Structural Geology Observations Derived From Full Tensor Gravity Gradiometry Over Rift Systems*

Desmond FitzGerald[1] and Horst Holstein[2]

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Abstract

Gravity gradiometry has an increasingly important role to play in minerals and petroleum exploration, particularly for facilitating automated structural analysis and the building of 3D geological boundaries and structural surfaces. To optimize use of this full tensor data, we propose a new method for 3D geology feature extraction directly from the components of the full tensor signal. Our technique finds strike and dip pairs for geological and fault contacts. Gravity profile data crossing a fault can be used to estimate the dip, block thickness, and density contrast across the structure. The strike is found using standard edge detection methods. An upward continuation strategy is employed. At each step, a double horizontal derivative is calculated so that a zero cross-over point, offset from the fault toe, can be found. This offset is then used to find the dip (the signal is in effect operating on Gxz). A progression towards a viable technique has been occurring over several years and is not being done in isolation, but rather by leveraging upon several key new technologies in related fields. This paper will explain some of the background and related work for this new technology. We will demonstrate the new technology with a case study from a rift system where the gravity gradiometry signal is unambiguous, strong and some existing structural knowledge is available to help calibrate the results.

Reference Cited

Lajaunie, C., G. Courrioux, and L. Manuel, 1997, Foliation Fields and 3D Cartography in Geology; Principles of a Method Based on Potential Interpolation: Mathematical Geology, v. 29, p. 571–584.

Structural geology observations derived from full tensor gravity gradiometry over rift systems

- *Des FitzGerald, Horst Holstein*

Challenges for Gravity

- *Ambiguity of potential field interpretation*
- *Sparse geophysics sampling*
  - *Aliasing*
- *Body shapes – linears, not 3D*
  - *Chicken scratchings*
  - *often not very realistic of geology bodies*

New Innovative Methods

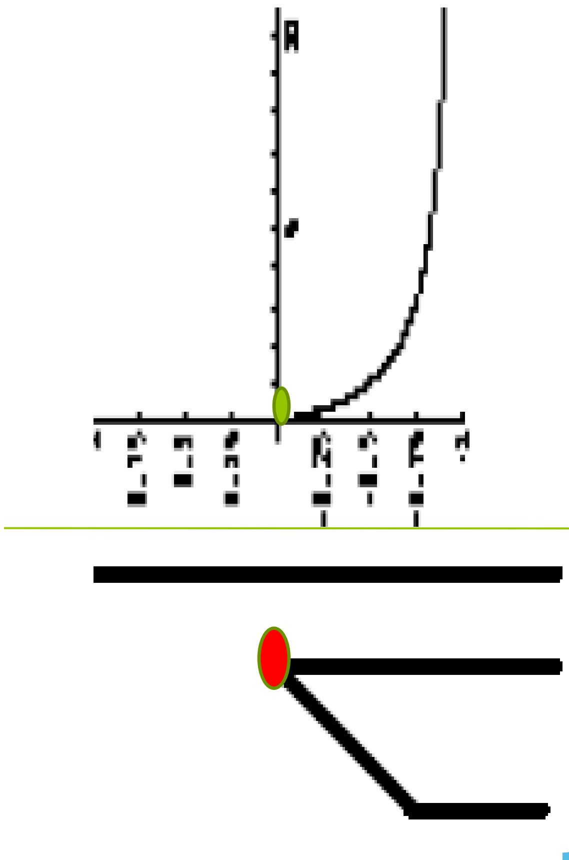
- *Geology and Implicit Functions*
  - *Co-kriging of foliation and interface data*
- Computational Geometry Engines
- Better ability to manage complexity with integrated toolkits such as Eclipse
- Create fit for purpose solutions!!

Outline

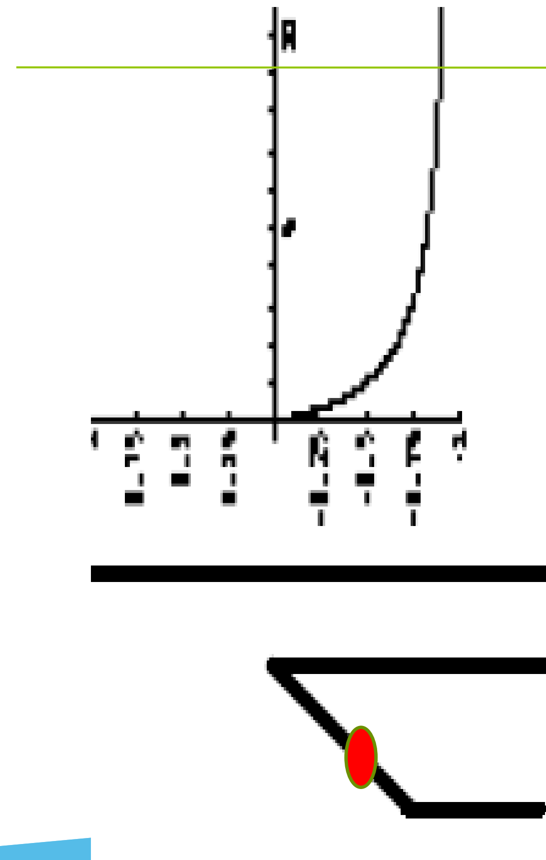
- Gz Dip calculation
- Darling Fault calibration
- FTG Dip calculation
- Nevada Case Study
- 3D fault network generation

Quantative Method for dip

- SI from the non-homogenous Euler should be 1



- SI from the barycenter, or HOT_SPOT is 0



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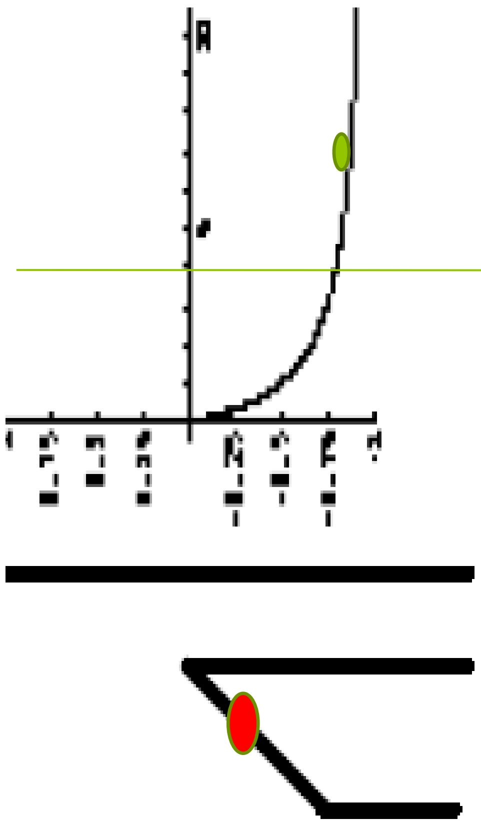

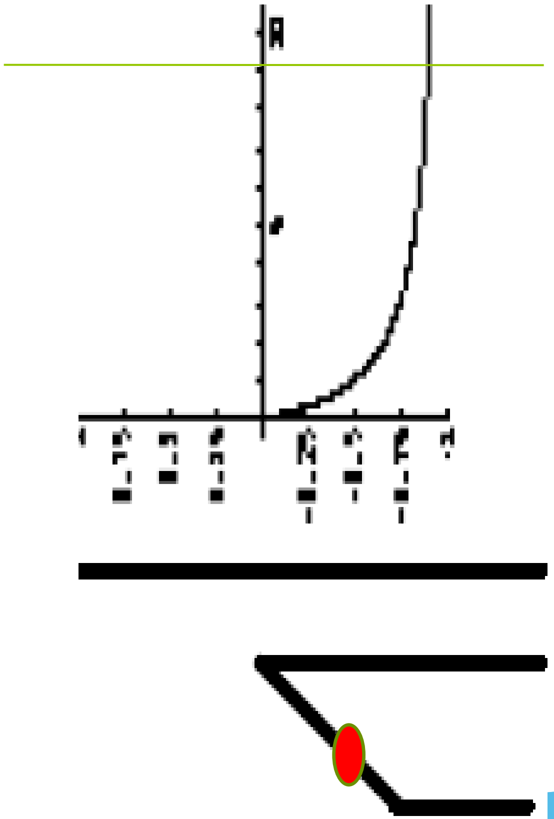

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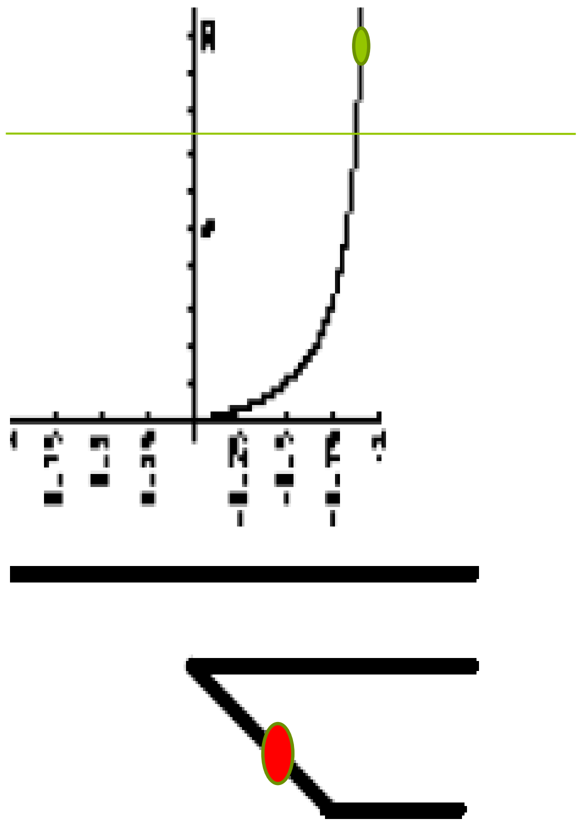
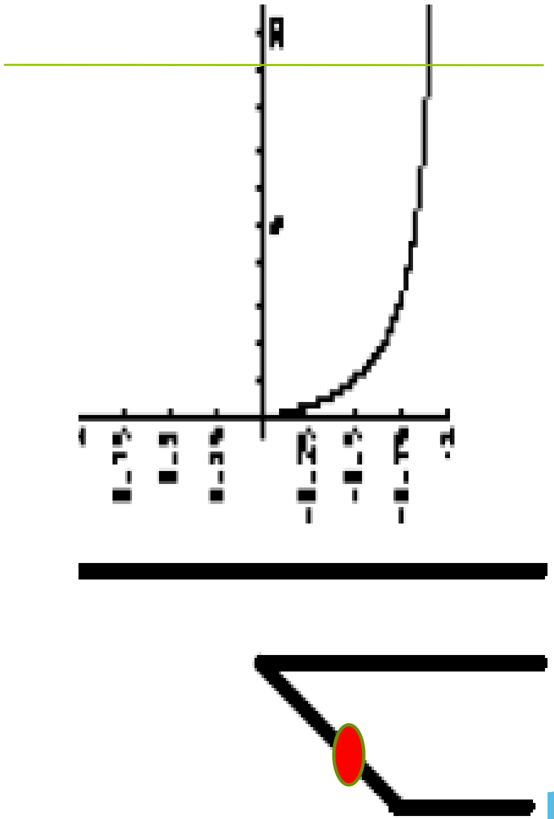
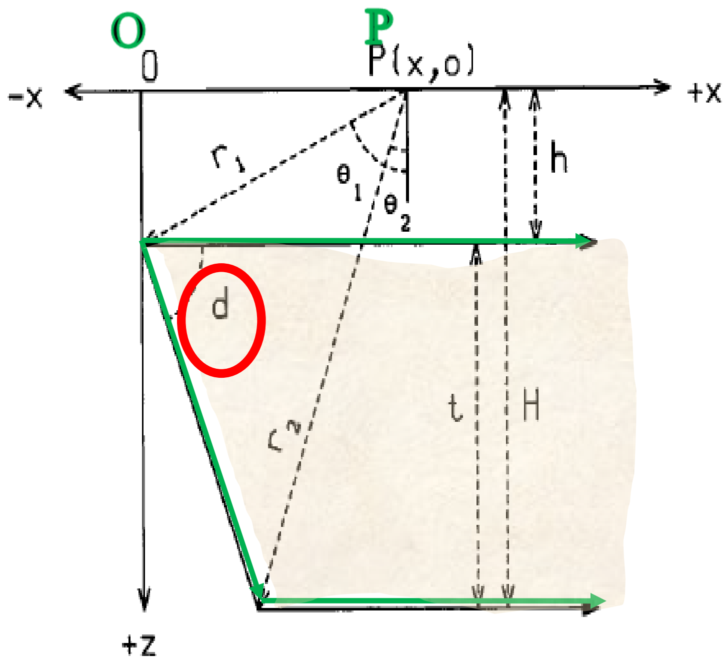


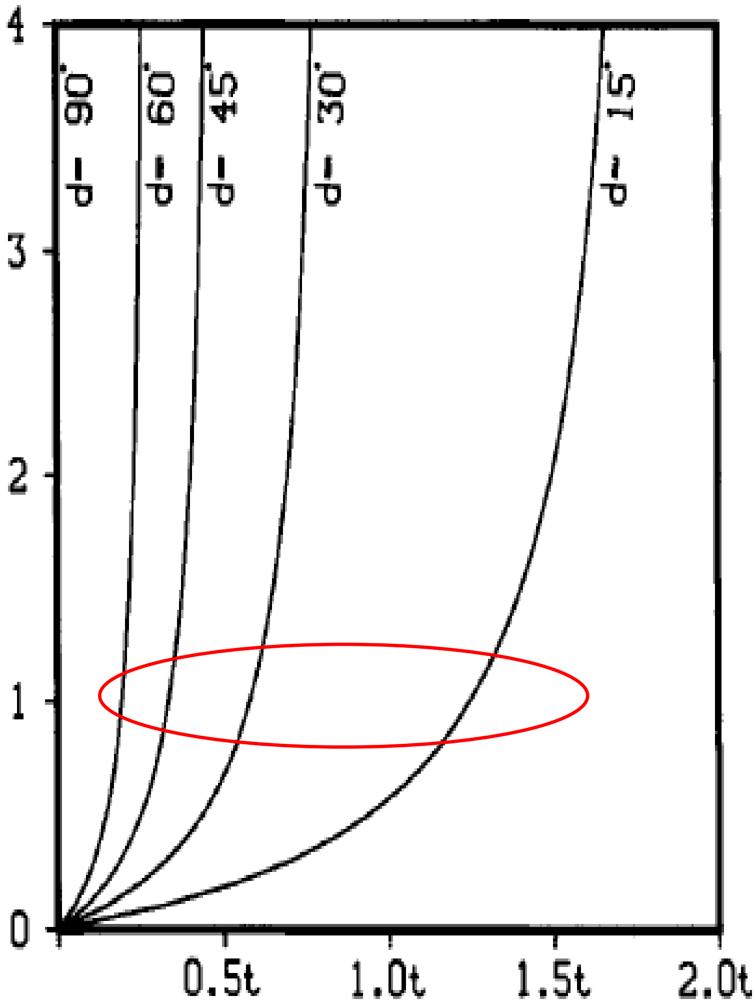


Quantative Dip



- Truncated horizontal-plate model,
- The origin 0 of the coordinate system is vertically above the upper edge of the model.
- P(x, 0) represents the location of a gravity station along the gravity profile.

Estimating Dip



X0 zero-cross over offset

Xo = th cot d/(H + h)t

- Successful application of the method depends on the magnitude and accuracy of these differences which are large where the curvature of the traces of the zero-crossover points is greatest, i.e., *h/t = 1*.
- h: continuation height
- t : plate thickness

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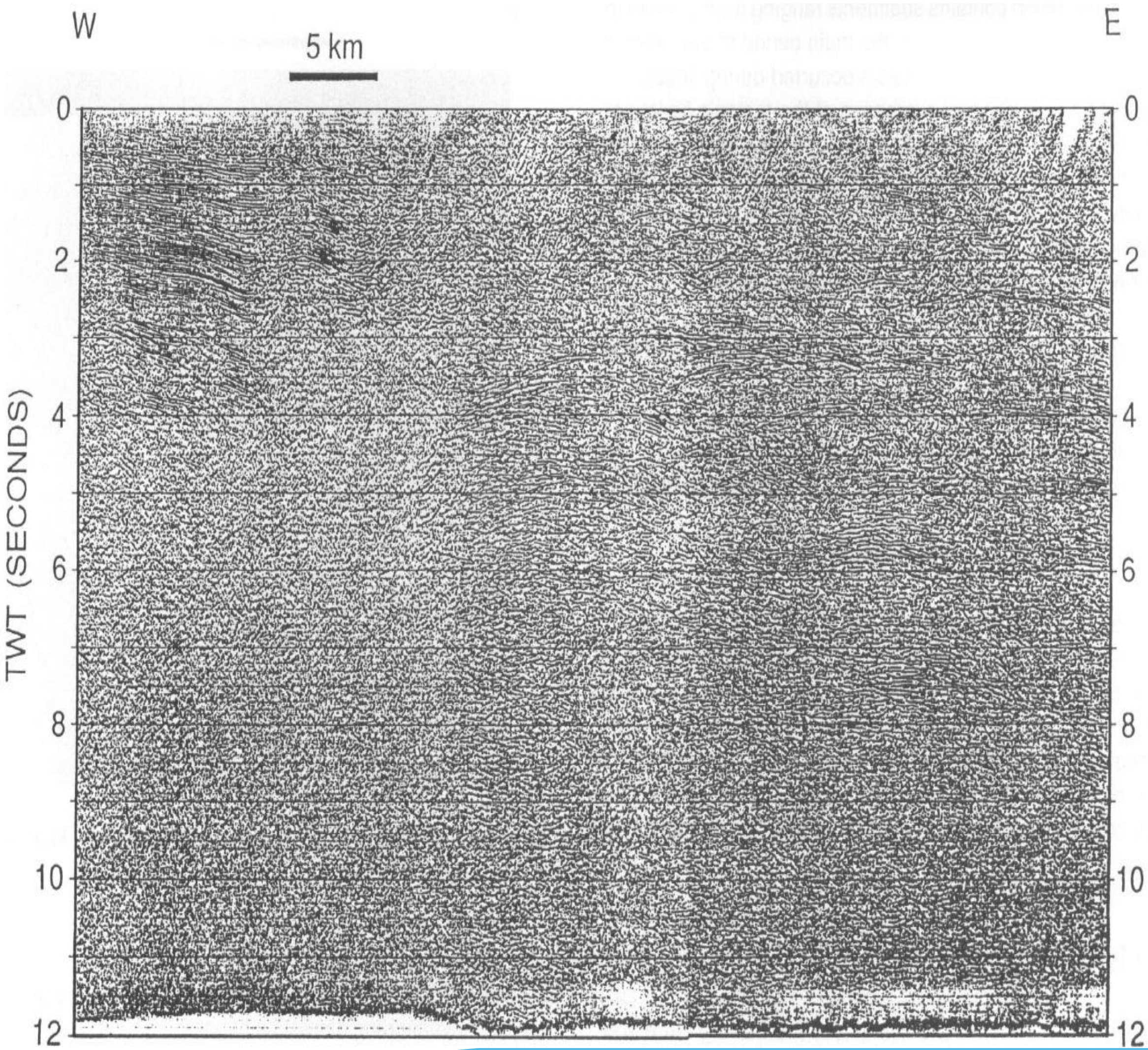
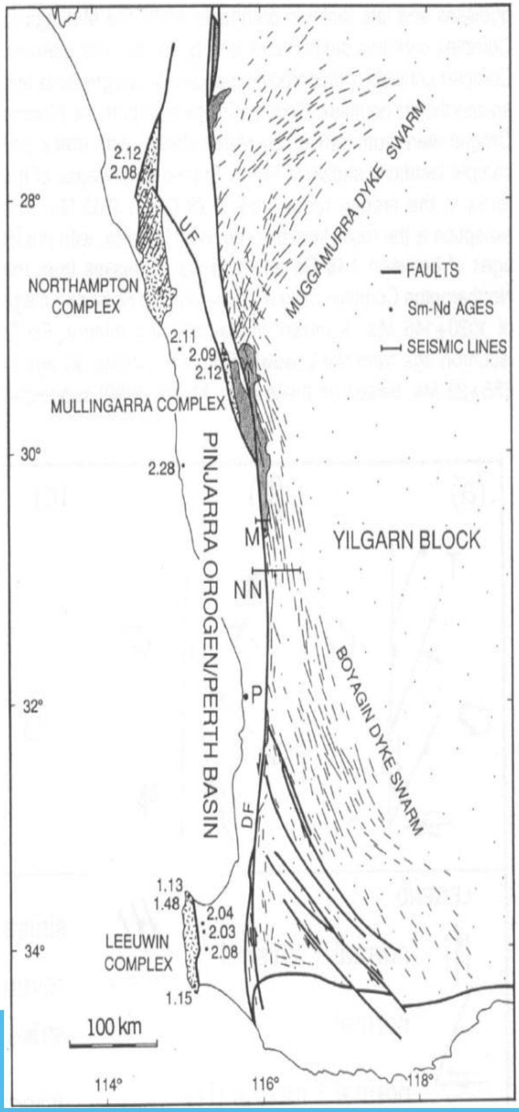
Darling Fault Calibration

