GeoModeller Stochastic Exploration

## Inversion (Stochastic Exploration)
## Geology … and Geology Tests



GeoModeller Stochastic Exploration

## Topics

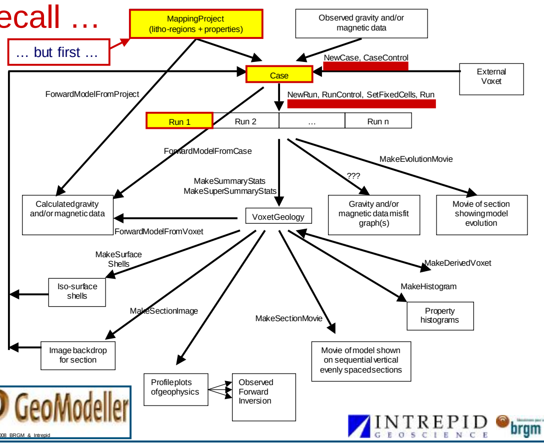
Before we start this section – a further look at 'what is a Case' and 'what is a Run' … and the batch scripts that set these up.

- Source of the Geology Model
- Known Geology: SetFixedCells
- Geology Constraints or Tests
  - Commonality
  - Shape Ratio
  - PreserveVerticalRelationship



GeoModeller Stochastic Exploration

## Recall …






GeoModeller Stochastic Exploration

## What Geology Model?

Where do we get the geology from?



GeoModeller Stochastic Exploration

## Source of the Geology Model

- Typically … a GeoModeller Project
  - In GeoModeller, it is the 'interpolator equations' that *are* the model. The equations are 'computed' using the GeoModeller GUI's 'Model – Compute' … and saved as part of the Project
  - For geophysics work we make a *copy* of the specified Project in the Case directory
  - Thus it is the saved, computed model that is interrogated to generate the voxel-geology model used in the geophysics computation
  - So … if you use GeoModeller to edit geology … remember to 're-compute' your revised model, and 'save' the new Project



GeoModeller Stochastic Exploration

## Source of the Geology Model

- It is possible to use geology from some third party source as the geology input to GeoModeller's geophysical forward modelling and inversion
- We have done this in the context of our geothermal calculations – where the source geology came from a voxet generated in GoCAD
  - If you plan to do this – liaise with Intrepid via email: support@geomodeller.com



GeoModeller Stochastic Exploration

## Source of the Geology Model
## NewCase Command

- The 'source' geology model is specifically defined is in the *NewCase* command. This 'creates a new Case' … and copies the GeoModeller Project to the Case directory. At the same time it also creates the Case's 'voxel model' of the geology …

Batch script "02_ … _RunAtStartOfSession.bat" …

```
rem ----------------------------------------------------------------------------
rem * Define the INPUT geology model (the GeoModeller Project) ...
rem ----------------------------------------------------------------------------

rem Define the input geology project XML file
set Proj=InputGeology\Slab_P_PERFECT_PROPERTIES_2000m\Slab_P_PERFECT_PROPERTIES_2000m.xml
```

Batch script "20_SetupCase.bat" …

```
call %DoTask% %Proj% NewCase %Case% %VoxelHeight% %ElevationVoxetBottom% %ElevationVoxetTop% ^
  Gravimetry %ElevationGeophysData% %ModellingUncertaintyGrav% %MatchTrend% %MatchTrendDegree% %M
  Magnetism %ElevationGeophysData% %ModellingUncertaintyMag% %MatchTrend% %MatchTrendDegree% %Mat
  %ToResultsDIR%
```

GeoModeller Stochastic Exploration

## Multiple Lithology Voxets

There will typically be several lithology (voxet) models used for different purposes …



GeoModeller Stochastic Exploration

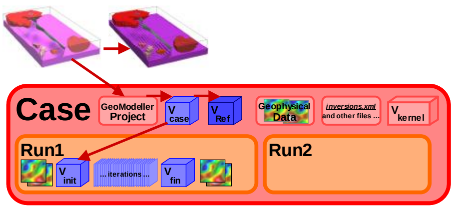
## Multiple Lithology Voxets

- Case GeoModeller Project
- Case lithology voxet – a voxel model of the Case GeoModeller Project, setup automatically by the NewCase command
- The ‘reference’ lithology voxet – used by the geology tests – and setup by the CaseControl SetReferenceLithology command
- The ‘initial’ lithology voxet (of a Run) … setup by the RunControl LithologyInitialiseStyle command
- The ‘final’ lithology voxet from a Run



GeoModeller Stochastic Exploration

## Multiple Lithology Voxets




NewCase: copies a GM Project … and makes the Case lithology voxet

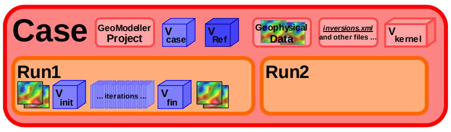
CaseControl SetReferenceLithology: creates ‘reference’ lithology voxet

RunControl LithologyInitialiseStyle: creates the ‘initial’ lithology voxet of a Run



## Quick look at Case and Run Scripts

- Using a text editor, look at …
  20_SetupCase.bat
  21_SetupRun_RunInversion.bat
  - There are many commands in these scripts … and in a moment we will be looking in detail at those commands used to control the geology tests
  - For the moment – lets just get a quick overview …
  - Note the NewCase and CaseControl commands
  - Also NewRun and RunControl commands. And SetFixedCells. And Run




GeoModeller Stochastic Exploration

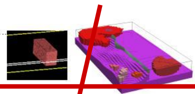
## Known Geology: SetFixedCells

- GeoModeller Stochastic Exploration is all about *uncertainty* … and exploring for alternative possible geology models.
- But if I know the geology … I don’t want inversion to change that part



## Recall the ‘modifiable’ voxet …

VOXET containing the 'Reference' Geology Model for THIS RUN …
(This is often the CASE Lithology Voxet … but it may not be)
Case_PERFPROP_Field5_Run_1_reference.vo
Case_PERFPROP_Field5_Run_1_reference.vop1



VOXET containing the record of 'fixed' voxels for THIS RUN …
(Setup using 'SetFixedCells' … voxels where the lithology cannot change)
Case_PERFPROP_Field5_Run_1_modifiable.vo
Case_PERFPROP_Field5_Run_1_modifiable.vop1

The RECO
(This file als
Case_PER

A REPORT
And providi
Case_PER

An abridge
Case_PER

By default, all voxels are ‘modifiable’ – the assigned geology may be changed to a new formation.

We can specify selected voxels to be ‘fixed’ … and the record of which voxels are fixed is maintained in the ‘…modifiable’ voxet in the Case directory.

HISTORICAL. A cryptic 'record' of the details of THIS RUN …
Case_PERFPROP_Field5_Run_1.txt

# SetFixedCells

```
rem ------------------------------------------------------------------------
rem SetFixedCells can be used to 'hold fixed' the lithology of specified voxels ...
rem ------------------------------------------------------------------------

rem SetFixedCells: the lithology (geology) of specified voxels can be 'fixed' and will not
rem change during inversion
rem Multiple commands are allowed; 'fixed' voxels are recorded in the Modifiable voxet in
rem the Case directory. Options are:
rem  - CLEAR - 'clears' all 'fixed' voxels in the Modifable voxet (i.e. all voxels can change)
rem  - SURFACE - 'fixes' those voxels that are intersected by the topographic surface
rem  - OBSERVED - 'fixes' those voxels which contain any 'geology contact' in the GeoModeller Project
rem  - XYZ<xyz-filename>: a voxel can be 'fixed' if any point from a supplied set of (x,y,z) data
rem                     (in an ASCII 'space-delimited' file) falls within that voxel
rem  - BOX Xmin Xmax Ymin Ymax Zmin Zmax Inside
rem                   (Inside=1 is 'fix inside' the box; Inside=0 is 'fix OUTside' the box)
call %DoTask% %CaseXML% SetFixedCells %Run% CLEAR
call %DoTask% %CaseXML% SetFixedCells %Run% SURFACE
call %DoTask% %CaseXML% SetFixedCells %Run% BOX -500 1500 -500 1500 -500 0 0

rem AllowPropertyChangeOnFixedCell: For 'fixed cells' it is the LITHOLOGY that is 'fixed'
rem and cannot change. PROPERTY values may change.
rem Choices: 0=NO, property changes disallowed; 1=YES, changes to voxel property values can be proposed
call %DoTask% %CaseXML% RunControl %Run% AllowPropertyChangeOnFixedCell 0
```

Note also: AllowPropertyChangeOnFixedCells

For ‘fixed’ cells, it is the lithology that is ‘fixed’. We can choose to allow the properties to vary. We typically assign properties by ‘sampling’ from a property distribution.

---

GeoModeller Stochastic Exploration

# Geology Boundaries ‘Movable’

- There is one further control we can use which has the effect of ‘fixing’ selected voxels …
- The “20_SetupCase.bat” script sets up a NewCase, and then uses CaseControl commands to further configure the various ‘known’ properties of the geology formations, such as density, etc.
- One of these ‘geology properties’ that we can set is to say ‘Formation “x” is movable’ (or not movable). We will look at this in the following discussion of setting ‘geology properties’

3D GeoModeller



INTREPID GEOSCIENCE brgm

**GeoModeller Stochastic Exploration**

# Geology Tests during Inversion

## Is my changing geology model valid?



**GeoModeller Stochastic Exploration**

# Recall …

Markov Chain
Monte Carlo
(MCMC)
Exploration 'Run'

Load geological and property models

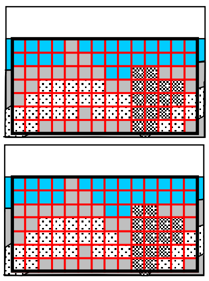
Propose a single voxel change to the models

Check that we still have a 'suitable' geological model

*Fail* / *Pass*

Forward model, compare with the observed geophysical data, and assess the likelihood of the misfit

*Fail* / *Pass*



(Modifications rejected, revert to previous models)

(Modifications accepted and saved)

Continue?

*Yes* / *No*

Finish

**GeoModeller Stochastic Exploration**

# Case and Run Commands

- The setting of ‘geology properties’ that we are about to examine in detail is done in the Case and Run scripts. In the main …
  - In the Case – we ‘set’ properties. The ‘setting’ of a geology property is really stating ‘something we know’ about the geology (or, at least’ something we can reasonably postulate about the geology). It uses ‘a priori’ knowledge.
  - In the Run – we make make choices, such as “for *this* Run, I choose to use geology tests ‘a’ and ‘b’, but not ‘c’, etc.”
- So … first … a quick look at where these commands are in the batch scripts …

3D GeoModeller



INTREPID GEOSCIENCE brgm Géosciences pour une Terre durable

# CaseControl – Geology Parameters

```
rem -----------------------------------------------------------------------------------
rem CaseControl commands defining INVERSION-CONTROL PROPERTIES of geology formations ...
rem -----------------------------------------------------------------------------------

rem Movable: 0=voxels for this formation are NOT moveable (i.e. fixed); 1=formation voxels are move
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          Movable 1 ^
 Host          Movable 1

rem Commonality: the extent to which formation-voxels remain 'in common' with that formation's voxe
rem              reference voxet. Use a Weibull distribution: Weibull(lambda,kappa) where ...
rem              - lambda ('scale' parameter) should be 'tuned'; 0.02 tight; 0.2 looser; 2.0 very l
rem              - kappa ('shape' parameter) should be 1.0
rem CAUTION: No spaces inside the 'Law(...)' brackets ...
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          Commonality Weibull(0.20,1.0) ^
 Host          Commonality Weibull(0.20,1.0)


rem CommonalityVolume: NOT RECOMMENDED: Instead use Commonality and VolumeRatio
rem            Expresses the extent to which BOTH the POSITION and VOLUME of a formation's voxels re
rem            same as for that formation's voxels in the reference voxet.
rem CAUTION: No spaces inside the 'Law(...)' brackets ...
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          CommonalityVolume Normal(0,1) ^
 Host          CommonalityVolume Normal(0,1)

rem ShapeRatio: the extent to which 'shape-ratio' (surface-area/volume) is maintained comparable to
rem CAUTION: No spaces inside the 'Law(...)' brackets ...
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          ShapeRatio LogNormal(0.00,0.05) ^
 Host          ShapeRatio LogNormal(0.00,0.05)

rem VolumeRatio: the extent to which the total volume of a formation's voxels remains the same
rem            as the total volume of that formation's voxels in the reference voxet
rem CAUTION: No spaces inside the 'Law(...)' brackets ...
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          VolumeRatio LogNormal(0,0.01) ^
 Host          VolumeRatio LogNormal(0,0.01)

rem PreserveVerticalRelationship: specifies if the 'normal' upwards-younging relationship should be
rem between any pair of formations. For N formations there will be an N x N array of 0 and 1
rem  - order of columns is youngest to oldest from left to right across the page
rem  - order of rows (RECOMMENDED) youngest to oldest DOWN the page (for READABILITY)
rem  0=no constraints enforced
rem  1 in top-right half enforces 'normal' upward-younging vertical relationship
rem  1 in bottom-left half enforces an 'alway overturned' relationship (VERY UNUSUAL)
CAUTION: No spaces inside the '(.,..,.)' brackets ...
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab          PreserveVerticalRelationship (0,0) ^
 Host          PreserveVerticalRelationship (0,0)
```

