &= \text{Cov}\left\{\sum_{i\in\mathcal{J}^l} \Delta\epsilon_i(\mathbf{x}), \sum_{j\in\mathcal{J}^k} \Delta\epsilon_j(\mathbf{y})\right\} \\ &= \sum_{i\in\mathcal{J}^l\cap\mathcal{J}^k} \text{Cov}\{\Delta\epsilon_i(\mathbf{x}), \Delta\epsilon_i(\mathbf{y})\} \\ &= \sum_{i\in\mathcal{J}^l\cap\mathcal{J}^k} \sigma_i(\mathbf{x})\,\sigma_i(\mathbf{y})\,\rho(\|\mathbf{x}-\mathbf{y}\|). \end{aligned} \tag{18.16}$$

5. In statistics the design matrix is often denoted by the symbol $\mathbf{X}$. We use $\mathbf{F}$ and $\mathbf{f}$ here to avoid confusion with the coordinates $\mathbf{x}$.

The double sum is removed by using the assumption that interval residuals from different intervals are independent; see the Kronecker delta in Eq. 18.3c. The significance of Eq. 18.16 is that it gives a simple recipe for calculating the covariance between two surface depths at two arbitrary well points. We see that the correlation between the surface depths at different well points is caused by spatial correlation and that surfaces have residuals in common.

The covariances between depths at all well points can be organized in a covariance matrix called the *kriging matrix*:

$$\mathbf{K} = \mathrm{Var}\{\mathbf{Z}\}\,. \tag{18.17}$$

It is possible to show (Mardia et al., 1979, p. 172) that the best linear unbiased estimator (BLUE) for the coefficients is the generalized least squares (GLS) estimator:

$$\widehat{\boldsymbol{\beta}}_{\mathrm{GLS}} = \left(\mathbf{F}'\,\mathbf{K}^{-1}\mathbf{F}\right)^{-1}\mathbf{F}'\,\mathbf{K}^{-1}\mathbf{Z} \tag{18.18a}$$

$$\widehat{\boldsymbol{\Sigma}}_{\mathrm{GLS}} = \left(\mathbf{F}'\,\mathbf{K}^{-1}\mathbf{F}\right)^{-1}. \tag{18.18b}$$

The correlations between the depths at different well points and the local varying variance, $\sigma_i(\mathbf{x})$, at different well points will influence the estimate through the kriging matrix. Note that the ordinary least squares estimate is retrieved if well points are independent and the variance is the same at all well points, that is, $\mathbf{K} = \sigma^2\mathbf{I}$.

If the number of well points, N, is very large, COHIBA uses a weighted least squares (WLS) estimate:

$$\widehat{\boldsymbol{\beta}}_{\mathrm{WLS}} = \left(\mathbf{F}'\,\mathbf{D}^{-1}\mathbf{F}\right)^{-1}\mathbf{F}'\,\mathbf{D}^{-1}\mathbf{Z} \tag{18.19a}$$

$$\widehat{\boldsymbol{\Sigma}}_{\mathrm{WLS}} = \left(\mathbf{F}'\,\mathbf{D}^{-1}\mathbf{F}\right)^{-1}, \tag{18.19b}$$

where $\mathbf{D} = \mathrm{Diag}\{\mathbf{K}\}$. This amounts to ignoring the correlation between well points. This approximation is necessary to avoid using too much CPU and RAM. The number of well points where COHIBA switches from GLS to WLS can be changed by `<max-obs-GLS-approx-trend-coef>`. The default is $N = 2000$.

18.3.2 Bayesian estimation

OLS, WLS and GLS methods requires that $N > P$ *and* that all columns of $\mathbf{F}$ are non-parallel so that $\mathrm{rank}(\mathbf{F}) = P$. If the columns of $\mathbf{F}$ are near parallel or linear combinations of the columns are near parallel a problem called *collinearity* occurs (Weisberg, 1985, p. 196). This is a serious problem since the estimates of the coefficients become unreliable and the estimation variance becomes very large. Collinearity occurs when the data is unable to distinguish the contribution from the different trend maps, $f_{i,p}(\mathbf{x})$. This is usually caused by too few well points, clustering of wells, unobserved surfaces due to pinch outs or too many coefficients in the trend model. Simplifying the thickness trends by removing some of the trend maps is one solution, but usually the chosen trend maps have a particular purpose. So COHIBA supports an alternative way of handling collinearity. This is done by specifying the coefficient values using `<coefficient-mean>` and `<coefficient-SD>`. These numbers are the prior means and the prior SDs in the prior P-dimensional multinormal distribution for the coefficient values

$$\boldsymbol{\beta} \sim N_P(\boldsymbol{\beta}_0, \boldsymbol{\Sigma}_0). \tag{18.20}$$

The diagonal elements of $\boldsymbol{\Sigma}_0$ are specified using `<coefficient-SD>` and some of the off-diagonals can be set to non-zero by using `<correlations>`.

The Bayesian estimate for the posterior expectations and covariances are

$$\widehat{\boldsymbol{\beta}}_{\mathrm{Bayes}} = \boldsymbol{\beta}_0 + \boldsymbol{\Sigma}_0\,\mathbf{F}'\left(\mathbf{K} + \mathbf{F}\,\boldsymbol{\Sigma}_0\,\mathbf{F}'\right)^{-1}(\mathbf{Z} - \mathbf{F}\,\boldsymbol{\beta}_0) \tag{18.21a}$$

$$\widehat{\boldsymbol{\Sigma}}_{\mathrm{Bayes}} = \boldsymbol{\Sigma}_0 - \boldsymbol{\Sigma}_0\,\mathbf{F}'\left(\mathbf{K} + \mathbf{F}\,\boldsymbol{\Sigma}_0\,\mathbf{F}'\right)^{-1}\mathbf{F}\,\boldsymbol{\Sigma}_0. \tag{18.21b}$$

This estimate is robust for any N, including $N = 0$. In that case the prior guess, $\boldsymbol{\beta}_0$, is returned. If the prior uncertainty vanishes, $\boldsymbol{\Sigma}_0 \to \mathbf{0}$, then the prior guess, $\boldsymbol{\beta}_0$, is also returned. It is also possible to fix one or more coefficients by specifying zero prior uncertainty and use the well points for estimating the rest. It can also be shown, on reasonable assumptions, that if $\boldsymbol{\Sigma}_0 \to \infty$ then we obtain the GLS estimate (Omre and Halvorsen, 1989).

Eq. 18.21a and Eq. 18.21b includes an inversion of the $N \times N$ matrix $(\mathbf{K} + \mathbf{F}\,\boldsymbol{\Sigma}_0\,\mathbf{F}')$. This is CPU and RAM demanding so alternative expressions are used when N is large:

$$\widehat{\boldsymbol{\beta}}_{\text{Bayes}} = \widehat{\boldsymbol{\Sigma}}_{\text{Bayes}}\left(\boldsymbol{\Sigma}_0^{-1}\boldsymbol{\beta}_0 + \widehat{\boldsymbol{\Sigma}}_{\text{xLS}}^{-1}\widehat{\boldsymbol{\beta}}_{\text{xLS}}\right) \tag{18.22a}$$

$$\widehat{\boldsymbol{\Sigma}}_{\text{Bayes}} = \left(\boldsymbol{\Sigma}_0^{-1} + \widehat{\boldsymbol{\Sigma}}_{\text{xLS}}^{-1}\right)^{-1}. \tag{18.22b}$$

These expressions are algebraically identically to Eq. 18.21a and Eq. 18.21b provided $\text{rank}(\mathbf{F}) = \text{rank}(\boldsymbol{\Sigma}_0) = P$ and $N > P$.

COHIBA uses the robust formulas Eq. 18.21a and Eq. 18.21b when the number of data, N, is few[6]. Otherwise Eq. 18.22a and Eq. 18.22b are used.

The estimates $\widehat{\boldsymbol{\Sigma}}_{\text{xLS}}$ and $\widehat{\boldsymbol{\beta}}_{\text{xLS}}$ are GLS estimates for moderate number of data, N, and WLS estimates for large N. The number of data where COHIBA switches from GLS to WLS can be changed by `<max-obs-GLS-approx-trend-coef>`.

COHIBA will automatically switch to Bayesian estimation using Eq. 18.21a and Eq. 18.21b if $\text{rank}(\mathbf{F}) < P$ even though the user has chosen `universal` for the `<kriging-method>`. This is necessary since the GLS and WLS estimates fail to exist if $\text{rank}(\mathbf{F}) < P$.

18.3.3 Trend and trend uncertainty

The estimated depth trend is

$$\widehat{m}^l(\mathbf{x}) = \mathbf{f}^{l\prime}(\mathbf{x}) \cdot \widehat{\boldsymbol{\beta}}, \tag{18.23}$$

where the estimates, $\widehat{\boldsymbol{\beta}}$, depends on the estimation methods. This map can be written to file using element `<depth-trend>`.

The estimation method is chosen using the element `<kriging-method>` in the COHIBA model file. Choosing `universal` amounts to using the GLS estimate, $\widehat{\boldsymbol{\beta}}_{\text{GLS}}$ (Eq. 18.18a) and choosing `bayesian` amounts to using $\widehat{\boldsymbol{\beta}}_{\text{Bayes}}$ (Eq. 18.21a or Eq. 18.22a). Choosing `simple` amounts to skipping estimation and use the prior guess $\boldsymbol{\beta}_0$ (Eq. 18.20).

The depth trend uncertainty is given by

$$\widehat{\sigma}^l(\mathbf{x}) = \sqrt{\mathbf{f}^{l\prime}(\mathbf{x})\widehat{\boldsymbol{\Sigma}}\,\mathbf{f}^l(\mathbf{x})}, \tag{18.24}$$

where the covariance estimate, $\widehat{\boldsymbol{\Sigma}}$, depends on the estimation methods. The estimation method is chosen by `<kriging-method>`; see discussion above. Choosing `simple` means that $\widehat{\boldsymbol{\Sigma}} = \mathbf{0}$ so that the trend uncertainty is zero. Eq. 18.24 ignores the local adaption to well points. This trend uncertainty map (SD) can be written to file using the element `<depth-trend-uncertainty>`.

18.3.4 Residual uncertainty

The surface residual variance is (compare Eq. 18.16)

$$\begin{aligned}\sigma^{l\,2}(\mathbf{x}) &= \text{Var}\{\epsilon^l(\mathbf{x})\} = \sum_{i\in\mathcal{I}^l}\text{Var}\{\Delta\epsilon_i(\mathbf{x})\} \\ &= \sum_{i\in\mathcal{I}^l}\sigma_i^2(\mathbf{x}).\end{aligned} \tag{18.25}$$

6. This number is set in the COHIBA model file using the element `<max-obs-direct-estim-trend-coef>`. The current default is 200

The residual uncertainty map (SD) can be written to file using the element <depth-residual-uncertainty>.

18.3.5 Quality control of the trend estimation

The QC consist of two main objectives: Removing corrupted well points and checking that the trend coefficient estimates are reliable.

18.3.5.1 Outliers

Outliers (Weisberg, 1985, pp. 114–118) are well points that match the trends poorly. This might be an indication that the well points are corrupted. Consider all trend estimates at the well points and organize them in an N dimensional vector similar to $\mathbf{Z}$. They are obtained by

$$\widehat{\mathbf{m}} = \mathbf{F}\,\widehat{\boldsymbol{\beta}}. \tag{18.26}$$

Denote $\mathbf{Z}_n, \widehat{\mathbf{m}}_n$ etc. as the values belonging to well point n.

Outliers are identified by calculating a t-value for every well point:

$$\mathbf{t}_n = \frac{|\mathbf{z}_n - \widehat{\mathbf{m}}_n|}{\sqrt{\mathbf{K}_{nn}}}, \qquad \text{for } n = 1, \ldots, N, \tag{18.27}$$

with the classification rules:[7]

(18.28)

$$\text{If} \quad \mathbf{t}_n \geq \begin{cases} 1.95996 & \text{then } n \text{ is an outlier (5 \%).} & \text{Action: Flag for inspection} \\ 2.57583 & \text{then } n \text{ is a severe outlier (1 \%).} & \text{Action: Add uncertainty} \\ 3.09023 & \text{then } n \text{ is an error. (0.2 \%).} & \text{Action: Delete from kriging} \\ 3.89059 & \text{then } n \text{ is an extreme error. (0.01 \%).} & \text{Action: Delete and reestimate trend.} \end{cases}$$

The uncertainty added to a severe outlier is $\sigma = |\mathbf{z}_n - \widehat{\mathbf{m}}_n|/2$.

The thresholds can be changed using <t-value-outlier>, <t-value-severe-outlier>, <t-value-error>, and <t-value-extreme-error>.

18.3.5.2 Leverage points

Leverage points are well points that strongly influence the estimated trend coefficients. A leverage point might not be identified as an outlier because the trend coefficient estimates adapts strongly to the leverage point.

Using Eq. 18.18a gives

$$\widehat{\mathbf{m}} = \mathbf{F}\,\widehat{\boldsymbol{\beta}}_{\text{GLS}} = \mathbf{H}\,\mathbf{Z}, \tag{18.29}$$

where the so-called hat matrix[8], $\mathbf{H}$, is

$$\mathbf{H} = \mathbf{F}\big(\mathbf{F}'\,\mathbf{K}^{-1}\mathbf{F}\big)^{-1}\mathbf{F}'\,\mathbf{K}^{-1}. \tag{18.30}$$

Consider

$$\mathbf{h}_n = \frac{\partial\,\widehat{\mathbf{m}}_n}{\partial \mathbf{Z}_n} = \mathbf{H}_{nn} \qquad \big(h_n \in [0, 1]\big). \tag{18.31}$$

Large $\mathbf{h}_n$ values indicates that the observed depth value, $\mathbf{Z}_n$, at well point n, has large influence on the estimated trend, $\widehat{\mathbf{m}}_n$, at that well point. Note that this analysis is only possible when $\text{rank}(\mathbf{F}) = P$ so that $\mathbf{H}$ exist. This often fails.

---

7. Percentages are the fraction of data classified if $\mathbf{t}_n$ has a normal distribution. This is a good approximation if $N \gg P$.
8. The name, hat matrix, comes from the observation that $\mathbf{H}$ puts the hat on $\mathbf{Z}$. According to Eq. 18.26: $\widehat{\mathbf{m}} = \mathbf{H}\,\mathbf{Z}$.

