ISR - Induced Source Resistivity
- Sierra Gorda Project -
ISR across a development-stage copper-molybdenum project
Atacama Desert, northern Chile.

Yves Lamontagne
Rob Langridge
Owen Fernley
Bill Spicer

LAMONTAGNE GEOPHYSICS LTD GEOPHYSIQUE LTEE

KGHM INTERNATIONAL

Sumitomo Corporation

UTEM Electric Field Measurements

- first measurements by Y. Lamontagne ~1975 (U of T)
- Ph.D. studies (U of T) by J. Macnae confirmed the method
- ISR evolved ~ 1986 for gold exploration (sillicification)
- clients included Noranda, BHP, etc - mid 80's to early 90's
- industry, company focus shifted
- ISR/ISR processing tested in a series of surveys:

  2006 Shea Creek (AREVA)

  alteration in sandstone

  2009 Sudbury Basin (FNX/Xstrata/Vale Inco)

  defining targets out into the footwall rocks

  2010 Thunder Bay North - TBN (Panoramic Resources)

  magma conduit system, Current Lake Intrusive Complex, Thunder Bay

all case histories available

Developing ISR

Test surveys in diverse geological environments required:

- adjustments to the survey method employed in the field
- further development of the ISR processing software

We were looking for a location to showcase:

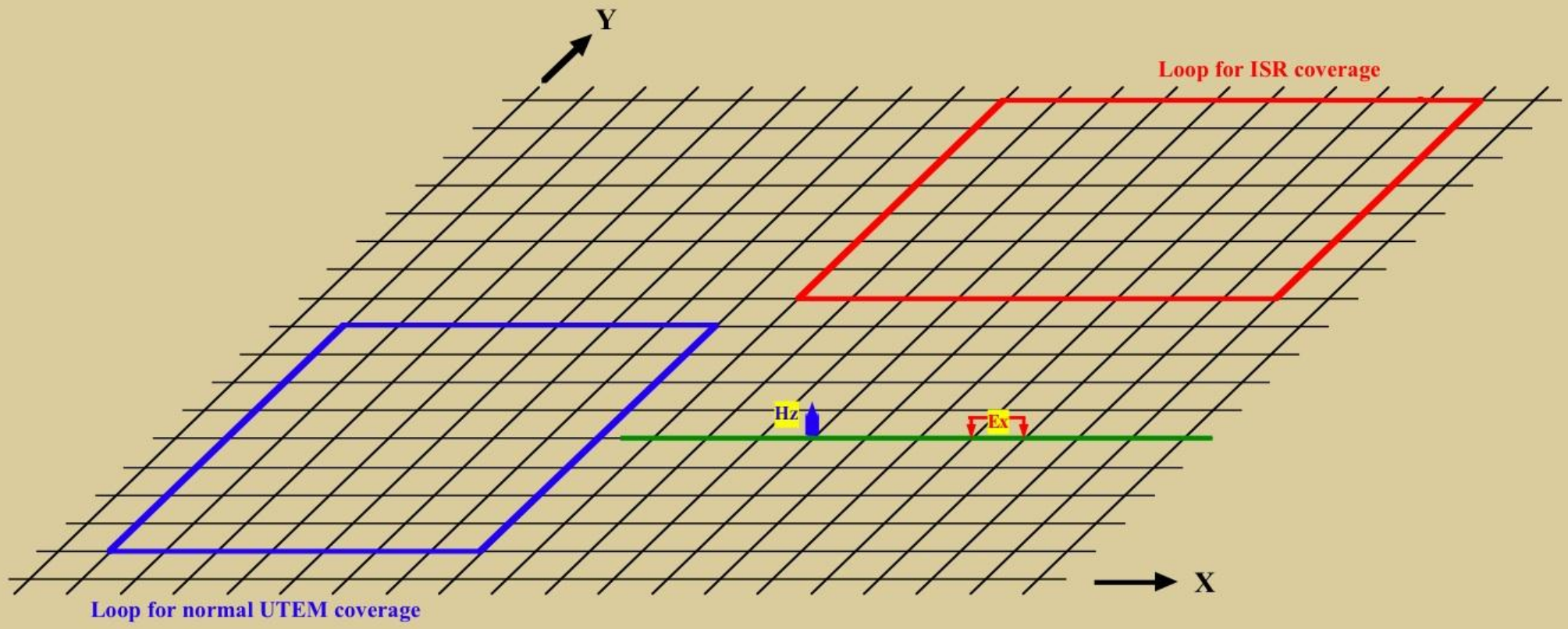
- depth penetration less dependent on the conductivity structure
- the advantages of employing an inductive source

The opportunity to carry out a test survey @ Sierra Gorda resulted from discussions with QuadraFNX in 2010.

ISR – Induced Source Resistivity

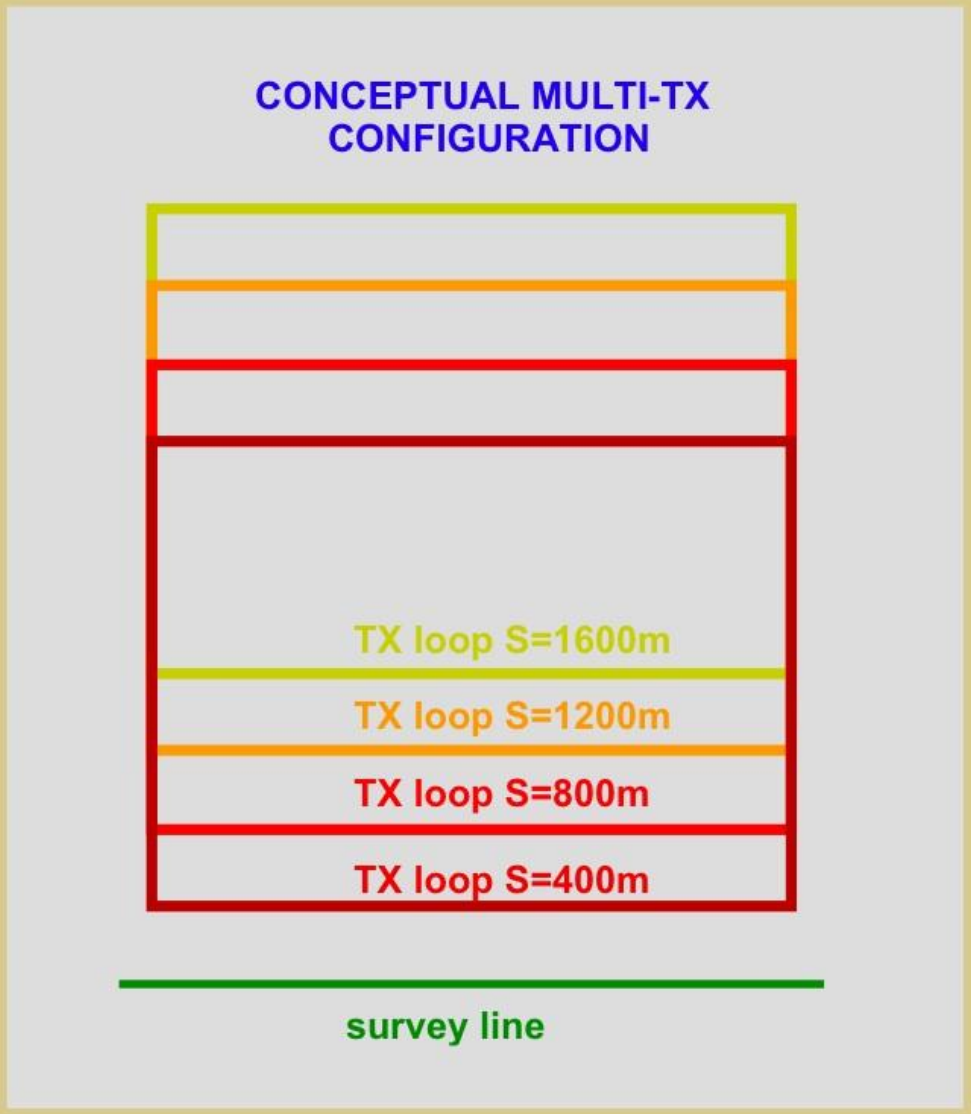
- large ungrounded loop source
- electric dipole sensor
- time domain wideband measurements
- UTEM system response – square wave

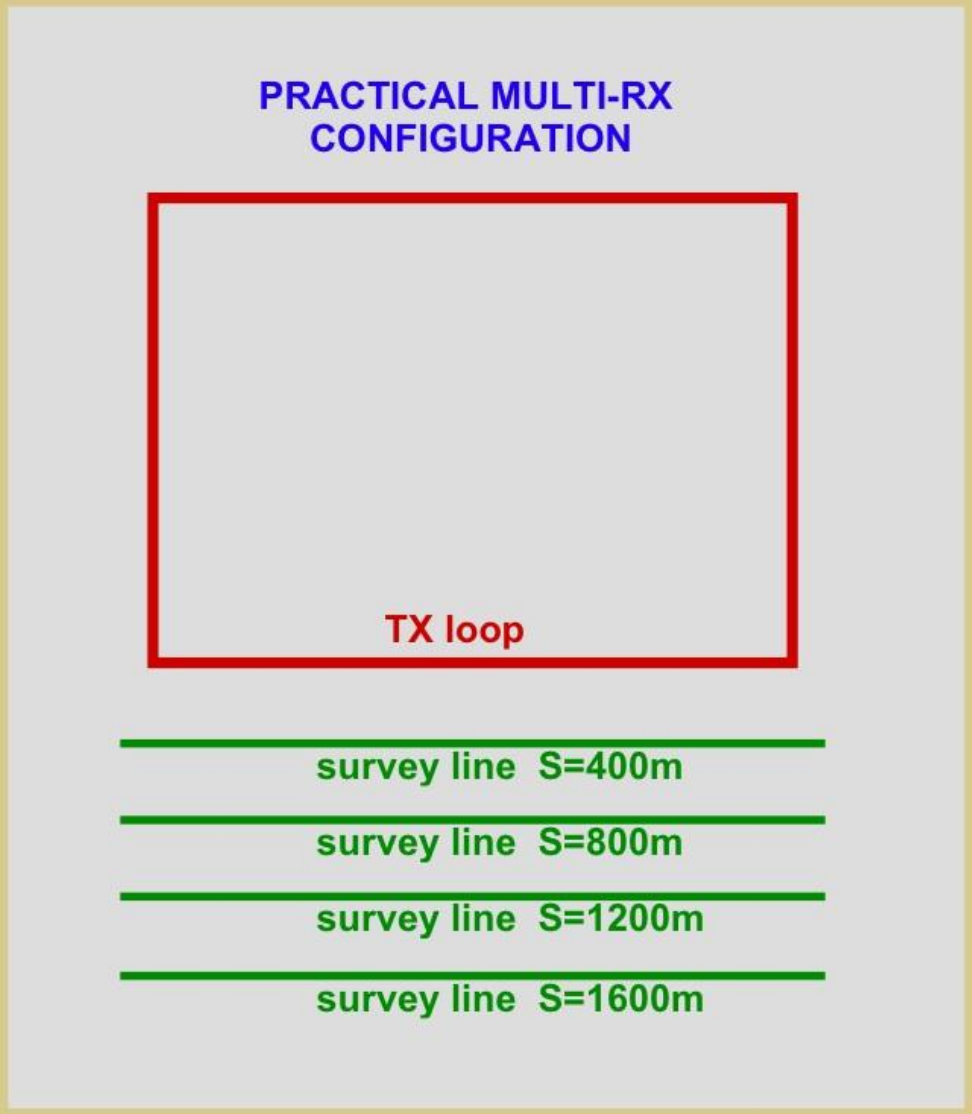
Geometry of ISR measurements



Y: strike direction
X: traverse line direction

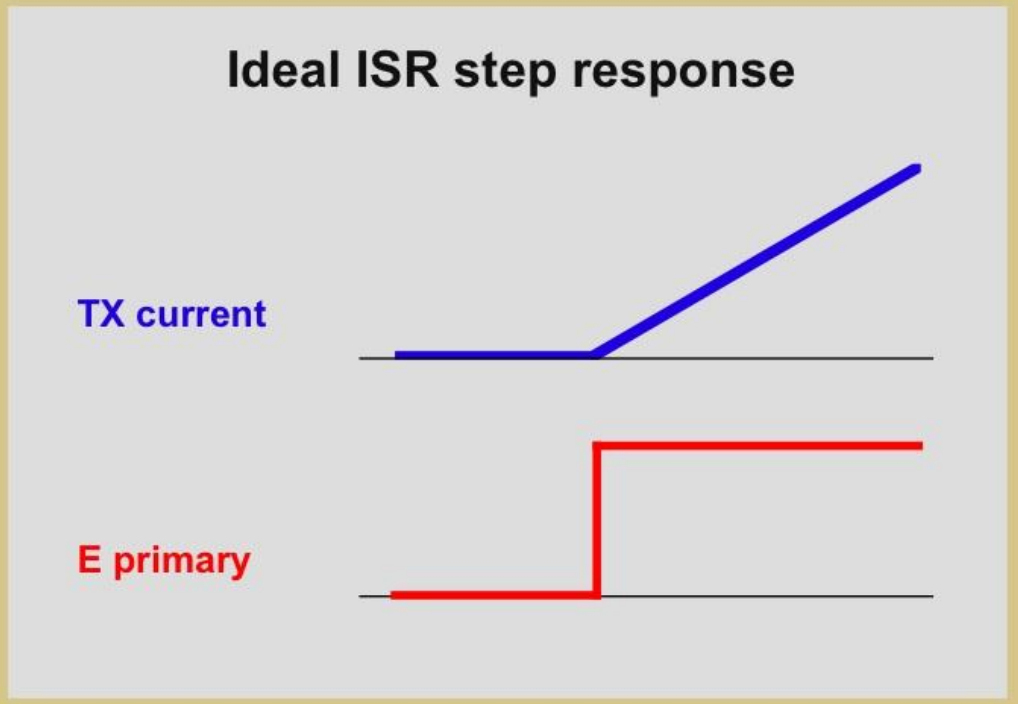
Multi-fold ISR measurements

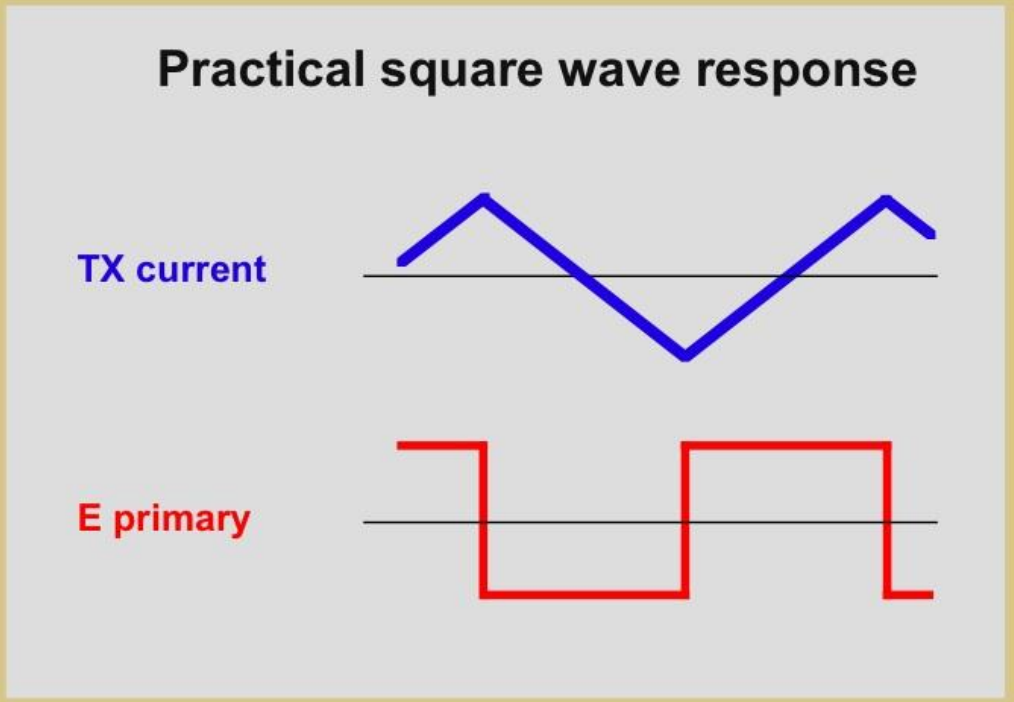




ISR waveform

- E field step response
- Constant primary E field at late time
- Late time response is a DC resistivity response excited by EM induction
- Reversing waveform used in practice

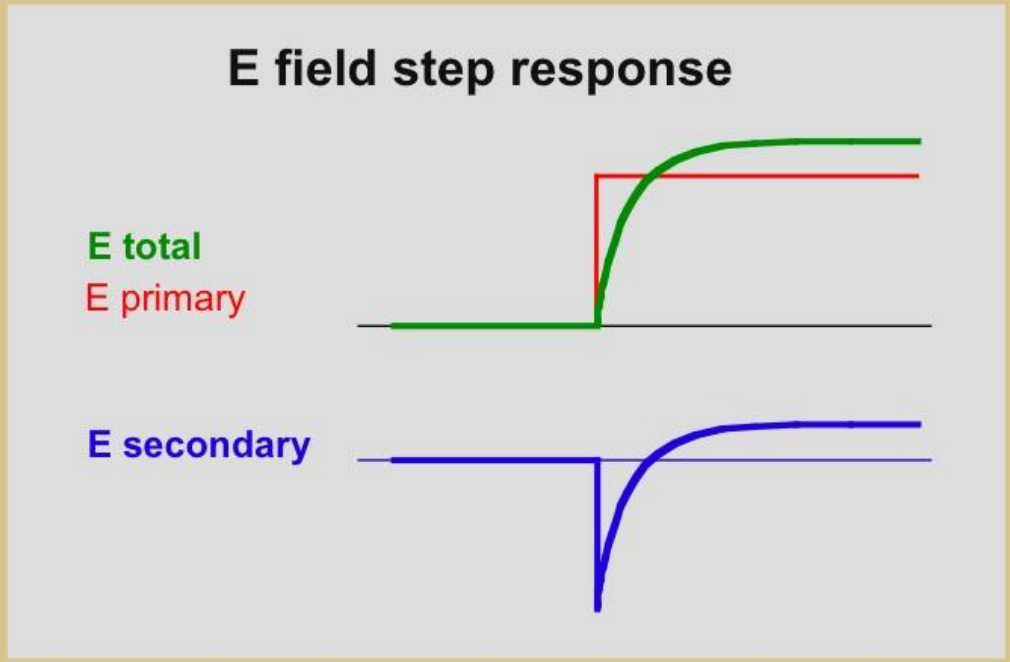




E field response

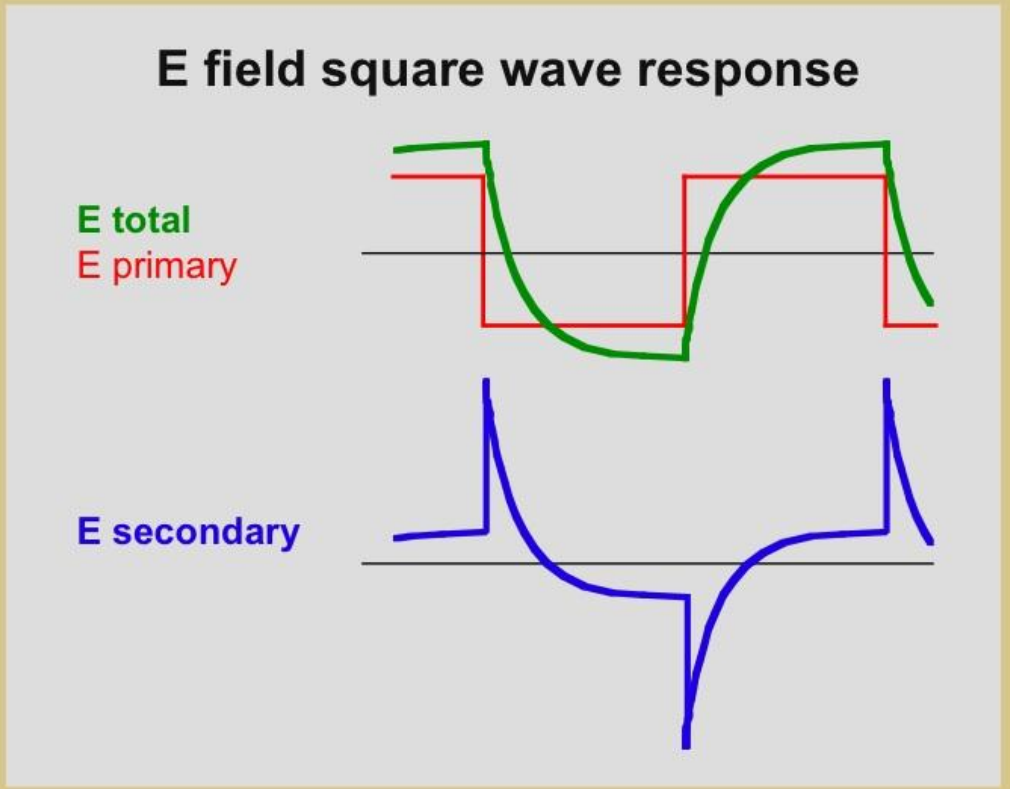
Step response

- transient from 0 to limiting field
- transient shape due to EM diffusion
- E primary field limit only for horizontally layered structures



Square wave response

- transient starts from end of previous half-cycle
- periodic effect if transient long



Conversion to step response

$$S(t) = 0.5\,[Q(t) + Q(t+h)]$$

S: step response
Q: square wave response
h: half period

ISR data Interpretation

Value of ISR

- sensitive to resistors and to contrast in very resistive rock
- useable with very resistive cover
- 10x tp 100x signal strength relative to H field
- typical repeatability <0.1%

Difficulty of ISR Interpretation

- depolarization effect of surficial conductors
- need to analyze channel-to-channel/loop-to-loop variation
- effect of large scale and deep resistivity structure

Need for data processing and inversion.

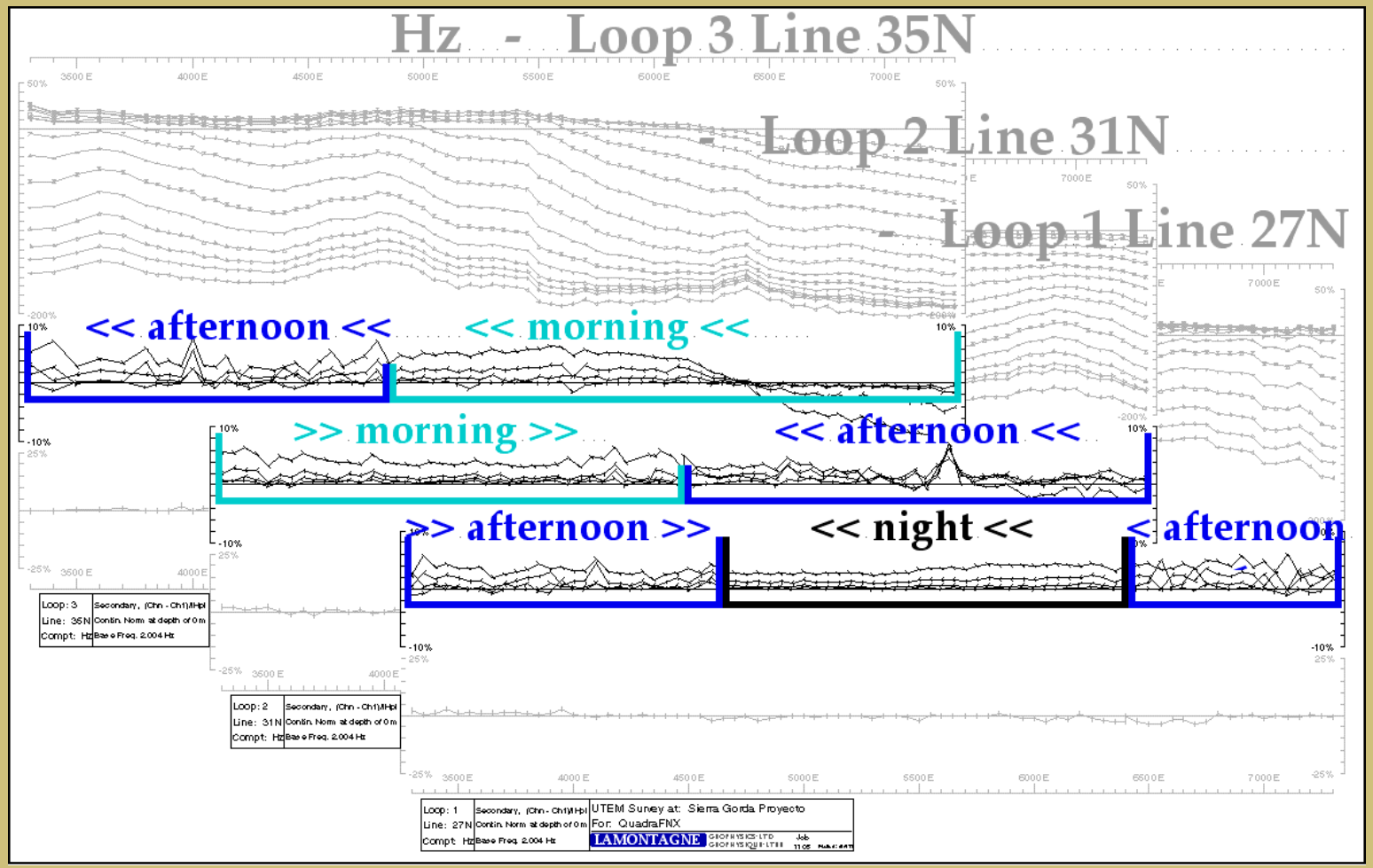
Sierra Gorda ISR Survey

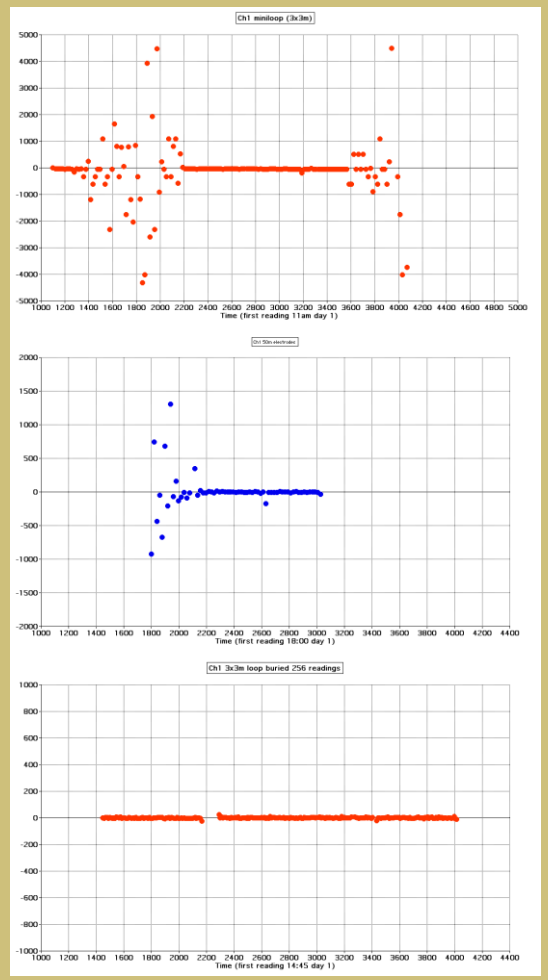
- December 2010 - initial phase of testing
- January 2011 - equipment modifications
- February 2011 - second phase of testing

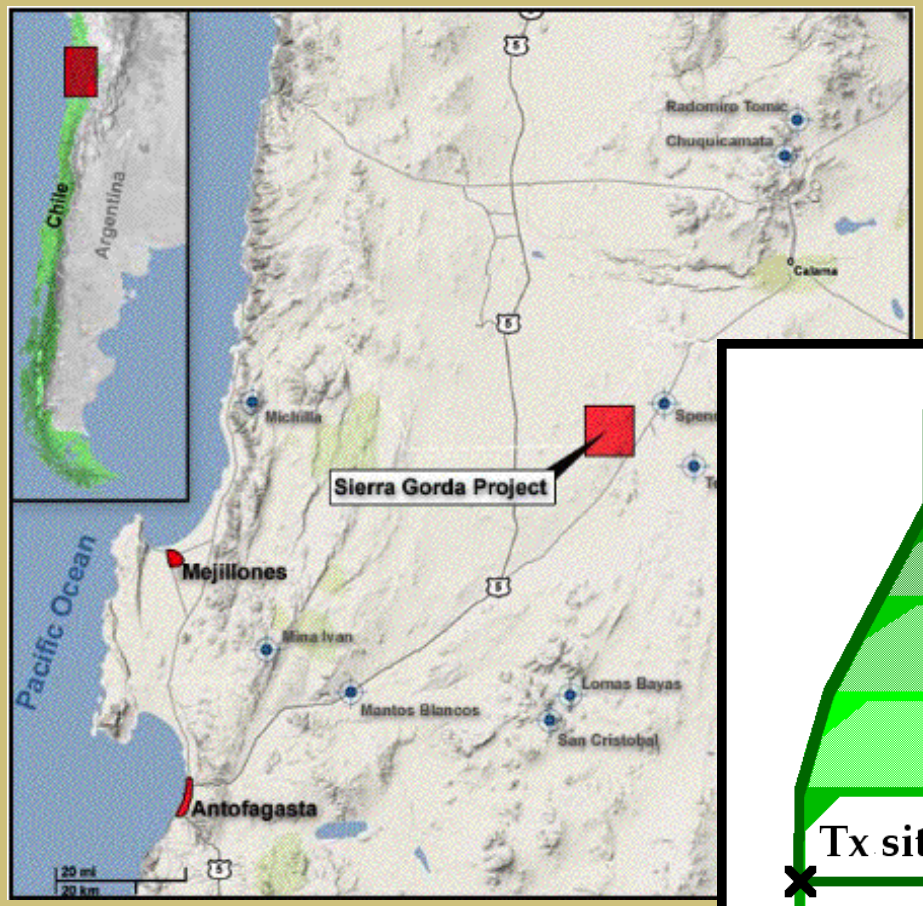
Based on the results of the testing phases the decision was made to carry out a full test survey with the following parameters:

