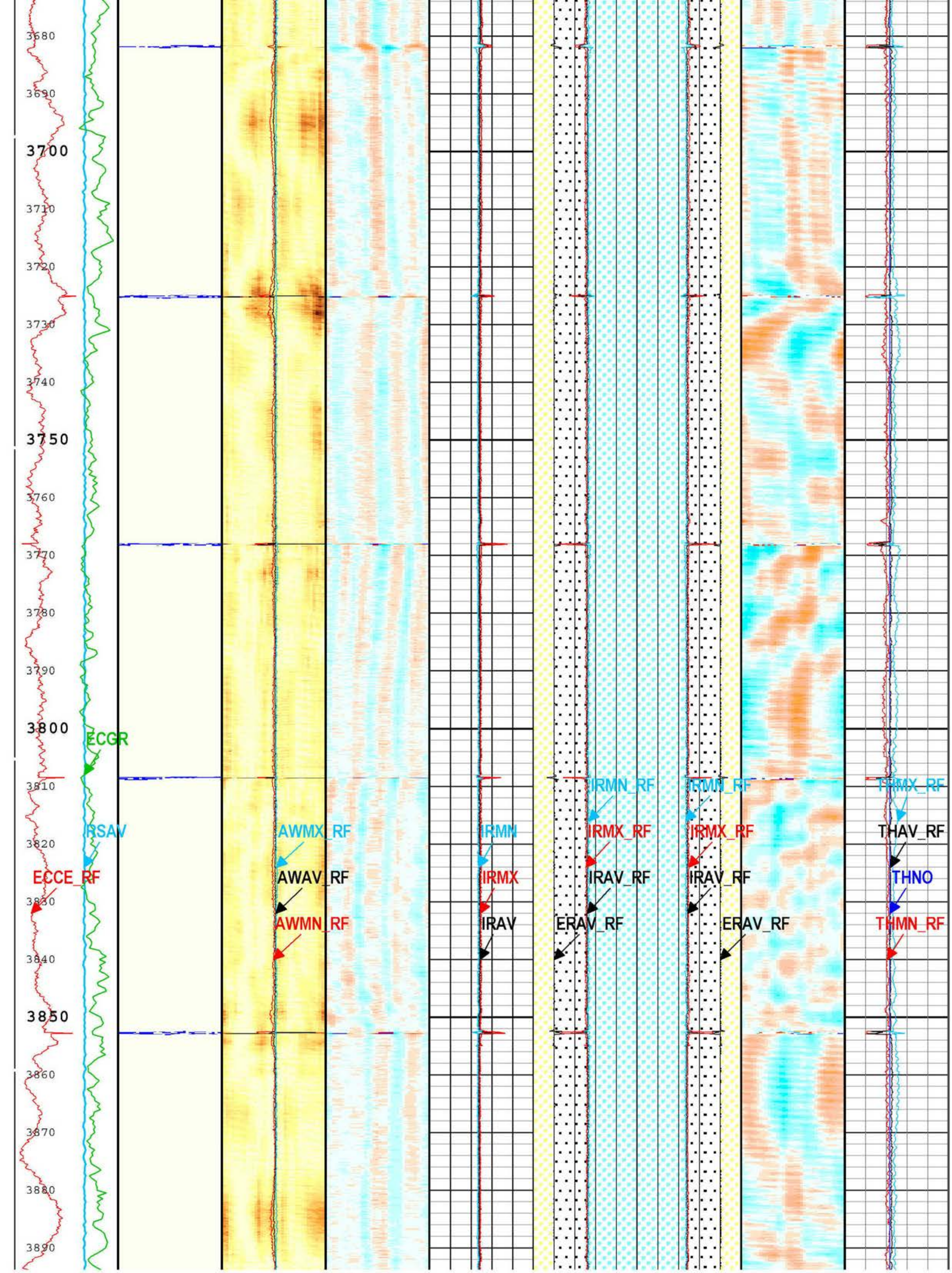
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AWAV_RF
AWMN_RF
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IRAV
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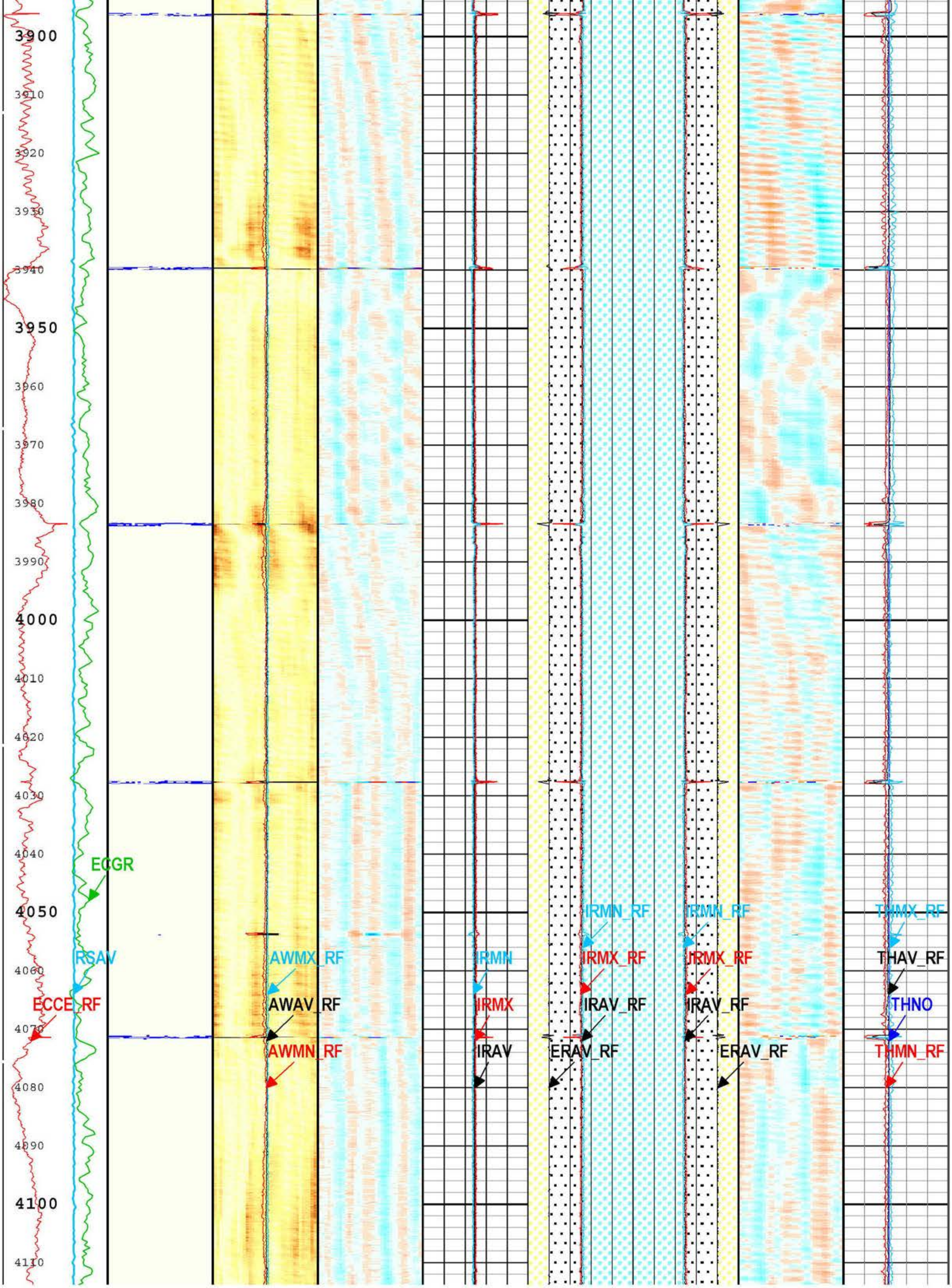
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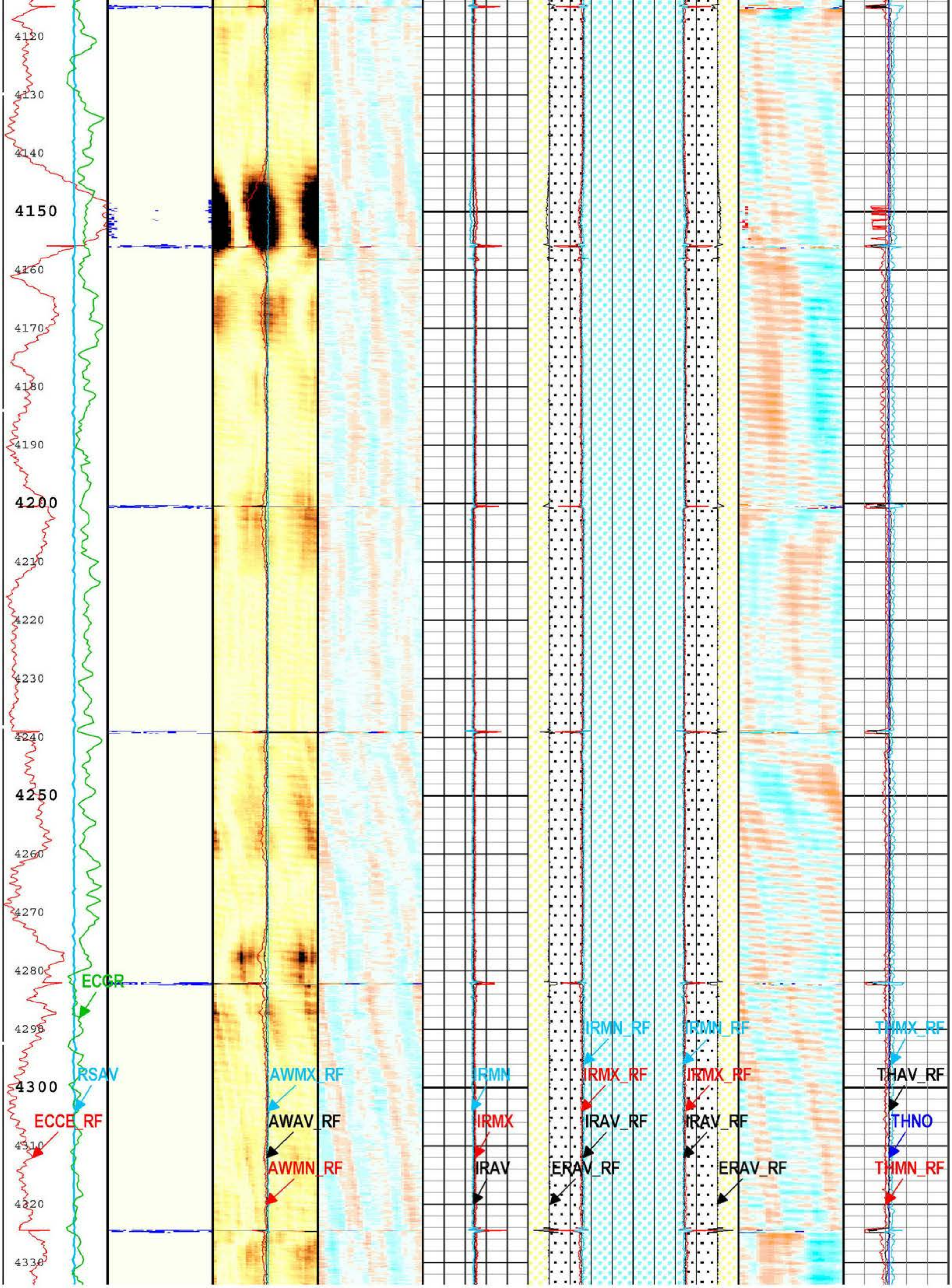
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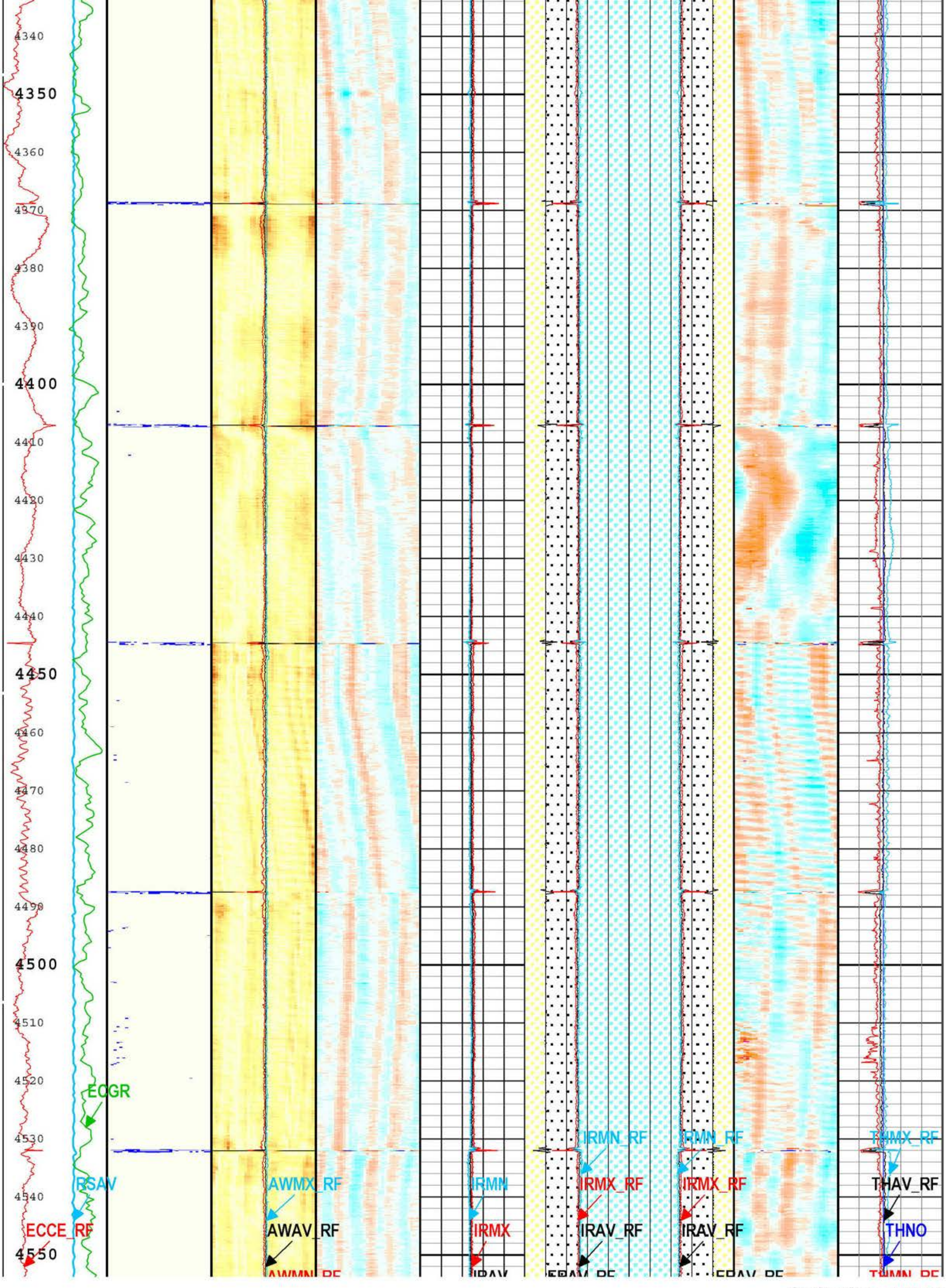
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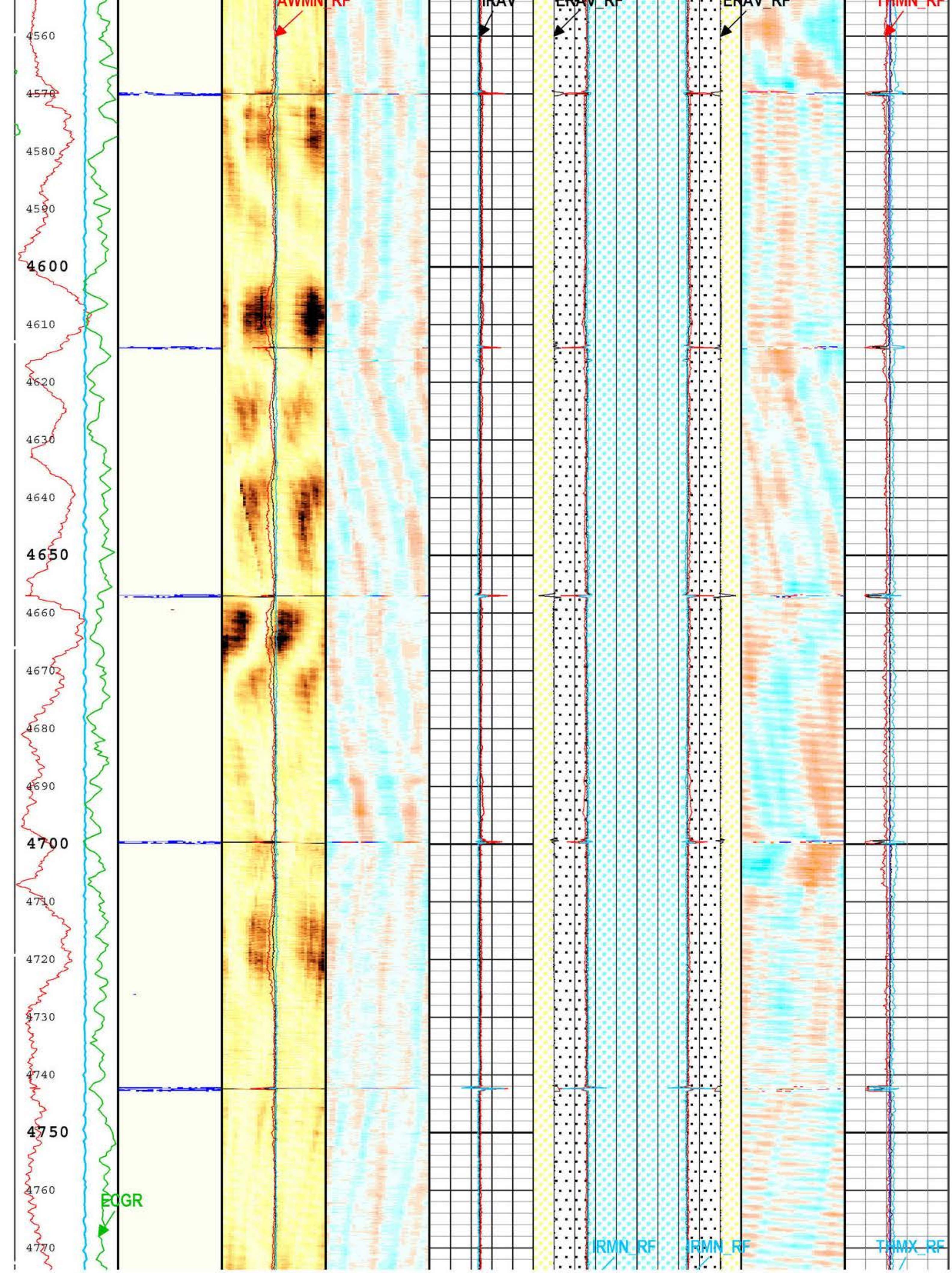
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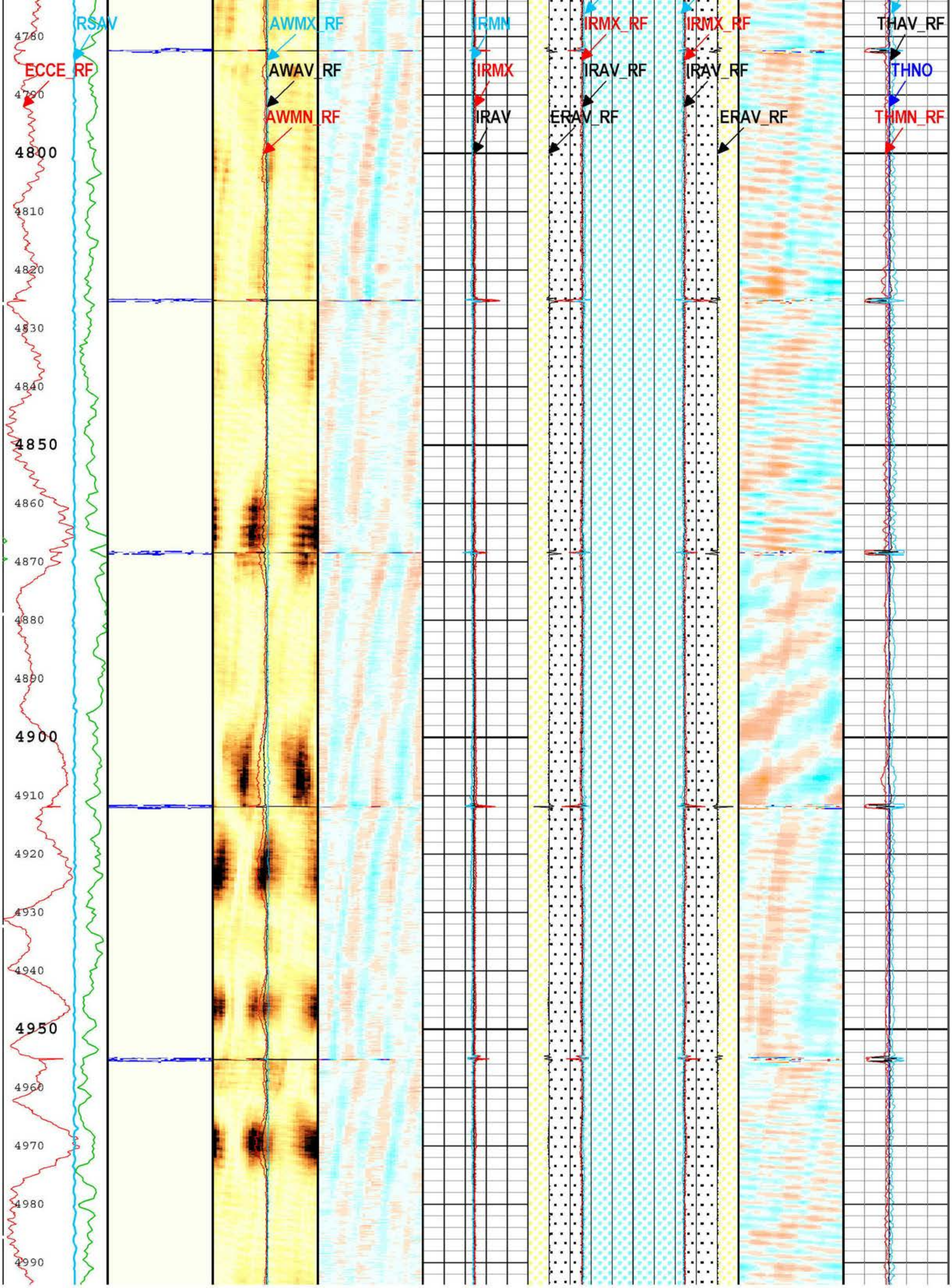
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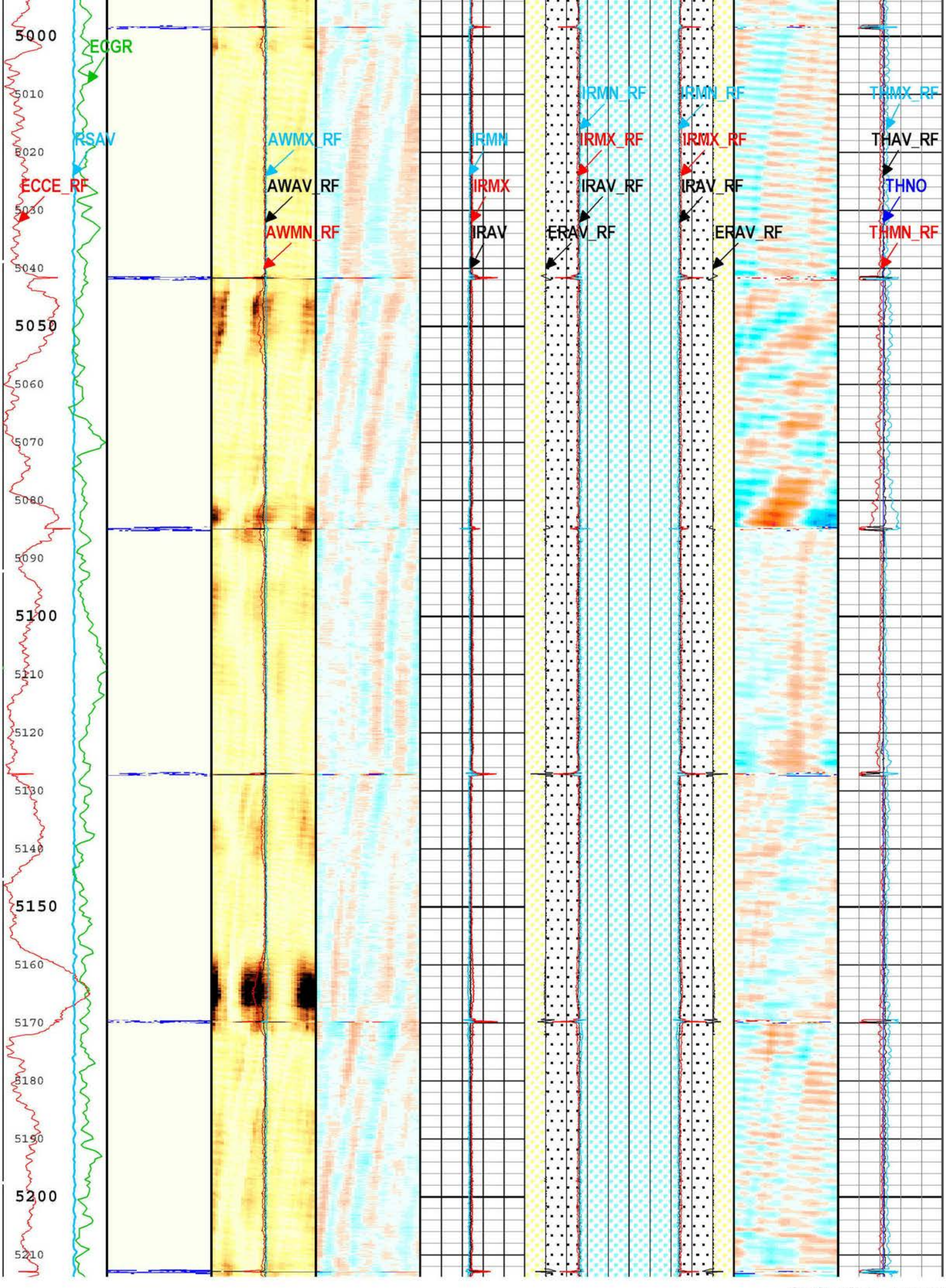
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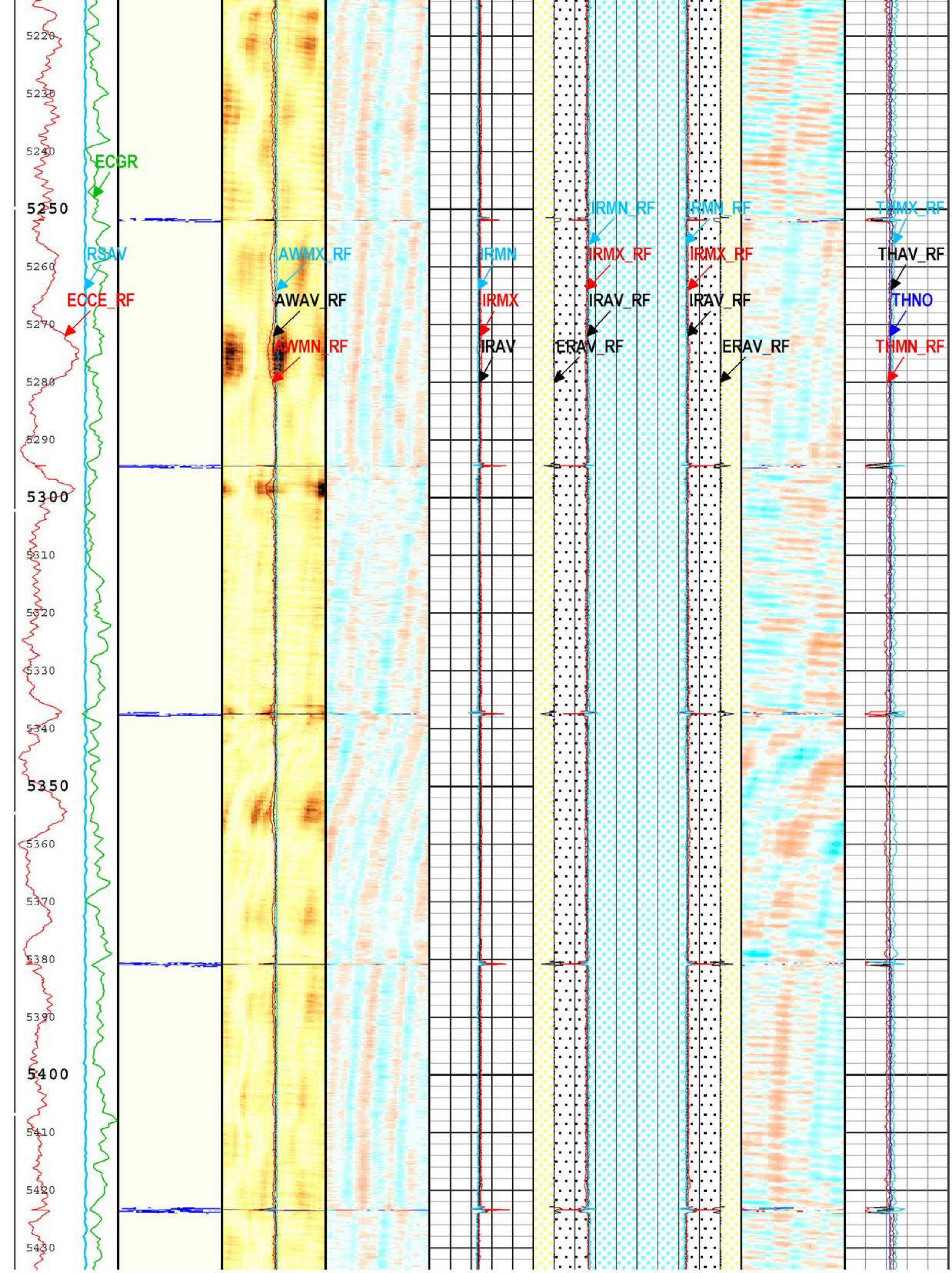
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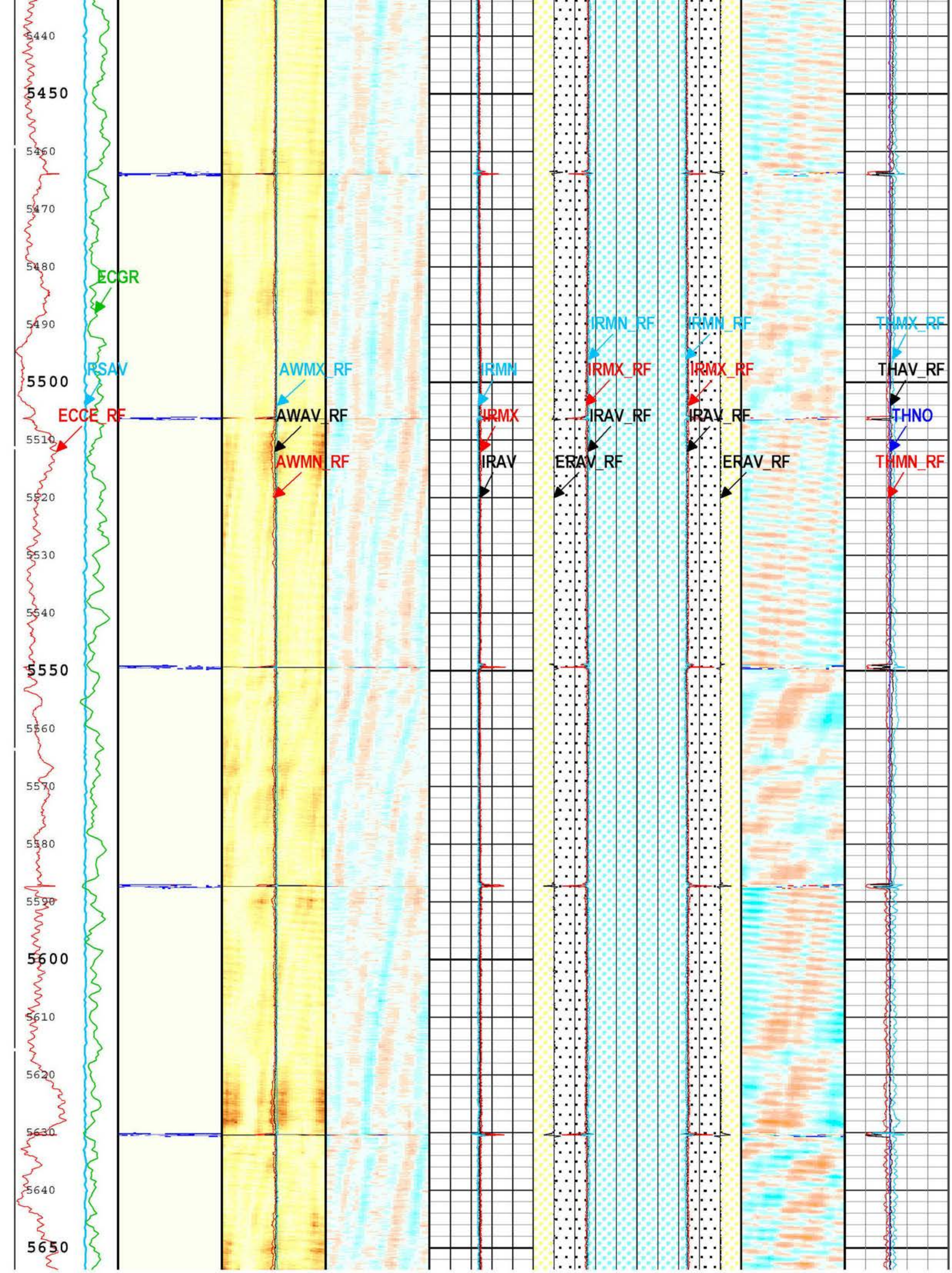
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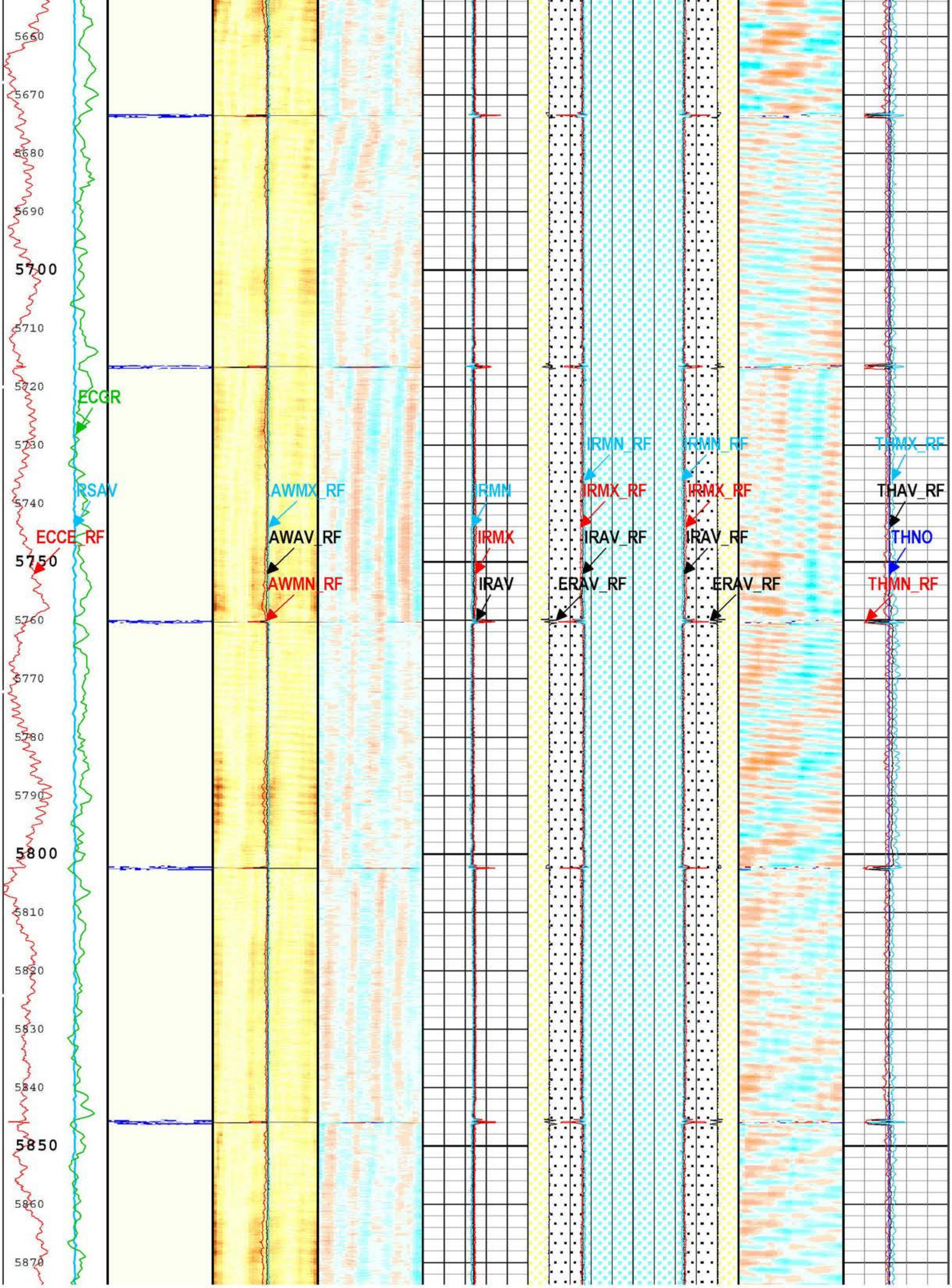