Table 18.1. Formulas used in `wellpoints.csv` for well point n. See Table 7.7 for description of all columns in `wellpoints.csv`.

Column name	Formula	Comment
`PriorTrend`	$m_0^{l_n}(\mathbf{x}_n) = \mathbf{f}^{l_n\prime}(\mathbf{x}_n) \cdot \boldsymbol{\beta}_0$	Prior guess on trend.
`EstimTrend`	$\widehat{m}_{\text{xLS}}^{l_n}(\mathbf{x}_n) = \mathbf{f}^{l_n\prime}(\mathbf{x}_n) \cdot \widehat{\boldsymbol{\beta}}_{\text{xLS}}$	Only relevant for universal and Bayesian kriging.
`PostTrend`	$\widehat{m}_{\text{Bayes}}^{l_n}(\mathbf{x}_n) = \mathbf{f}^{l_n\prime}(\mathbf{x}_n) \cdot \widehat{\boldsymbol{\beta}}_{\text{Bayes}}$	Only relevant for Bayesian kriging.
`SimTrend`	$m^{l_n,s}(\mathbf{x}_n) = \mathbf{f}^{l_n\prime}(\mathbf{x}_n) \cdot \boldsymbol{\beta}^s$	Simulated trend.
`PriorTrendSD`	$\sigma_0^{l_n}(\mathbf{x}_n) = \sqrt{\mathbf{f}^{l_n\prime}(\mathbf{x}_n)\boldsymbol{\Sigma}_0\,\mathbf{f}^{l_n}(\mathbf{x}_n)}$	Prior guess on uncertainty (SD).
`EstimTrendSD`	$\widehat{\sigma}_{\text{xLS}}^{l_n}(\mathbf{x}_n) = \sqrt{\mathbf{f}^{l_n\prime}(\mathbf{x}_n)\widehat{\boldsymbol{\Sigma}}_{\text{xLS}}\,\mathbf{f}^{l_n}(\mathbf{x}_n)}$	Only relevant for universal and Bayesian kriging.
`PostTrendSD)`	$\widehat{\sigma}_{\text{Bayes}}^{l_n}(\mathbf{x}_n) = \sqrt{\mathbf{f}^{l_n\prime}(\mathbf{x}_n)\widehat{\boldsymbol{\Sigma}}_{\text{Bayes}}\,\mathbf{f}^{l_n}(\mathbf{x}_n)}$	Only relevant for Bayesian kriging.
`TrendSDRed`	$100 \cdot \frac{\sigma_0(\mathbf{x}_n) - \widehat{\sigma}_{\text{Bayes}}(\mathbf{x}_n)}{\widehat{\sigma}_{\text{Bayes}}(\mathbf{x}_n)}$	Only relevant for Bayesian kriging.
`PickSD`	$\sigma_{\text{pick}}^{l_n}(\mathbf{x}_n)$.	User specified well point TVD pick uncertainty (SD). (Usually zero.)
`TotPickSD`	$\sqrt{{\sigma^{l_n}}_{\text{pick}}^2(\mathbf{x}_n) + {\sigma^{l_n}}_{\text{aut.add.}}^2(\mathbf{x}_n)}$	User specified + automatically added TVD pick uncertainty (SD).
`Residual`	$z^{l_n}(\mathbf{x}_n) - \widehat{m}^{l_n}(\mathbf{x}_n)$.	Data − estimated trend.
`ResidualSD`	$\sigma^{l_n}(\mathbf{x}_n) = \sqrt{\mathbf{K}_{nn}}$, see Eq. 18.25.	Specified residual uncertainty (SD).
`TotSD`	$\widehat{\sigma}^{l_n}(\mathbf{x}_n)$, see Eq. 18.24	Residual uncertainty + trend uncertainty.
`Mismatch`	$z^{l_n}(\mathbf{x}_n) - z_{\text{bilinear}}^{l_n}(\mathbf{x}_n)$	$z_{l_n\,\text{bilinear}}(\mathbf{x}_n)$ is the bilinear interpolation of the four closest values in grid.
`h`	$\mathbf{h}_n = \mathbf{H}_{nn}$	Used to detect leverage points.
`t`	$\mathbf{t}_n$, see Eq. 18.27.	Used to detect outliers.
`tStud`	$\mathbf{t}_n^{\text{Student}}$, see Eq. 18.33.	Used to detect outliers when available.

A well point n is classified as a leverage point using the following classification rule:

(18.32) If $\mathbf{h}_n \geq 2 \cdot P/N$ then n is a leverage point. Action: Flag for inspection.

Leverage points are seldom classified as outliers using Eq. 18.27 since the estimate is highly influenced by the well points depth value. An alternative is to use the Studentized residuals (Weisberg, 1985, pp. 113-116):

$$\mathbf{t}_n^{\text{Student}} = \frac{|\mathbf{z}(\mathbf{x}_n) - \widehat{\mathbf{m}}_n|}{\sqrt{\mathbf{K}_{nn}}\sqrt{1-\mathbf{h}_n}}, \tag{18.33}$$

which will identify outliers that are leverage points using the criteria in Eq. 18.28. COHIBA uses $\mathbf{t}_n^{\text{Student}}$ rather than $\mathbf{t}_n$ for classifying outliers when $\mathbf{t}_n^{\text{Student}}$ is available, that is, when $\text{rank}(\mathbf{F}) = P$.

The `wellpoints.csv` file contains one row for each well point. It is the most important source of information for analyzing the consistency between well points and trends. All columns in `wellpoints.csv` are described in Table 7.7 The formulas used for the calculating the values in `wellpoints.csv` are listed in Table 18.1.

18.3.5.3 Checking the trend coefficient estimates

The trend coeficients, $\boldsymbol{\beta}$, are distributed according to the the prior guess, $N(\boldsymbol{\beta}_0, \boldsymbol{\Sigma}_0)$, the least squares estimates (GLS or WLS), $N(\widehat{\boldsymbol{\beta}}_{\text{xLS}}, \widehat{\boldsymbol{\Sigma}}_{\text{xLS}})$, or the posterior estimate, $N(\widehat{\boldsymbol{\beta}}_{\text{Bayes}}, \widehat{\boldsymbol{\Sigma}}_{\text{Bayes}})$. Inter-

esting checks are to compare prior versus xLS and Bayesian estimates for both expectation and standard error. Check if

$$\boldsymbol{\Sigma}_{0,pp} > \widehat{\boldsymbol{\Sigma}}_{\text{xLS},pp}. \tag{18.34}$$

Violation of this means that the prior distribution carry more information than the well points. This is not a healthy sign if there is a lot of data. However, this situation is common when there is little data supporting the estimation of a particular trend coefficient.

The following inequality is always satisfied:

$$\widehat{\boldsymbol{\Sigma}}_{\text{Bayes},pp} \leq \begin{cases} \boldsymbol{\Sigma}_{0,pp} \\ \widehat{\boldsymbol{\Sigma}}_{\text{xLS},pp}. \end{cases} \tag{18.35}$$

Note that $\widehat{\boldsymbol{\Sigma}}_{\text{xLS}}$ fails to exist if the least squares problem has a non-unique solution, that is, $\text{rank}(\mathbf{F}) < P$.

Too many trend coefficients compared to the number of data gives inaccurate estimates. A simple t-statistic is again efficient:

$$t_p = \widehat{\beta}_p / \sqrt{\widehat{\boldsymbol{\Sigma}}_{pp}}. \tag{18.36}$$

Finding $t_p < 2$ is a *possible* sign of a trend not supported by the well data.

The `trend-estimation.csv` has one row for each trend coefficient. The six first columns identify the coefficient (interval, surfaces, number of well points etc.). The next columns are described in Table 18.2.

18.4 Prediction of surfaces using kriging

COHIBA uses kriging for interpolation and extrapolation between well points.

The user choose the kriging method by selecting `universal`, `bayesian`, or `simple` in the element `<kriging-method>` in the COHIBA model file. The predicted depth for all these three choices is given by the so-called kriging predictor:

$$Z^{*l}(\mathbf{x}) = \widehat{m}^l(\mathbf{x}) + \mathbf{k}^{l'}(\mathbf{x})\,\mathbf{K}^{-1}\big(\mathbf{Z} - \widehat{\mathbf{m}}\big), \tag{18.37}$$

where the N covariances

$$\mathbf{k}^{l'}(\mathbf{x}) = \text{Cov}\big\{Z^l(\mathbf{x}), \mathbf{Z}\big\} \tag{18.38}$$

are calculated using Eq. 18.16 and $\widehat{m}^l(\mathbf{x})$ is the estimated depth trend given by Eq. 18.23. So the difference between the three available kriging methods is the choice of trend estimation.

Note that the kriging predictor consists of the estimated trend and the predicted residual:

$$\epsilon^{*l}(\mathbf{x}) = Z^{*l}(\mathbf{x}) - \widehat{m}^l(\mathbf{x}) = \mathbf{k}^{l'}(\mathbf{x})\,\mathbf{K}^{-1}\big(\mathbf{Z} - \widehat{\mathbf{m}}\big). \tag{18.39}$$

Estimating the trend is fast compared to predicting the residual at every grid node. To speed up the calculation of the residual, COHIBA calculates

$$\mathbf{w} = \mathbf{K}^{-1}\big(\mathbf{Z} - \widehat{\mathbf{m}}\big) \tag{18.40}$$

once, and use

$$\epsilon^{*l}(\mathbf{x}) = \mathbf{k}^{l'}(\mathbf{x}) \cdot \mathbf{w} \tag{18.41}$$

for every grid node. This is called the dual kriging system. The most time consuming task is therefore to calculate all the N covariances at every grid node for every surface.

Table 18.2. Formulas used in `trend-estimation.csv` for trend coefficient p. See Table 7.6 for description of all columns in `trend-estimation.csv`.

Column name	Value	Comment
`PriorMean`	$\boldsymbol{\beta}_{0p}$	Prior guess on coefficient. (User specified.)
`EstimMean`	$\widehat{\boldsymbol{\beta}}_{\text{xLS},p}$	Estimated coefficient (least squares). This might fail to exist if there are to few data.
`PostMean`	$\widehat{\boldsymbol{\beta}}_{\text{Bayes},p}$	Posterior mean. This value is calculated if `<kriging-method>` is `bayesian` *or* least squares estimation fails.
`PostMeanUpd`	$\widehat{\boldsymbol{\beta}}_{\text{Bayes},p}$	Posterior mean including zone log information.
`SimMean`	$\boldsymbol{\beta}_p^s$	Simulated value. The value is drawn from estimated or posterior distribution depending on `<kriging-method>`.
`PriorSD`	$\sqrt{\boldsymbol{\Sigma}_{0,pp}}$	Prior SD.
`EstimSD`	$\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{xLS},pp}}$	Estimation SD.
`PostSD`	$\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{Bayes},pp}}$	Posterior SD.
`PostSDUpd`	$\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{Bayes},pp}}$	Posterior SD including zone log information.
`UncertRed`	$100\frac{\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{Bayes},pp}}-\sqrt{\boldsymbol{\Sigma}_{0,pp}}}{\sqrt{\boldsymbol{\Sigma}_{0,pp}}}$	Uncertainty reduction in percent.
`tPrior`	$\boldsymbol{\beta}_{0p}/\sqrt{\boldsymbol{\Sigma}_{0,pp}}$	t-statistic for prior guess.
`tEstim`	$\widehat{\boldsymbol{\beta}}_{\text{xLS},p}/\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{xLS},pp}}$	t-statistic for estimated coefficient.
`tPost`	$\widehat{\boldsymbol{\beta}}_{\text{Bayes},p}/\sqrt{\widehat{\boldsymbol{\Sigma}}_{\text{Bayes},pp}}$	t-statistic for posterior estimate.

The prediction uncertainty (prediction error, kriging error) that correspond to the three different kriging choices can not be formulated as one single formula, although they are closely related. The prediction uncertainties are

(18.42a) $$\sigma^{*l^2}(\mathbf{x}) = \sigma^{l^2}(\mathbf{x}) - \mathbf{k}^{l'}(\mathbf{x})\mathbf{K}^{-1}\mathbf{k}^{l}(\mathbf{x})$$ Simple kriging

(18.42b) $$\begin{aligned}\sigma^{*l^2}(\mathbf{x}) = \sigma^{l^2}(\mathbf{x}) &- \mathbf{k}^{l'}(\mathbf{x})\mathbf{K}^{-1}\mathbf{k}^{l}(\mathbf{x}) \\ &+ \left(\mathbf{f}^{l'}(\mathbf{x}) - \mathbf{k}^{l'}(\mathbf{x})\mathbf{K}^{-1}\mathbf{F}\right)\left(\mathbf{F}'\,\mathbf{K}^{-1}\mathbf{F}\right)^{-1} \\ &\cdot \left(\mathbf{f}^{l'}(\mathbf{x}) - \mathbf{k}^{l'}(\mathbf{x})\mathbf{K}^{-1}\mathbf{F}\right)'\end{aligned}$$ Universal kriging

(18.42c) $$\begin{aligned}\sigma^{*l^2}(\mathbf{x}) = \sigma^{l^2}(\mathbf{x}) &+ \mathbf{f}^{l'}(\mathbf{x})\,\boldsymbol{\Sigma}_0\,\mathbf{f}^{l}(\mathbf{x}) \\ &- \left(\mathbf{k}^{l'}(\mathbf{x}) + \mathbf{f}^{l'}(\mathbf{x})\boldsymbol{\Sigma}_0\mathbf{F}'\right)\left(\mathbf{K} + \mathbf{F}\,\boldsymbol{\Sigma}_0\,\mathbf{F}'\right)^{-1} \\ &\cdot \left(\mathbf{k}^{l'}(\mathbf{x}) + \mathbf{f}^{l'}(\mathbf{x})\boldsymbol{\Sigma}_0\,\mathbf{F}\right)'.\end{aligned}$$ Bayesian kriging

These expressions are more cumbersome to evaluate than the kriging predictor since we can't use the dual kriging system, Eq. 18.41, and must calculate the so-called kriging weights:

(18.43) $$\mathbf{w}^{l'}(\mathbf{x}) = \mathbf{k}^{l'}(\mathbf{x})\mathbf{K}^{-1}.$$

This involves solving an N-dimensional linear equation system for every grid node for every surface. So execution time is longer when choosing to include the prediction uncertainty. This is chosen by `<depth-uncertainty>`.