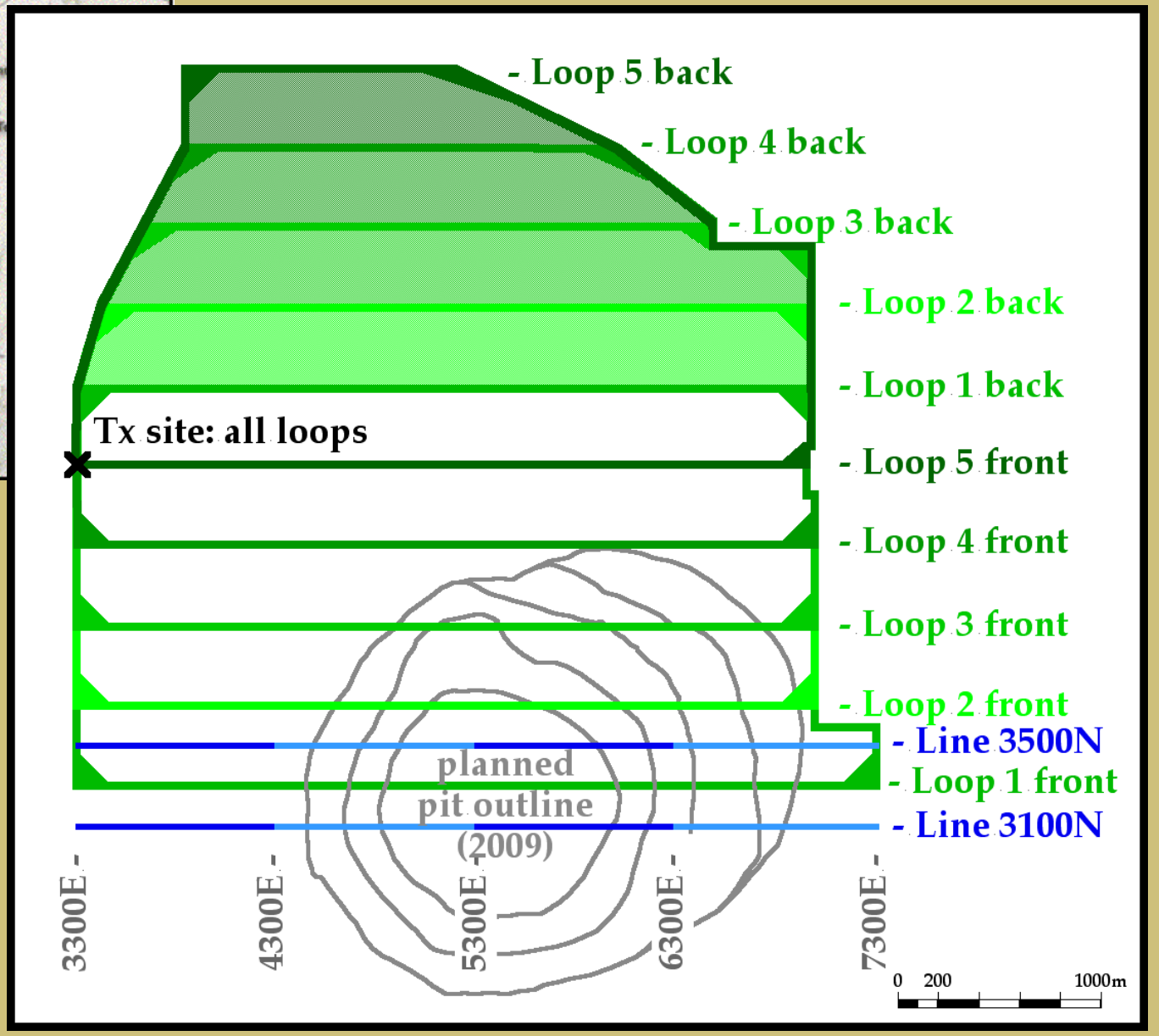
- two 4000m survey lines ~centred over the planned pit
- 50m dipoles, capacitive electrodes
- ~2000x4000m double loops 12AWG w Master-slave Tx
- 20Ch surveying @ a frequency of 2Hz

Wind-generated electrostatic noise contact electrification triboelecticity






Chile
Argentina
Pacific Ocean
Radomiro Tomic
Chuquicamata
Calama
Michilla
Sierra Gorda Project
Mejillones
Mina Ivan
Mantos Blancos
Lomas Bayas
San Cristobal
Antofagasta
20 mi
20 km


- Loop 5 back
- Loop 4 back
- Loop 3 back
- Loop 2 back
- Loop 1 back
Tx site: all loops
- Loop 5 front
- Loop 4 front
- Loop 3 front
- Loop 2 front
- Line 3500N
- Loop 1 front
- Line 3100N
planned
pit outline
(2009)
3300E -
4300E -
5300E -
6300E -
7300E -
0 200 1000m

Sierra Gorda 2011

Sierra Gorda 2012

Stripping and stockpiling of oxide mineralization to expose sulphide ore

Sierra Gorda 2012

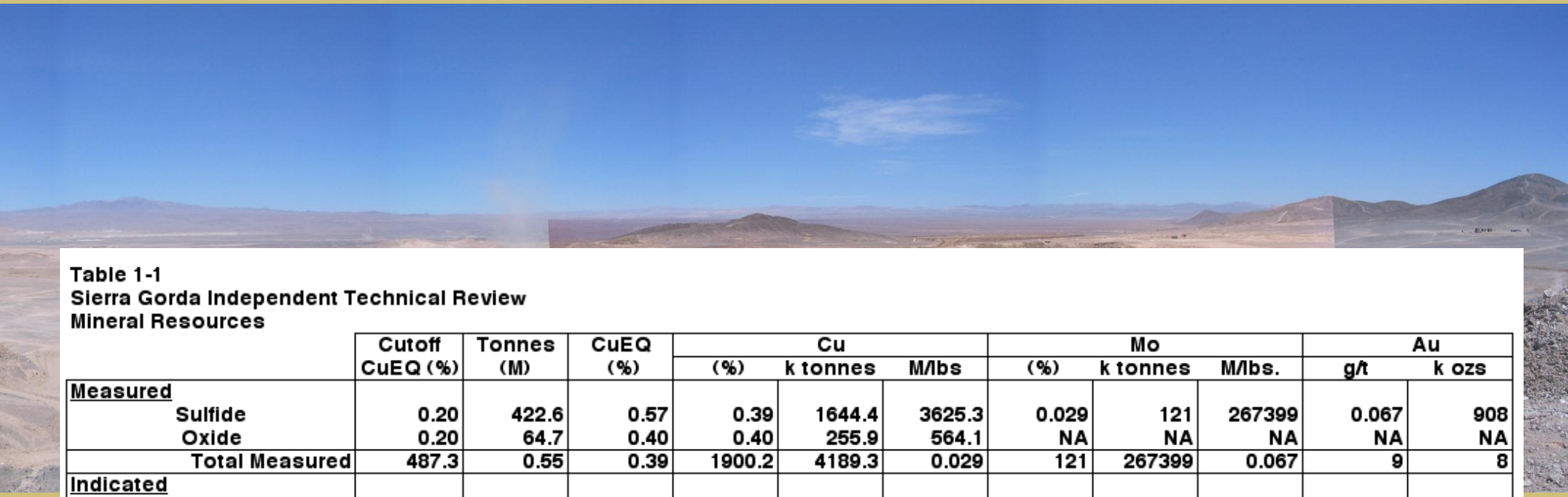


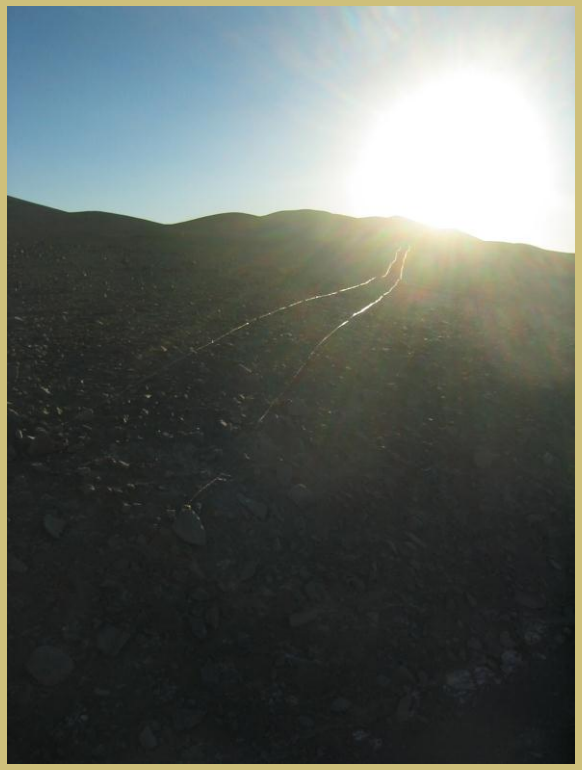
Table 1-1
Sierra Gorda Independent Technical Review
Mineral Resources

	Cutoff	Tonnes	CuEQ	Cu			Mo			Au	
	CuEQ (%)	(M)	(%)	(%)	k tonnes	M/lbs	(%)	k tonnes	M/lbs.	g/t	k ozs
Measured											
Sulfide	0.20	422.6	0.57	0.39	1644.4	3625.3	0.029	121	267399	0.067	908
Oxide	0.20	64.7	0.40	0.40	255.9	564.1	NA	NA	NA	NA	NA
Total Measured	487.3	0.55	0.39	1900.2	4189.3	0.029	121	267399	0.067	9	8
Indicated											
Sulfide	0.20	1576.3	0.49	0.37	5788.1	12760.6	0.018	290	639421	0.057	2894
Oxide	0.20	172.5	0.32	0.32	551.4	1215.7	NA	NA	NA	NA	NA
Total Indicated		1748.8	0.47	0.36	6339.5	13976.3	0.018	290	639421	0.057	2894
Measured and Indicated											
Sulfide	0.20	1998.9	0.51	0.37	7432.5	16385.9	0.021	411	906820	0.059	3801
Oxide	0.20	237.2	0.34	0.34	807.3	1779.7	NA	NA	NA	NA	NA
Total Measured+Indicated		2236.1	0.49	0.37	8239.8	18165.6	0.021	411	906820	0.059	3801
Inferred											
Sulfide	0.20	665.1	0.38	0.31	2087.2	4601.5	0.009	59	130507	0.035	744
Oxide	0.20	16.5	0.24	0.24	39.6	87.4	NA	NA	NA	NA	NA
Total Inferred		681.6	0.37	0.31	2126.8	4688.8	0.009	59	130507	0.035	744

Table 1-1, Technical report for the Sierra Gorda Project, Chile

Tx Loop

double loop
~4000x2000m
12 AWG



UTEM 3 Transmitter

Master-Slave pair…

Capacitive Electrodes

0.9m x 1.9m (3’x6’)

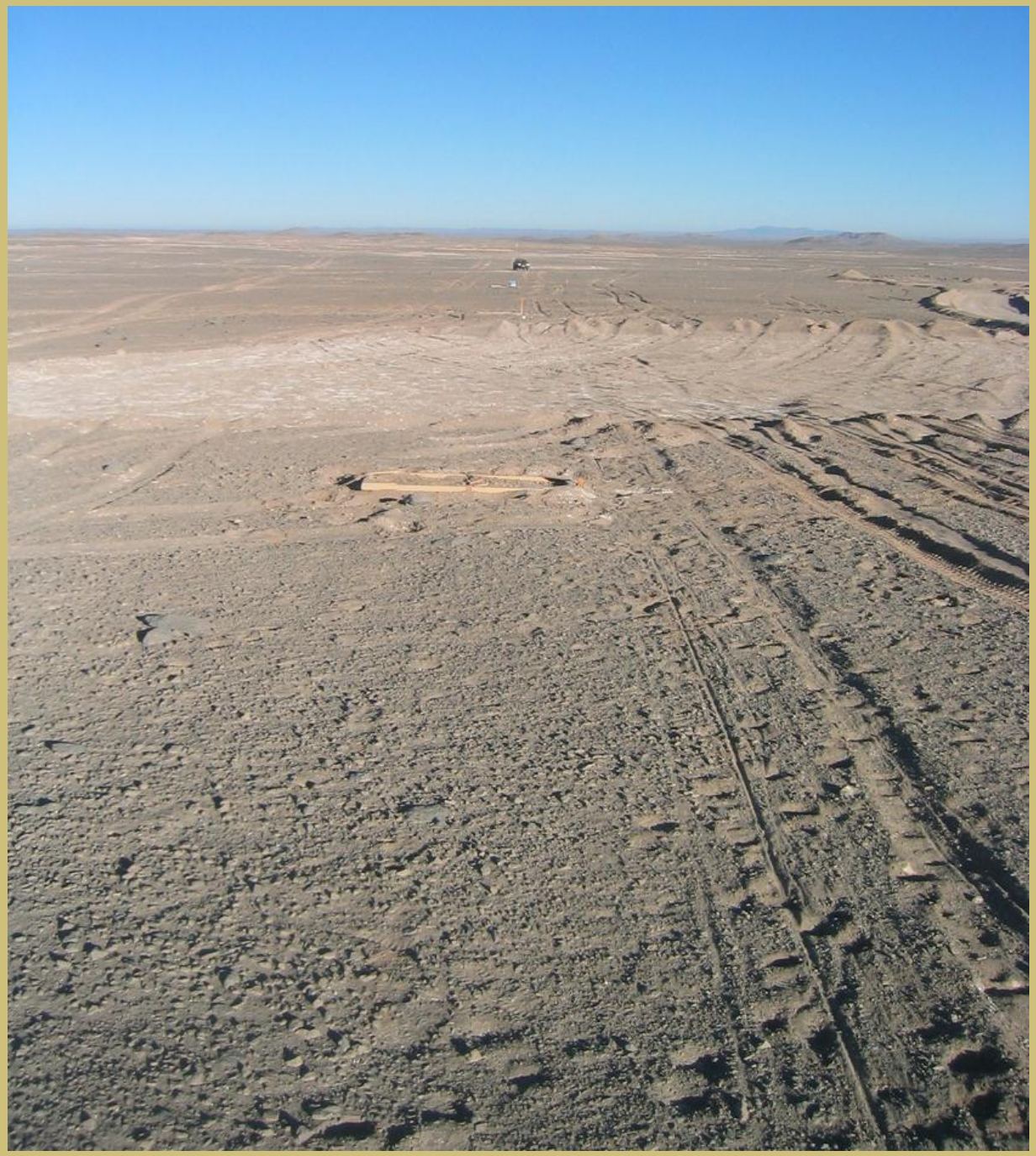
UTEM 3 Receiver

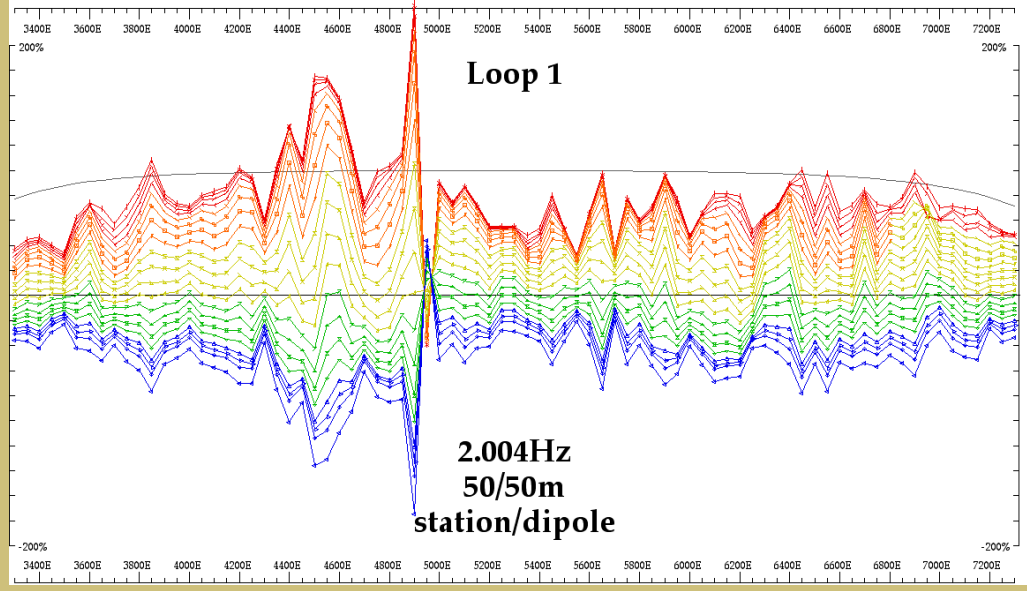
Capacitive Electrode (covered)

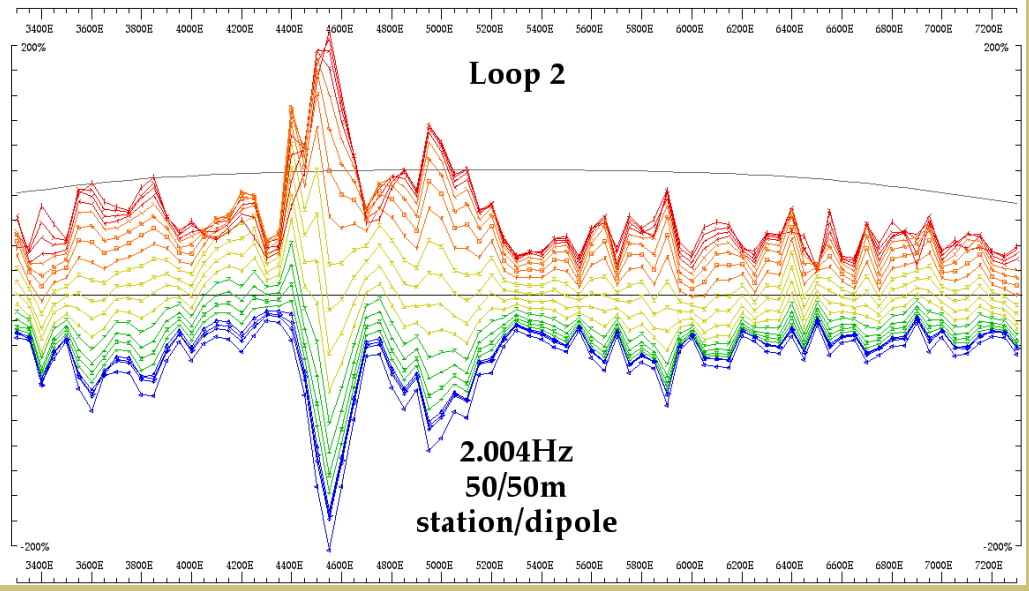
UTEM 3 Receiver

50m dipole setup

Line 31N 1225O

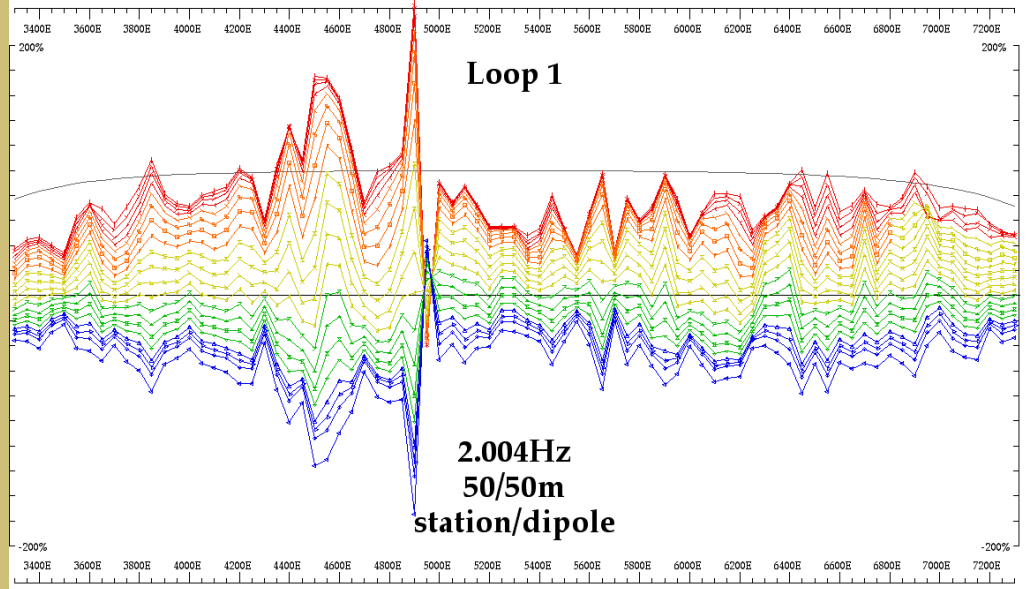


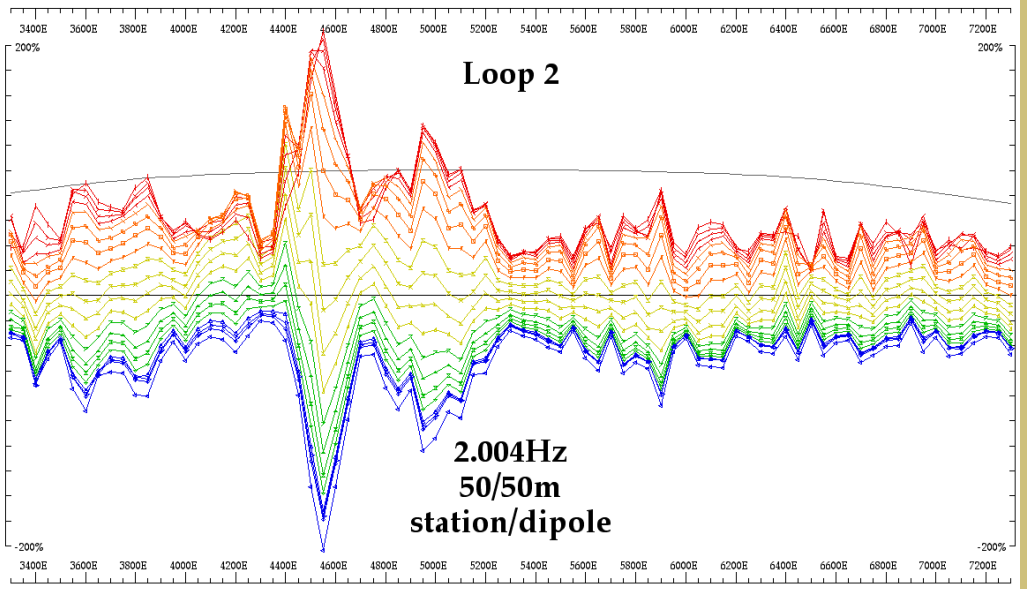


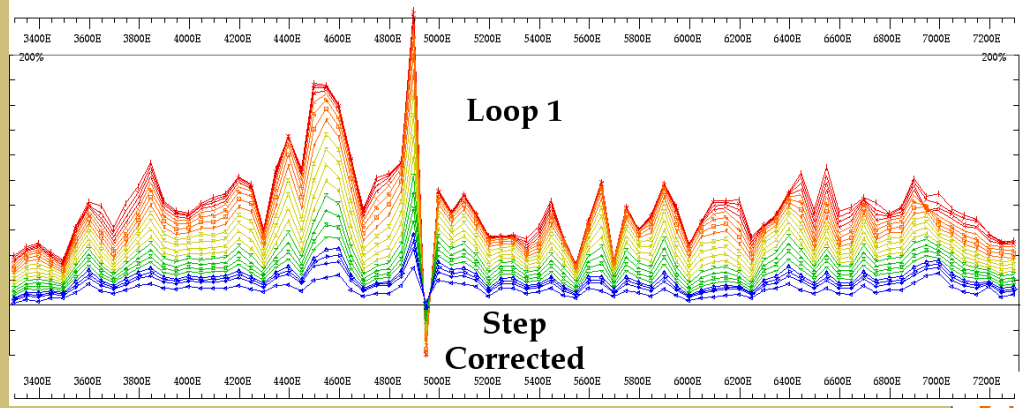


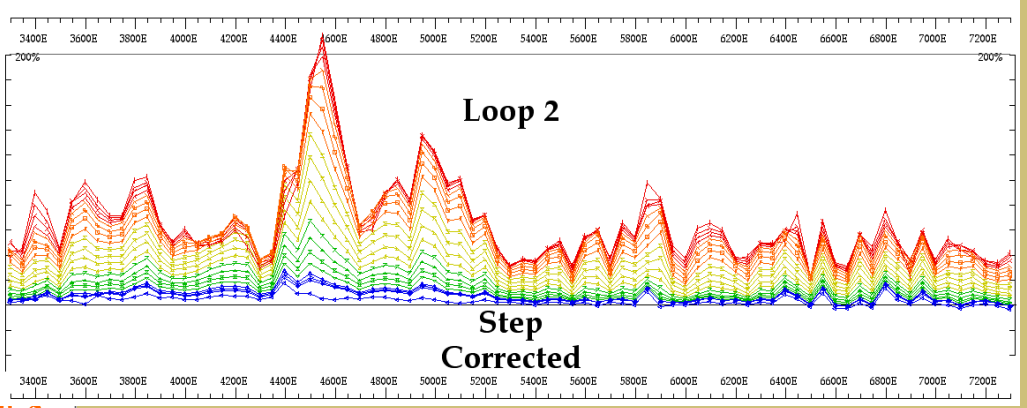
late time
Ch 1
Ch 2
Ch 3
Ch 4
Ch 5
Ch 6
Ch 7
Ch 8
Ch 9
Ch10
Ch11
Ch12
Ch13
Ch14
Ch15
Ch16
Ch17
Ch18
Ch19
Ch20
early time

Line 31N



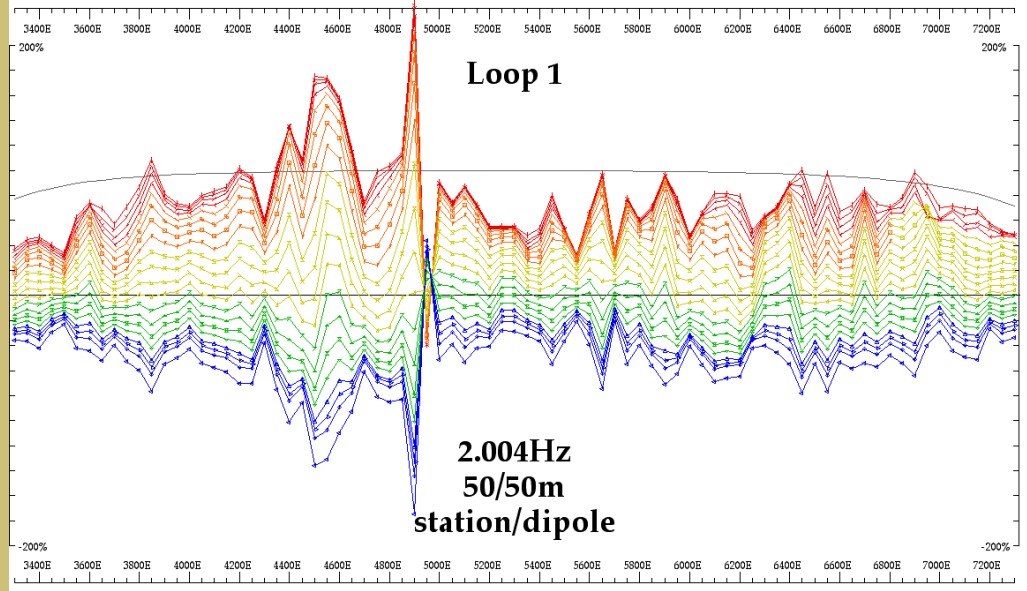


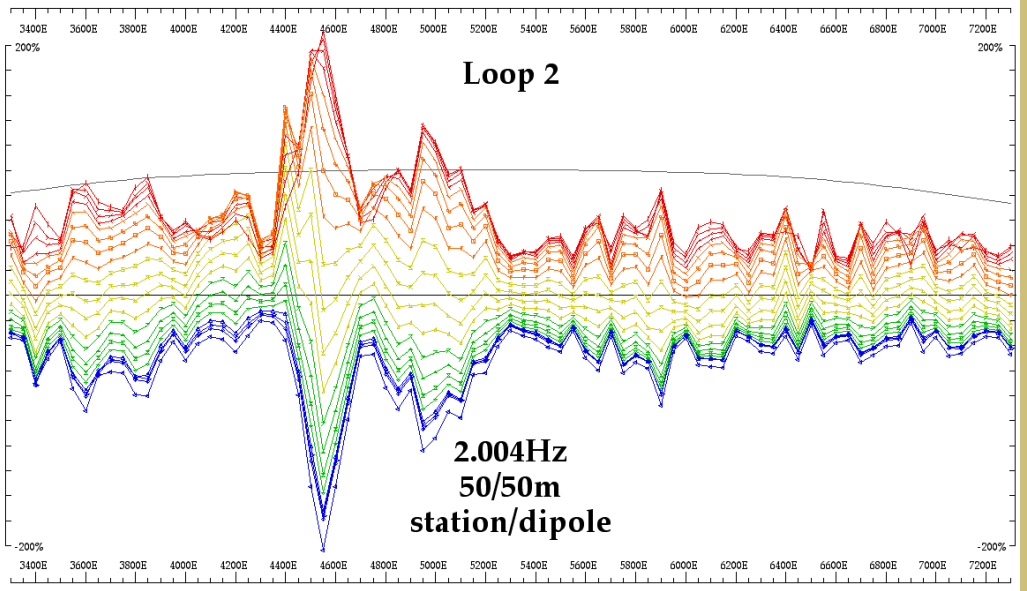


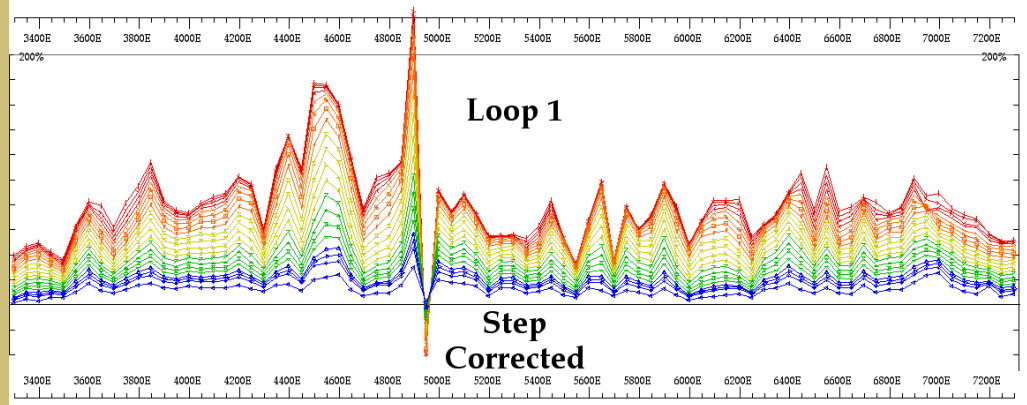


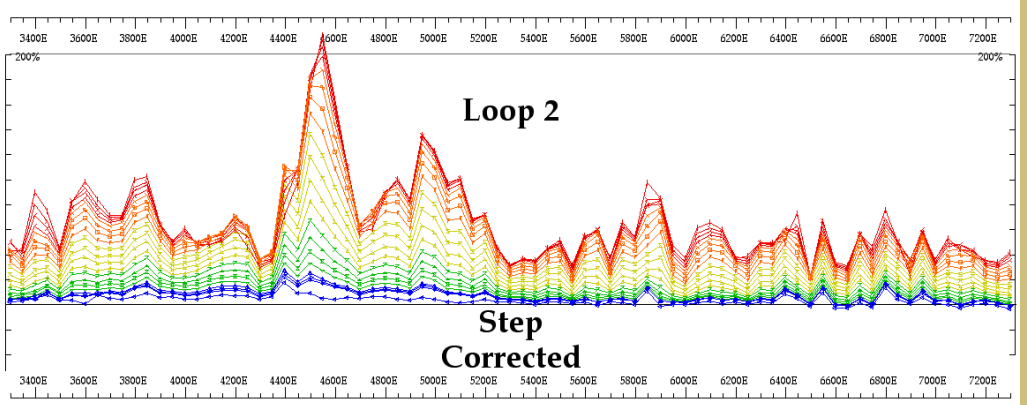
Ch 9
Ch10
Ch11
Ch12
Ch13
Ch14
Ch15
Ch16
Ch17
Ch18
Ch19
Ch20
early
time