# RunControl – Geology Parameters

```
rem ---------------------------------------------------------------------------------------
rem Geology Tests - Can be turned 'on' or 'off'. Specify related parameter choices ...
rem ---------------------------------------------------------------------------------------

rem AllowCommonalityTest: 0=NO; 1=YES, DO execute the Commonality test
call %DoTask% %CaseXML% RunControl %Run% AllowCommonalityTest 1

rem SetCommonalityTestWeights: Specify weighting options for the Commonality test. Options are:
rem  - none
rem  - LocalAbundance
rem  - LocalCommonality
rem  - GlobalCommonality
call %DoTask% %CaseXML% RunControl %Run% SetCommonalityTestWeights none

rem AllowCommonalityVolumeTest: 0=NO; 1=YES, DO execute the CommonalityVolume test
call %DoTask% %CaseXML% RunControl %Run% AllowCommonalityVolumeTest 0

rem SetCommonalityVolumeTestWeights: Specify weighting options for the CommonalityVolume test. Optio
rem  - none
rem  - LocalAbundance
call %DoTask% %CaseXML% RunControl %Run% SetCommonalityVolumeTestWeights LocalAbundance

rem AllowShapeRatioTest: 0=NO; 1=YES, DO execute the ShapeRatio test
call %DoTask% %CaseXML% RunControl %Run% AllowShapeRatioTest 1

rem SetShapeRatioTestWeights: Specify weighting options for the ShapeRatio test. Options are:
rem  - none
rem  - LocalAbundance
call %DoTask% %CaseXML% RunControl %Run% SetShapeRatioTestWeights LocalAbundance

rem IncludeAboveTopoFacesInShapeRatio: 0=NO; 1=YES, DO include the AboveTopo (topographic surface) v
call %DoTask% %CaseXML% RunControl %Run% IncludeAboveTopoFacesInShapeRatio 1

rem IncludeOutsideFacesInShapeRatio: 0=NO; 1=YES, DO include the 'outside' (model edge) voxel-faces
call %DoTask% %CaseXM

rem AllowVolumeRatioT
call %DoTask% %CaseXM

rem SetVolumeRatioTestWeights: Specify weighting options for the VolumeRatio test. Options are:
rem  - none
rem  - LocalAbundance
call %DoTask% %CaseXML% RunControl %Run% SetVolumeRatioTestWeights LocalAbundance

rem AllowPreserveVerticalRelationshipTest: 0=NO; 1=YES, DO execute the PreserveVerticalRelationship
call %DoTask% %CaseXML% RunControl %Run% AllowPreserveVerticalRelationshipTest 0
```

Turn 'on'

Turn 'off'

PriorOnly

```
rem PriorOnly: 0=standard inversion Run using both geology and geophysics tests;
rem            1=Use ONLY 'geology', with NO TESTS of geophysics misfits
call %DoTask% %CaseXML% RunControl %Run% PriorOnly 0
```

GeoModeller Stochastic Exploration

## Tune Commonality
## Tune ShapeRatio

Two important geology tests!

These contribute significantly to maintaining a credible geology model

See document: 08b_Note_Tuning_Commonality_and_ShapeRatio

3D GeoModeller



INTREPID GEOSCIENCE brgm

3D GeoModeller



User Note

# Slab Tutorial

# Tuning Commonality, ShapeRatio

YYMM_GeoModellerUserNote_FileName



GeoModeller Geophysics Workshops – February-March 2009

The exercises associated with this document are in Directory "L_TUNING_GeologyTests"

# 1 No Tests

PriorOnly 1 has the effect of switching off any geophysics tests, leaving only geology tests.

But if we then individually turn off all geology tests (e.g. AllowCommonalityTest 0, etc.), we have a situation where ***no tests are performed***. The basic process of selecting a voxel on a boundary at random, and proposing to change the geology (+ physical properties), or selecting a voxel at random and proposing to change the physical properties – continues to operate. Since there are no tests – no asking "is this a valid geology model?" – then ***all proposed changes*** are accepted. The result is a rapid deterioration from the Reference (geology) Model to a state of random distribution of geology voxels with highly convoluted boundary arrangements.

**BATCH SCRIPTS**

Create a new Case … and set PriorOnly 1 … and turn off all 'geology tests' …

► A_20_CaseA_NoTests_CreateNewCase.bat

Three Runs … will generate different results …

► A_21_CaseA_NoTests_Run1_Inversion.bat

► A_21_CaseA_NoTests_Run2_Inversion.bat

► A_21_CaseA_NoTests_Run3_Inversion.bat

And then generate reports so that we can examine the outcomes …

► A_30_CaseA_NoTests_MakeEvolutionMovie.bat

Play the movies (*EvolutionMovie_CaseA_NoTests_Run1…*, etc.). Some snaps from the Run1 movie are shown in Figure 1. Note that the movies – and Figure 1 – show the geology on Section 500N for ***individual*** models. Of the 100,000 models generated, the movies show 1 in every 500.

► A_31_CaseA_NoTests_MakeSuperSummaryStats.bat

The above 'statistics' are used to make the following products …

► A_32_CaseA_NoTests_MakeSectionImage.bat

The section images – showing the 'Probability of Slab (Formation)' for Section 500N are shown in Figure 2. These images are a *statistical report, derived from many models (5000 through to 100,000)*.

► A_33_CaseA_NoTests_MakeSectionMovie.bat

Play the movies (*SectionSweepMovie_CaseA_NoTests_Run1…*, etc.). These movies are very similar to the above section; they report the same *statistical* data, derived from *many* models. But, whereas the above is just one section (Section 500N), the movie is a *series of sections* that sweep across the model from south to north (there are 21 sections shown in the movie, sweeping from 0N to 1000N).

**RESULT** With no tests being performed at all – no asking "is this a valid geology model?" – the model rapidly deteriorates to random nonsense. After just 10,000 iterations (Figure 1) the geology model is quite meaningless.

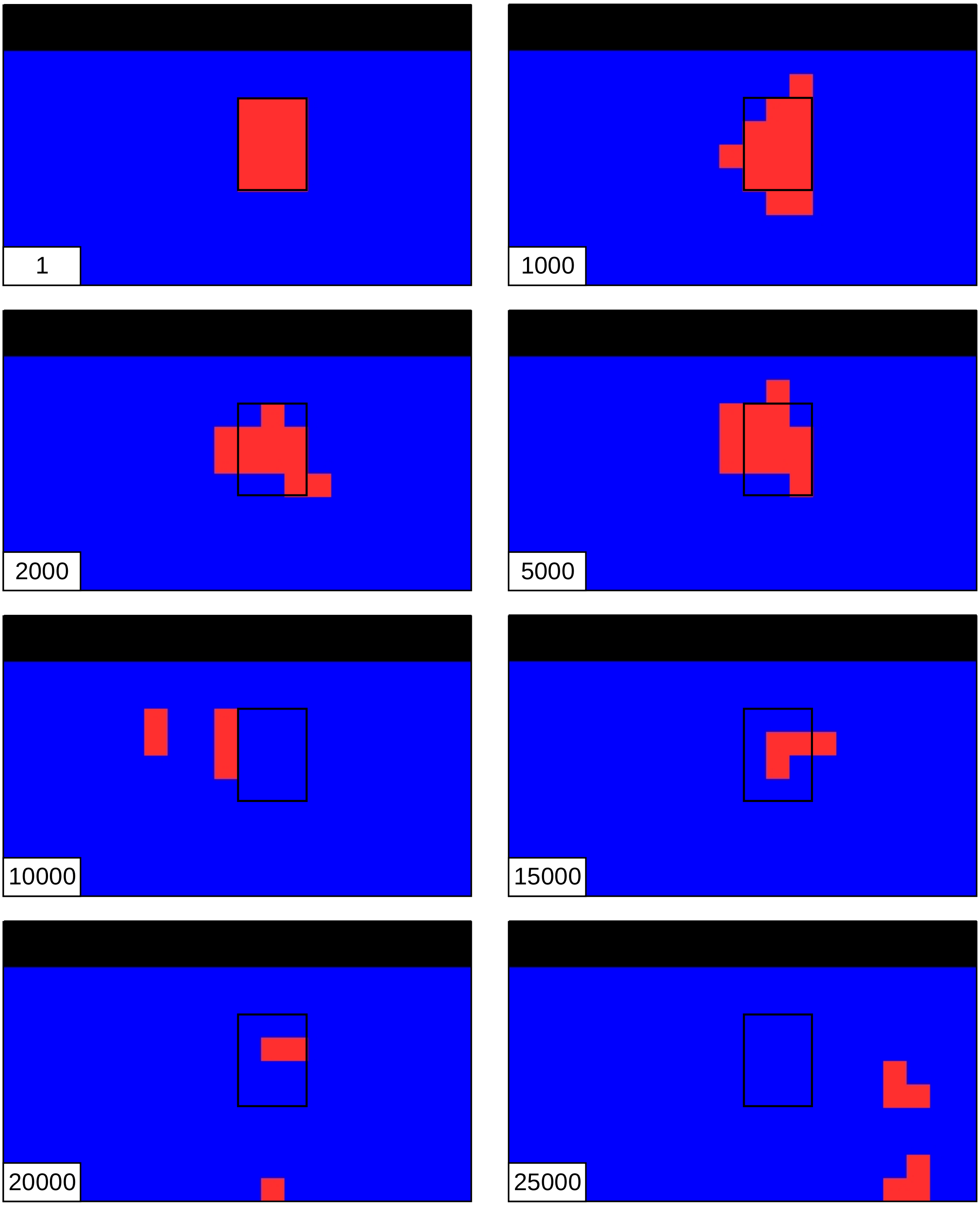



Figure 1. Images of Lithology on Section 500N for selected models generated in Run 1 for the ‘No Tests’ case. Host is blue, Slab is red. The eight individual models were those that existed at the iteration-number shown. Observe that the geology model rapidly deteriorates to a nonsense after only a few iterations. The box shows the location of the Reference Model.