To speed up calculations COHIBA divides the `<output-grid>` area into smaller rectangles[9]. A

9. COHIBA subdivides into rectangles and uses well points from neighborhoods if the number of well points exceed the

subset of the N well points are selected for each rectangle. The subset contains all well points within the rectangle as well as all well points within a neighborhood of the rectangle defined by the variogram ranges. The number of well points in the subset and therefore the size of $\mathbf{Z}$, $\mathbf{F}$, $\mathbf{k}(\mathbf{x})$ and $\mathbf{K}$, can be dramatically reduced in this way giving short execution time even with thousands of well points. The approach is an adaption of the ideas presented in Vigsnes et al. (2017).

It is easy to see that Bayesian kriging becomes simple kriging if $\boldsymbol{\Sigma}_0 \to \mathbf{0}$ since all expressions involving $\boldsymbol{\Sigma}_0$ vanish. It is also possible to show that Bayesian kriging becomes unversal kriging if $\boldsymbol{\Sigma}_0 \to \boldsymbol{\infty}$ (Omre and Halvorsen, 1989). This limit is not numerically stable so we discourage the specification of large uncertainties in $\boldsymbol{\Sigma}_0$.

18.4.1 Well point pick uncertainty and well path uncertainty

COHIBA gives the possibility of specifying a TVD pick uncertainty for well points. Pick uncertainty is automatically added when COHIBA detects inconsistent well points at the same map location.

The user may add pick uncertainty to well points using ROXAR ATTRIBUTES TEXT files or COHIBA well points file. It is also possible to specify a well path TVD uncertainty using `<wellpoint-TVD-pick-SD-log-name>`. The well point pick uncertainties are assumed to be independent whereas the well path uncertainties are highly correlated along the well path.

The TVD pick uncertainty, ϵ_{pick}, in the well points is introduced as

$$Z^l_{\text{well point}}(\mathbf{x}) = m^l(\mathbf{x}) + \epsilon^l(\mathbf{x}) + \epsilon^l_{\text{pick}}(\mathbf{x}). + \epsilon^l_{\text{w}}(\mathbf{x}). \tag{18.44}$$

The pick uncertainty is assumed to be a Gaussian probability distribution with zero expectation. It is assumed that the pick uncertainty and the depth residuals are uncorrelated.

The equations for the trend coefficient estimates and the kriging equations are unaltered, but the kriging matrix, $\mathbf{K}$, that is, the covariances between well points, is modified:

$$\begin{aligned} \mathbf{K} &= \text{Var}\{\mathbf{Z}_{\text{well point}}\} \\ &= \text{Var}\{\boldsymbol{\epsilon}\} + \text{Var}\{\boldsymbol{\epsilon}_{\text{pick}}\} + \text{Var}\{\boldsymbol{\epsilon}_{\text{w}}\}\,. \end{aligned} \tag{18.45}$$

The TVD pick uncertainty specified in the COHIBA well points file are assumed independent so $\text{Var}\{\boldsymbol{\epsilon}_{\text{pick}}\}$ is diagonal. The well path TVD uncertainties are correlated among well points belonging to well branches from one multilateral well. The well path TVD uncertainty is strongly correlated along the well path so $\text{Var}\{\boldsymbol{\epsilon}_{\text{w}}\}$ will normally be non-diagonal. This correlation can be modified using `<wellpath-TVD-SD-range>`.

The surfaces themselves have no pick uncertainty or well path uncertainty so these uncertainties do not affect $\mathbf{k}^l(\mathbf{x})$ in the kriging predictor since $\mathbf{k}^l(\mathbf{x})$ is the covariances between all the well points and surface l at $\mathbf{x}$.

Non-zero pick uncertainty implies that the kriging predictor is no longer a perfect interpolator. This means that the predicted or simulated surfaces will not honor the well points exactly. Significant well pick uncertainties will also increase the uncertainty in the trend coefficient estimates.

If the pick uncertainties are zero and the well path TVD uncertainty is non-zero and `<allow-wells-to-move>` is `yes` (default `no`), then the surfaces will interpolate the wells exactly at the well points at their modified positions.

---

number set by `<threshold-for-conditioning-in-neighbourhood>`.

18.5 Depth conversion

COHIBA uses vertical depth conversion defined by the basic kinematic relation

$$z = v \cdot \Delta t, \tag{18.46}$$

where v is the *interval velocity* and Δt is the seismic *travel time* in the interval.

The interval velocities are not exactly known so they are modeled as the sum of an interval velocity trend and an interval velocity residual:

$$V_i(\mathbf{x}) = v_i(\mathbf{x}) + \epsilon_{v,i}(\mathbf{x}). \tag{18.47}$$

The interval velocity trend

$$v_i(\mathbf{x}) = \mathbf{f}_i{}'(\mathbf{x}) \cdot \boldsymbol{\beta}_i \tag{18.48}$$

consist of known trend maps $\mathbf{f}_i{}'(\mathbf{x})$ and the trend coefficients $\boldsymbol{\beta}_i$. The trends have exactly the same form as the interval thickness trend in Eq. 18.5. The interval velocity residuals, $\epsilon_{v,i}(\mathbf{x})$, are zero mean Gaussian random fields and they are assumed to be independent of residuals from other intervals. The residual represents local interval velocity variations that the interval velocity trend is unable to capture.

The seismic travel times are modeled as

$$T^l(\mathbf{x}) = t^l(\mathbf{x}) + \epsilon_t^l(\mathbf{x}), \tag{18.49}$$

where $t^l(\mathbf{x})$ is the interpreted travel times to surface l and the travel time residual $\epsilon_t^l(\mathbf{x})$ is a zero mean Gaussian random field that accounts for measurement uncertainty and interpretation uncertainty. The travel time residuals for different surfaces are assumed independent[10].

By inserting the interval velocity model and the travel time model into the basic kinematic relation Eq. 18.46, we get

$$\Delta Z_i(\mathbf{x}) = V_i(\mathbf{x})\, \Delta T_i(\mathbf{x}), \tag{18.50}$$

where $\Delta T_i(\mathbf{x})$ is the difference between $T^l(\mathbf{x})$ at the base and at the top of interval i.

According to Eq. 18.1 the depth to a surface l is obtained by adding (or subtracting) intervals:

$$Z^l(\mathbf{x}) = \sum_{i \in \mathcal{I}^l} \Delta Z_i(\mathbf{x}), \tag{18.51}$$

where $\mathcal{I}^l$ is the set of intervals that contributes to surface l. This general notation is inconvenient for explaining depth conversion of a set of surfaces. Therefore, the notation is simplified by assuming a set of stacked intervals that can be ordered by the surfaces between them. This makes it possible to replace the sum over all contributing intervals by an ordinary sum over surface and interval order:[11]

$$Z^l(\mathbf{x}) = \sum_{i=1}^{l} \Delta Z_i(\mathbf{x}). \tag{18.52}$$

10. The assumption of independence is unreasonable when two reflectors are close. It is therefore possible to relax this assumption. See `<correlate-close-reflectors>` for details.
11. Note that COHIBA always uses the general form Eq. 18.51 so Eq. 18.52 is only used to simplify the notation when explaining the details of the uncertainty models used for travel times and interval velocities.

This sum can be expanded and reordered in the following way:

$$
\begin{aligned}
Z^l(\mathbf{x}) &= \sum_{i=1}^{l} V_i(\mathbf{x})\,\Delta T_i(\mathbf{x}) \\
&= \sum_{i=1}^{l} \Big(v_i(\mathbf{x}) + \epsilon_{v,i}(\mathbf{x})\Big)\,\Big(t^i(\mathbf{x}) + \epsilon_t^i(\mathbf{x}) - t^{i-1}(\mathbf{x}) - \epsilon_t^{i-1}(\mathbf{x})\Big), \\
&= \sum_{i=1}^{l} v_i(\mathbf{x})\,\Big(t^i(\mathbf{x}) - t^{i-1}(\mathbf{x})\Big) + \epsilon_{v,i}(\mathbf{x})\,\Big(t^i(\mathbf{x}) - t^{i-1}(\mathbf{x})\Big) \\
&\quad + v_i(\mathbf{x})\,\Big(\epsilon_t^i(\mathbf{x}) - \epsilon_t^{i-1}(\mathbf{x})\Big) + \epsilon_{v,i}(\mathbf{x})\,\Big(\epsilon_t^i(\mathbf{x}) - \epsilon_t^{i-1}(\mathbf{x})\Big) \\
&= \sum_{i=1}^{l} v_i(\mathbf{x})\,\Delta t_i(\mathbf{x}) + \epsilon_{v,i}(\mathbf{x})\,\Delta t_i(\mathbf{x}) + v_i(\mathbf{x})\,\Big(\epsilon_t^i(\mathbf{x}) - \epsilon_t^{i-1}(\mathbf{x})\Big) + \mathcal{O}(\epsilon^2),
\end{aligned}
\tag{18.53}
$$

where $\Delta t_i(\mathbf{x}) = t^i(\mathbf{x}) - t^{i-1}(\mathbf{x})$ is the interval travel time. This can be written as

$$
Z^l(\mathbf{x}) = \sum_{i=1}^{l}\Big(\Delta m_i(\mathbf{x}) + \Delta\epsilon_i(\mathbf{x})\Big) + \epsilon_z^l(\mathbf{x}) + \sum_{i=1}^{l-1}\Delta\epsilon_t^i(\mathbf{x}) + \mathcal{O}(\epsilon^2),
\tag{18.54}
$$

where

$$
\Delta m_i(\mathbf{x}) = v_i(\mathbf{x})\,\Delta t_i(\mathbf{x}) \qquad \text{Interval thickness trend.}
\tag{18.55a}
$$

$$
= \big(\mathbf{f}_i{}'(\mathbf{x}) \cdot \boldsymbol{\beta}_i\big)\,\Delta t_i(\mathbf{x}) \qquad \text{(See Eq. 18.48.)}
$$

$$
\Delta\epsilon_i(\mathbf{x}) = \epsilon_{v,i}(\mathbf{x})\,\Delta t_i(\mathbf{x}) \qquad \text{Interval thickness residual.}
\tag{18.55b}
$$

$$
\epsilon_z^l(\mathbf{x}) = \epsilon_t^l(\mathbf{x})\,v_l(\mathbf{x}) \qquad \text{Depth residual.}
\tag{18.55c}
$$

$$
\Delta\epsilon_t^i(\mathbf{x}) = \epsilon_t^i(\mathbf{x})\,\Big(v_i(\mathbf{x}) - v_{i+1}(\mathbf{x})\Big) \qquad \text{Velocity contrast residual.}
\tag{18.55d}
$$

$$
\mathcal{O}(\epsilon^2) = \sum_{i=1}^{l} \epsilon_{v,i}(\mathbf{x})\,\Big(\epsilon_t^i(\mathbf{x}) - \epsilon_t^{i-1}(\mathbf{x})\Big).
\tag{18.55e}
$$

These five contributions deserves some explanations:

$\Delta m_i(\mathbf{x})$ is the *interval thickness trend* formed by the interval velocity trend multiplied by the interpreted interval travel time. This thickness trend enters the surface models similar to interval thickness trend in Eq. 18.2.

$\Delta\epsilon_i(\mathbf{x})$ is the *interval thickness residual* caused by the the *interval velocity residual*, $\epsilon_{v,i}(\mathbf{x})$, tmultiplied by the interval travel time, $\Delta t_i(\mathbf{x})$. This residual plays the exact same role as the interval thickness residual in Eq. 18.2.

$\epsilon_z^l(\mathbf{x})$ is a *depth residual* at surface l caused by the travel time uncertainty at surface l multiplied by the interval velocity in the interval above surface l. This residual is unique for seismic reflectors and have no parallel when considering interval thickness models.

$\Delta\epsilon_t^i(\mathbf{x})$ is a *velocity contrast residual* caused by the travel time uncertainties at surfaces i. The velocity contrast residual adds uncertainty to all surfaces below surface i. The velocity contrast residual is proportional to the interval velocity *contrast*, $v_i(\mathbf{x}) - v_{i+1}(\mathbf{x})$, at surface i and the travel time residual, $\epsilon_t^i(\mathbf{x})$, at surface i.

This residual is usually small compared to the depth residual, $\epsilon_z^l(\mathbf{x})$, since the interval velocity contrasts are small compared to the interval velocities[12].

12. The predecessor of COHIBA called HORIZON ignored this residual since it is dominated by the depth residual and the interval thickness residuals.

$\mathcal{O}(\epsilon^2)$ is the sum of all products of two residuals. This second order residual is ignored in the calculations since it would destroy the Gaussianity and thereby make it impossible to use the efficient methods used by COHIBA for prediction and conditional simulation. Ignoring $\mathcal{O}(\epsilon^2)$ is a good approximation since the product of two residuals will be small compared to other residuals given the reasonable assumptions that $t(\mathbf{x}) \gg \mathrm{Var}\{\epsilon_t^l(\mathbf{x})\}^{1/2}$ and $v_i(\mathbf{x}) \gg \mathrm{Var}\{\epsilon_{v,i}(\mathbf{x})\}^{1/2}$.

The principal difference between Eq. 18.1 for interval thickness models and Eq. 18.54 for interval velocity models are the additional residuals $\epsilon_z^l(\mathbf{x})$ and $\Delta\epsilon_t^i(\mathbf{x})$. These will enter the calculation of covariances so that for instance Eq. 18.16 must include contributions from these additional residuals.

COHIBA allows any combination of thickness interval models and velocity interval models. This may become quite complex when combined with the possibility to use multiple models (Section 11). However, COHIBA keeps track of the bookkeeping so this is not a problem.

18.6 Gridding effects

COHIBA represents surfaces and trend maps on regular grids where the grid nodes represent the accurate value at that point. Well data however, are located at arbitrary locations and these are rarely at the grid nodes. COHIBA must therefor interpolate grid values at well data locations using bilinear interpolation. This introduces a gridding error.

Kriging is an exact interpolation technique and will always honor the well points provided that no well point TVD pick uncertainty has been introduced. However, COHIBA represent surfaces by regular grids so kriging is only performed at grid nodes. This implies that comparing surfaces to well points will always give a small gridding mismatch unless the well point is located exactly at a grid node. This is illustrated in Figure 18.1. The gridding mismatch is reported in the `wellpoints.csv` file as `Mismatch`. A similar problem will occur along well paths.