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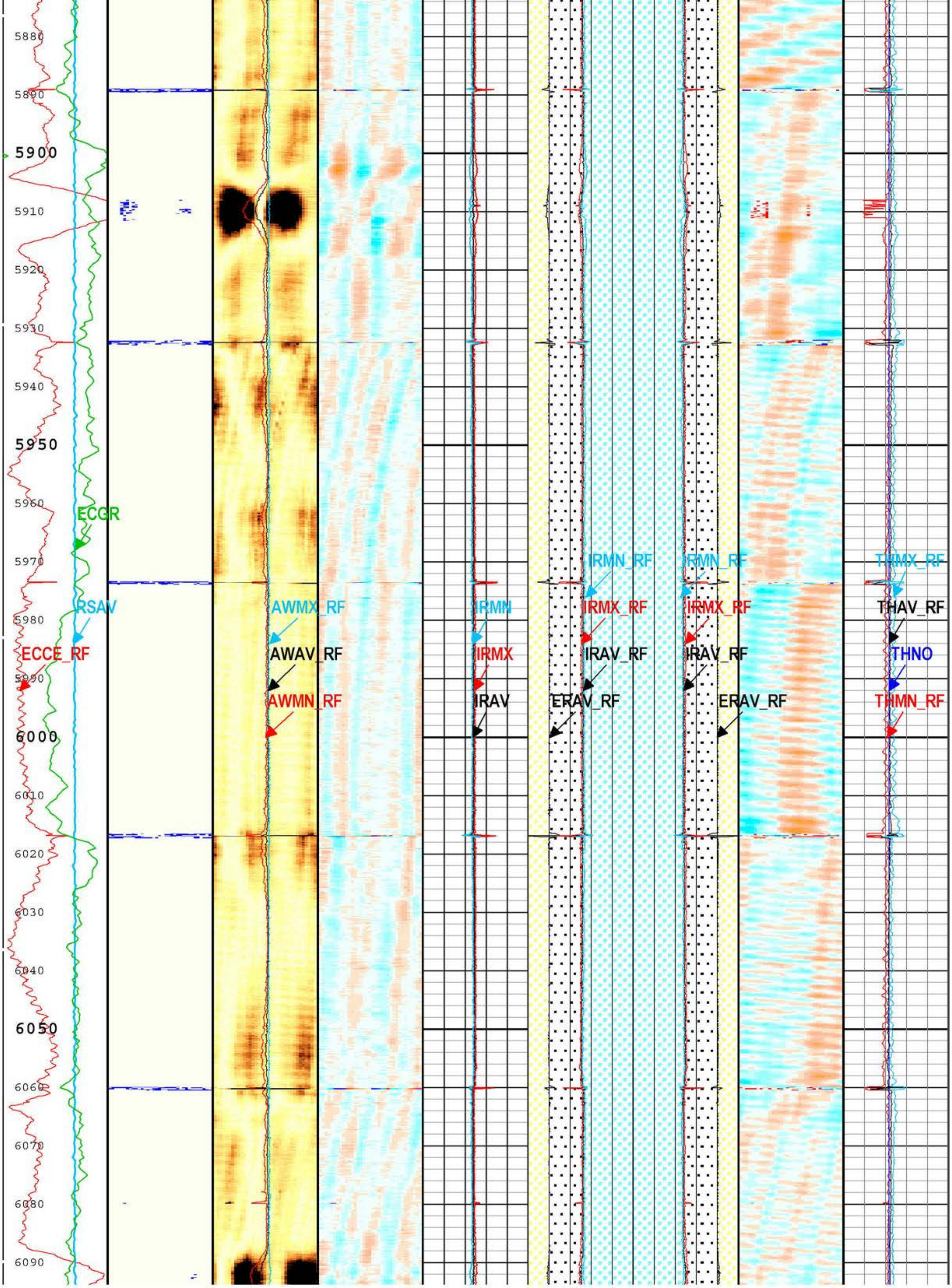
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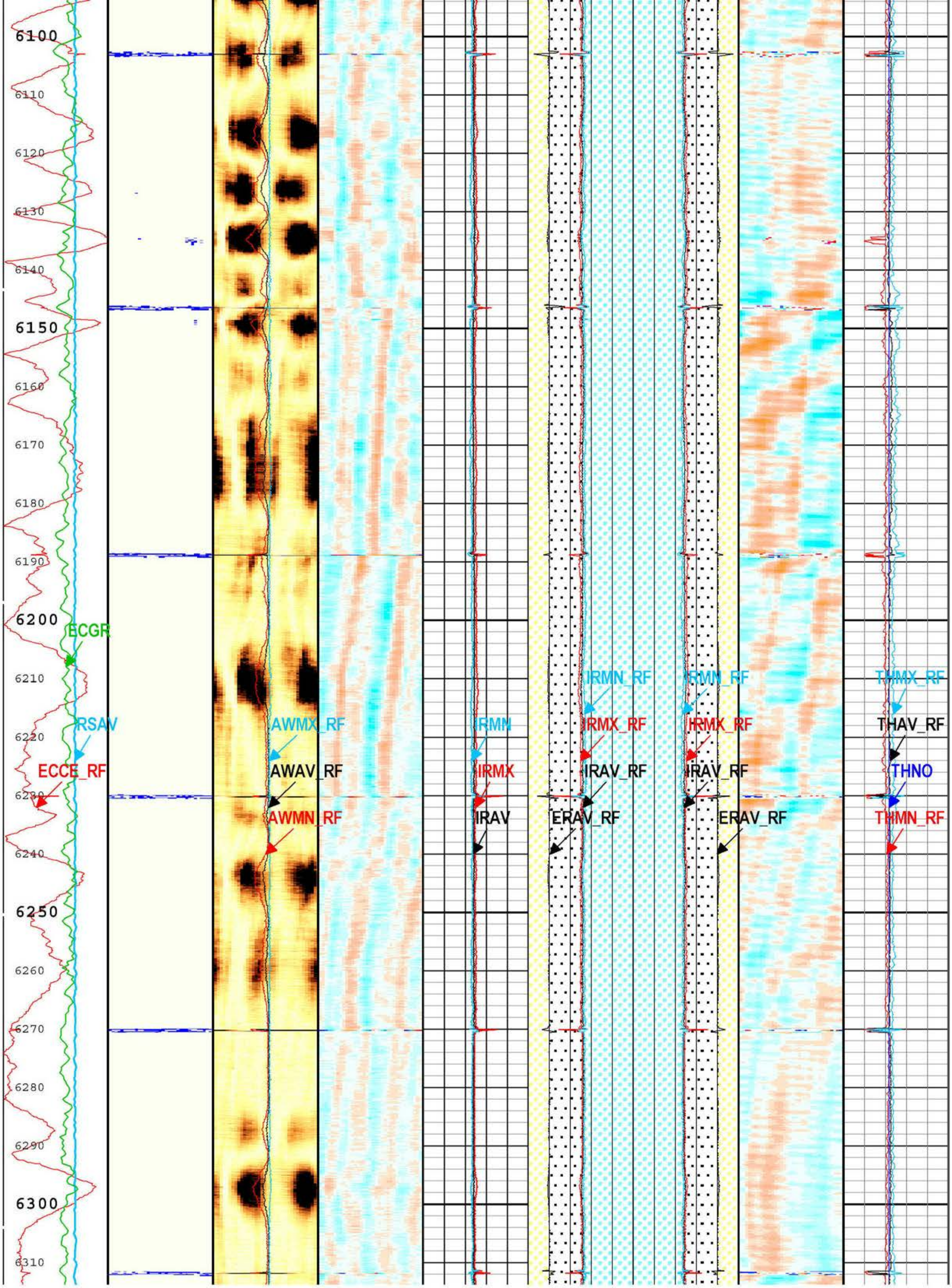
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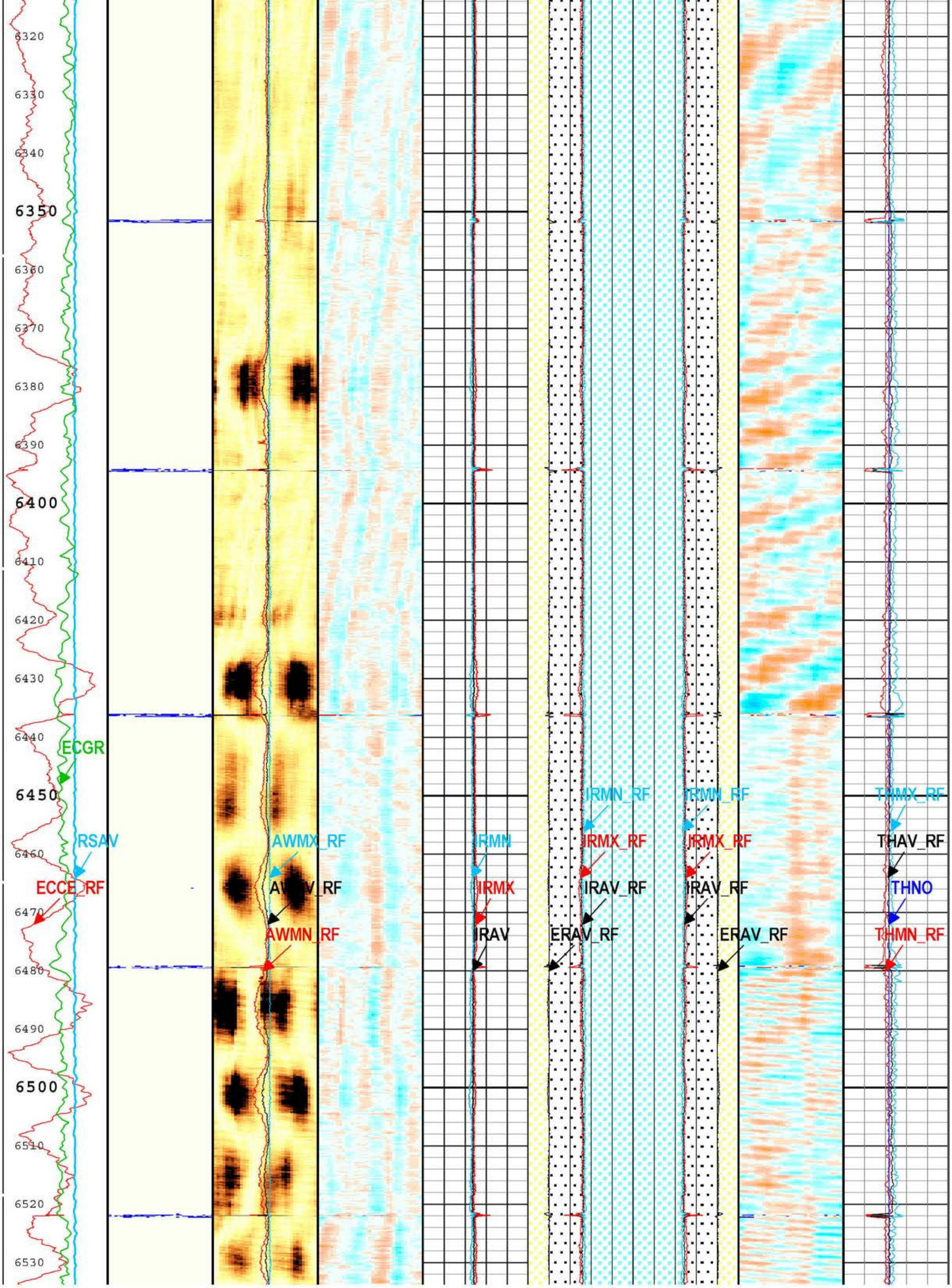
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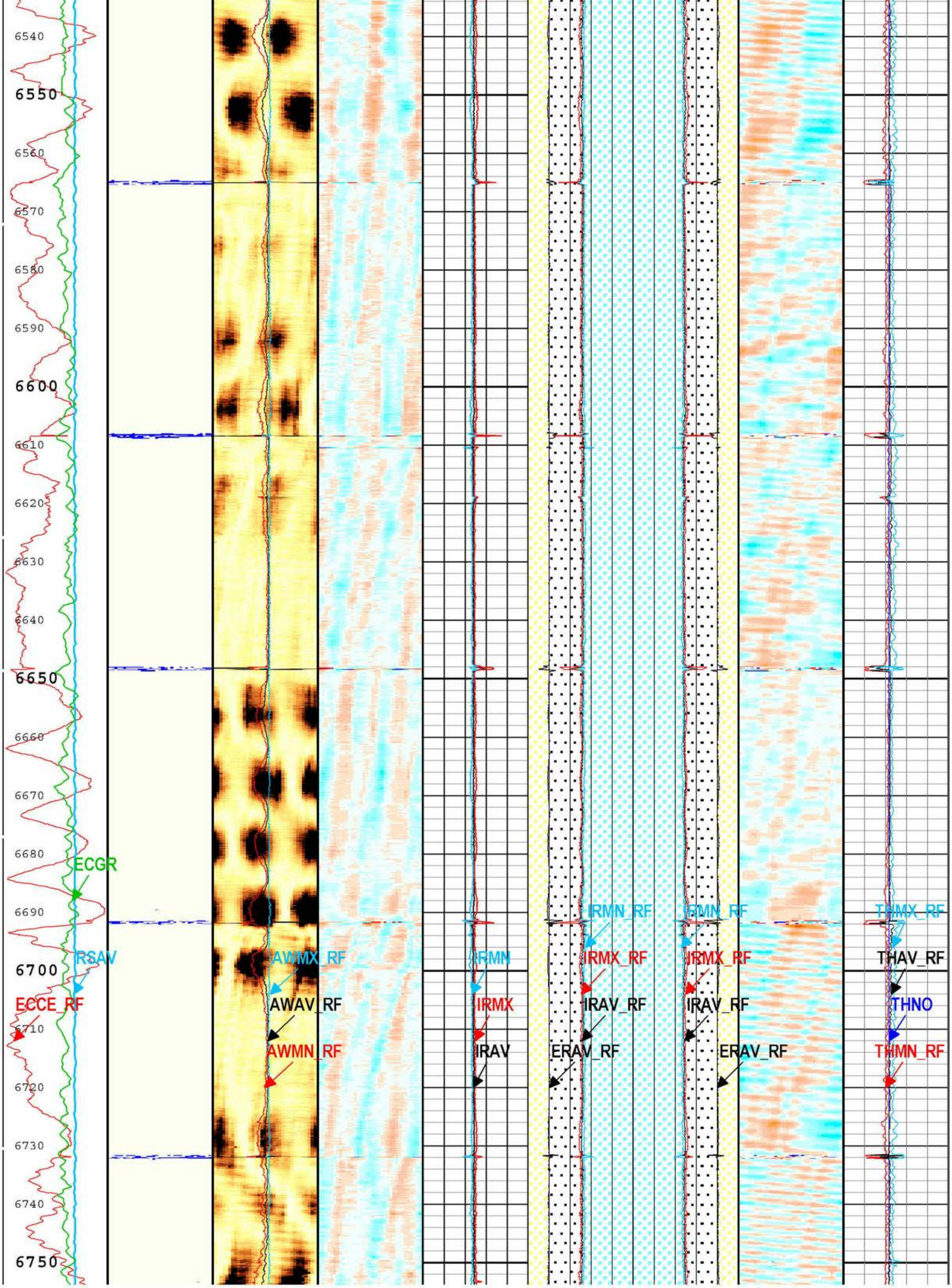
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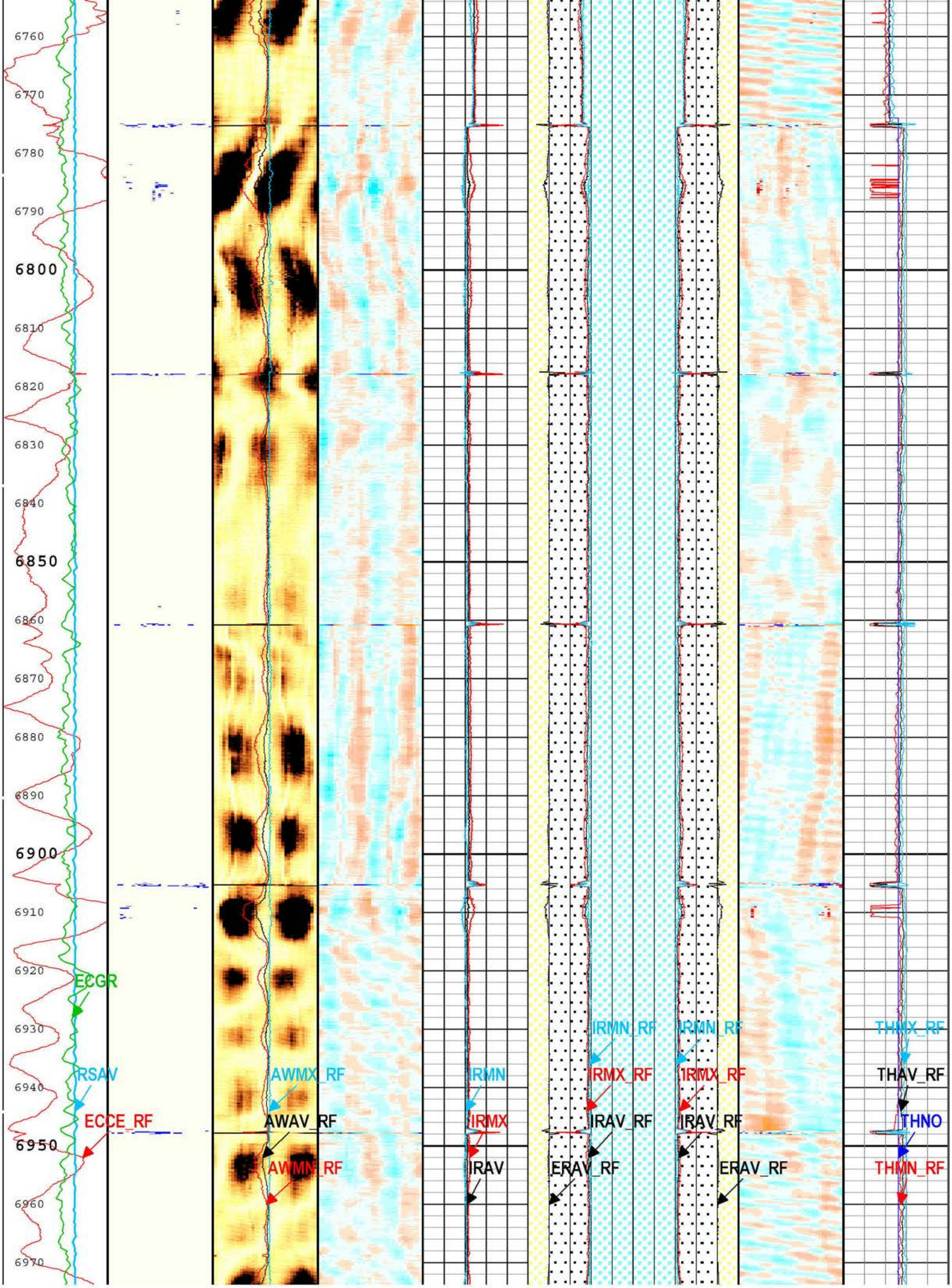
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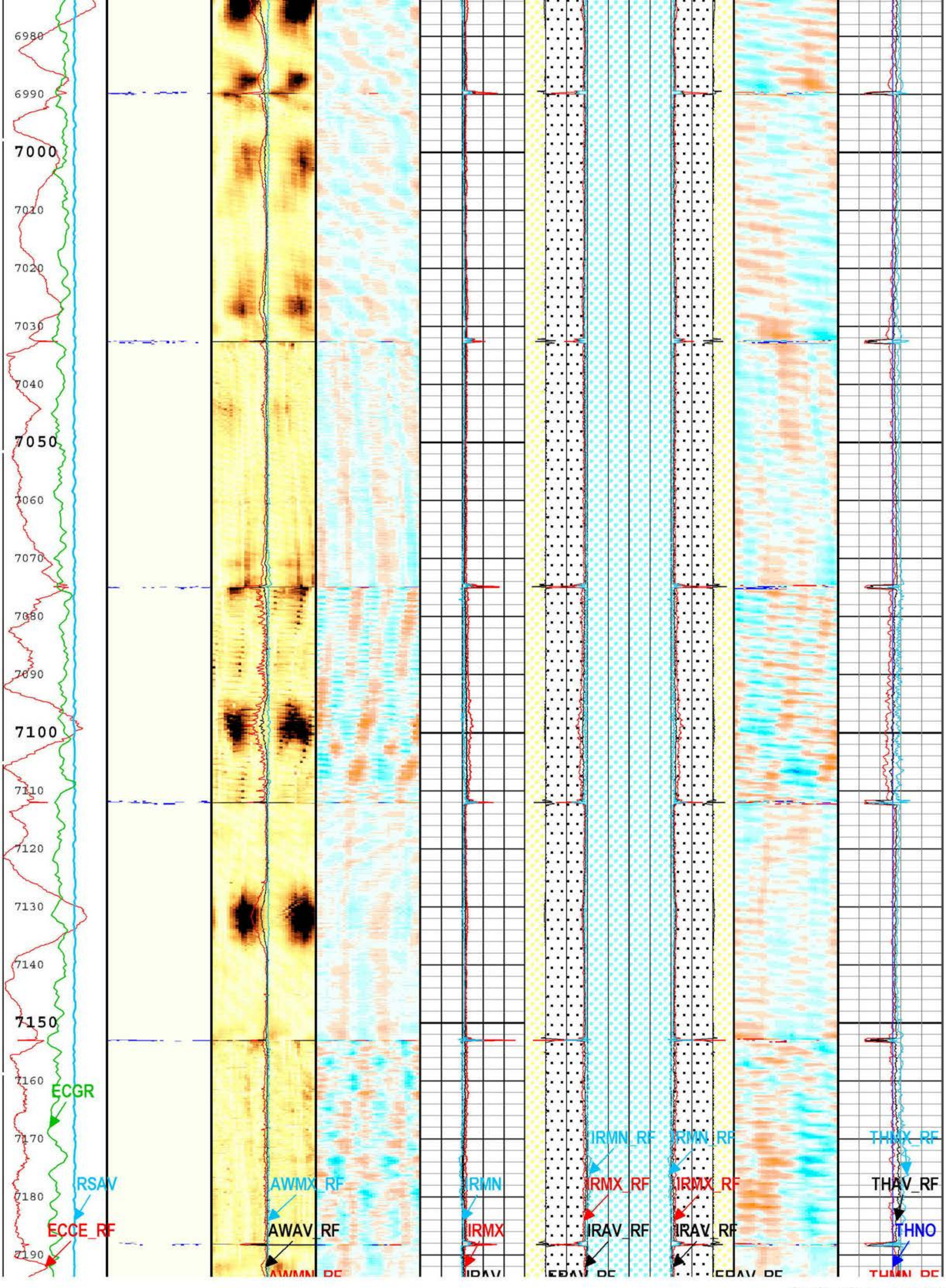
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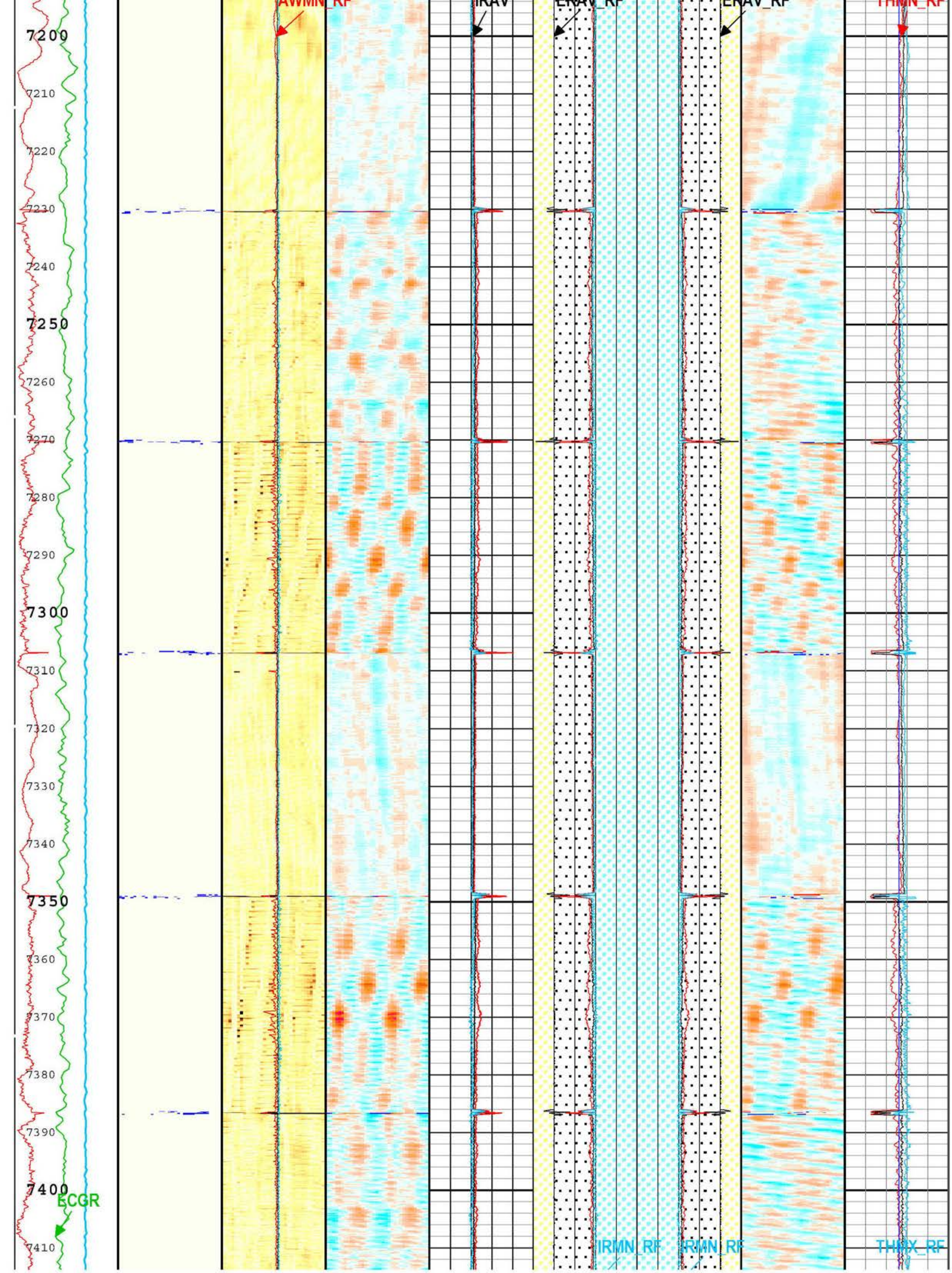
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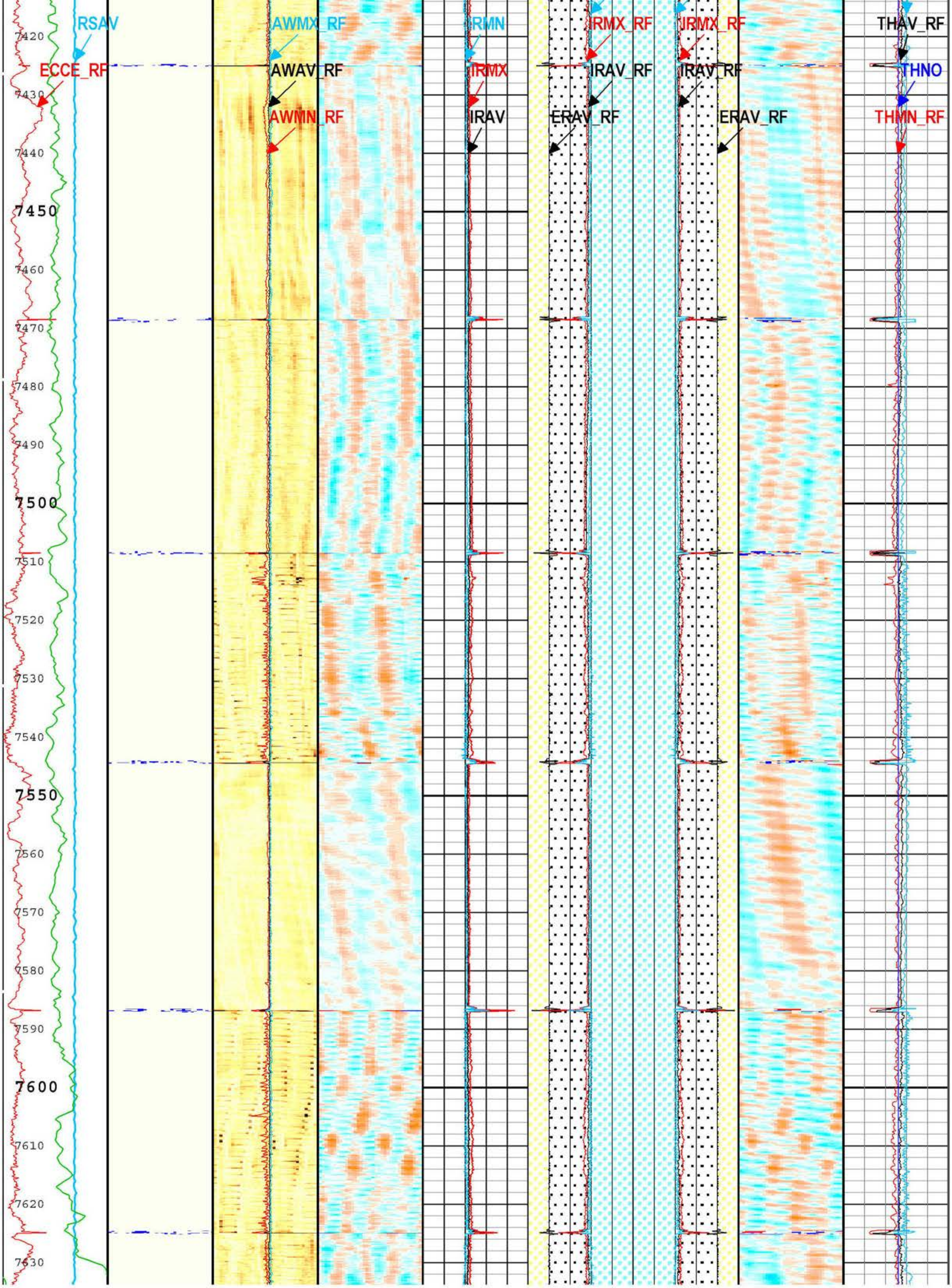
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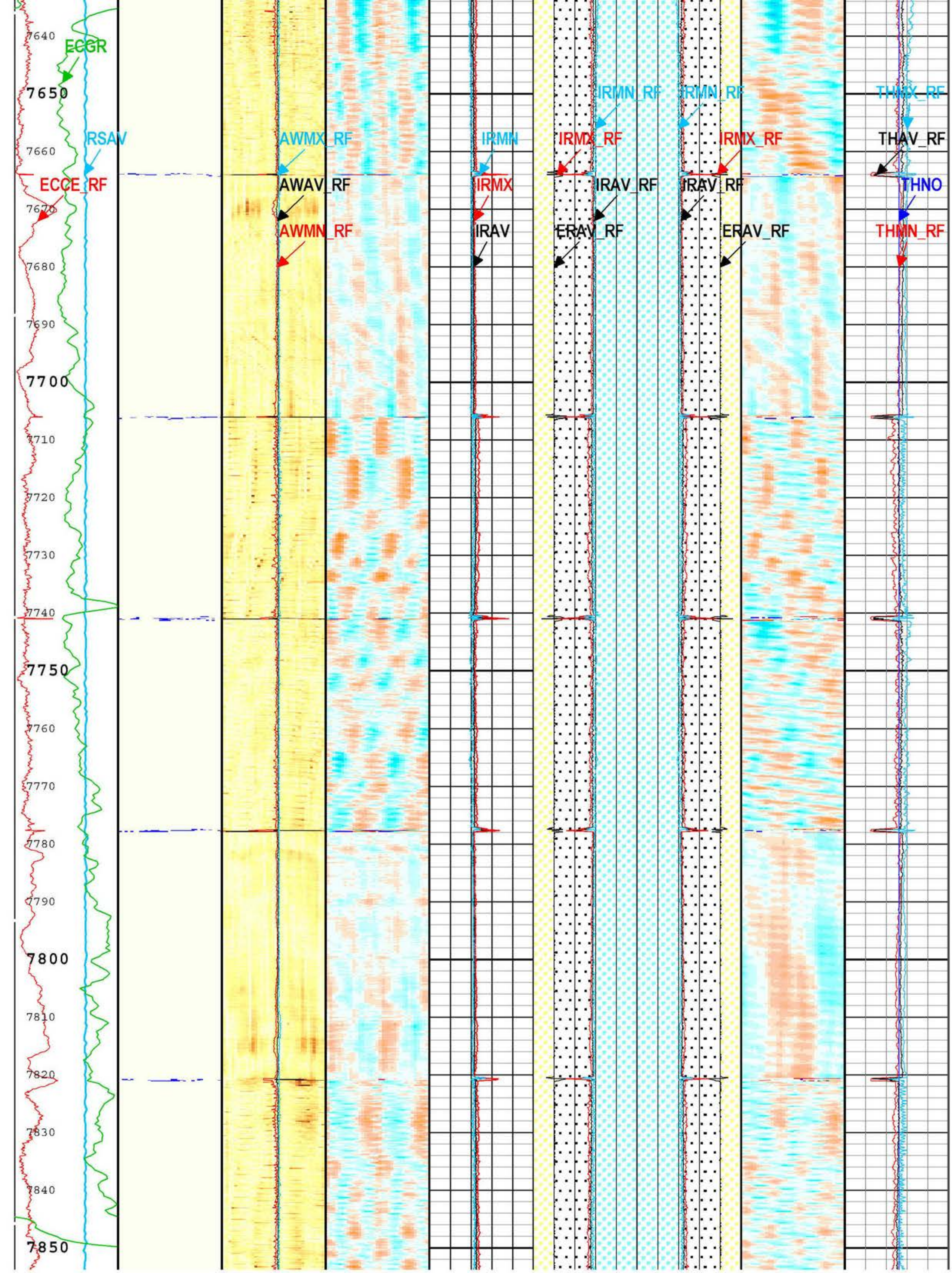
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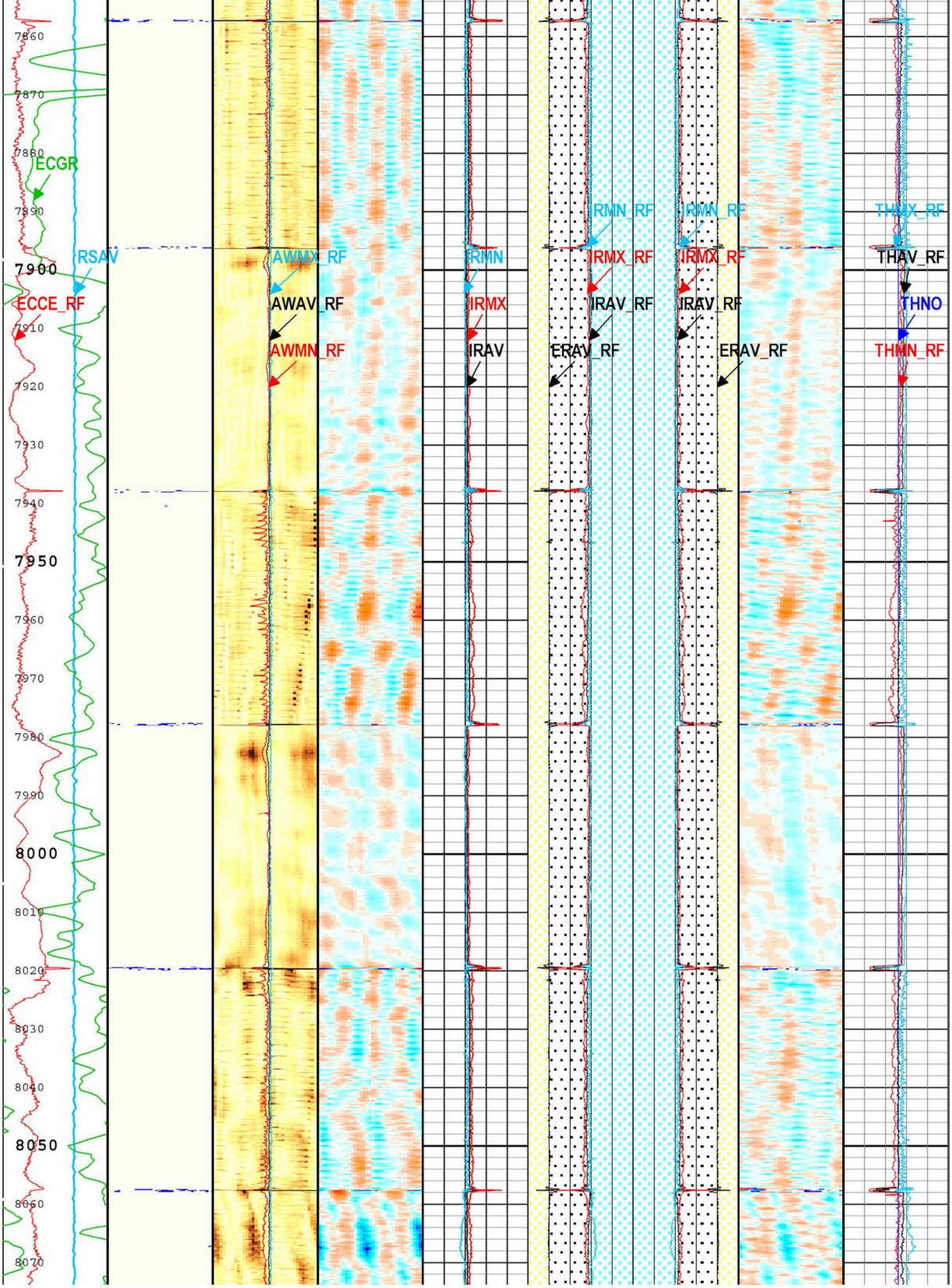
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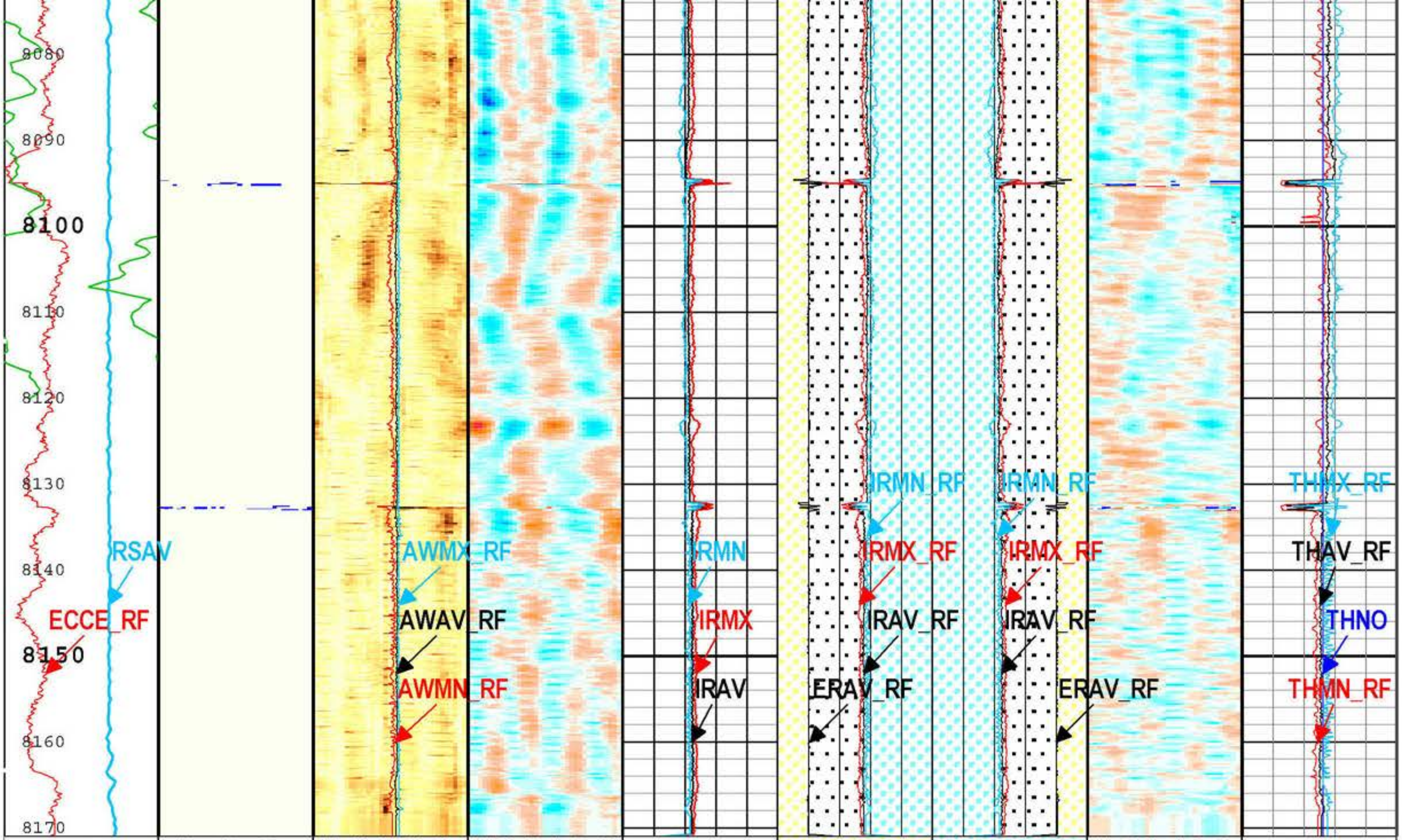


Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5

Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8

Gamma Ray (ECGR) HGNS[1]
0 gAPI 150

Absent 1.500 3.500

Explicit Normalization

USIT - USIT Processing Flags (UFLG) USIT-E[1]

USIT Processing Flags (UFLG[0]) USIT-E[1]
1 5

Absent -5.200 -3.600 -2.000 -0.400

Explicit Normalization

USIT - Amplitude of Unflagged Wave (AWBK_RF) USIT-E[1] (dB)

Minimum of Unflagged Wave Amplitude (AWMN_RF) USIT-E[1]
0 dB 75

Average of Unflagged Wave Amplitude (AWAV_RF) USIT-E[1]
0 dB 75

Maximum of Unflagged Wave Amplitude (AWMX_RF) USIT-E[1]
0 dB 75

Absent -0.059 -0.028 0.004 0.035 0.068

Explicit Normalization

USIT - Unflagged Internal Radii minus Median Internal Radius (IRBKM_RF) USIT-E[1] (in)

Internal Radius Averaged Value (IRAV) USIT-E[1]
2.7 in 3.7

Internal Radius Maximum Value (IRMX) USIT-E[1]
2.7 in 3.7

Internal Radius Minimum Value (IRMN) USIT-E[1]
2.7 in 3.7

ERAV
ERAV-IRAV
IRAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7

IRAV
ERAV
IRAV-ERAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7

Absent -0.059 -0.028 0.004 0.035 0.068

Explicit Normalization

USIT - Unflagged Casing Thickness minus Median of Unflagged Casing Thickness (THBKM_RF) USIT-E[1] (in)

Minimum of Unflagged Casing Thickness (THMN_RF) USIT-E[1]
0.1 in 0.6

Nominal Casing Thickness (THNO) USIT-E[1]
0.1 in 0.6

Median of Unflagged Casing Thickness (THAV_RF) USIT-E[1]
0.1 in 0.6

Maximum of Unflagged Casing Thickness (THMX_RF) USIT-E[1]
0.1 in 0.6

USIT Processing Flags (UFLG[0]) USIT-E[1]

1 - UFLG 1 Value within [0.0 - 1.5] - :	⬛	UTIM Error
2 - UFLG 2 Value within [1.5 - 2.5] - :	🟫	Pulse Origin Not Detected
3 - UFLG 3 Value within [2.5 - 3.5] - :	🟥	WINLEN Error
4 - UFLG 4 UFLG 5 UFLG 6 Value within [3.5 - 6.5] - :	🟦	Casing Thickness Error
5 - UFLG 7 UFLG 8 UFLG 9 Value within [6.5 - 10] - :	■	Loop Processing Error

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Composite Format: Log (LBV1_USI Corrosion 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:48

Composite 1

USI Compressed Goodwin

Composite Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[9]:Up	Up	6640.29 ft	8171.85 ft	20-Oct-2016 9:51:39 AM	20-Oct-2016 10:20:40 AM	ON	1.47 ft	No
Two	Log[11]:Up	Up	36.69 ft	6737.51 ft	20-Oct-2016 10:24:53 AM	20-Oct-2016 12:34:00 PM	ON	1.35 ft	No
Two	Log[14]:Up	Up	5.56 ft	155.15 ft	20-Oct-2016 12:53:24 PM	20-Oct-2016 12:58:23 PM	ON	1.96 ft	No