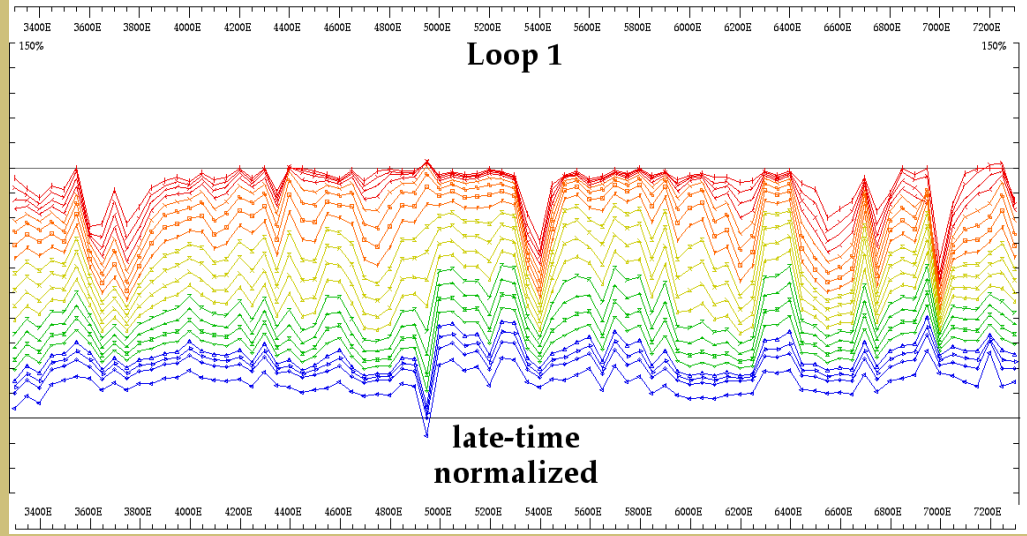
Line 31N

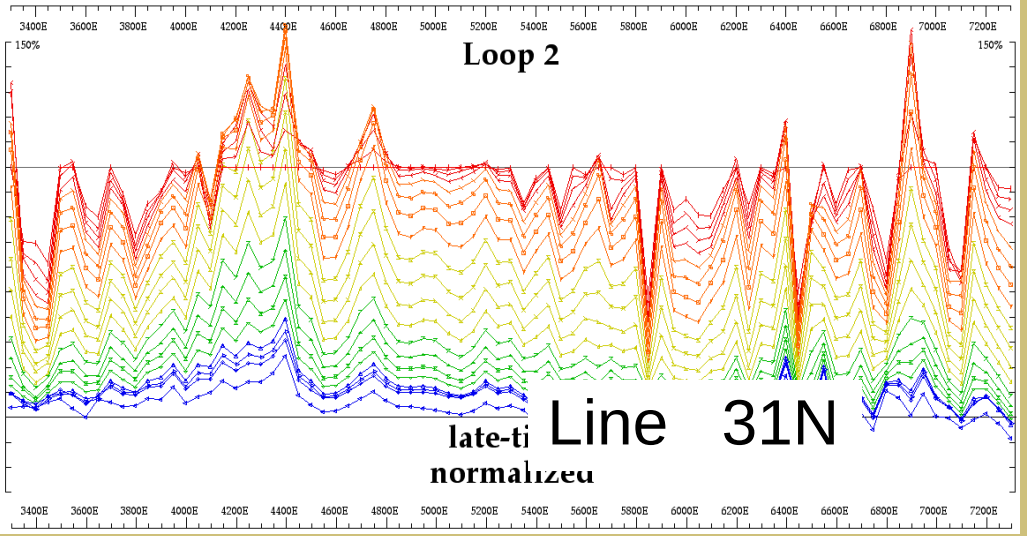

Loop 1
2.004Hz
50/50m
station/dipole


Loop 2
2.004Hz
50/50m
station/dipole

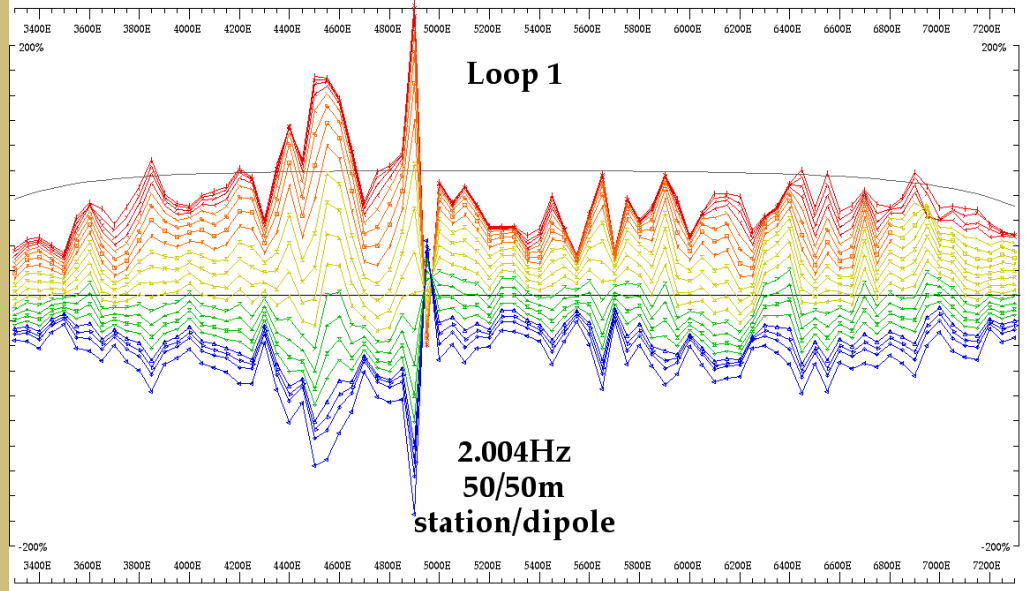

Loop 1
Step
Corrected

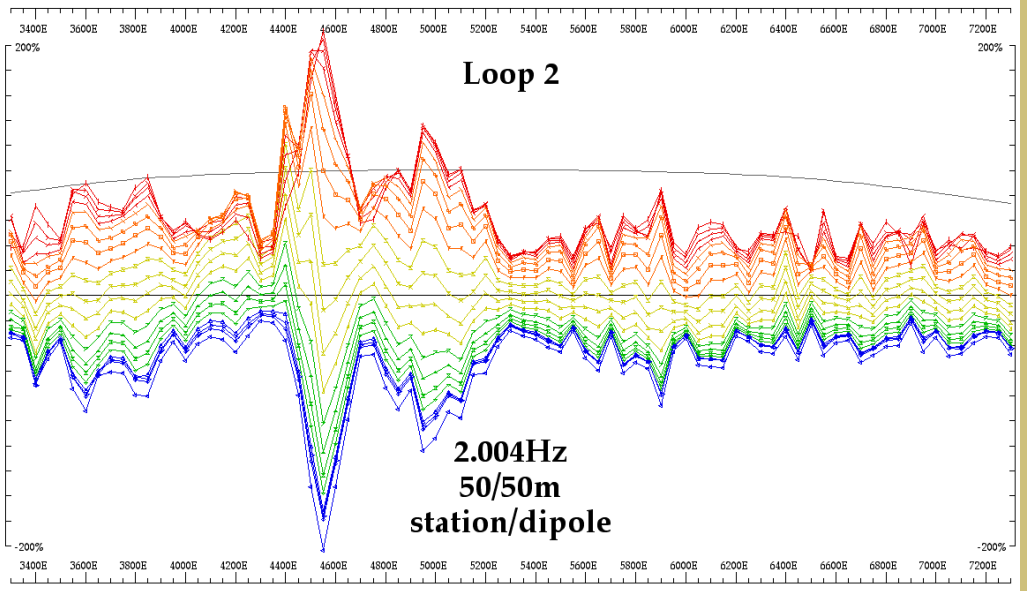

Loop 2
Step
Corrected

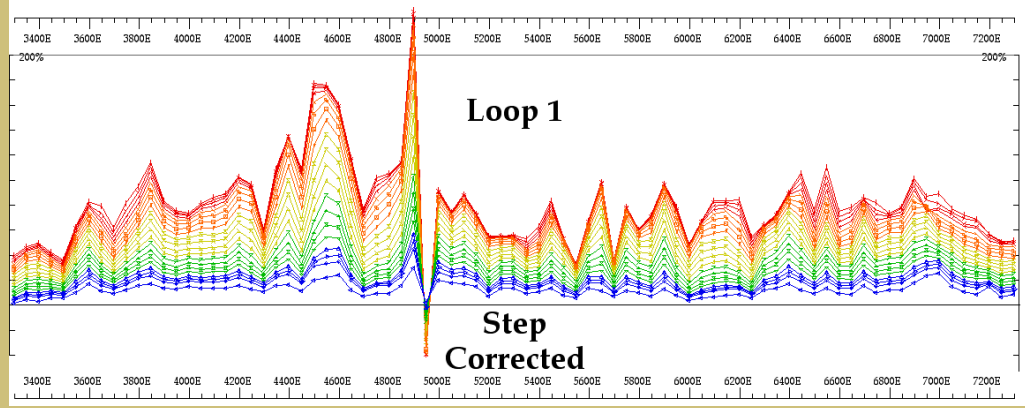

Loop 1
late-time
normalized

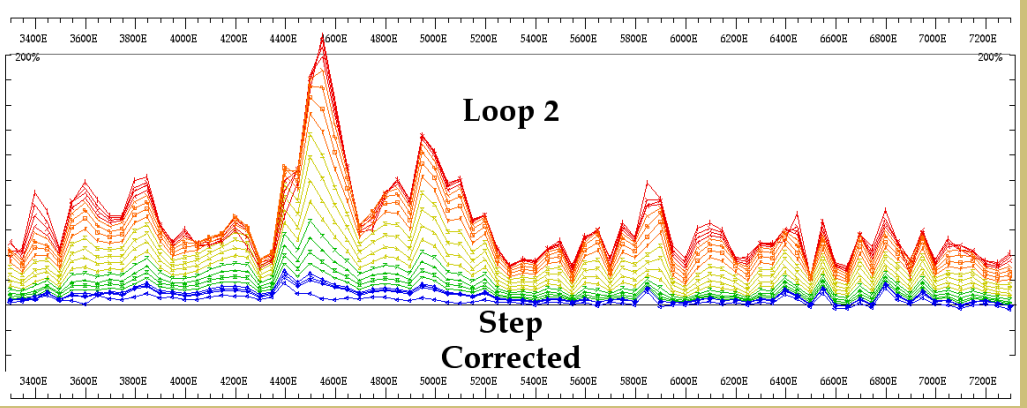

Loop 2
late-ti
normalized

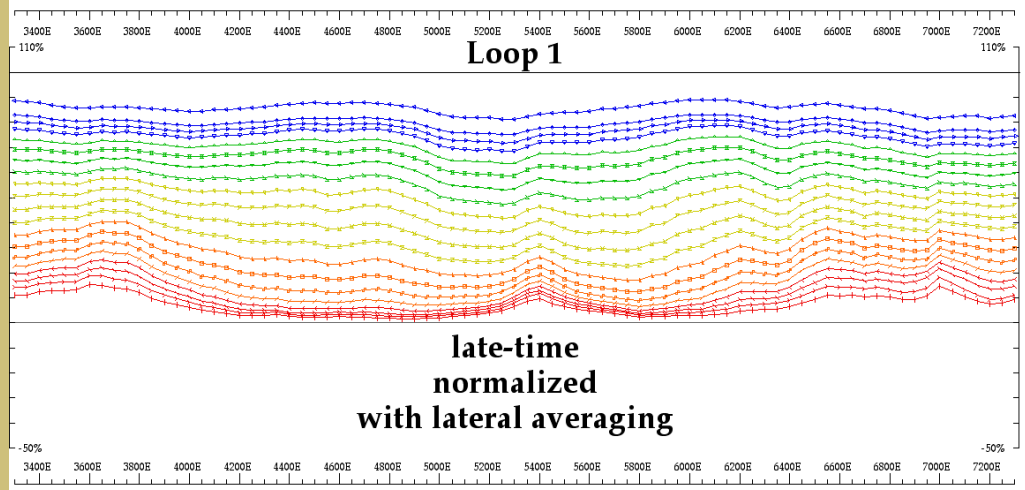
Line 31N

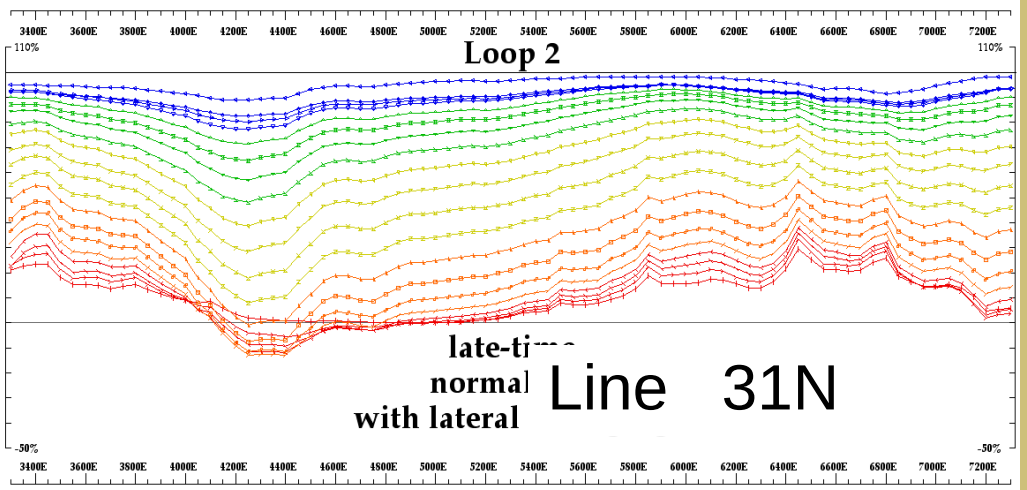

Loop 1
2.004Hz
50/50m
station/dipole


Loop 2
2.004Hz
50/50m
station/dipole


Loop 1
Step
Corrected


Loop 2
Step
Corrected


Loop 1
late-time
normalized
with lateral averaging


Loop 2
with lateral

Line 31N


Loop 1
2.004Hz
50/50m
station/dipole
Loop 2
2.004Hz
50/50m
station/dipole
Loop 3
2.004Hz
50/50m
station/dipole
Loop 4
2.004Hz
50/50m
station/dipole
Loop 1
Step
Corrected
Loop 2
Step
Corrected
Loop 3
Step
Corrected
Loop 4
Step
Corrected
Loop 1
late-time
normalized
Loop 2
late-time
normalized
Loop 3
late-time
normalized
Loop 4
late-time
normalized
Loop 1
late-time
normalized
with lateral averaging
Loop 2
late-time
normalized
with lateral averaging
Loop 3
late-time
normalized
with lateral averaging
Loop 4
late-time
normalized
with lateral averaging

Line 31N


Loop 2
2.004Hz
50/50m
station/dipole
Loop 3
2.004Hz
50/50m
station/dipole
Loop 4
2.004Hz
50/50m
station/dipole
Loop 5
2.004Hz
50/50m
station/dipole
Loop 2
Step
Corrected
Loop 3
Step
Corrected
Loop 4
Step
Corrected
Loop 5
Step
Corrected
Loop 2
late-time
normalized
Loop 3
late-time
normalized
Loop 4
late-time
normalized
Loop 5
late-time
normalized
Loop 2
late-time
normalized
with lateral averaging
Loop 3
late-time
normalized
with lateral averaging
Loop 4
late-time
normalized
with lateral averaging
Loop 5
late-time
normalized
with lateral averaging

Line 35N

Resistivity imaging with ISR data

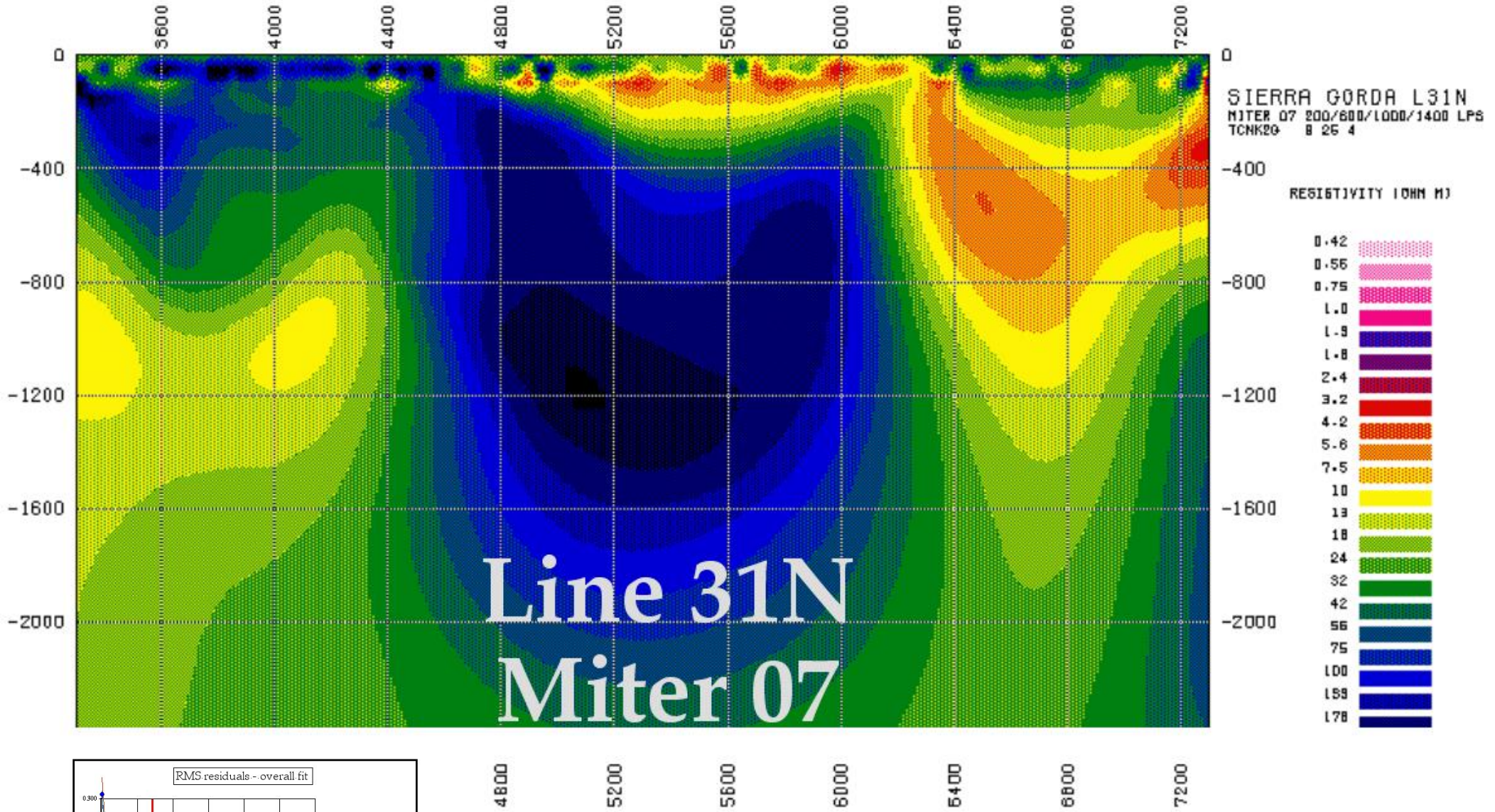
combined conductivity-depth imaging and 2D resistivity inversion

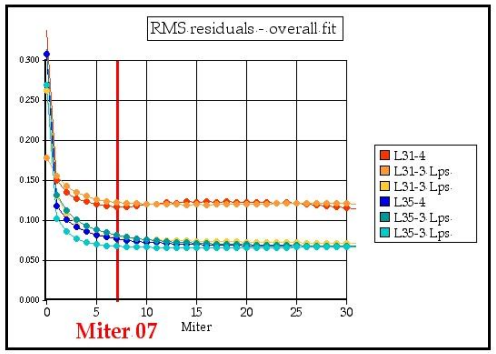
ECDI step

- Step Correct E field data
- normalize to the late time limit and apply lateral averaging
- fit these data to apparent diffusion time as a function of depth

2D resistivity inversion step

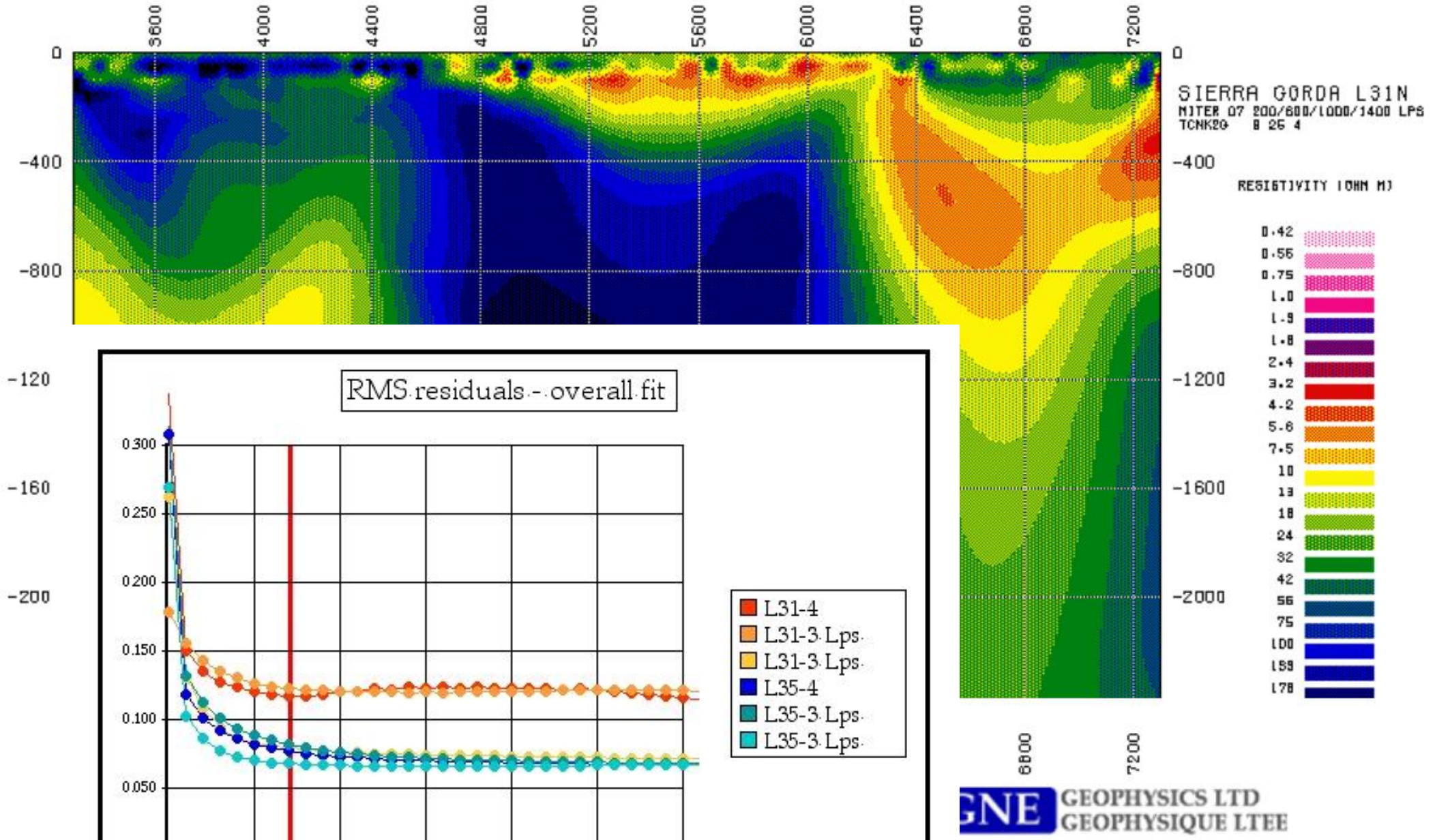
- incident E field with depth diffusion based on ECDI
- fit data with ECDI diffusion time/model smoothness constraints
- depth-variable modeling grid and inversion grid size
- major iterations (Miter) until RMS residuals no longer decrease





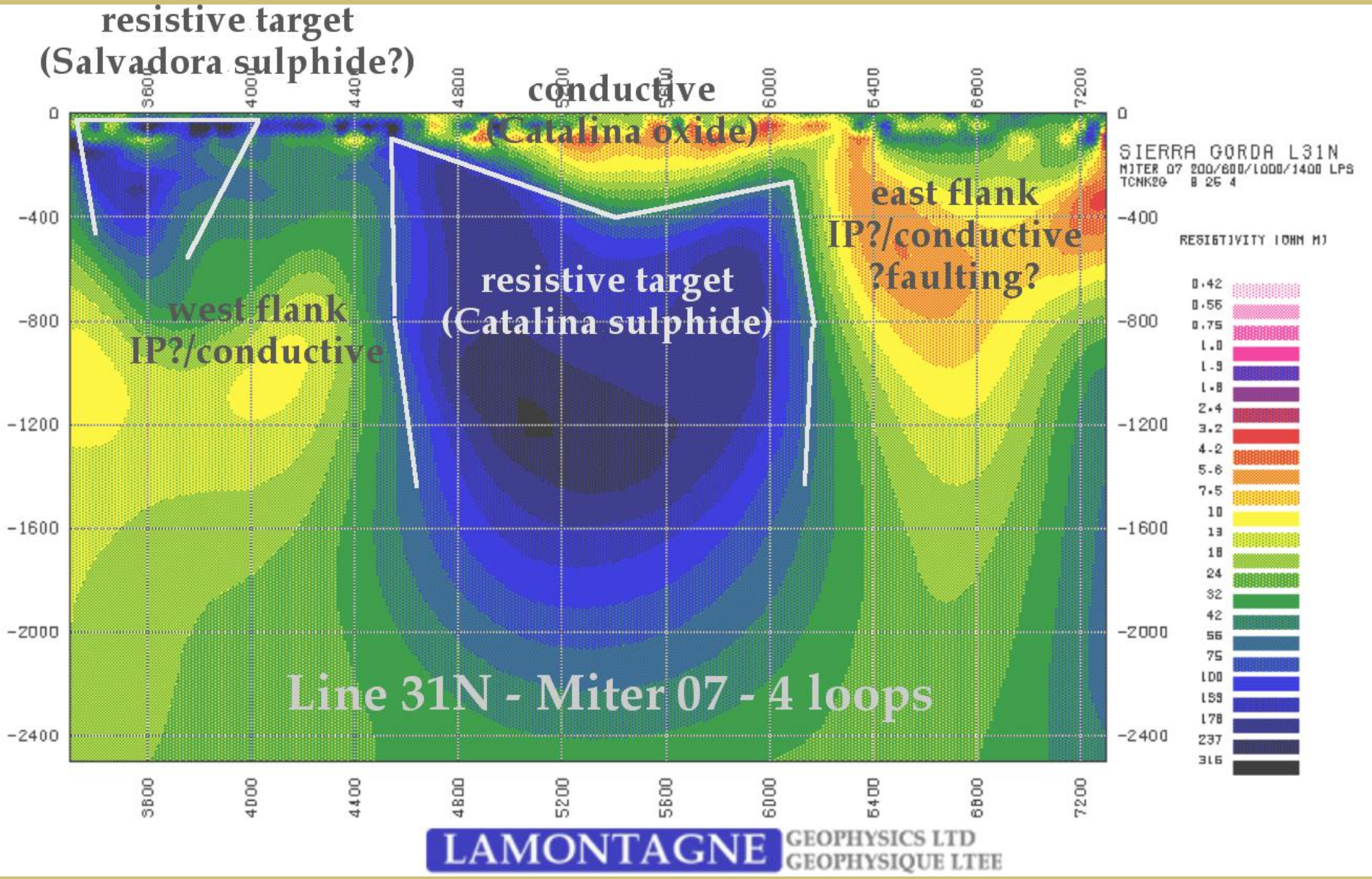
LAMONTAGNE GEOPHYSICS LTD
GEOPHYSIQUE LTEE

Line 31N

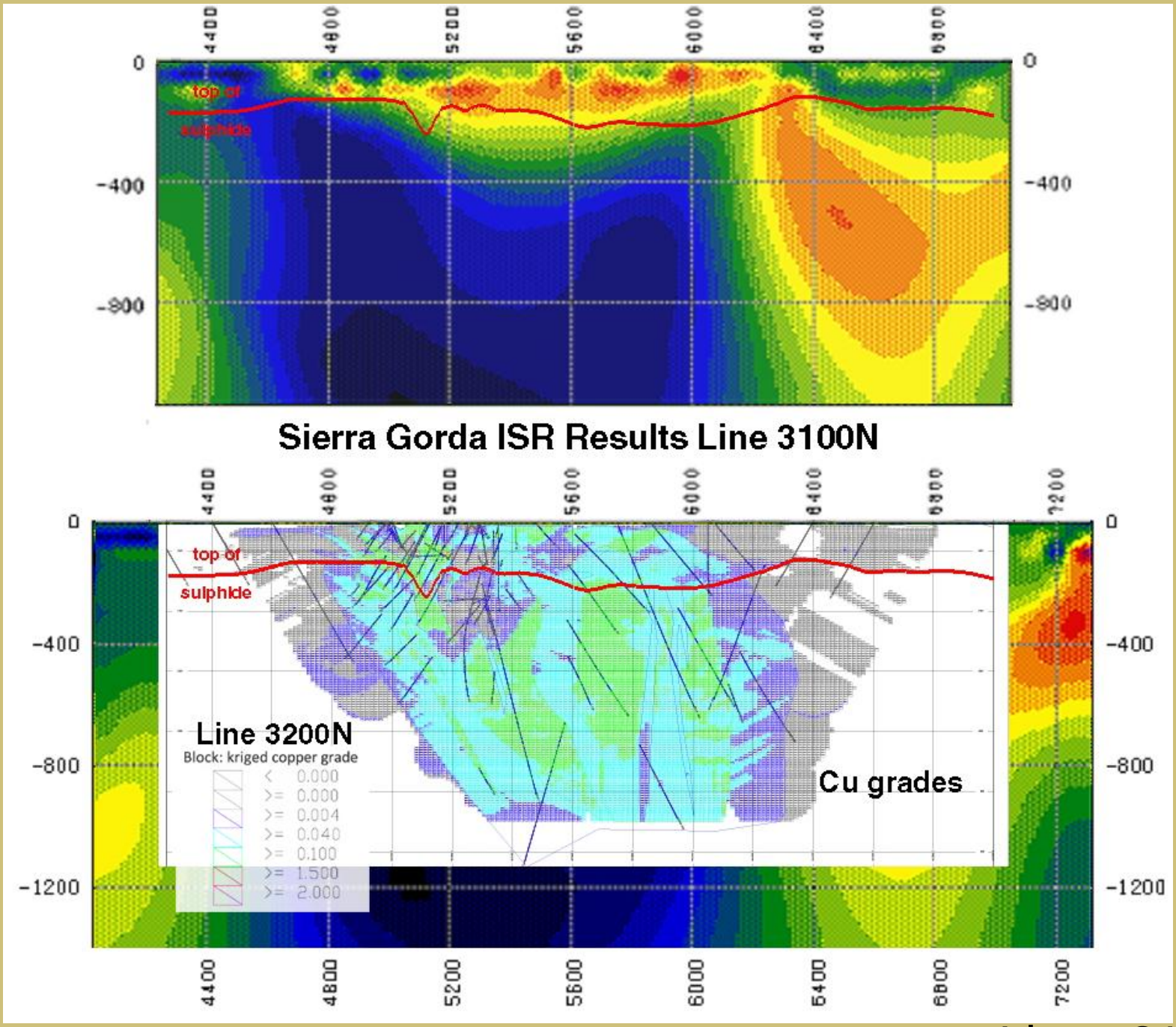


GNE GEOPHYSICS LTD
GEOPHYSIQUE LTEE

Line 31N


resistive target
(Salvadora sulphide?)
conductive
(Catalina oxide)
east flank
IP?/conductive
?faulting?
resistive target
(Catalina sulphide)
west flank
IP?/conductive
Line 31N - Miter 07 - 4 loops
SIERRA GORDA L31N
MITER 07 200/600/1000/1400 LPS
TCNK20 8 25 4
RESISTIVITY (OHM M)
0.42
0.56
0.75
1.0
1.3
1.8
2.4
3.2
4.2
5.6
7.5
10
13
18
24
32
42
56
75
100
133
178
237
316
0
-400
-800
-1200
-1600
-2000
-2400
3600
4000
4400
4800
5200
5600
6000
6400
6800
7200
LAMONTAGNE
GEOPHYSICS LTD
GEOPHYSIQUE LTEE