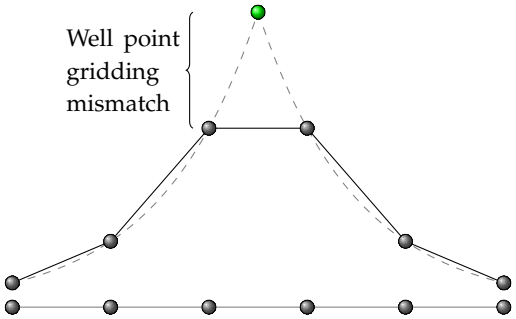


Figure 18.1. Vertical cross section of a surface. Grid nodes are marked as grey dots. A single well point is marked as a green dot. The dashed line is the kriging predictor and the solid line is the bilinear interpolation between the grid nodes. The gridding error is the vertical difference between the dashed line (kriging) and the solid line segments (bilinear interpolation). The gridding mismatch at a well point is the vertical difference between the green dot and the solid line connecting the two nearest grid nodes.

The gridding mismatch is by default removed in the post processing. The four grid nodes closest to well points and zonation points along the well paths are modified so that bilinear interpolation of these nodes will give perfect match at all the well points and zonation points. All the affected grid nodes are adjusted so that the sum of all adjustments is as small as possible. There are rare situations where this approach will fail such as multiple well points within a single cell. The adjustment of grid nodes around well points can be turned off by `<make-surfaces-interpolate-well-points>` and the adjustment of grid nodes along well paths can be turned off by `<allow-small-surface-adjustment-at-zonation-points>`.

18.6.1 Bilinear interpolation

Bilinear interpolation provides a simple and fast way of interpolating four grid node values at any point inside a rectangular cell and is therefore widely used. COHIBA uses bilinear interpolation to interpolate trend values at well points and zonation points.

Consider a rectangle defined by the four corners (x_1, y_1), (x_1, y_2), (x_2, y_1), and (x_2, y_2) and assume that a function $f(x, y)$ is known at these four corners. Bilinear interpolation provides an approximation to $f(x, y)$ at any arbitrary location in that rectangle and is defined as

$$f_{BL}(x,y) = c_{11}\, f(x_1,y_1) + c_{21}\, f(x_2,y_1) + c_{12}\, f(x_1,y_2) + c_{22}\, f(x_2,y_2), \quad \text{for} \quad x_1 \geq x \geq x_2, \text{ and } y_1 \geq y \geq y_2, \tag{18.56}$$

where

$$c_{11} = \frac{(x_2 - x)(y_2 - y)}{\Delta_x\, \Delta_y} \qquad c_{21} = \frac{(x - x_1)(y_2 - y)}{\Delta_x\, \Delta_y}$$

$$c_{12} = \frac{(x_2 - x)(y - y_1)}{\Delta_x\, \Delta_y} \qquad c_{22} = \frac{(x - x_1)(y - y_1)}{\Delta_x\, \Delta_y}$$

$$\Delta_x = x_2 - x_1 \qquad \Delta_y = y_2 - y_1.$$

Note that the weights sum to one: $c_{11} + c_{21} + c_{12} + c_{22} = 1$. The weights, c_{ij}, are proportional to the area of the rectangle opposite to the corner point. This is illustrated in Figure 18.2.

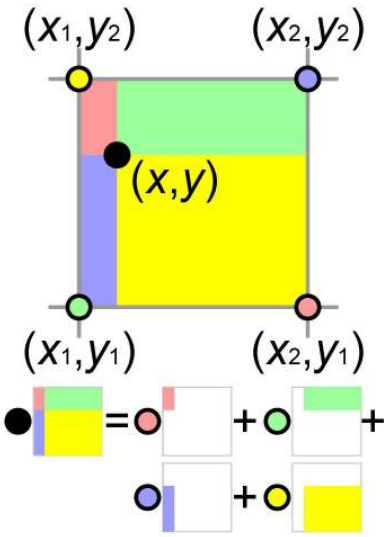
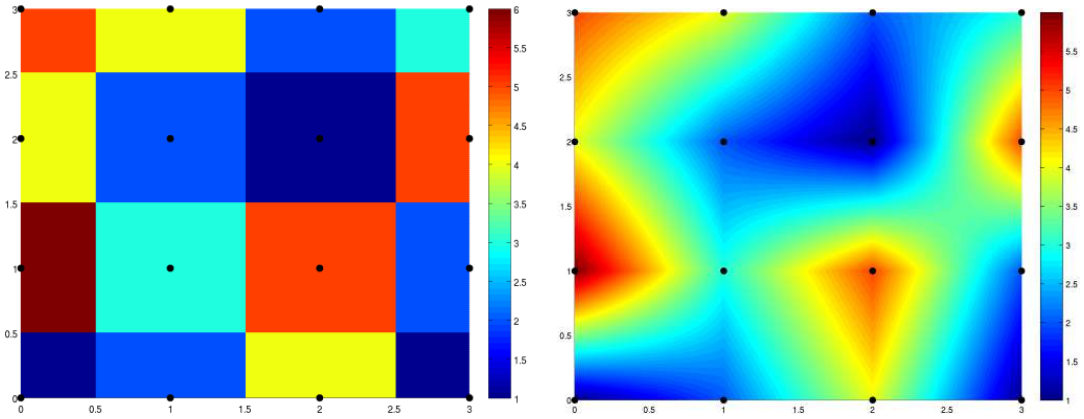


Figure 18.2. Illustration of bilinear interpolation. The value at the black dot, (x, y), is the weighted average of the values at the colored dots, (x_i, y_j); $i, j = 1, 2$, where the weights are proportional to the area of the rectangle of the same color. The illustration is taken from Wikipedia.

The bilinear interpolation surface is continuous but the derivatives are discontinuous perpendicular to cell edges. The bilinear interpolation surface follow straight lines along the x- and y-direction of the grid. Following any direction not parallel with the x- or y-direction gives a second order polynomial. Bilinear interpolation is illustrated in Figure 18.3.



(a) Nearest neighbor interpolation (b) Bilinear interpolation

Figure 18.3. The images show how interpolation is applied to a series of data points (black dots) in the box $[0, 3] \times [0, 3]$. Pictures are taken from www.codecogs.com.

The integral of the bilinear interpolation in the rectangle is

$$\int_{x_1}^{x_2} \int_{y_1}^{y_2} f_{BL}(x, y)\, \mathrm{d}x\, \mathrm{d}y = \Delta_x\, \Delta_y\, \frac{f(x_1, y_1) + f(x_2, y_1) + f(x_1, y_2) + f(x_2, y_2)}{4}. \tag{18.57}$$

This can be used for finding volume of the rectangle between two surfaces. The situation is slightly more complicated for the volume between two crossing surfaces since only the positive part contribute. This is also possible to calculate analytically and is used when `<volume-calculation-method>` is `bilinear`.

19 Stochastic simulation

Stochastic simulation is chosen by selecting `simulation` in `<mode>`. Stochastic simulation generates a set of realizations by randomly drawing all the trend coefficients and all the Gaussian residuals. The trend coefficients are drawn from the posterior distributions and the Gaussian residuals are drawn conditioned on the well points and well paths. The number of realizations can be specified by `<number-of-realizations>`.

COHIBA uses a simulation algorithm for conditional simulation that is based on (Journel and Huijbregts, 1978, pp. 495–498)

$$Z^{l^s}(\mathbf{x}) = m^{l^s}(\mathbf{x}) + \epsilon^{l^s}(\mathbf{x}) + \mathbf{k}^l(\mathbf{x})\mathbf{K}^{-1}\left(\mathbf{Z} - \mathbf{m}^s - \boldsymbol{\epsilon}^s\right), \tag{19.1}$$

where superscript s indicates simulated (randomly drawn) and where

$$m^{l^s}(\mathbf{x}) = \mathbf{f}^{l'}(\mathbf{x}) \cdot \boldsymbol{\beta}^s \tag{19.2a}$$

$$\mathbf{m}^s = \mathbf{F}\,\boldsymbol{\beta}^s \tag{19.2b}$$

$$\epsilon^{l^s}(\mathbf{x}) = \sum_{i \in \mathcal{I}^l} \Delta\epsilon_i^s(\mathbf{x}). \tag{19.2c}$$

Eq. 19.1 should be compared to the kriging predictor Eq. 18.37. The differences are that a simulated trend is used instead of an estimated trend, and a simulated residual, $\epsilon^{l^s}(\mathbf{x})$, is added to the trend. Note that the marginal expectation and SD of $Z^{l^s}(\mathbf{x})$ are $Z^{*l}(\mathbf{x})$ and $\sigma^{*l}(\mathbf{x})$. It is possible to show that $Z^{l^s}(\mathbf{x})$ has the correct conditional spatial covariance.

Expression Eq. 19.1 gives the following simulation algorithm:

1. Estimate the trend coefficients in the linear trends. The estimation method will depend on the chosen `<kriging-method>`.
2. Randomly draw the trend coefficients from the multi-normal distribution

   $$\boldsymbol{\beta}^s \sim N_P\left(\widehat{\boldsymbol{\beta}}, \widehat{\boldsymbol{\Sigma}}\right),$$

   where $\widehat{\boldsymbol{\beta}}$ and $\widehat{\boldsymbol{\Sigma}}$ are the estimated expectations and the estimation variances. Use the drawn coefficients to form the *simulated trends* (Eq. 19.2a).
3. Randomly draw all the interval residuals, $\Delta\epsilon_i^s(\mathbf{x})$, using an fast Fourier transform (FFT) algorithm. See Dietrich and Newsam (1993), Wood and Chan (1994) and Abrahamsen et al. (2018). These simulated interval residuals are added to form the simulated surface residuals according to Eq. 19.2c.
4. The *simulated residuals* are added to the simulated trends to obtain the *unconditionally simulated surfaces* $m^{l^s}(\mathbf{x}) + \epsilon^{l^s}(\mathbf{x})$.
5. Extract the simulated trends and residuals at the well points to form the vectors $\mathbf{m}^s$ and $\boldsymbol{\epsilon}^s$. Subtract these simulated trend values from the well point depths, $\mathbf{Z}$, and add the simulated residuals to obtain the vector $\mathbf{Z} - \mathbf{m}^s + \boldsymbol{\epsilon}^s$.
6. The final step is to condition the unconditionally simulated surfaces to the well points by performing simple kriging. This is done by solving $\mathbf{k}^l(\mathbf{x})\mathbf{K}^{-1}\left(\mathbf{Z} - \mathbf{m}^s + \boldsymbol{\epsilon}^s\right)$ and adding the result to the unconditionally simulated surfaces.

The first and the last step are by far the most time consuming, and they are identical to the operations performed when doing deterministic modeling using the kriging predictor, Eq. 18.37. Therefore, the CPU time for prediction and stochastic simulation is comparable.

The stochastic simulation algorithm is very accurate and will ensure almost perfect agreement with the specified model (trends, variograms, uncertainties, dependencies, pick uncertainties, etc.) and the supplied data. The expectation of Eq. 19.1 gives the kriging predictor Eq. 18.37.

19.1 Unconditional simulation

The simulated residuals, $\Delta\epsilon_i^s(\mathbf{x})$, are realizations from *Gaussian random fields*. These are drawn using an FFT simulation algorithm. See Ripley (1987), Dietrich and Newsam (1993), Wood and Chan (1994) and Abrahamsen et al. (2018). The FFT algorithm reproduces any variogram almost perfect. It is superior to any other algorithm for stochastic simulation of unconditional Gaussian random fields including the two most common approaches: Sequential Gaussian simulation (SGS) and turning bands simulation. Section 20 contains examples of simulated residuals.

19.2 Depth conversion

The situation is in principal identical when intervals are formed using depth conversion. However, the details are slightly more complex: Interval velocity residuals and travel time residuals are drawn independently and the interval thickness residuals, depth residuals and velocity contrast residuals are formed according to Eq. 18.55b, Eq. 18.55c and Eq. 18.55d respectively. These residuals are used to obtain the simulated surfaces according to Eq. 18.54. Note that the second order residual, Eq. 18.55e, is dropped to guarantee perfect data conditioning and to ensure consistency with prediction of deterministic surfaces. The simulated travel time maps are written to file (Table 7.2). The simulated travel time residual can be obtained by subtracting the specified `<travel-time>` surface. The velocity residual is not written to file.

19.3 Stochastic simulation versus prediction

19.3.1 Monte Carlo uncertainty

The average of a large number of simulated realizations will approximate the kriging predictor. Also the (pointwise) empirical SD of a large set of simulated realizations will approximate the prediction uncertainty. Note however that the Monte Carlo uncertainty converges slowly. The average of N samples from a normal distribution is distributed as

$$\bar{x} \sim N\big(\mu, \sigma/\sqrt{N}\big), \quad \text{where} \quad x \sim N(\mu, \sigma).$$

So the average of 100 simulated realizations has a SD that is 10 % of the SD of the set of realizations. So the average map of 100 simulated surface realizations can easily differ from the predicted surface by 20 % of the prediction uncertainty. Increasing the number of realizations to 1000 helps but the SD of the average is still 3.2 % of the prediction uncertainty. Again, differences of 6 % of the prediction uncertainty is not unlikely.

The situation is slightly more complicated for the uncertainty of the empirical SD. The empirical SD has a χ-distribution that is skewed and the estimate is biased. The bias is insignificant for large samples (> 100) and it will drown in the estimation uncertainty even for small samples sizes. From Wikipedia on SD:

> To show how a larger sample will increase the confidence interval, consider the following examples: For a small population of $N = 2$, the 95 % confidence interval of SD is from 0.45 SD to 31.9 SD. In other words, the SD of the distribution in 95 % of the cases can be larger by a factor of 31 or smaller by a factor of 2. For a larger population of $N = 10$, the confidence interval is 0.69 SD to 1.83 SD. So even with a sample population of 10, the actual SD can still be almost a factor 2 higher than the sampled SD. For a sam-

ple population $N = 100$, this is down to 0.88 SD to 1.16 SD. To be more certain that the sampled SD is close to the actual SD we need to sample a large number of points.

So expect to find a lot of noise in the empirical SD maps. Again the noise drops at approximately $1/\sqrt{N}$.

19.3.2 Systematic differences

There are also a few approximations that might introduce differences between prediction and stochastic simulation.