All depths are referenced to toolstring zero

Log

Company:Southern California Gas Company Well:Frew 4

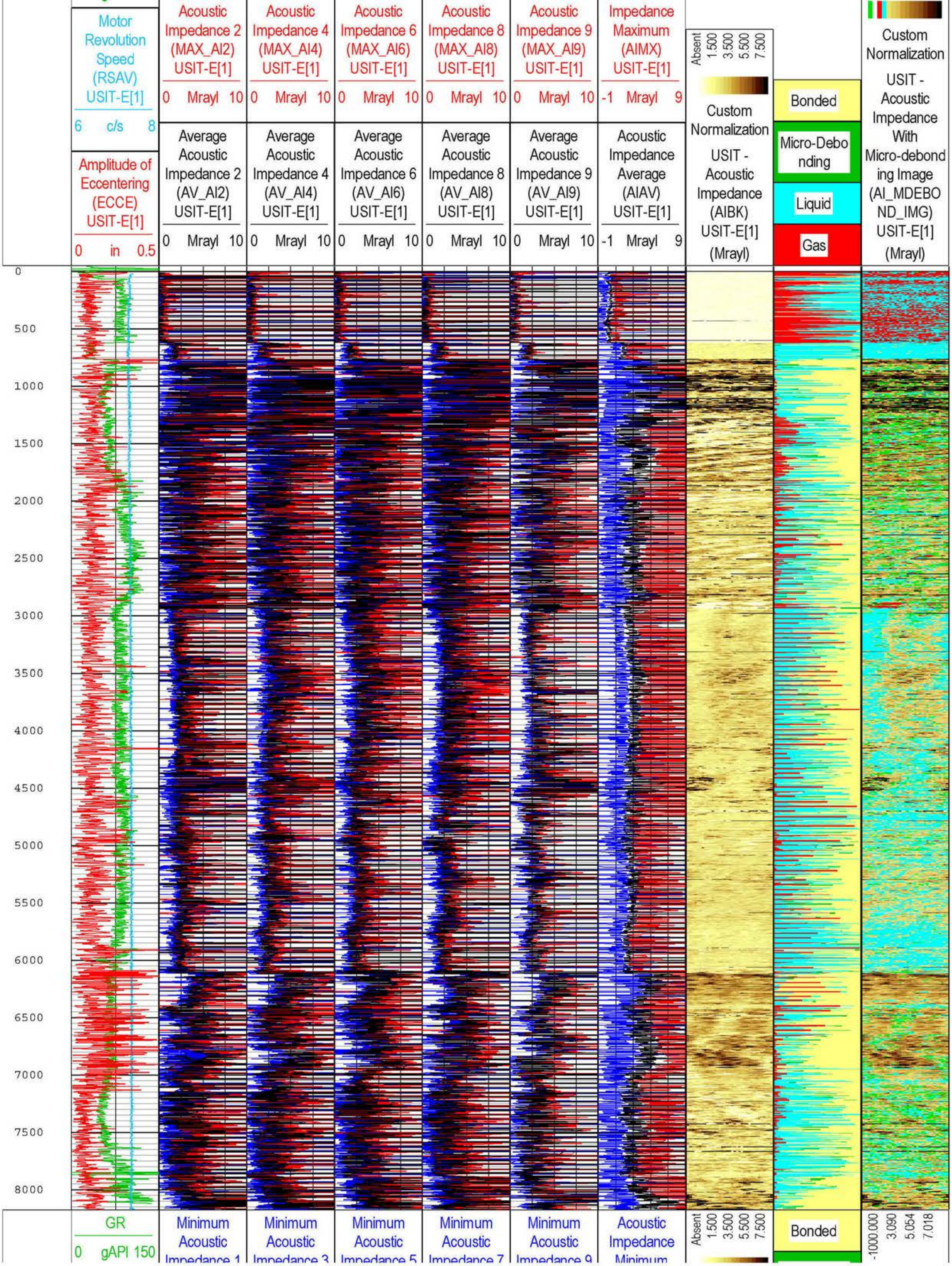
Composite 1:S008

Description: USI Goodwin Format: Log (Import of USI Goodwin) Index Scale: 0.1 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:29:06

TIME_1900 - Time Marked every 60.00 (s)

	Minimum Acoustic Impedance 1 (MIN_AI1) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 3 (MIN_AI3) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 5 (MIN_AI5) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 7 (MIN_AI7) USIT-E[1] 0 Mrayl 10		
	Maximum Acoustic Impedance 1 (MAX_AI1) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 3 (MAX_AI3) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 5 (MAX_AI5) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 7 (MAX_AI7) USIT-E[1] 0 Mrayl 10		
	Average Acoustic Impedance 1 (AV_AI1) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 3 (AV_AI3) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 5 (AV_AI5) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 7 (AV_AI7) USIT-E[1] 0 Mrayl 10		
GR 0 gAPI 150	Minimum Acoustic Impedance 2 (MIN_AI2) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 4 (MIN_AI4) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 6 (MIN_AI6) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 8 (MIN_AI8) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 9 (MIN_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Minimum (AIMN) USIT-E[1] -1 Mrayl 9
	Maximum	Maximum	Maximum	Maximum	Maximum	Acoustic

-1000.000 3.090 5.054 7.018


Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8
Amplitude of Eccentering (ECCE) USIT-E[1]
0 in 0.5
Acoustic Impedance 2 (MAX_AI2) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 2 (AV_AI2) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 4 (MAX_AI4) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 4 (AV_AI4) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 6 (MAX_AI6) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 6 (AV_AI6) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 8 (MAX_AI8) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 8 (AV_AI8) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 9 (MAX_AI9) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 9 (AV_AI9) USIT-E[1]
0 Mrayl 10
Impedance Maximum (AIMX) USIT-E[1]
-1 Mrayl 9
Acoustic Impedance Average (AIAV) USIT-E[1]
-1 Mrayl 9
Absent 1.500 3.500 5.500 7.500
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)
Bonded
Micro-Debonding
Liquid
Gas
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
GR
0 gAPI 150
Minimum Acoustic Impedance 1
Minimum Acoustic Impedance 3
Minimum Acoustic Impedance 5
Minimum Acoustic Impedance 7
Minimum Acoustic Impedance 9
Acoustic Impedance Minimum
Absent 1.500 3.500 5.500 7.500
Bonded
-1000.000 3.090 5.054 7.018

Motor Revolution Speed (RSAV) USIT-E[1] 6 c/s 8	Impedance 1 (MIN_AI1) USIT-E[1] 0 Mrayl 10	Impedance 3 (MIN_AI3) USIT-E[1] 0 Mrayl 10	Impedance 5 (MIN_AI5) USIT-E[1] 0 Mrayl 10	Impedance 7 (MIN_AI7) USIT-E[1] 0 Mrayl 10	Impedance 9 (MIN_AI9) USIT-E[1] 0 Mrayl 10	Minimum (AIMN) USIT-E[1] -1 Mrayl 9	Custom Normalization USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)	Micro-Debonding Liquid Gas	Custom Normalization USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)
Amplitude of Eccentering (ECCE) USIT-E[1] 0 in 0.5	Maximum Acoustic Impedance 1 (MAX_AI1) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 3 (MAX_AI3) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 5 (MAX_AI5) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 7 (MAX_AI7) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 9 (MAX_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Maximum (AIMX) USIT-E[1] -1 Mrayl 9			
	Average Acoustic Impedance 1 (AV_AI1) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 3 (AV_AI3) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 5 (AV_AI5) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 7 (AV_AI7) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 9 (AV_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Average (AIAV) USIT-E[1] -1 Mrayl 9			
	Minimum Acoustic Impedance 2 (MIN_AI2) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 4 (MIN_AI4) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 6 (MIN_AI6) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 8 (MIN_AI8) USIT-E[1] 0 Mrayl 10					
	Maximum Acoustic Impedance 2 (MAX_AI2) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 4 (MAX_AI4) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 6 (MAX_AI6) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 8 (MAX_AI8) USIT-E[1] 0 Mrayl 10					
	Average Acoustic Impedance 2 (AV_AI2) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 4 (AV_AI4) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 6 (AV_AI6) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 8 (AV_AI8) USIT-E[1] 0 Mrayl 10					

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Goodwin Format: Log (Import of USI Goodwin) Index Scale: 0.1 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:29:06

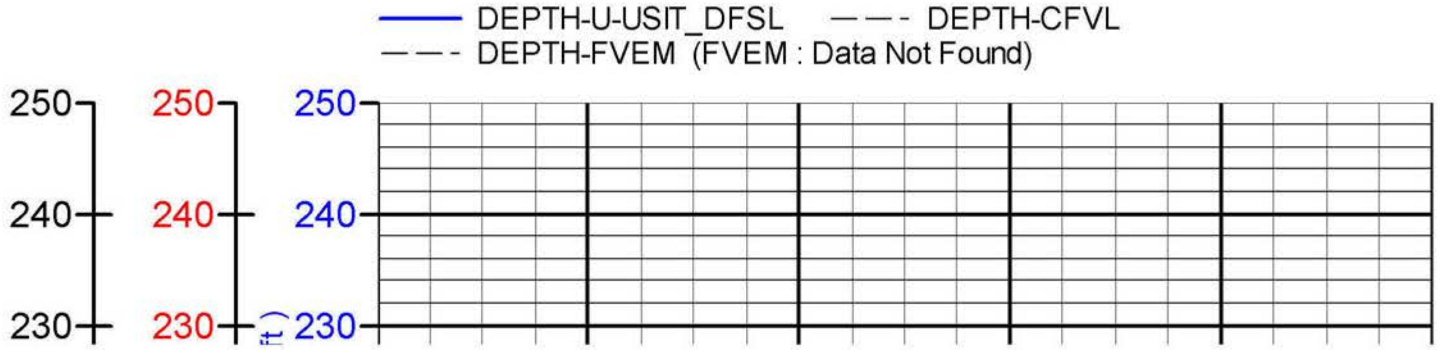
XYZ

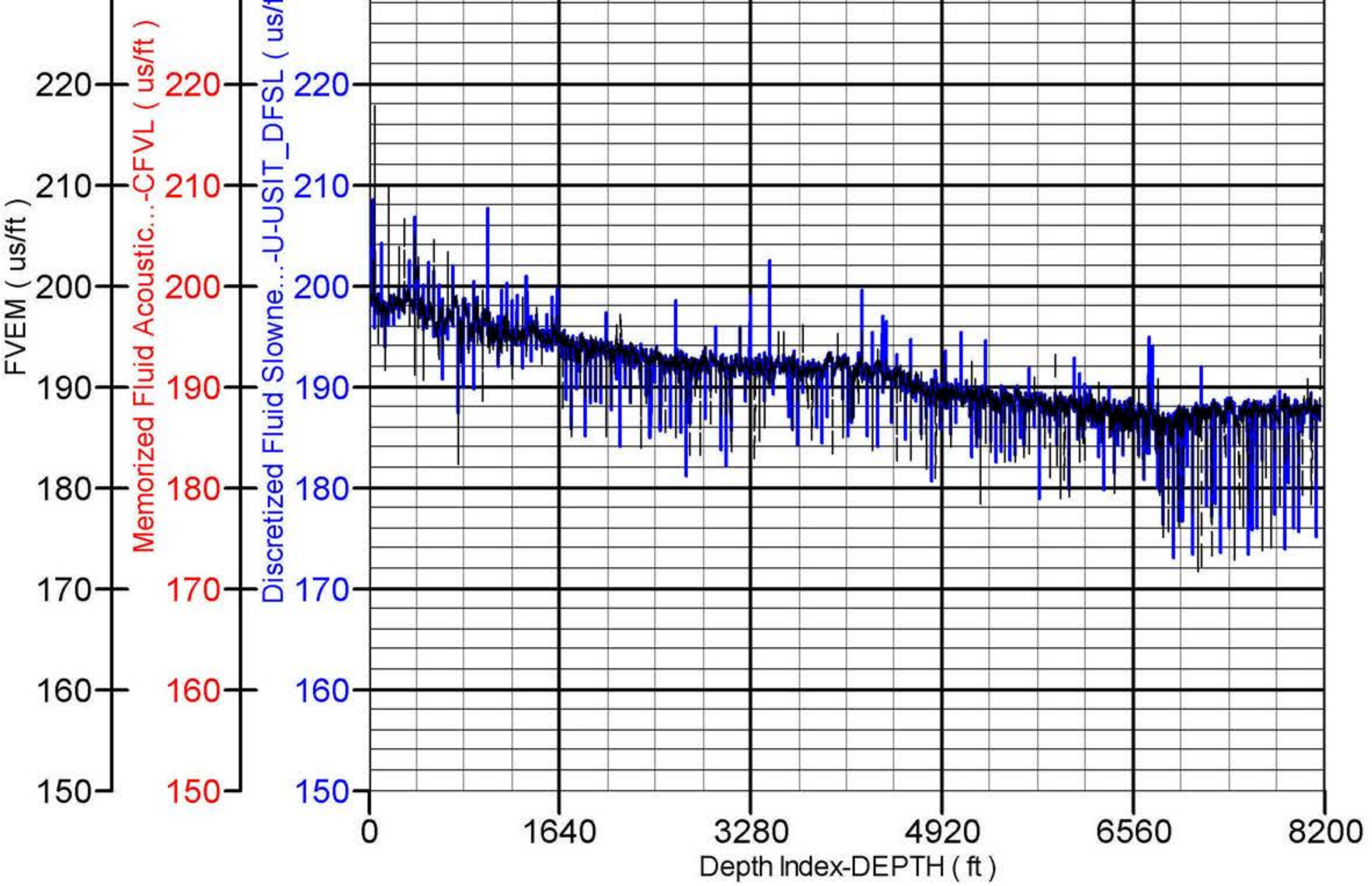
Company:Southern California Gas Company Well:Frew 4
Composite 1:S008

Fluid Acoustic Slowness vs Depth

2D Cross Plot

Index Range: From 5.25 to 8171.50 ft





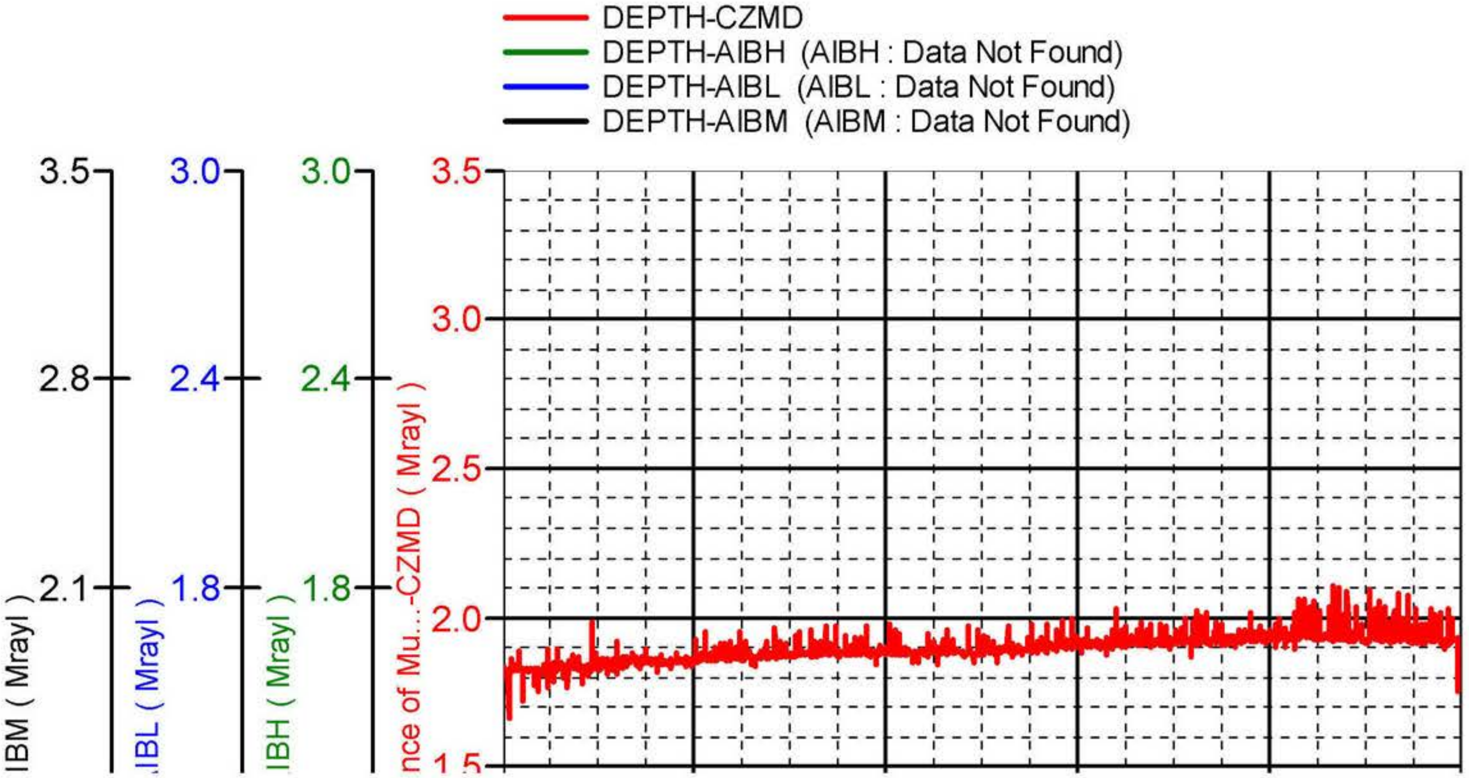
XYZ

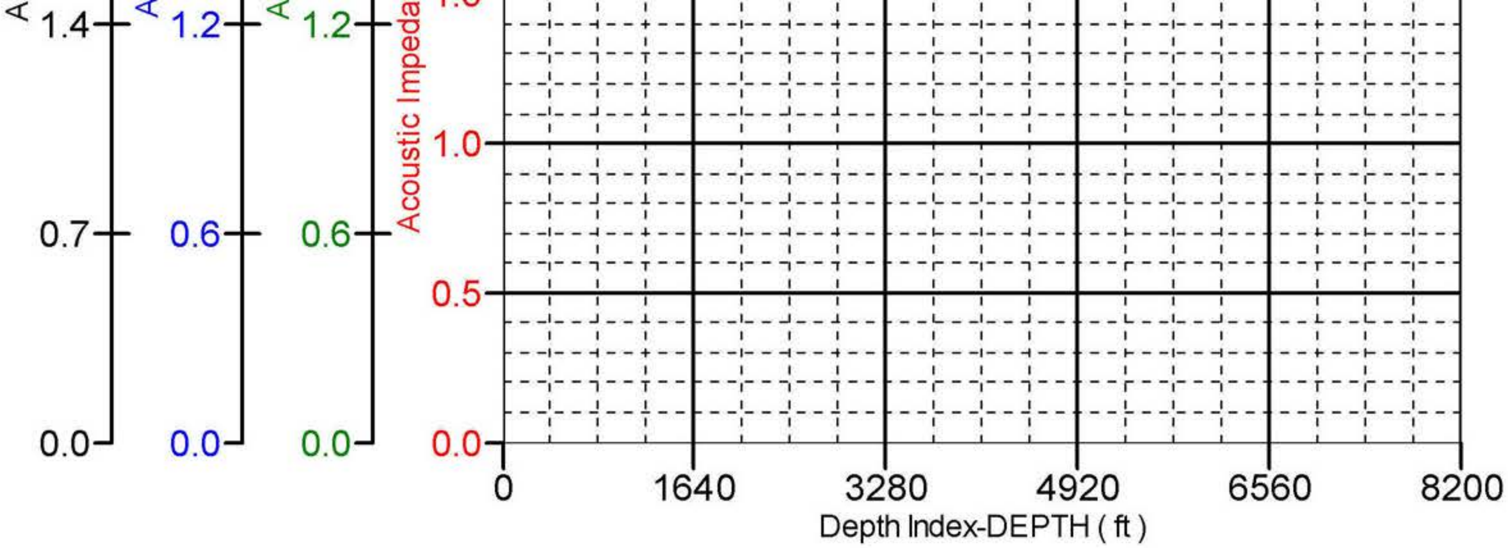
Company:Southern California Gas Company Well:Frew 4
Composite 1:S008

Theoretical Acoustic Impedance of Mud vs Depth

2D Cross Plot

Index Range: From 5.25 to 8171.50 ft





Company:	Southern California Gas Company	Schlumberger
Well:	Frew 4	
Field:	Aliso Canyon	
County:	Los Angeles	
State:	California	

Ultrasonic Imager

Ultrasonic Imager

Gamma Ray - CCL

7" casing

Ex. II - 23

Due to the large file size, please view document DOGGR_03700667_Vertilog_9-6-1988 at the below publicly available website. The native file of this document is available upon request.

(https://secure.conservation.ca.gov/WellRecord/037/03700667/03700667%20Vertilog_9-6-88.pdf) (accessed March 20, 2020)

VERTILOG®

Dresser Atlas DRESSER

CUSTOMER SOUTHERN CALIFORNIA GAS COMPANY DATE 9-6-88

WELL FREW No. 4 SERVICE ORDER NO. 124201

FIELD ALISO CANYON COUNTY LOS ANGELES STATE CALIFORNIA

CASING SIZE 7" WEIGHT(S) 23#, 26# GRADE N-80, J-55 NOMINAL WALL THICKNESS

TOTAL FOOTAGE INSPECTED 8180' FROM SURFACE TO 8180' DEPTH

SUBSURFACE CASING INSPECTION REPORT

SUMMARY

172	LENGTHS WERE FOUND TO SHOW NO EVIDENCE OF CORROSION EXCEEDING 20 PERCENT OF THE NOMINAL BODY WALL.	20	CLASS 1
12	LENGTHS WERE FOUND TO SHOW EVIDENCE OF CORROSION EXCEEDING 20 PERCENT BUT LESS THAN 41 PERCENT OF THE NOMINAL BODY WALL.	20	CLASS 2
12	LENGTHS WERE FOUND TO SHOW EVIDENCE OF CORROSION EXCEEDING 40 PERCENT BUT LESS THAN 61 PERCENT OF THE NOMINAL BODY WALL.	40	CLASS 3
2	LENGTHS WERE FOUND TO SHOW EVIDENCE OF CORROSION EXCEEDING 60 PERCENT OF THE NOMINAL BODY WALL.	60	CLASS 4
198	TOTAL LENGTHS		
8180'	TOTAL FOOTAGE		

REFERENCE FOR FOOTAGE MEASURE GROUND LEVEL + 8.25'

LENGTHS ARE NUMBERED FROM SURFACE

COMMENTS

CHART # 7N20E
CHART # 7N1E
CHART # 7J6E

SERVICED BY

DA-1363-C (08/82)

VERTILOG®

Western Atlas International
A Litton/Dresser Company

PAGE________ OF________

CUSTOMER	SOUTHERN CALIFORNIA GAS COMPANY	**WORK ORDER NO.**	124201	**DATE**	9-6-88
LEASE/WELL NO.	FREW No. 4	**CUSTOMER ORDER NO.**			
FIELD	ALISO CANYON	**COUNTY**	LOS ANGELES	**STATE**	CALIFORNIA
CASING O.D.	7"	**WEIGHT(S)**	23#, 26#	**NOMINAL WALL THICKNESS**	**GRADE** N-80, J-55
TOTAL FOOTAGE INSPECTED	8180'	**FROM**	SURFACE	**TO**	8180' **DEPTH**

SUBSURFACE CASING DEFECT REPORT

LENGTH NO.	TYPE DEFECT	PENETRATION
INSIDE 13-3/8" CASING		
7	OD IP	21 - 40
13	OD IP	21 - 40
20	OD IP	41 - 60
21	OD IP	41 - 60
OUTSIDE 13-3/8" CASING		
23	OD IP	41 - 60
25	OD IP	21 - 40
26	OD IP	21 - 40
27	OD IP	41 - 60
28	OD IP	41 - 60
29	OD GC	21 - 40
30	OD IP	21 - 40
31	OD IP	21 - 40
32	OD IP	41 - 60
47	OD IP	21 - 40
49	OD IP	21 - 40
56	OD IP	21 - 40
61	OD IP	21 - 40
72	OD IP	61 - 80
83	OD IP	21 - 40
106	OD IP	41 - 60
107	OD IP	41 - 60
108	OD IP	41 - 60
109	OD IP	61 - 80
111	OD IP	41 - 60
113	OD IP	41 - 60
114	OD IP	41 - 60

ABBREVIATIONS:

O.D. – OUTSIDE DIAMETER
I.D. – INSIDE DIAMETER
I.S. – INSIDE SURFACE PIPE
T.L. – THROUGHOUT LENGTH
I.P. – ISOLATED PITTING
C.C. – CIRCUMFERENTIAL CORROSION
G.C.-GENERAL CORROSION

WA-1364-C (10/87)

Ex. II - 24

Schlumberger

Company: Southern California Gas Company
Well: Frew 4
Field: Aliso Canyon
County: Los Angeles State: California

Ultrasonic Imager
Gamma Ray - CCL
7" casing

Location:

Elev.: K.B. 2428.00 ft
G.L. 2419.75 ft
D.F.