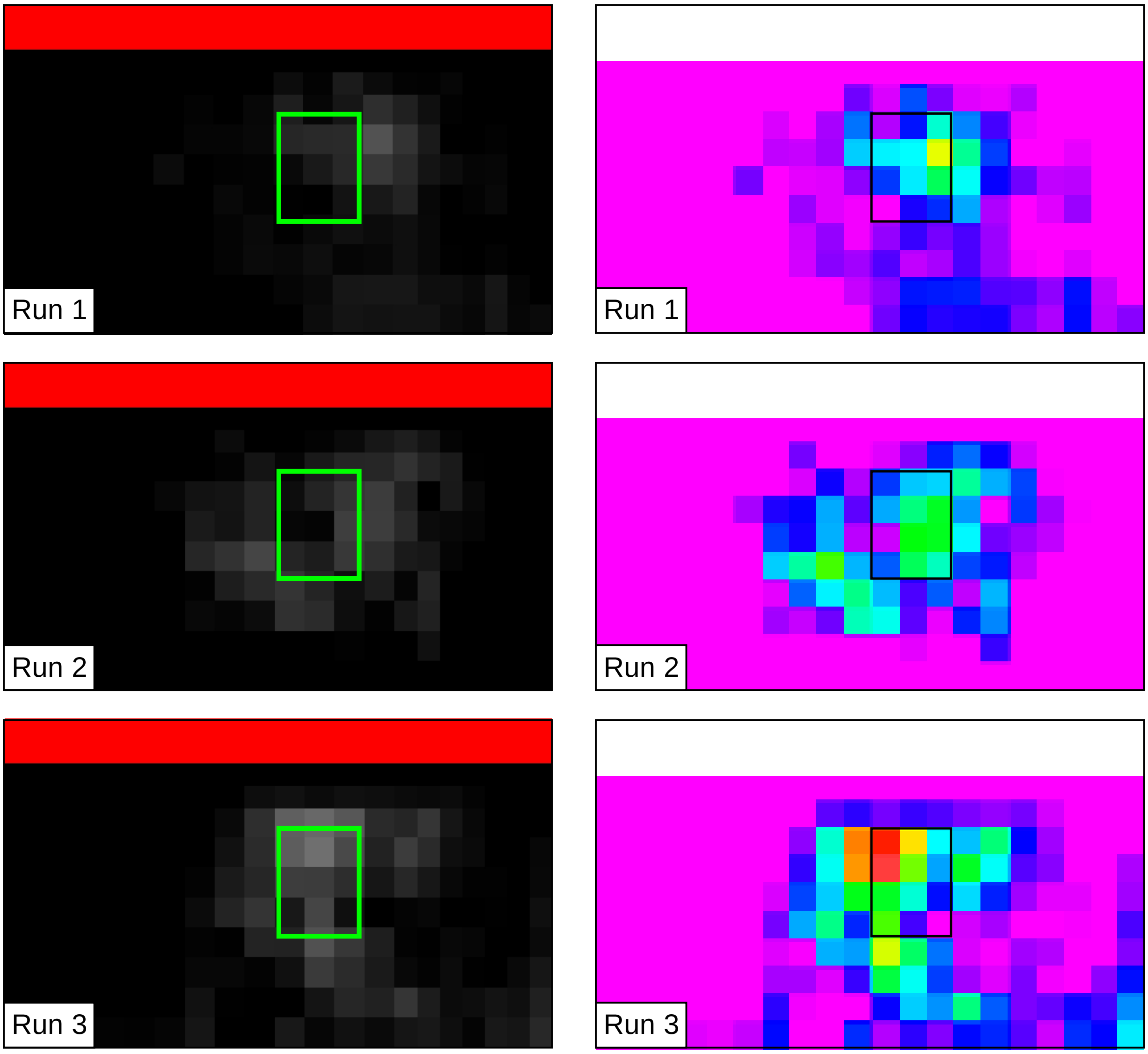



Figure 2. Images of ‘Probability of Slab’ geology on Section 500N for three different Runs of the ‘No Tests’ case. On the left are three JPGs as created by the MakeSectionImage command. On the right the same data using the ERS files (also created by MakeSectionImage) and displayed in Intrepid Visual using the same linear rainbow colour stretch for the three images (Range: 0% to 50% ‘probability of Slab’). Statistics derived from models 5,000 to 100,000. The box shows the location of the Reference Model.

## 2 PriorOnly – Tune the Commonality Parameter

PriorOnly 1 and AllowCommonalityTest 1

> In a nutshell: Do three or four Runs with different parameter values for the Commonality property. Start with higher values of the scale parameter (see below) and progress to lower values so that the appropriate value is bracketed (e.g., from lambda=1 to lambda=0.01). There will some extreme high or low values that are clearly undesirable, and an intermediate range within which any value would be acceptable.

For the Commonality property of geology formations we use a Weibull distribution. The Weibull distribution has two parameters ... Weibull($\lambda$, $\kappa$)

- 1st - $\lambda$ - a scale parameter - needs to be ***tuned*** for each inversion job
- 2nd - $\kappa$ - a shape parameter - we always use 1.0

(For $\kappa$=1.0, Weibull reduces to an exponential probability distribution)

If, for some geology formation, we were reasonably confident in our initial model then we might wish to specify that the inversion retains, say, an 80% overlap – or ***commonality*** - with that formation's voxels in the initial model ...

- for this, use $\lambda$=0.25 (see graph in Reference Manual)

For ***more confidence*** in my initial model ... more Commonality with initial voxels

- use a smaller value of $\lambda$ (e.g. 90% overlap or commonality ... use $\lambda$=0.1)

For ***less confidence*** in my initial model ... less Commonality with initial voxels

- use a larger value of $\lambda$ (e.g. 70% overlap or commonality ... use $\lambda$=0.5)

In Run_1 use $\lambda$=0.02 - a ***tight constraint*** on geology

... allows little change away from the initial model

In Run_2 use $\lambda$=0.2 - a ***looser constraint*** on the geology

... allows more change away from the initial model

In Run_3 use $\lambda$=2.0 - ***very little constraint*** on the geology

... allows almost any change away from initial model

In tuning the $\lambda$ parameter for ***your project***, try test cases that are too high and too low. It is recommended that you produce additional Runs as required until you have solutions that 'bracket' your chosen solution – i.e. you have a result demonstrating your considered choice of $\lambda$, and two alternative results that demonstrate the 'too constrained' ($\lambda$ too low) and the too un-constrained ($\lambda$ too high) cases.

This tuning process need not be too pedantic. It is really a matter of making a choice of $\lambda$ which is *OK to within an order of magnitude* … we do *not* need to do a 'fine tuning'!

**BATCH SCRIPTS**

Create a new Case … and set PriorOnly 1 … and turn on the Commonality test (AllowCommonalityTest 1) …

► B_20_CaseB_PriorOnly_TuneComm_CreateNewCase.bat

Three Runs, with the scale parameter (λ) of the Commonality set to 0.02, 0.2 and 2.0 respectively.

► B_21_CaseB_PriorOnly_TuneComm_Run1_0p02_100K_Inversion.bat

► B_21_CaseB_PriorOnly_TuneComm_Run2_0p2_100K_Inversion.bat

► B_21_CaseB_PriorOnly_TuneComm_Run3_2p0_100K_Inversion.bat

And then generate reports so that we can examine the outcomes …

► B_30_CaseB_PriorOnly_TuneComm_MakeEvolutionMovie.bat

Play the movies (*EvolutionMovie_CaseB_PriorOnly_TuneComm_Run1…*, etc.). Some snaps from the Run1 movie are shown in Figure 3. Note that the movies – and Figure 3 – show the geology on Section 500N for ***individual*** models. Of the 100,000 models generated, the movies show 1 in every 250.

**RESULT** The results presented in Figure 3 are very demonstrative of this tuning process. The Commonality property for the Slab geology will only influence any changes to voxels that are 'Slab' geology in the Reference Model – so - for the moment – *focus only the small rectangular box* representing the Slab geology in the Reference Model (marked in Figure 3 … but try to imagine it in the movies). If we do that, we clearly see three different results for the three settings of the λ parameter.

- For λ=0.02 a consistently high degree of 'overlap' or commonality with the Reference Model is maintained … perhaps 95 - 98%, say
- At the other end of the scale is the Run 3 result for λ=2.0 … and the commonality with the Reference Model is very low – less than 10%, say.
- Run 2 (λ=0.2) maintains a modest degree of commonality … perhaps 30 – 50%

Now generate the statistics for models 5000 through to 100,000 …

► B_31_CaseB_PriorOnly_TuneComm_MakeSuperSummaryStats.bat

► B_32_CaseB_PriorOnly_TuneComm_MakeSectionImage.bat

The section images – showing the 'Probability of Slab (Formation)' for Section 500N are shown in Figure 4. These images are a statistical report, *derived from many models*. Note that Figure 4 also shows results from the 'C' series of operations (see below) which were identical except that 1 million iterations were generated.

The colour plots are presented with identical colour range; pink = 0% probability, through to red = 100% probability (of Slab). If the statistics of the ERMapper grids are examined, the peak probabilities for the three Runs are: 97% for the λ=0.02, 60-70% for λ=0.2, and 33% for λ=2.0 The greyscale plots are comparable – but the colour plots highlight the differences more clearly?

Essentially these plots also demonstrate the higher degree of commonality maintained for λ=0.02, and the considerably lesser commonality for the other two Runs.

► B_33_CaseB_PriorOnly_TuneComm_MakeSectionMovie.bat

Play the movies (*SectionSweepMovie_CaseB_PriorOnly_TuneComm_Run1…*, etc.). These movies – like the greyscale section-images above – show the same outcome, but with less clarity that the other plots.

**ADDITIONAL BATCH SCRIPTS**

The following batch scripts execute identical tasks, except that 1 million iterations are produced.

► C_21_CaseB_PriorOnly_TuneComm_Run4_0p02_1M_Inversion.bat

► C_21_CaseB_PriorOnly_TuneComm_Run5_0p2_1M_Inversion.bat

► C_21_CaseB_PriorOnly_TuneComm_Run6_2p0_1M_Inversion.bat

These batch scripts report the results. Since these deal with 1 million iterations, a couple of the reporting commands use slightly different parameters.

► C_30_CaseB_PriorOnly_TuneComm_MakeEvolutionMovie.bat

The movies show similar results to those plotted in Figure 3; … just more of the same!

► C_31_CaseB_PriorOnly_TuneComm_MakeSuperSummaryStats.bat

► C_32_CaseB_PriorOnly_TuneComm_MakeSectionImage.bat

The section images are shown in Figure 4; the results are statistically ‘cleaner’, and the boundaries between zones of higher probability and lower probability (for the $\lambda$=0.02 and $\lambda$=0.2 Runs) are sharper.

► C_33_CaseB_PriorOnly_TuneComm_MakeSectionMovie.bat

**CONCLUDING REMARK re TUNING the COMMONALITY**

The choice of this commonality scale parameter ($\lambda$) needs to be guided by the behaviours demonstrated in these movies and section-images … and by our confidence in the geology model that we have constructed. For this Slab geology model, a value for $\lambda$ somewhere around 0.2 should be OK. If we have some nagging doubts about the reliability of the Reference Model – we may want not want to be too tightly constrained to that model … and could increase $\lambda$ a little. In the inversion processing examples for this Slab model a value $\lambda$=0.5 was used … allowing a little more scope for the inversion geology to more away from the Reference Model.

Do I really need to look at the movies? They’re a bit ‘gimmicky’ … don’t you think?

The images generated by MakeSectionImage present a result derived from all models … and is thus an average of many models. And these single images (from different Runs) should present results from which I can make choices about the choice of parameters.

The importance of the movies is that they show (a selection of) actual, individual geology models that did exist during the Run … and the acceptable choice of settings should also be clear from individual frames captured in an EvolutionMovie. Remember that each and every model generated must be acceptable as a viable geological configuration. We cannot rely on statistics to mask this requirement. The average of junk is junk.

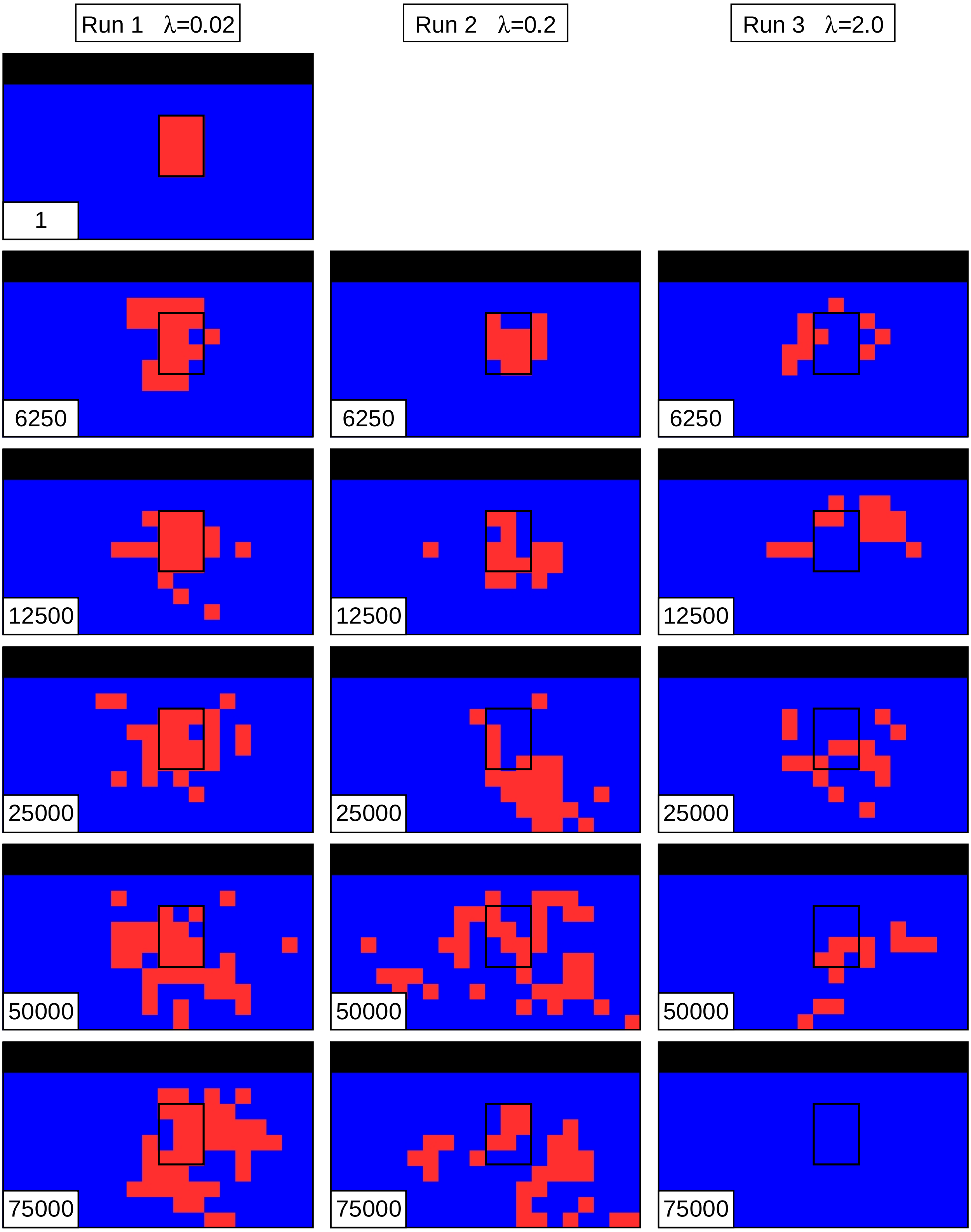



Figure 3. Images of Lithology on Section 500N for selected models generated in Run 1 (λ=0.02), Run 2 (λ=0.2) and Run 3 (λ=2.0) for the 'Tune Commonality' case. Host is blue, Slab is red. The fifteen individual models were those that existed at the iteration-number shown (for the respective Run). The box shows the location of the Reference Model. Observe the degree of overlap (or commonality with the Reference Model) that is maintained for the three values of λ - a high degree of commonality for the λ=0.02 Run, but very little commonality constraint for the λ=2.0 Run.