Line 31N

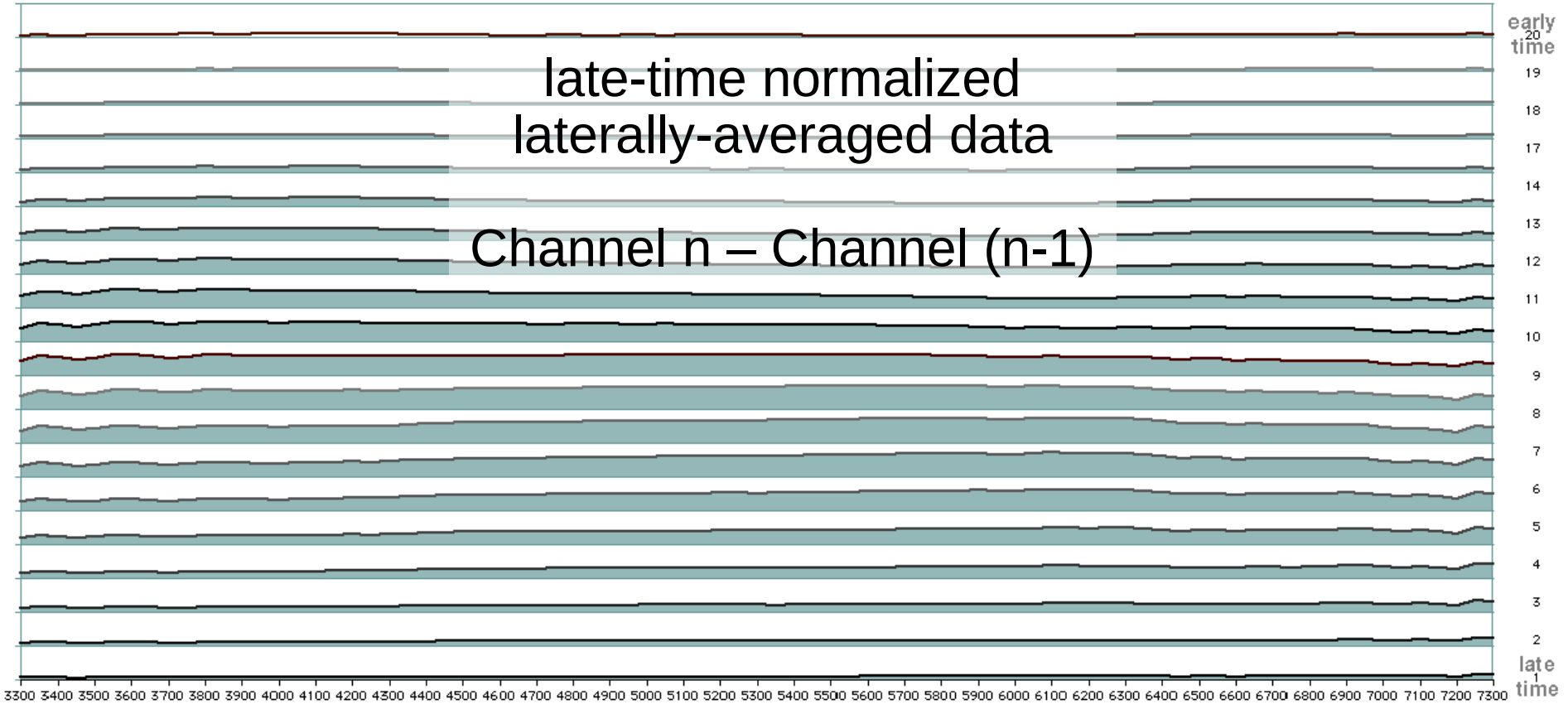


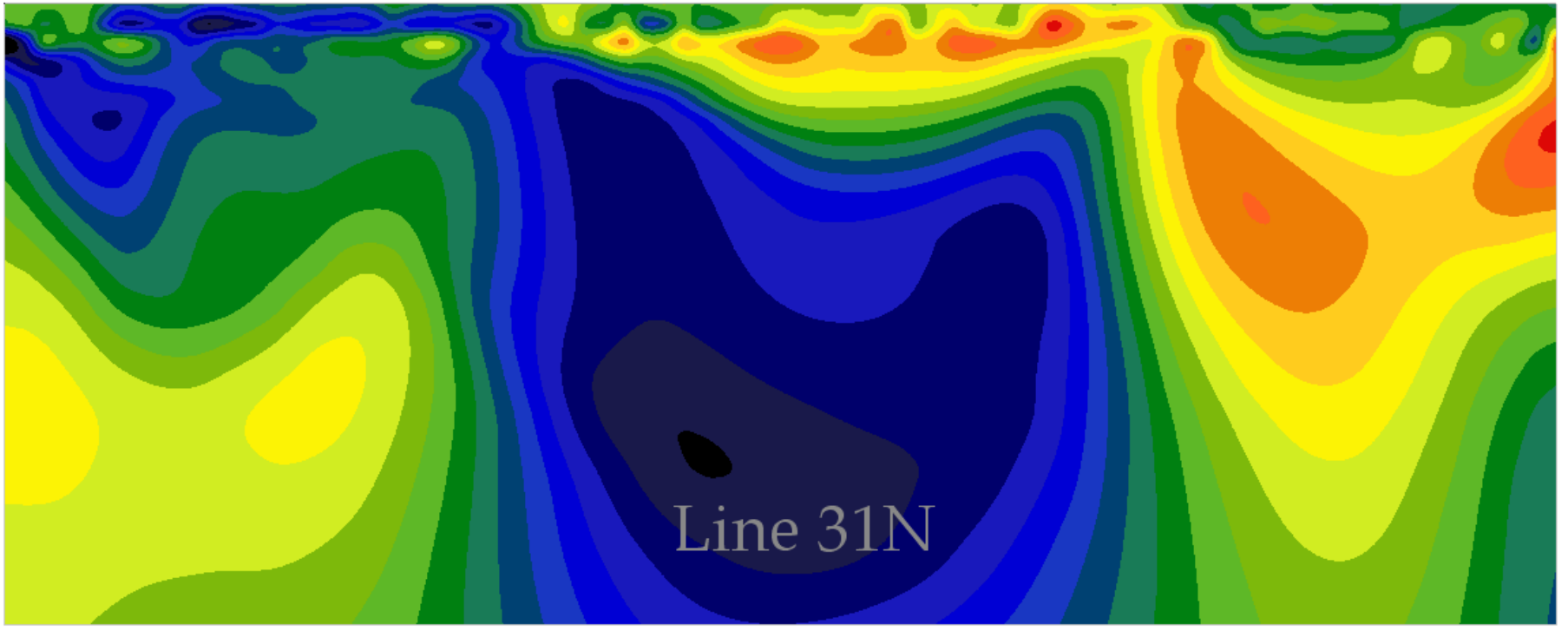
Sierra Gorda ISR Results Line 3100N

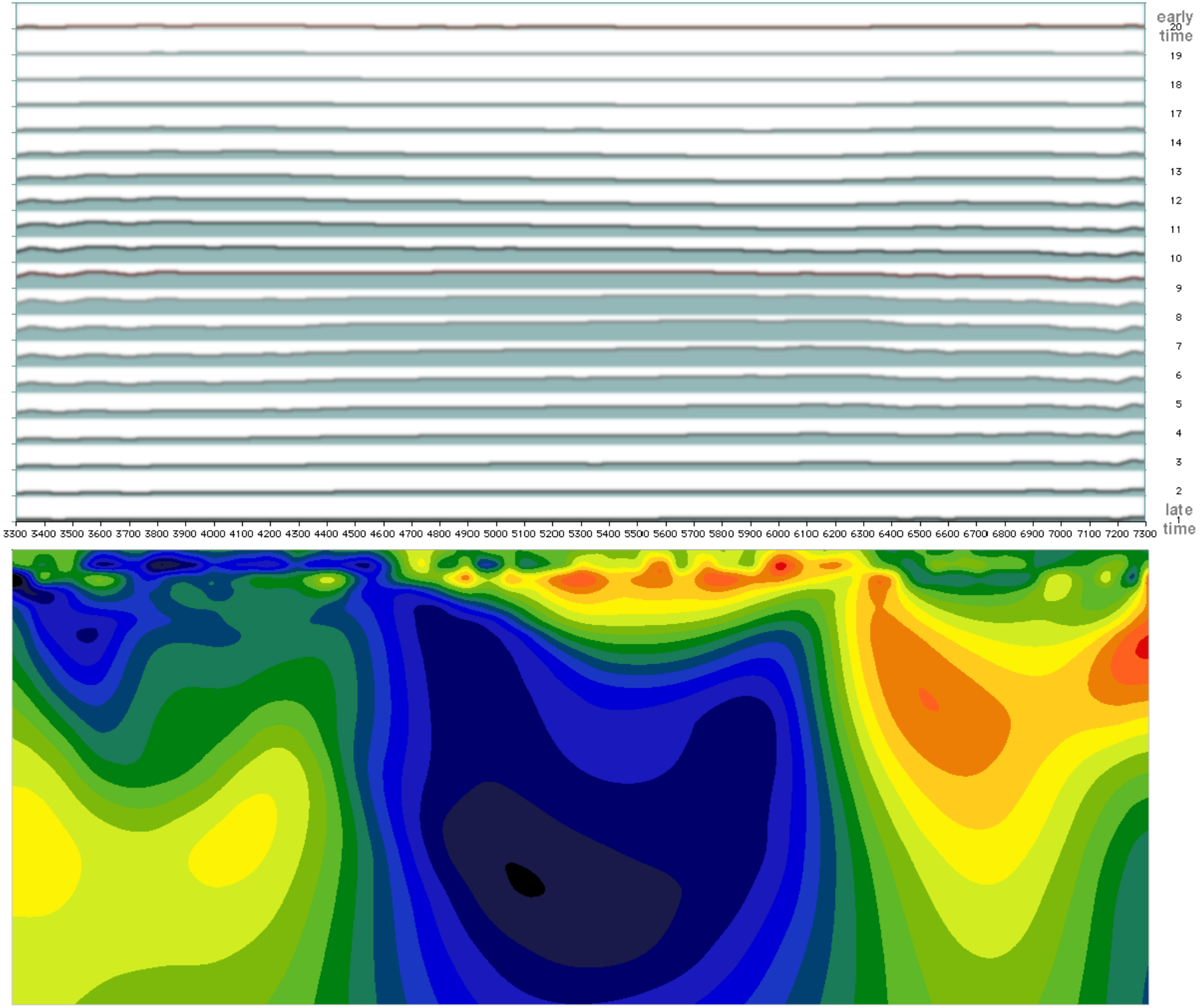
Line 31N

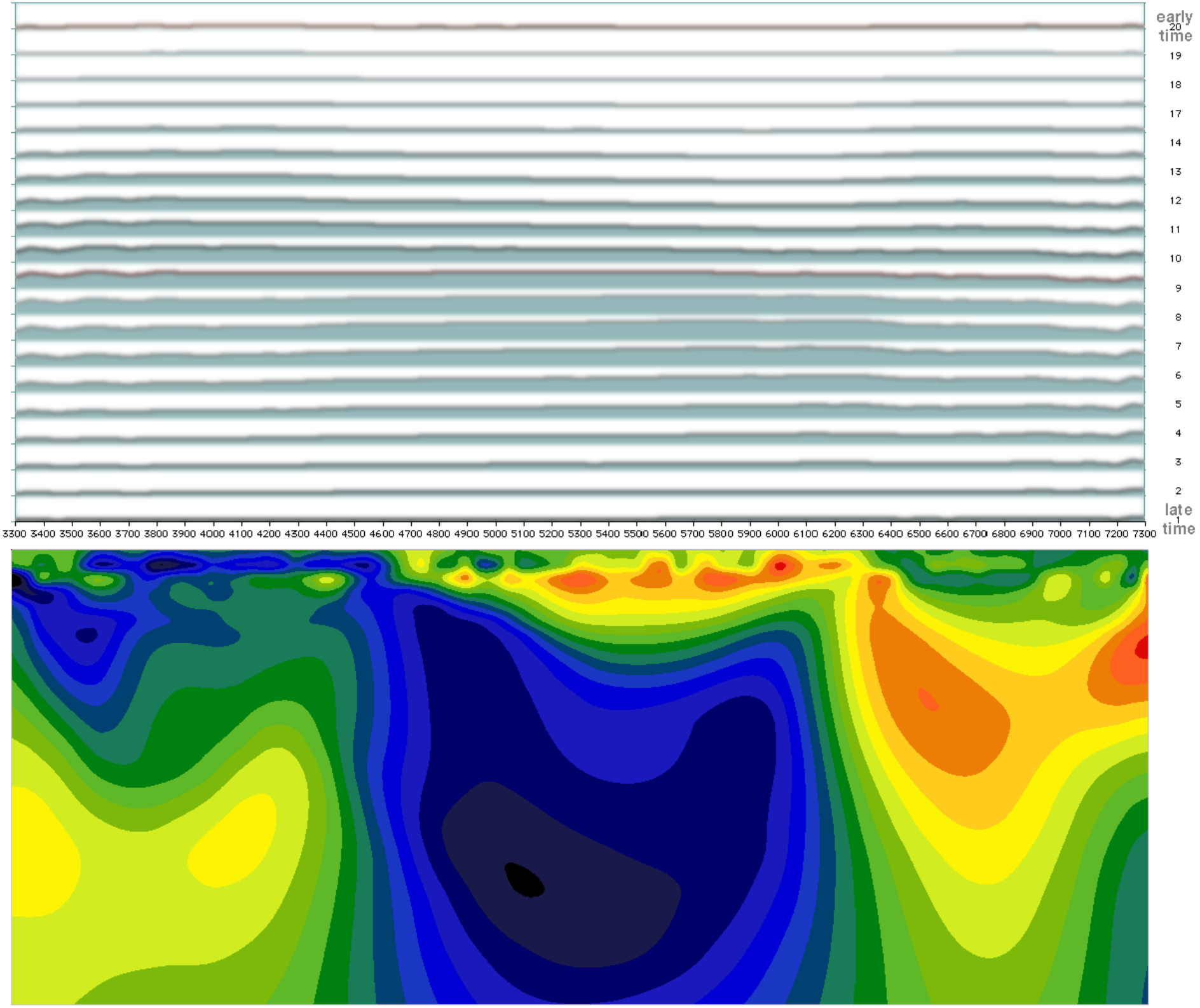
late-time normalized
laterally-averaged data

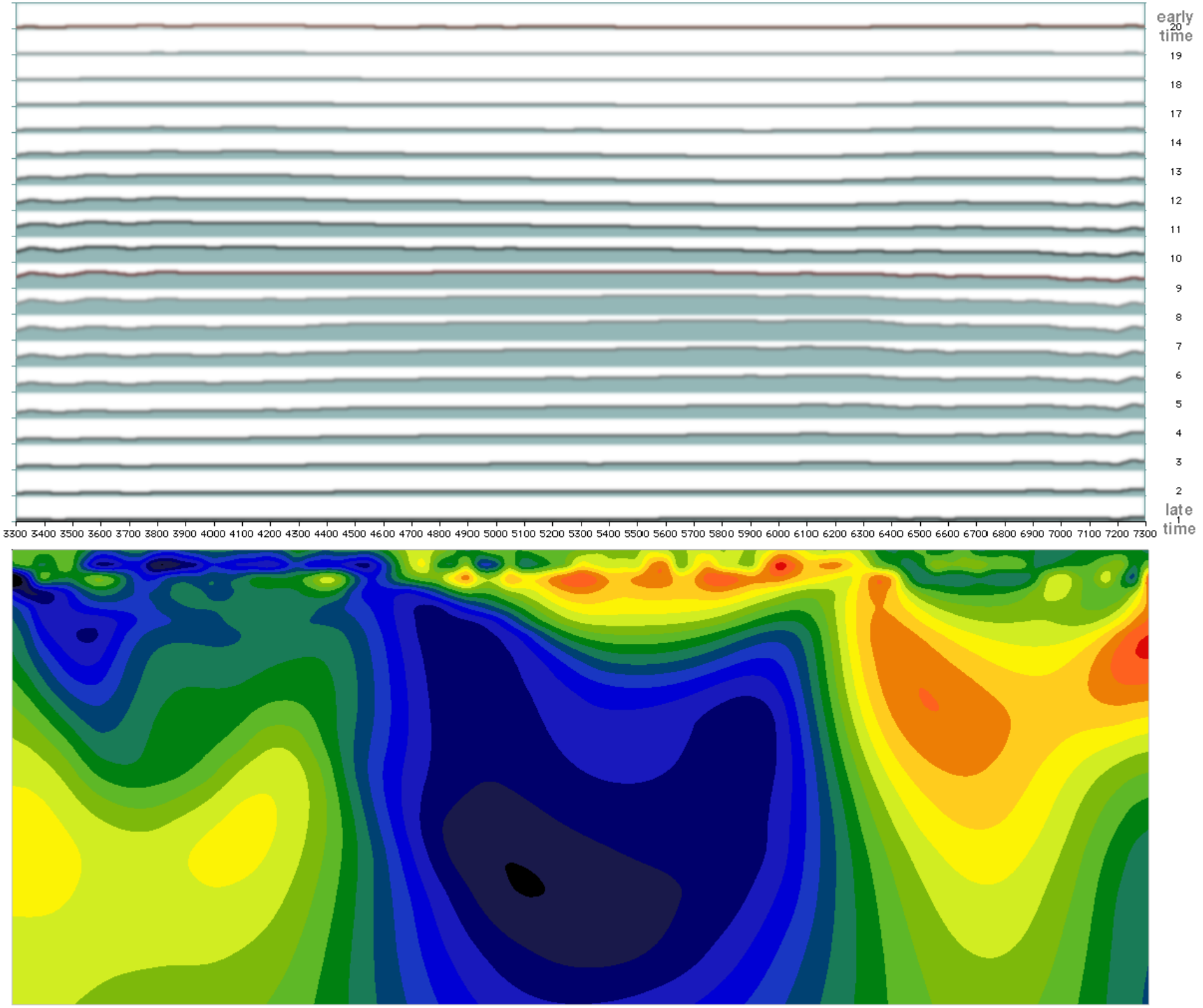
Channel n – Channel (n-1)

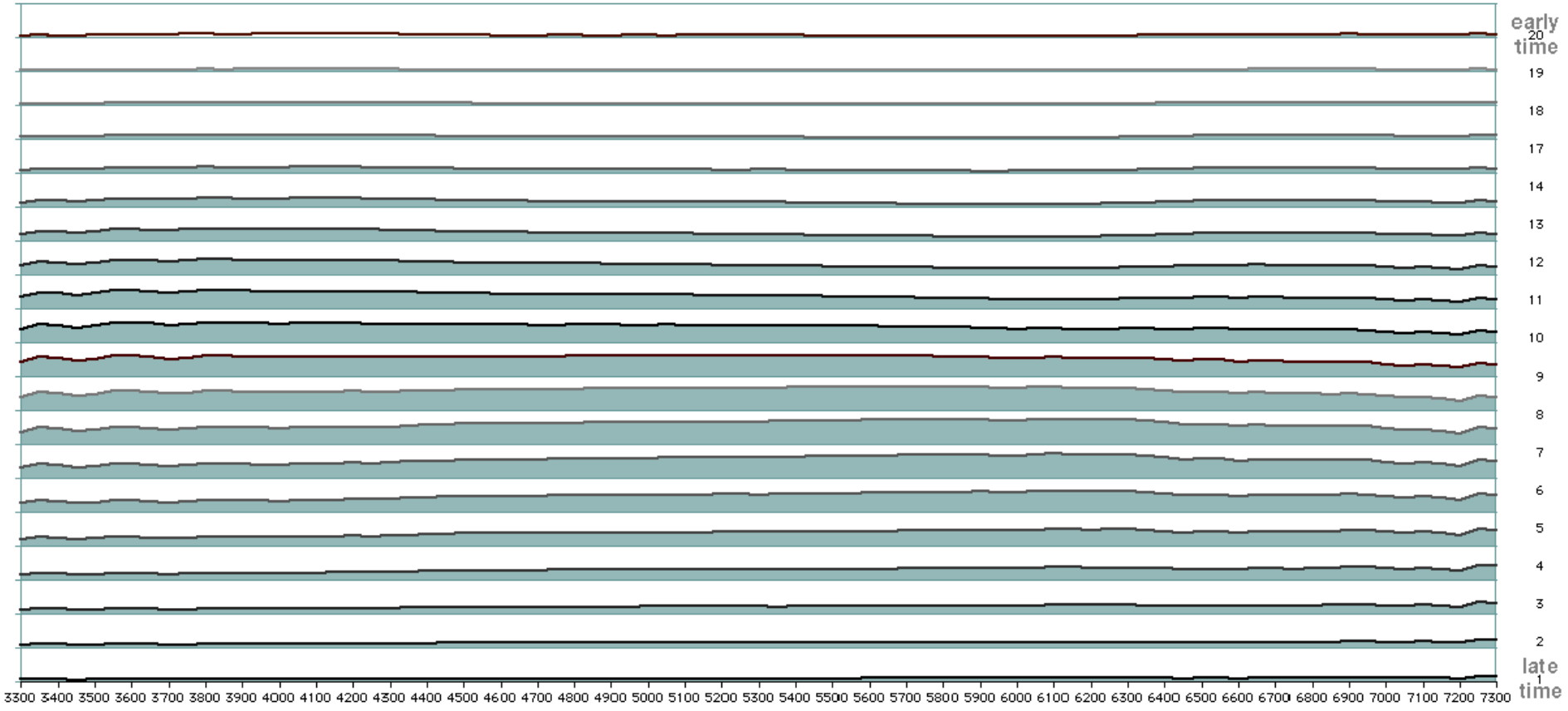


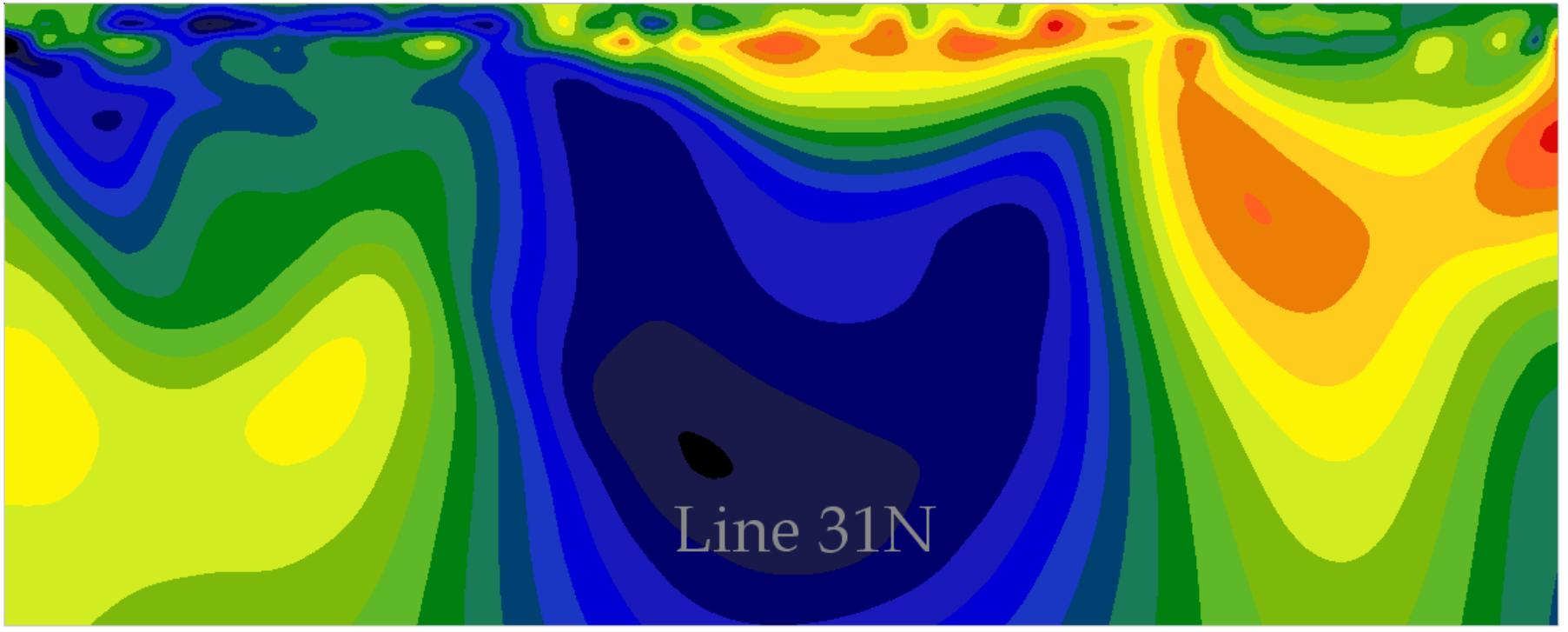



early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300


early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300


early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300


early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
1
late time
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300


Line 31N

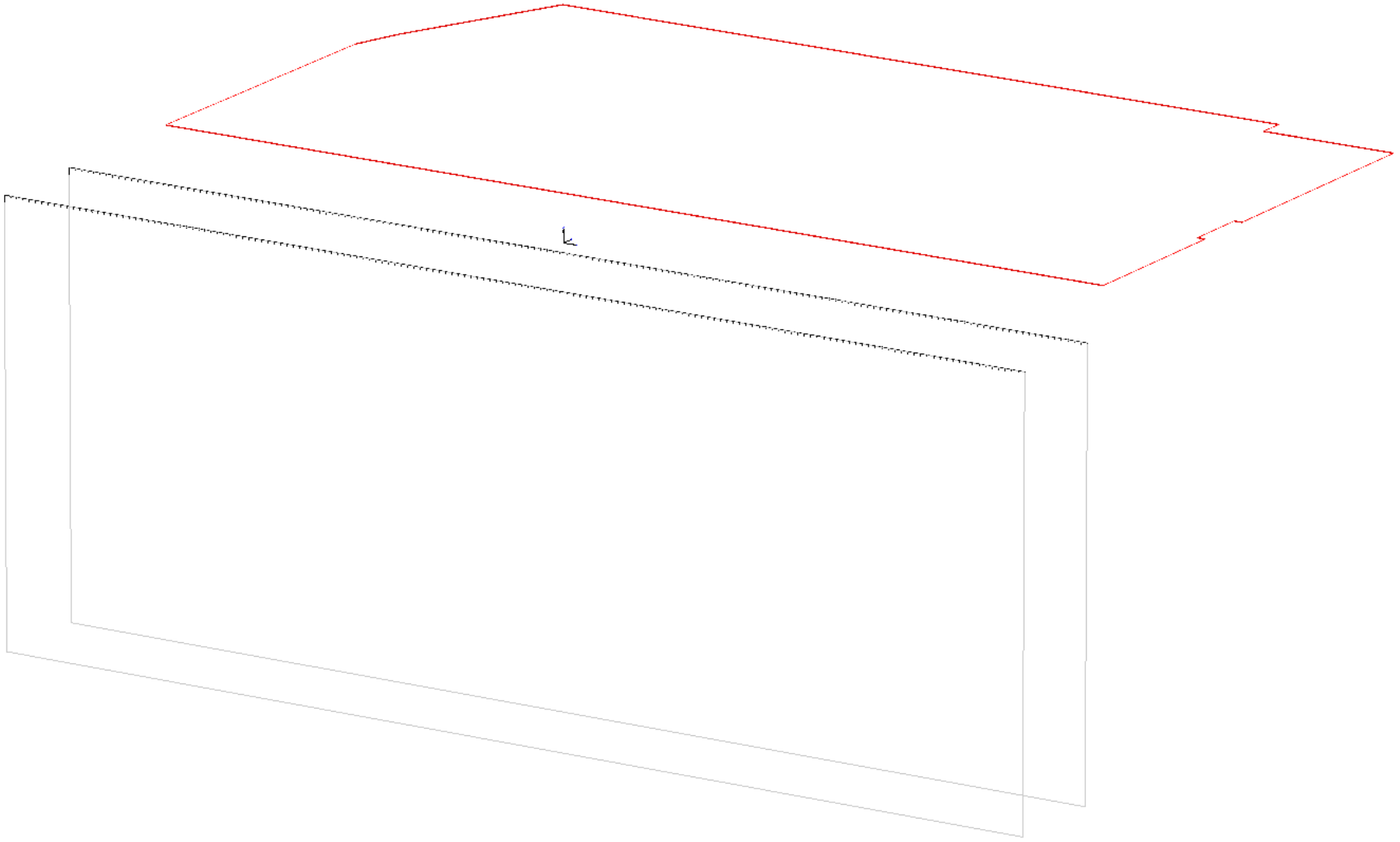
Where are we now

A 2D resistivity inversion that can handle greater geological compexity and tolerate IP effects.

working towards a 3D process… currently:

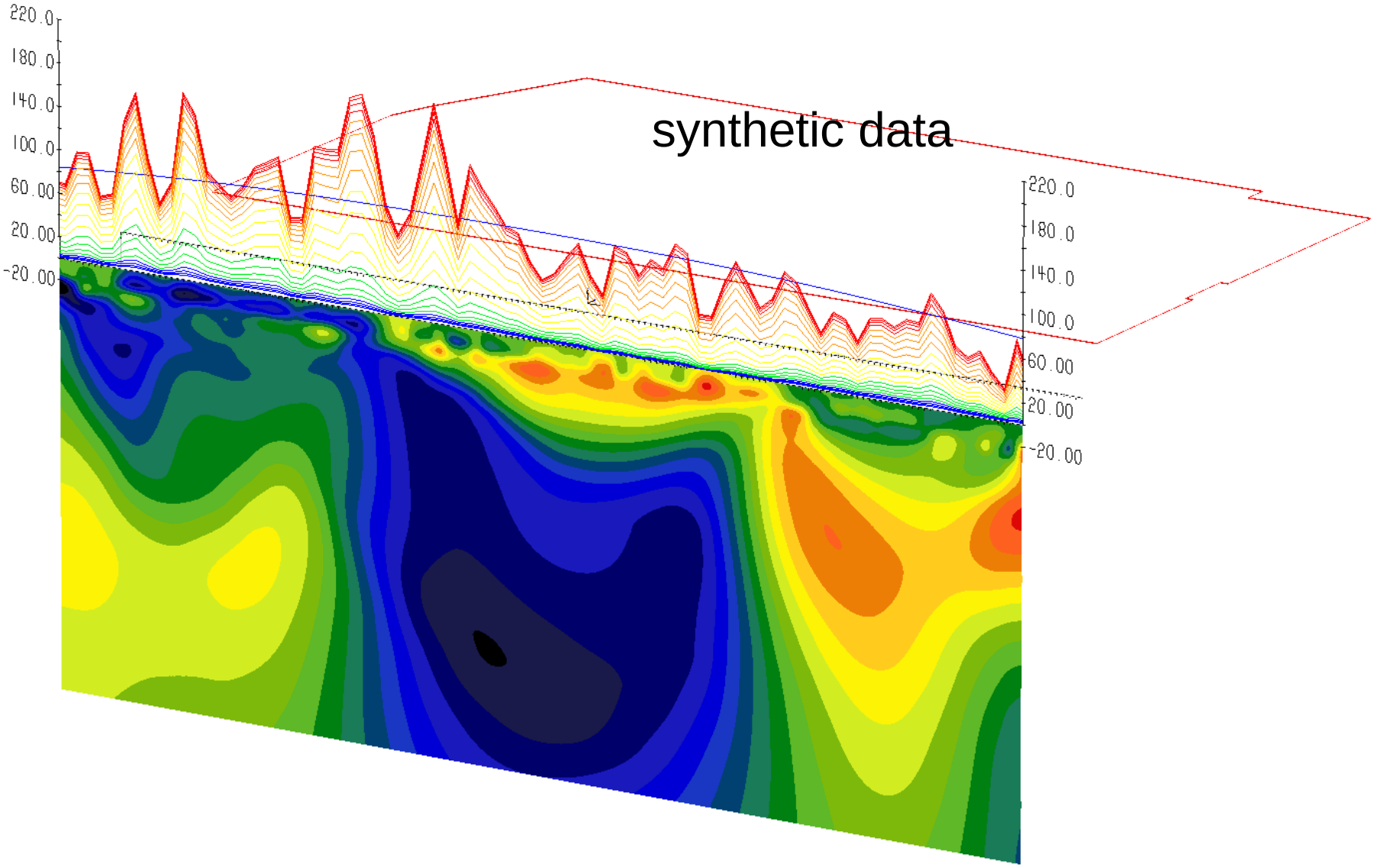
- assemble the sections into a (more) 3D model
- 3D finite difference routine generates synthetic E field profiles
- synthetic results are compared with the Step Corrected profiles