Permanent Datum: Ground Level Elev.: 2419.75 f
Log Measured From: Kelly Bushing 8.25 ft above Perm.Datum
Drilling Measured From: Kelly Bushing

API Serial No.	Section:	Township:	Range:
04-037-00667-00	29	3N	16W

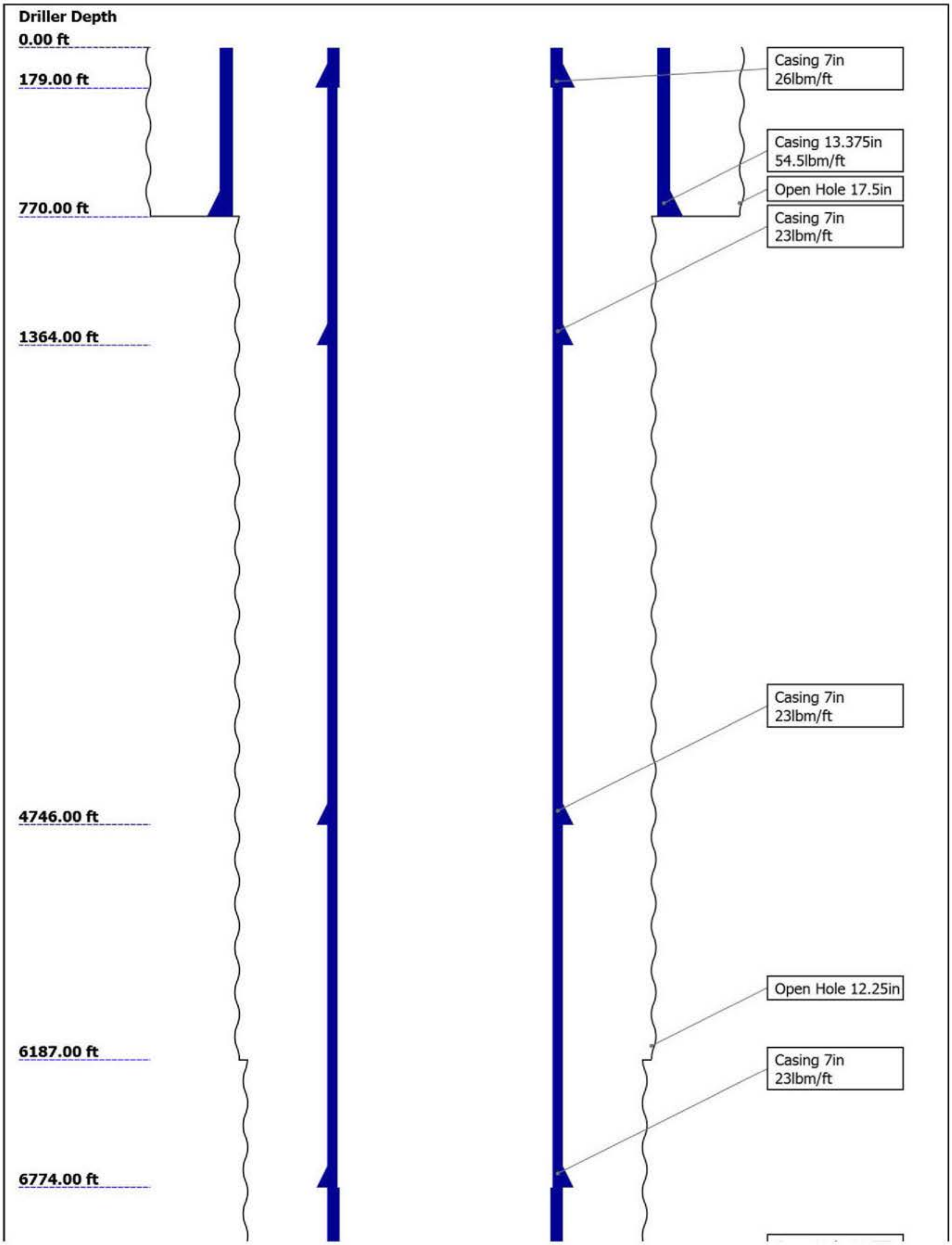
County: Los Angeles
Field: Aliso Canyon
Location:
Well: Frew 4
Company: Southern California Gas Company

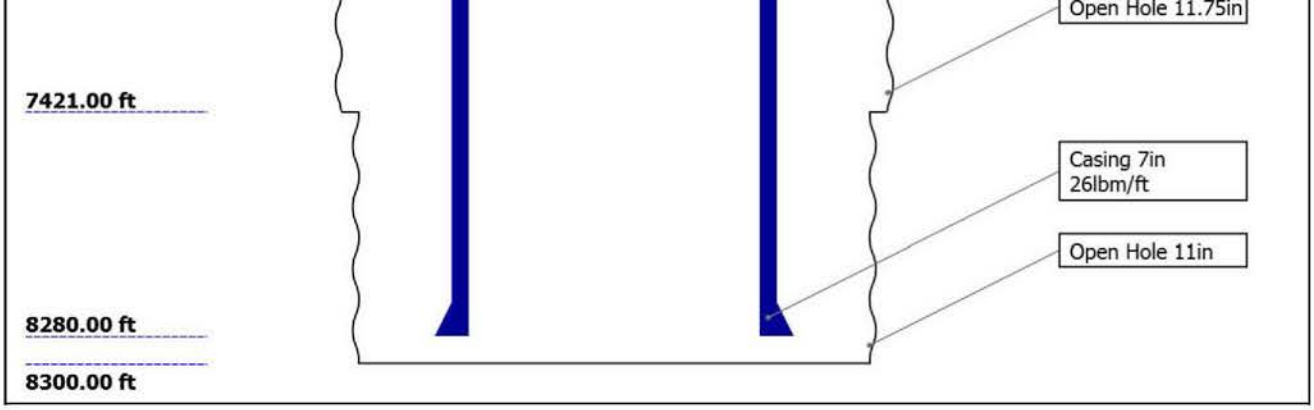
Logging Date	19-Oct-2016
Run Number	Two
Depth Driller	8176.00 ft
Schlumberger Depth	8176.00 ft
Bottom Log Interval	8168.00 ft
Top Log Interval	7.00 ft
Casing Fluid Type	KCl Brine with Polymer
Salinity	
Density	9 lbm/gal
Fluid Level	8.00 ft
BIT/CASING/TUBING STRING	
Bit Size	11.00 in
From	7421.00 ft
To	8300.00 ft
Casing/Tubing Size	7 in
Weight	26 lbm/ft
Grade	N80
From	6774.00 ft
To	8280.00 ft
Max Recorded Temperatures	
Logger on Bottom Time	20-Oct-2016 09:51:00
Unit Number Location:	3189 Ventura
Recorded By	I. Kartawidjaja
Witnessed By	Mr. Tom McMahon

Disclaimer

Contents

Well Sketch


Driller Depth
0.00 ft
179.00 ft
770.00 ft
1364.00 ft
4746.00 ft
6187.00 ft
6774.00 ft
Casing 7in
26lbm/ft
Casing 13.375in
54.5lbm/ft
Open Hole 17.5in
Casing 7in
23lbm/ft
Casing 7in
23lbm/ft
Open Hole 12.25in
Casing 7in
23lbm/ft



Borehole Size/Casing/Tubing Record

Bit						
Bit Size (in)	17.5	12.25	11.75	11		
Top Driller (ft)	0	770	6187	7421		
Top Logger (ft)	0	770	6187	7421		
Bottom Driller (ft)	770	6187	7421	8300		
Bottom Logger (ft)	770	6187	7421	8300		
Casing						
Size (in)	13.375	7	7	7	7	7
Weight (lbm/ft)	54.5	26	23	23	23	26
Inner Diameter (in)	12.615	6.276	6.366	6.366	6.366	6.276
Grade	J55	N80	N80	J55	N80	N80
Top Driller (ft)	0	0	179	1364	4746	6774
Top Logger (ft)	0	0	179	1364	4746	6774
Bottom Driller (ft)	770	179	1364	4746	6774	8280
Bottom Logger (ft)	770	179	1364	4746	6774	8280

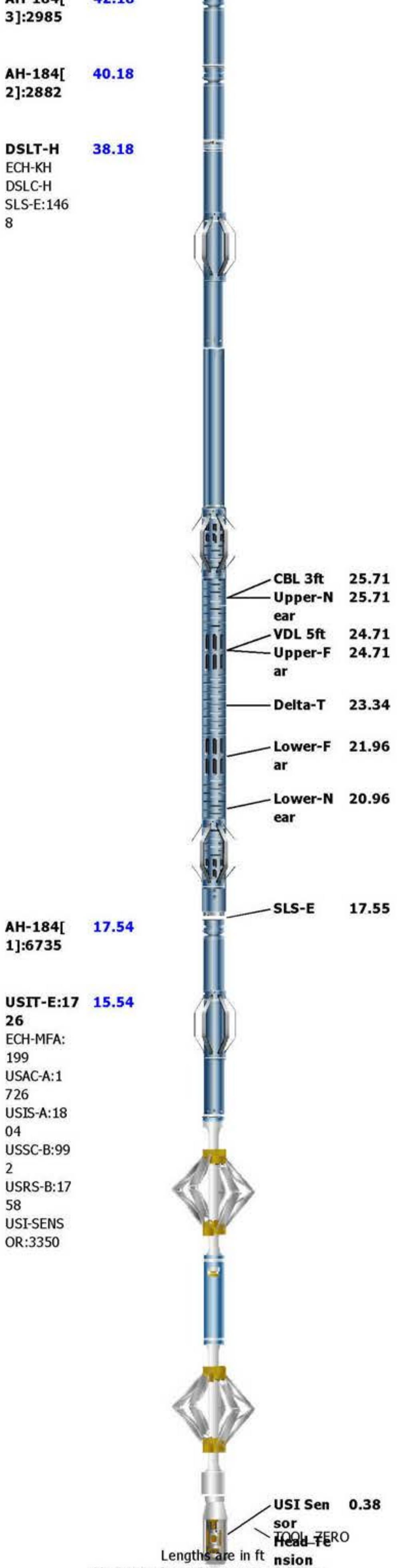
Remarks and Equipment Summary

Two: Toolstring

Equip name	Length
LEH-QT:2867 LEH-QT:2867	57.51
DTC-H ECH-KC DTC-H	54.59
HGNS-H:3923 HGNH:4819 NPV-N NSR-F:1303 HMCA-H HGNS-H:3923 HACCZ-H:4177	51.59
AH-184	42.18

MP name	Offset
Red	
CTEM	53.69
HV	0.00
TelStatus	51.59
ToolStatus	51.59
Temperature	51.57
GR	50.85
CNL Porosity	44.52
HGNS	42.18
HMCA	42.18
Accelerometer	0.00

Two: Remarks
Depth correlated to Neutron Lifetime Log dated 4-19-74. Tied-in to Neutron curves between 7700-8100 ft
USIT logged at 10 deg 1.5 inch, speed 3200 fph. No hi-res repeat recorded as requested by client.
Main pass recorded with 0 psi surface pressure. Repeat pass recorded with 1000 psi from TD to ~6900 ft.
Logged from above top of sand at ~8168 ft to surface.
Rig: Ensign 334
Toolstring ran as per toolsketch.
Two centralizers on USIS and two CME-Y used to centralize ultrasonic tool.
Thank you for choosing Schlumberger!



Lengths are in ft
Maximum Outer Diameter = 6.250 in
Line: Sensor Location, Value: Gating Offset
All measurements are relative to TOOL_ZERO

Job Event Summary

Event	Time	Duration	Interval	Remark

Event	Time	Duration	Interval	Remark
Log[1]:Down	Oct-19-2016 13:19	01:54:44	185.28 - 8127.82 ft	Fluid Properties Measurement
Log[6]:Up	Oct-19-2016 14:46	00:24:25	8162.42 - 6845.38 ft	Repeat Pass 1000 PSI
Log[9]:Up	Oct-20-2016 09:51	00:29:01	8170.38 - 6638.82 ft	Main Pass #1 0 PSI
Log[11]:Up	Oct-20-2016 10:24	02:09:06	6736.16 - 35.34 ft	Main Pass #2 0 PSI
Log[14]:Up	Oct-20-2016 12:53	00:04:58	153.18 - 3.59 ft	Main Pass #3 0 PSI

USIT - Fluid Properties Measurement

Run Name	Pass Name	Start Depth(ft)	Stop Depth(ft)
Run 1	Log[11]:Up	6737.51	36.69

Fluid Velocity = "Automatic".
CFVL equals DFSL channel

Start Depth(ft)	Stop Depth(ft)	Start Value(us/ft)	End Value(us/ft)

Mud Impedance = "FreePipe Norm.".
Free Pipe normalization zone is : 120.75m(396.17ft) to 129.39m(424.50ft)
MUD_N_FRP = 1.10
DFD = 1.08g/cm3(9.00lbm/gal)
CZMD median computed in free pipe normalization interval = 1.80 MRayl

Start Depth(ft)	Stop Depth(ft)	Start Value(Mrayl)	End Value(Mrayl)

Composite 1

Main Pass 5 in = 100 ft

Software Version

Acquisition System	Version
Maxwell 2016 SP1	6.1.58882.3100
Application Patch	Wireline_Hotfix-Perfo-2016SP1_6.1.63773

Computation	Description	Version
CEVAL	Sonic Cement Evaluation Computation Ensemble provides common Parameters and Channels	6.1.58882.3100
Cementation	Cementation Computation Application	6.1.58882.3100

SoftwareVersion_Tool	SoftwareVersion_Run Version	SoftwareVersion_Build Version
WAFE-SEC	Synergy SV451EC version 9.10	Synergy SV451EC version 9.10
WAFE-FEC	Synergy SV451EC version 9.10	Synergy SV451EC version 9.10
WAFE-TMDI	Synergy SV451EC version 46.19	Synergy SV451EC version 46.19

Tool Elements	Description	Software Version	Firmware Version
HGNS-H	HILT Gamma-Ray and Neutron Sonde, 150 degC	6.1.58882.3100	2.0
SLS-E	Sonic Logging Sonde E supports 3'-5'BHC DT and CBL/VDL	6.1.58882.3100	4.0
USI-SENSOR	USIT Transducer Element	6.1.58882.3100	DSP: v1.82

Composite Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[9]:Up	Up	6640.29 ft	8171.85 ft	20-Oct-2016 9:51:39 AM	20-Oct-2016 10:20:40 AM	ON	1.47 ft	No
Two	Log[11]:Up	Up	36.69 ft	6737.51 ft	20-Oct-2016 10:24:53 AM	20-Oct-2016 12:34:00 PM	ON	1.35 ft	No
Two	Log[14]:Up	Up	5.56 ft	155.15 ft	20-Oct-2016 12:53:24 PM	20-Oct-2016 12:58:23 PM	ON	1.96 ft	No

All depths are referenced to toolstring zero

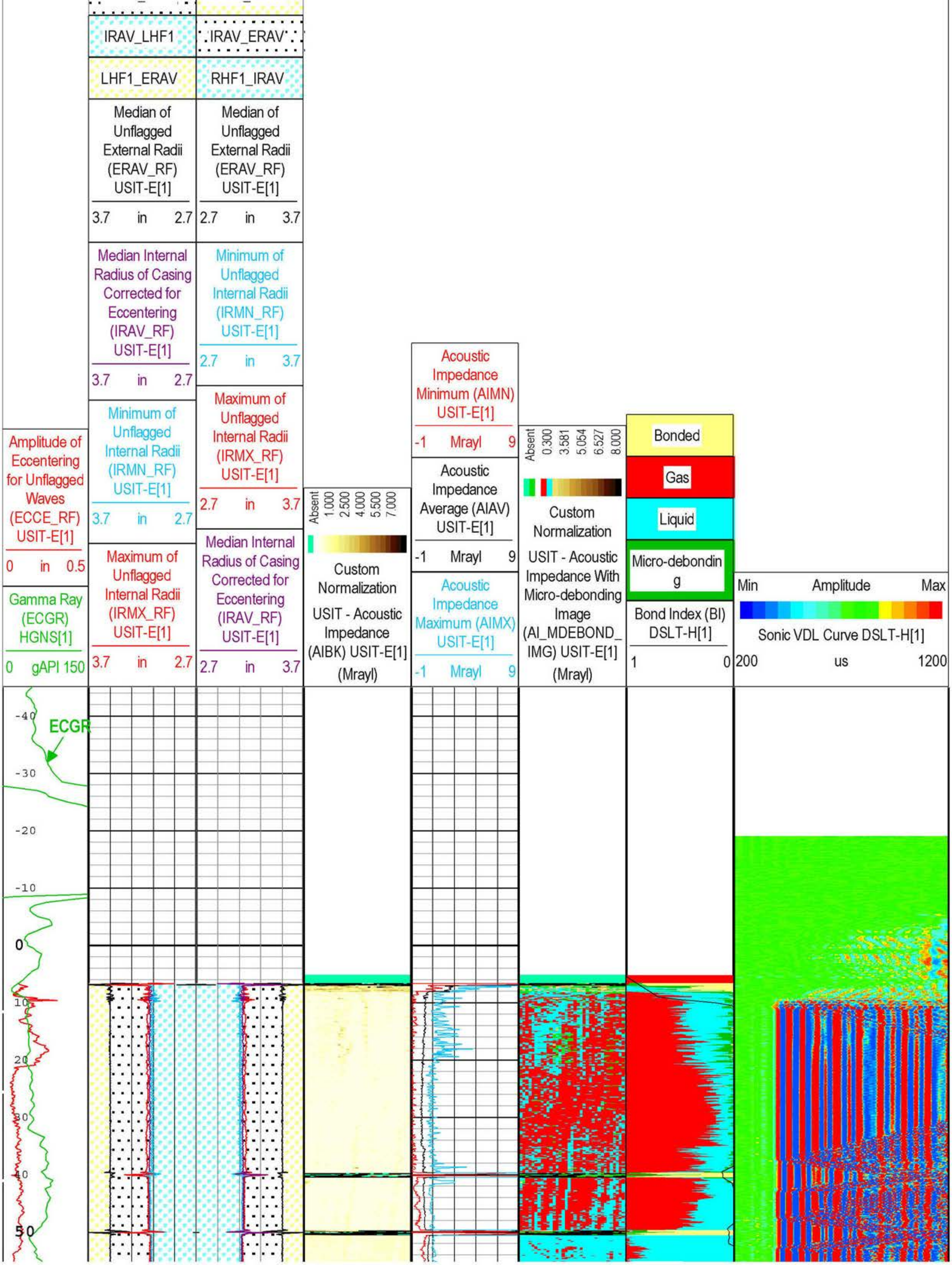
Log

Company:Southern California Gas Company Well:Frew 4
Composite 1:S008

Description: USI VDL Cement Format: Log (LBV1_USI-VDL (DSLT) Cement 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:02

TIME_1900 - Time Marked every 60.00 (s)