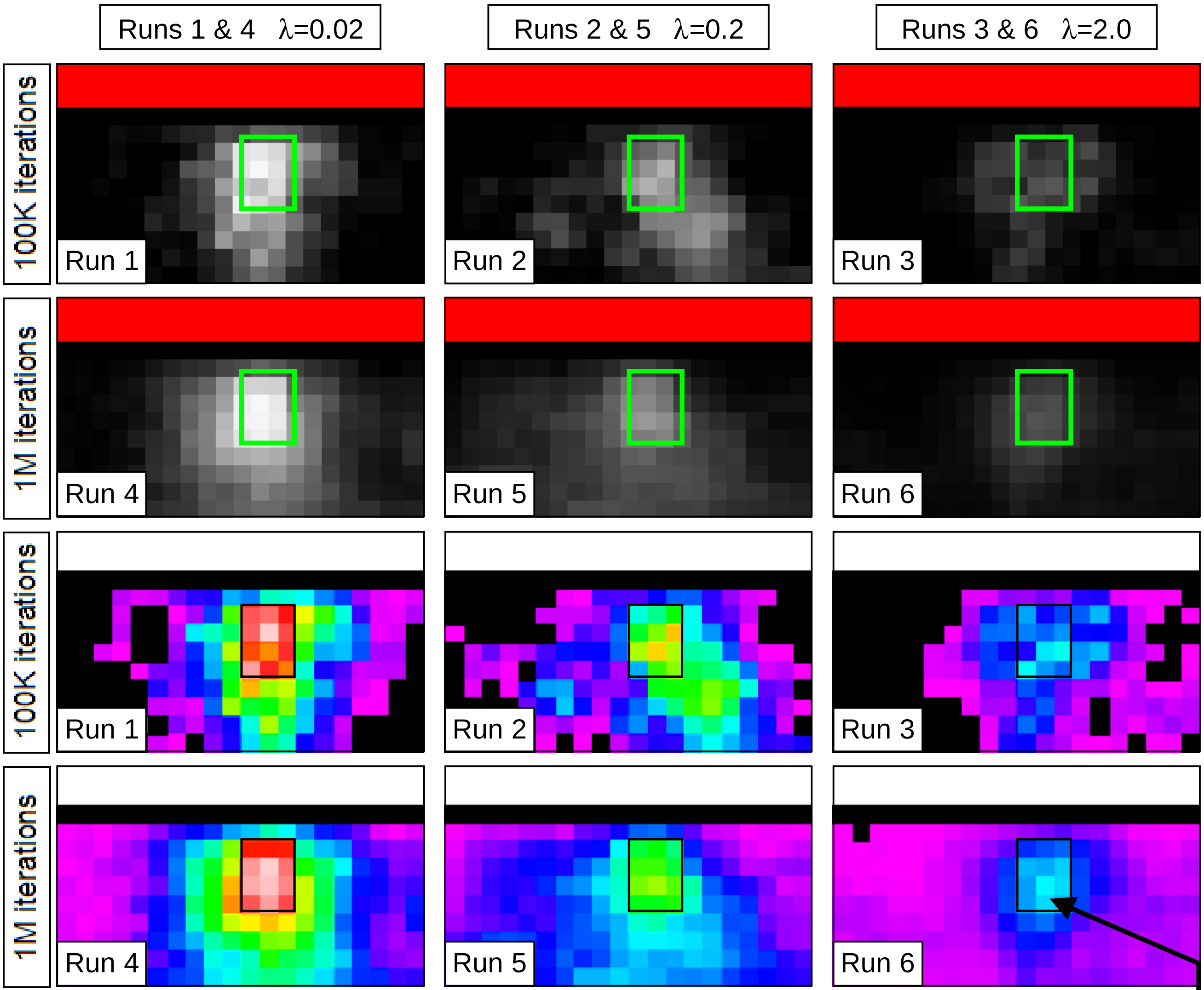



Figure 4. Images of 'Probability of Slab' geology on Section 500N generated in Runs 1 & 4 (λ=0.02), Runs 2 & 5 (λ=0.2) and Run 3 & 6 (λ=2.0) for the 'Tune Commonality' case. At the top are JPG images as created by the MakeSectionImage command. At the bottom the same data using the ERS files (also created by MakeSectionImage) and displayed in Intrepid Visual using the same linear rainbow colour stretch for the six images (Range: 0% to 100% 'Probability of Slab'). Statistics derived from models 5,000 to 100,000 for Runs 1, 2 & 3, and derived from models 5,000 to 1,000,000 for Runs 4, 5 & 6. The box shows the location of the Reference Model. Observe the degree of overlap (or commonality with the Reference Model) that is maintained for the three values of λ - a high degree of commonality for the λ=0.02 Runs, but very little commonality constraint for the λ=2.0 Runs. Note also the relatively noisier data from those Runs with 100,000 iterations compared to the statistically smoother results where 1,000,000 iterations were used.

PMM Note: Strictly the batch scripts need to be revised – to gather the statistics after a longer 'burn-in' phase – because the starting configuration is not representative of what eventuates. Eventually, λ=1.0 or higher ***should*** produce *low* probability (of Slab) ***almost everywhere***. The images above (for λ=2.0) show a higher probability at the original location of the Slab in the Reference Model because a large number of 'early models' have been included in the statistics.

## 2.1 Nonsense Geology Models?

We noted above that a high degree of commonality was maintained with the Reference Model (for λ=0.02, and acceptable commonality for λ=0.2). How can that be? … surely these models shown in Figure 5 are nonsense geology models? … these look nothing like our Reference Model!

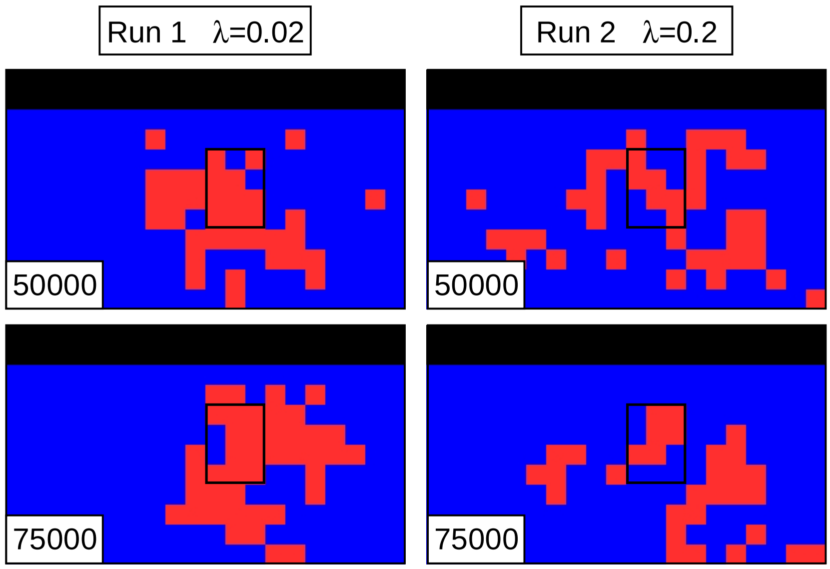



Figure 5. Images of Lithology on Section 500N for selected models generated in Run 1 (λ=0.02) and Run 2 (λ=0.2). (Extracted from Figure 3). Surely these models of the Slab geology are garbage?

Three comments …

- Yes … these models (shown in Figure 5) are nonsense! But ***we will shortly be turning on the ShapeRatio geology test***. These models have many voxels of Slab geology randomly spreading out into areas that were Host geology in the Reference Model. The impact of this is that the ***shape ratio*** for the Slab geology would be significantly higher in these geology models – compared to what it was in the Reference Model. (Shape ratio is the ratio of square root of Formation surface to the cube root of Formation volume).

  With the ShapeRatio test we will specify a constraint on the allowed variation of the Slab's shape ratio – and this will limit the tendency towards randomly distributed voxels of Slab geology. It will tend to maintain the Slab geology as a more coherent geology body.

- The considerable discussion with reference to Figure 3 above was entirely about the Commonality property ***for the Slab geology formation***. The setting of that property – for the Slab geology – ***only*** has an influence on those (relatively few) voxels that were Slab geology in the Reference Model. The Commonality property for Slab ***exerts no control*** over those many voxels of the Reference Model that were Host geology!

- OK … but we also set the same Commonality property for the Host geology. Check the batch scripts …

  *B_21_CaseB_PriorOnly_TuneComm_Run1_0p02_100K_Inversion.bat* has the following:

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab         Commonality Weibull(0.02,1.0) ^
 Host         Commonality Weibull(0.02,1.0)
```

  Why has this setting for the Host allowed so many voxels of Slab geology to now replace voxels that were Host in the Reference Model?

  The reason is that Host has something like 30x as many voxels as Slab … and it is quite easy - with this many voxels to work with – for the Host geology to maintain a very high degree of Commonality with the Reference Model – but at the same time allow what appears to be a large number of voxels of *other geology formations* to occur at voxels that *were* Host in the Reference Model.

  We **do not** recommend the following … but you could demonstrate this point with the following experiment. Try the same batch scripts … but set the Host's $\lambda$ parameter to a much more tightly constraining value … try $\lambda$=0.0002

  See *D_21_CaseB_PriorOnly_TuneComm_Run7_EXPERIMENT_100K_Inversion.bat* …

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
 Slab         Commonality Weibull(0.2,1.0) ^
 Host         Commonality Weibull(0.0002,1.0)
```

**EXPERIMENTAL BATCH SCRIPTS**

Compare the EvolutionMovies and the Section-Images for these 'D' series of scripts with the corresponding ones from the 'C' series.

► D_21_CaseB_PriorOnly_TuneComm_Run7_EXPERIMENT_100K_Inversion.bat

► D_21_CaseB_PriorOnly_TuneComm_Run8_EXPERIMENT_100K_Inversion.bat

► D_30_CaseB_PriorOnly_TuneComm_MakeEvolutionMovie.bat

► D_31_CaseB_PriorOnly_TuneComm_MakeSuperSummaryStats.bat

► D_32_CaseB_PriorOnly_TuneComm_MakeSectionImage.bat

## 3 PriorOnly – Tune the ShapeRatio Parameter

PriorOnly 1 and AllowCommonalityTest 1 and AllowShapeRatioTest 1

> In a nutshell: Do three or four Runs with different parameter values for the ShapeRatio property. Start with higher values of the spread measure (= std. dev.) parameter (see below) and progress to lower values. Typically start with spread measure = 0.20 (i.e. maintain ShapeRatio within 20%). For the Slab Project a value of 0.05 yielded acceptable results.

For the ShapeRatio property of geology formations always use a Log-normal distribution. The Log-normal distribution has two parameters ... Log-normal(mean, std. dev.)

Note: Strictly speaking the terms 'mean' and 'standard deviation' apply to normal distributions and are not correct for a log-normal distribution. A more generalised terminology would be …

Log-normal(central measure, spread measure)

- 1st parameter - central measure (= mean) - typically close to 0.0
- 2nd parameter – spread measure (=std. dev.) - needs to be ***tuned*** for each inversion job

Following notes 'pasted in' here; these are somewhat 'colloquial' notes that should be reviewed.

**Shape** is defined as the dimensionless number square_root (boundary_counts) / cube_root (volume_counts) where "boundary_counts" is the number of faces of voxels occupied by a particular formation that are in contact with voxels of another formation. Note that the RunControl parameter settings IncludeAboveTopoFacesInShapeRatio and IncludeOutsideFacesInShapeRatio control whether voxels in contact through a face to a voxel of the AboveTopo lithology or voxel faces forming part of the outside of the mesh contribute to the boundary_count. "volume_counts" is the number of voxels occupied by the particular formation.