Transmitter Loop 3



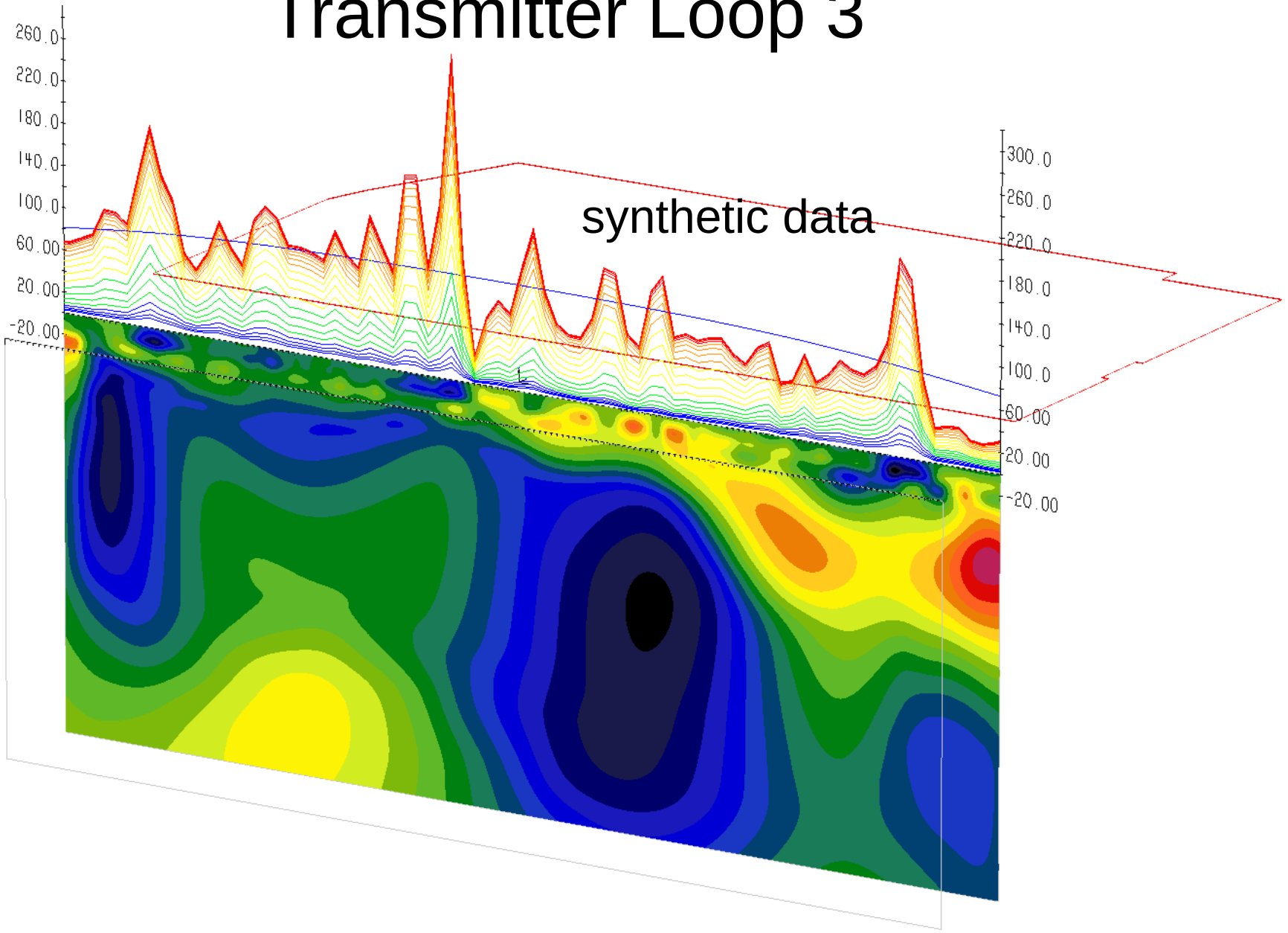
Lines 31N/35N

Transmitter Loop 3

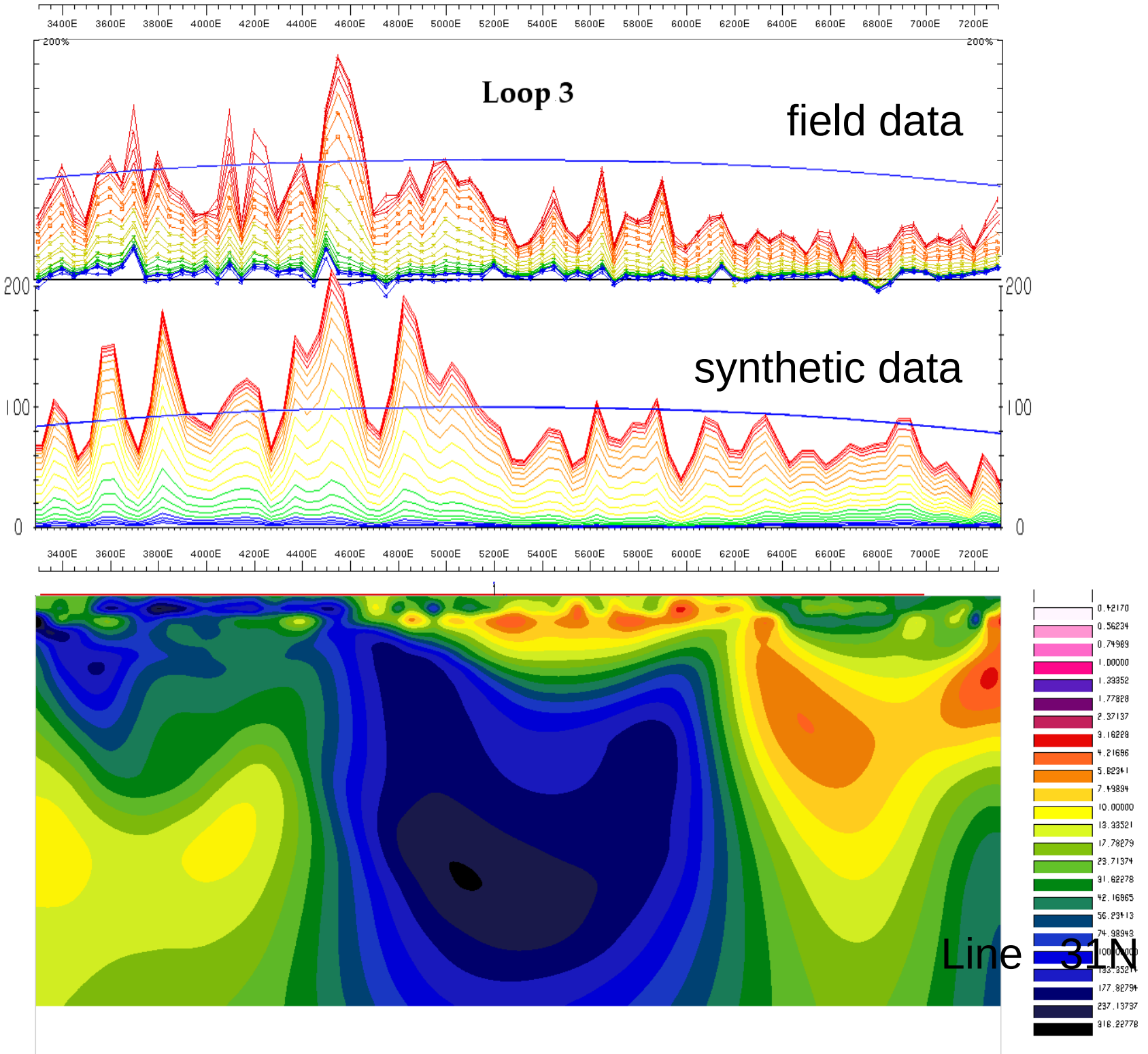


Line 31N

Transmitter Loop 3



Line 35N


3400E 3600E 3800E 4000E 4200E 4400E 4600E 4800E 5000E 5200E 5400E 5600E 5800E 6000E 6200E 6400E 6600E 6800E 7000E 7200E
200%
200%
Loop 3
field data
200
100
0
synthetic data
0.42170
0.56234
0.74989
1.00000
1.33352
1.77828
2.37137
3.16228
4.21696
5.62341
7.49894
10.00000
13.33521
17.78279
23.71374
31.62278
42.16965
56.23413
74.98943
177.82794
237.13737
316.22778
Line 31N

Where are we now

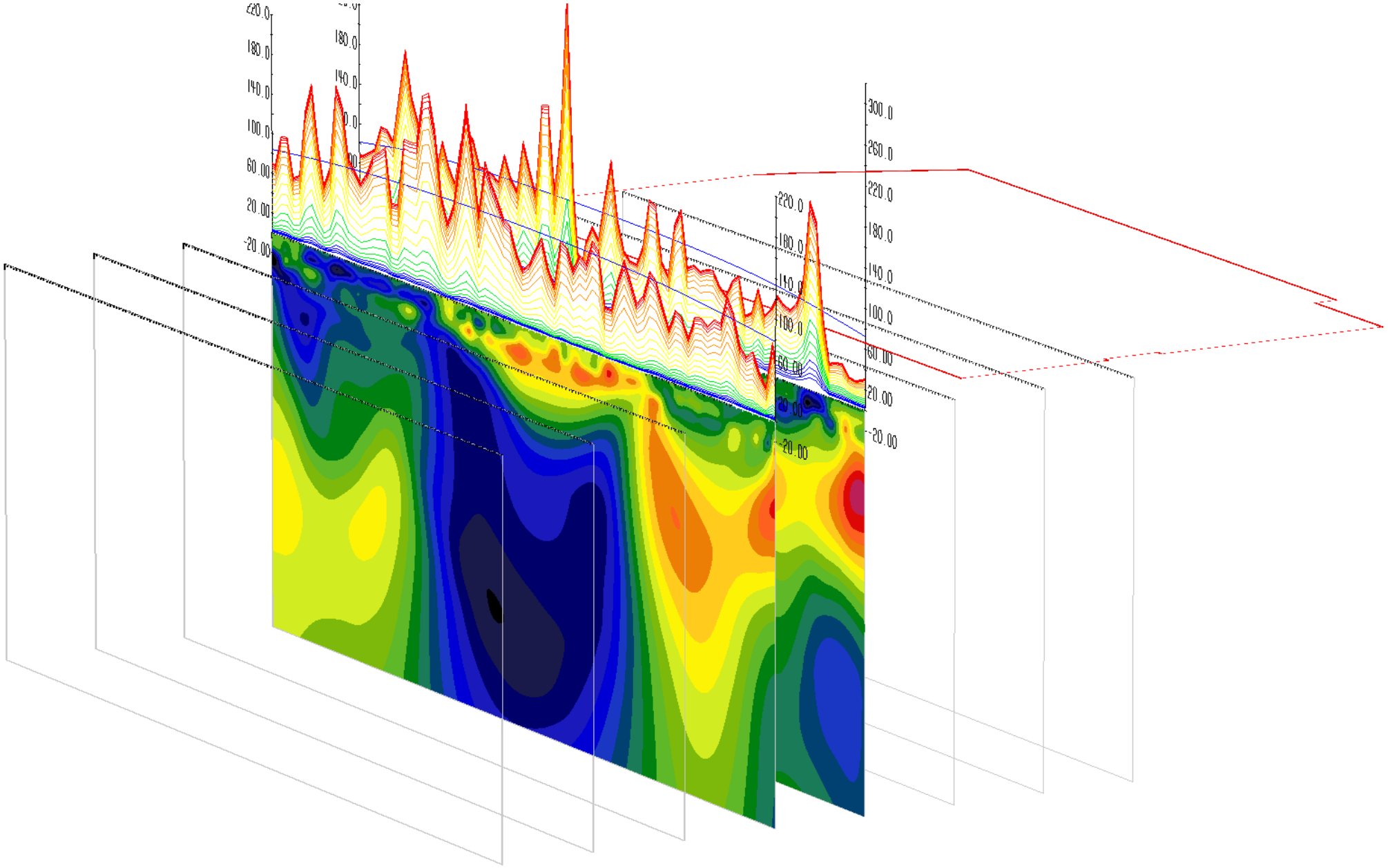
A 2D resistivity inversion that can handle greater geological compexity and handle IP effects.

working towards a 3D process… currently:

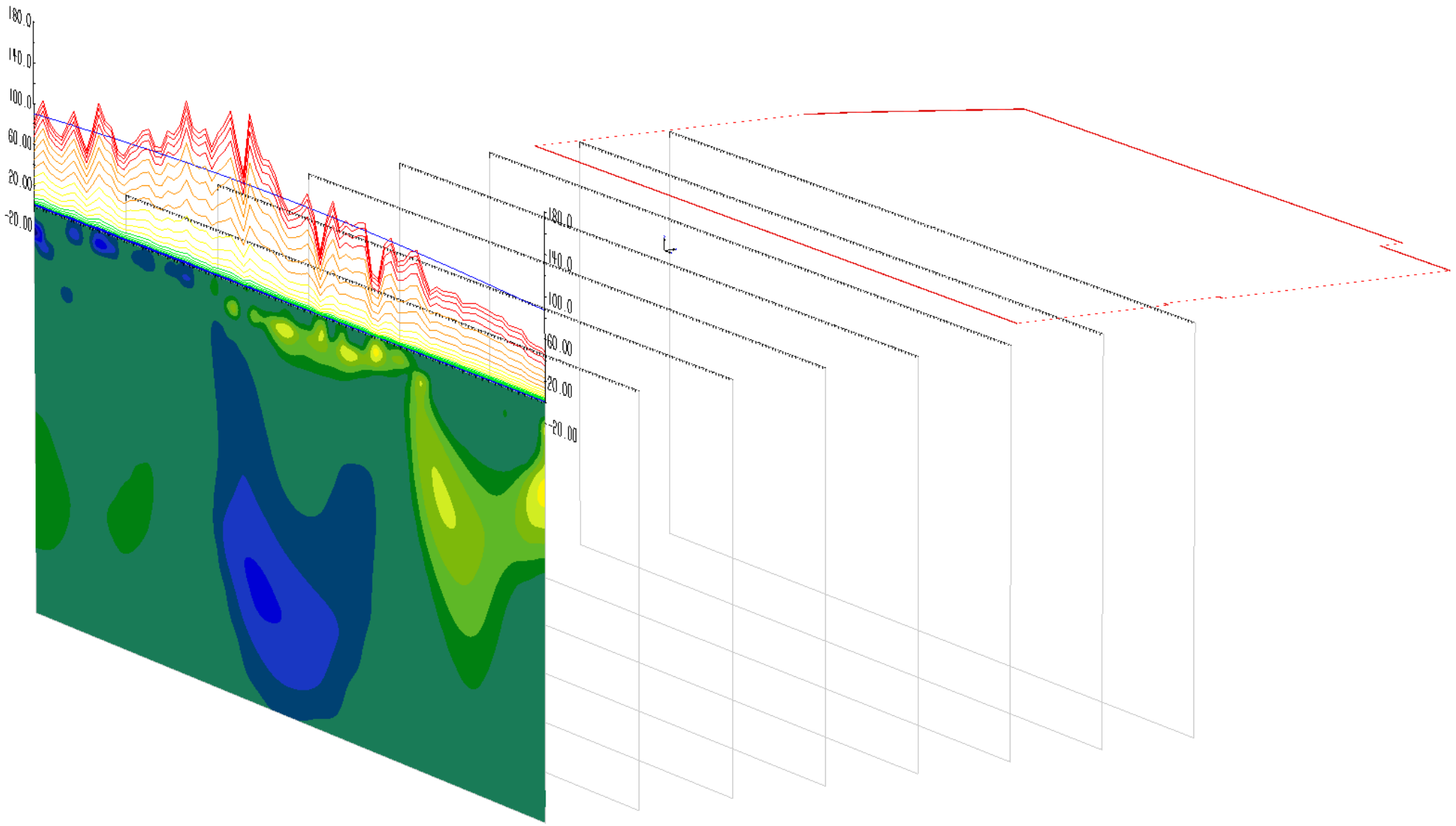
- assemble the sections into a (more) 3D model
- a 3D finite difference routine generates synthetic E field profiles
- synthetic results are compared with the Step Corrected profiles

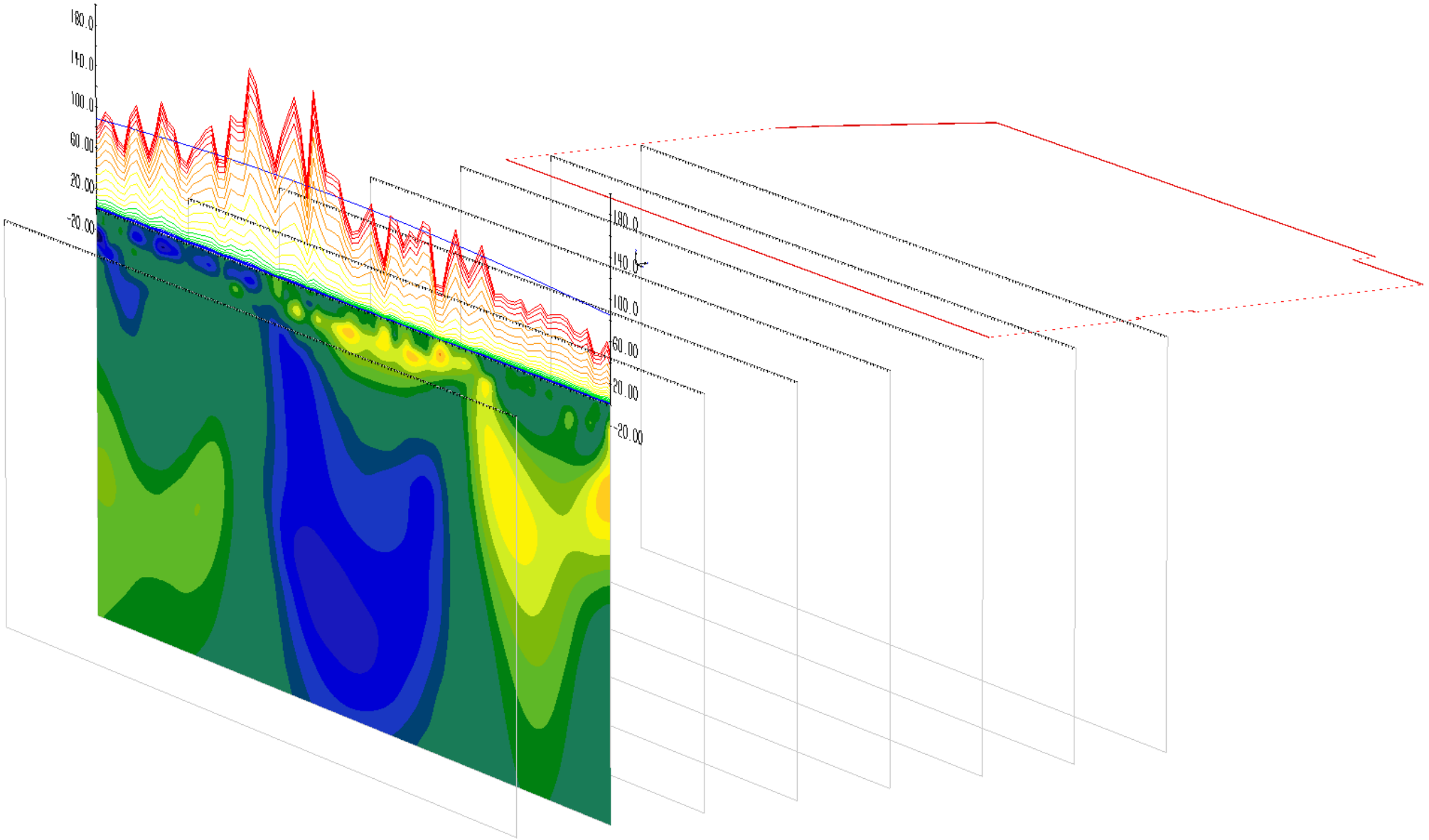
With the goal of putting these pieces together:

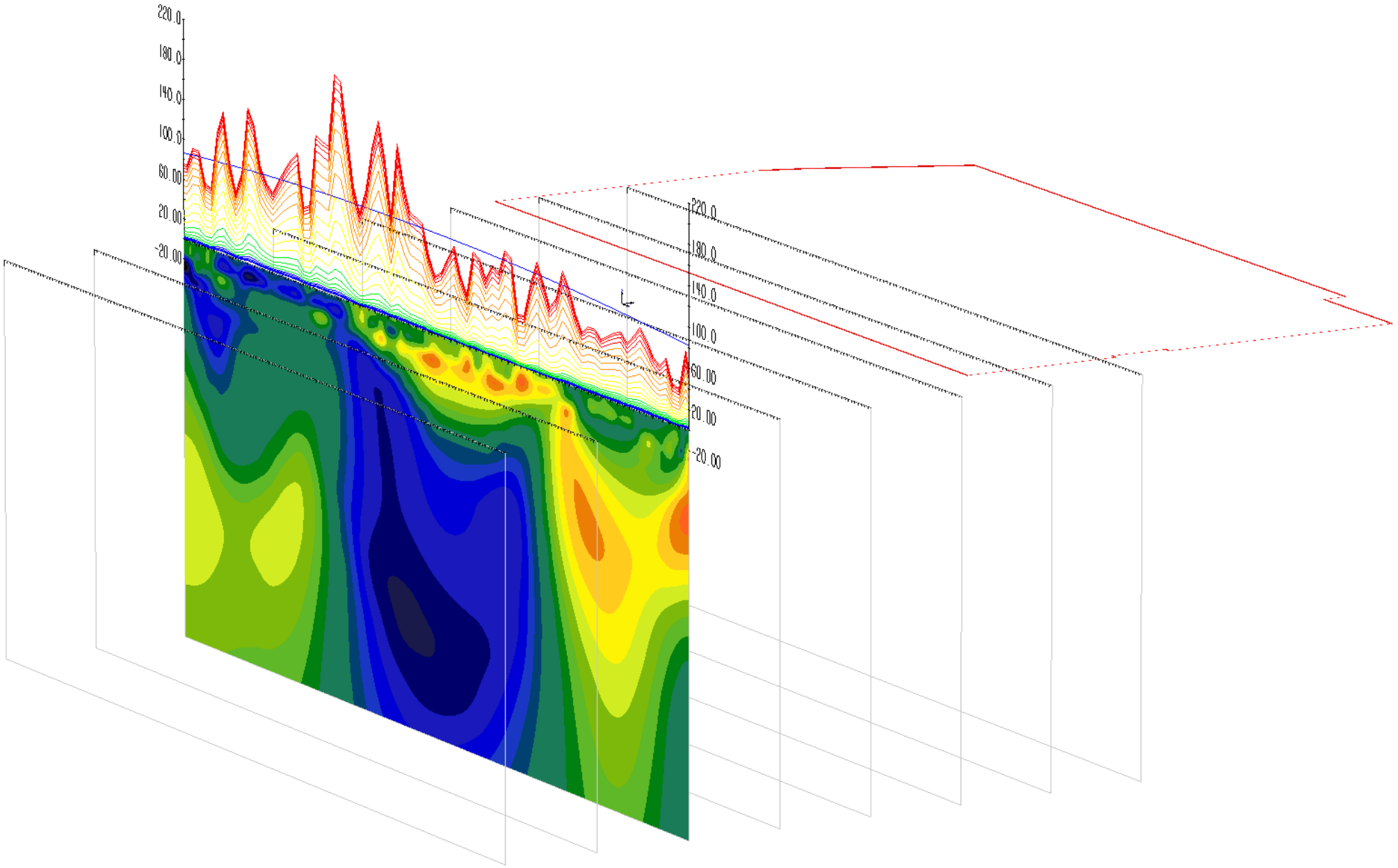
- inversion of field profiles to produce resistivity-depth sections
- assemble all resistivity-depth sections into a model
- 3D finite difference routine generates synthetic E field profiles
- major iterations (Miter) until RMS residuals no longer decrease