New Norcia Seismic line

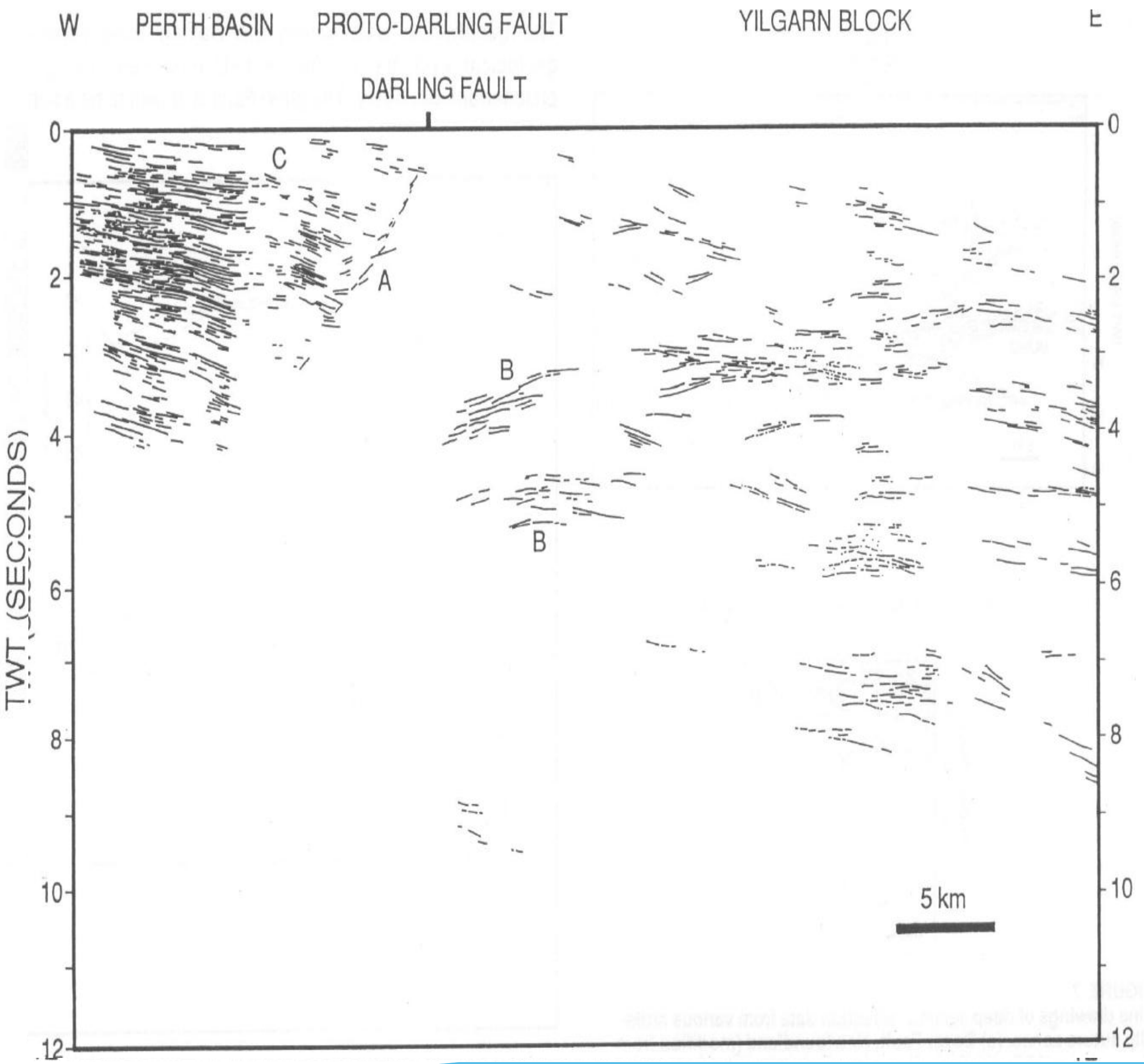


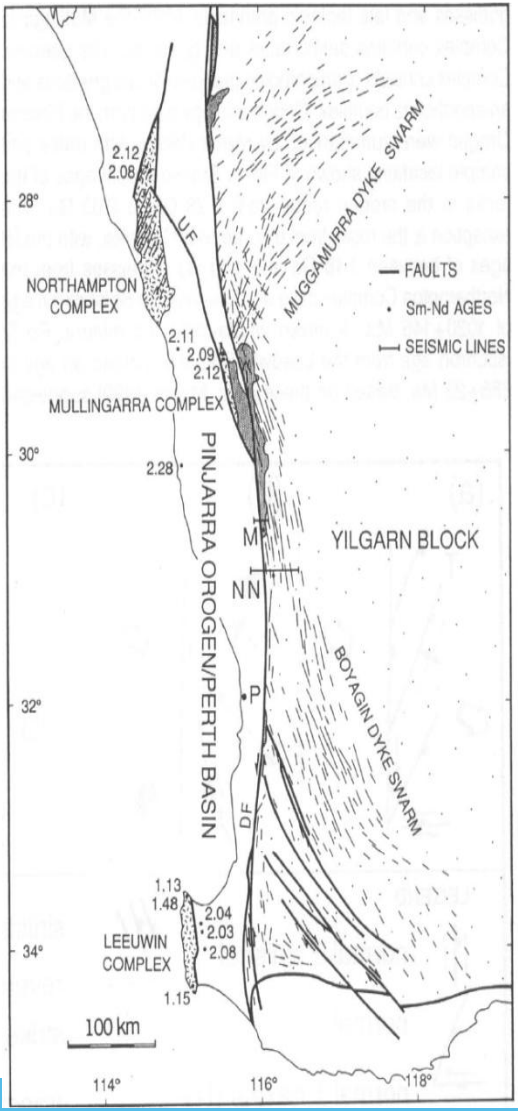
120km North Perth



Darling Fault Calibration

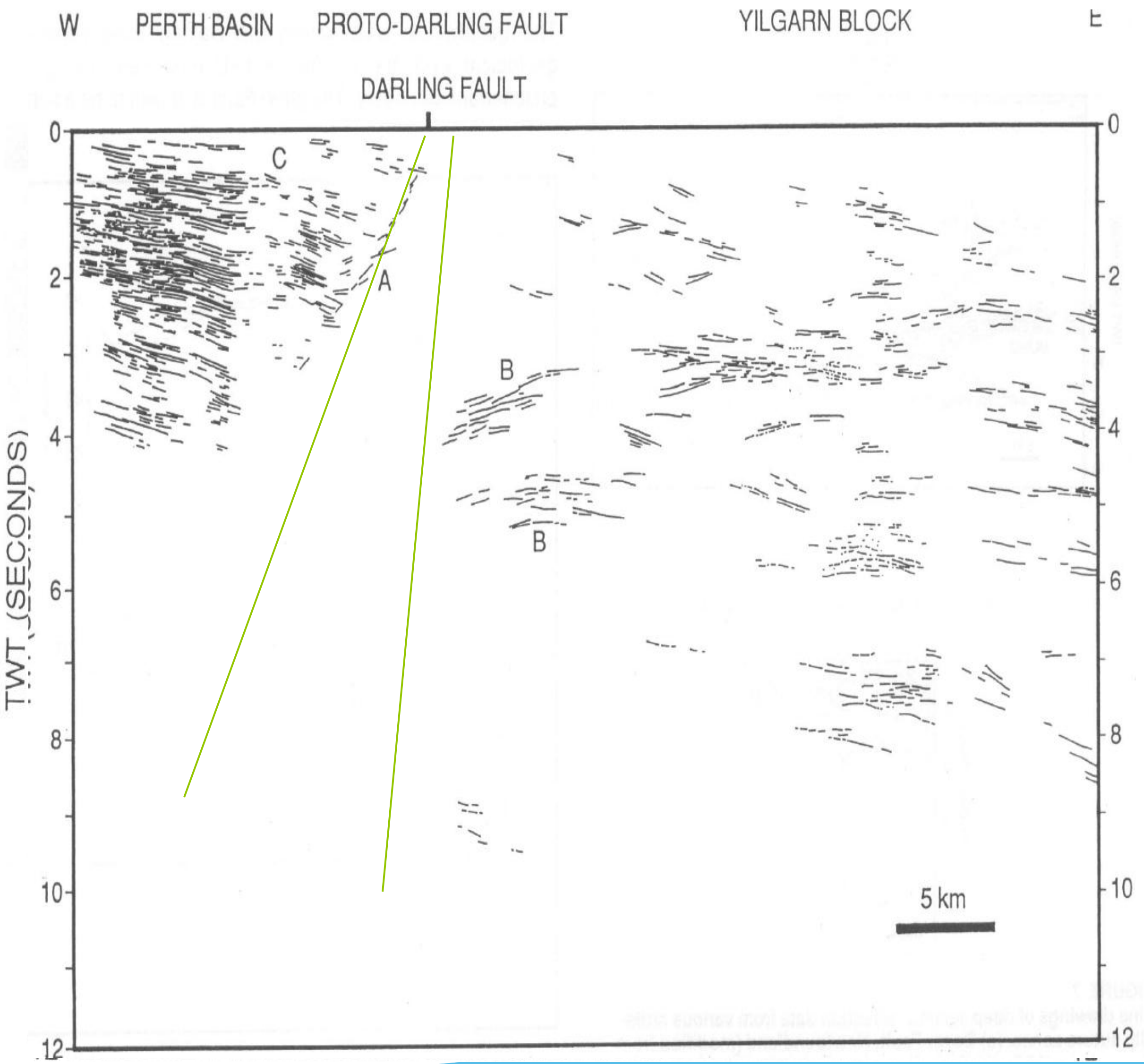
New Norcia Seismic line **120km North Perth**