**Shape*Ratio*** is the ratio of the Shape of the present model divided by the Shape of the same formation in the reference model.

For ShapeRatio always use Log-normal distribution.

If we want a 'shape' to be the ***same*** as the 'shape' in a Reference Model … the ratio for this case is 1. But since we use a log-normal distribution, we use the 'log of 1' … viz. 0

ShapeRatio Log-normal(central measure, spread measure)

### Central Measure (Mean) … the first parameter

The first parameter in setting the shape-ratio is the 'mean' … a mean of '0' is basically saying - maintain the initial (reference) shape ratio.

One is tempted to write "always use mean = 0" … but this is not strictly correct.

A very likely case is that my Reference Model is a slightly simplified, smoother model ('smoother' and thus pushing the 'shape-ratio' down to a relatively lower value). In practice, the evolving voxel-model of the inversion really must have some nooks and crannies and edges and protuberances and holes (i.e. tendency towards a higher shape-ratio) – ***and*** in the ***real geology world also*** the likelihood is that geology reality will also have these same 'rough' characteristics compared to an idealised, smooth Reference Model.

Thus … the ShapeRatio ‘mean’ could usefully be set to, say, 0.1 - meaning "I ***expect*** that the geology is actually ***rougher*** than my idealised starting model" … rougher to the tune of 10% higher shape-ratio. Specifying this mean will actually ***push*** the evolving (inversion) model ***away from*** the reference shape-ratio, and towards a rougher model.

But note also … you could set the ‘mean’ to be -0.1 … meaning I want to ***force*** the model in the direction of ***becoming smoother*** than my starting model. It is not easy to visualise a case where you might choose to do this, but one possible example: Imagine you choose a voxel model from some point along the progress of a ***previous*** inversion Run, and chose to use that (probably ‘rough’) model as the Reference (starting) Model for a new inversion Run. You might say “this is a suitable Reference Model … but it’s a bit rough … I want a result that is smoother than this!” If you specify, say, ‘mean’ is -0.1 you are saying “I want the result to have a ShapeRatio that is about 10% smoother than in my Reference Model”

### Spread Measure (Standard Deviation) … the second parameter

This is the parameter that should be *tuned* by doing a small series of PriorOnly Runs.

Start with a value which is too large: say, 0.2 (=allow 20% variation of ShapeRatio away from the Reference). This will allow the changing geology model to change significantly away from the ‘shape’ defined in the Reference Model.

Do a series of Runs using progressively lower values for the spread measure. For the Slab Project a value of 0.05 is good - representing "allow 5% variation of ShapeRatio"

If I chose 0.01 – I’d probably have too many rejections; many of the proposed changes that are put up for consideration would be knocked out by this tight criterion to maintain a ShapeRatio closely aligned with the reference model.

On the other hand, 0.2 (= allow 20% variation) is pretty much saying ‘allow anything’. In fact, a very large spread measure for the ShapeRatio starts to emulate the PriorOnly No-Tests case (which is essentially allow ‘infinite’ variation of shape-ratio).

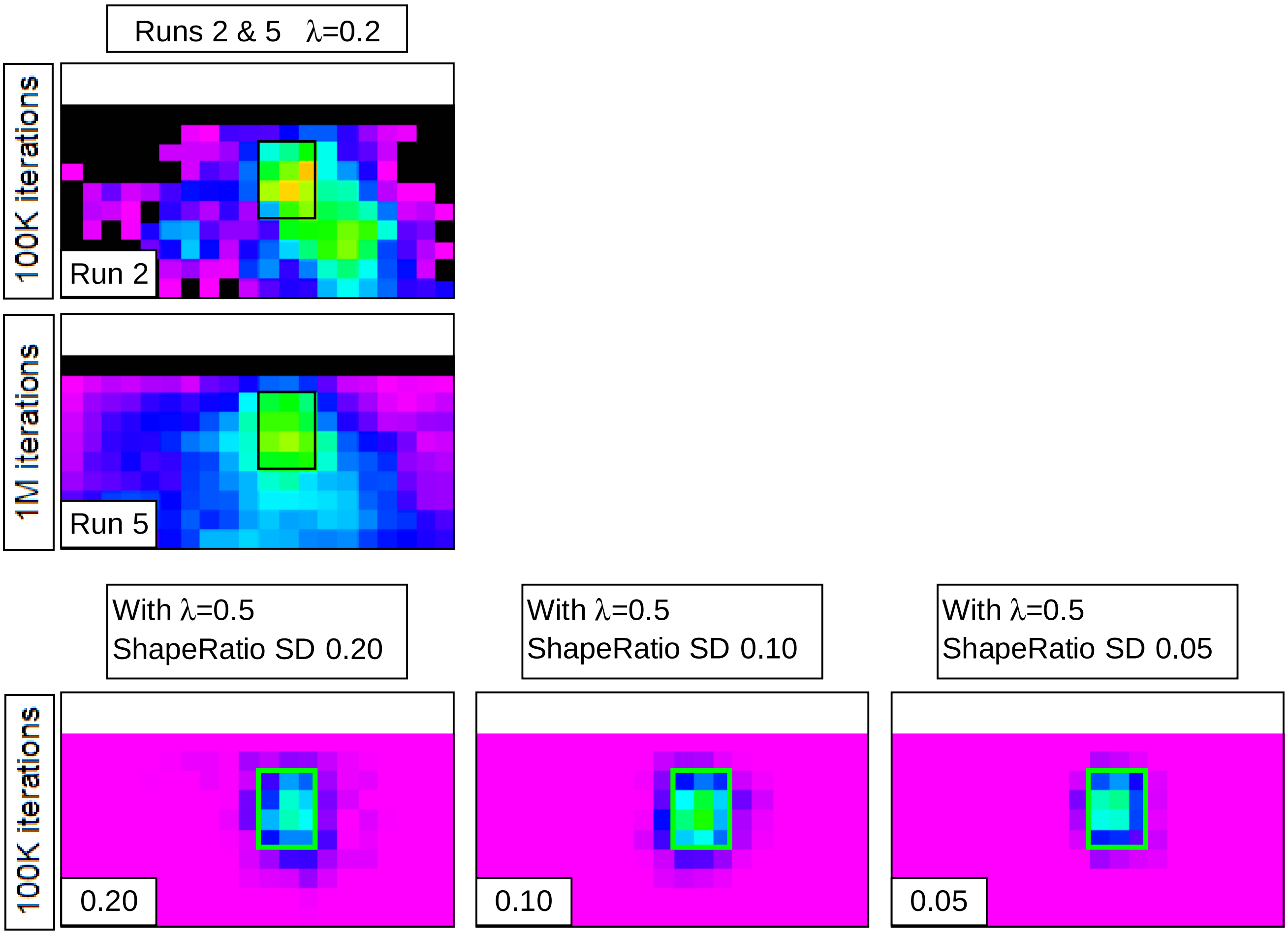



Figure 6. Images of 'Probability of Slab' geology on Section 500N. Upper two images from the 'Tuning Commonality' Runs 2 & 5 ($\lambda$=0.2) and ShapeRatio testing 'turned off'. Lower three images from 'Tuning ShapeRatio', using three different values for the 'spread measure' of the ShapeRatio log-normal distribution. Turning 'on' the ShapeRatio test produces a much more constrained set of 'new' geology models. All images from the ERS files (created by MakeSectionImage) and displayed in Intrepid Visual using the same linear rainbow colour stretch for the five images (Range: 0% to 100% 'Probability of Slab'). The box shows the location of the Reference Model.

## After Tuning Commonality, ShapeRatio

Turn on the Geophysics Tests





## PriorOnly Revisited

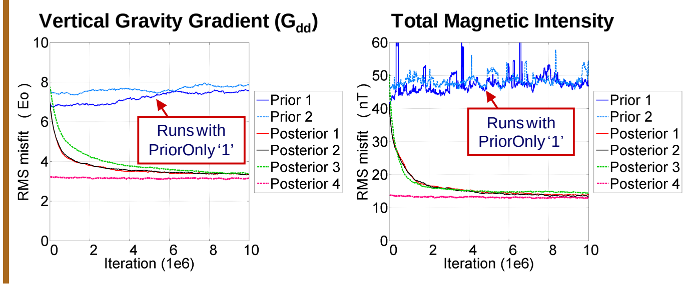
- Tuning Commonality and ShapeRatio were done with PriorOnly ‘1’ … meaning that ‘prior’ knowledge (i.e. geology) only was used, and no geophysics testing was performed
- With the geophysics tests turned ‘off’, the inversion proceeds without any bias towards improved misfit … and you see this in the misfit plot …





## Bet Bet: Evolution of Data RMS Misfit

With PriorOnly ‘1’ … All ‘model acceptances’ are based entirely on whichever of the geology tests are turned ‘on’. These have a completely random effect of whether the geophysical misfit is better or worse!








## Turn Geophysics Tests ‘On’

- Set PriorOnly to ‘0’ to now ‘turn on’ the geophysics testing.
- Set the number of iterations large enough to be gathering statistically meaningful statistics (from that portion of iterations where there is a low misfit between the computed and observed geophysics
- Do repeated inversion Runs … and compare outcomes. With MakeSuperSummaryStats you can gather together the statistics from several Runs





## Other Geology Tests

- CommonalityVolume – see notes
- VolumeRatio – see notes
- ProbabilityOfPropertyChangeOnly
  - follows … Not really a ‘test’ – but influences how an inversion proceeds
- Topology Operators – see notes
- PreserveVerticalRelationship
  - next





## ProbabilityOfPropertyChangeOnly

- ProbabilityOfPropertyChangeOnly: default 50 - which means a 50% chance of doing a property change only (i.e. no change to a voxel’s lithology), and a 50% chance of possibly changing a boundary (by changing a voxel’s lithology). Setting this to 100 will generate a Run which does property changes ***only***, and never changes geology boundaries
- Recommended: ProbabilityOfPropertyChangeOnly 100 … to test the behavior of the inversion for this scenario of only properties being allowed to vary, and there being no lithology changes

GeoModeller Stochastic Exploration

# PreserveVerticalRelationship

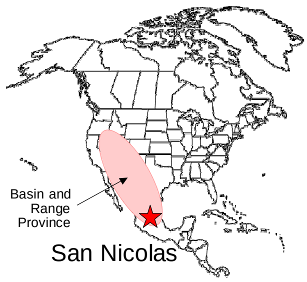
GeoModeller Stochastic Exploration

## Preserve Vertical Relationship

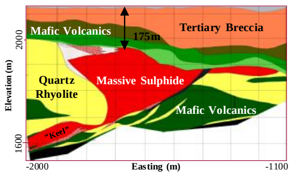
- One of the key features of GeoModeller (Gravity/Mag) Inversion is that we apply *geology tests* …
  - – Is this proposed geology model still a valid geology model?
  - – e.g. 'commonality', 'shape-ratio'
- PreserveVerticalRelationship is a new, practical geology test that we can apply

GeoModeller Stochastic Exploration

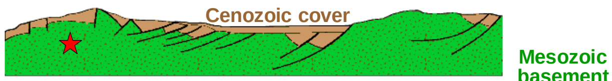
## San Nicolas VMS deposit, Mexico



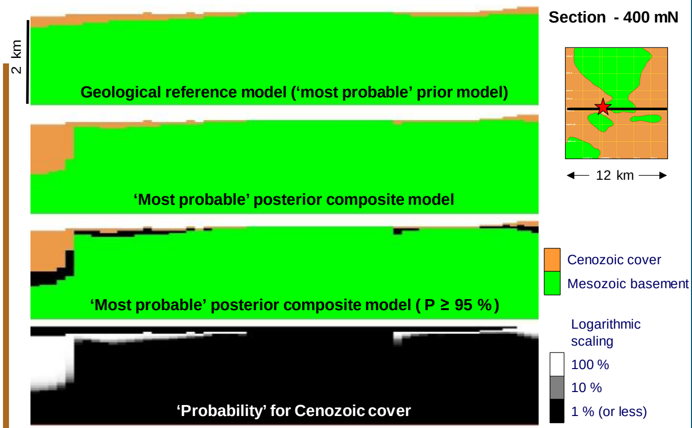

Vertical section -400 mN




(Section from Phillips et al., 2001)




(Section adapted from a figure supplied by the USGS)




( Vertical exaggeration 1:1 )

Movie - Without

Movie – With PVR

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

- PreserveVerticalRelationship is a new command within the group of CaseControl SetLaw commands
- The recommended practice is to structure the command an as n x n array of 0=off / 1=on switches

CaseControl SetLaw Command …

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

For a Project with *N* formations there must be *N* entries (of '0' or '1') within the brackets. These entries refer to each formation in order from youngest (left) to oldest (right).