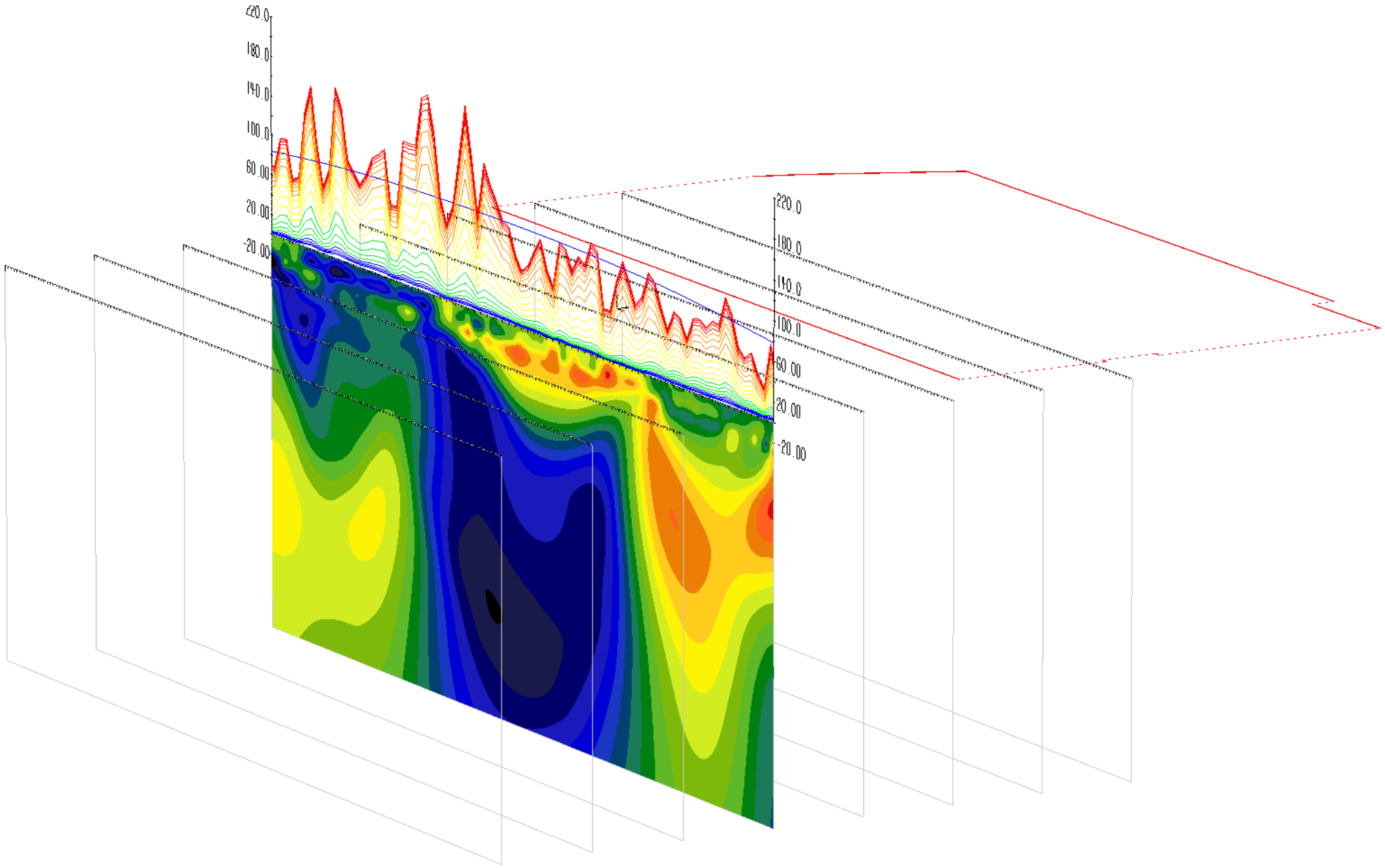


Lines 31N/35N

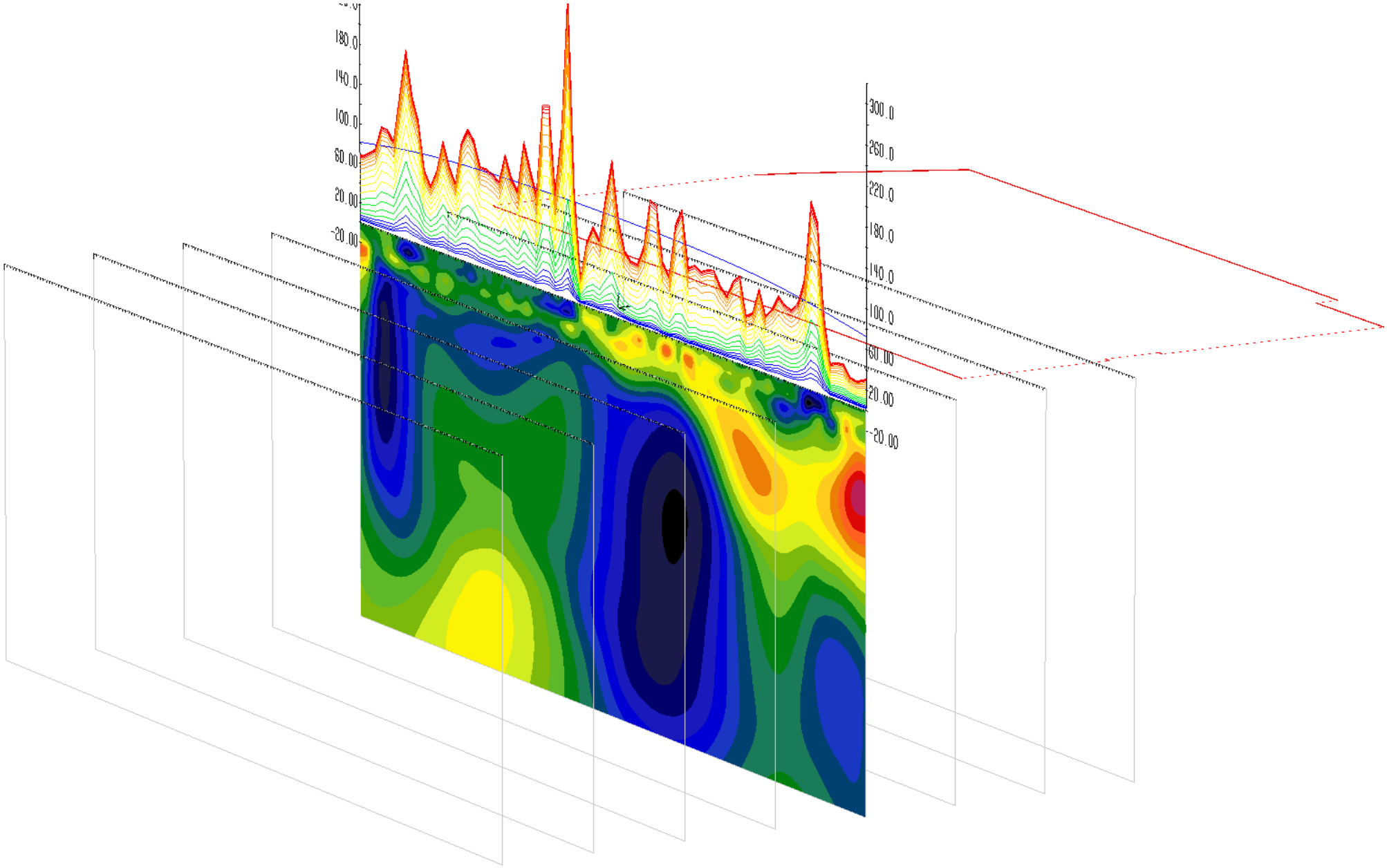

180.0
140.0
100.0
60.00
20.00
-20.00
Line 19N


180.0
140.0
100.0
60.00
20.00
-20.00
Line 23N

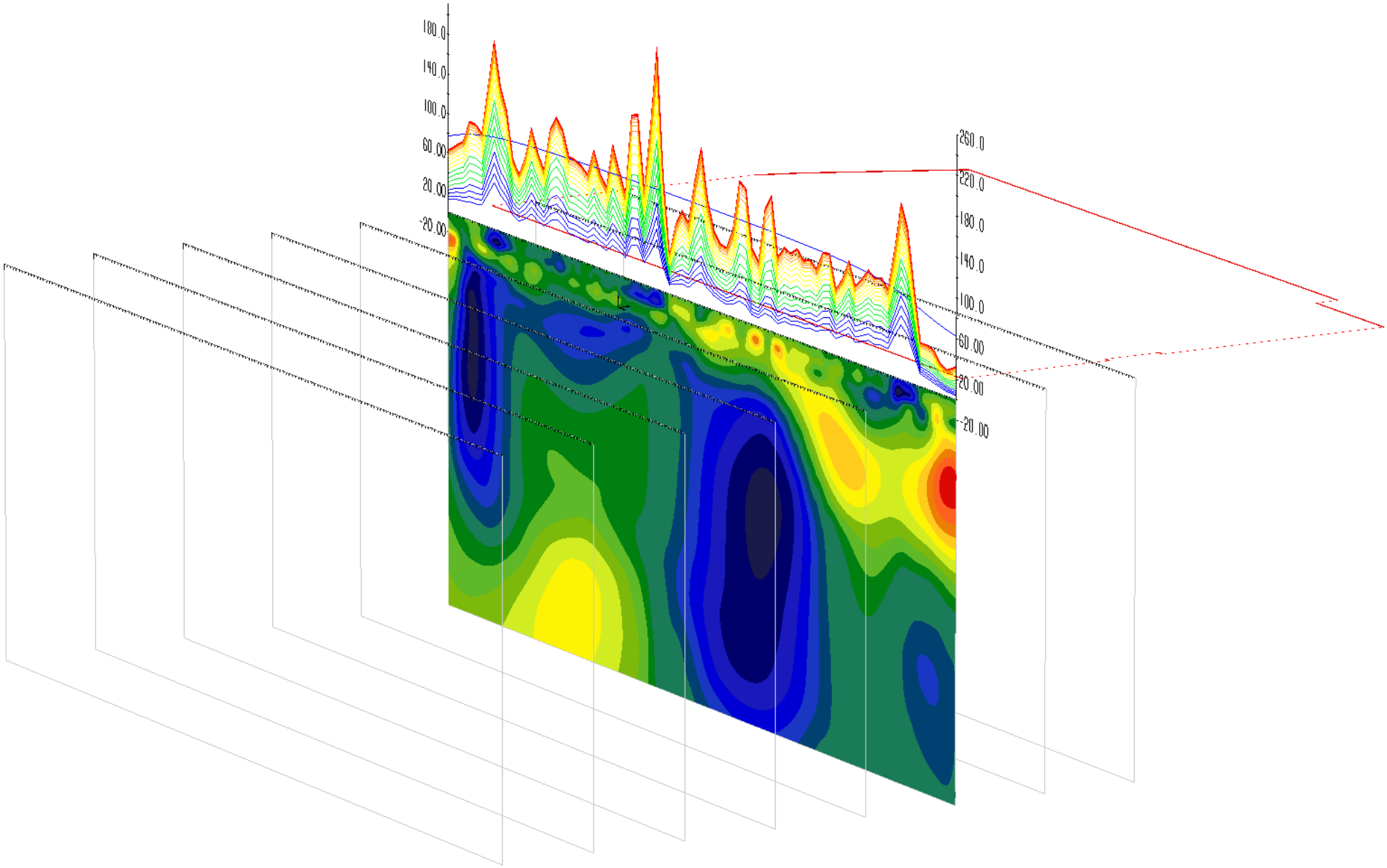

220.0
180.0
140.0
100.0
60.00
20.00
-20.00
220.0
180.0
140.0
100.0
60.00
20.00
-20.00
Line 27N

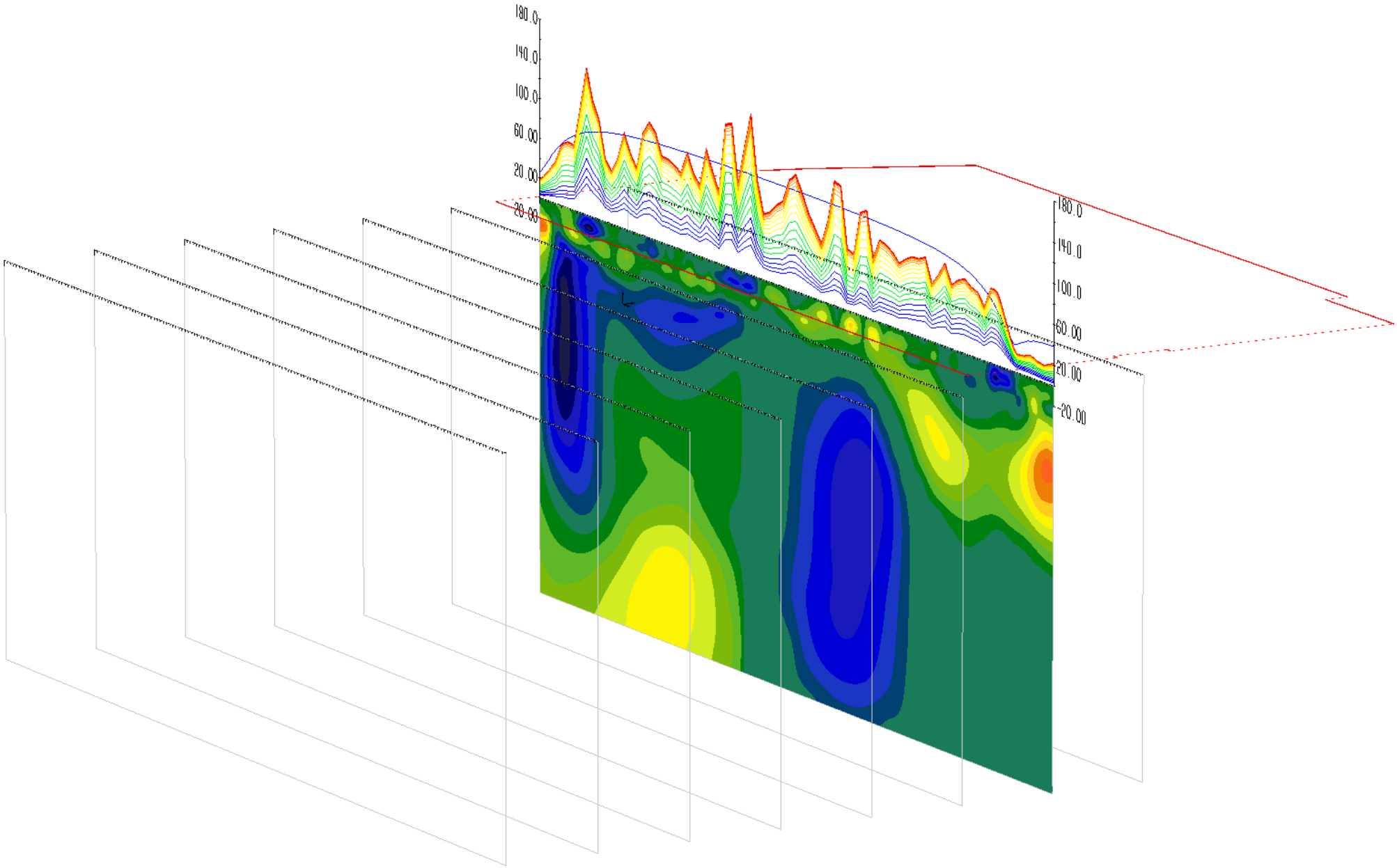


Line 31N

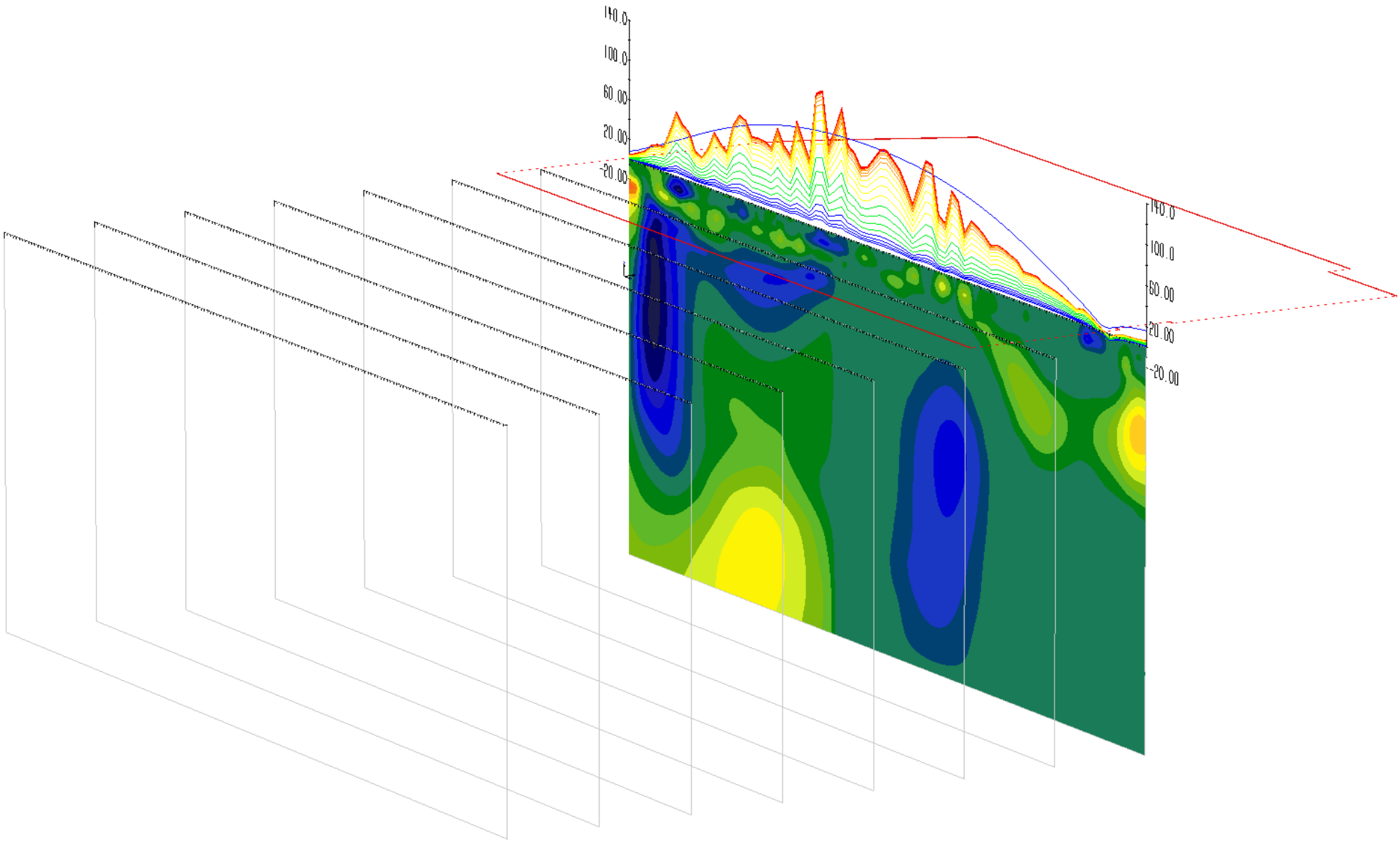

180.0
140.0
100.0
60.00
20.00
-20.00
300.0
260.0
220.0
180.0
140.0
100.0
60.00
20.00
-20.00

Line 35N

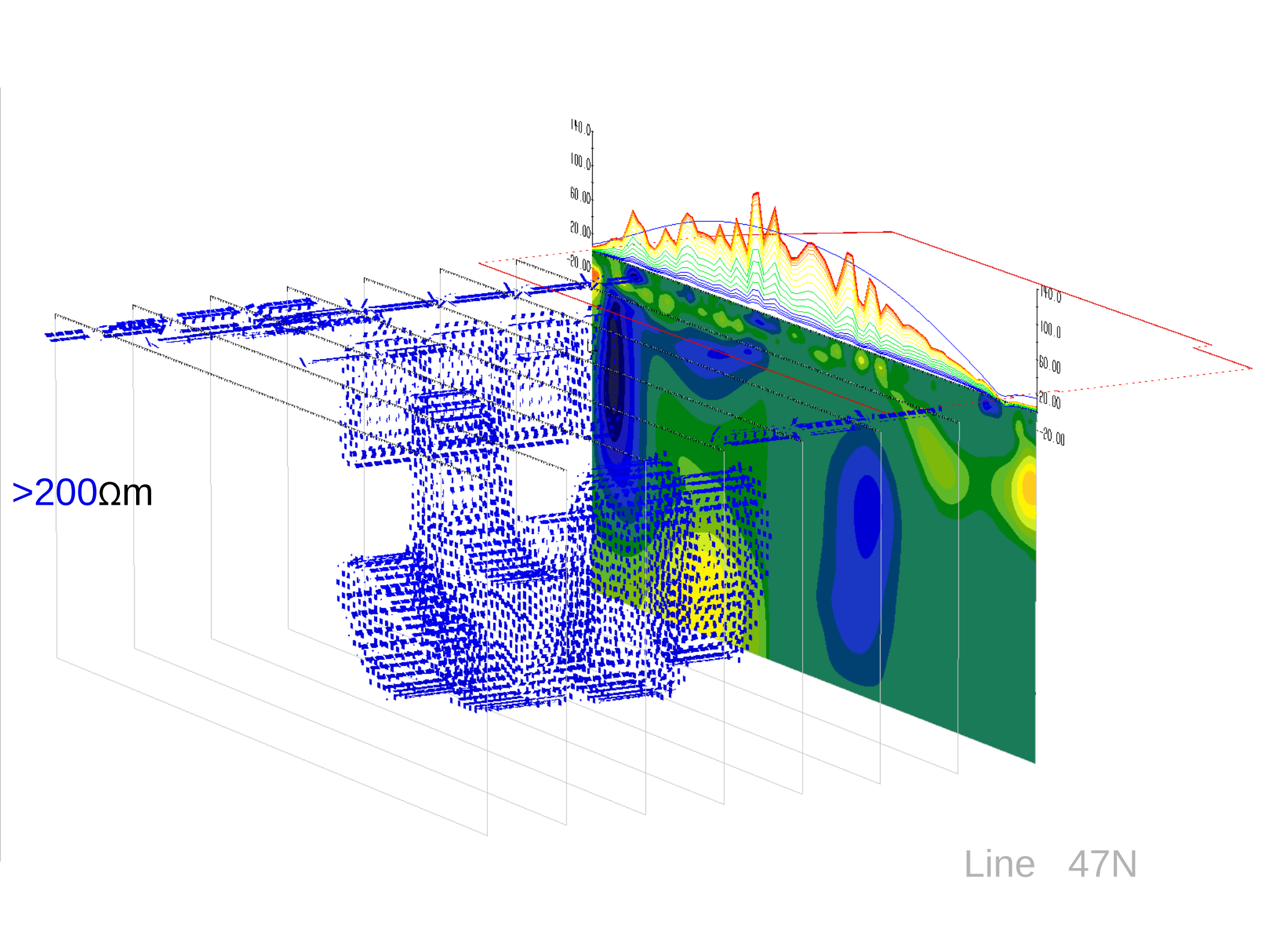

180.0
140.0
100.0
60.00
20.00
-20.00
260.0
220.0
180.0
140.0
100.0
60.00
20.00
-20.00
Line 39N

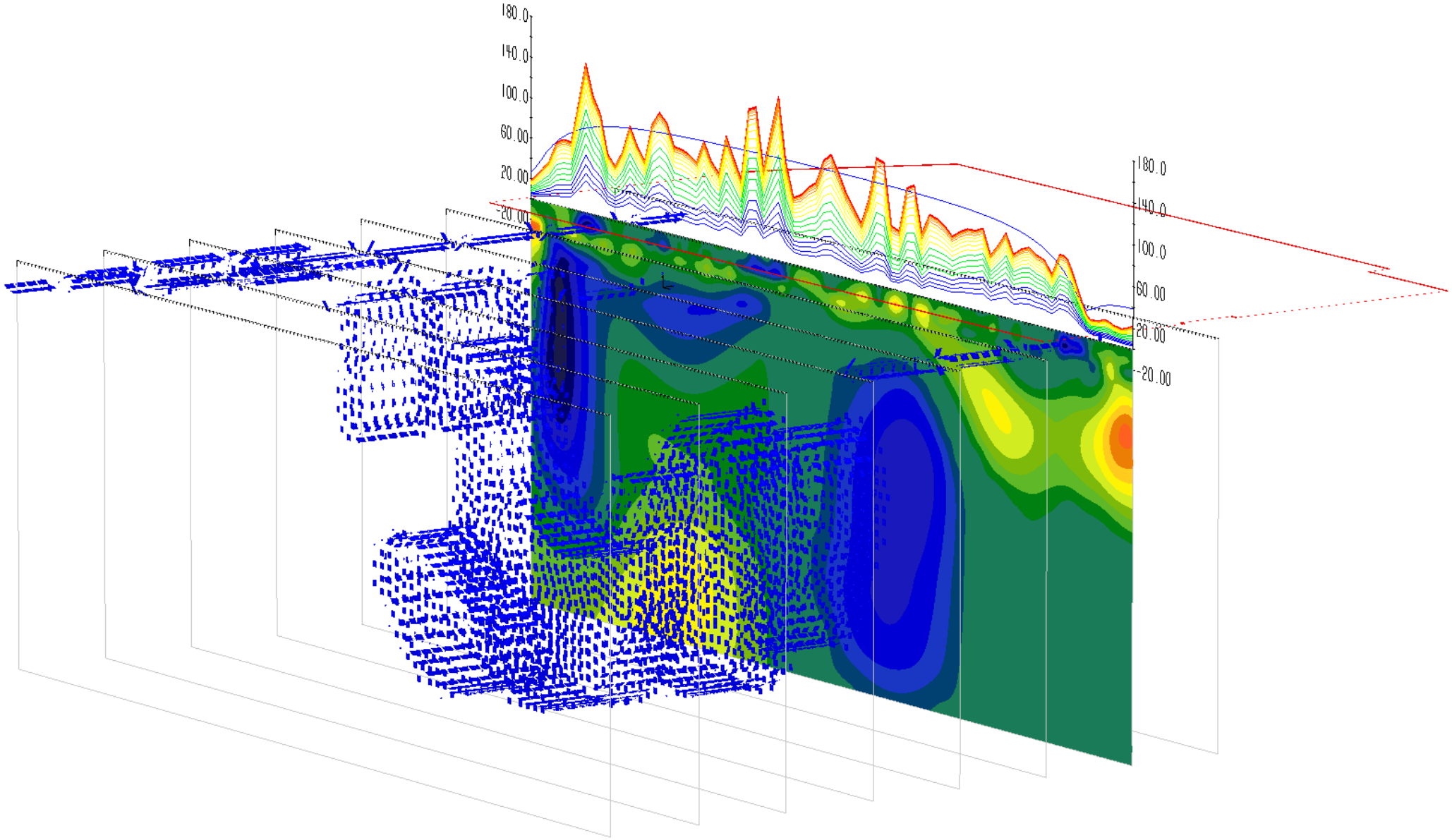


Line 43N

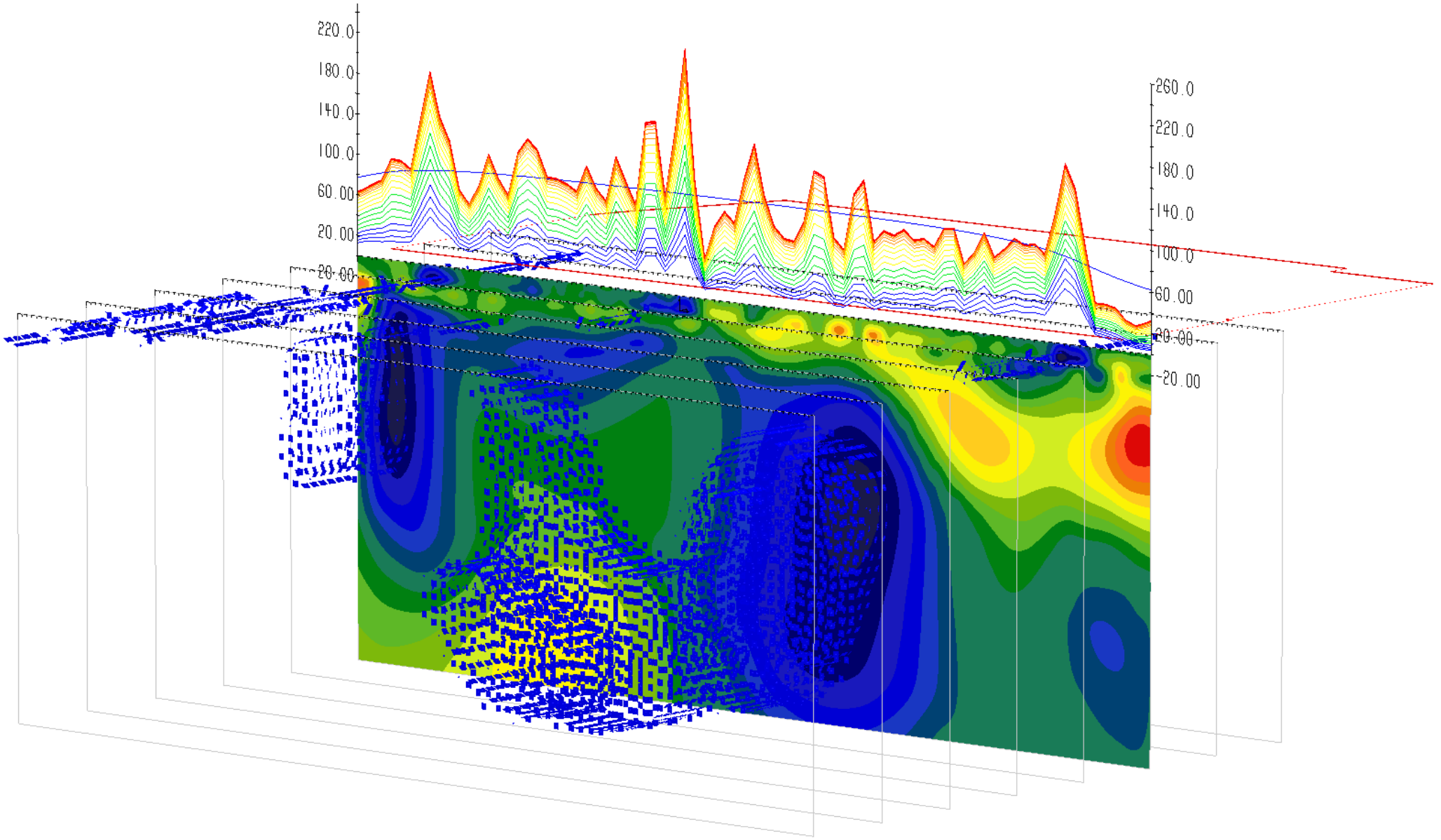


Line 47N

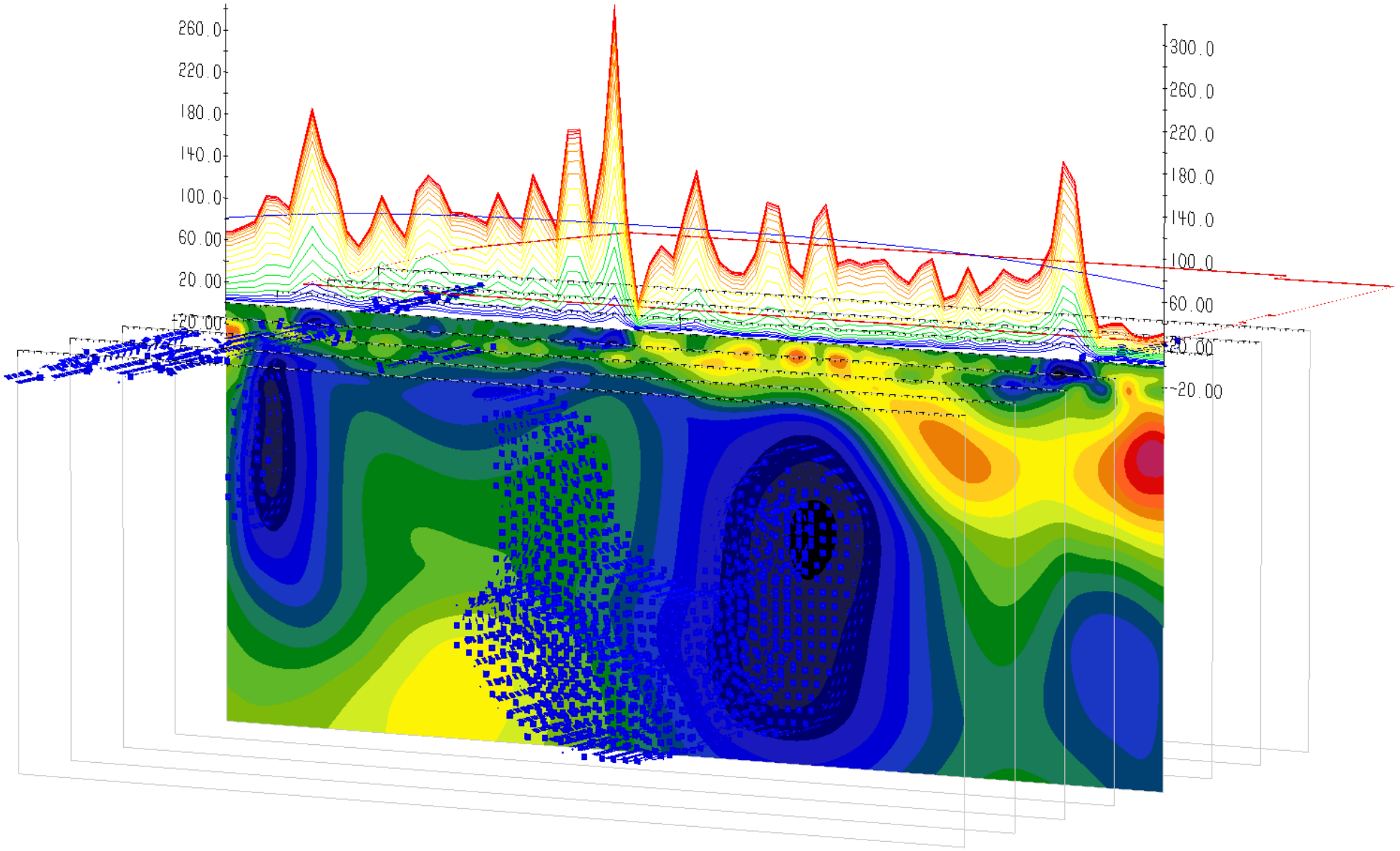

>200Ωm
140.0
100.0
60.00
20.00
-20.00
Line 47N



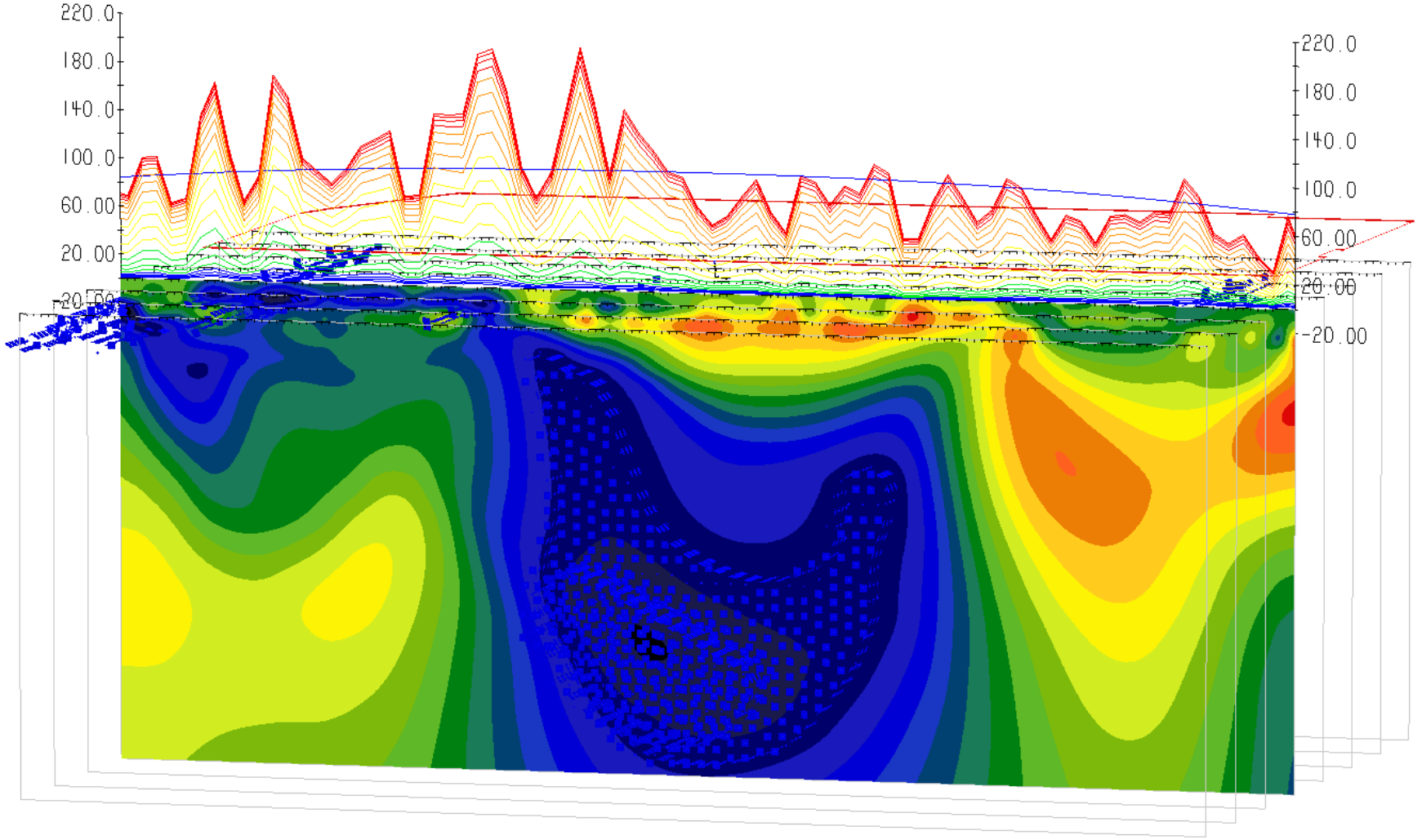
Line 43N


220.0
180.0
140.0
100.0
60.00
20.00
-20.00
260.0
220.0
180.0
140.0
100.0
60.00
20.00
-20.00