1. The $\boldsymbol{\beta}^s$ is drawn independently of $R^{ls}(\mathbf{x})$ and this is not strictly correct. The (posterior) distribution of $\boldsymbol{\beta}^s$ depend on the residuals since observations include the residuals.
2. Predictions conditioned on well paths introduces *surface help points*. These surface help points replaces the constraints imposed by the well path. This replacement is an approximation that might introduce bias. Stochastic simulation does not require any surface help points and a set of simulated realizations will have the correct non-Gaussian distribution. See Section 21.1 for some detail on conditioning on well paths and Abrahamsen and Benth (2001) for the technical details.
3. Rejection sampling will affect stochastic simulation and not prediction. See Section 19.4.

19.4 Rejection sampling

Rejection sampling is a stochastic simulation technique tha can be used in simulation <mode> to draw realizations that are in agreement with some acceptance criteria.

Rejection sampling is a way of drawing perfect samples from a prior probability distribution conditioned on data such as well points or other constraints. The simple idea is to draw a random sample from the prior probability distribution and accept it as a realization if the sample is consistent with all the data. The set of realizations will be a perfect representation of the posterior distribution, that is the prior distribution constrained by the data.

Unfortunately, rejection sampling will often fail because the acceptance rate is too small. Just matching a single well point by coincidence is extremely unlikely and only possible because the computer has a finite numerical resolution. Therefore, conditioning to well points is done by calculating the posterior probability distribution using kriging and drawing from this probability distribution instead. Handling surface constraints imposed by the well paths is also handled in this way.

Rejection sampling is used when the conditioning criteria are highly non-linear and no approximate analytic solution exist. COHIBA use rejection sampling to ensure that the following possible acceptance criteria are fulfilled: <spill-point-above>, <spill-point-below>, <spill-point-at>, and <trap-larger-than>. All of these criteria are related to spill point calculations triggered by the element <spill-point>. Note that it is possible to impose several acceptance criteria on multiple surfaces.

There is a risk of getting extremely high rejection (low acceptance) rates, and therefore extremely slow generation of accepted realizations. This is in particular true if multiple acceptance criteria are imposed. COHIBA will abort execution during the initial realizations if the rejection rate is higher than <max-rejection-rate>. The default maximum rejection rate is 90 %. The estimation of the rejection rate is performed during the first 10 % of the specified <number-of-realizations>. The estimation is performed during the 10 first simulations if the number of realizations is less than 100. If the estimated rejection rate is so high that it is improbable (less than 5 %) that it is less than the maximum rejection rate, then the simulation is aborted during these initial simulations. COHIBA will provide an estimate of the true rejection rate if the simulations are aborted.

If COHIBA estimates a rejection rate higher than <max-rejection-rate> the user must make changes to obtain the required <number-of-realizations>. One possibility is to increase the <max-rejection-rate> and be patient. The alternative is to relax the <acceptance-criteria> or modify the stochastic model for the surfaces so that acceptance criteria are less challenging.

The average maps (see Section 7.1) will normally be similar to the predicted maps if the number of realizations is large[1]. This is not so if an <acceptance-criteria> apply, unless the rejection rate is zero. It is recommended to compare the predicted depth to the average map from a stochastic simulation. A difference shows that the acceptance criteria have a noticeable impact on the surface depths. It can also be interesting to compare the prediction uncertainty map to the empirical uncertainty (SD) maps obtained from all the realizations. The empirical uncertainty maps are usually quite noisy but it is usually possible to see reduction in uncertainty due to the acceptance criteria.

For an example illustrating rejection sampling see Section 10.

1. See Section 19.3 for a discussion on the difference between average maps and predicted maps.

20 Variogram examples

This section contains some realizations made by stochastic simulation to illustrate different variograms specified by <type> in <variogram>. All realizations have the same expectation and SD. The <range> is one fifth of the length of the sides. All realizations are generated using the same random <seed> so that many features appear similar.

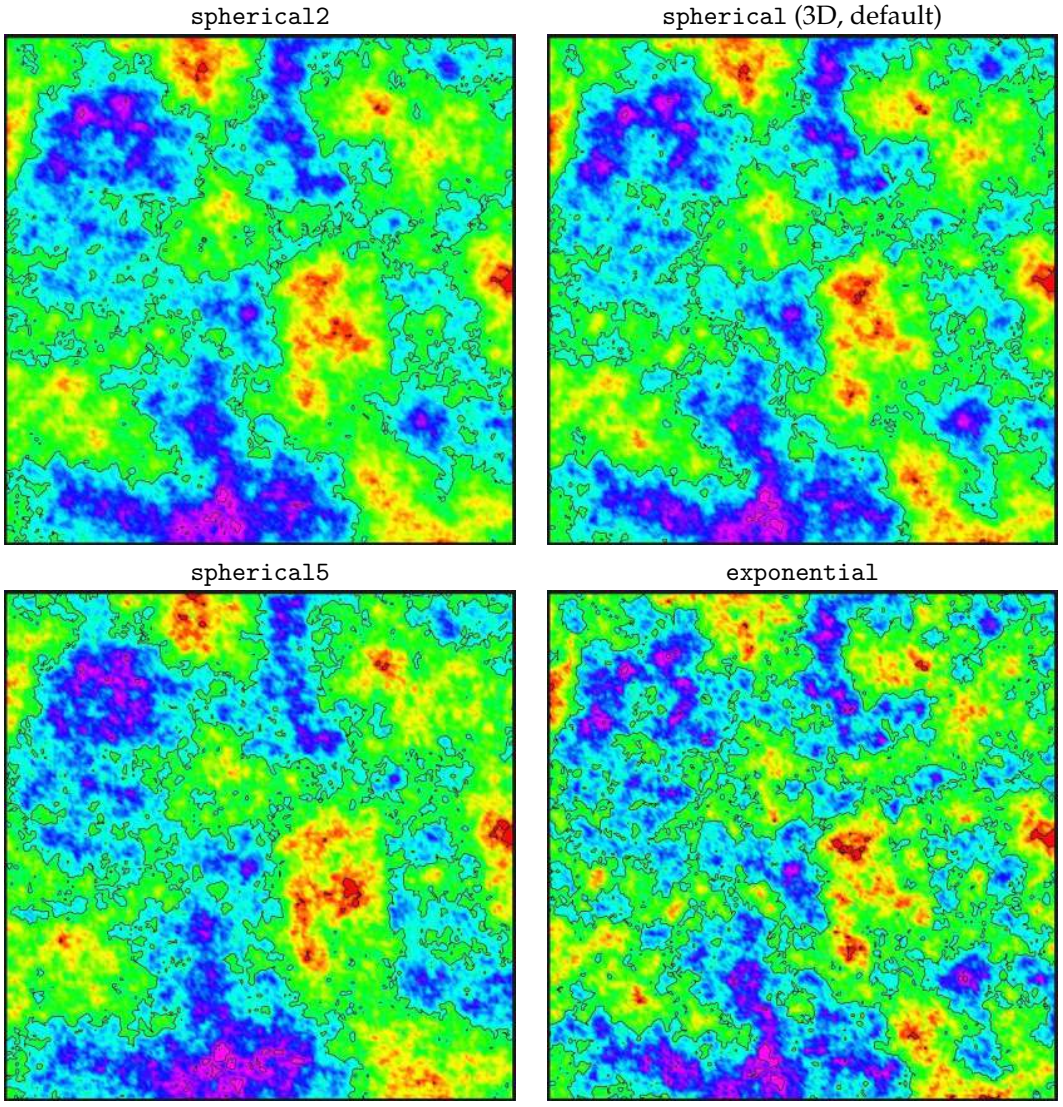


Figure 20.1. Spherical and exponential variograms.

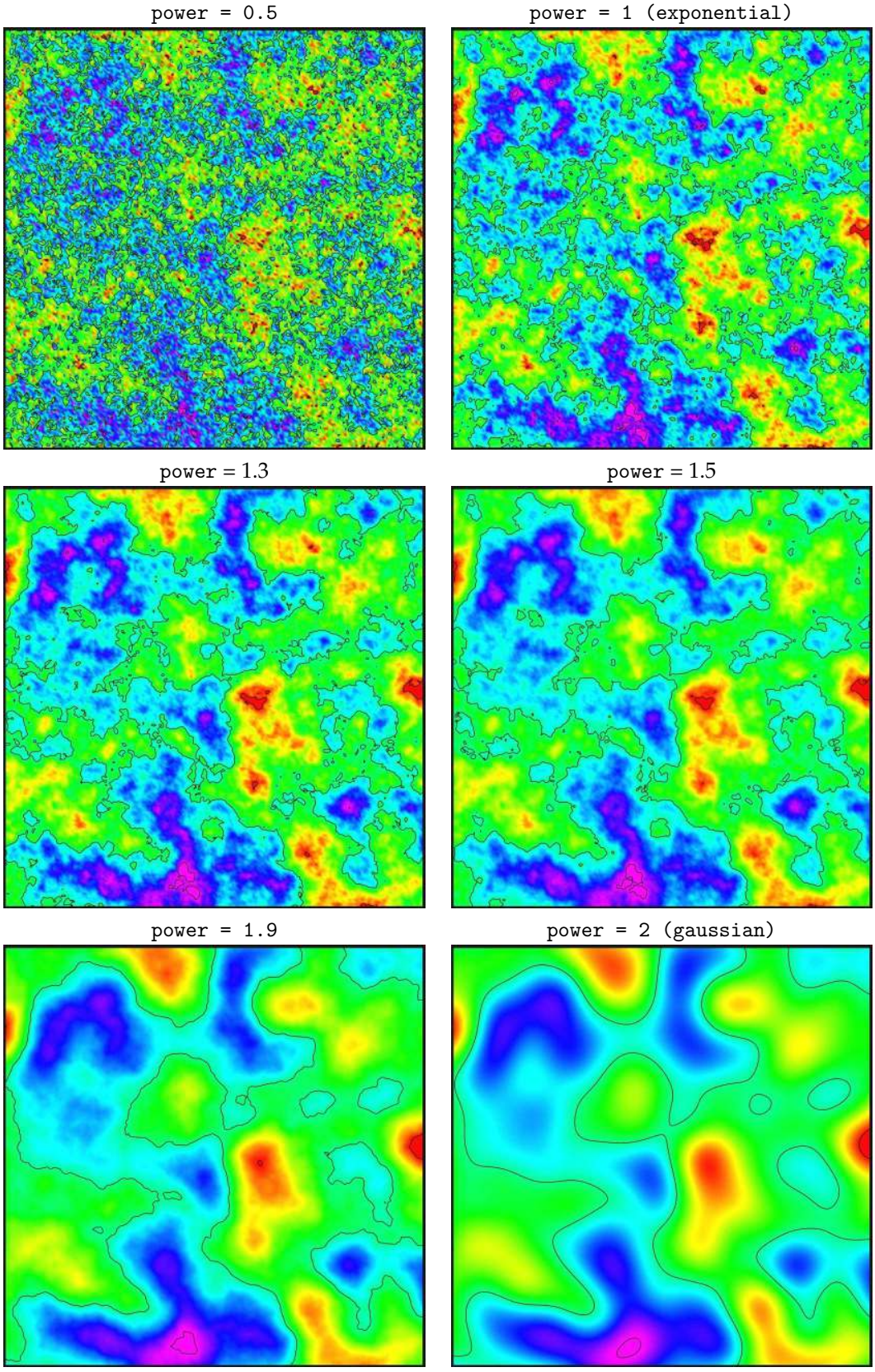


Figure 20.2. General exponential variograms for different <power>. Note that the exponential variogram is identical to power = 1 and the gaussian variogram is identical to power = 2.

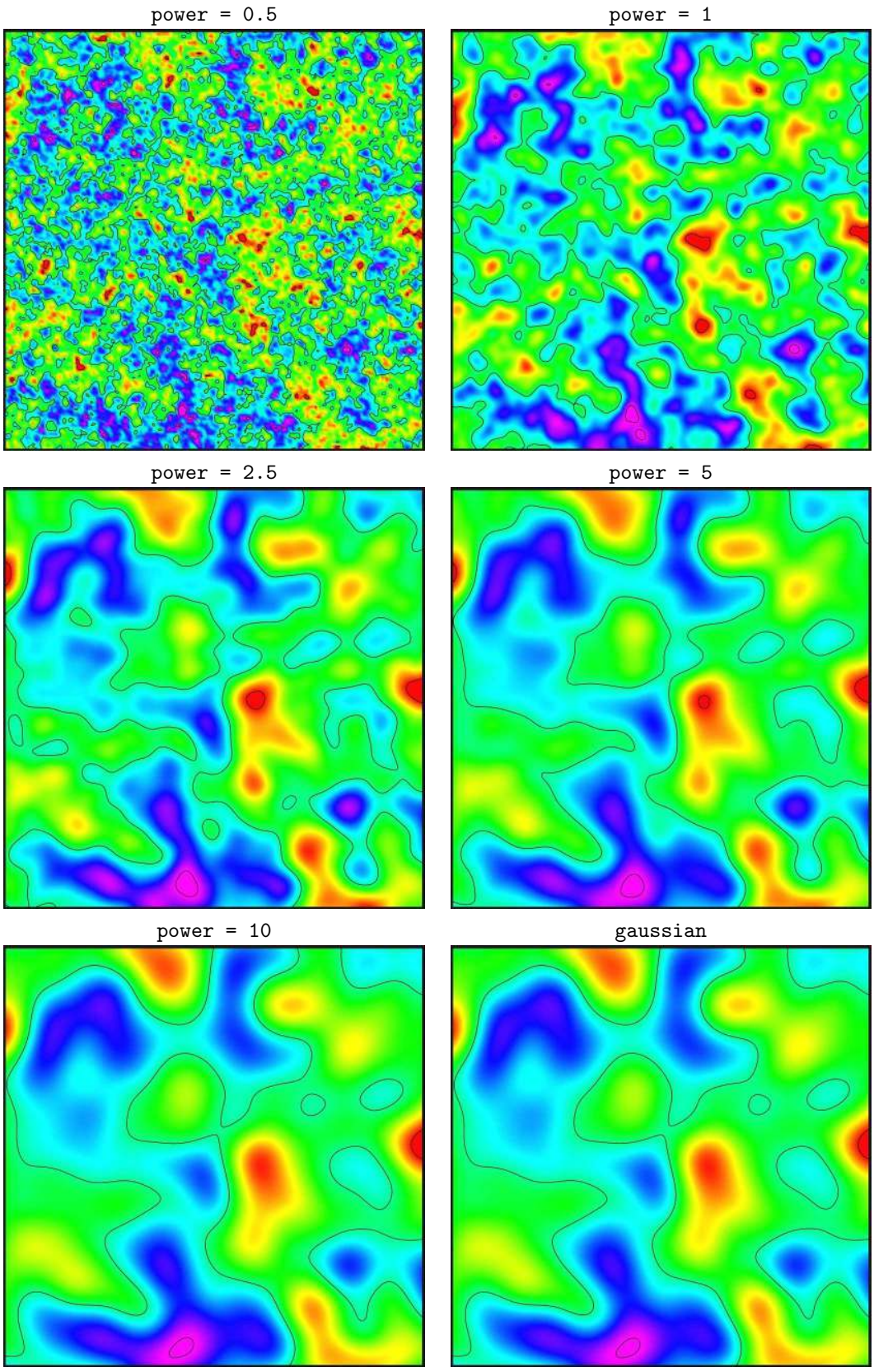


Figure 20.3. Rational quadratic variograms. Note that these variograms approach the `gaussian` variogram when `power` becomes large. This variogram is not numerically stable for large values of `power` so we recommend to use the `gaussian` variogram instead for `power` > 10.