ERAV IRAV ERAV RHF1


IRAV_LHF1
IRAV_ERAV
LHF1_ERAV
RHF1_IRAV
Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7
Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7
Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5
Gamma Ray (ECGR) HGNS[1]
0 gAPI 150
Absent 1.000 2.500 4.000 5.500 7.000
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)
Acoustic Impedance Minimum (AIMN) USIT-E[1]
-1 Mrayl 9
Acoustic Impedance Average (AIAV) USIT-E[1]
-1 Mrayl 9
Acoustic Impedance Maximum (AIMX) USIT-E[1]
-1 Mrayl 9
Absent 0.300 3.581 5.054 6.527 8.000
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)
Bonded
Gas
Liquid
Micro-debonding
Bond Index (BI) DSLT-H[1]
1 0
Min Amplitude Max
Sonic VDL Curve DSLT-H[1]
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ECGR
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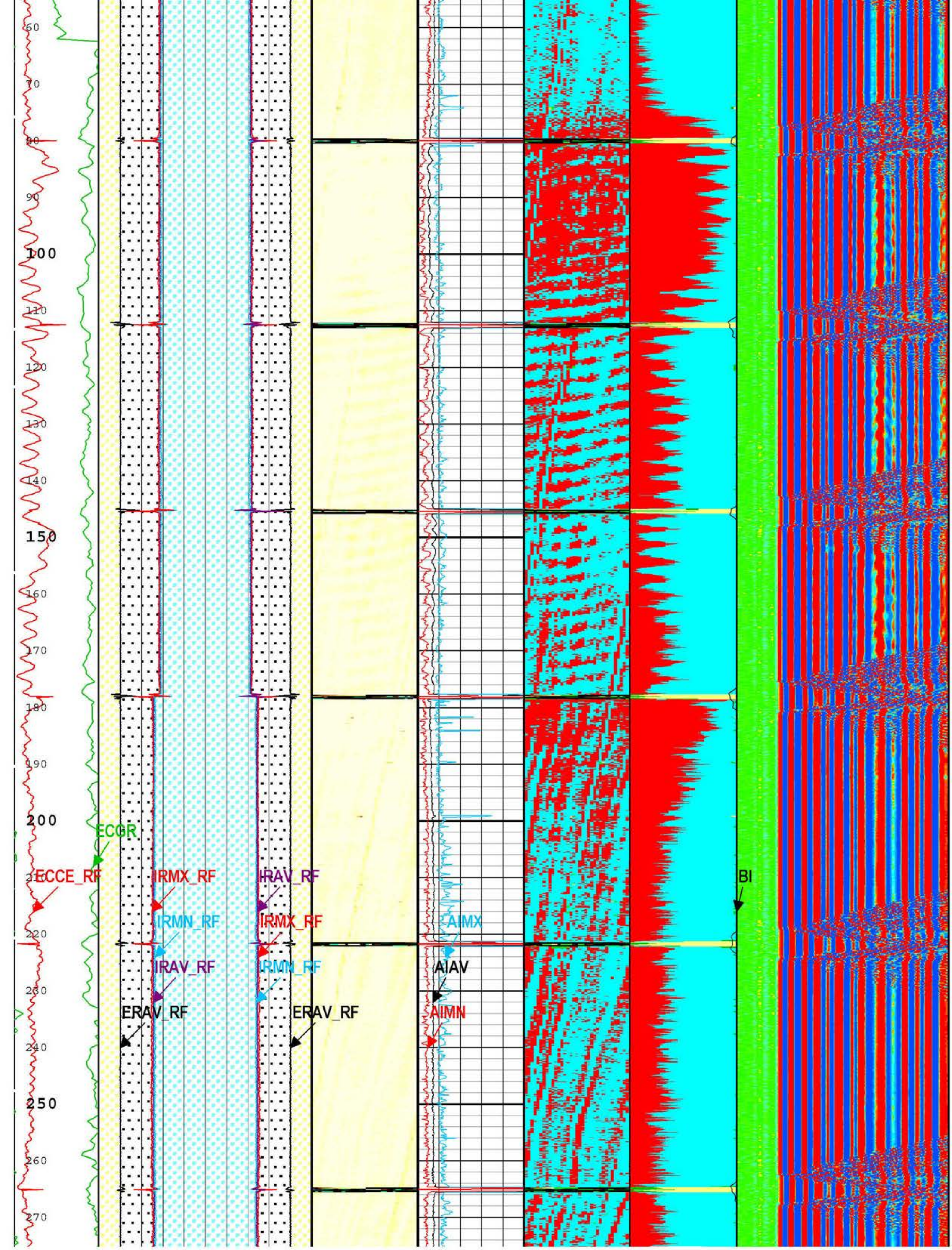
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IRAV_RF
BI
IRMN_RF
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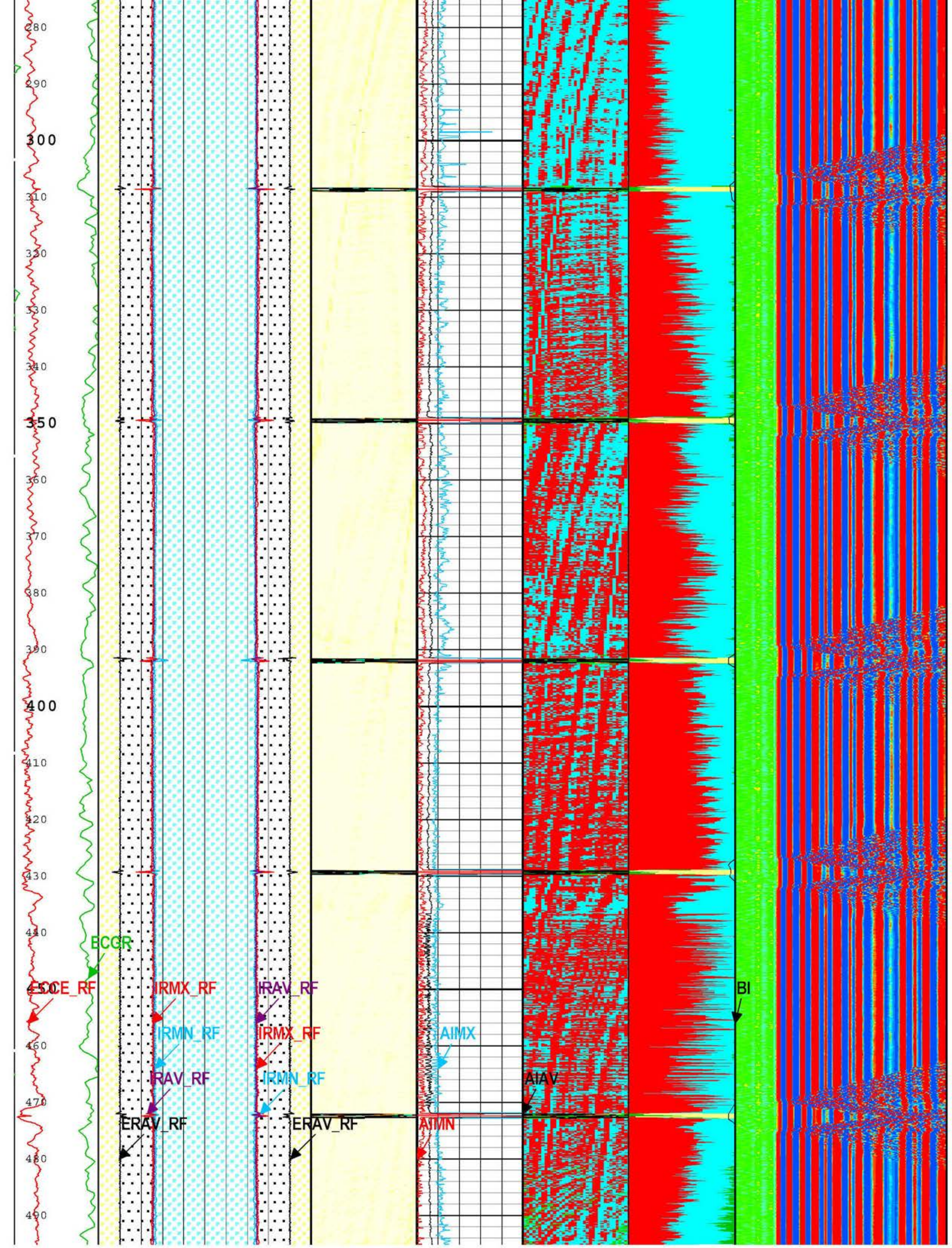
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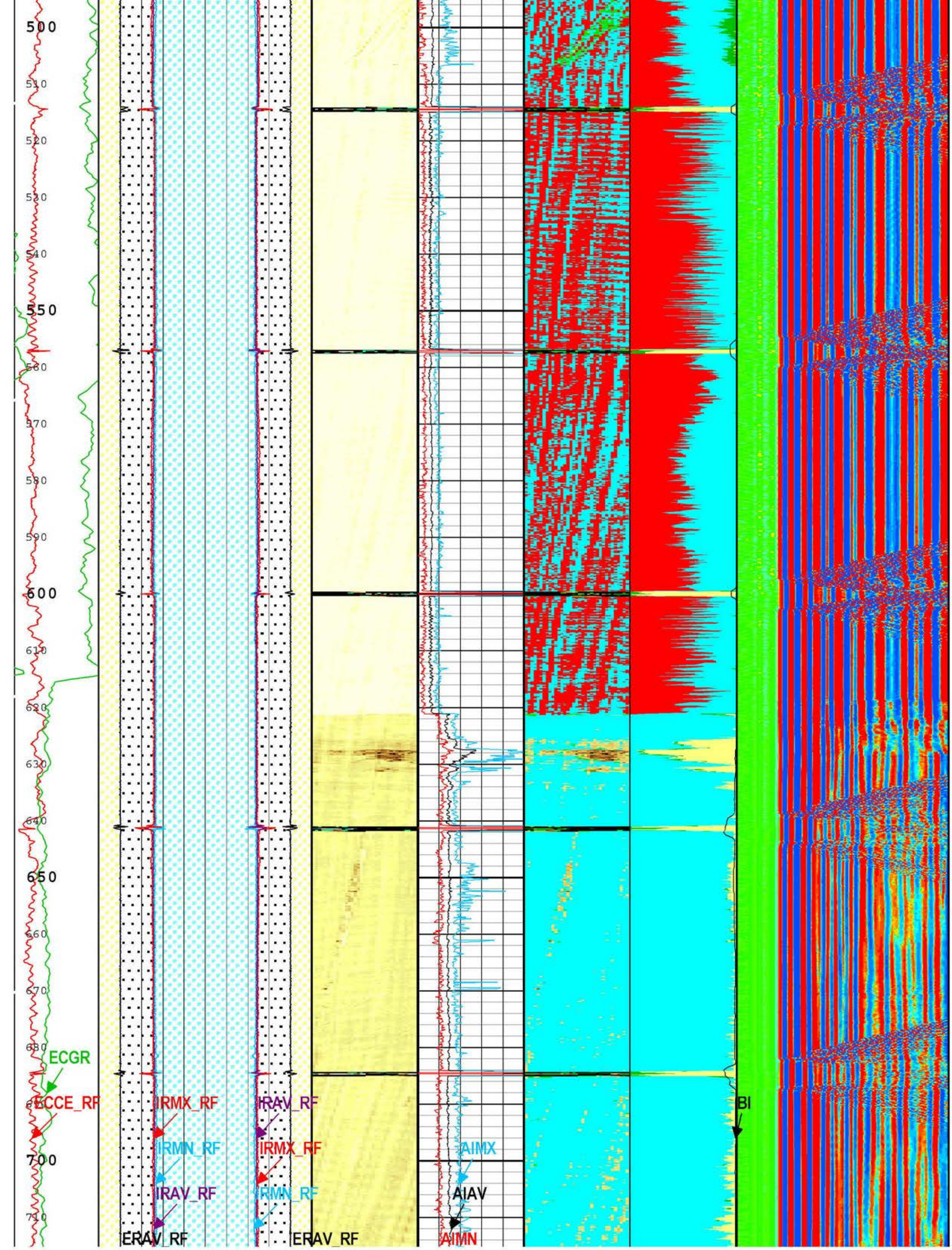