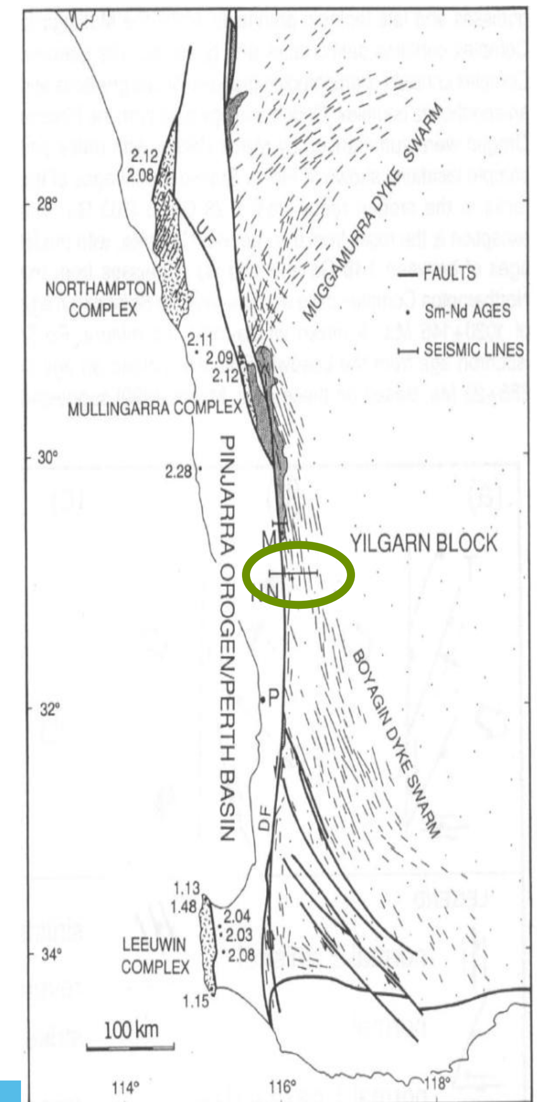


Darling Fault Calibration

New Norcia Seismic line

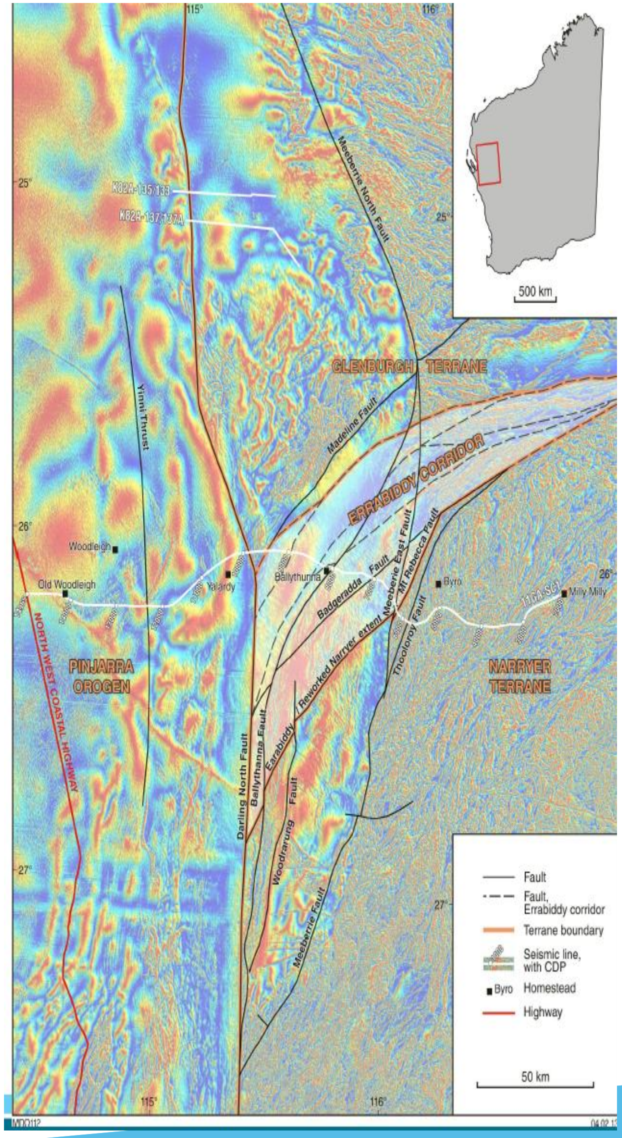


120km North Perth

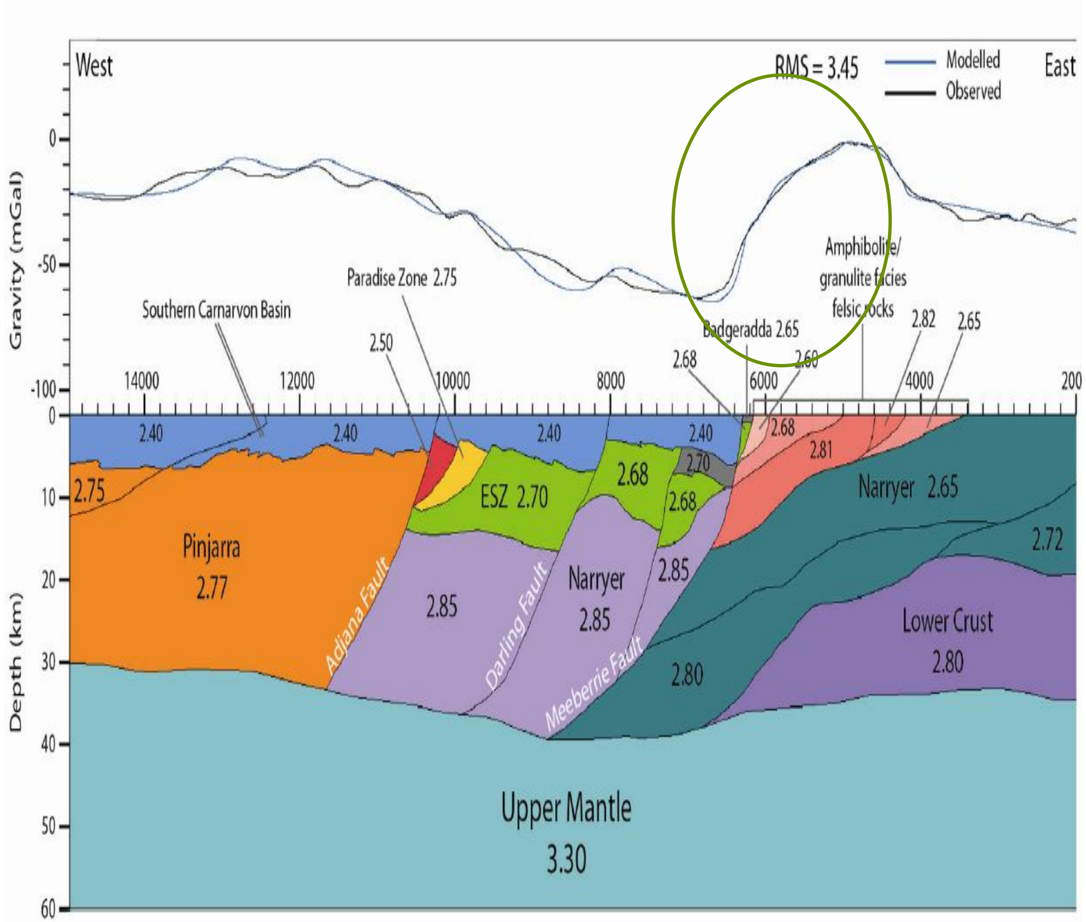


Southern Carnarvon Seismic Line

Aeromagnetic Location

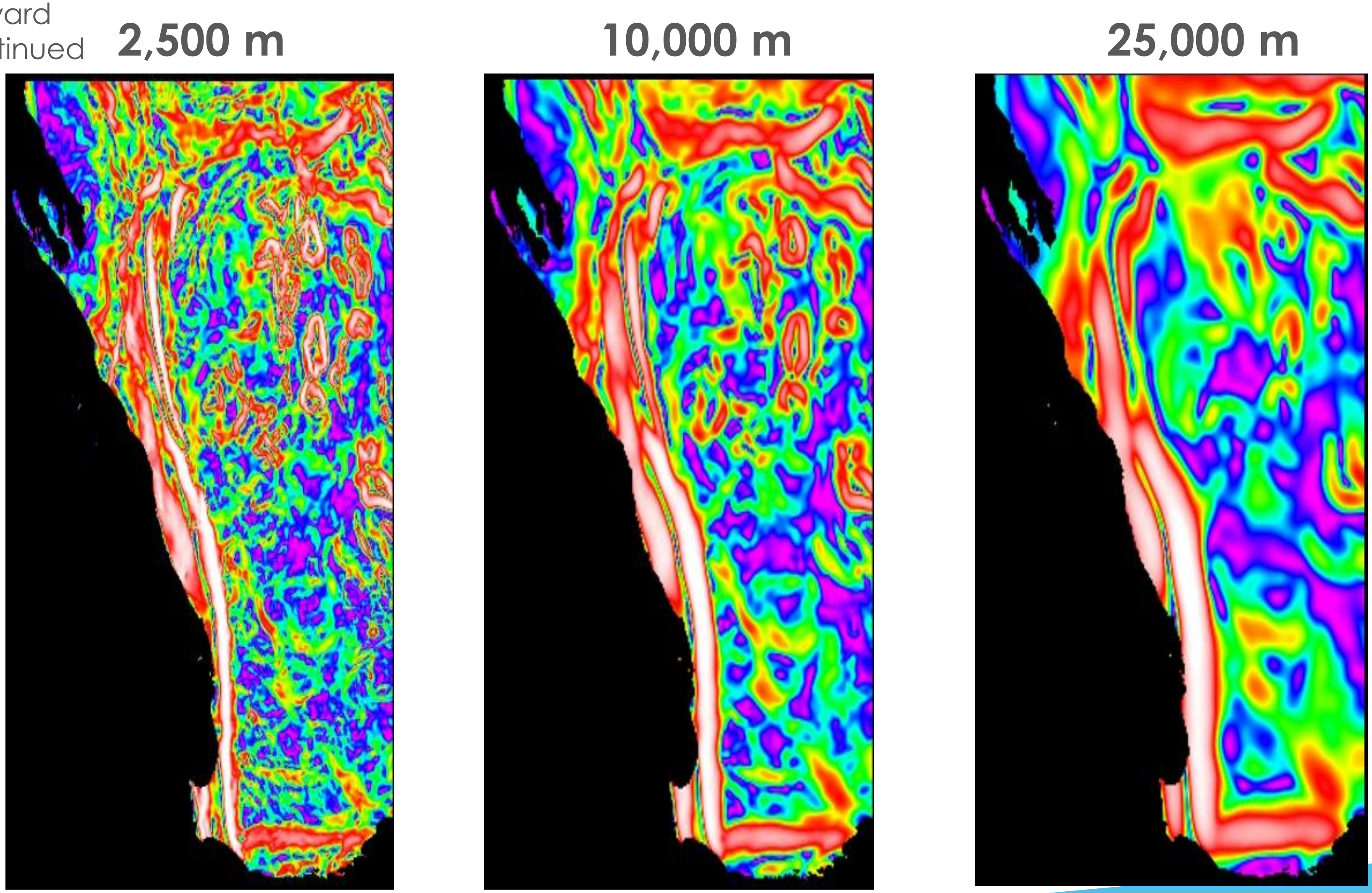


Meeberrie Fault – gravity model



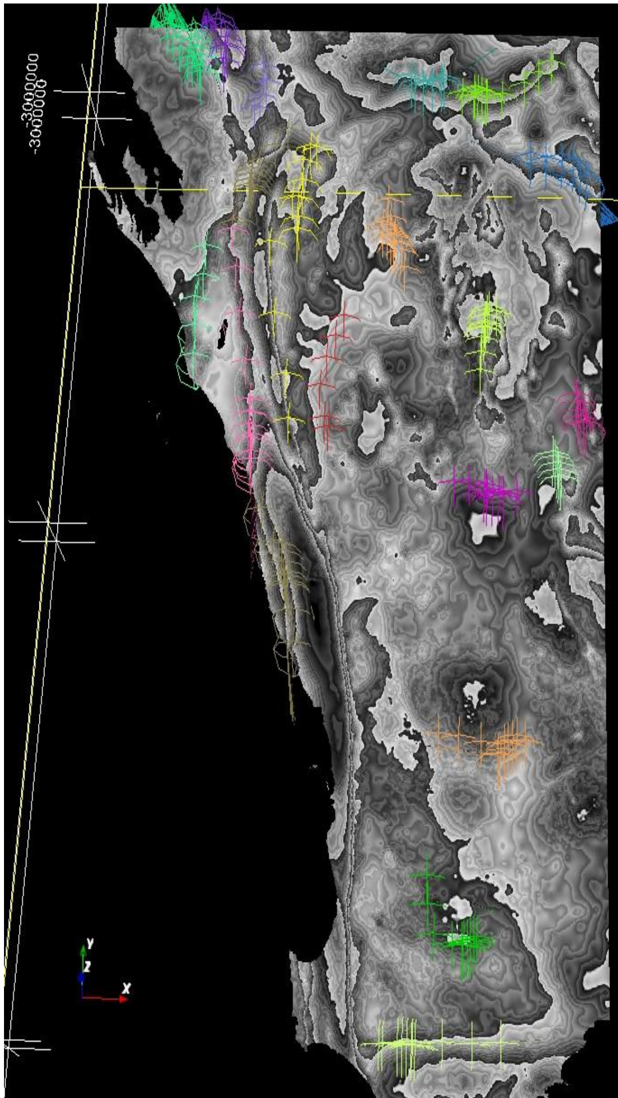
Darling Fault Total Horizontal Gradient

Upward continued

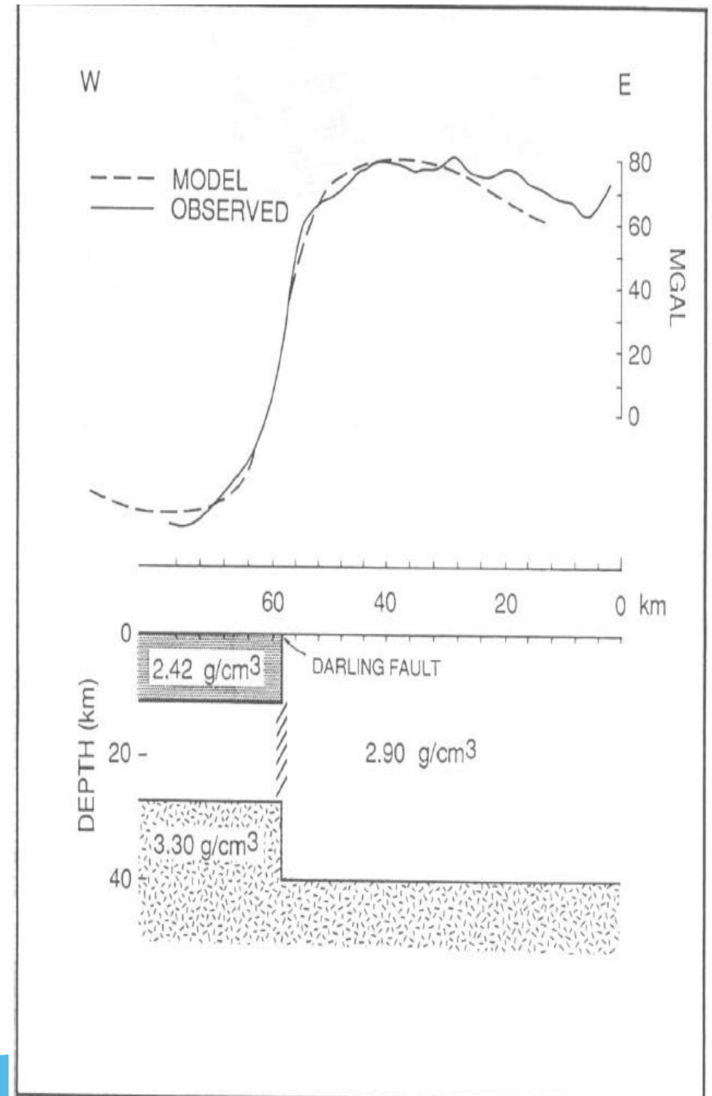


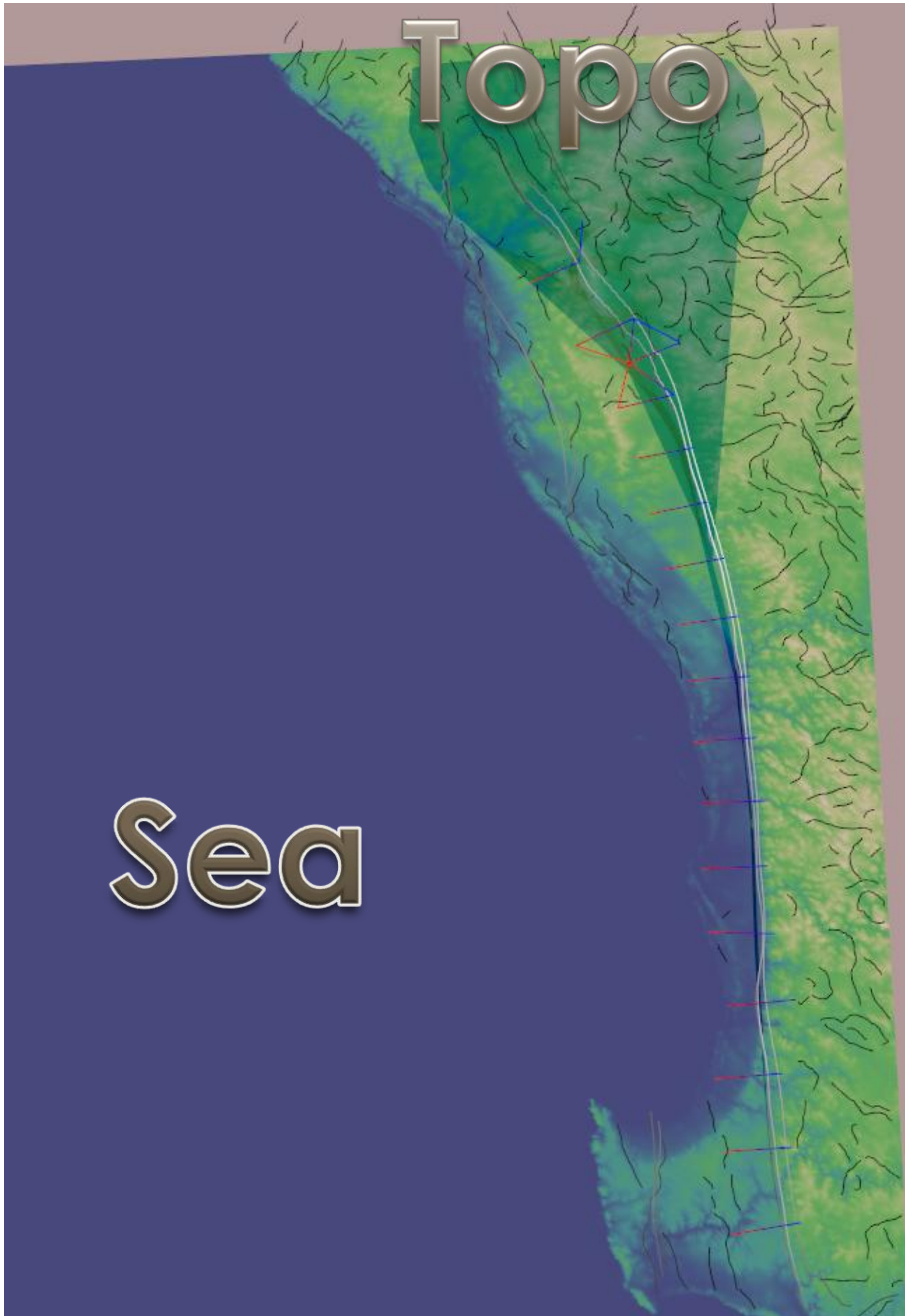
Darling Fault Calibration

Automatic Model



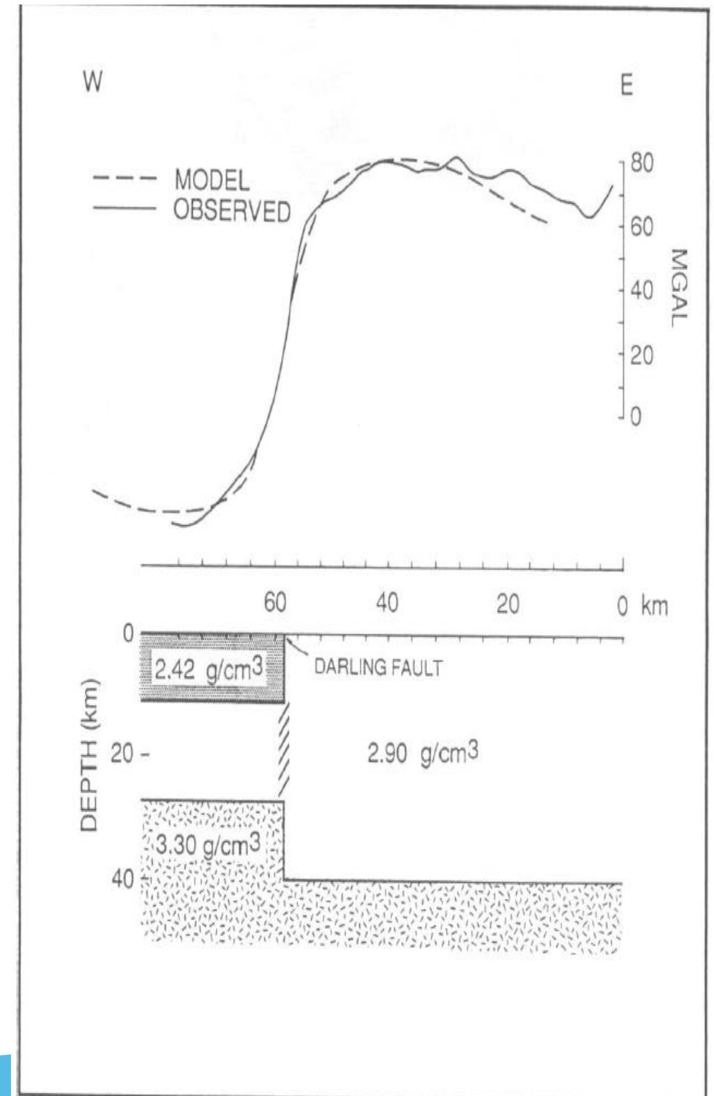
Original Gravity Model

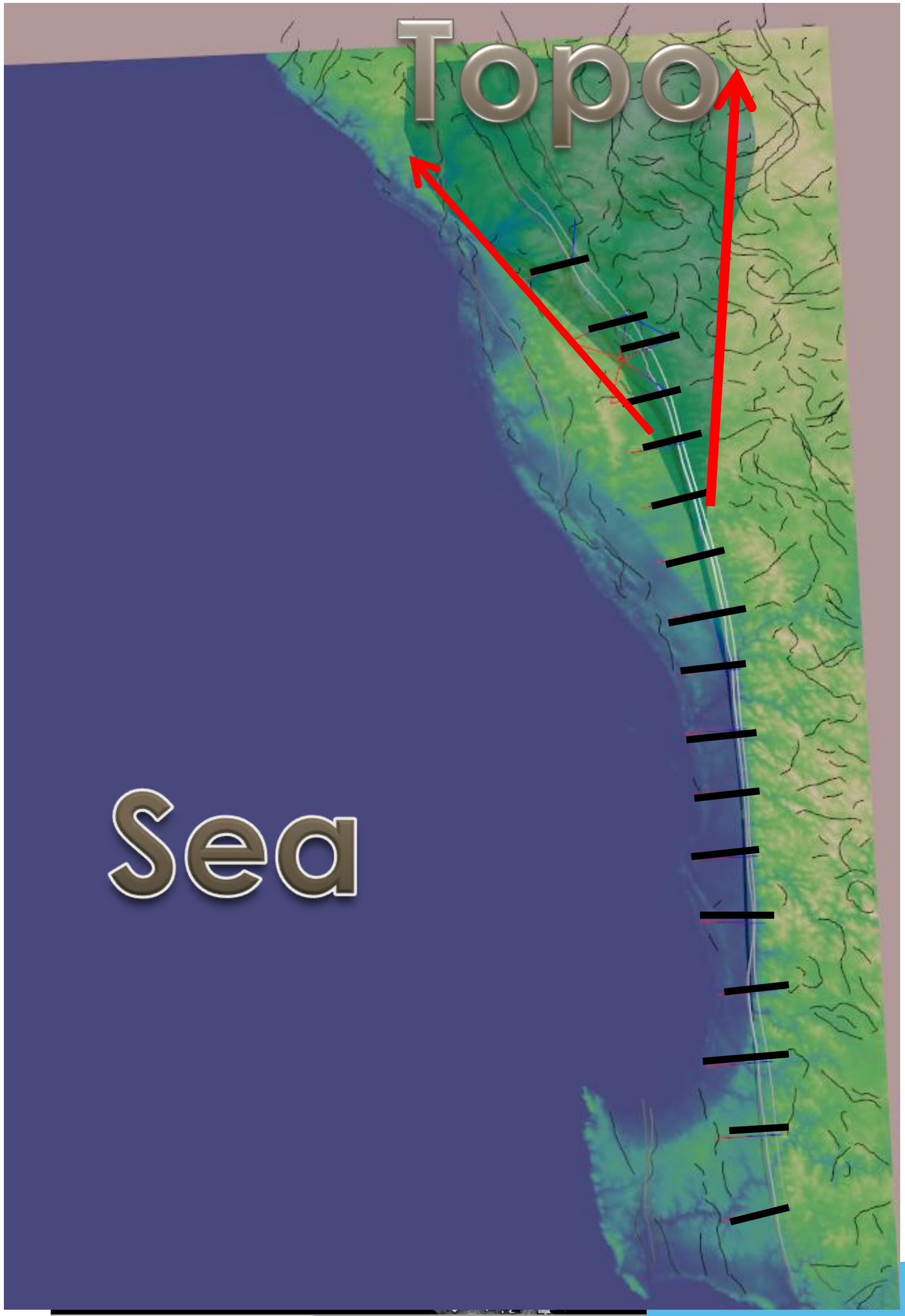




Calibration

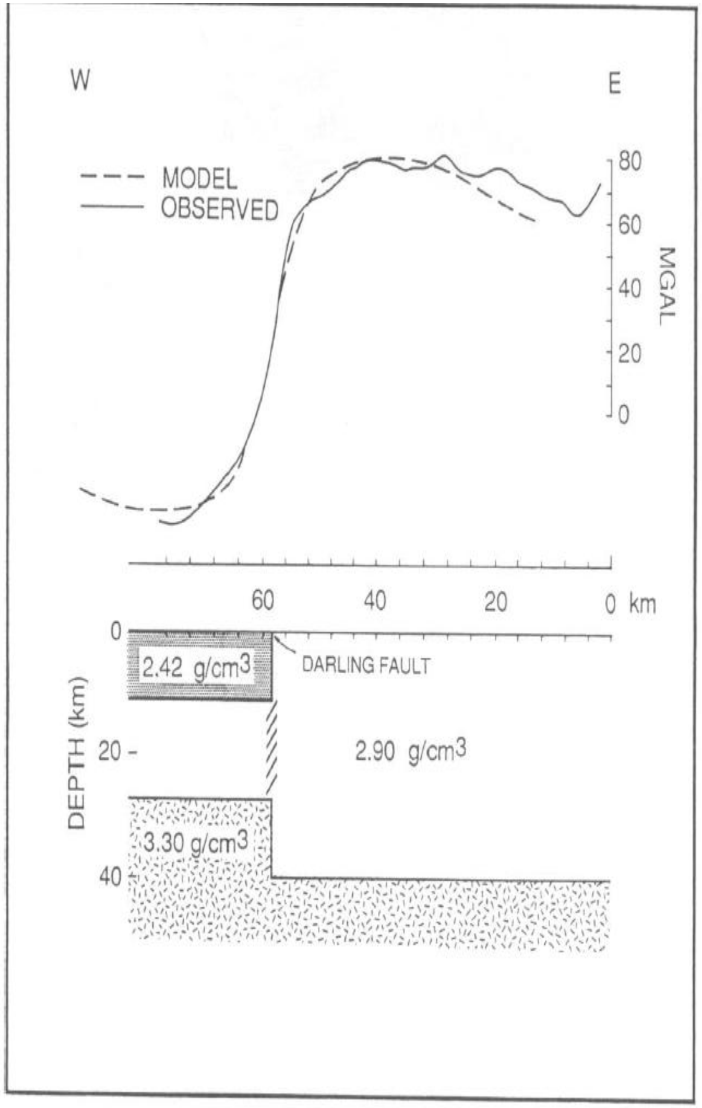
Original Gravity Model



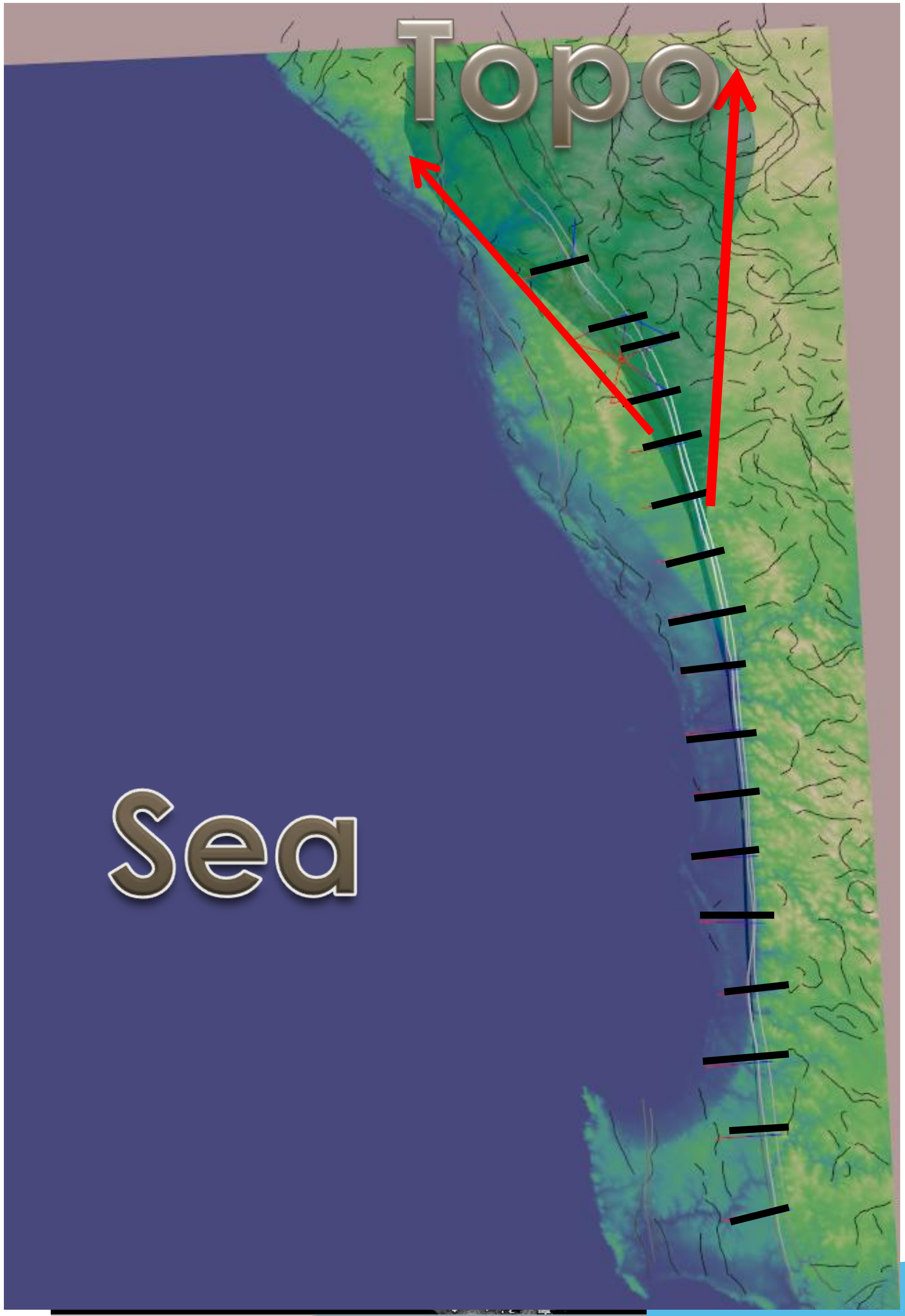


Calibration

Original Gravity Model



Calibration



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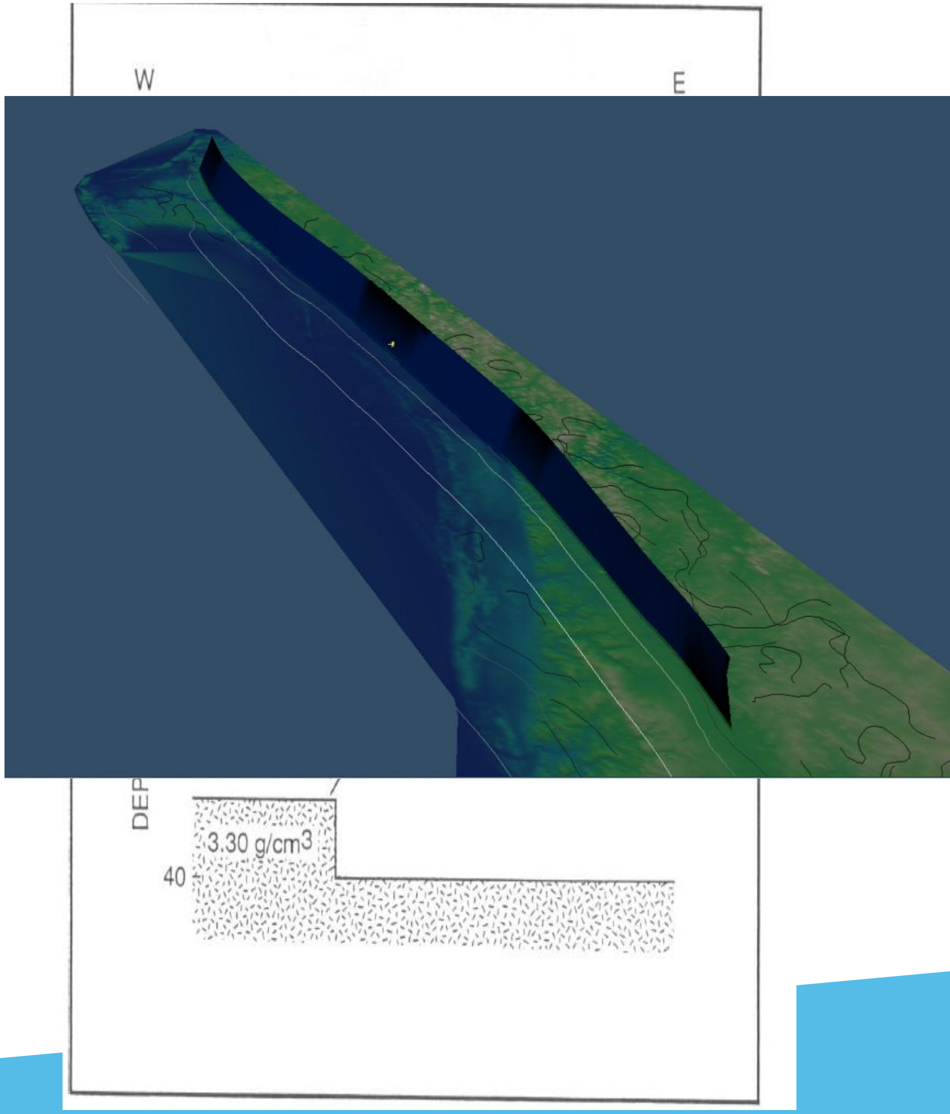
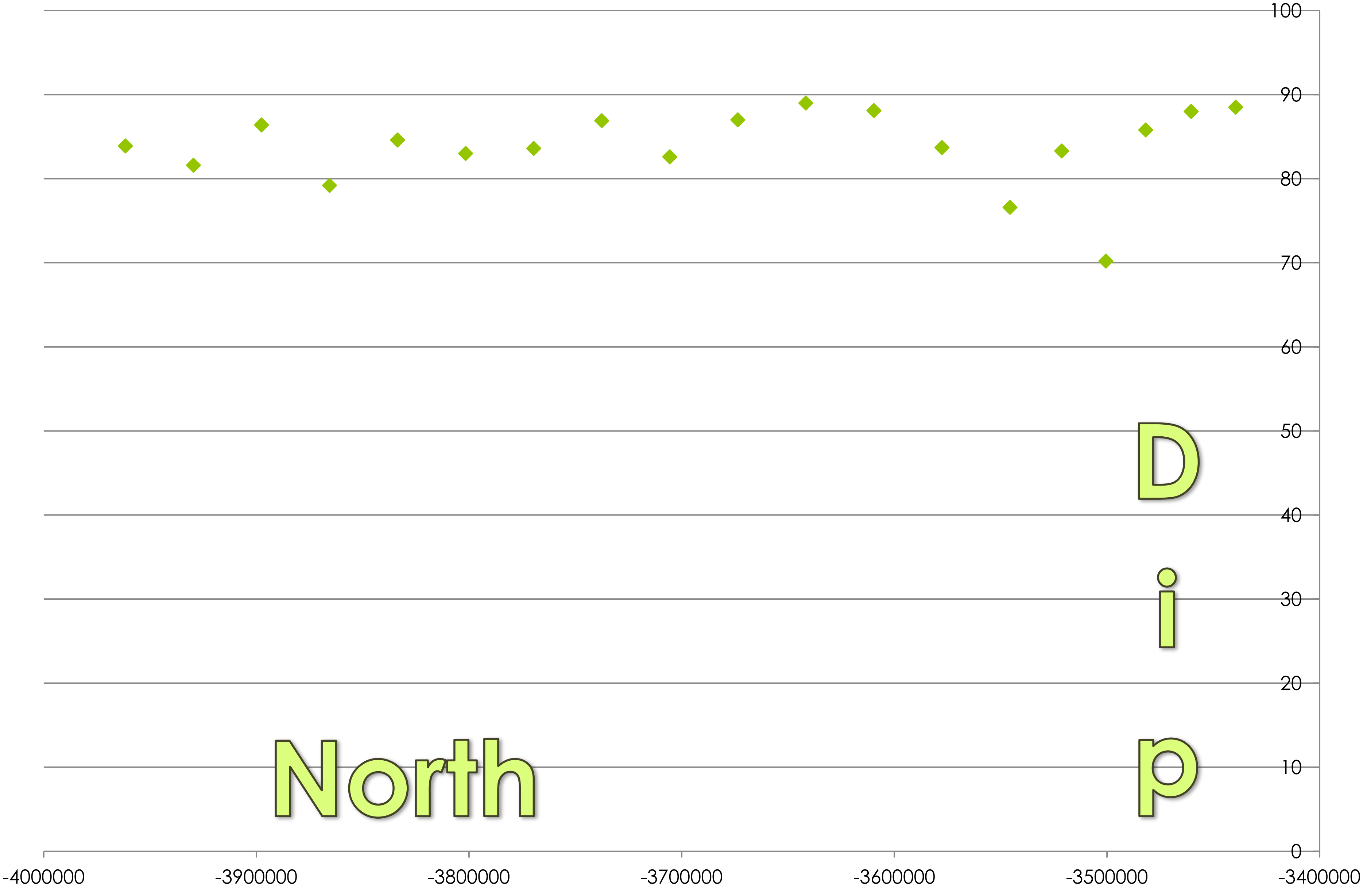


Mid - Darling Fault – 604 points

n	Ht	XnRel	Error	R	Thick	Offset	Origin	Dip	Density
0	17	56.355	-1439						
1	33	58.038	-131	0.937					
2	49	58.586	-103	1.480	127	2.54	56.04	84.8	-0.030
3	65	58.997	-61	1.385	232	2.375	56.62	86.7	-0.016
4	81	59.342	-34	1.281	258	2.622	56.72	87.0	-0.015
5	97	59.638	-18	1.171	174	3.465	56.17	85.7	-0.022
6	113	59.887	-10	1.069	68	6.706	53.18	75.7	-0.055