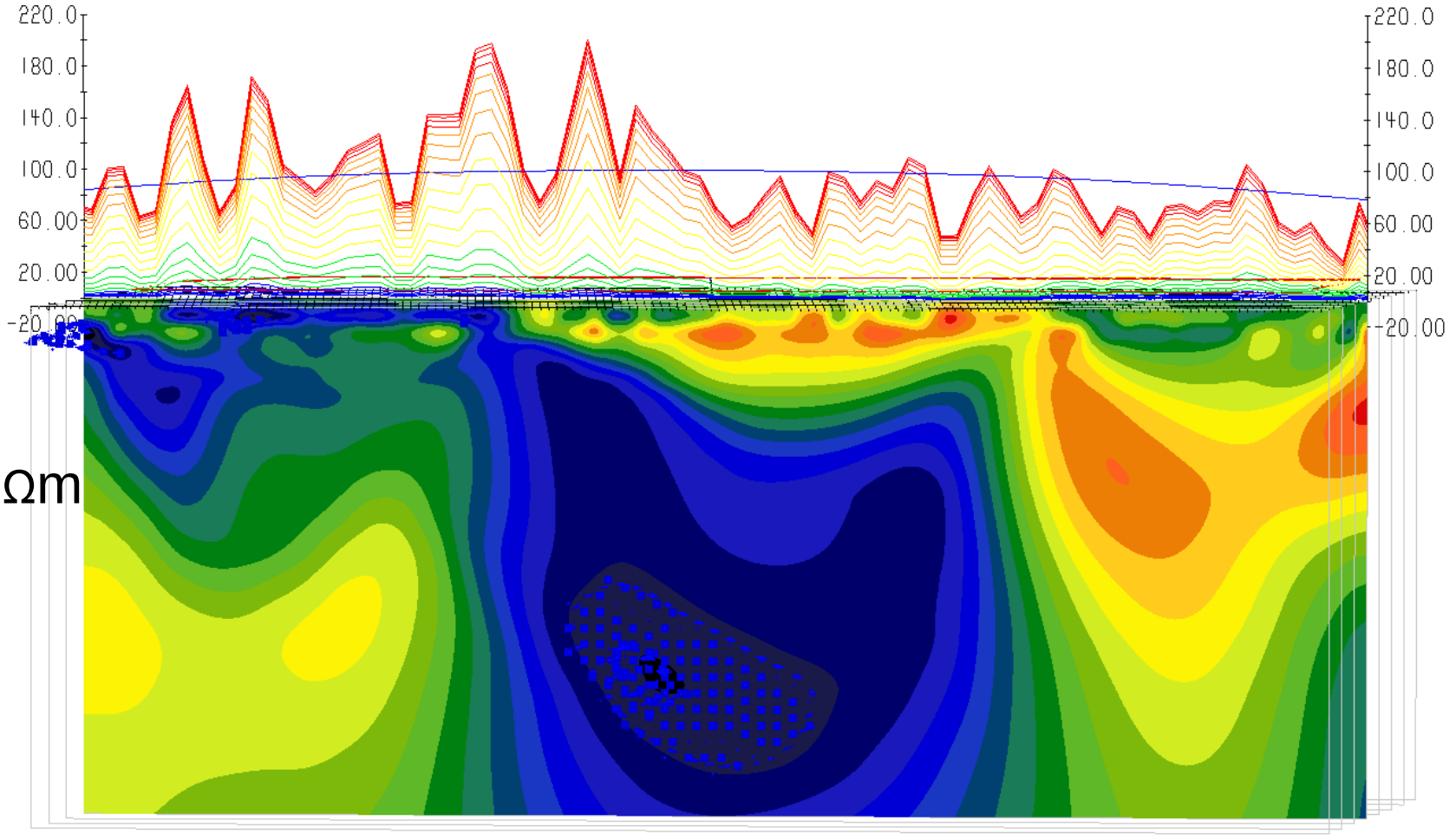
Line 39N


260.0
220.0
180.0
140.0
100.0
60.00
20.00
-20.00
300.0
260.0
220.0
180.0
140.0
100.0
60.00
20.00
-20.00

Line 35N

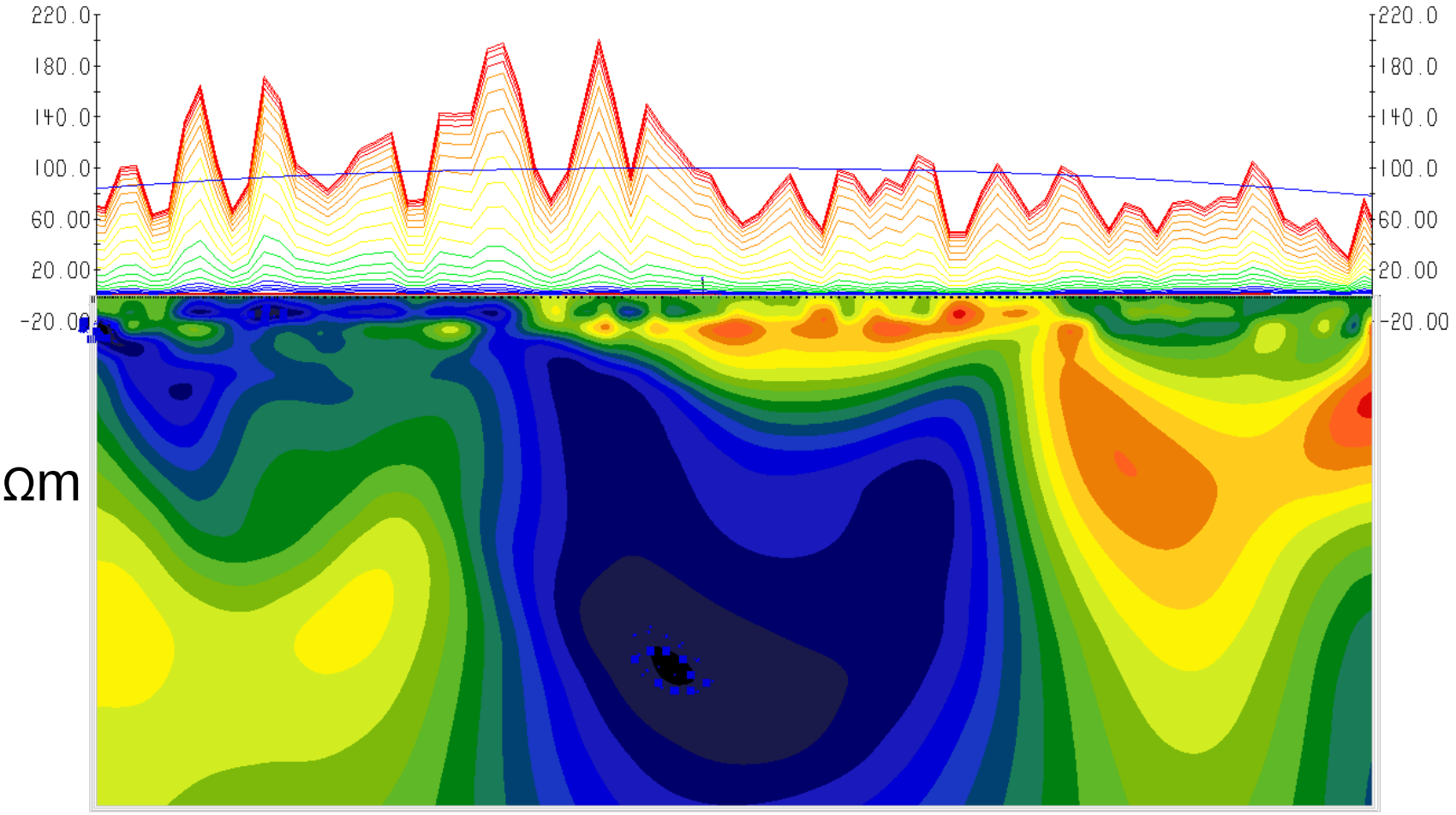

220.0
180.0
140.0
100.0
60.00
20.00
-20.00
220.0
180.0
140.0
100.0
60.00
20.00
-20.00

Line 31N



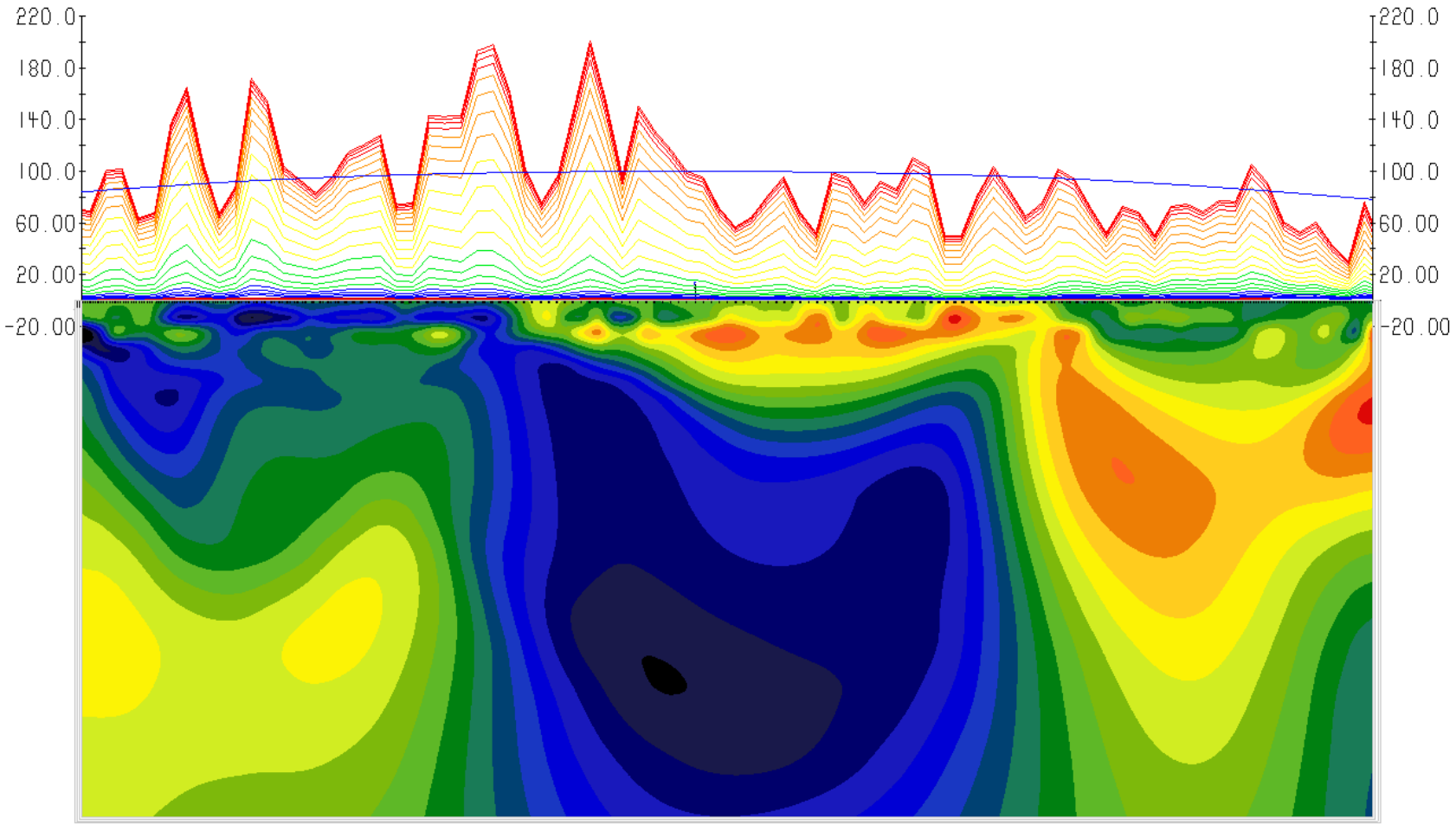
>300Ωm

Line 31N



>400Ωm

Line 31N


220.0
180.0
140.0
100.0
60.00
20.00
-20.00
220.0
180.0
140.0
100.0
60.00
20.00
-20.00

Line 31N

Acknowledgements

Thanks to:

KGHM International for allowing us to share the data.

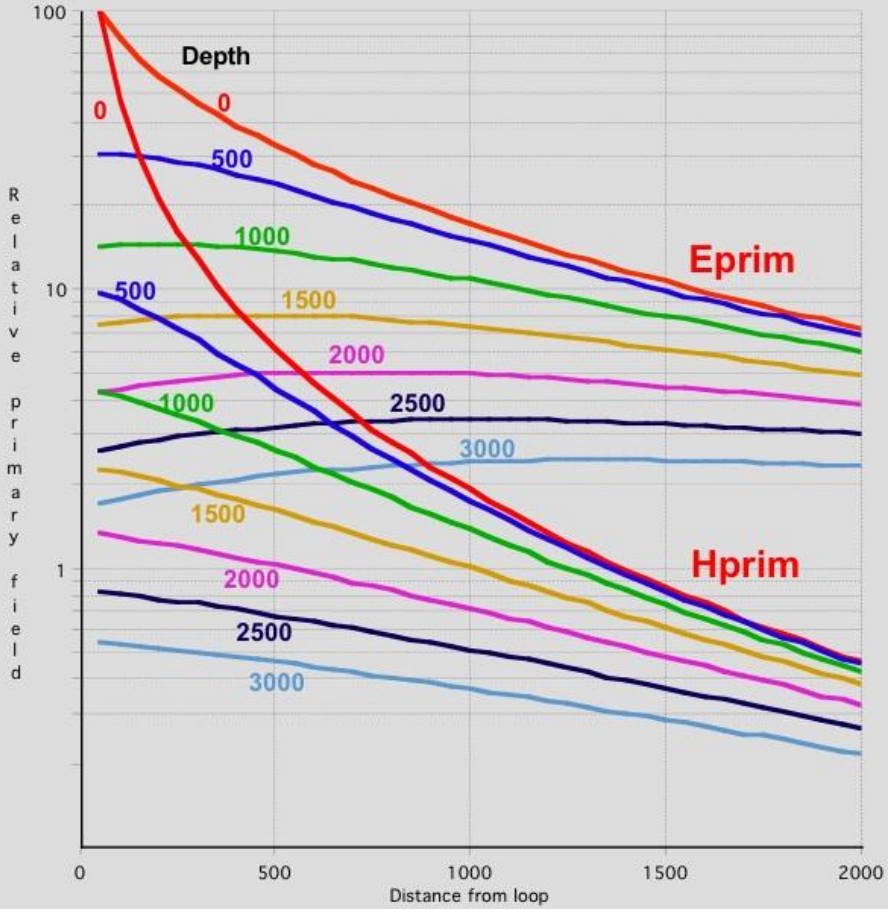
The management, staff and field workers involved at all levels at the Sierra Gorda site.

Peter Walker

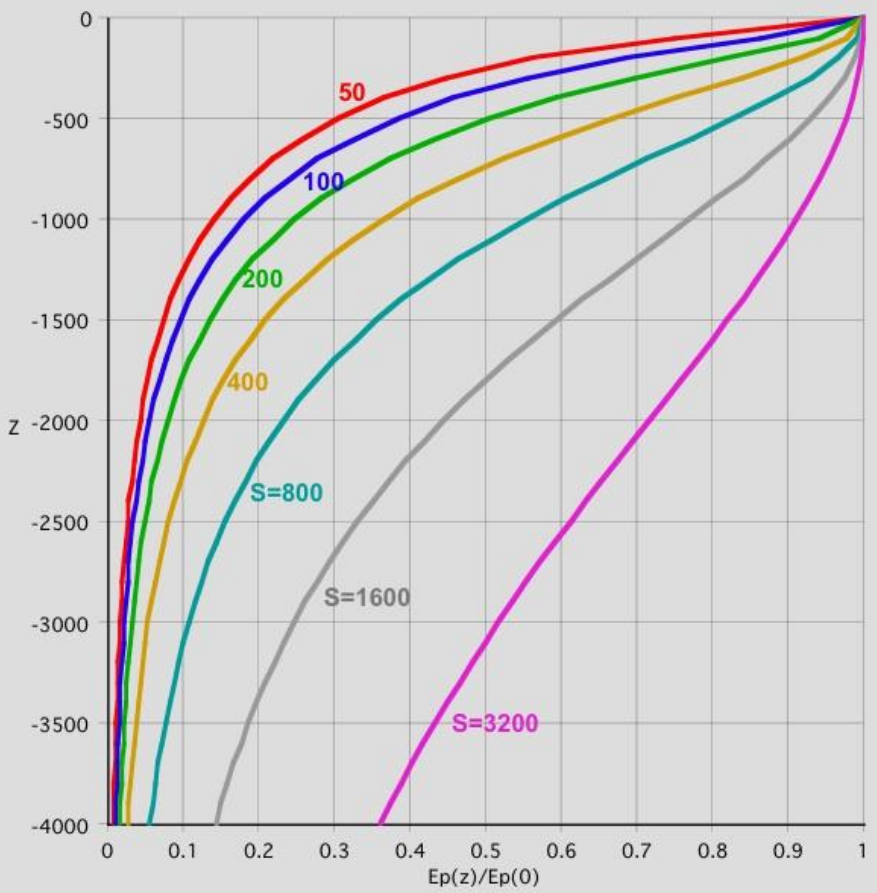
end of talk as presented

E primary field

- Slow geometrical fall-off
- Transmitter distances can be used for geometrical "sounding"
- Deep sounding potential but coarse depth resolution



Eprim & Hprim vs distance from loop



Eprim vs depth

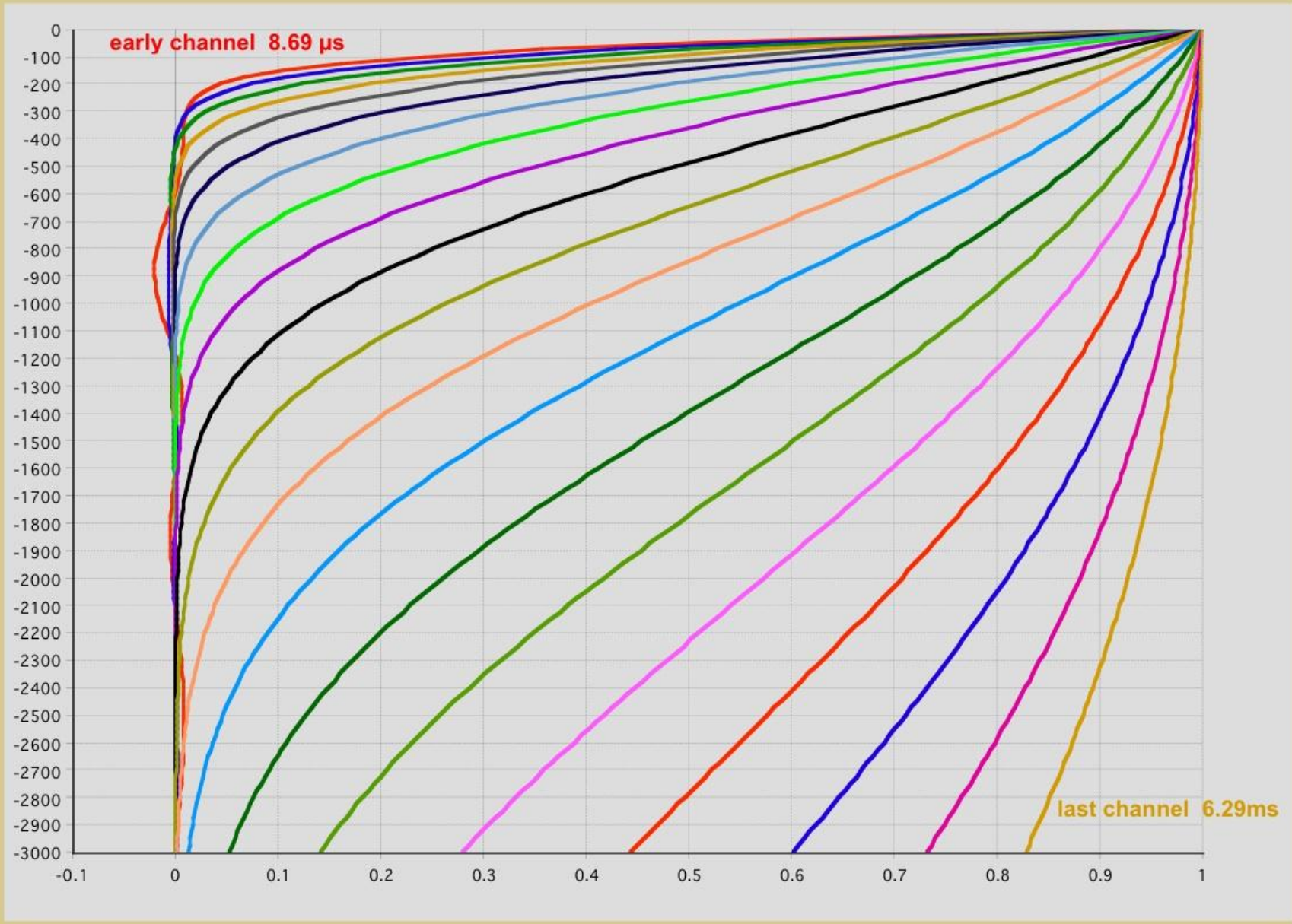
2000x2000m
TX loop
at S=1200m

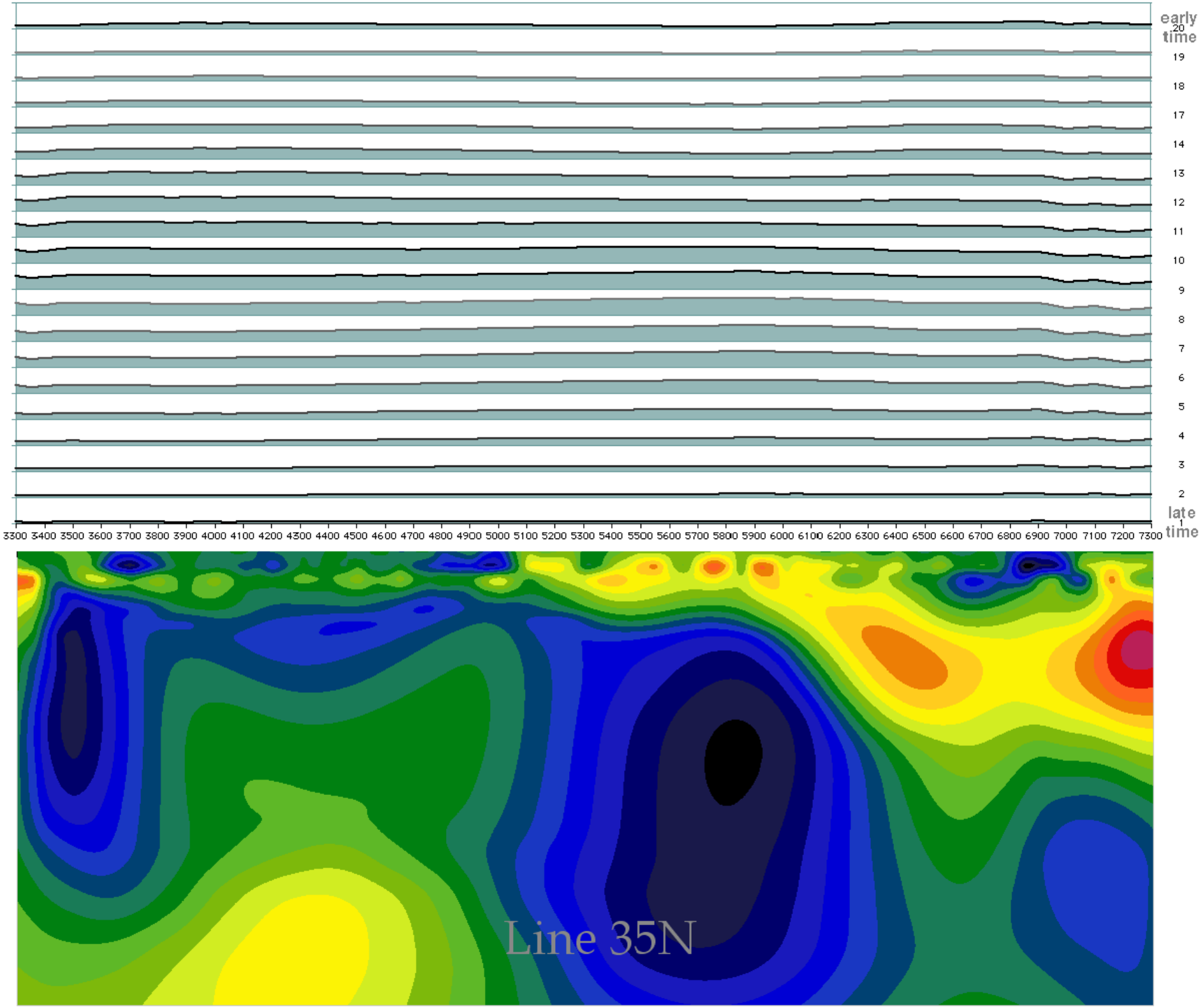
Effective ISR section in a one sided loop survey

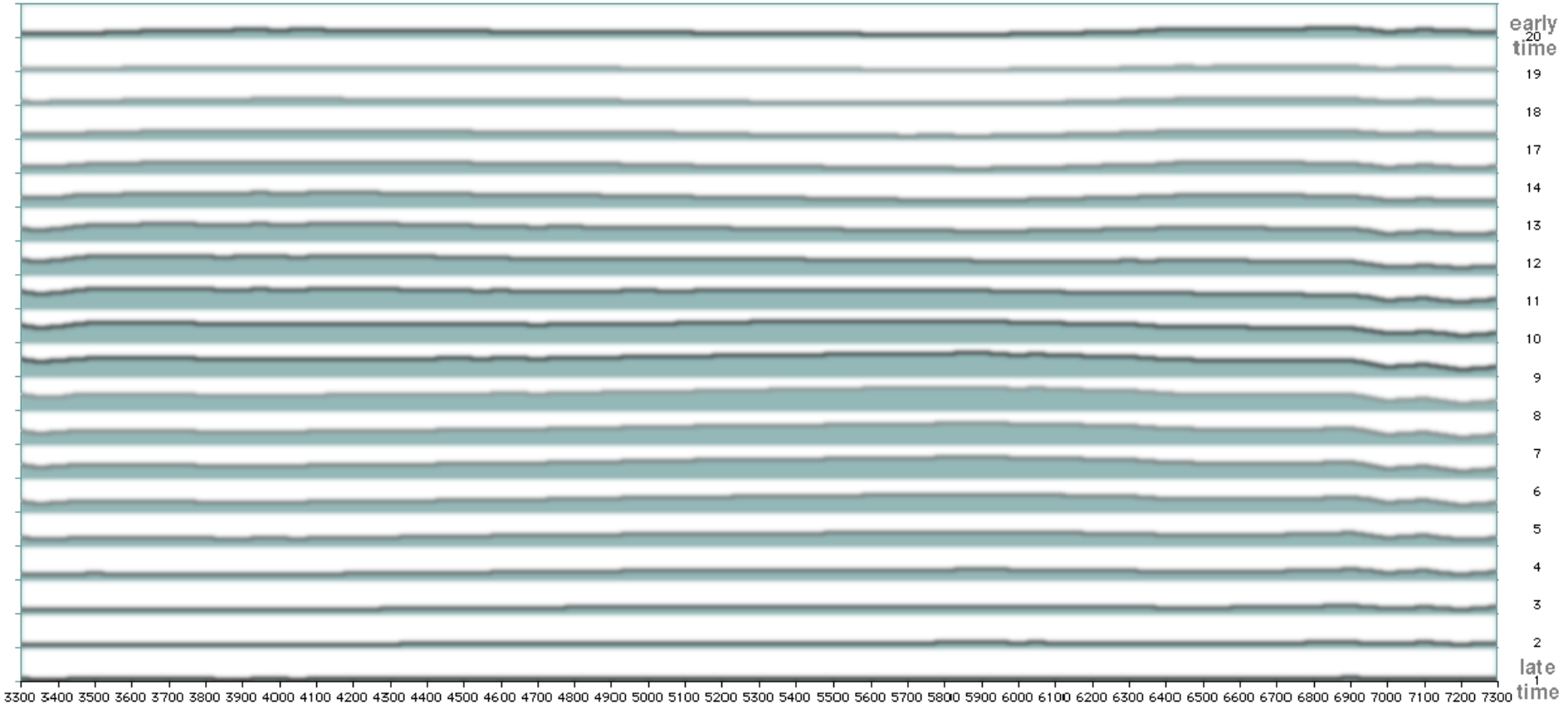
Maximum lateral sensitivity at each depth at the late time limit