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AIMN
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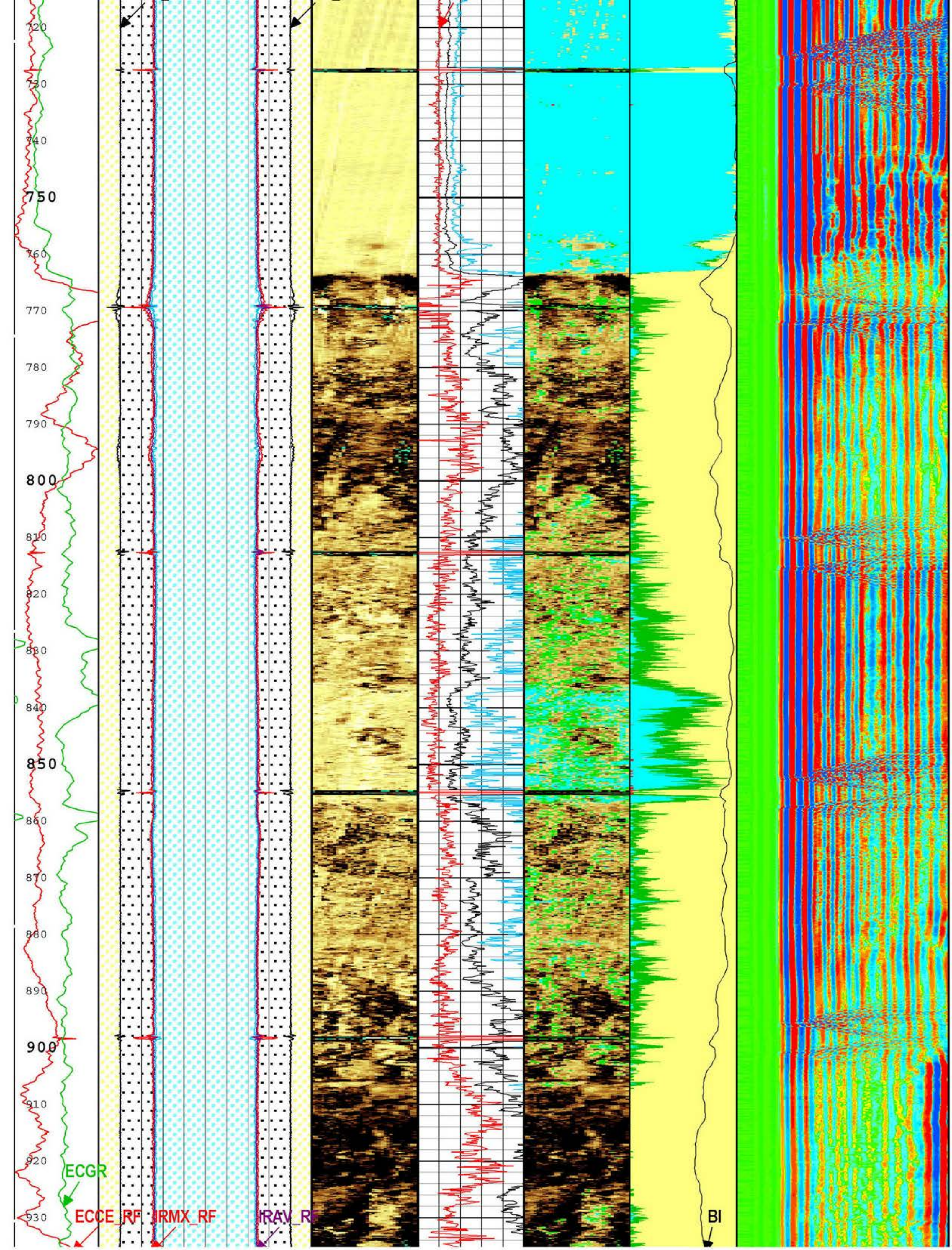
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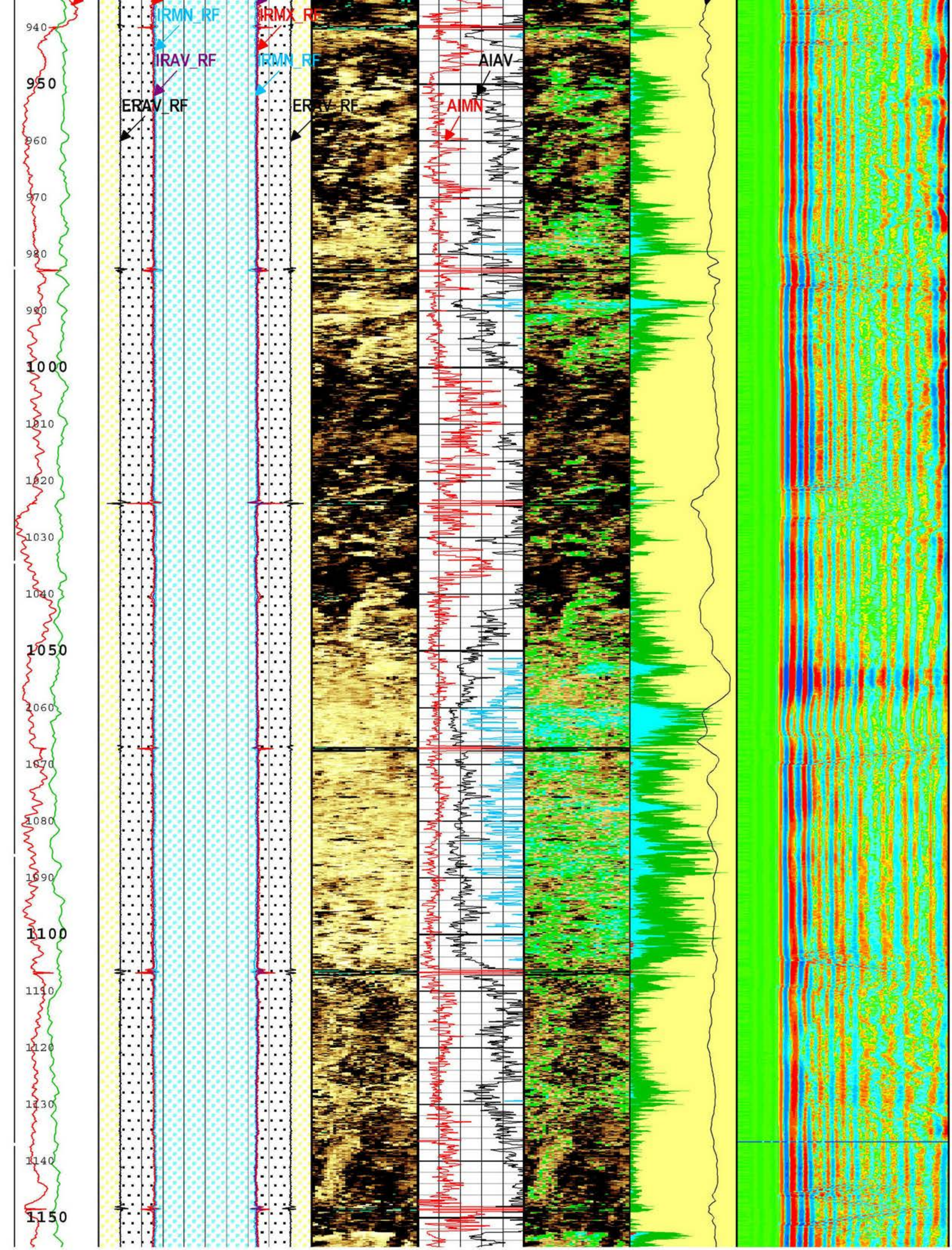
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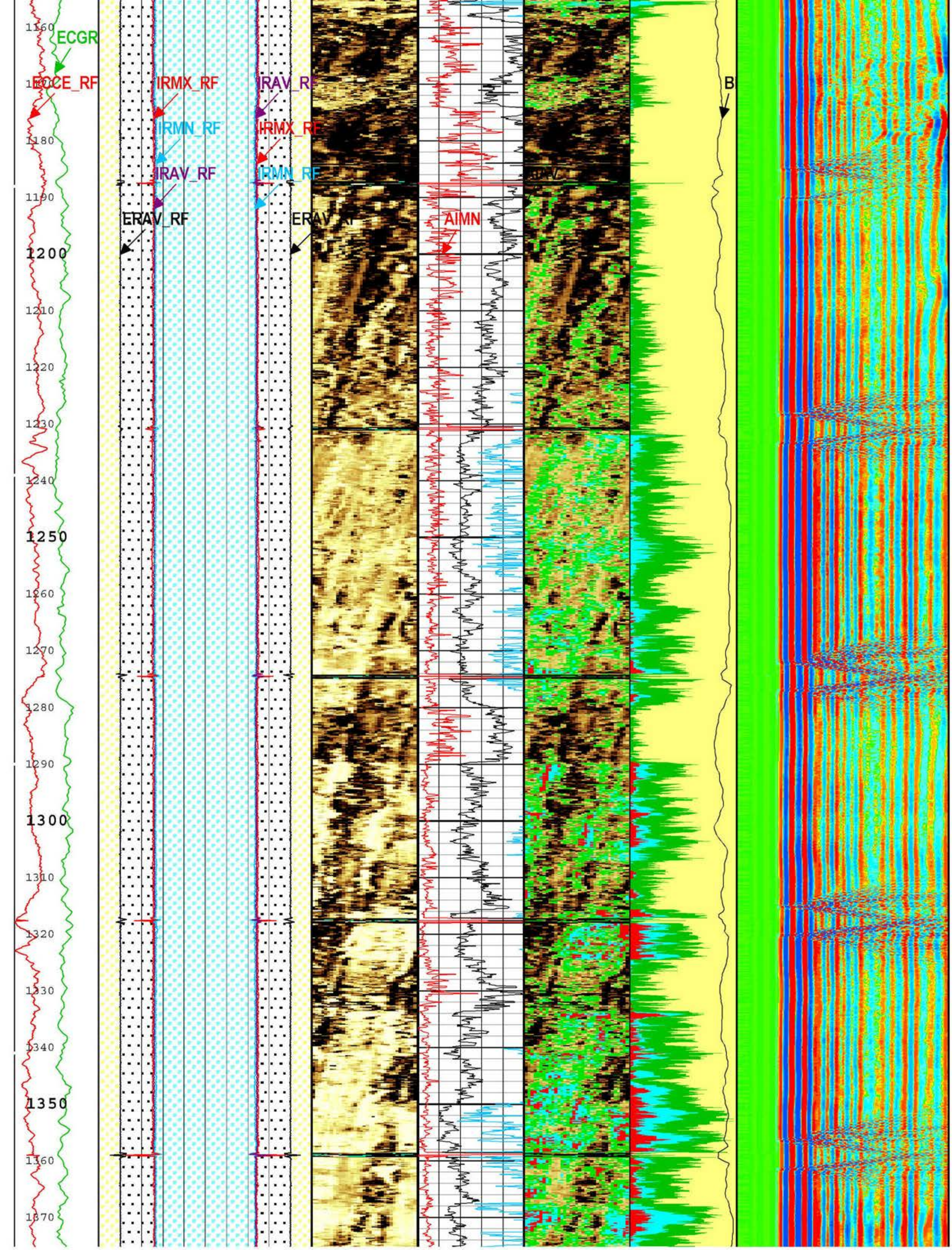
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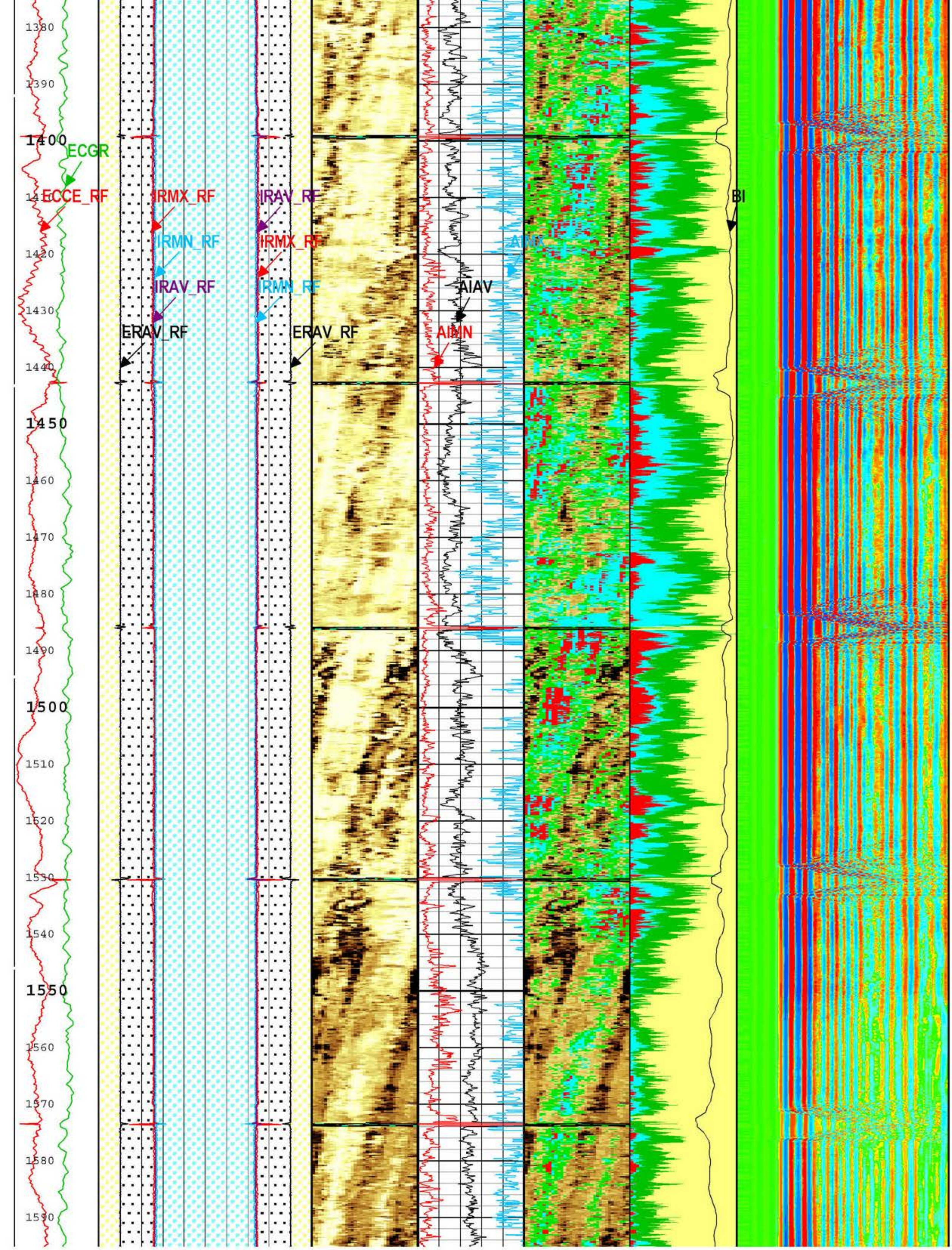
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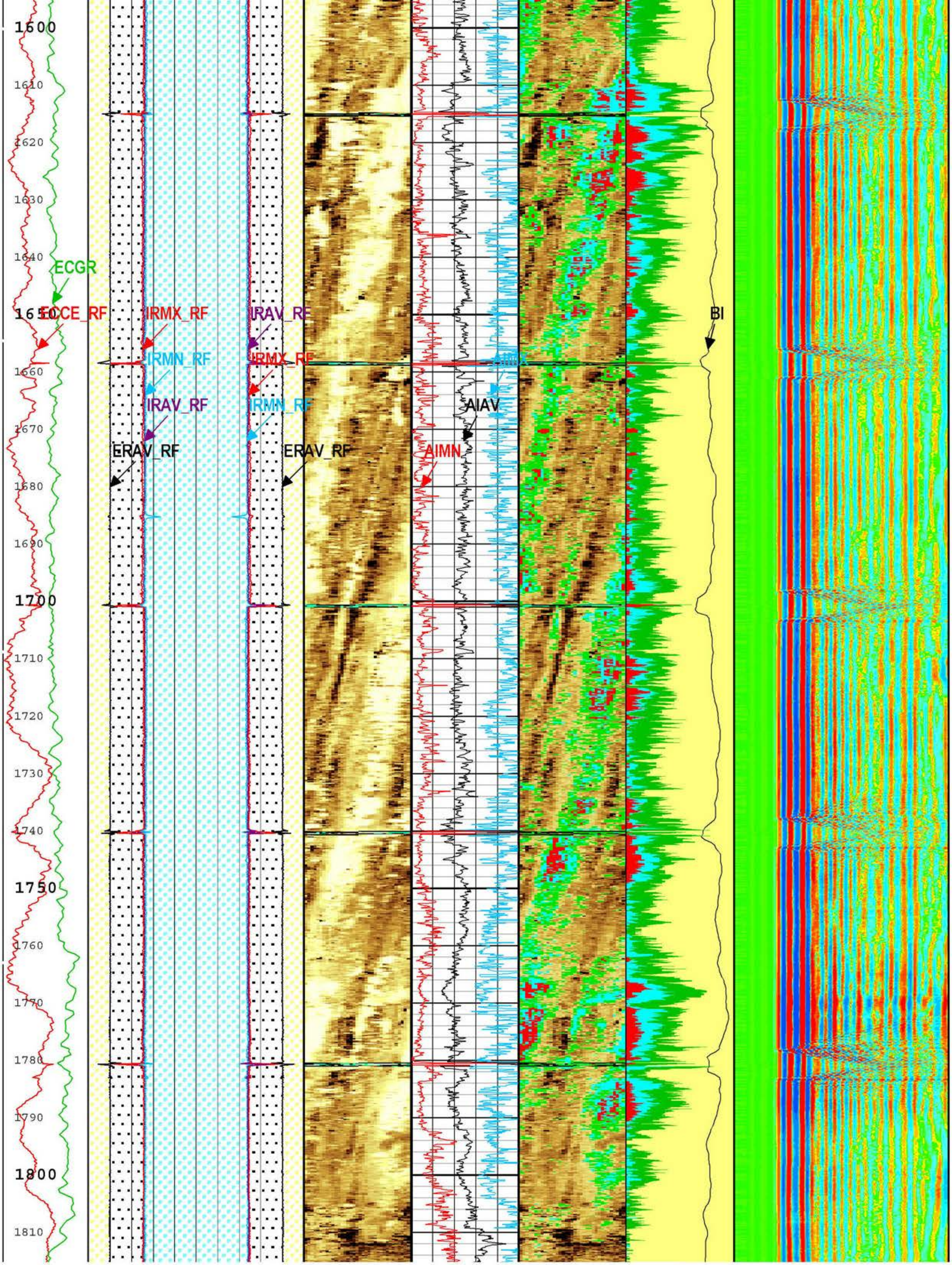
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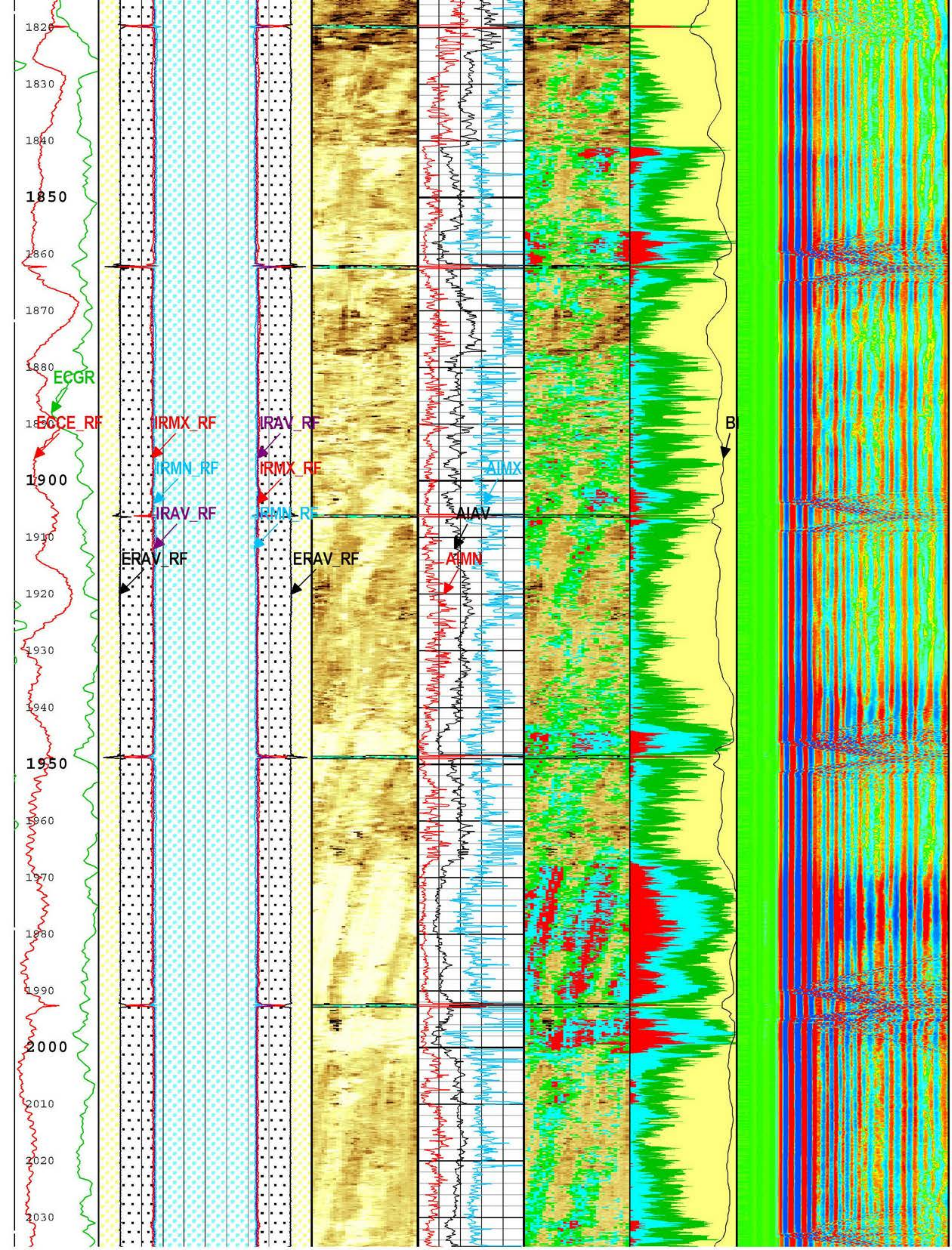
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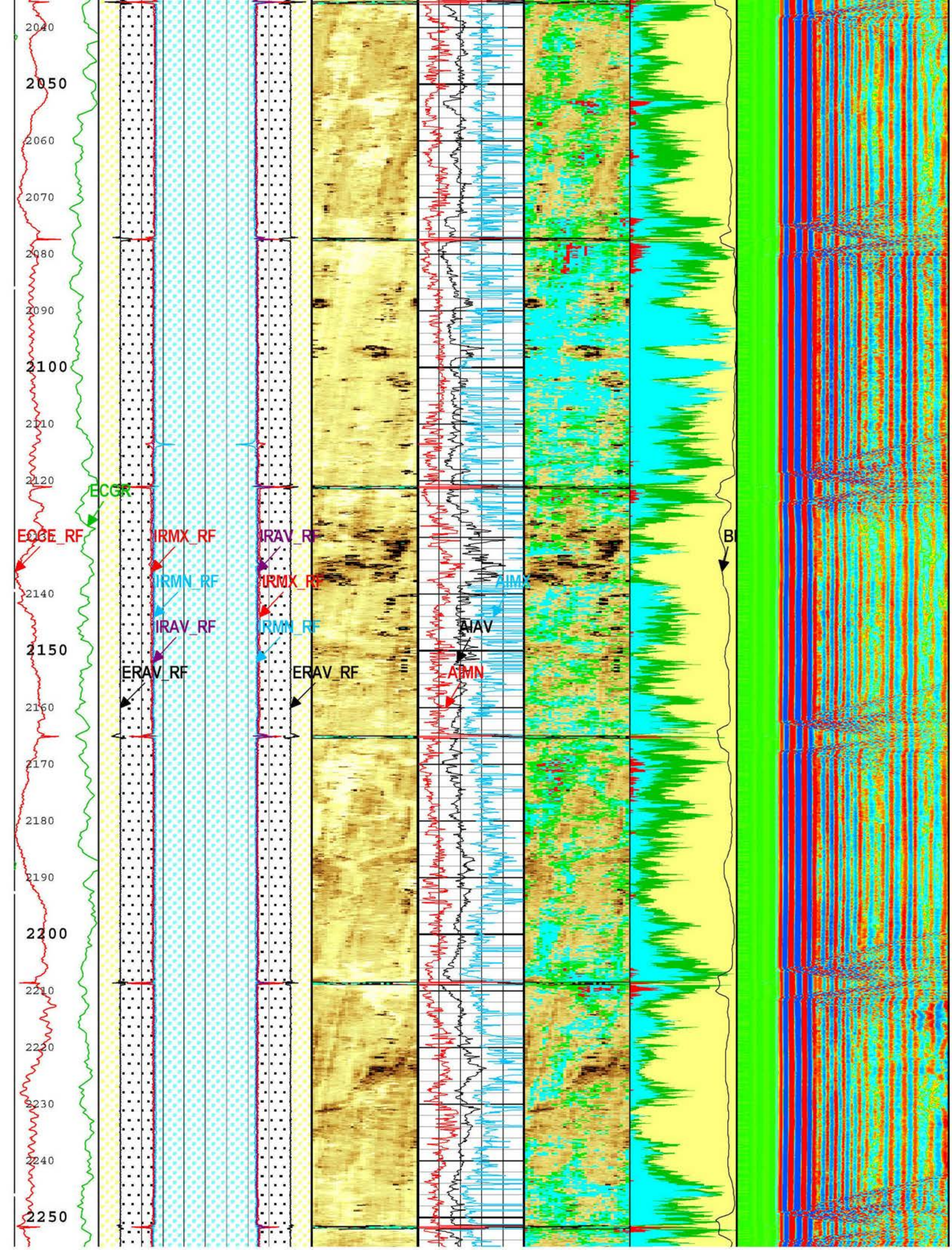
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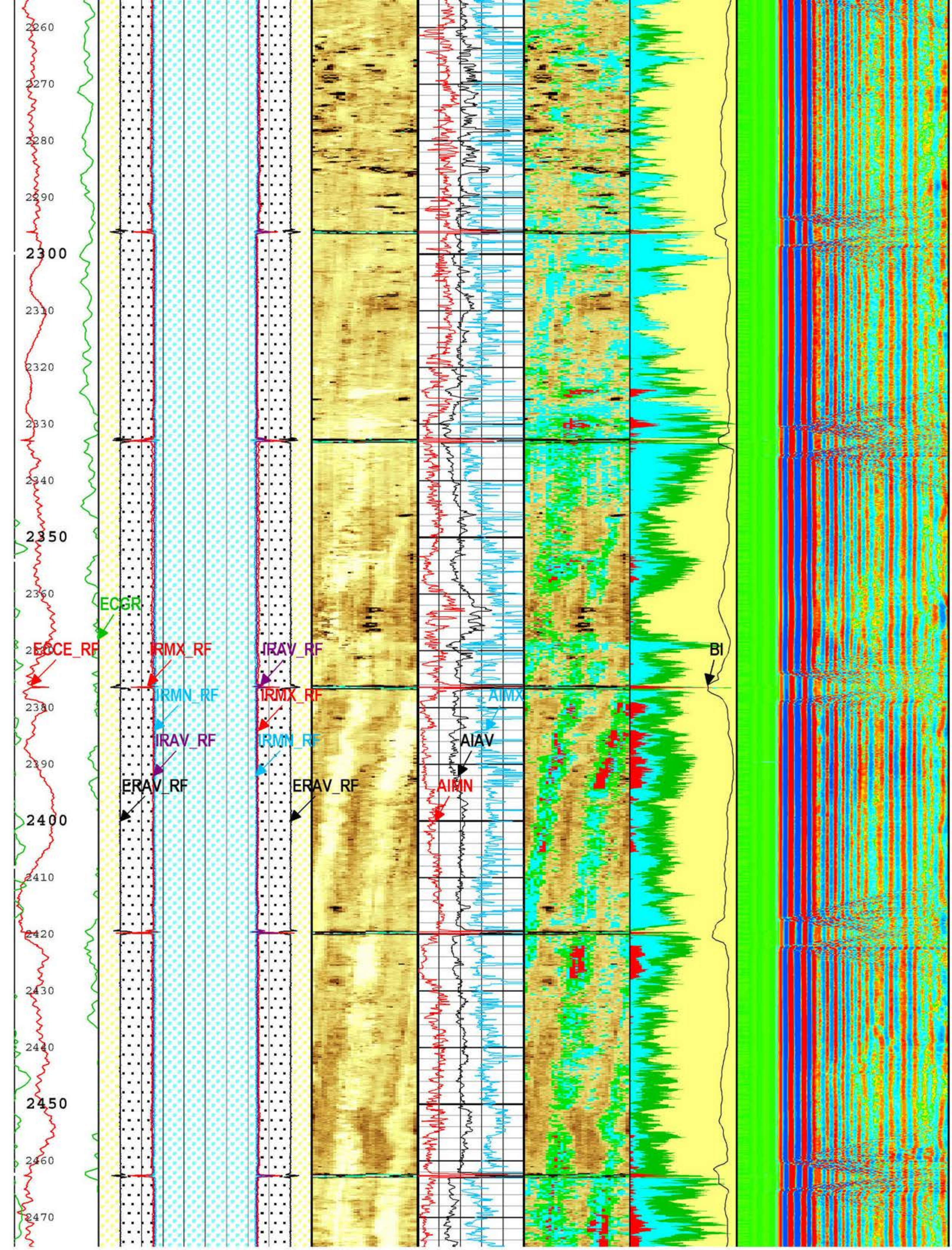
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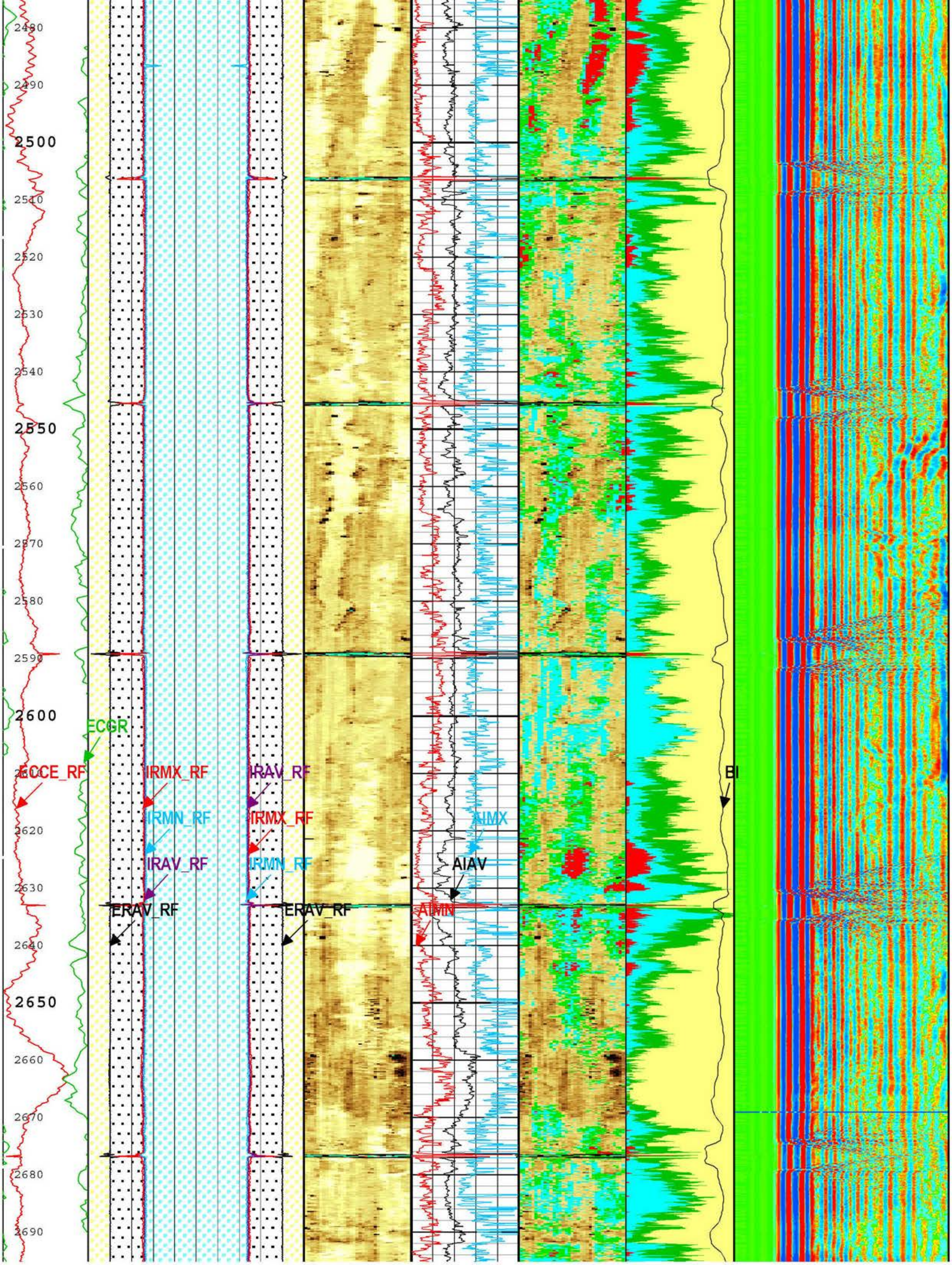
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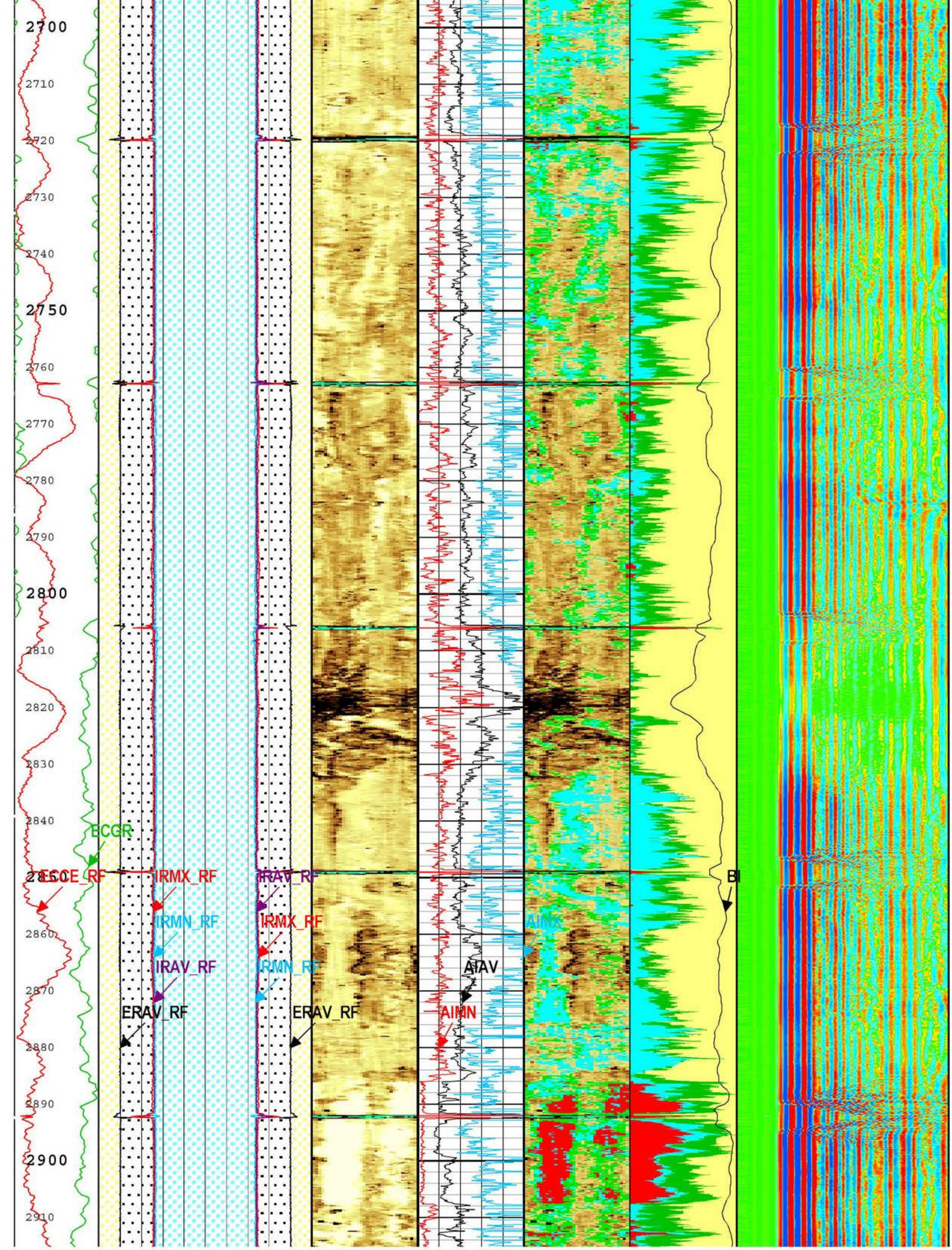
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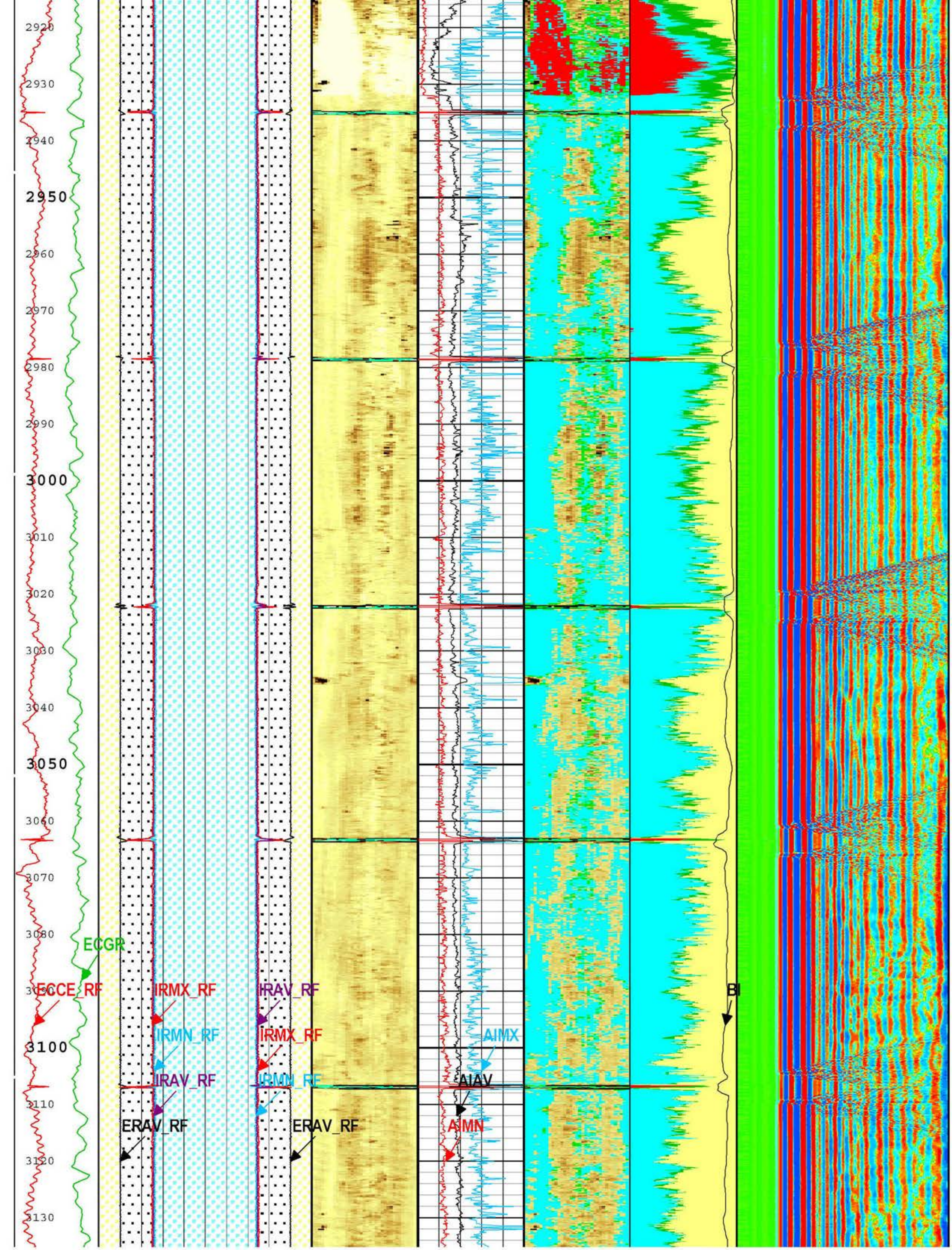