7	129	60.087	-5.9	0.972					
8	145	60.238	-3.5	0.869					

20 Dip calculated along the fault



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Field gradient tensor

$$\mathbf{G} = \begin{pmatrix} g_{xx} & g_{xy} & g_{xz} \\ g_{yx} & g_{yy} & g_{yz} \\ g_{zx} & g_{zy} & g_{zz} \end{pmatrix} = \begin{pmatrix} g_{xx} & g_{xy} & g_{xz} \\ & g_{yy} & g_{yz} \\ & & \end{pmatrix}$$

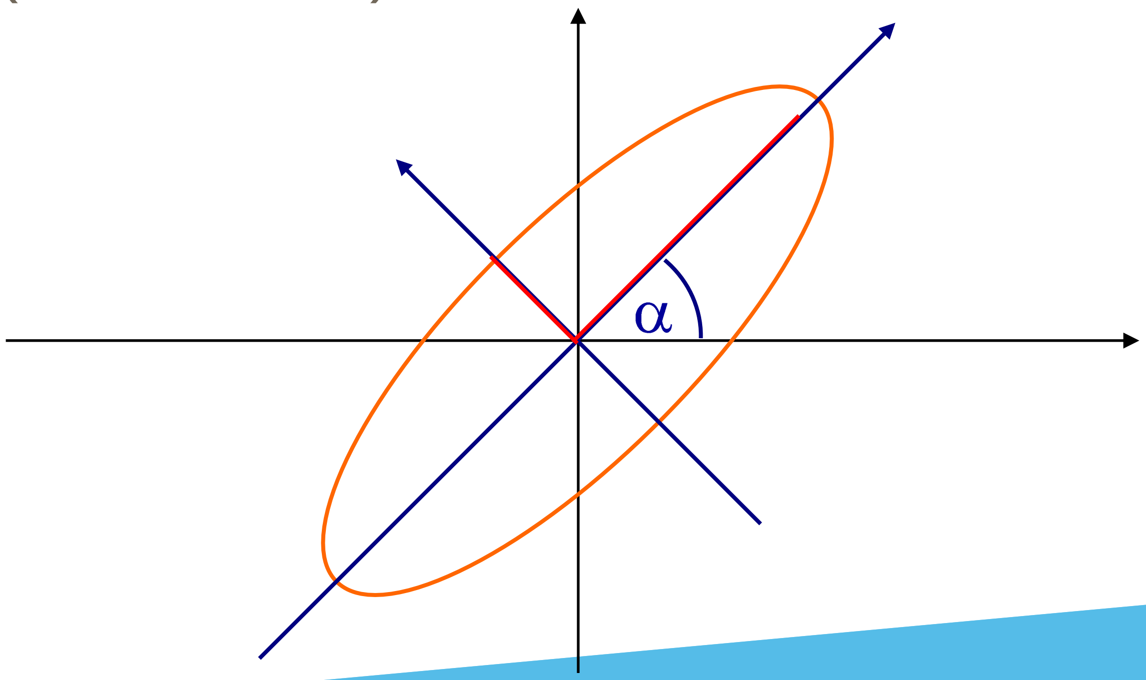
Theory:

- **G** is symmetric,
- trace(**G**)=0

5 independent quantities

Properties of the gradient tensor

- Classic principal component analysis problem
- In this example, tensor is represented by an ellipse
- Tensor is easiest described by Eigenvalues and Eigenaxis
- Eigenaxis are rotated by angle α with respect to reference system (i.e. observer)



Tensor components

- A coordinate system can be found in which the tensor has only diagonal components

$$\begin{pmatrix} g'_{xx} & & \\ & g'_{yy} & \\ & & g'_{zz} \end{pmatrix}$$

  - Separation of concerns
    - structure of target
    - orientation of viewer relative to target

Tensor components

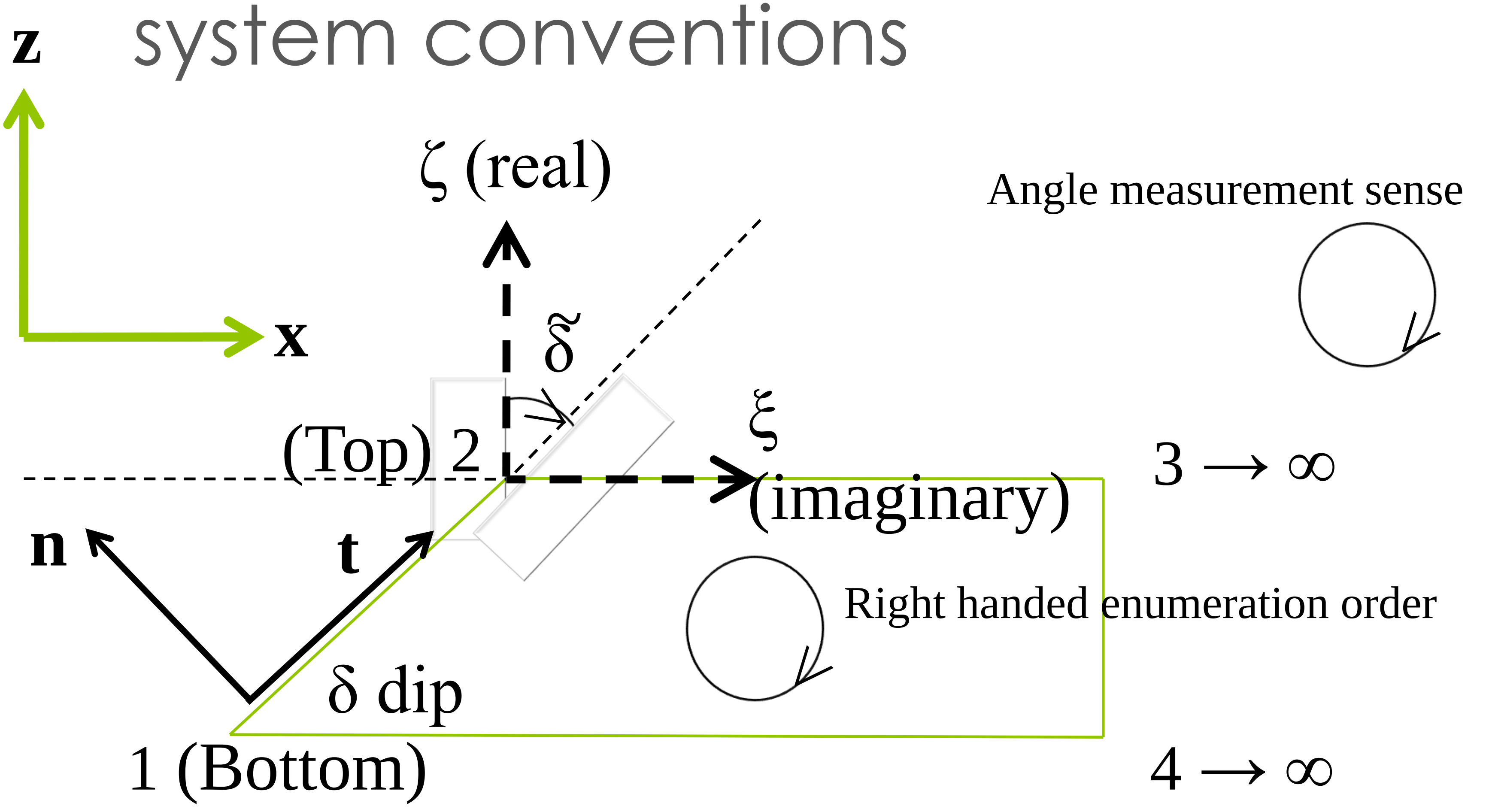
- A coordinate system can be found in which the tensor has only diagonal components

$$\begin{pmatrix} g'_{xx} & & \\ & 0 & \\ & & g'_{zz} \end{pmatrix}$$

  - Separation of concerns
    - structure of target
    - orientation of viewer relative to target