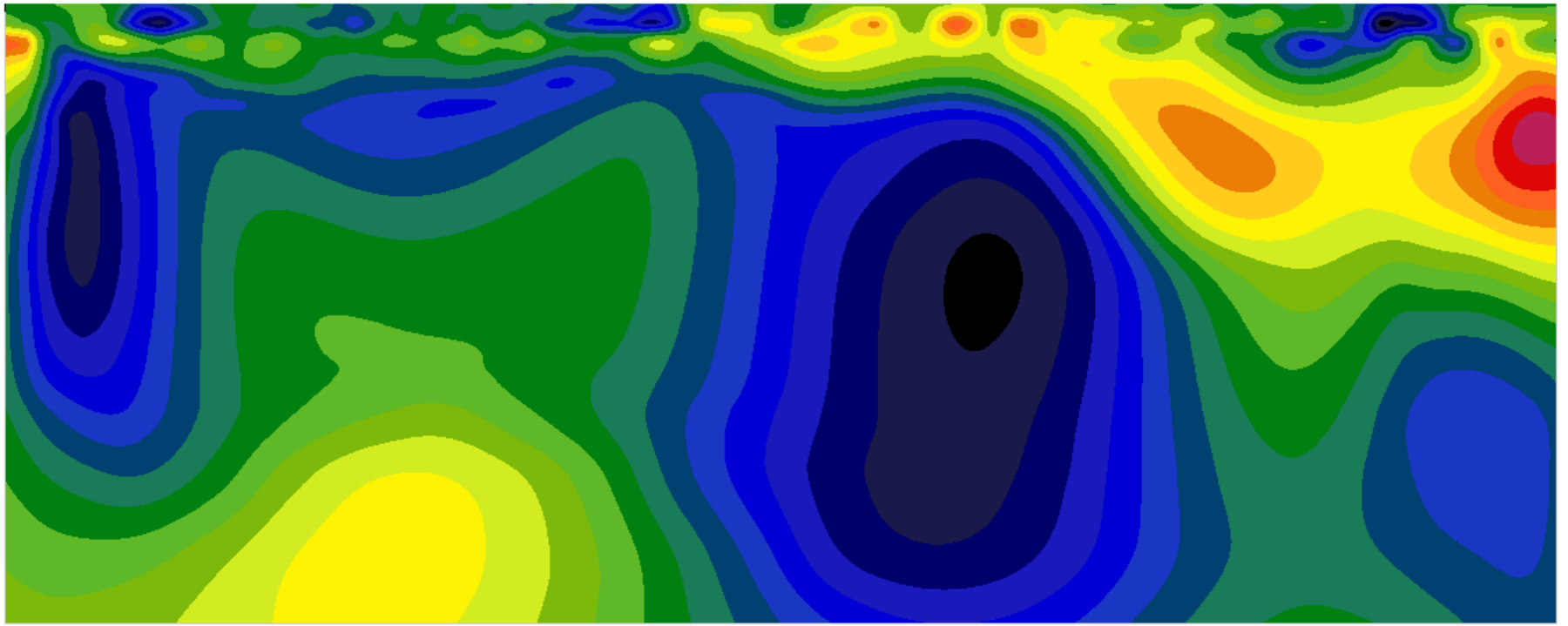
Diffusion depth effect

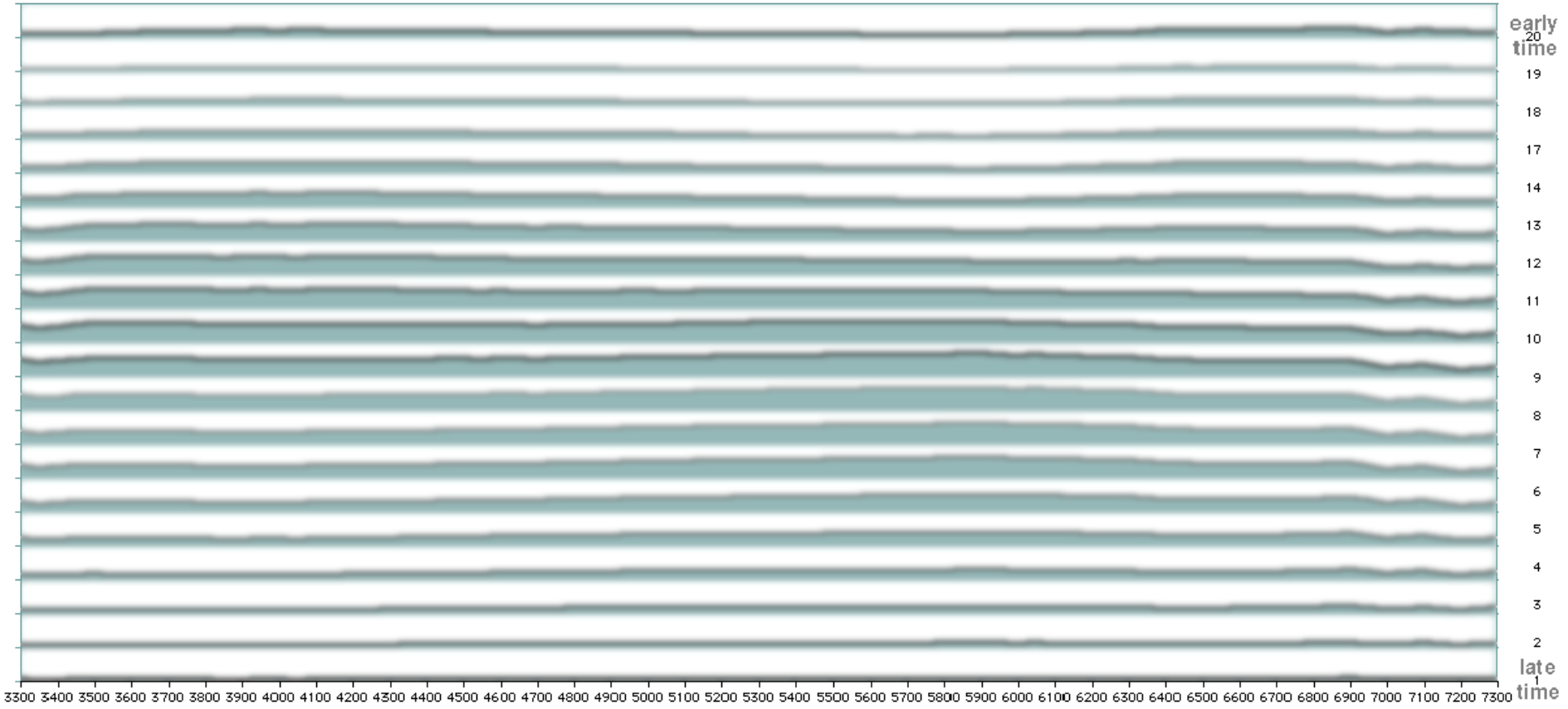
factor multiplying the free-air primary field
S=800m, 1000 Ωm half-space, base frequency=65Hz

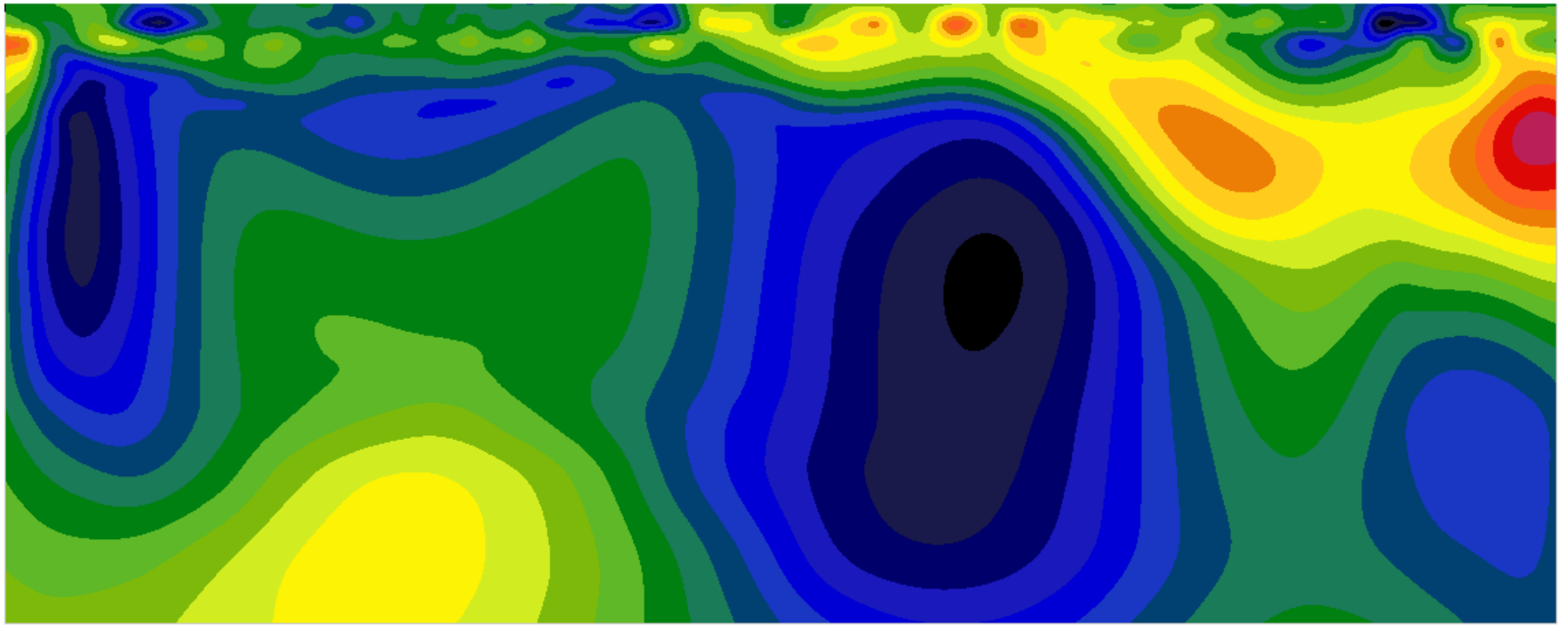


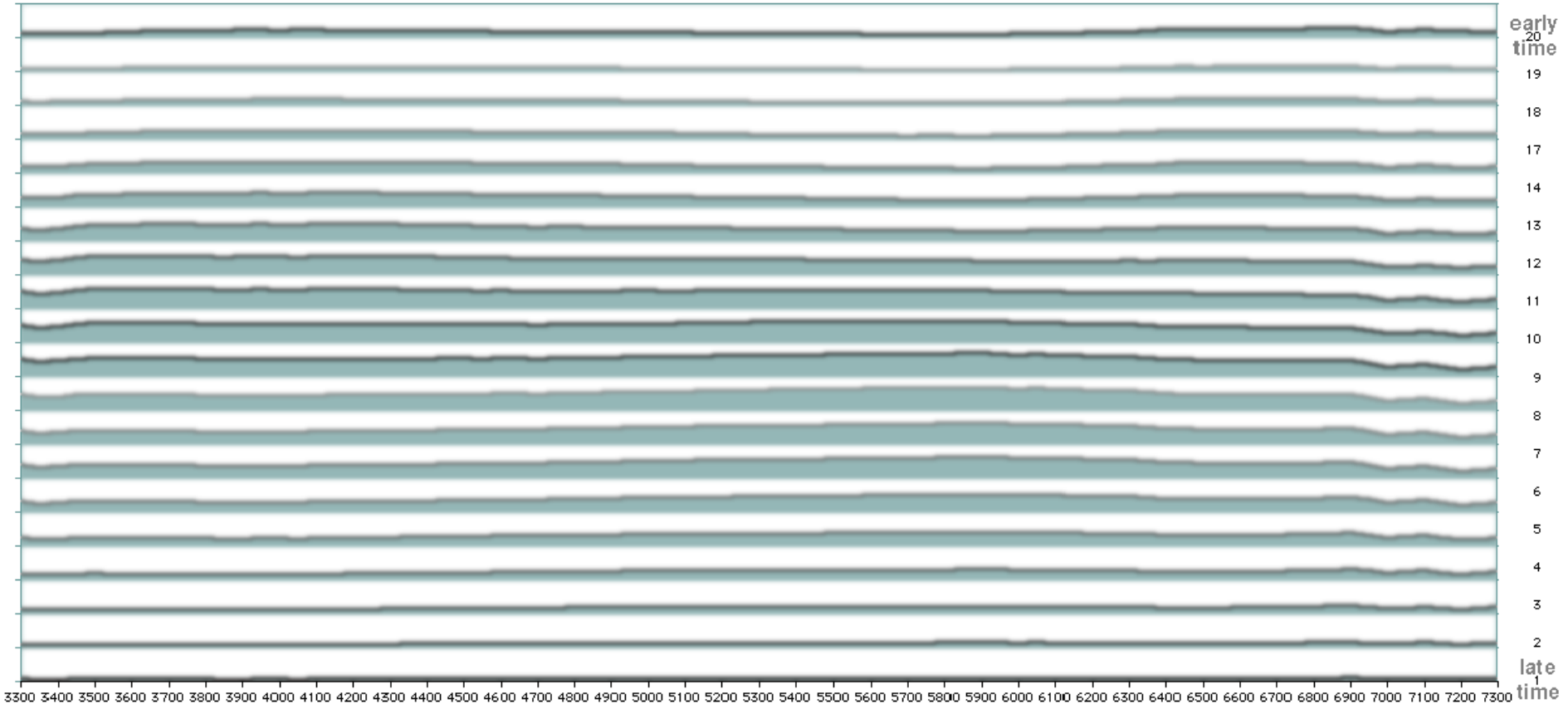

early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300
Line 35N

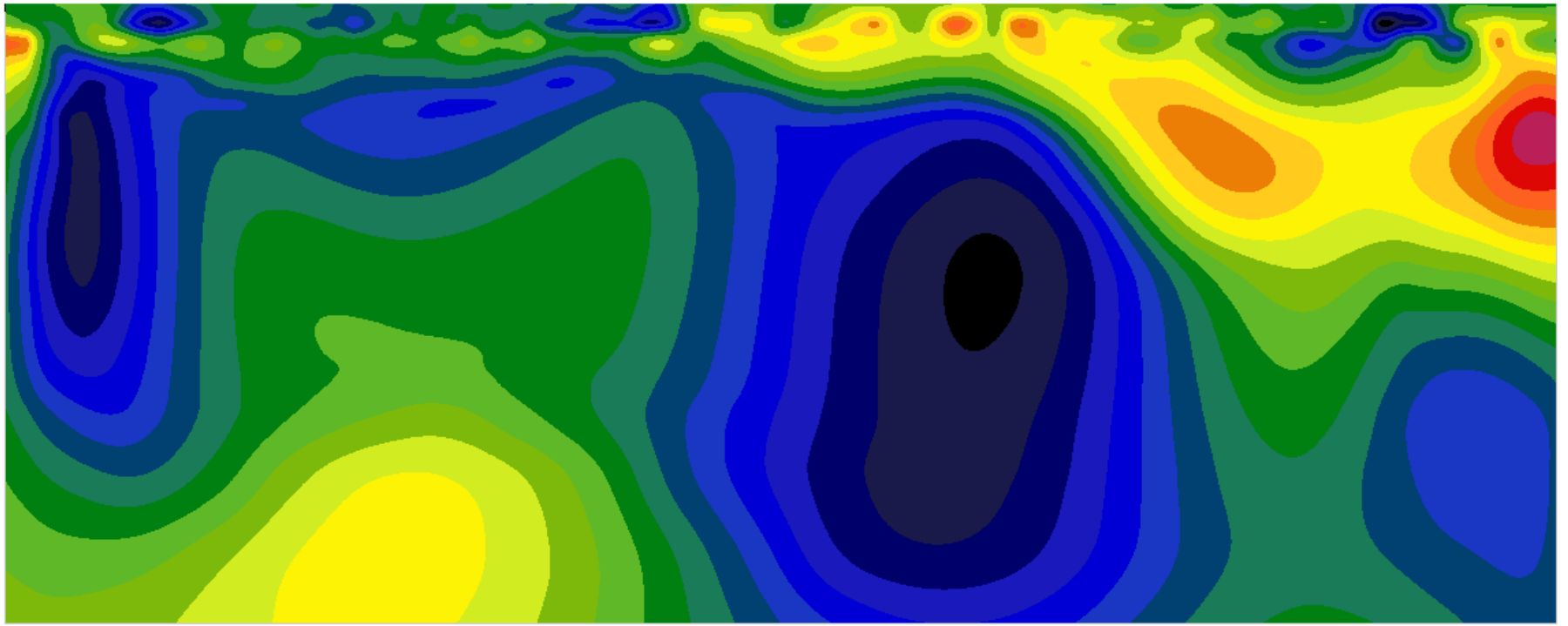

early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300

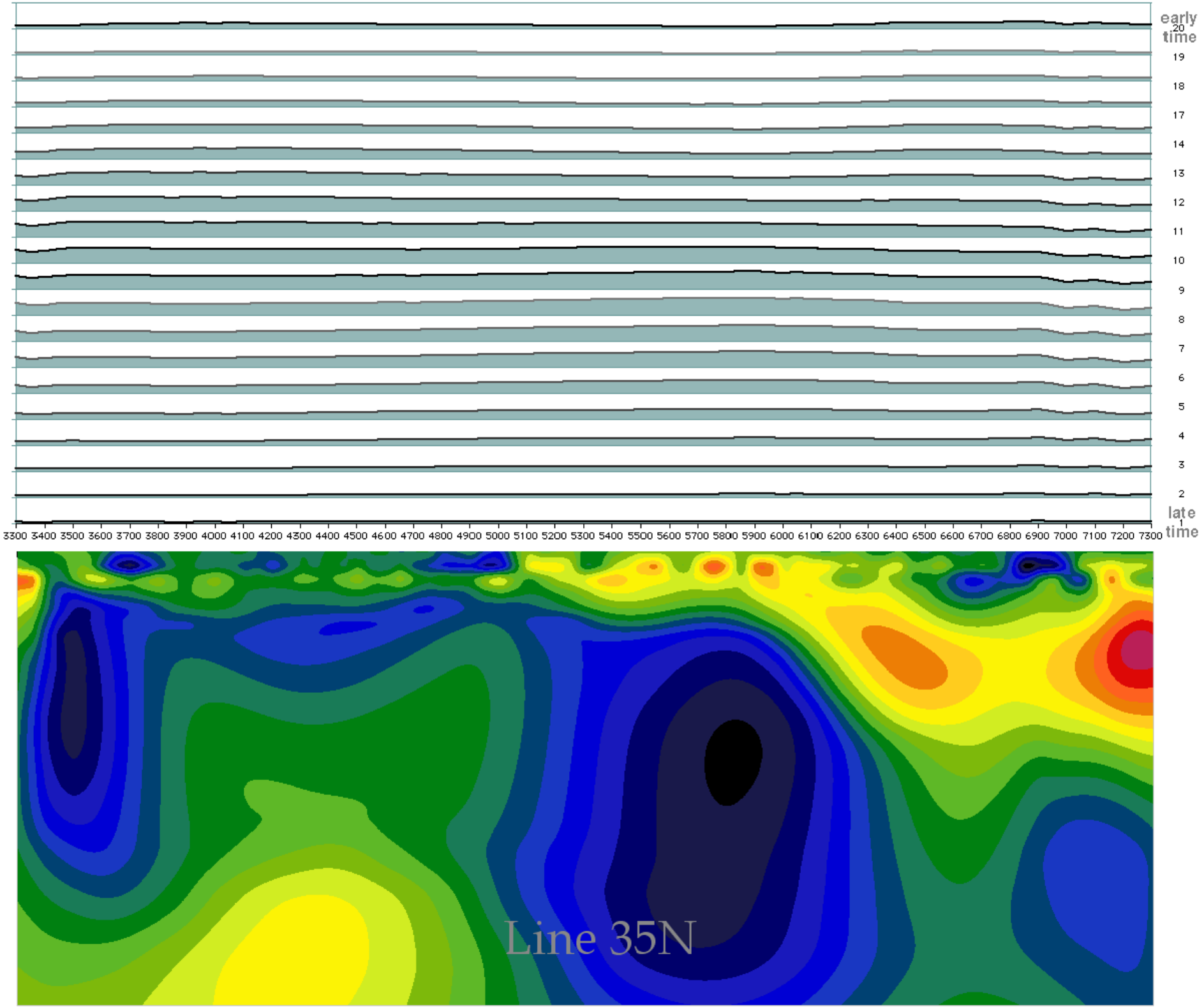



early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300



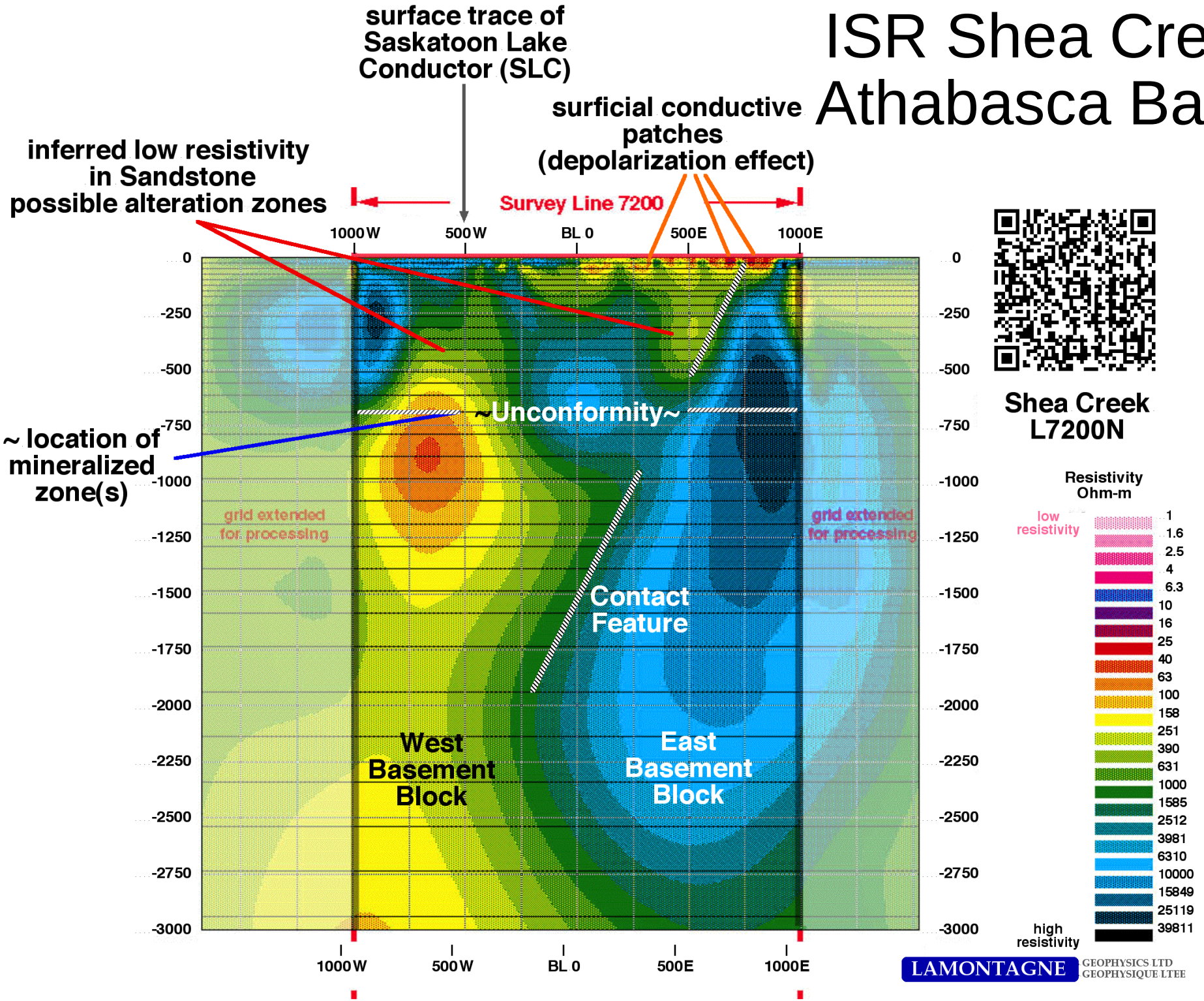

early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300



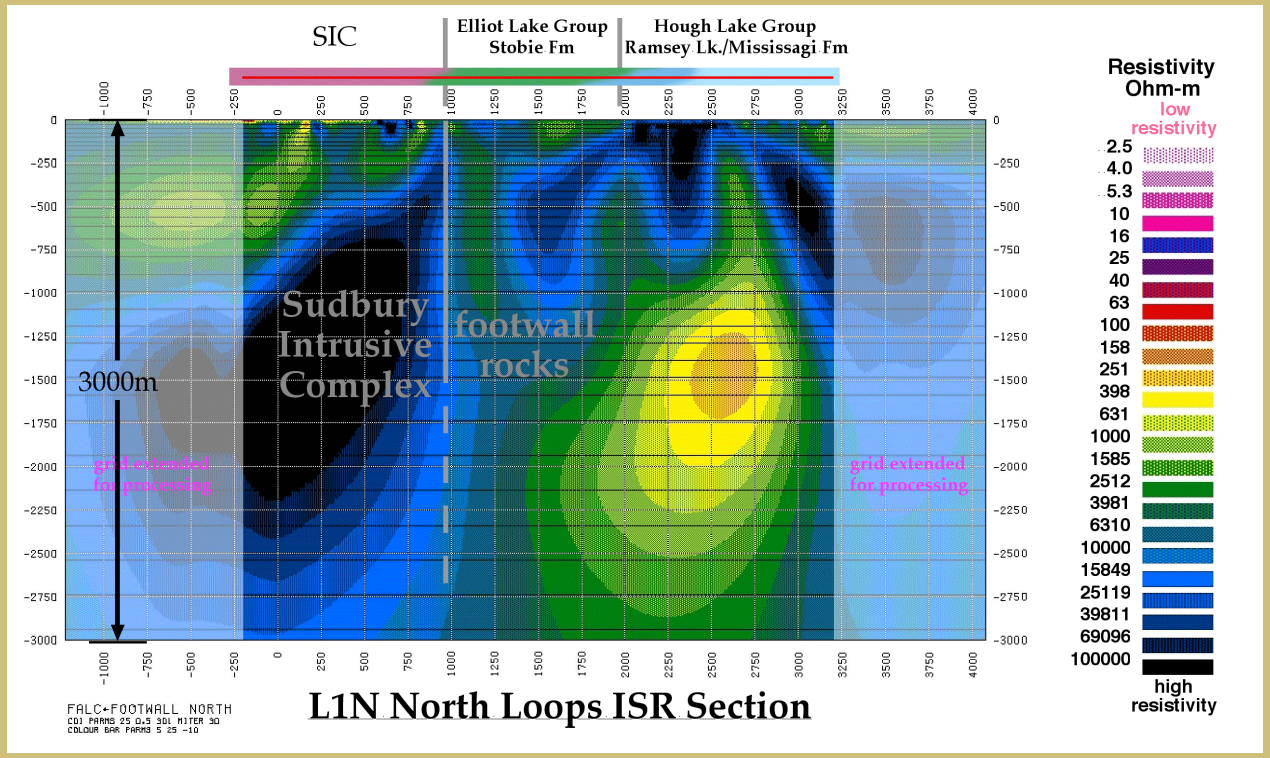

early time
20
19
18
17
14
13
12
11
10
9
8
7
6
5
4
3
2
late time
1
3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 6100 6200 6300 6400 6500 6600 6700 6800 6900 7000 7100 7200 7300
Line 35N

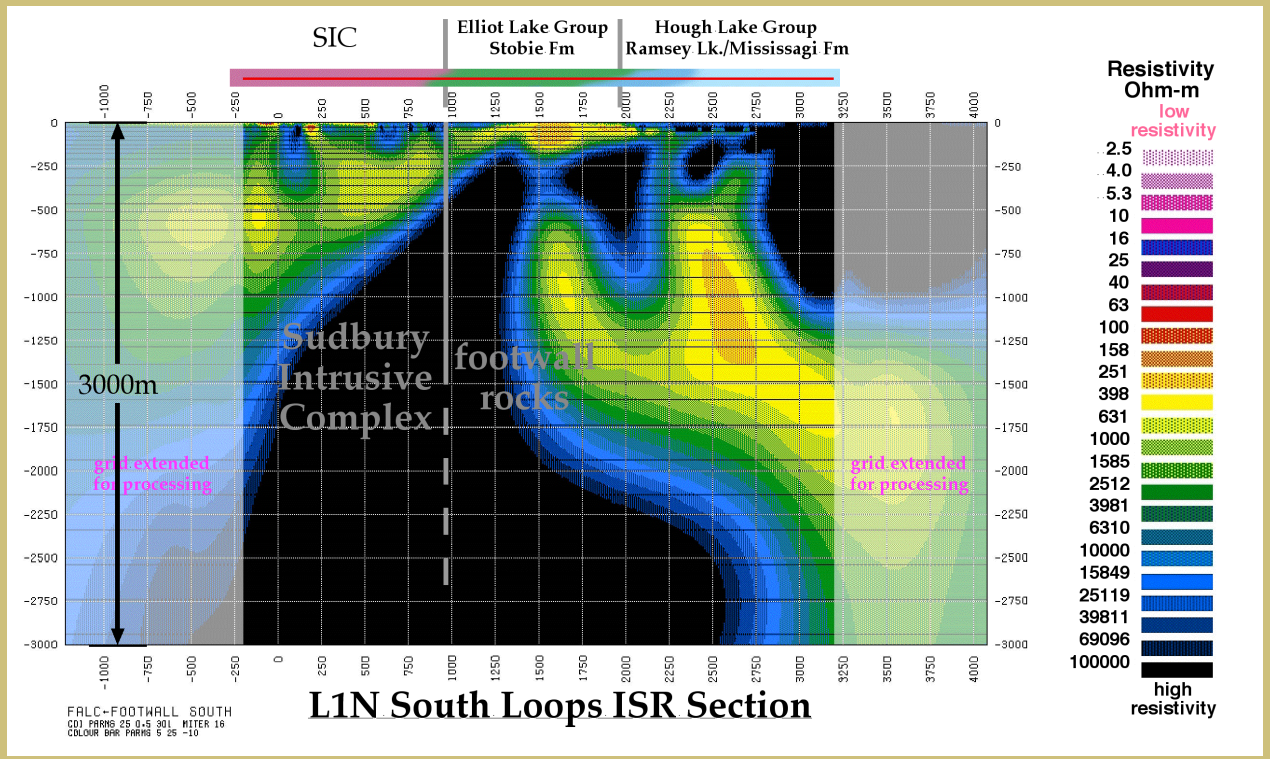
additional
ISR resistivity-depth sections

ISR Shea Creek Athabasca Basin

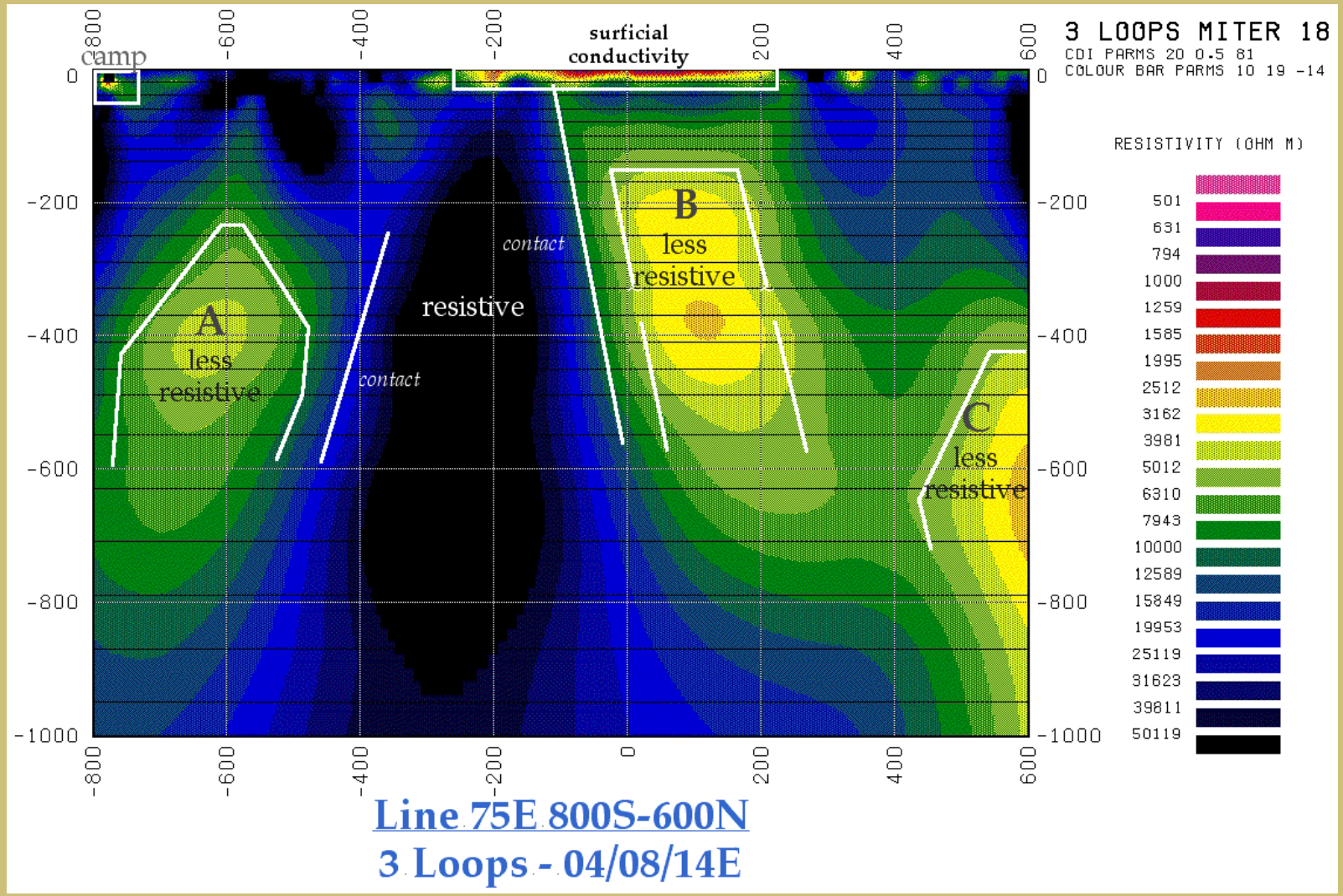


ISR - Sudbury Falconbridge Footwall





ISR – TBN – Ni-Cu-PGM
Thunder Bay North



Line 75E 800S-600N
3 Loops - 04/08/14E