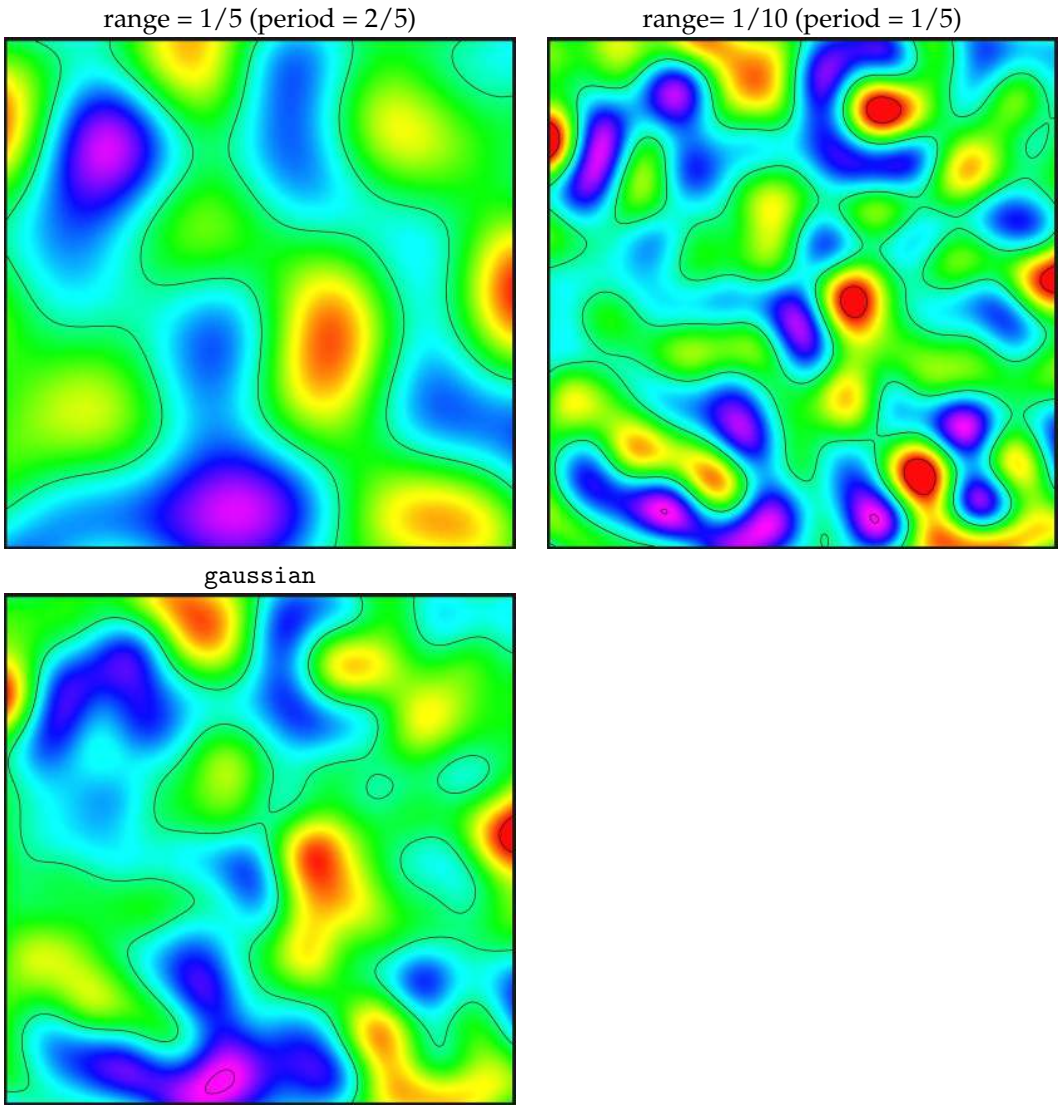


Figure 20.4. Damped sine variograms. The damped sine variogram gives a smooth regular cyclic appearance. The full period is twice the specified range. The `gaussian` variogram is added for comparison.

21 Conditioning to zone logs

The challenge of using the full well path is that these impose a soft restriction on the surfaces. The zone logs tells that surfaces are above or below the well path at any particular location. This boils down to conditioning surfaces to inequality constraints. Standard kriging techniques does not include the possibility to condition on constraints (or inequalities).

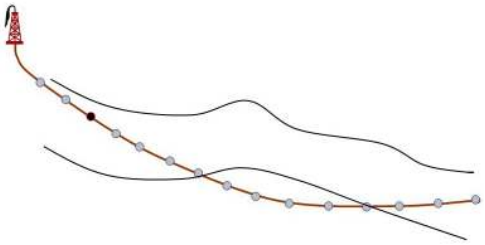
The approach used by COHIBA is a development of the ideas in Abrahamsen and Benth (2001). The article shows how to use inequality constraints in a kriging setting. Here we outline the basic ideas and the modifications necessary to make this work for a multi layered model.

Using zone log information is activated by choosing `yes` in the `<condition-to-well-paths>` element. This is the default.

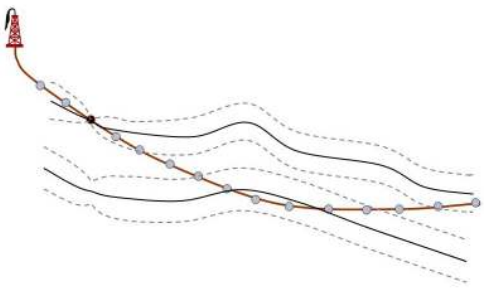
21.1 Procedure for conditioning to zone logs

The approach can be looked upon as a sequence of steps:

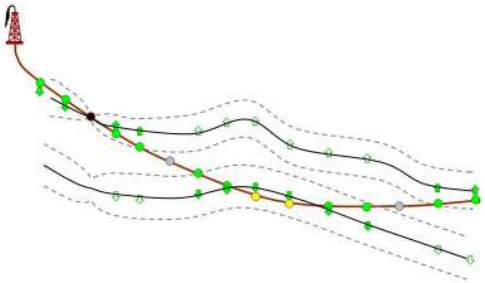
1. Select **zonation points** (gray discs) along the well path at a resolution approximately twice the grid resolution. (Typically at 100 meter intervals.) The well path is shown as a red line. The well point is shown as a black disc and the **zonation points** are the gray discs. The two black lines are cross sections of the surfaces above and below the main part of the well path.



2. Along the well paths, calculate the deterministic surface (solid lines), and the prediction uncertainty (dashed lines) given the well points. This is quite efficient since only a fraction of the grid nodes are close to the well paths.



3. Select the zonation points that are in conflict with the zone log, that is, they are on the wrong side of the deterministic surface. Two yellow zonation points are on the wrong side.

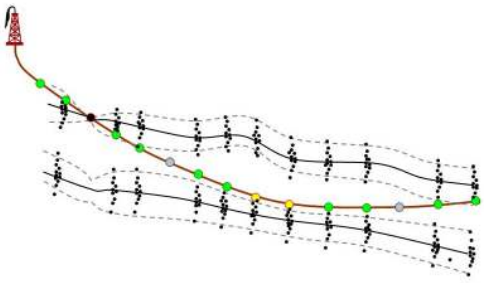


Also select the zonation points that are on the correct side of the deterministic surface but are *close* to the deterministic surface. By close is meant less than 2.0 prediction uncertainty. This thresholds can be modified using `<t-value-first-help-point>`. These additional selected zonation points are marked green in the figure. More zonation points are selected for stochastic simulation than deterministic surfaces because there is a higher risk of ending up on the wrong side for stochastic simulation.

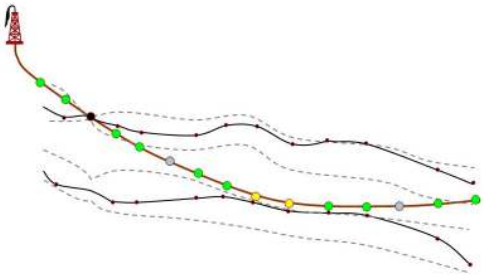
The zonation points that are in conflict with the zone log and the zonation points that are *close* are called the **selected zonation points**. The **surface constraints** that must be fulfilled at the selected zonation points are indicated by the green arrows.

Surface constraints usually come in pairs — one constraint on the surface above and one constraint on the surface below. This is to ensure that the primary surface constraint does not cause a violation of the other. These additional surface constraints are indicated by light green arrows. A single constraint is used when there is no risk of violating the other constraint.

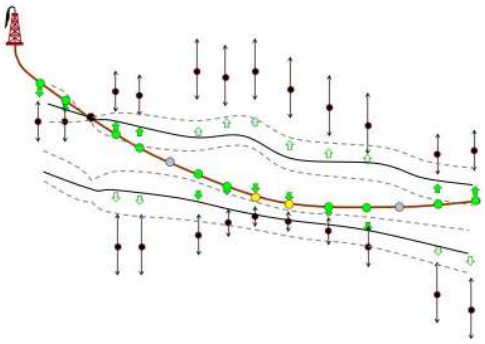
4. Run the Data Augmentation Algorithm to obtain 256 simulated surface realizations at the surface constraints. These 256 realizations represent the non-Gaussian probability distribution for depth at the selected zonation points. The 256 realizations will all be in agreement with the well points and the surface constraints at the selected zonation points. The small black dots in the figure illustrates the spread of the 256 realizations at each surface constraint. The Data Augmentation Algorithm is a stochastic simulation technique for evaluating numerical integrals. The method was introduced by Tanner and Wong (1987).



5. **For stochastic simulation:** Select randomly one of the 256 realizations. This set of simulated depth values of the surfaces are called **surface target points**. The simulated trend use the coefficients belonging to the selected realization. The surface target points are seen as small points along the surfaces. The selected surface target points are included as additional well points when conditioning the simulated realization. So the stochastic simulation is essentially made exactly as usual except that the additional surface target points make the kriging system (a lot) larger.



6. **For deterministic surfaces:** Calculate the expectation and the covariances of the 256 simulated realizations at the surface constraints. The expectations at the surface constraints are called **surface target points** since this is where we want the predicted surfaces to go. These surface target points and the covariances are used to calculate a set of **surface help points** that replace the surface constraints. These help points have an associated TVD pick uncertainty that are illustrated by the error-bars in the figure. The help points are included as additional well points in the prediction and prediction uncertainty expressions. The expectations and TVD pick uncertainty of the surface help points are chosen so that predictions and prediction uncertainty exactly reproduce the surface target points at the selected zonation points.



21.2 Well path TVD uncertainty

The well path TVD uncertainty describes the difference between the true well path TVD values and the TVD values obtained from the positioning survey along the well path. This is discussed in Section 8.5.2.

The stochastic model for the true well path TVD is

$$Z_{\mathrm{w}}(t) = m_{\mathrm{w}}(t) + \epsilon_{\mathrm{w}}(t), \tag{21.1}$$

where t is measured depth (MD) along the well path, $m_{\mathrm{w}}(t)$ is the TVD values obtained from the positioning survey at t, and $\epsilon_{\mathrm{w}}(t)$ is the unknown TVD residual. The TVD residual is a modeled as a one-dimensional Gaussian process (random field) with expectation zero and a correlation structure determined by the integrated Ornstein-Uhlenbeck process. The stochastic model for the well path is in principal equal to the stochastic model for a surface, see Eq. 18.6. Both have a (known) trend m and an unknown residual ϵ that is modeled as a Gaussian spatially correlated variables. The surface residuals are specified using (a sum of) variograms whereas the well path TVD residual use a process that can be thought of as a smoothed random walk.

The integrated Ornstein-Uhlenbeck process that is used as a model the well path TVD residual

can be expressed as

$$\epsilon_{\mathrm{w}}(t) = a(t)\,\phi \int_0^t X(s)\,ds, \tag{21.2}$$

where

$$X(s) = \int_0^s e^{\phi(\tau - s)}\,dW_\tau \tag{21.3}$$

is the Ornstein-Uhlenbeck process with mean 0, variance 1 and mean-reverting parameter ϕ. The stochastic integral in Eq. 21.3 is an Itô integral with respect to a standard Wiener (white noise) process, W_t. The deterministic function a_t is chosen such that $\mathrm{Var}\{\epsilon_{\mathrm{w}}(t)\} = \sigma_{\mathrm{w}}^2(t)$, the uncertainty (SD) specified by `<wellpath-TVD-SD-log-name>`. See Barndorff-Nielsen (1997) for more details on the integrated Ornstein-Uhlenbeck process.

The `<wellpath-TVD-SD-range>` relates to the mean-reverting parameter ϕ as range $= 1/\phi$. A large range (small ϕ) gives a stiffer well path residual, that is, the inclination variations are smaller. For a short range, the residual behaves as a random walk model, which produces unrealistically wiggly well paths. The default range (300 meters) is based on a heuristic estimation from a few horizontal wells. See Figure 8.11 for some examples of simulated residuals.