- If $\boldsymbol{g}_{yy}$ equals zero, we have a 2D geological structure eg fault or contact

Tensor Gravity - Coordinate system conventions



$\tilde{\delta}$ is the co-dip. The fault tangent is along $\exp(i\,\tilde{\delta})$

$$\hat{\mathbf{t}} = \hat{\mathbf{x}}\sin\tilde{\delta} + \hat{\mathbf{z}}\cos\tilde{\delta} \rightarrow \cos\tilde{\delta} + i\sin\tilde{\delta}$$

Tensor Innovation –
New 2D tensor fault modelling code

With measured Gxx and Gxz

Much less ambiguity & uncertainity in dip calculation

Stronger evidence of 2D nature
  Gyy = 0.0

```
*************************************************
 FaultDip Cppunit test Start processing - 21/02/2014 12:11:46.1
 *************************************************
Test Regime for FaultDip Model
Observation point    ^z
 -X---------------------|------------
                        |
                        ---> x
            v2  ------------------> infinite
              /                    |
             /                     |
            /
          v1  --------------------> infinite
Tensor components
[-1.31525, -0, 1.70646]
[-0,         0,        -0]
[ 1.70646, -0, 1.31525]
Trace 0
gz   =  296
 *************************************************
  End   processing - 21/02/2014 12:11:46.1
 *************************************************
```

Tensor Innovation –
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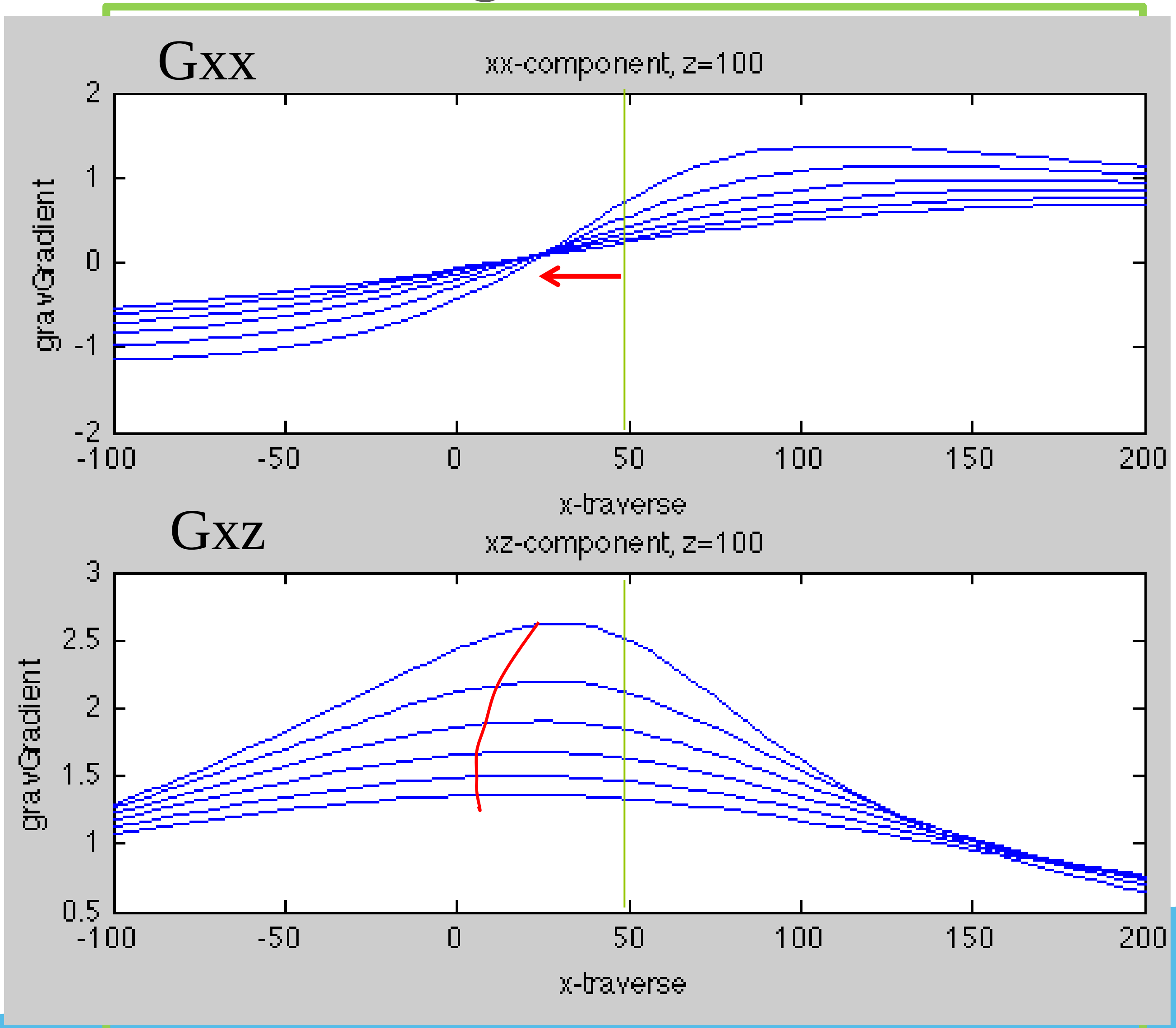

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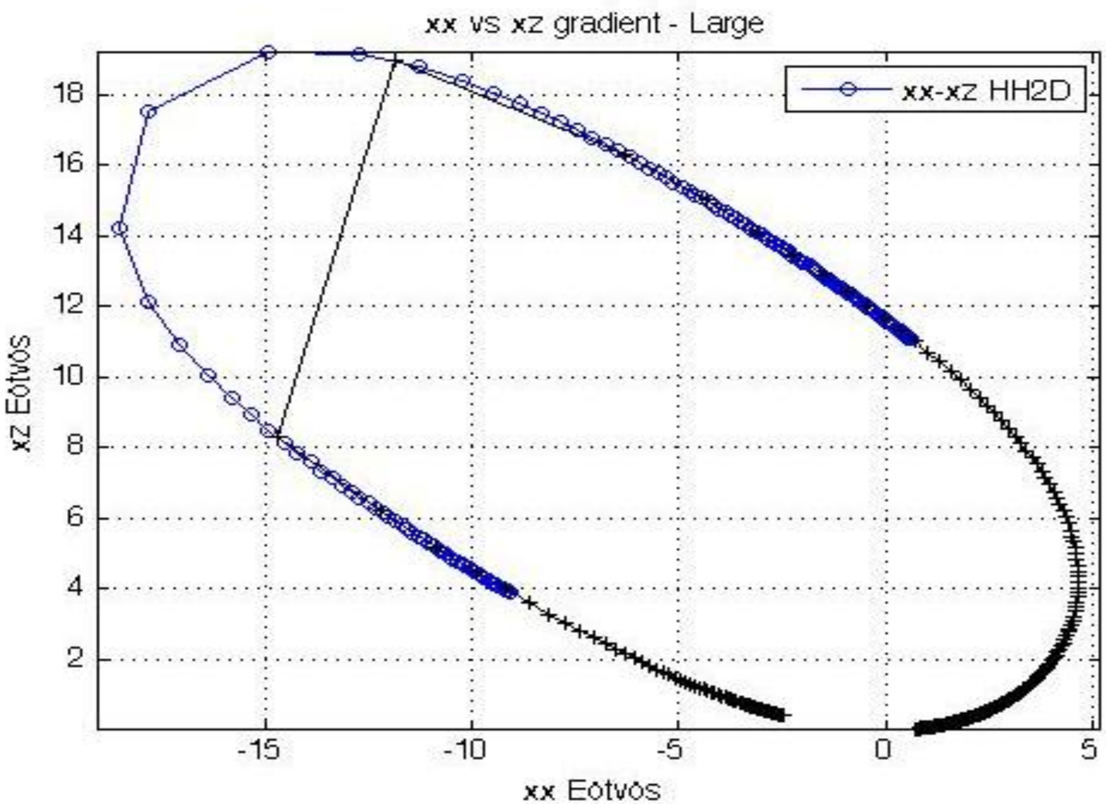

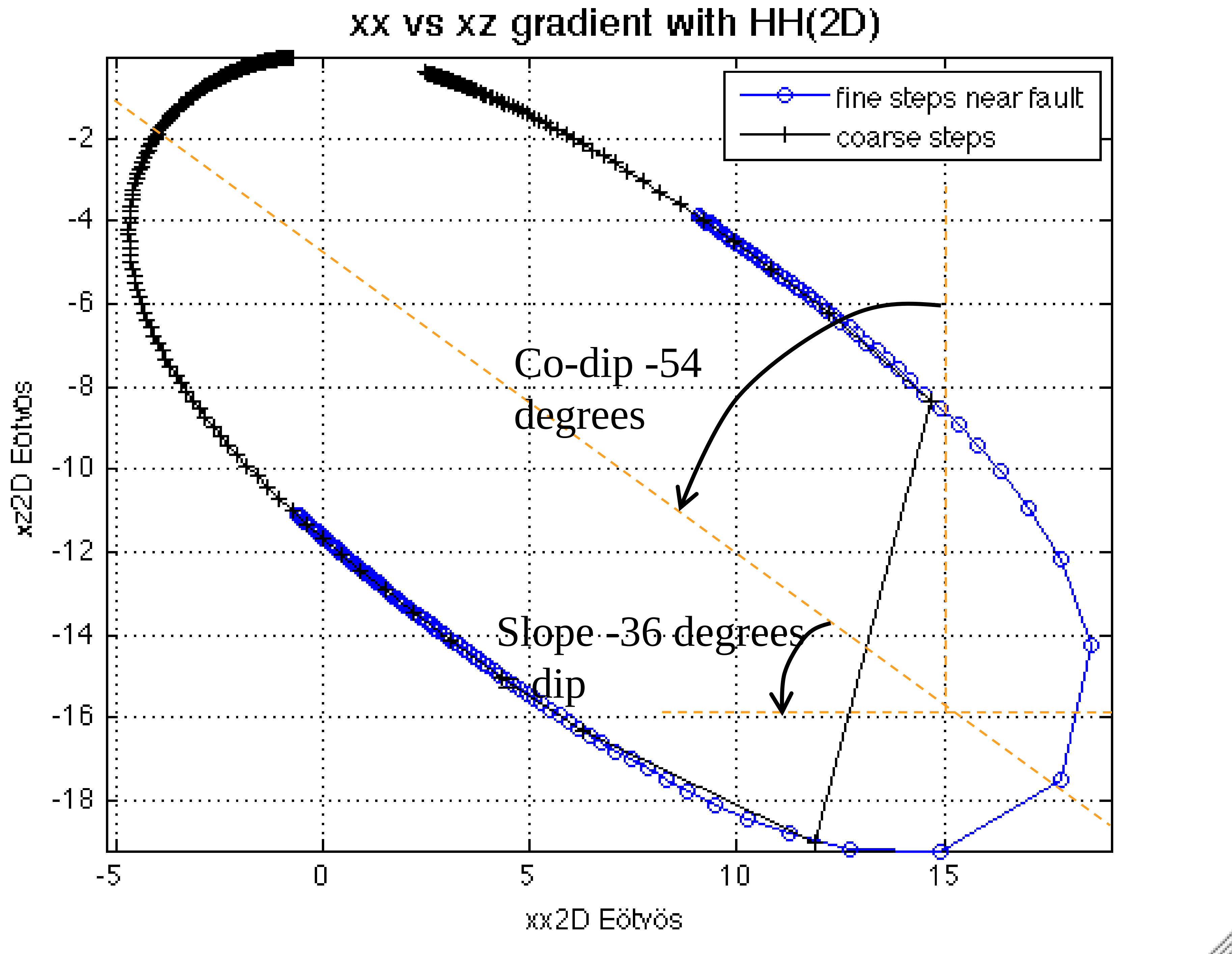
xx vs xz gradient with HH(2D)
fine steps near fault
coarse steps
Co-dip -54
degrees
Slope -36 degrees
= dip
-2
-4
-6
-8
-10
-12
-14
-16
-18
-5
0
5
10
15
xz2D Eötvös
xx2D Eötvös

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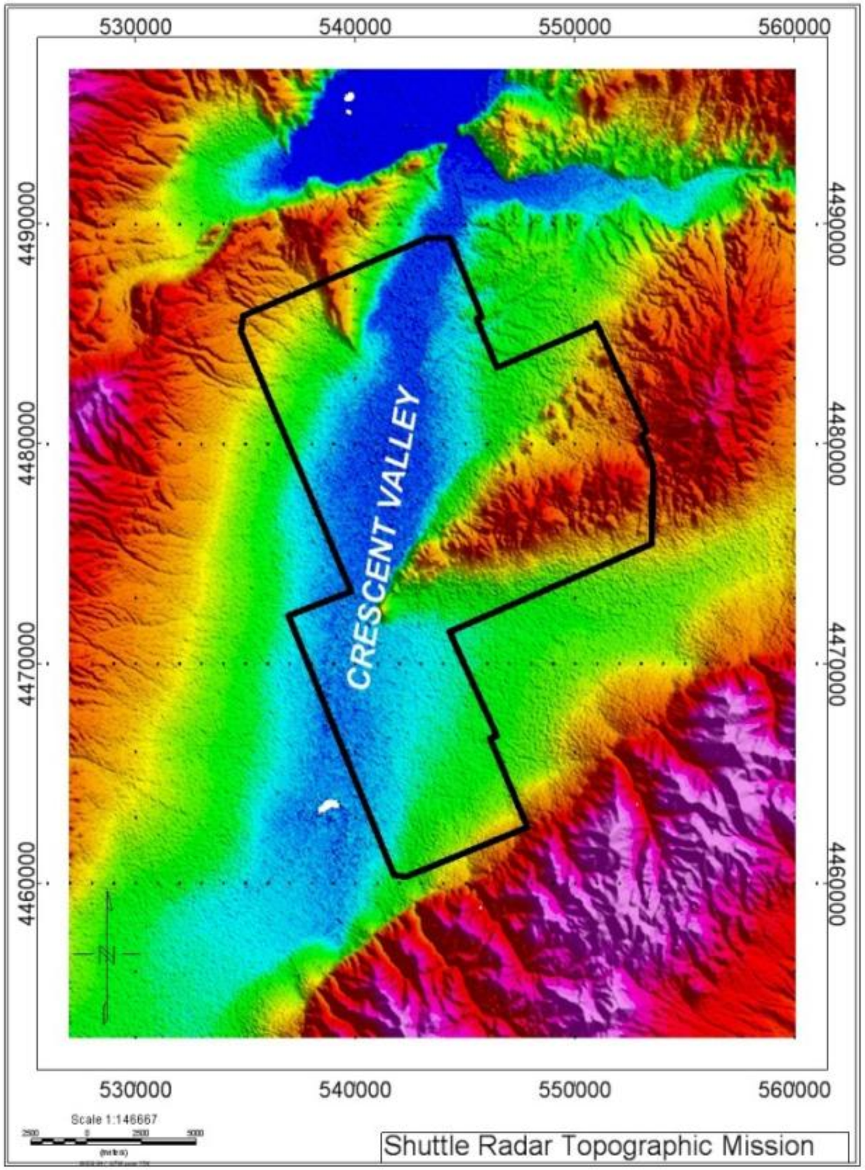
Full Tensor Gravity Gradiometry Survey plus Shuttle Radar Topographic Mission digital terrain model

The deep blue is an area of Crescent Valley, Nevada.
(approx. 10km x 15km).