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

For clarity, it is recommended you have an entry for every formation in the Project, and that these be listed in order from youngest (top) to oldest (bottom).

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

is always above

Form. 'B'

Form. 'A'

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

'0' implies no specific relationship

'1' enforces a vertical relationship …
Formation 'A' is always above Formation 'B'

3D GeoModeller



INTREPID GEOSCIENCE brgm

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

is always above

Form. 'B'

Form. 'A'

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

If you layout the command in this way then '1' entries …
- *above* the diagonal refer to *normal* relationships
- *below* the diagonal refer to *overturned* relationships

3D GeoModeller



INTREPID GEOSCIENCE brgm

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

is always above

Form. 'B'

Form. 'A'

| | T | P | B |
|---|---|---|---|
| T | 0 | 1 | 1 |
| P | 0 | 0 | 1 |
| B | 0 | 0 | 0 |

Normal Relationships
… '1' means *is always above*

Tertiary is always above Palaeozoic

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

3D GeoModeller



INTREPID GEOSCIENCE brgm

GeoModeller Stochastic Exploration

## Preserve Vertical Relationship Command

is always above

Form. 'B'

Form. 'A'

| | T | P | B |
|---|---|---|---|
| T | 0 | 0 | 0 |
| P | 1 | 0 | 0 |
| B | 0 | 0 | 0 |

```
call %DoTask% %CaseXML% CaseControl SetLaw ^
Tertiary     PreserveVerticalRelationship (0,1,1) ^
Palaeozoic PreserveVerticalRelationship (0,0,1) ^
Basement  PreserveVerticalRelationship (0,0,0)
```

Palaeozoic is always above Tertiary

Overturned Relationships …
'1' means *is always above*
(this would be quite rare!)

3D GeoModeller



INTREPID GEOSCIENCE brgm

### 3.2.8 SetReferenceLithology (Default: the Case Voxet) - EDIT

The SetReferenceLithology command is used to specify a ***reference geology model*** … the Reference Lithology Voxet. This reference geology model is used by the commonality tests. See Notes.

ManageLithoInversion <CaseXML> CaseControl SetReferenceLithology <ReferenceLithologyVoxetPath>
where

- <ReferenceLithologyVoxetPath> = the relative (or absolute) path and filename of a 'reference Voxet geology model' – see Notes.

Notes:

- This command updates the ***inversions.xml*** file. This is the all important file that contains all the process instructions for your current case and run!!
- The Reference Lithology Voxet can be any Voxet which has the same dimensions as the Voxet geology model being inverted, and which has a field called Lithology, where the Lithology field contains only integers in the range 0-n, corresponding to the 0-n lithology entries listed in the *inversions.xml* file.
- The default - if not explicitly set by this command – is the Case Voxet … the voxel geology model created by the NewCase command (Figure 19, top).
- It is not uncommon to continue an inversion Run from, say, the end of an earlier Run. For this case, the Initial Voxet would be derived from ***the final iteration of the earlier Run***, but the Reference Lithology Voxet might be set explicitly with the SetReferenceLithology command to be ***the Initial Voxet of the earlier Run***. In this way, the commonality tests for the re-started Run would continue to be ***with reference to the original starting model of the earlier Run*** (Figure 19, bottom).
- Whilst the above two examples are typical, the Reference Lithology Voxet may be ***any*** appropriate Voxet … possibly even constructed using third-party software.

Comment – Commonality Tests: The commonality tests are one of the mechanisms for setting ***geological constraints*** which are designed to limit the geology-voxel-model-changes that can be proposed, such that the evolving geological model ***always remains a realistic geology model***. This geological realism is achieved by specifying that the progressively changing (inversion) geology model must maintain some reasonable degree of ***commonality*** with reference to a specified Reference Lithology Voxet. For more details, see …

- Section 3.2.9.5… specifying the degree of commonality – this is a setting of a 'property law'
- Sections 9.1.1, 9.1.2 … turning 'on' the commonality tests

In all CaseControl commands …

- <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case.

#### 3.2.9.5 SetLaw Type 2: Inversion Control Properties of Geology Formations - EDIT

The CaseControl SetLaw command is also used to set *inversion control properties* of geology formations. These additional properties of the geology formations are used to 'control' or 'limit' the changes to geology formation boundaries that can be proposed during the inversion iterations. There are six ***inversion control properties*** that can be set: Movable, Index, Commonality, CommonalityVolume, ShapeRatio and VolumeRatio.

**For Property = Movable**

- Syntax: Formation Movable <0 | 1> where
    - < 0 | 1 > 0=the voxels assigned to this formation can be considered for change (default), 1=all voxels assigned to the formation will be considered fixed.
- Examples: Formation Movable 1

**For Property = Index**

- Syntax: Formation Index <integer> where
    - < integer > the voxel value assigned to this formation within the voxet. This is useful when setting the initial lithology from a voxet created by some third-party software.
- Examples: Formation Index 6

**For Property = Commonality**

- Syntax: Formation Commonality <StatisticalLaw> … where …
    - <StatisticalLaw>=< Weibull | Rayleigh >
    - Associated parameters for Weibull are lambda and kappa, whilst the associated parameter for Rayleigh is beta.
- Examples: Formation Commonality Rayleigh(beta)

  Formation Commonality Weibull(lamda,kappa)

  Pitfield_Volcanics Commonality Rayleigh(0.20)

  Ercildoun_Granite Commonality Rayleigh(0.20)

A Weibull distribution has Weibull (lambda, kappa), where lambda>0 is the scale parameter and kappa>0 is the shape parameter. It is defined for x>=0. The probability density function is (kappa/lambda) * (x/lambda)^( kappa -1) * exp(-(x/lambda)^kappa), where x is the Commonality Misfit function defined below. We would typically use kappa=1 for Commonality, in which case, it reduces to an exponential PDF. The expected value is lambda*F(1+1/k) where F() is the gamma function. If we were 80% confident in the location of a formation, we would specify Weibull(0.25, 1) for Commonality.

$$\text{Commonality}(j) = \frac{Same(j)}{Ref(j)}$$

| |
|---|
| In all CaseControl commands … |
| • <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case. |

$$\text{Commonality } Misfit(j) = \frac{1}{Commonality(j)} - 1$$
$$= \frac{\|Ref(j)\|}{Same(j)} - 1$$

where $j$ is the index for a movable formation, $\|$ means the length or number of elements, $Ref(j)$ is the set of voxels assigned to this formation in the reference geological model, and $Same(j)$ is the number of voxels in the intersection between the set of voxels in the current model assigned to this formation and $Ref(j)$.

For a Rayleigh distribution, the probability density function is given by

((ratio-1)/b^2).exp(-((ratio-1)^2)/(2b^2)).

A Weibull distribution has Weibull(lambda, kappa), where lambda>0 is the scale parameter and kappa>0 is the shape parameter. It is defined for Commonality Misfit >=0. The probability density function is

(kappa/lambda) * ((x/lambda)^(k-1)) * exp(-(x/lambda)^kappa).

The expected value is lambda*F(1+1/k) where F() is the gamma function. If we use kappa=1 for Commonality, the Weibull distribution reduces to an exponential-type PDF, whilst if we use kappa=2, the Weibull distribution reduces to an Rayleigh-type PDF

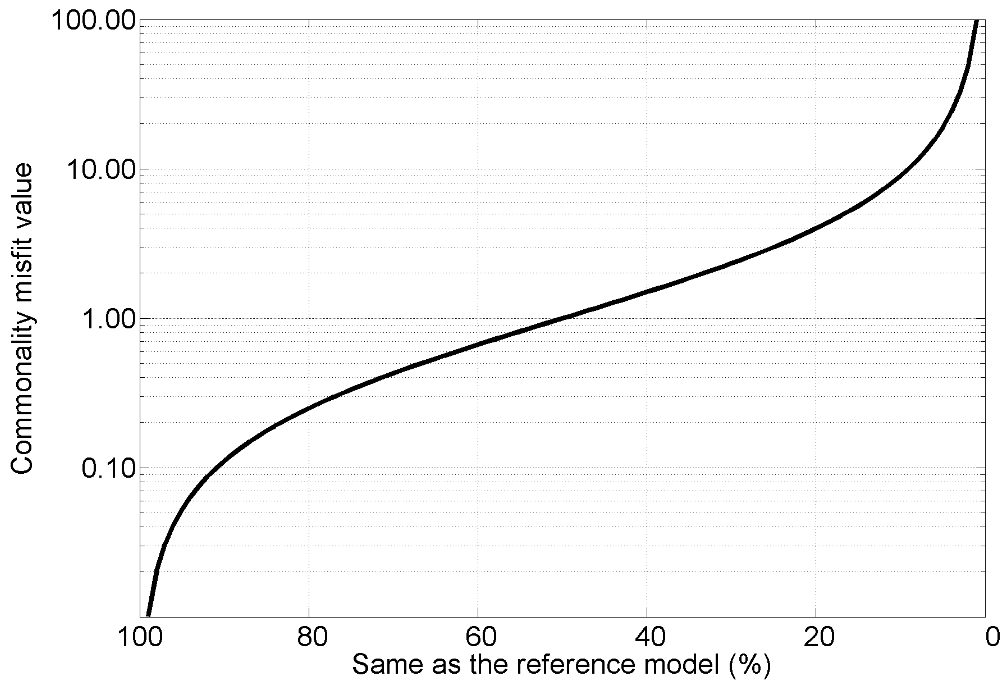



Figure 21. Graph showing the relationship between “Same” and Commonality Misfit.

| |
|---|
| In all CaseControl commands … |
| • <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case. |

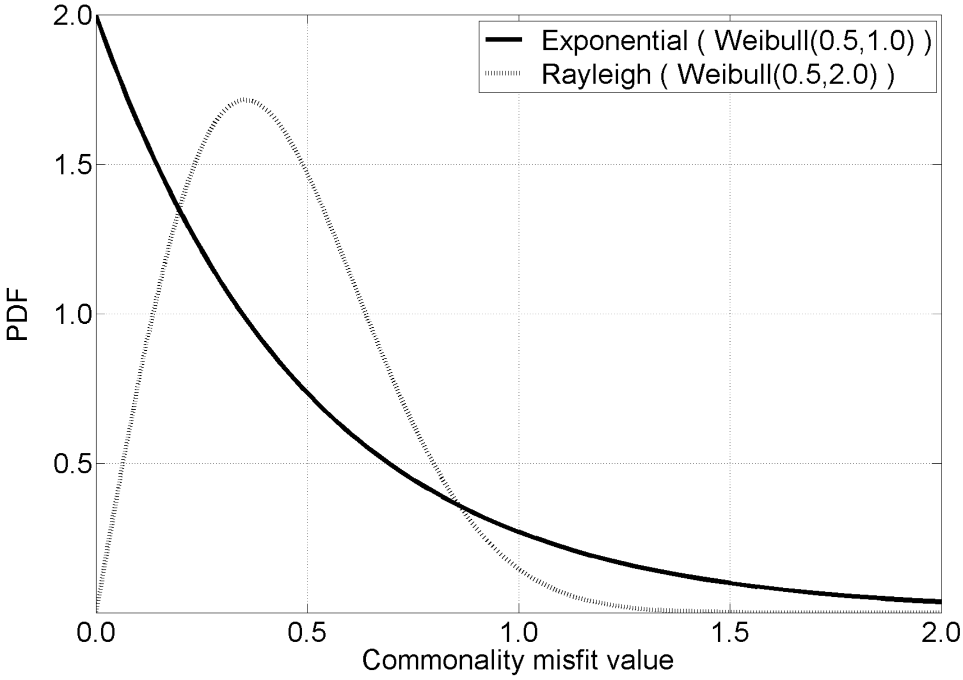



Figure 22. Plots of Commonality Misfit and the probability distribution function (PDF) for two different Weibull specifications.