The integrated Ornstein-Uhlenbeck model provides a continuous and smooth (differentiable) model for the residuals. And importantly, it is possible to find formulas for the variance

$$\sigma_{\mathrm{w}}^2(t) = a^2(t)\Big[t - \frac{2}{\phi}\Big(1 - e^{-\phi t}\Big) - \frac{1}{2\phi}\Big(1 - e^{-2\phi t}\Big)\Big], \tag{21.4}$$

and the covariance between any pair of zonation points:

$$\begin{aligned}\mathrm{Cov}\{\epsilon_{\mathrm{w}}(t), \epsilon_{\mathrm{w}}(u)\} = a(t)\,a(u)\Big[t - \frac{1}{\phi}\Big(1 - e^{-\phi t} - e^{-\phi u} + e^{-\phi(u-t)}\Big) \\ + \frac{1}{2\phi}\Big(e^{-\phi(u-t)} - e^{-\phi(u+t)}\Big)\Big], \qquad \text{for } t \le u.\end{aligned} \tag{21.5}$$

The integrated Ornstein-Uhlenbeck process is naturally extended to calculate covariances between zonation points from different branches of a multilateral well. (21.4) gives a recipe for finding $a(t)$ given the specified $\sigma_{\mathrm{w}}(t)$,

If `<allow-wells-to-move>` is `yes` and `<wellpath-TVD-SD-log-name>` is not used, a parametric TVD uncertainty log is generated as

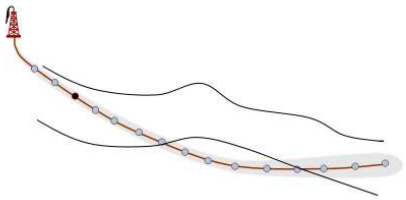
$$\begin{aligned}\sigma_{\mathrm{w}}(t_n) &= c\sum_{i=2}^{n}\big|\sin\alpha(t_i)\big|\big(t_i - t_{i-1}\big) \\ &= c\sum_{i=2}^{n}\sqrt{\big(x_i - x_{i-1}\big)^2 + \big(y_i - y_{i-1}\big)^2},\end{aligned} \tag{21.6}$$

where t_i is the MD value and $\alpha(t_i)$ is the inclination at zonation point i. The formula essentially says that the well path TVD uncertainty increases proportional to the *lateral distance* of the well. The increase rate, c, is by default 4 mm per meter. This amounts to an increase of 4 meters SD for every 1000 meters along a horizontal section. The increase rate is modified by `<wellpath-TVD-SD-increase-rate>`.

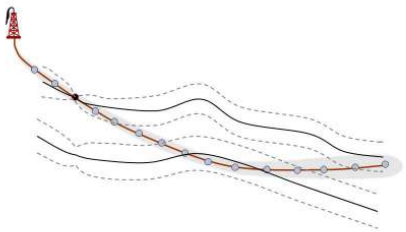
21.3 Procedure for conditioning to zone logs with well path TVD uncertainty

This procedure is almost identical to the procedure in Section 21.1. We therefore repeat the steps with focus on the extensions needed to handle the well path TVD uncertainty:

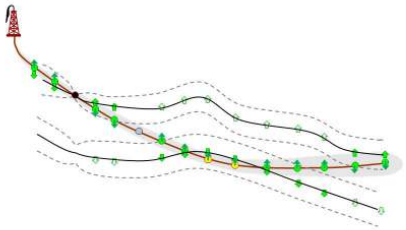
1. The well path is shown as a red line. The well point is shown as a black disc and the **zonation points** are the gray discs. The two black lines are cross sections of the surfaces above and below the main part of the well path. The uncertainty envelope (shaded cone) represents one SD away from the well path (cf. `<wellpath-TVD-SD-log-name>`).



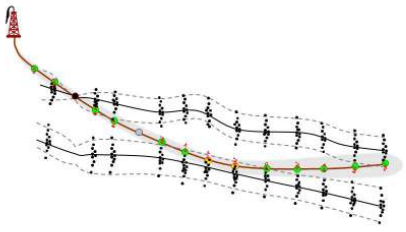
2. Along the well paths, calculate the deterministic surface (solid lines), and the prediction uncertainty (dashed lines) given the well points.



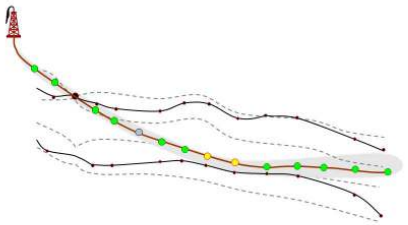
3. Select the zonation points that are in conflict with the zone log or are *close*. The closeness criteria also account for the uncertainty in the well path. Consequently, more zonation points will be selected compared to the case with a certain well path. The associated **surface constraints** are indicated by green and light-green arrows. Note that in this case the surfaces also impose a well position constraint since the wells can move vertically.



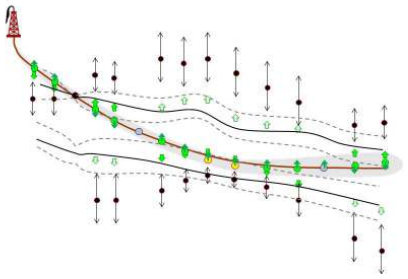
4. Run the Data Augmentation Algorithm to obtain 256 simulated realizations of surface depth values at the surface points *and* 256 samples of well TVD values. The small black dots in the figure illustrates the spread of the 256 surface depth realizations and the small red triangles shows realizations of TVD at the selected zonation points.



5. **For stochastic simulation:** Select randomly one of the 256 realizations of surface depths and the corresponding TVD values at the selected zonation points. The selected realization of surface depths and well TVD values are used as **surface target points** for the surfaces *and* the well paths.



6. **For deterministic surface:** Calculate the expectation and the covariances of the 256 simulated realizations at the surface constraints. Use the 256 realizations of surface depths and the corresponding TVD values at the selected zonation points to obtain the average depth and TVD values. As in Step 6 in Section 21.1 above, the expectations at the surface constraints are called **surface target points** since this is where we want the predicted surfaces to go. These surface target points are again replaced by **surface help points**.



   To predict a new well path, the average of the 256 realizations of the TVD values at the selected zonation points are used. The difference between these average values and the original well path is interpolated using simple kriging and added to the original well path. The kriging uses the covariances from the integrated Ornstein-Uhlenbeck process. See Section 8.5.2 for some details.

21.4 Clusters of surface constraints

The drawing of the 256 depth samples at the surface constraints in Step 4 in the previous section, can be very time consuming if the constraints are strong and there are many constraints. Therefore COHIBA splits the target points and the corresponding surface constraints into *clusters* and treats each cluster independently. A cluster contains target points that constrain highly correlated surface areas. Typically, well points decouple target points so that clusters are split at these well points. This is illustrated in Figure 21.1. The element `<threshold-for-trace-clustering>` specifies the threshold for the correlations. Specifying a high value means that constrained surface values must be strongly correlated to be in the same cluster. Small clusters are important to obtain fast performance. The default correlation threshold is 0.1.

The drawing of the depth samples for each cluster is based on surrounding well points. All points closer than one range and all points on the corresponding well path is collected, before a filtering based on correlation is done. The threshold for this filtering can be specified by `<threshold-for-well-point-cluster-inclusion>`, with a default value of 0.1. Specifying a high value means that fewer well points are used in each cluster. Note that filtering based on this correlation threshold is only done if the number of well points considered is above 200.

Target points from different well paths can belong to the same cluster if they constrain surface values that have a correlation larger than the threshold specified by `<threshold-for-cluster-merging>`. A small value can cause (very) large clusters. The default value is 0.2. Note that correlation with a second well, may force target points that are separated by a well point in their well to be in the same cluster.

If `<threshold-for-trace-clustering>` and `<threshold-for-cluster-merging>` are chosen close to 0, then all target points may end up in one cluster. This is prohibitive for large problems with many well points and many target points and we may get convergence problems. On the other hand, too low correlation thresholds cause COHIBA to treat all surface constraints independently and this will underestimate the true uncertainty and cause zonation errors. So, there is a trade-off between speed and quality. The files `cluster-large-mismatch-Num.rxat` and `cluster-large-mismatch-Well.rxat` contain target points for which there are large mismatches between the target point depth (ie. the predicted surface depth) and the actual surface depth (as interpolated between grid nodes), and may be used to identify problems.

The distribution of the size of clusters are reported in `Section 13.x: Finding help points for well path conditioning` in the COHIBA log file and in section `Section 17.x: Target point QC` we give statistics of mismatches between predicted and actual surface depths. The target points and well points in the clusters can be written to files for inspection (see Section 7.8.2).

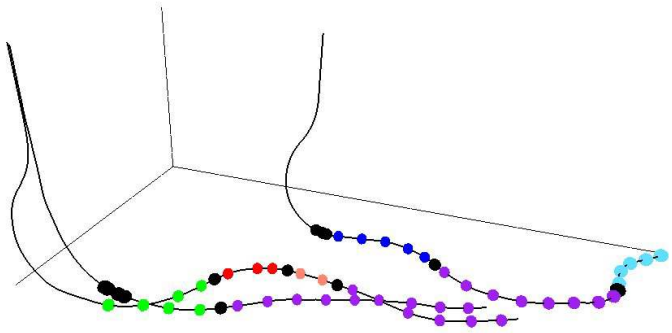


Figure 21.1. Selected zonation points belonging to the same cluster have the same color. The well points are the black. Note how well points splits zonation points in a well into separate clusters. Also note that the two largest clusters contain zonation points from two or three wells.

Part VI
Appendix

A Release notes

The tags, e.g. COH-49, are links to the COHIBA project management system called JIRA. Permission is required to access the links.

Changes from COHIBA Version 5.6 to Version 6.0

New features:

- The main new development in COHIBA Version 6 is the integration with fault modeling in ROXAR RMS. To fully benefit from this development COHIBA must be run from ROXAR RMS 12 or higher. This development involve several new features and extensions to existing functionality:
  - Overall restructuring of code to accommodate handling of different fault blocks semi-independently. COH-423, COH-755, COH-762, COH-893
  - Allocate input information to each fault block. Fault block information is automatically provided by ROXAR RMS. COH-758, COH-759
  - Export of fault block dependent surfaces using a new export format called ROXAR PATCH BINARY. This format is used for output if imported surfaces have this format. It is only intended to work with the ROXAR RMS structural model. COH-754, COH-818, COH-829, COH-898
  - Estimate trend coefficients using fault block specific trend surfaces. COH-760
  - Add fault block label to COHIBA log file, other log-files and to various export files for well data such as `wellpoints-Well.rxat`. COH-764, COH-832
- Now, residuals and trend coefficients from different intervals can be correlated. This is triggered by selecting a `<common-top-for-correlated-intervals>` under `<reference>` or `<surface>`. See Section 14 for details. COH-715

Improvements:

- Wells exported in LAS 2.0 well format now include calculated logs (`CalcMD, DeltaMD, DeltaTVD, Wellpath-TVD-SD, PosteriorUncertainty, Mismatch`). COH-401
- Each task in `Section 25: Suggested tasks` in the COHIBA log file is now listed once. For tasks that are in the simulation loop, the percent of simulations where this task is relevant is printed. For instance: `Check posterior depth surfaces. Crossing surfaces detected. (77.0% of realizations)`. COH-539
- Output posterior correlation matrix written to `posterior-correlation-matrix.dat` in `expert-log-files/`. COH-716, COH-885
- Removed repeated printing in `Section 3: Pre-processing input data` in the COHIBA log file. COH-834
- Speed improvements when calculating the number of meters the wells are in the correct zone. Results are reported in `Section 18.x: Checking zonation` in the COHIBA log file and in various other files. COH-864
- LAS 2.0 wells might use positive or negative TVD values to measure depth. This can now be specified using `<TVD-values-are-negative>`. COH-867
- When `<allow-wells-to-move>` is set to `yes` the original MD values are now kept in the modified wells. COH-868

- Improved selection of identical well points (see Section 8.3.1). Now, well points from well point files will replace well points extracted from zone logs. This can be used to add well point TVD pick uncertainty to well points extracted from a zone log. COH-886
- Significant speed improvements on huge data set (more than ten thousand well points). These changes have little effect on smaller data sets. COH-897
- Significant speed improvement for data-sets with many close horizontal wells. A lot of time was spent on calculating help points in large clusters of surface constraints (Section 21.4). Now, clusters are smaller. This is partly achieved by increasing the default value of `<threshold-for-well-point-cluster-inclusion>` from 0.0 to 0.1. COH-902
- Parallelize merging of clusters of surface constraints. COH-905
- Renaming `<threshold-for-high-correlation>` to `<threshold-for-high-correlation-wp-wp>` and introducing `<threshold-for-high-correlation-wp-ip>` and `<threshold-for-high-correlation-wp-ep>`. These are used when removing highly correlated well points, inequality points and extra points. COH-916
- When `<allow-wells-to-move>` is set to `yes`, the moved well points should interpolate the surfaces exactly (assuming no well point measurement uncertainty). This requires that exactly the same selection data are used when calculating surfaces and new well paths close to well points. Previously, the selection of data was different. The kriging of surfaces is done in rectangular data neighborhoods whereas the kriging of wells was done in well clusters. Now, wells also use data from neighborhoods. Note that this may cause a small jump in the well path at edges between data neighborhoods. COH-922

Bug fixes:

- Large rectangular shaped artifacts in surfaces in rare occasions when using universal kriging has been removed. COH-588
- Corrected calculation of the length of correct well zonation. The results are reported in `Section 18.x: Checking zonation` in the COHIBA log file. COH-860
- When `<allow-wells-to-move>` is set to `yes`, well points without an MD value caused COHIBA to crash. COH-865
- COHIBA could crash in some situations when writing expert log files. COH-870
- Automatically give wells the default well path TVD uncertainty (SD) if `<allow-wells-to-move>` is yes and `<wellpath-TVD-SD-log-name>` is unspecified. The default can be modified using `<wellpath-TVD-SD-increase-rate>`. COH-871
- COHIBA could crash when trying to sample wells with only undefined zonation. COH-872
- The MD log specified by `<MD-log-name>` could not be imported into COHIBA. COH-873
- MD logs read from file were incorrectly converted to integers that could cause a crash (division by zero). COH-875
- For stability reasons, the trend coefficient SD were (incorrectly) truncated at 1000. It is now truncated relative to the mean value. COH-876
- Some ROXAR ATTRIBUTES TEXT files with Windows line endings were not correctly parsed in Linux. COH-877
- Assigning MD and MDxy to well points from well logs failed in some cases. COH-878
- Incorrect reporting to COHIBA log file when assigning uncertainty from well logs to well points taken from well points files (Section 6.3.2). COH-882
- Old nomenclature `WellTVD-SD` changed to `PickTVD-SD` in `Section 8: Sampling well trajectories and logs` in COHIBA log file. COH-883