FTG survey

91 lines
22609 tensor samples



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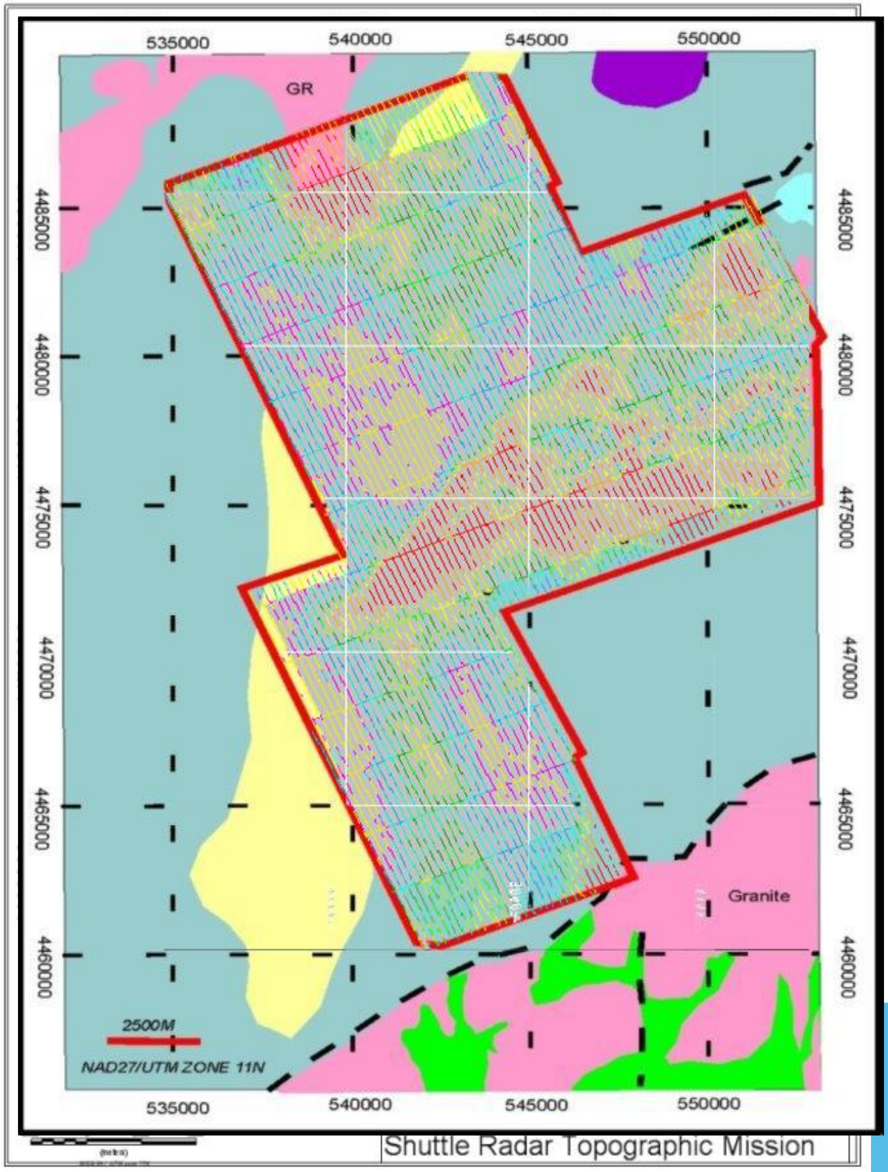
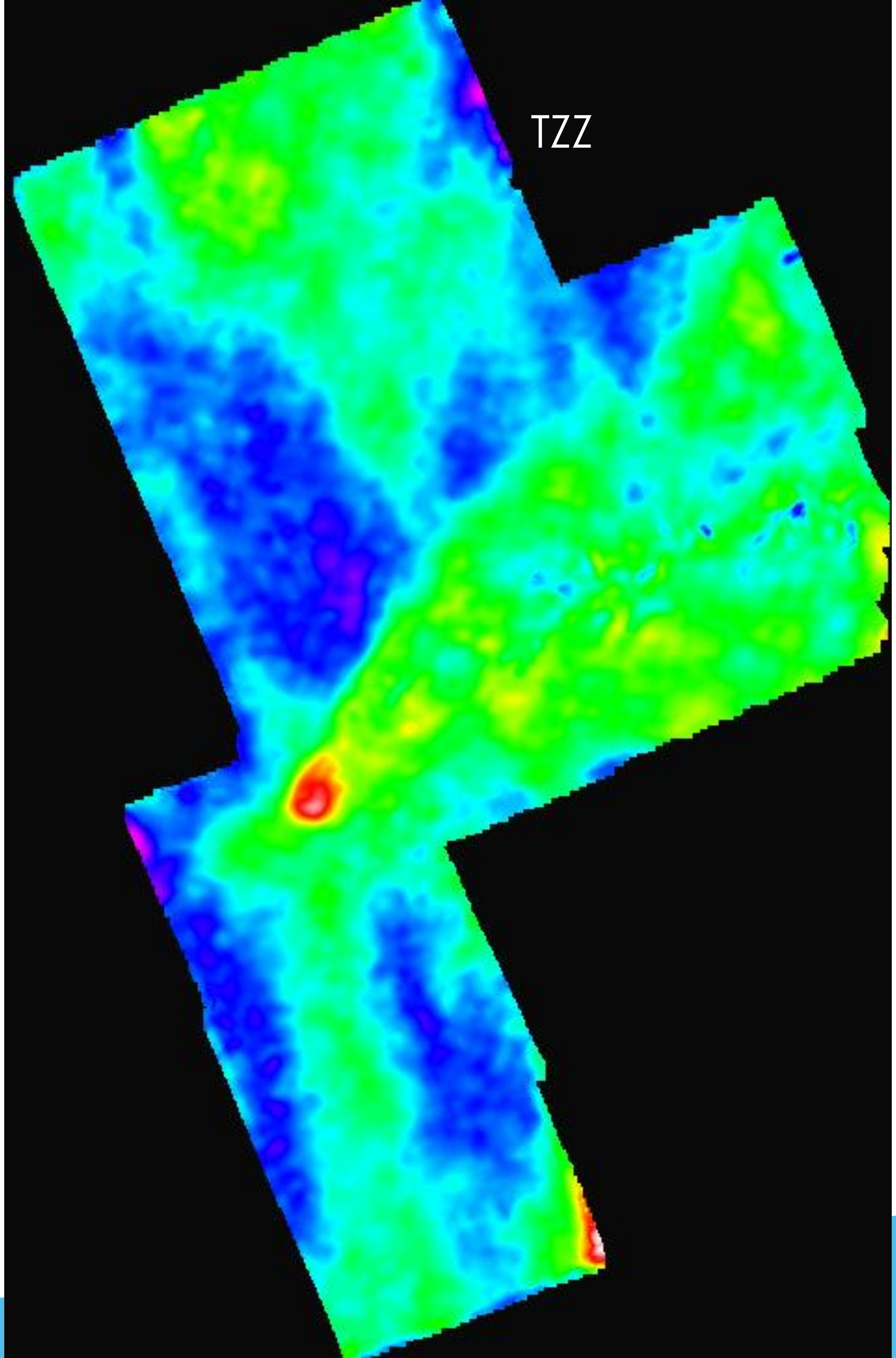


Crescent Valley, Nevada Tensor Gridding

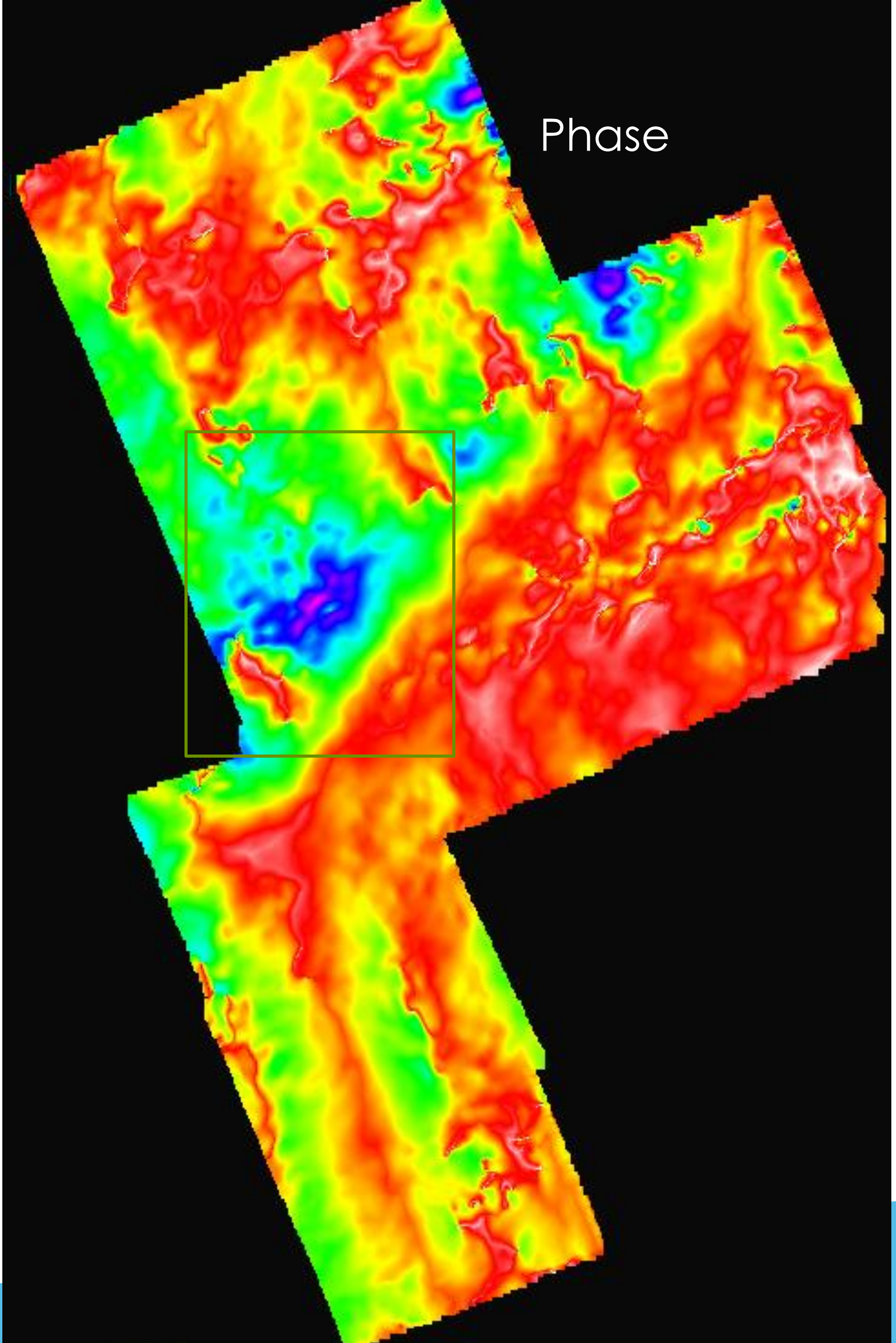
Cell size: 40 m
Rows: 724
Cols: 466
Gradients stored: END
Samples: 172205
Nulls: 165179
Terrain corrected



Crescent Valley, Nevada Tensor Gridding

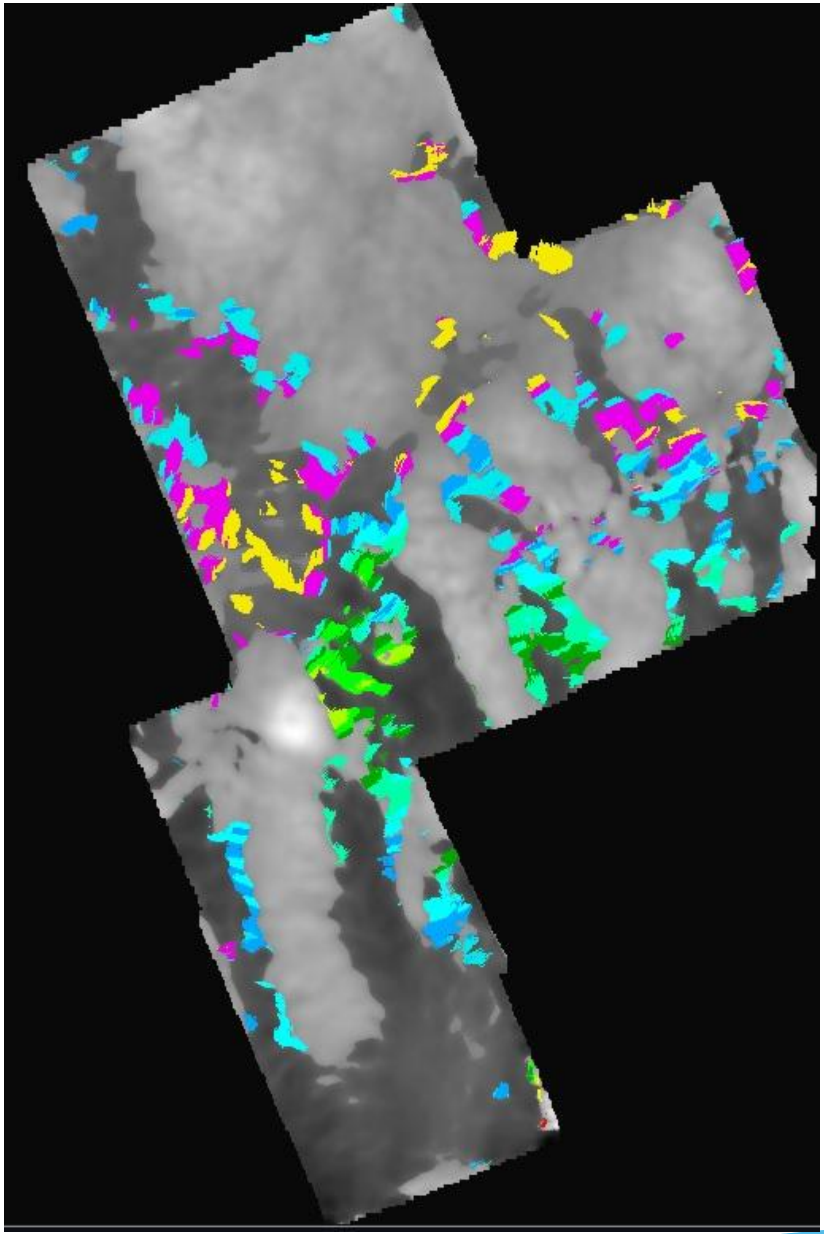
Cell size: 40 m
Rows: 724
Cols: 466
Gradients stored: END
Samples: 172205
Nulls: 165179
Terrain corrected

- Phase enhancement derived from rotating each tensor to solve the Eigen system.
- The NE cross-cutting fault and the N20W rift bounding faults are clear.
- Box shows subset working area for this study



2D Body zones

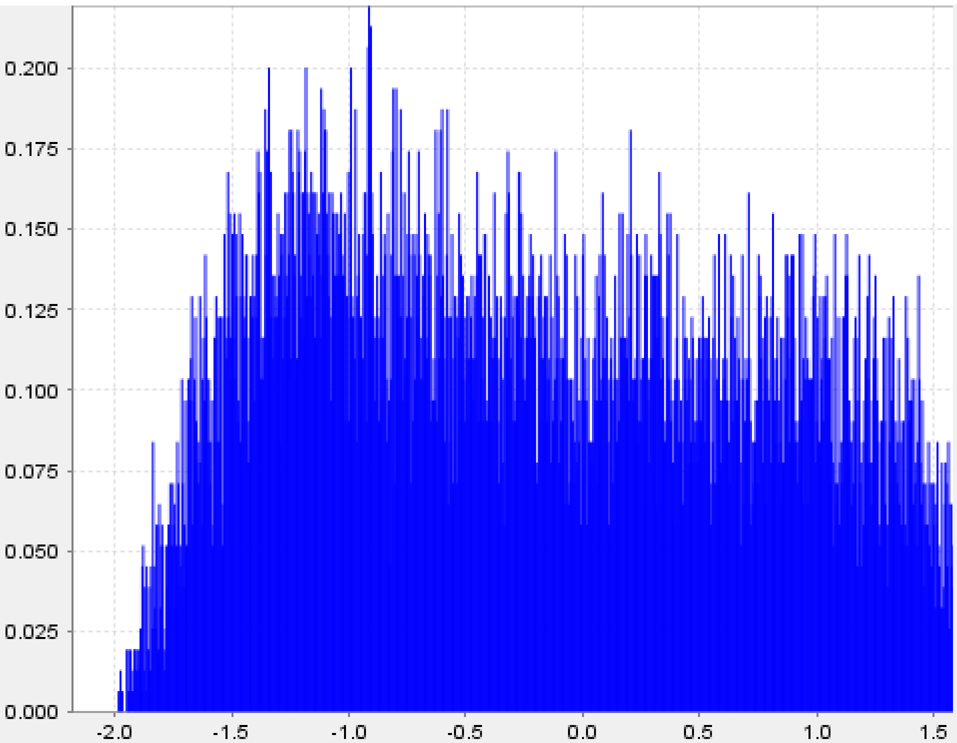
- Solve the tensor eigenvector system for each grid cell
- When the middle eigenvector less than noise floor, assume we have a 2D body
- Capture points in a database with all the eigenvectors, strike and tilt
- We have "zones" of 2D body influence



Check Statistics - 15487 samples

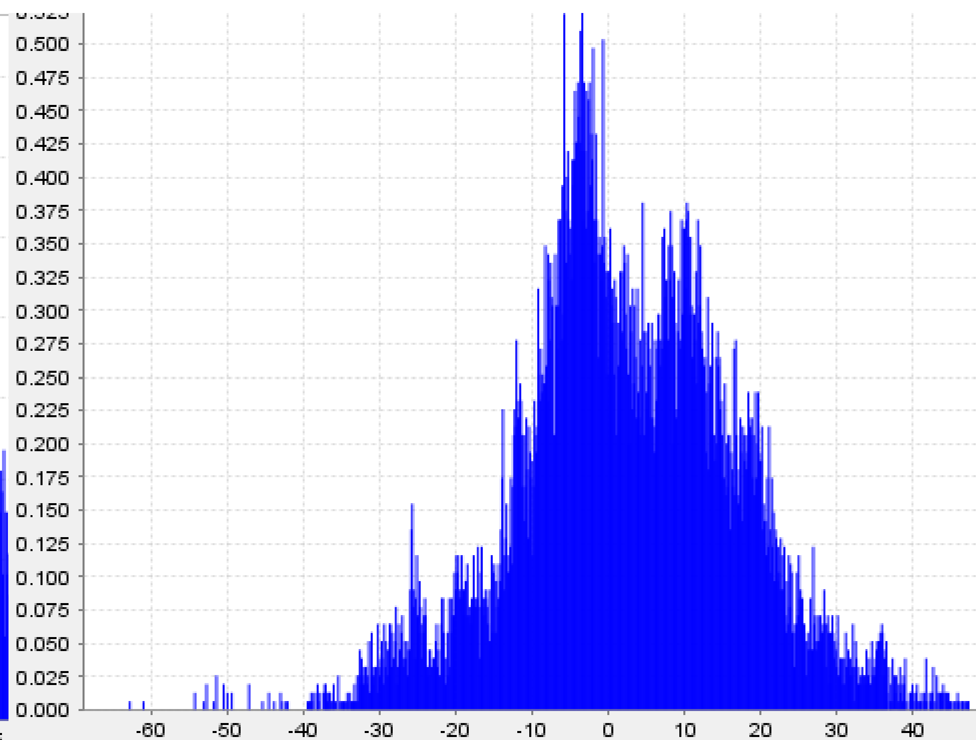
Middle Eigenvalue

- 2 E cutoff



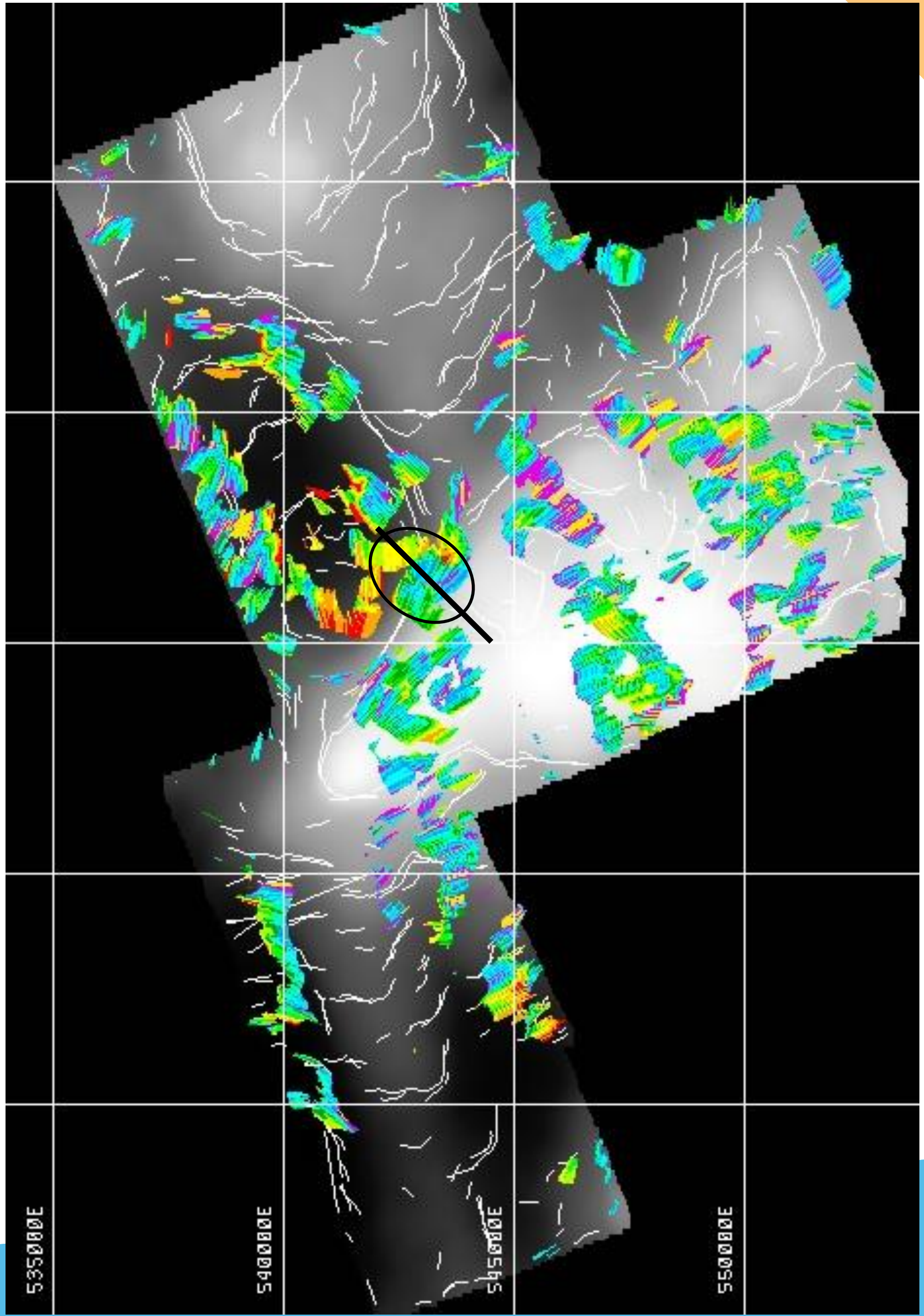
Structural Tilt

- Mean 2.4 degrees
- Std dev 14.2 degrees



Montezuma - Nevada

- 3 levels of upward continued multiscale edge picks or worms,
- full tensor eigensystem derived strike vectors,
    - showing the zones where a 2D signal character dominates the observed signal.
    - Requires 400m zone at right angles to strike where response is 2D