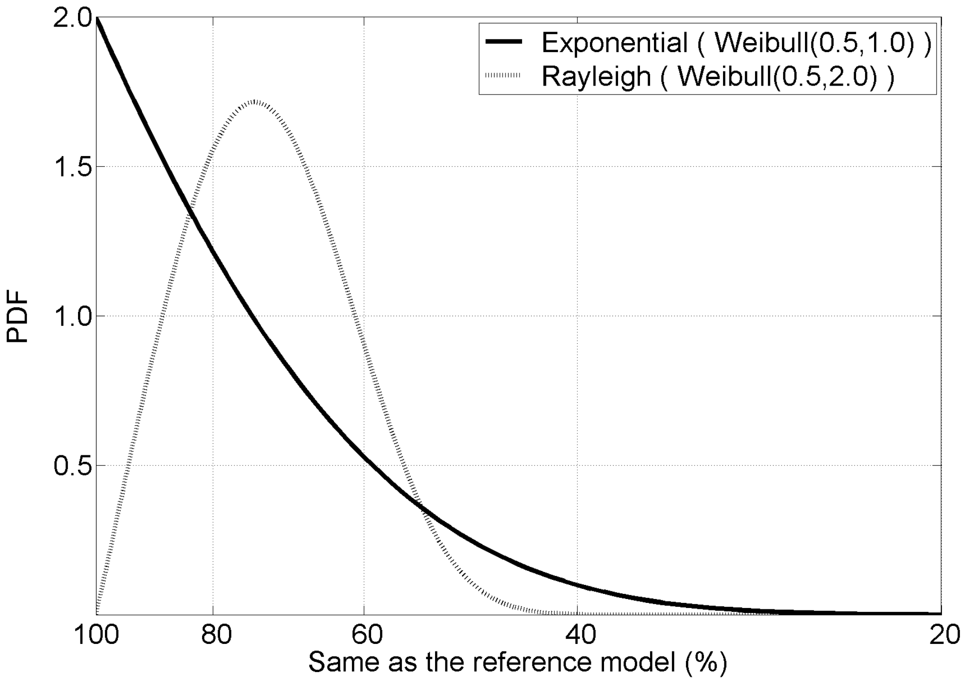



Figure 23. Plots of “Same” and the probability distribution function (PDF) for the same two Weibull specifications given in

In all CaseControl commands …

- <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case.

the figure above.

Users need to make their choice of kappa and lambda to suit their prior knowledge of the geology in comparison with the representation in the reference model.

Use of kappa=1 is akin to saying that the reference model is the best estimate of the geology and this should be the most likely arrangement presented for evaluation with respect to the potential field data. Lambda is an expression of the uncertainty, with larger values indicating greater uncertainty in the arrangement in the reference model.

Use of kappa>1 indicates that we are absolutely certain that the arrangement in the reference model is wrong, but that the arrangements to be sent for evaluation should still have a degree of similarity with the reference model. The arrangement in the reference model has a zero probability of being sent for evaluation.

In mathematical terms, for kappa=1, the Weibull distribution is identical to an exponential-type distribution with the PDF for Commonality Misfit=0 (i.e., Commonality=1) being 1/lambda. For kappa=1+eps, the Weibull distribution begins a transition to more bell shaped distributions (such as the Rayleigh distribution), and the PDF for Commonality Misfit =0 is 0. The mode (peak of the PDF) is at lambda*pow((kappa-1)/kappa,1/kappa) for kappa>1.

For kappa=1, this peak is at zero. With kappa>0 (and constant lambda), the peak moves to increasing values as kappa increases. Note that for kappa=2, the Weibull distribution is identical to a Rayleigh-type distribution.

## For Property = CommonalityVolume

- Syntax: Formation CommonalityVolume <StatisticalLaw> … where …
  - <StatisticalLaw>=< Normal | LogNormal | Poisson | Equal | EqualPlus | EqualMinus | Weibull | Rayleigh >
  - Associated parameters: PercentageOfCommonalityVolume,
- **Units for CommonalityVolume**: CommonalityVolume central values (e.g., mean for a Normal distribution) and spread parameters (e.g., standard deviation for a Normal Distribution) are expressed as a percentage.
- Examples: Formation CommonalityVolume Normal(0,5)

  Pitfield_Volcanics Commonality Normal(0,1)

  Ercildoun_Granite Commonality Normal(0,1)

If we define "Same(j)" to be the number of voxels in the intersection of the lithological region(s) for the “$j^{th}$” formation between the reference and the present model, "gain(j)" is the number of voxels in the present model that are outside the region occupied by this formation in the reference model, and "loss(j)" is the number of voxels in the reference model that are outside the region occupied by this formation in the present model, then CommonalityVolume is given by

Commonality Volume = 100 * ( gain(j) - loss(j) ) / Same(j)

"Commonality Volume" might be assumed to have a normal distribution with a user-specified mean and standard deviation, for example, a mean of zero and standard deviation of 5%.

With this constraint operating, we might reasonably expect that the most probable model from a Prior Only run would have no net gain or loss (and hence this is a volume constraint) and a large number of voxels in common with the reference model (and hence it is a Commonality constraint).

In all CaseControl commands …

- <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case.

"Commonality Volume" is not as restrictive as FixedCells, because we don't need to specify which cells are in common with the reference model, but each of the modified models ought to look a lot like the reference model! With informative geophysical data, we would preferentially accept and keep models with slightly biased characteristics (except in the very unlikely situation that the reference model is completely compatible with the geophysical data). Thus, any difference in the most probable model could be immediately interpreted as being a consequence of the geophysical data.

## For Property = ShapeRatio

- Syntax: Formation ShapeRatio <StatisticalLaw> … where …
  - <StatisticalLaw>=< Normal | LogNormal | Poisson | Equal | EqualPlus | EqualMinus | Weibull | Rayleigh >
  - Associated parameters: Mean, StandardDeviation

Examples: Formation ShapeRatio LogNormal (mean, std)

Pitfield_Volcanics ShapeRatio LogNormal(0,0.05)

"Shape" is defined as the dimensionless number square_root (boundary_counts) / cube_root (volume_counts) where "boundary_counts" is the number of faces of voxels occupied by a particular formation that are in contact with voxels of another formation. Note that the RunControl parameter settings IncludeAboveTopoFacesInShapeRatio and IncludeOutsideFacesInShapeRatio control whether voxels in contact through a face to a voxel of the AboveTopo lithology or voxel faces forming part of the outside of the mesh contribute to the boundary_count. "volume_counts" is the number of voxels occupied by the particular formation.

ShapeRatio is the ratio of the Shape of the present model divided by the Shape of the same formation in the reference model.

We might expect that the ratio of present to reference values for a collection of models where the regions for each formation have similar shapes might be a population with a LogNormal distribution. A specification of LogNormal(0,0.05) would indicate a mean VolumeRatio of 1 and a standard deviation of 5%. Due to the competing influences of many constraints, this tight specification would be unlikely to be achieved, but might produce a satisfactory constraint over the ShapeRatio values observed in the proposed models. PriorOnly runs should be used to establish appropriate settings for the geological test parameters.

## For Property = VolumeRatio

- Syntax: Formation VolumeRatio <StatisticalLaw> … where …
  - <StatisticalLaw>=< Normal | LogNormal | Poisson | Equal | EqualPlus | EqualMinus | Weibull | Rayleigh >
  - Associated parameters: Mean, StandardDeviation

Examples: Formation VolumeRatio LogNormal(mean, std)

Pitfield_Volcanics VolumeRatio LogNormal(0,0.01)

VolumeRatio is defined as the ratio of the number of voxels in the present model assigned to a particular formation divided by the number of voxels assigned to this formation in the reference model.

In all CaseControl commands …
- <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case.

We might expect that the VolumeRatio for models with similar proportions might be a population with a LogNormal distribution. A specification of LogNormal(0,0.01) would indicate a mean VolumeRatio of 1 and a standard deviation of 1%. Due to the competing influences of many constraints, this tight specification would be unlikely to be achieved, but might produce a satisfactory constraint over the VolumeRatio values observed in the proposed models. PriorOnly runs should be used to establish appropriate settings for the geological test parameters.

In all CaseControl commands …

- <CaseXML> = the relative (or absolute) path of the XML project file for the GeoModeller inversion Case.

Notes on Topology Operators from …

Physics of the Earth and Planetary Interiors 171 (2008) 158–169

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

# Geological modelling from field data and geological knowledge Part II. Modelling validation using gravity and magnetic data inversion

A. Guillen[a,*], Ph. Calcagno[a], G. Courrioux[a], A. Joly[b], P. Ledru[a]

[a] BRGM, BP 6009, 45060 Orléans Cedex 02, France
[b] Centre for Exploration Targeting, M006, 35 Stirling Highway CRAWLEY WA 6009, Australia

ARTICLE INFO

*Article history:*
Received 31 October 2007
Received in revised form 24 April 2008
Accepted 11 June 2008

*Keywords:*
3D geology
Inverse problem
Metropolis
Potential field
Probability
Gravity
Magnetism
Tensors

ABSTRACT

The analysis of multiple data sets is required to select a realistic 3D geological model among an infinite number of possibilities. An inverse method that aims at describing the 3D geometry of geological objects is presented. The method takes into account the geology and the physical properties of rocks, while respecting the topological properties of an a priori model. The a priori model is built from the geological data set and its geometry is largely dependent upon assumptions about inaccessible geology at depth. This method, referred to as "total litho-inversion" is a generalised 3D inversion that results in quantifying the lithology and the distribution of rock property in a probabilistic way. Its application is demonstrated through (i) a simple synthetic case and (ii) the relative distribution characterization of granites and diorites in an orogenic domain.



## 7. Disturb the model: erosion, dilation, opening, closing

### *7.1. Preservation of an acceptable geometry*

From the convergence point of view, the Metropolis algorithm is designed to obtain geophysical effects in the final models that are close to the measured effect. Unfortunately the geological contents of the 3D models can lose their consistency, with various geologi-

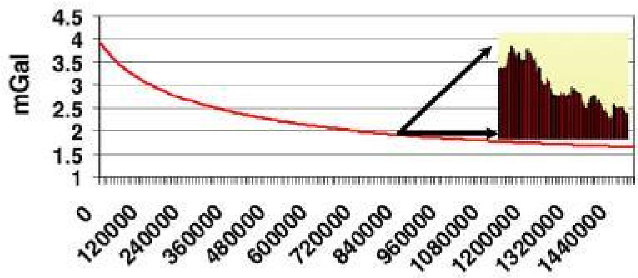



**Fig. 1.** Evolution of the likelihood, showing that in some areas it can increase to explore the space model.

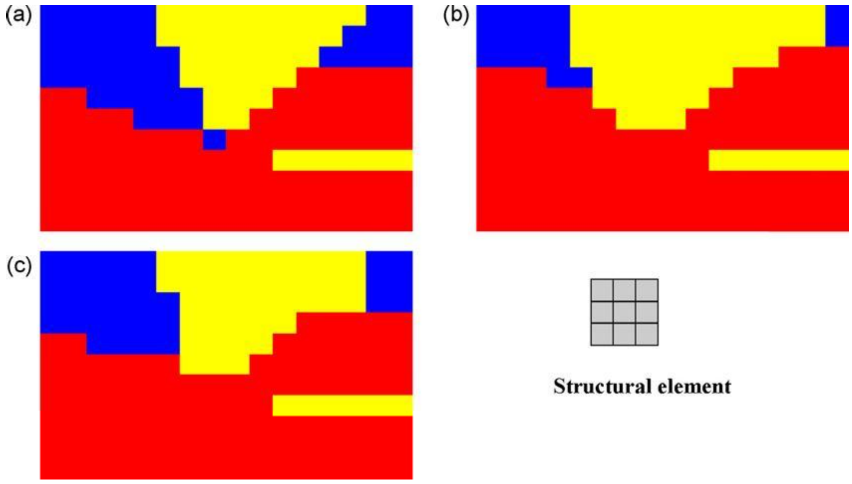



**Fig. 2.** (a) The geological model. (b) Same model after an erosion of the blue unit. (c) Dilation applied to (b), which represents an opening on blue unit of the original model in (a).

cal layers losing their homogeneity and their cells being scattered. The method is able to optimize a mathematical criterion effectively, but fails to guarantee that the model obtained will be geologically acceptable. For this reason, during the inversion process, at Step 9, after some iterations a morphology-based operation is applied to homogenise the current model (Serra, 1982, 1988). Erosion, dilation and their combinations are used to:

- add or remove voxels from the boundaries of features in order to smooth them;
- join separated portions of features or separate touching features;
- remove isolated voxels, representing noise, from the model.

Dilation turns voxels “on” according to rules based on the number or arrangement of neighbouring voxels; erosion turns pixels “off” according to similar rules, while Opening – an erosion followed by a dilation – and Closing – the reverse sequence – attempt to restore the original features but with some rearrangement of the boundary pixels. These operations will control the “quality” of the model.