- Modified and corrected calculation of reports in the COHIBA log file that involved undefined properties. COH-887, COH-888, COH-889
- Undefined variance in wells where a very small MD was encountered. COH-890
- `<make-surfaces-interpolate-well-points>` did not work when `<allow-wells-to-move>` was set to `yes`. COH-891
- The size of some data neighborhoods became very large in certain circumstances. COH-892
- Missing column in `wellpoints.csv` for deleted points when using comma-separation. COH-894
- Now duplicate well points inherit attributes calculated for their twin points. COH-899
- Corrected reporting of zone tops MD values in COHIBA log file when using erosion. COH-901
- When `<allow-wells-to-move>` was set to `yes` simulated well paths were not identical before branching point. This is now corrected. COH-909
- Previously COHIBA crashed when surface constraints enforced by erosion or onlap ended up in same location as a regular well point. COH-911
- Post process did not account for status of well points and zonation points. This could cause some kinks in the surfaces. COH-912
- Deactivated well points not taken into account when sampling well path. COH-913
- Well log files that could not be read are now reported as a warning with some explanation in COHIBA log file. COH-914
- Surface constraints very close to well points caused errors and they are now removed. COH-915
- When `<allow-wells-to-move>` was set to `yes`, there was an error in the computation that led to inaccurate distances between surfaces and moved well paths. COH-920, COH-923
- Well points taken from well points files (Section 6.3.2) were not removed if they were in a fault region marked by the fault indicator log. COH-921
- The calculation of `Preparing prediction` and `Predicting surfaces` in `Section 24: Timings summary` in the COHIBA log file is now thread safe (affects parallelization). COH-927
- Residuals not correctly calculated when COHIBA do a Bayesian kriging fall-back from universal kriging (necessary when universal kriging becomes unstable). COH-924
- Default column separator for CSV files was incorrectly set to " " (one blank). The default is used if `<additional-output-control>` is not specified. COH-928
- Memory leaks removed. COH-934

B The future

B.1 Ongoing funded developments

Linear velocity (LINVEL) depth conversion model. This is a widely used model for instantaneous velocity first introduced by Slotnick (1936). It is commonly fitted to velocity log data in vertical wells. The implementation will include two linearizion schemes for the interval velocities, the traditional second order Taylor expansion in travel times and a novel expansion in V_0 and k. The latter expansion makes it possible to use prior estimates for V_0 and k (from vertical wells) directly and update these prior estimates using well points from vertical *and* horizontal wells. COH-700

Cross validation for model selection. We are currently coding some basic functionality to test ideas. The ultimate goal is to (partly) automate the process of selecting surfaces and trends that enter the model. See below. COH-653, COH-631, COH-937

Use of deep directional resistivity (DDR) data: COHIBA is well suited for handling observations of distances between wells and surfaces. This is exactly what DDR data provides. An important ingredient is the possibility to move wells since the DDR data provide information on distances, not on TVD. This could be used in a modeling-while-drilling setting but also in a post-drill situation to increase the accuracy of depth predictions. This initiative is partly funded and would benefit a lot from additional funding. COH-952

Use of dip data: Dip meters and image logs can carry information on surface gradients. The development will include the possibility of including surface dip and azimuth at well points. COH-958

B.2 Possible major developments lacking funding

Compaction and subsidence: COHIBA can provide a perfect integration tool that can consistently combine vintage data with recent observations by taking into account posible uncertainty in vintage observations. We believe this approach would be very powerful when operating carbonate fields where compaction makes it almost impossible to combine all data using standard software. All data (wells, travel times,...) must be tagged by date so that they can be moved vertically using a compaction model. It will be possible to predict or simulate surfaces at any time such as today or any time in the past or future. COH-421

Ranking of alternative models by cross validation: The goal is to (partly) automate the process of selecting surfaces and trends that enter alternative surface models. Possibilities are to replace, include or remove surfaces, intervals or individual trend elements. The ultimate goal would be a fully automated process where the user include several options and COHIBA ranks the alternatives and suggests the optimal models for one or more surfaces. There are several challenges since the number of alternatives easily becomes very large and the selection criteria are not unique. COH-631, COH-714

Volume calculations: COHIBA can already calculate gross rock volume (GRV) between surfaces and HCC. This could be taken a step further to be able to calculate HCPV[1] or STOOIP[2] by

1. Hydrocarbone pore volume.
2. Stocked tanked oil originally in place.

including parameters such as water saturation, porosities, net/gross fraction and fluid factors. There are many levels of sophistication from simple constants to surfaces and vertical proportion curves with or without uncertainty. COH-638

Interval velocities from stacking velocities: Use stacking velocities as input and extract interval velocities by Dix inversion (Buland et al., 2011). The method provide uncertainty estimates for the velocities that will be used directly by COHIBA. COH-437

B.3 Known issues

- Conditioning to well paths using universal kriging does not work. COH-23
- Warning and error handling when inversion of Y matrix fails. The Y matrix is only relevant when using universal kriging when depth error is requested. COH-562
- Post processing (erosion and on lapping) may break the conditioning in rare situations. COH-592
- The check for large deviations between velocity and posterior velocity must be improved to take into account the travel time uncertainty. Otherwise thin intervals are triggered as problematic to often. COH-595
- Coordinate MD logs of side tracks in multilateral wells. If side-tracks of a multilateral well have its MD log calculated then this MD log should be coordinated with other MD logs from the same multilateral well. COH-649
- Residuals in `wellpoints.csv` become wrong for Universal kriging when well points have TVD pick uncertainty. COH-895
- Add realization index to `wellpoints.rxat` and output wells when doing simulation. COH-896
- Change default values for TVD uncertainty and TVD pick uncertainty to undefined instead of zero. COH-900
- Bogus logging for zonation points marked as duplicate when surface/intervals are undefined. COH-907
- Possible crash when moving multi-lateral wells where the branching points do not become the same. COH-908
- Extra points needed for erosion/onlapped surfaces do not have MD assigned. This may lead to a crash when moving wells. COH-910
- Updating MD for wells can make updated well picks miss the updated well path. COH-932
- Possible collinearity in rare case of branching wells with same xy-trajectory (but different TVD). COH-933

References

Abrahamsen, P. (1993). Bayesian kriging for seismic depth conversion of a multi-layer reservoir. In Soares, A., editor, *Geostatistics Tróia '92*, pages 385–398, Dordrecht. proc. '4th Inter. Geostat. Congr.', Tróia Portugal, 1992, Kluwer Academic Publ. Available from: http://dx.doi.org/10.1007/978-94-011-1739-5_31. 9

Abrahamsen, P. (1997). A review of Gaussian random fields and correlation functions. Report 917, Norwegian Computing Center, P.O.Box 114 Blindern, N-0314 Oslo, Norway. Available from: http://publications.nr.no/2437/Abrahamsen_-_A_Review_of_Gaussian_random_fields_and_correlation.pdf. 134, 176

Abrahamsen, P. (2005). Combining methods for subsurface prediction. In Leuangthong, O. and Deutsch, C. T., editors, *Geostatistics Banff 2004*, volume 2, pages 601–610, Dordrecht. proc. '7th Inter. Geostat. Congr.', Banff, Canada 2004, Springer-Verlag Inc. Available from: http://dx.doi.org/10.1007/978-1-4020-3610-1_61. 9

Abrahamsen, P. and Benth, F. E. (2001). Kriging with inequality constraints. *Mathematical Geology*, 33(6):719–744. Available from: http://dx.doi.org/10.1023/A:1011078716252. 9, 59, 192, 198

Abrahamsen, P., Hauge, R., Heggland, K., and Mostad, P. (2000). Estimation of gross rock volume of filled geological structures with uncertainty measures. *SPE Reservoir Evaluation & Engineering*, 3(4):304–309. Available from: http://dx.doi.org/10.2118/65419-PA. 9

Abrahamsen, P., Kvernelv, V., and Barker, D. (2018). Simulation of gaussian random fields using the fast Fourier transform (FFT). In *ECMOR XVI - 16th European Conference on the Mathematics of Oil Recovery*. EAGE. Available from: http://dx.doi.org/10.3997/2214-4609.201802134. 190, 191

Barndorff-Nielsen, O. E. (1997). Processes of normal inverse gaussian type. *Finance and Stochastics*, 2(1):41–68. Available from: http://dx.doi.org/10.1007/s007800050032. 201

Buland, A., Kolbjørnsen, O., and Carter, A. J. (2011). Bayesian dix inversion. *GEOPHYSICS*, 76(2):R15–R22. Available from: http://dx.doi.org/10.1190/1.3552596. 210

Chilés, J.-P. and Delfiner, P. (1999). *Geostatistics: Modeling Spatial Uncertainty*. John Wiley & Sons, New York. 9

Cressie, N. (1993). *Statistics for Spatial Data*. John Wiley & Sons, New York, revised edition. 9

Dietrich, C. R. and Newsam, G. N. (1993). A fast and exact method for multidimensional gaussian stochastic simulations. *Water Resources Research*, 29(8):2861–2869. Available from: http://dx.doi.org/10.1029/93WR01070. 190, 191

Isaaks, E. H. and Srivastava, R. M. (1989). *An Introduction to Applied Geostatistics*. Oxford University Press Inc., New York. 9

Journel, A. G. and Huijbregts, C. J. (1978). *Mining Geostatistics*. Academic Press Inc., London. 190

Lantuéjoul, C. (2002). *Geostatistical Simulation: Models and Algorithms*. Springer-Verlag Inc., Berlin. 9

Mardia, K. V., Kent, J. T., and Bibby, J. M. (1979). *Multivariate Analysis*. Academic Press Inc., London. 178

Omre, H. and Halvorsen, K. B. (1989). The bayesian bridge between simple and universal kriging. *Mathematical Geology*, 21(7):767–786. Available from: http://dx.doi.org/10.1007/BF00893321. 179, 184

Ripley, B. D. (1987). *Stochastic Simulation*. John Wiley & Sons, New York. 191

Slotnick, M. M. (1936). On seismic computations, with applications, I. *GEOPHYSICS*, 1(1):9–22. Available from: http://dx.doi.org/10.1190/1.1437084. 209

Tanner, M. A. and Wong, W. H. (1987). The calculation of posterior distributions by data augmentation. *Journal of the American Statistical Association*, 82(398):528–550. Available from: http://dx.doi.org/10.2307/2289457. 199

Vigsnes, M., Kolbjørnsen, O., Hauge, V. L., Dahle, P., and Abrahamsen, P. (2017). Fast and accurate approximation to kriging using common data neighborhoods. *Mathematical Geosciences*, 49(5):619–634. Available from: http://dx.doi.org/10.1007/s11004-016-9665-7. 184

Weisberg, S. (1985). *Applied Linear Regression*. John Wiley & Sons, New York, 2nd edition. 9, 178, 180, 181

Wood, A. T. A. and Chan, G. (1994). Simulation of stationary gaussian processes in $[0, 1]^d$. *Journal of Computational and Graphical Statistics*, 3(4):409–432. Available from: http://dx.doi.org/10.1080/10618600.1994.10474655. 190, 191

Some references are available as pdf's at the bottom of: www.nr.no/COHIBA.

Acronyms

ASCII American Standard Code for Information Interchange: Simplest standard character set used in files. See Wikipedia for details. 25–27, 29, 47, 48, 126, 127, 218

BCU Base Cretaceous Unconformity. 141

CPU Central processing unit in a computer. All modern CPUs have multiple physical cores to accomodate parallell processing. The number of processes used by COHIBA is chosen using `<number-of-threads>`. 37, 84, 98, 105, 110, 117, 120, 121, 139, 178, 179, 191, 219, 223

CSV Comma-separated-values: File format (Section 6.3.3) where values are separated by comma or other special characters. 26, 35, 39, 107, 208, 219, 220

FFT Fast Fourier transform. See Wikipedia for details. 9, 190, 191, 220

GLS Generalized least squares: Least squares method that takes into account uncertainty *and* correlations between well points. See Eq. 18.18a. 14, 40, 41, 46, 120, 178, 179, 181, 218, 220, 221

GOC Gas oil contact. 69, 89, 147, 213, 221

GRV Gross rock volume. 209

GWC Gas water contact. 89, 147, 213, 221

HCC Hydrocarbon contact: Short for OWC, GOC or GWC. 69, 89, 132, 147, 209, 218, 220, 221, 226, 227

MD Measured depth: The distance from RKB along the well path. 29, 41, 46, 50, 60, 62, 98, 99, 110, 121, 125, 127, 128, 201, 206–208, 210, 222

MSL Mean sea level: Defined as TVD = 0 meters. 38, 54, 56, 57, 59, 69, 90, 129, 131, 175, 214, 216, 222, 223

OLS Ordinary least squares: Least squares method that minimizes the sum of squares of mismatch between observation and trend. This is the standard linear regression minimization criteria. See Eq. 18.15a. 177, 178, 220, 223

OWC Oil water contact. 69, 70, 72–74, 147, 213, 223

QC Quality control. 11, 27, 31, 35, 39, 47, 61, 104, 106, 128, 180, 219, 223, 224

RKB Rotary Kelly bushing: An adapter that connect the rotary table to the Kelly, which turns the entire drill-string. 213, 224

SD Standard deviation: Measure of uncertainty. See Wikipedia for details. 2, 3, 15, 16, 20, 30, 31, 33, 35, 38, 40–43, 46, 47, 49, 53, 60, 63, 73–78, 80, 81, 84–86, 89, 106, 109, 111, 113, 114, 118, 119, 121, 126–128, 130, 134, 135, 139, 142–144, 176, 178–181, 183, 190–194, 201, 202, 207, 215, 216, 223, 224, 226, 227

TVD True vertical depth: The vertical depth from MSL. COHIBA uses positive values below MSL so negative values means that the location is above sea level. iv, 2, 4, 10, 11, 26, 27, 29–31, 37, 39, 41–46, 48, 52, 53, 59–62, 89, 98, 99, 109, 110, 121, 122, 125–130, 177, 181, 184, 188, 200–203, 206, 207, 209, 210, 213, 215, 227, 228

TWT Two-way travel time: Seismic travel time measure travel time to surface and back. 7, 80, 81, 99, 134, 227

WLS Weighted least squares: Least squares method that takes into account uncertainty of well points. See Eq. 18.19a. 120, 178, 179, 181, 218, 220, 228

XML Extensible Markup Language. File format used by the COHIBA model file. See Wikipedia for details. 18, 23, 95, 220, 224, 228

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