Profile sampling of tensor signal every 40m

Gxx	Gxz	Gyy	distance	-Gxx/Gxz	Gxx_scale	Gxz_scale	x	y
10.63	50.42	0.74	-200	-210.811	0.004	0.01899	542600	4475883
8	51.99	0.326	-160	-153.928	0.00289	0.01879	542636.4	4475866
5.2	53.68	-0.226	-120	-96.8279	0.00179	0.01846	542672.8	4475850
2.56	55.62	-0.099	-80	-45.9421	0.00082	0.01794	542709.2	4475833
-0.59	57.46	-0.031	-40	10.21682	-0.00018	0.0174	542745.6	4475817
-4.17	58.83	0.09	0	70.96709	-0.0012	0.01691	542782	4475800
-8.31	60.26	0.334	40	137.9018	-0.00225	0.01628	542818.4	4475783
-12.94	60.99	0.445	80	212.2416	-0.00333	0.01569	542854.8	4475767
-18.05	60.85	0.443	120	296.6128	-0.00448	0.0151	542891.2	4475750
-23.17	60.42	0.255	160	383.5356	-0.00553	0.01443	542927.6	4475734
-28.09	58.46	-0.011	200	480.5832	-0.00668	0.0139	542964	4475717
-33.93	55.99	-0.322	240	605.9515	-0.00792	0.01306	543000.4	4475700

Profile sampling of tensor signal every 40m

Gxx	Gxz	Gyy
10.63	50.42	0.74
8	51.99	0.326
5.2	53.68	-0.226
2.56	55.62	-0.099
-0.59	57.46	-0.081
-4.17	58.83	0.09
-8.31	60.26	0.334
-12.94	60.99	0.445
-18.05	60.85	0.443
-23.17	60.42	0.255
-28.09	58.46	-0.011
-33.93	55.99	-0.322

Best Fit Ellipse fitting

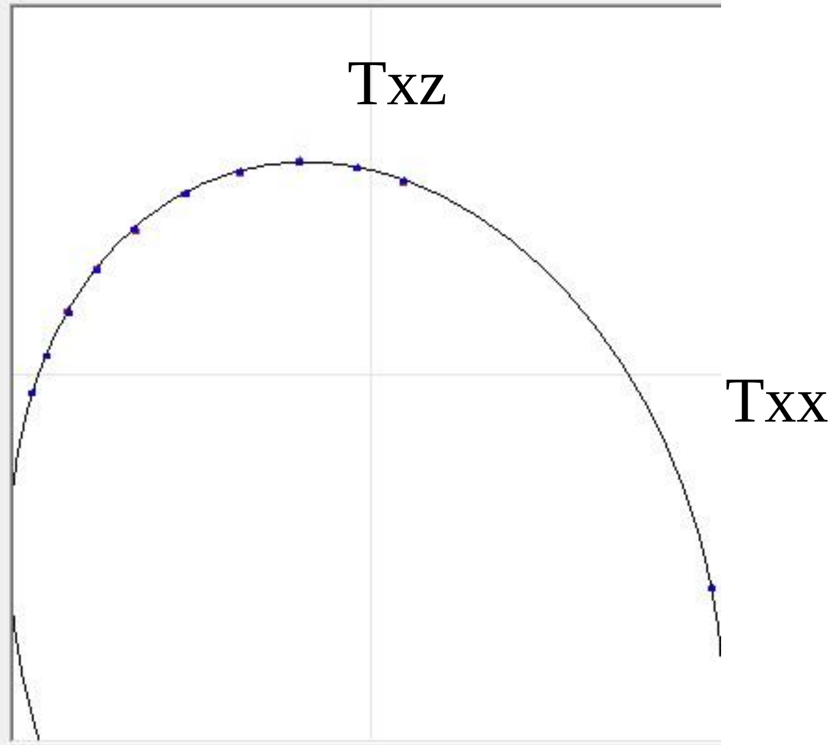
Use best-fitting algorithm for: Ellipse

Points:

	Prov. X	Prov. Y	Adj. X	Adj. Y	Residual
1	-32.300000	42.530000	-32.258168	42.646644	6,610.899827
2	-37.300000	44.130000	-37.305649	44.099531	6,096.715129
3	-43.310000	44.830000	-43.304980	44.624530	4,703.376692
4	-49.520000	43.580000	-49.544632	43.671969	2,719.810356
5	-55.340000	41.430000	-55.302416	41.360504	8,167.826571
6	-60.500000	37.570000	-60.659219	37.751031	9,469.667635
7	-64.580000	33.510000	-64.518722	33.461632	5,563.073812
8	-67.570000	29.050000	-67.525254	29.024319	3,621.287044
9	-69.830000	24.460000	-69.787987	24.442385	3,411.913658
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Solution:

	Solution
Centre X	-36.212272
Centre Y	-4.444134
Major axis	49.932897
Minor axis	36.259528
Ellipse rotation (radians)	4.992343



Output

```
--------------------------------------------------------------------------------
Global check of the adjustment      ***PASSES***
Check of the evaluated unknowns     ***PASSES***
Number of observations              11
Number of unknowns                  5
Degrees of freedom                  6
Iterations until convergence        13
Variance                            0.022000
Std. dev. observation unit weight   0.148325
***********************************
Adj. ellipse centre X               -36.212272
Adj. ellipse centre Y               -4.444134
Adj. ellipse semi-major axis        49.932897
Adj. ellipse semi-minor axis        36.259528
Adj. ellipse rotation               4.992343
```

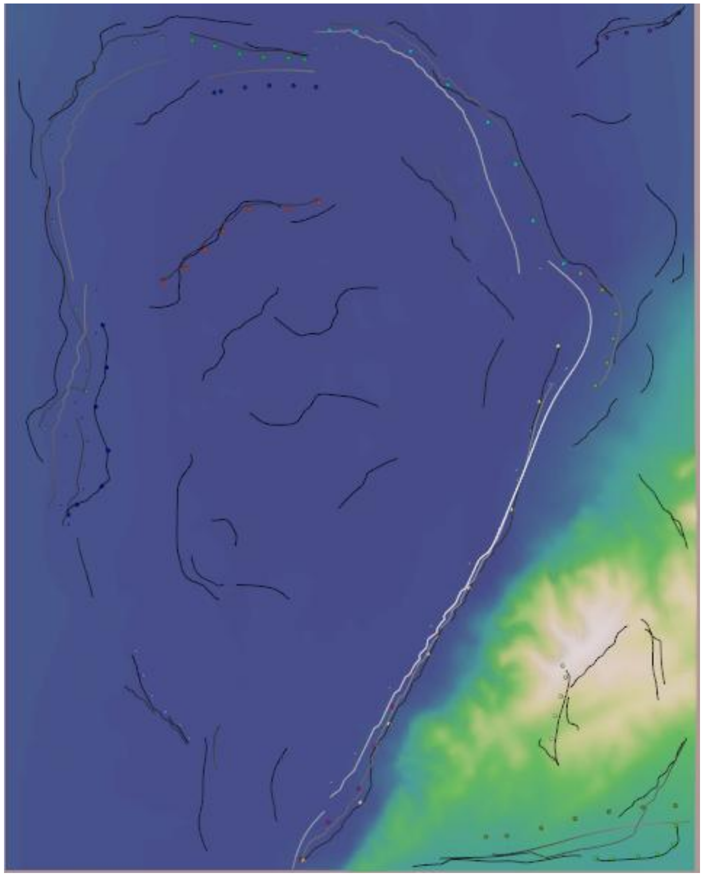
Solve for 5 inversion parameters

Outline

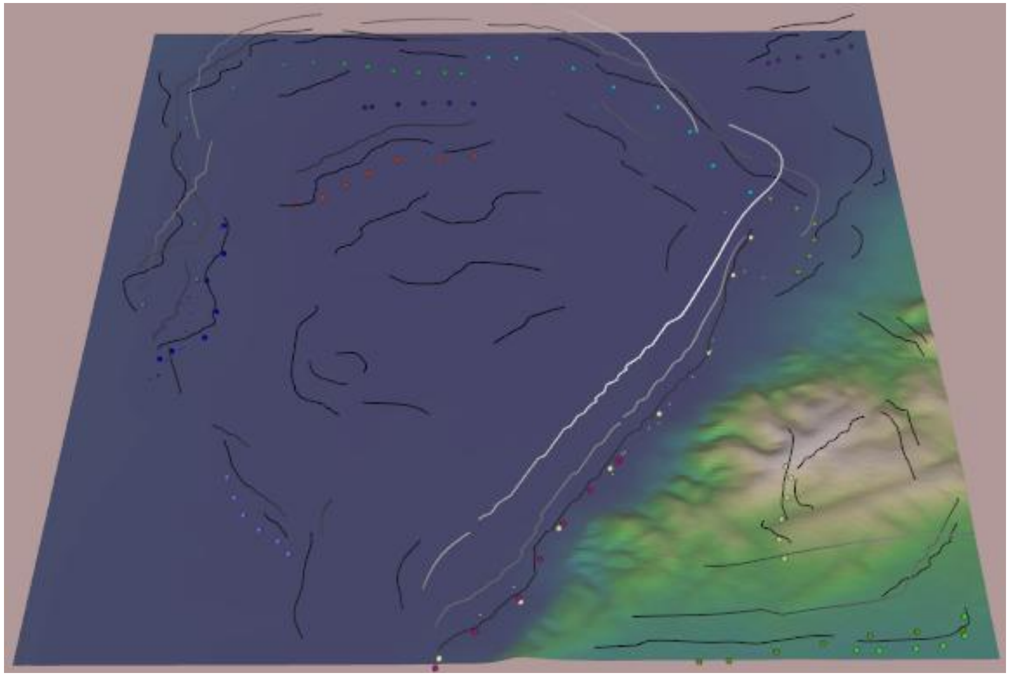
- Gz Dip calculation
- Darling Fault calibration
- FTG Dip calculation
- Nevada Case Study
- 3D fault network generation

3 levels Upward continuation Multi-scale edge picking

plan



perspective

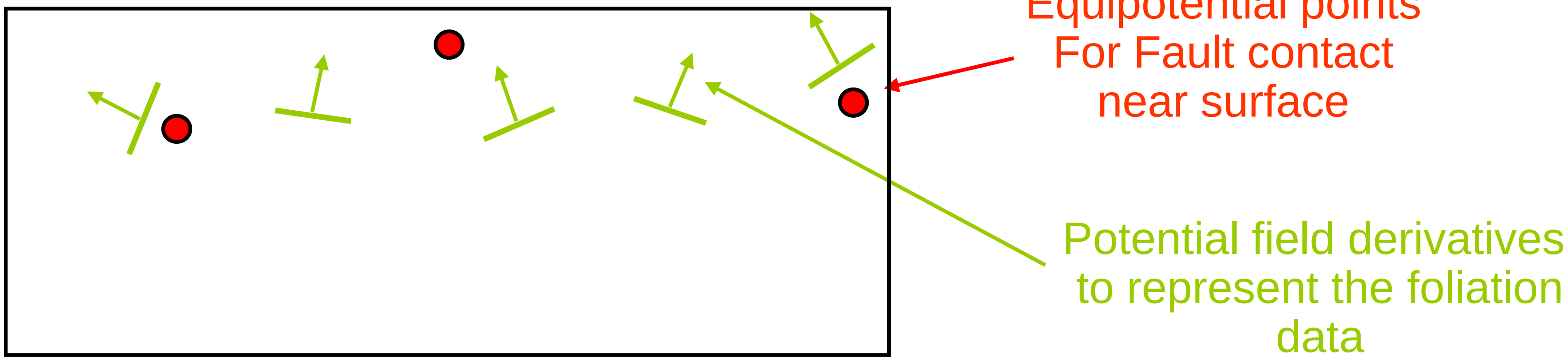


3D Surfaces

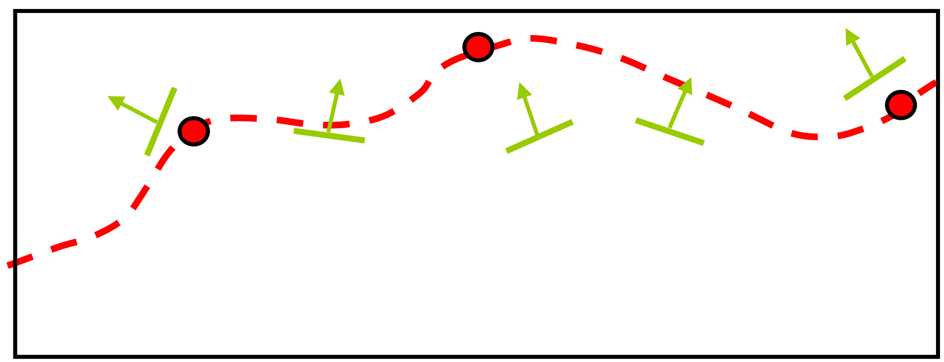
- Merge and chop short limbs, to match a longer worm at lower levels – allow 2 or more branches at shallower levels
- Estimate the shallowest contact depths.
  - This forms the near surface “contacts”
- Estimate dip one or more times for each feature
- Classify feature as linear/curvy
- Estimate the box that limits the extent of each feature

Interpolation method

Potential field Equation



The scalar field is interpolated by cokriging
the increments and their derivatives (Lajaunie & al., 1997)



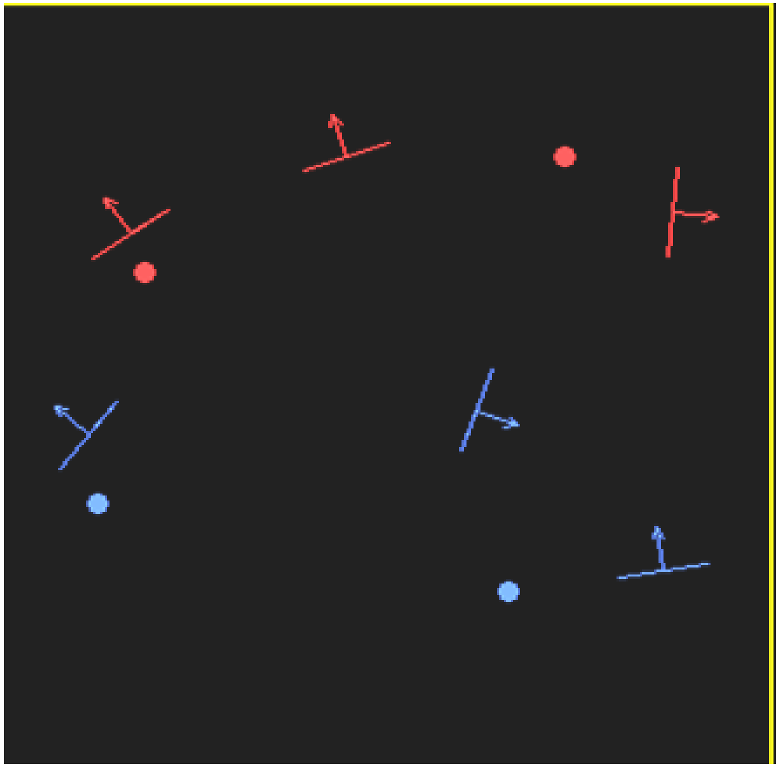
Faults are drawn as isovalues of the interpolated scalar field.

The fault is an Isosurface for a 3d scalar field

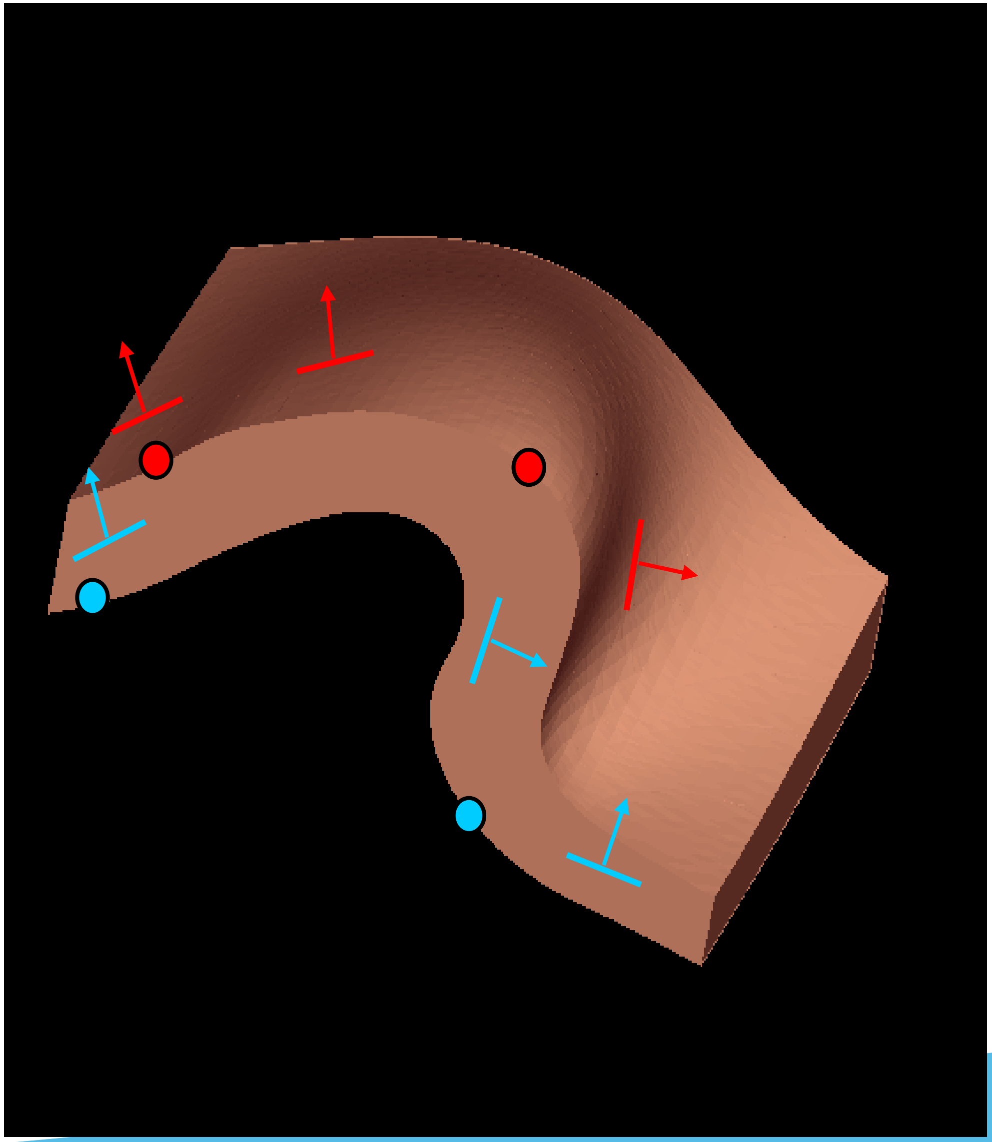
3D surfaces calculation and render

- Create new feature in the dataset
- Assign the contact data
- Assign the dips as an observation of a foliation, and its direction
- Limit the fault extent with the bounding box
- Calculate geometry using implicit function and sampling algorithm eg marching cube