### 7.2. Definitions

The object **A** consists of those voxels $v$ that share some common property. In our case, **A** is the set of voxels which are in the same geological unit:

Object $\mathbf{A} = \{v | \mathrm{property}(v) == \mathbf{TRUE}\}$

The background of **A** is given by $\mathbf{A}^c$ (the complement of **A**) which is defined as those elements that are not in **A**:

Background : $\mathbf{A}^c = \{v | v \notin \mathbf{A}\}$

We will define quickly the fundamental operations associated with an object in mathematical morphology. The standard set operations are union, intersection, and complement plus translation:

Translation—given a vector **x** and an object **A**, the translation **A**+**x** is defined as

$$\mathbf{A} + \mathbf{x} = \{v + \mathbf{x} | v \in A\}$$

The basic Minkowski set operations – addition and subtraction – can now be defined. Given two objects **A** and **B**:

Minkowski addition

$$\mathbf{A} \oplus \mathbf{B} = \bigcup_{\beta \in \mathbf{B}} (\mathbf{A} + \beta)$$

Minkowski subtraction

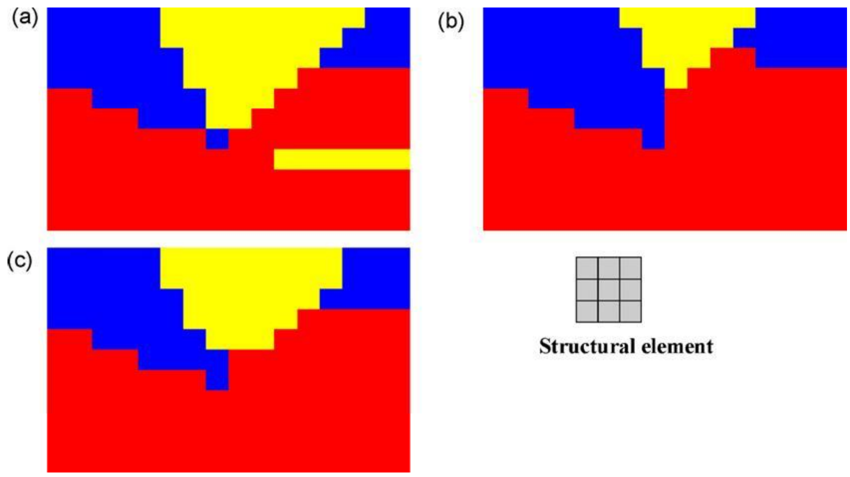



**Fig. 3.** (a) The geological model. (b) Same model after an erosion of the yellow unit. (c) Dilation applied to (b), which represent an opening on yellow unit of the original model in (a).

$$\mathbf{A}\ominus\mathbf{B} = \bigcap_{\beta\in\mathbf{B}}(\mathbf{A}+\beta)$$

### 7.3. Dilation and erosion

From these two Minkowski operations we define the fundamental mathematical morphology operations dilation and erosion:

Dilation

$$D(\mathbf{A},\mathbf{B}) = \mathbf{A}\oplus\mathbf{B} = \bigcup_{\beta\in\mathbf{B}}(\mathbf{A}+\beta)$$

Erosion

$$E(\mathbf{A},\mathbf{B}) = \mathbf{A}\ominus(-\mathbf{B}) = \bigcap_{\beta\in\mathbf{B}}(\mathbf{A}-\beta)$$

where

$$-\mathbf{B} = \{-\beta|\beta\in\mathbf{B}\}$$

**A** is usually considered as an "image" and **B** is called a structuring element. The structuring element is to mathematical morphology what the convolution kernel is to linear filter theory.

Dilation and erosion share the main properties (associative, translation invariance and duality).

### 7.4. Opening and closing

We can combine dilation and erosion to build two important higher order operations: opening and closing.

Opening

$$O(\mathbf{A},\mathbf{B}) = \mathbf{A}\circ\mathbf{B} = D(E(\mathbf{A},\mathbf{B}),\mathbf{B})$$

Closing

$$C(\mathbf{A},\mathbf{B}) = \mathbf{A}\bullet\mathbf{B} = E(D(\mathbf{A},\mathbf{B}),\mathbf{B})$$

The opening and closing operations also have many properties. The opening operation can separate geological unit that are connected with an isthmus. The closing operation can fill in small holes. Both operations generate a certain amount of smoothing on an object contour, given a "smooth" structuring element. The opening smoothes from the inside of the object contour while the closing smoothes from the outside of the object contour.

### 7.5. Examples

These operations are illustrated in Figs. 2 and 3 on 2D examples; the extension to 3D is straightforward. When erosion is applied, the eroded voxel will be assigned to a geological unit randomly selected in the set of units present in the structural element.

The process of opening, on the blue unit, is illustrated Fig. 2 with three geological units and a structural element with a size of 3 × 3. In Fig. 3, the opening operation is applied on the yellow unit, which makes the yellow band included in the red unit disappear.

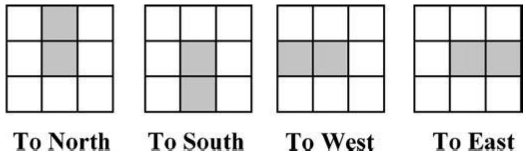



**Fig. 4.** 2D structural element use for directional growing/thinning.

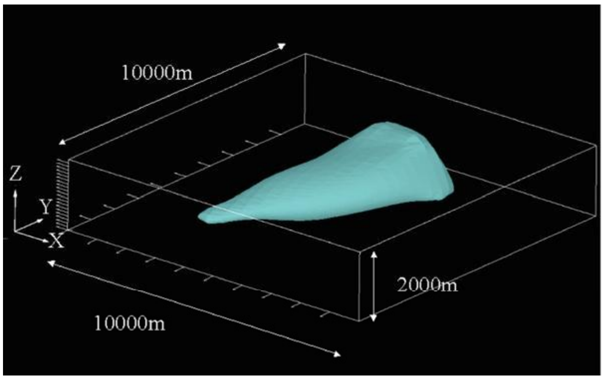



**Fig. 5.** South-East view of the synthetic 3D model.

### 7.6. Growing and shrinking geological units

The previous method allows modifying the shape of the geological units using growing (dilation process) or shrinking (erosion process). This operation occurs during Step 9 of the inversion process. After a random number of iterations, a geological unit is randomly selected. For this unit an operation (growing or shrinking) is randomly selected as well as one of the six possible directions (to North, to South, to East, to West, to Top, to Bottom). Fig. 4 illustrates the different 2D structural elements used with dilation and erosion to obtain growing or shrinking of the shapes in the different directions.

## 8. Synthetic example

The method is tested on a synthetic case assumed to represent the sought after reality. The geological model is represented in Figs. 5 and 6. The body has a constant contrast of volumetric mass equal to 1000 kg/m$^3$, the top of the body is at 260 m depth, and the bottom is 2000 m depth. For this body the gravity effect and the tensor are shown in Fig. 7.

The main point to note here is that the gravity gradient clearly defines the top of the structure and its main NE–SW orienta-

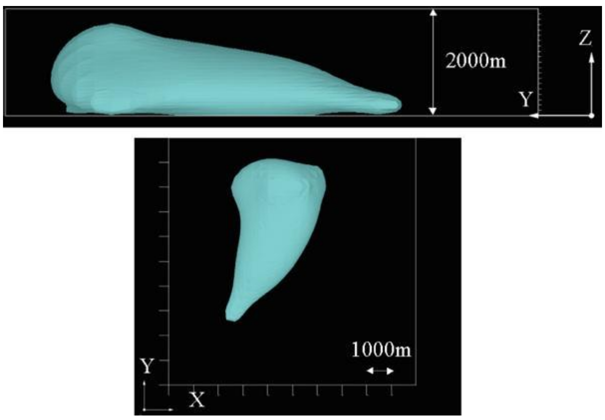



**Fig. 6.** Different points of view of the synthetic 3D model. On the upper part: view from the west. On the lower part: view from the top.

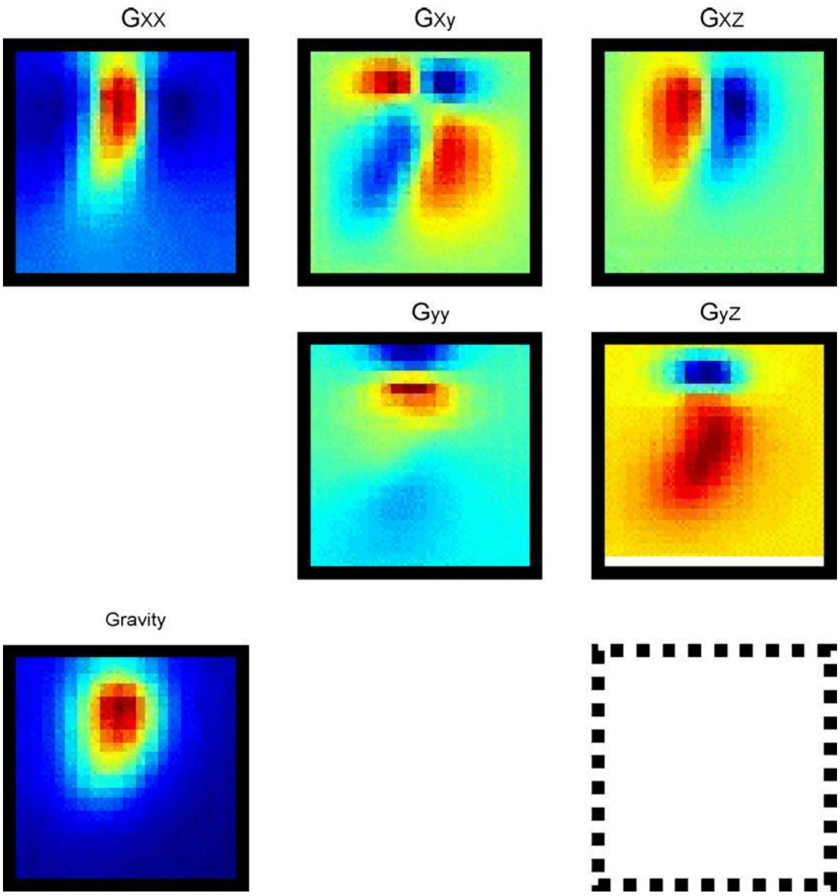



**Fig. 7.** Tensor components and gravity effect of the synthetic 3D model. The *Gzz* component is not represented since equal to $-(Gxx + Gyy)$.

tion. The gravity field displays the same feature but with less contrast.

The inversion method is tested with an a priori model, simpler than the synthetic one (Fig. 8). This model is smaller and shallower, with a N–S orientation. The starting tensor and gravity field effect are shown in Fig. 9.

The starting gravity field and gravity tensor are computed assuming the volumetric mass property contrast according to a Gaussian distribution with mean equal to 1000 kg/m$^3$ and standard deviation equal to 200 kg/m$^3$. The standard deviation error on the measurements is 3 $\mu$m s$^{-2}$ for the gravity field and 3 E.U. ($10^{-9}$ s$^{-2}$) for each tensor component. The result after 100,000 iterations is shown in Fig. 9.

Fig. 10 shows the comparison along a SW–NE cross-section with the "real model in (a) and the results of the inversion in (b) and (c). In (b) we have the probability to obtain the body using only gravity field inversion. In (c) we have the probability to obtain the body with gravity field inversion plus the inversion of the five components tensor. In (b) and (c) the red lines represent the a priori model shown in 3D in the previous figures. Using tensor data, the results show closer agreement to the synthetic model in the northern, the south-western and bottom parts. In both cases results can be qualified as acceptable. However, the quality of the results increases using simultaneous inversion of independent fields.

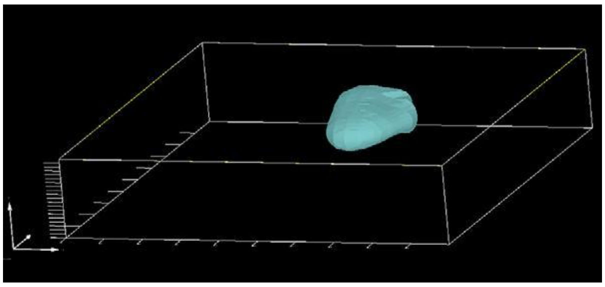


**Fig. 8.** Starting model for inversion, viewed from the South.

## 9. Application to a case history: modelling of granitic intrusions along a vertical crustal-scale fault from the French Massif Central

### 9.1. Geological context

Granite generation and emplacement during orogenesis is a widespread phenomenon that remains debated in terms of mechanism of ascent and intrusion. Thus, the drain role of the vertical fault system is often invoked to justify the transfer of large amounts of granitic melt from the middle crust towards upper levels. Such situation has been studied in the case of the Montmarault plutonic complex that is situated in the northern part of the French Massif Central (Joly, 2007; Joly et al., 2008). Several bodies, with different gravimetric and magnetic properties, are aligned on the Western side of a sub-vertical crustal-scale fault system that extends over more than 500 km from North to South, the Sillon Houiller Fault (SHF). Mapping, lithological and mineralogical studies, U–Th/Pb dating, field structural observation and magnetic susceptibility anisotropy studies, have shown that the Montmarault plutonic complex emplaced within host metamorphic series during the Namurian at about 320 Ma. The intrusion is controlled by a regional NW–SE maximum stretching direction, also recorded by other