Interpolation method

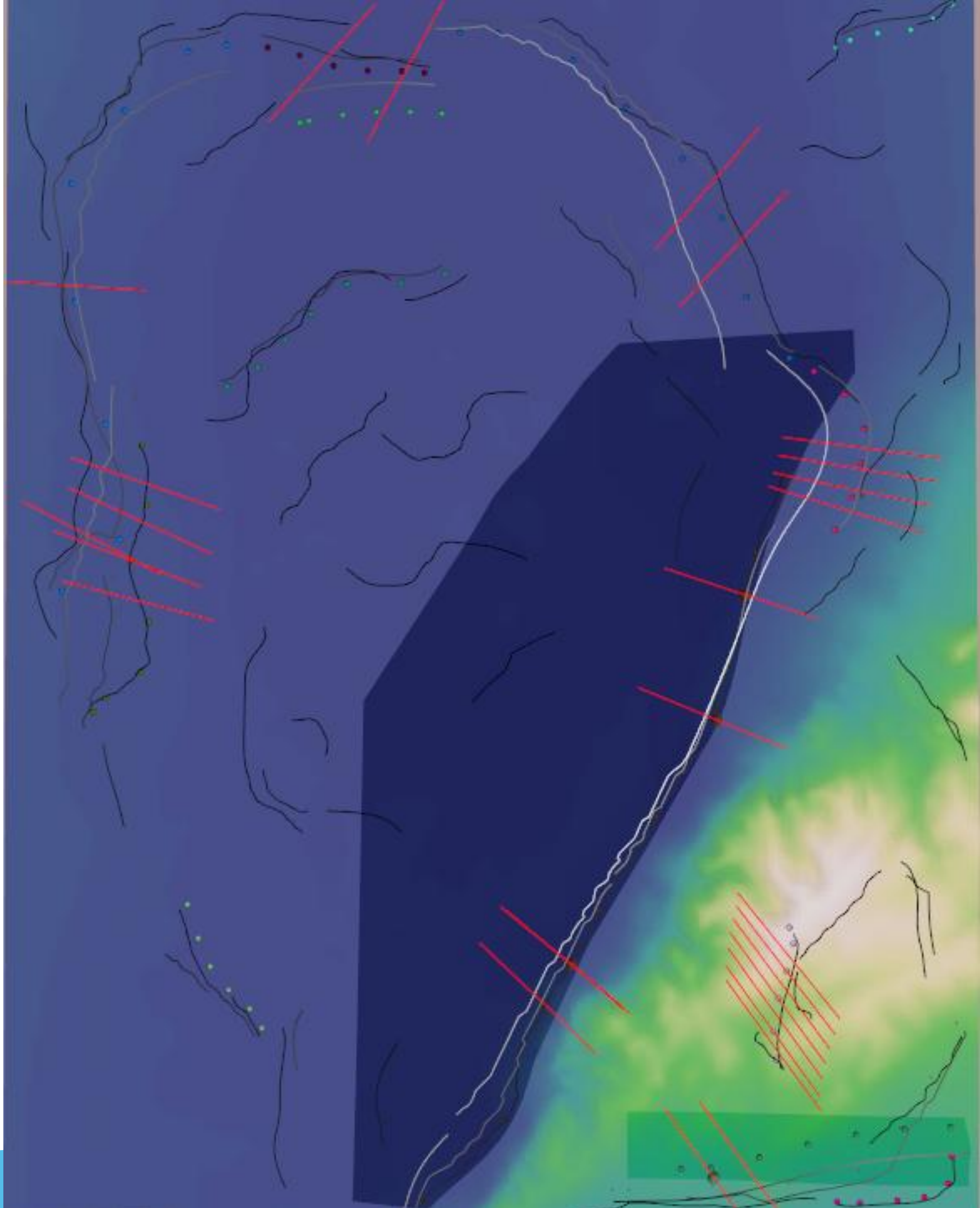


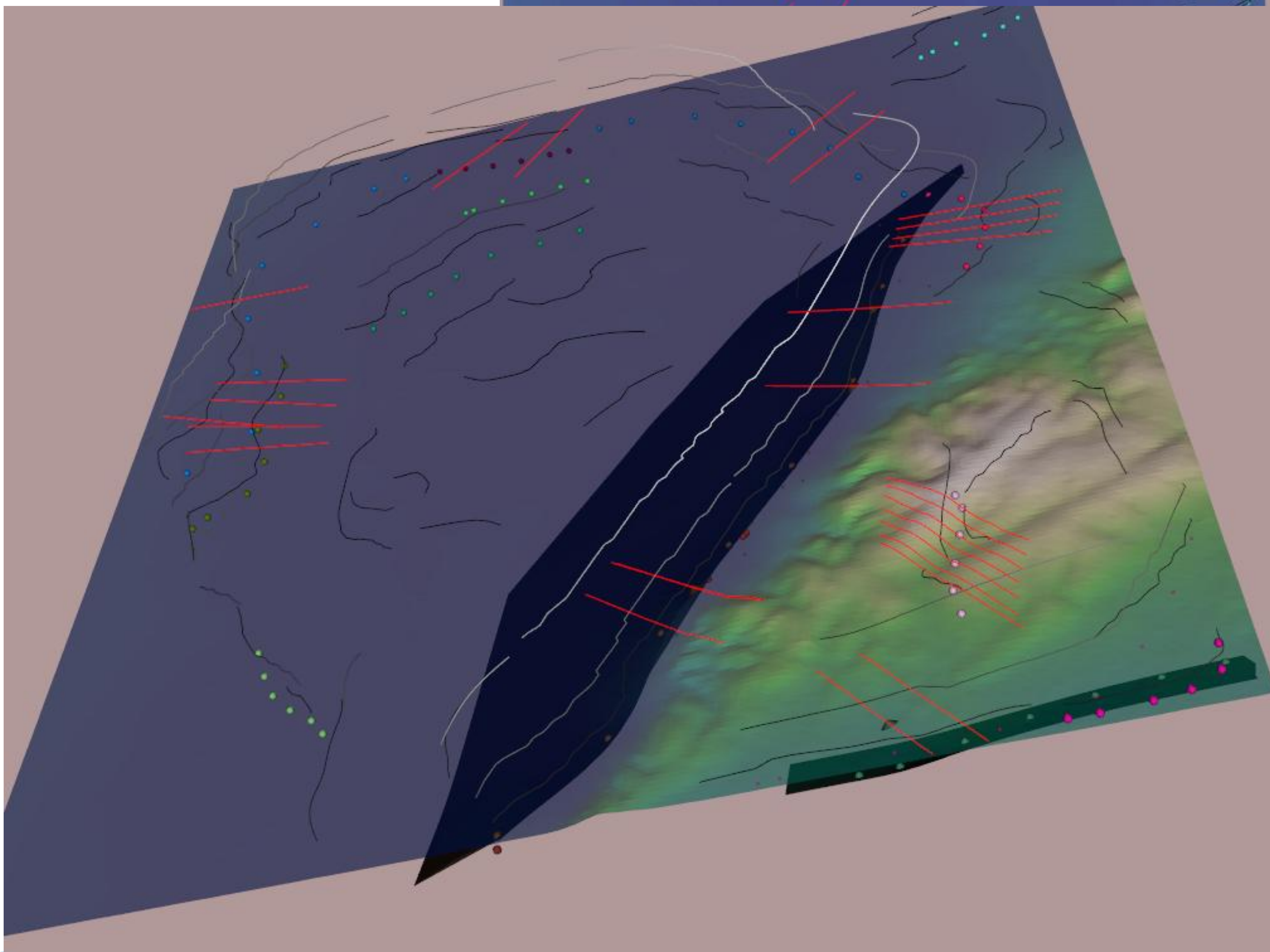
Isosurfaces in 3D space



3D surface intersecting with topography

Same Montezuma survey
Shows the dip sampling lines





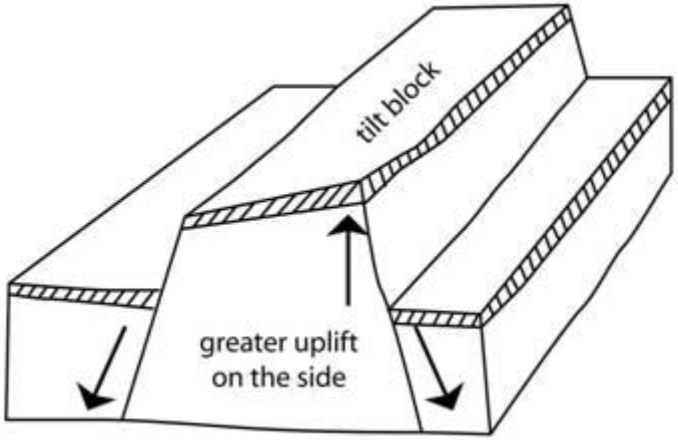
Structural Tilts

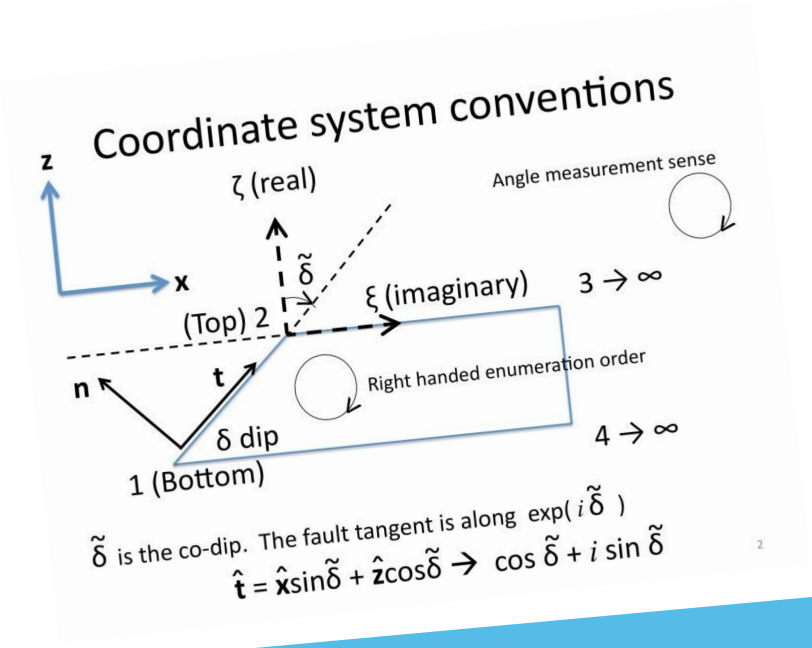
- How many rotational degrees of freedom are measured?
- Strike/Dip/Tilt!!!
- Are all these geological surface orientations??

Tilt Blocks & FTG survey data

Tilt blocks are formed when one side of the middle block is uplifted higher than the other side.

The top of the middle block will not be flat but will be tilted.

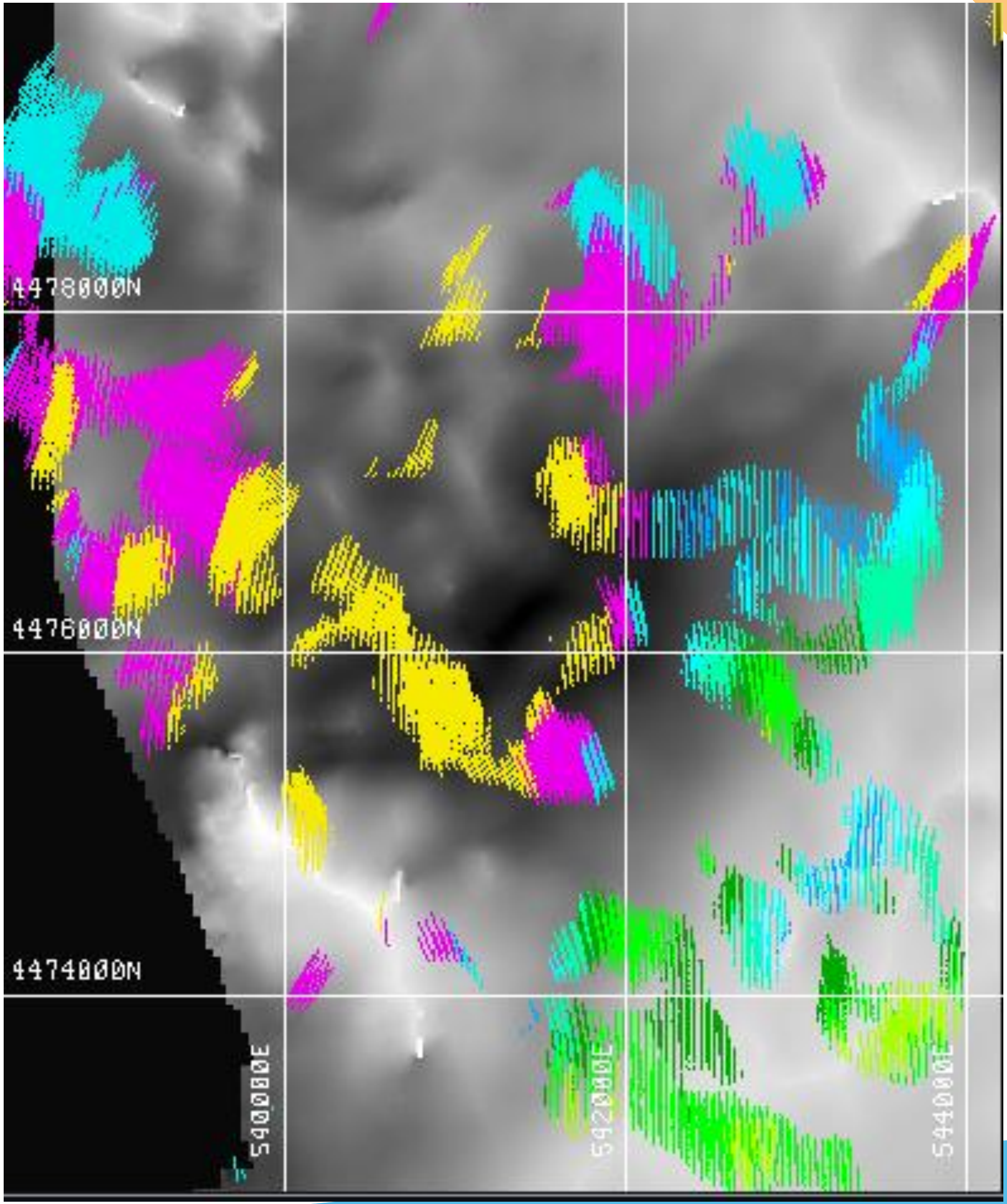




Detail showing tilt distribution spatially

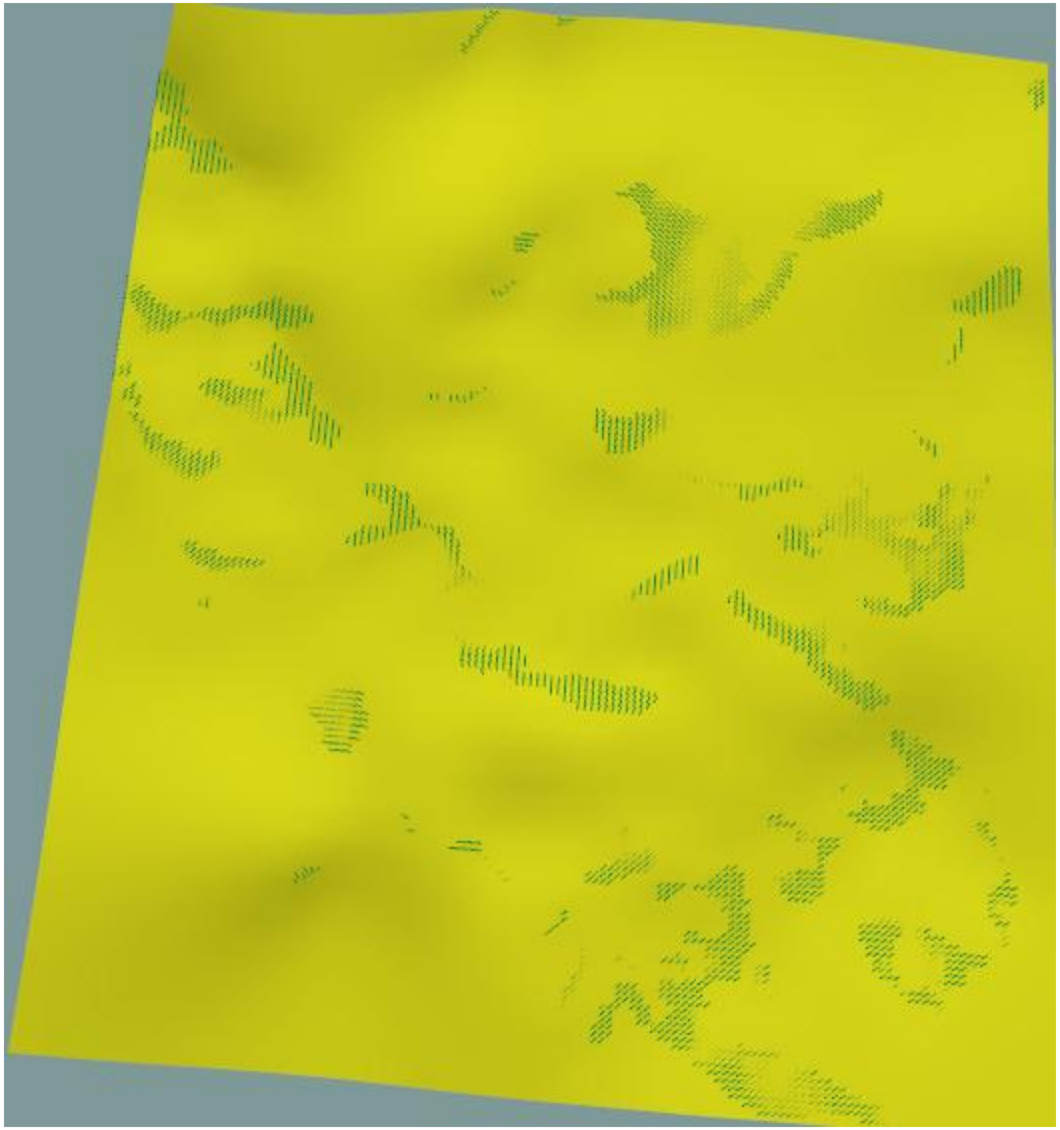
Tilt angle interpreted as a "STRIKE"

So zero tilt is NS



Montezuma Tilt Surface

- Extrapolate between 2D zones
- Continuous surface
- Not the terrain, as this has been removed



Conclusions

- Dip estimate using
  - Profile sampling, across the 2D feature
    - **least squares ellipse fitting for tensor gradients**
    - **Upward continuation and zero point determination for gravity**

- Benefits are explicit 3D surfaces, unambiguous, with audit trail.

- Don’t be scared of 9 components of a tensor, because you can reduce it to a dip/strike and throw which a geologist will understand

Structural Geophysics

Not just seeing structural geology in the magnetics

Direct measures of 2D structures from the Gravity Gradient Data.

The End

INTREPID GEOPHYSICS