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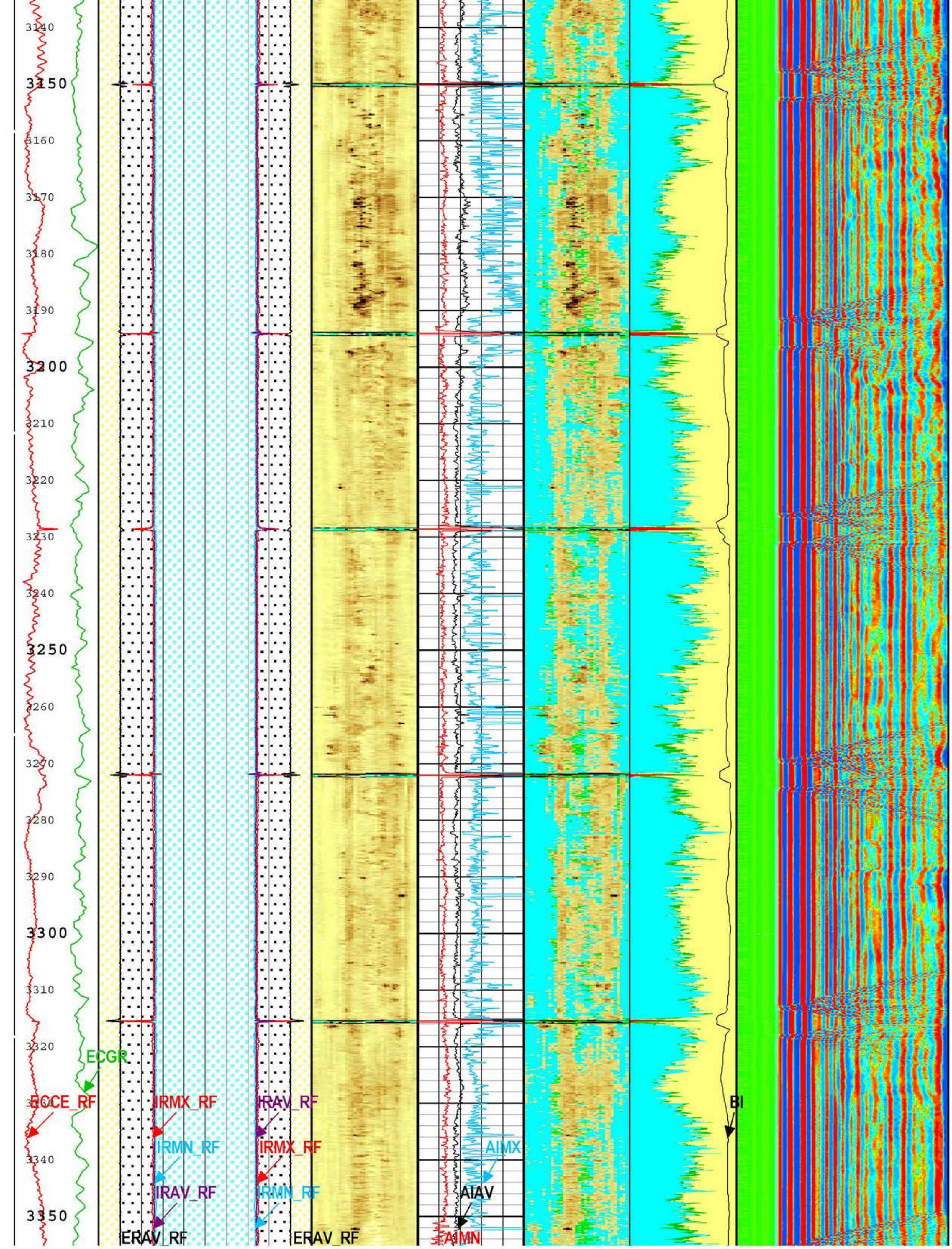
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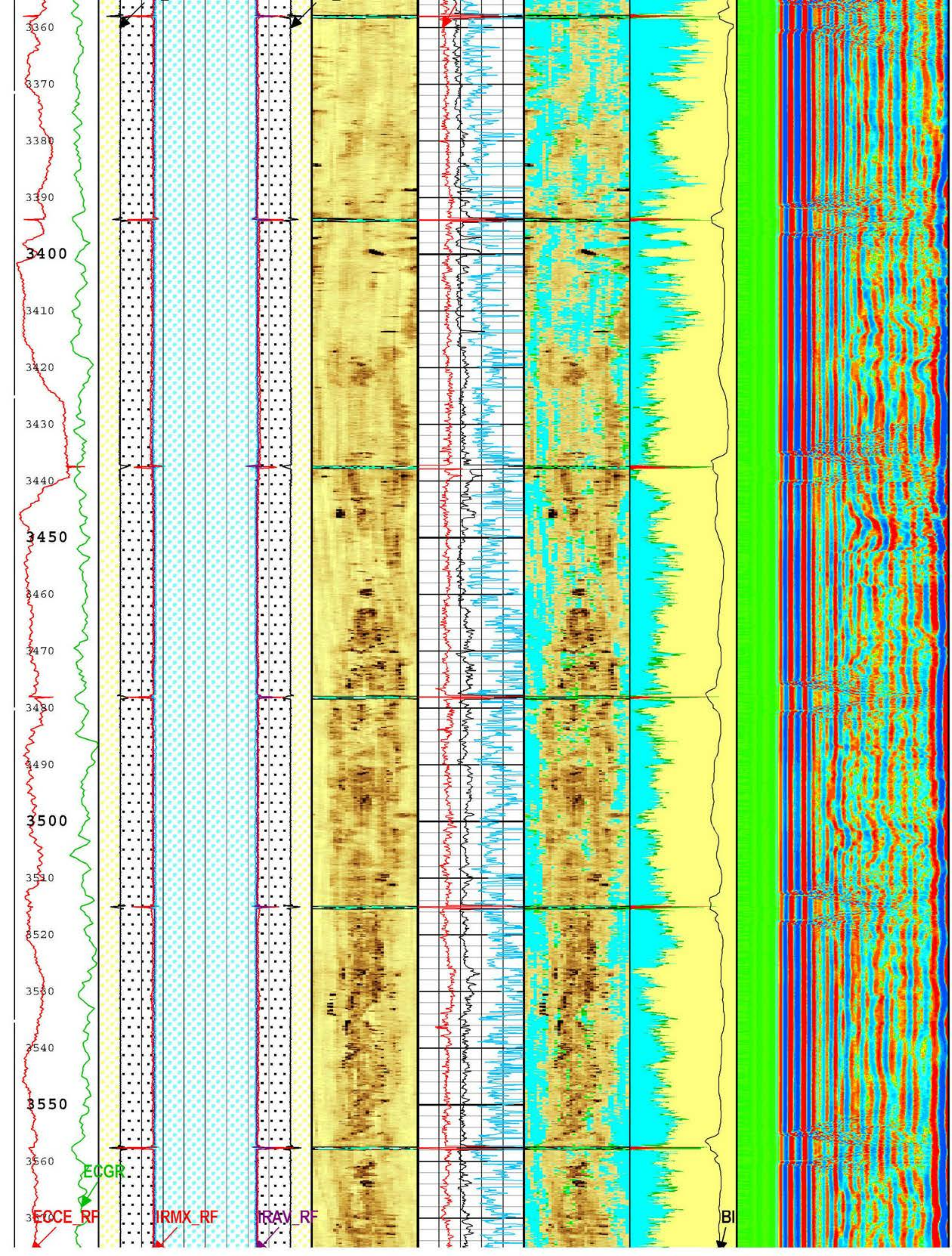
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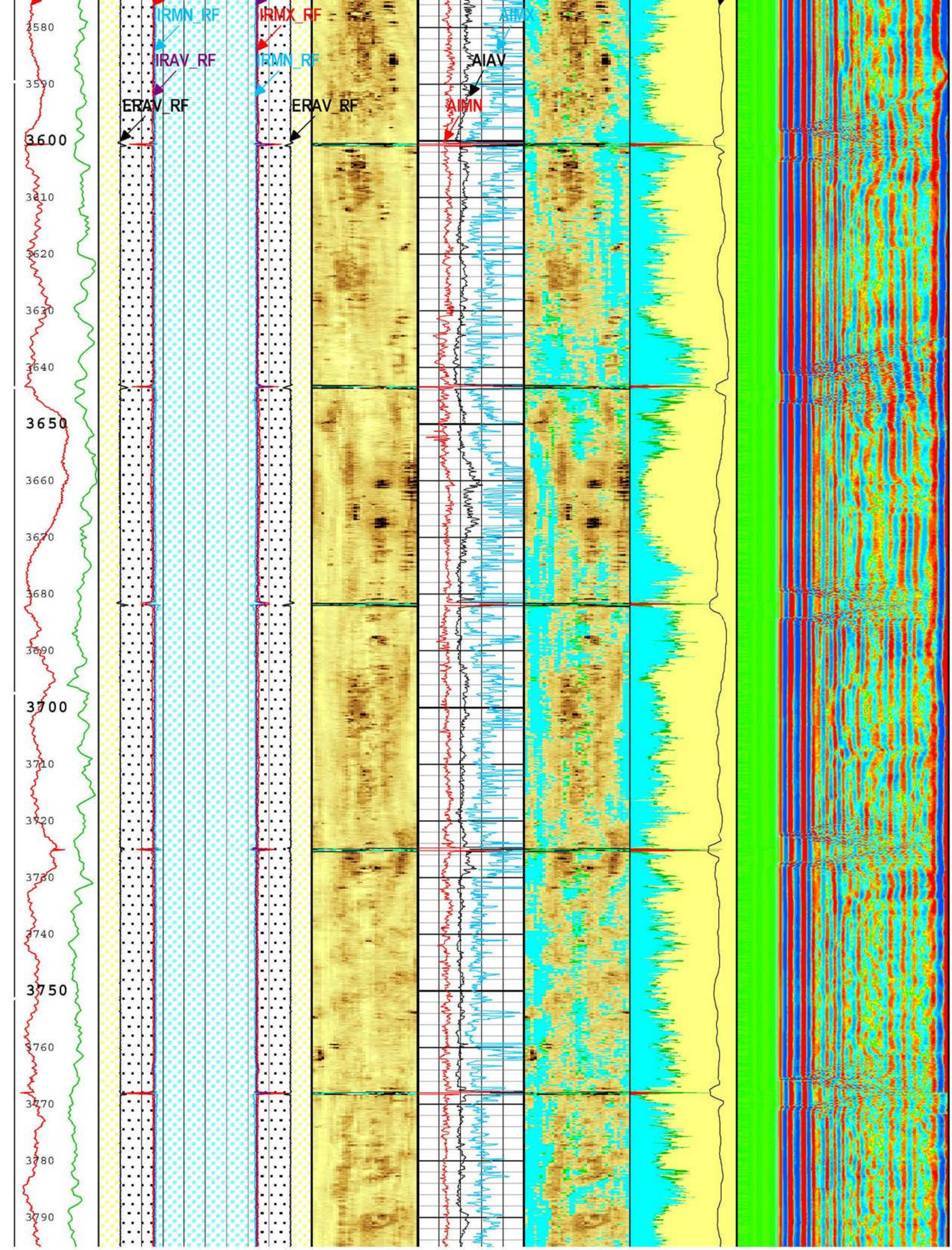
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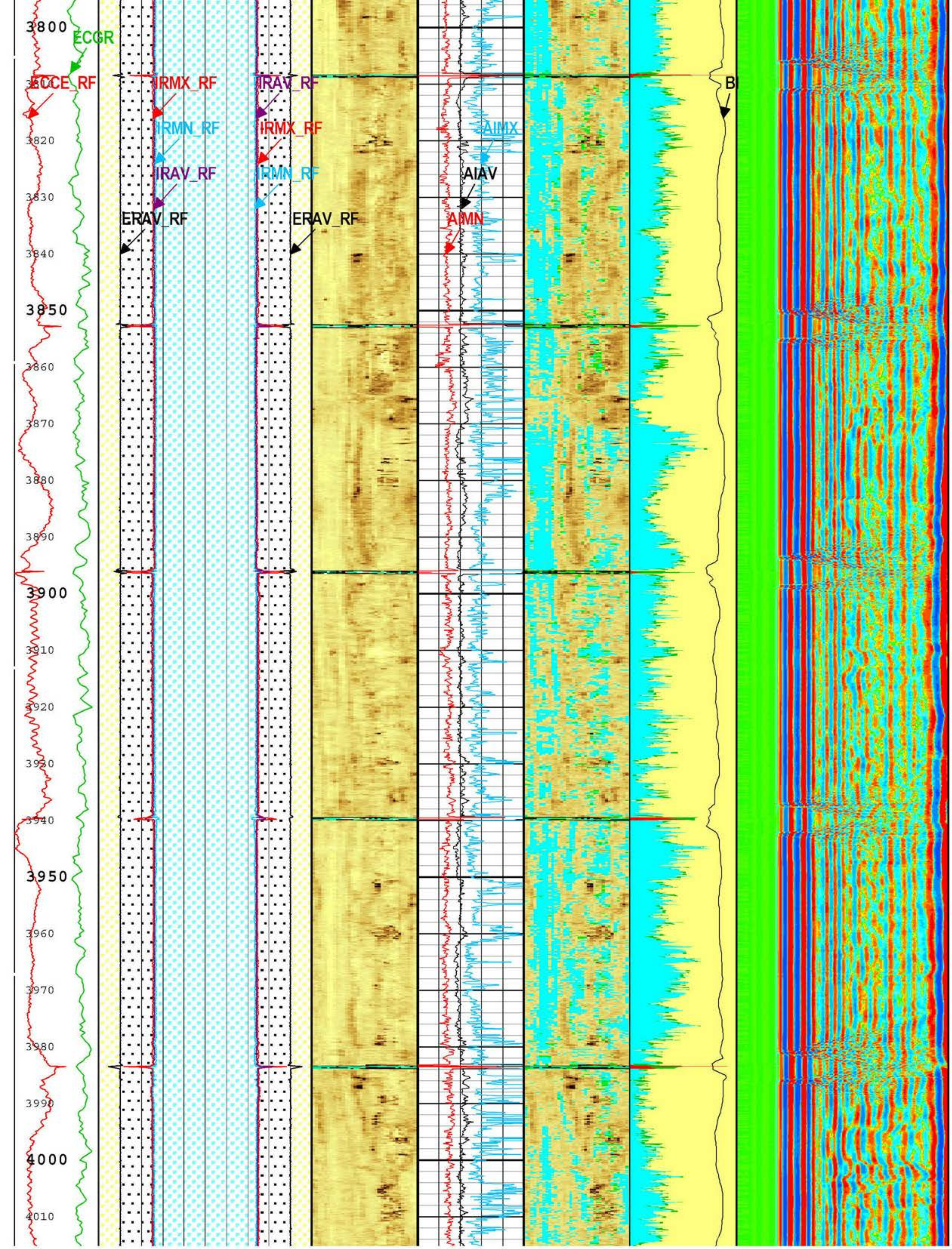
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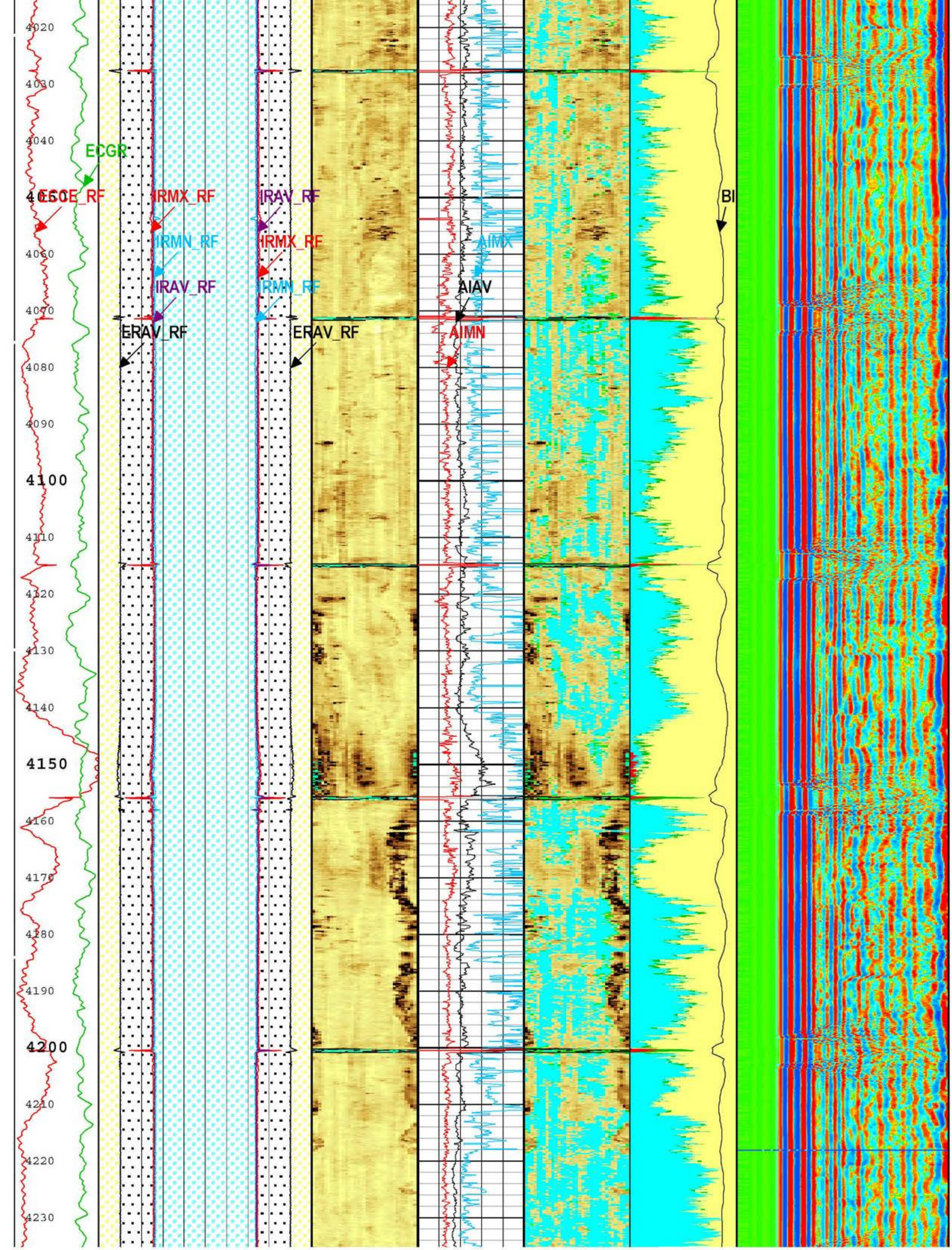
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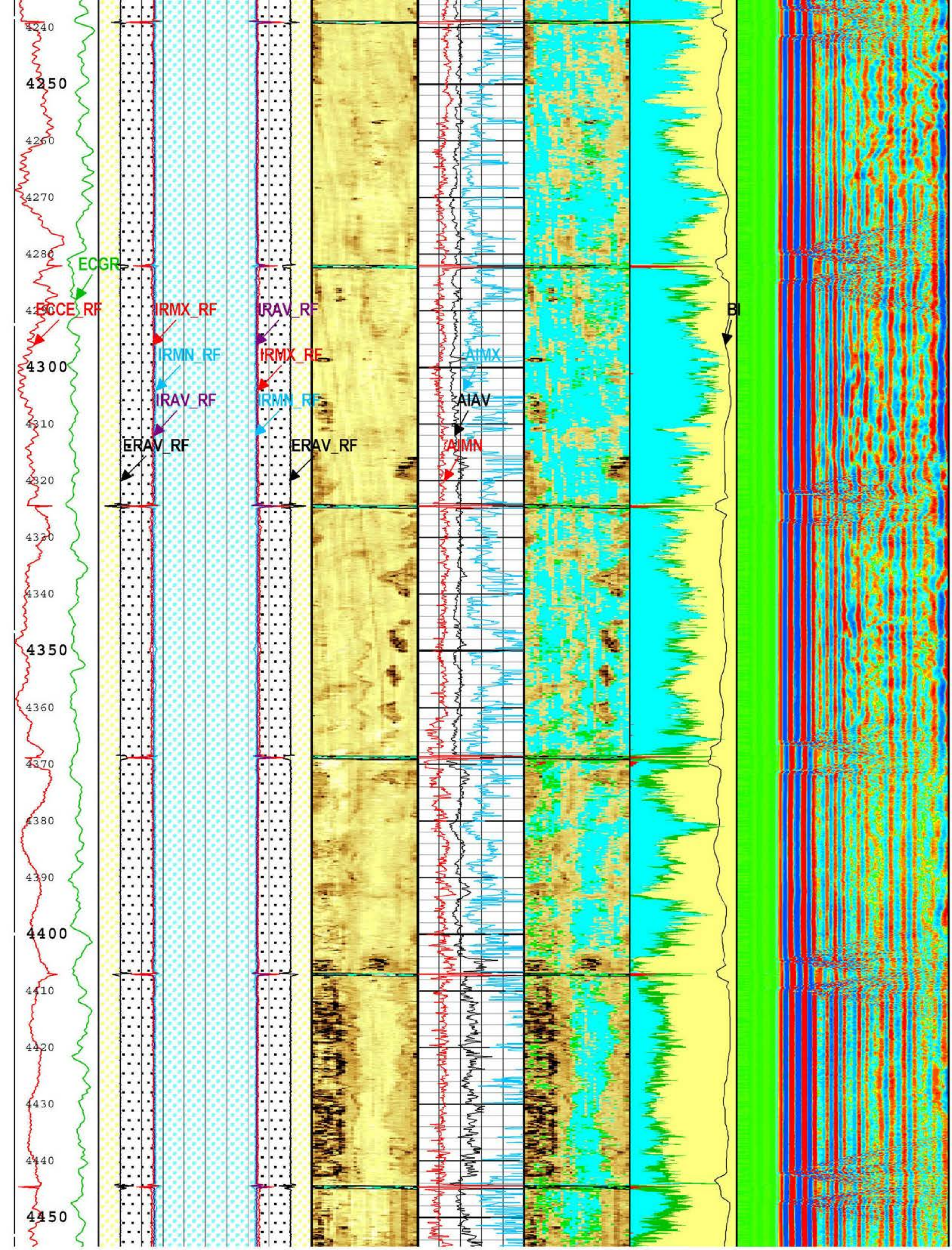
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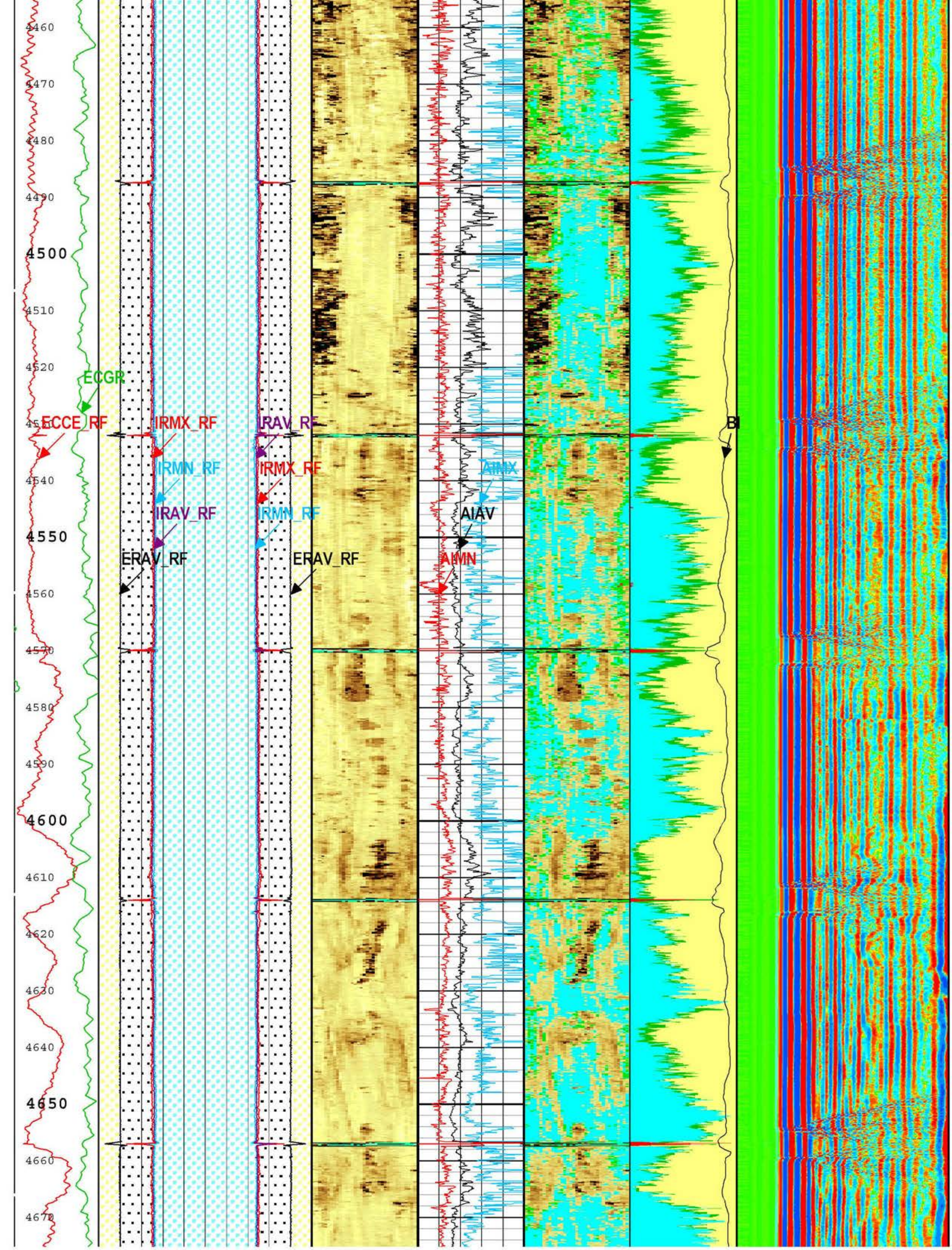
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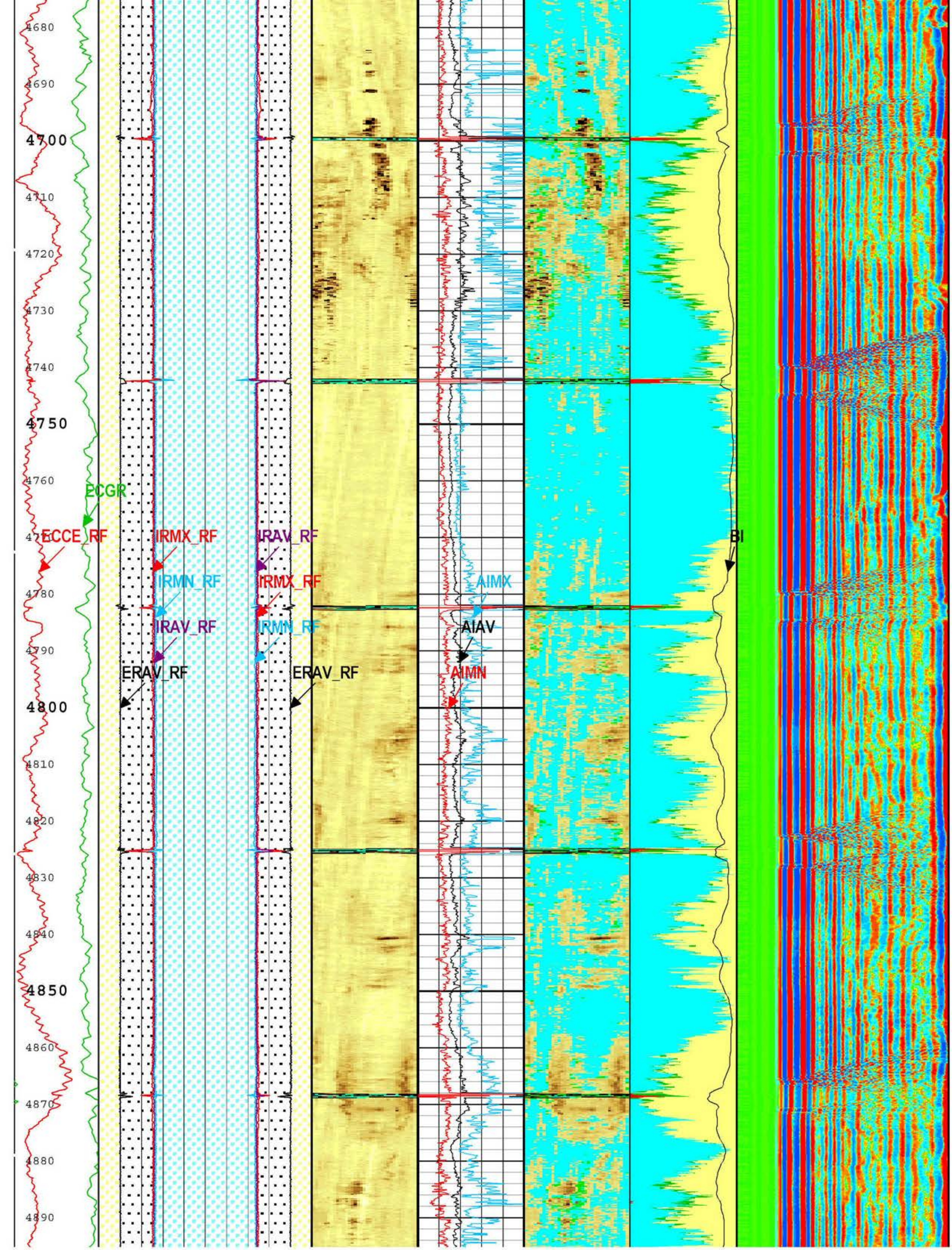
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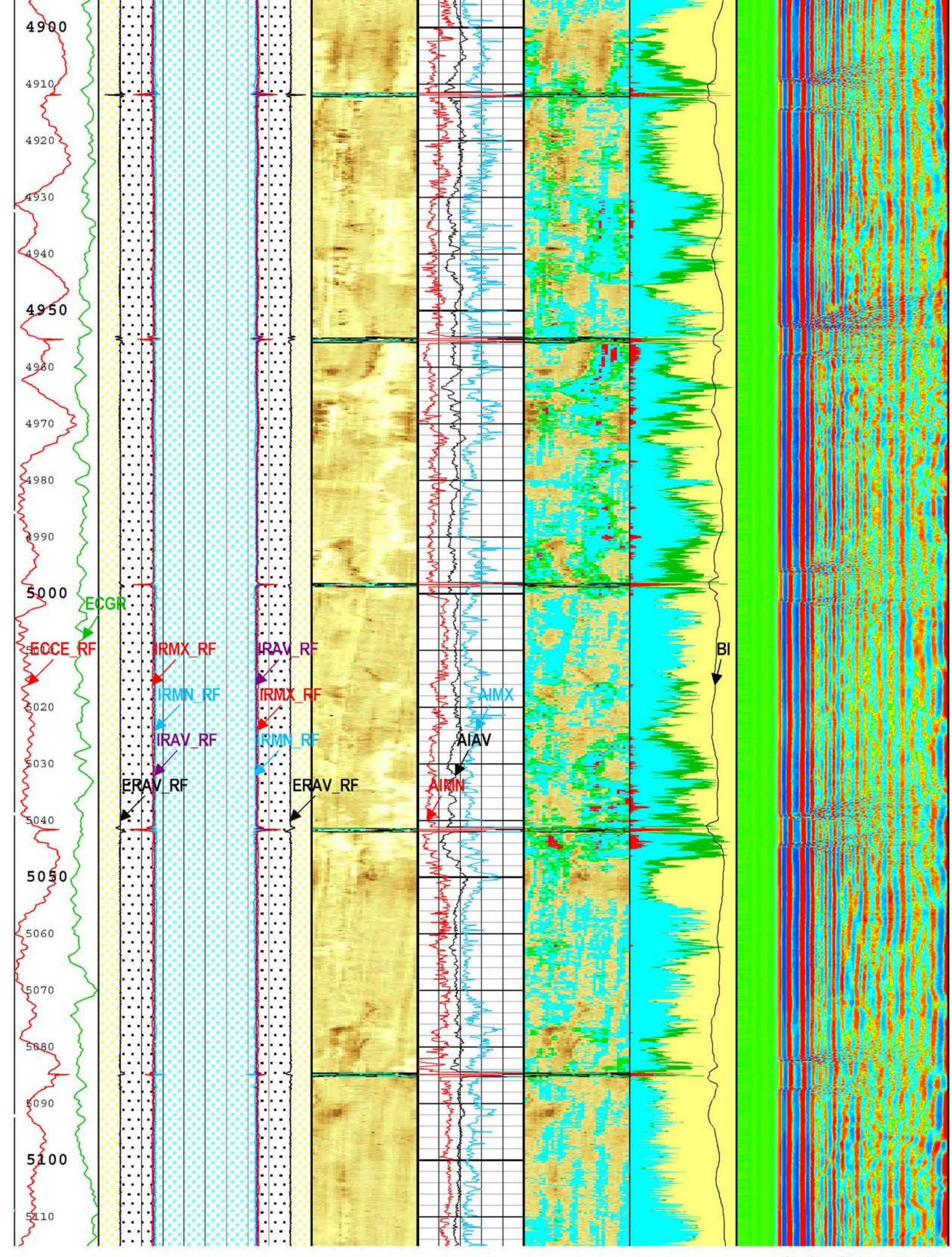
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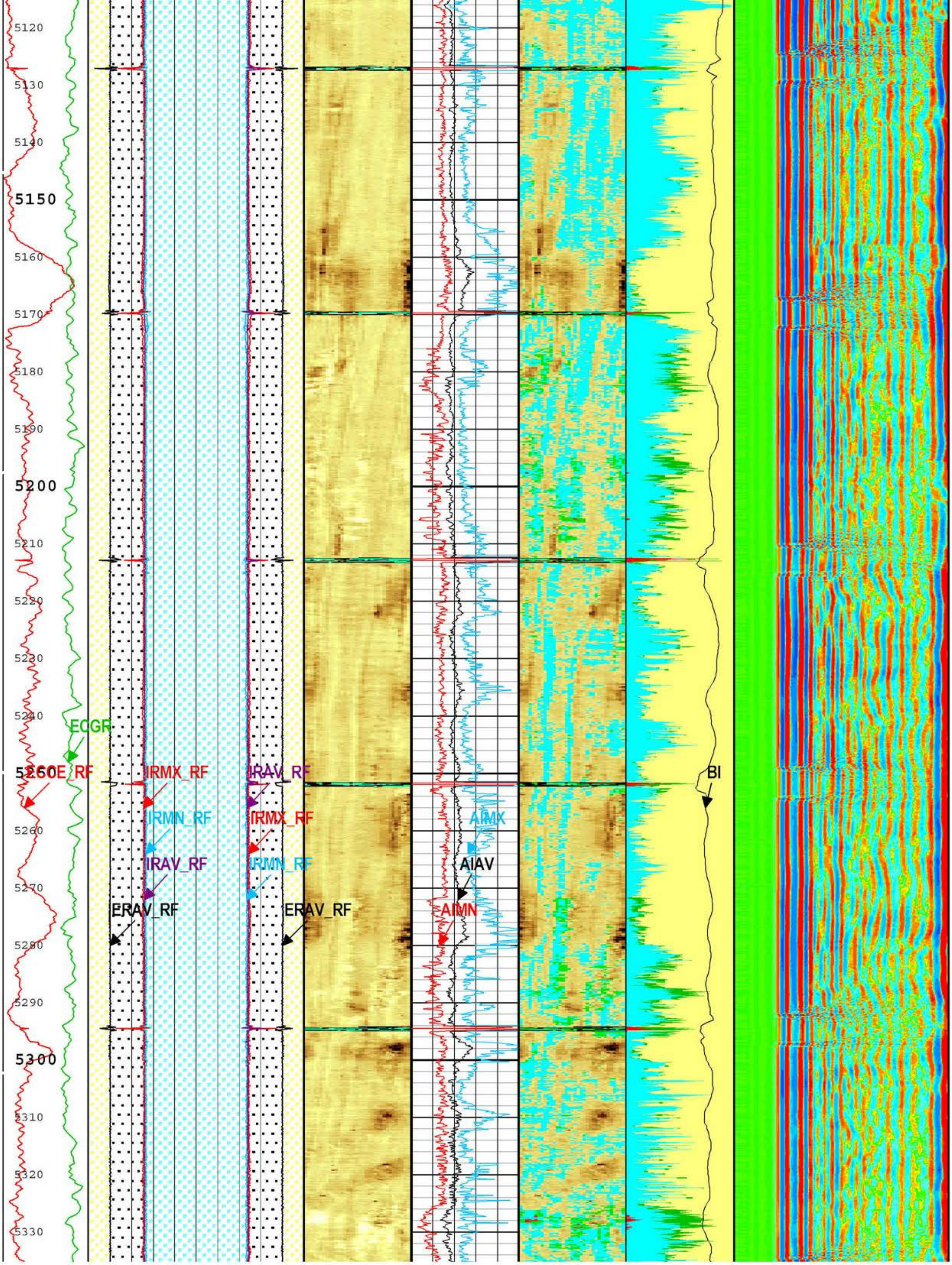
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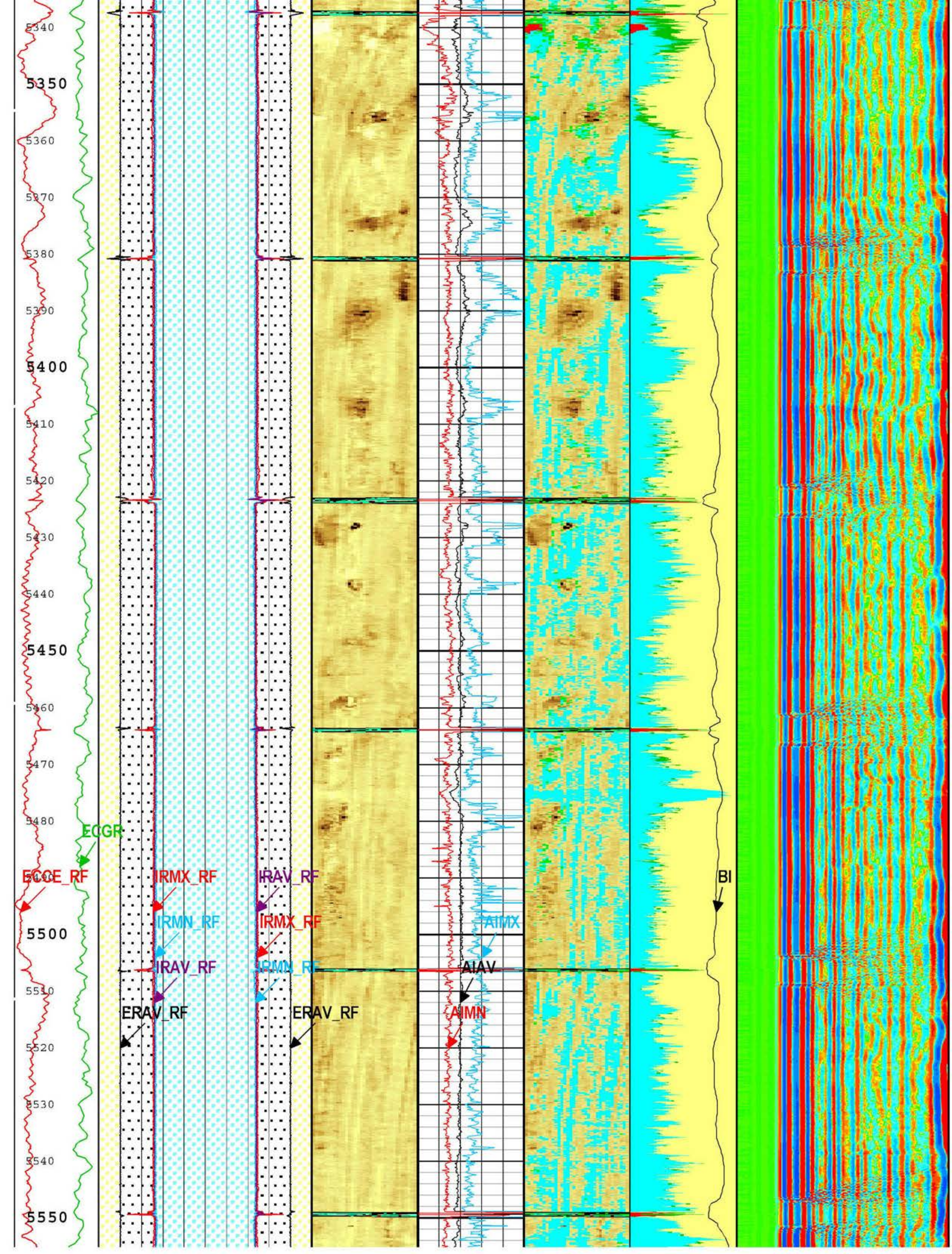
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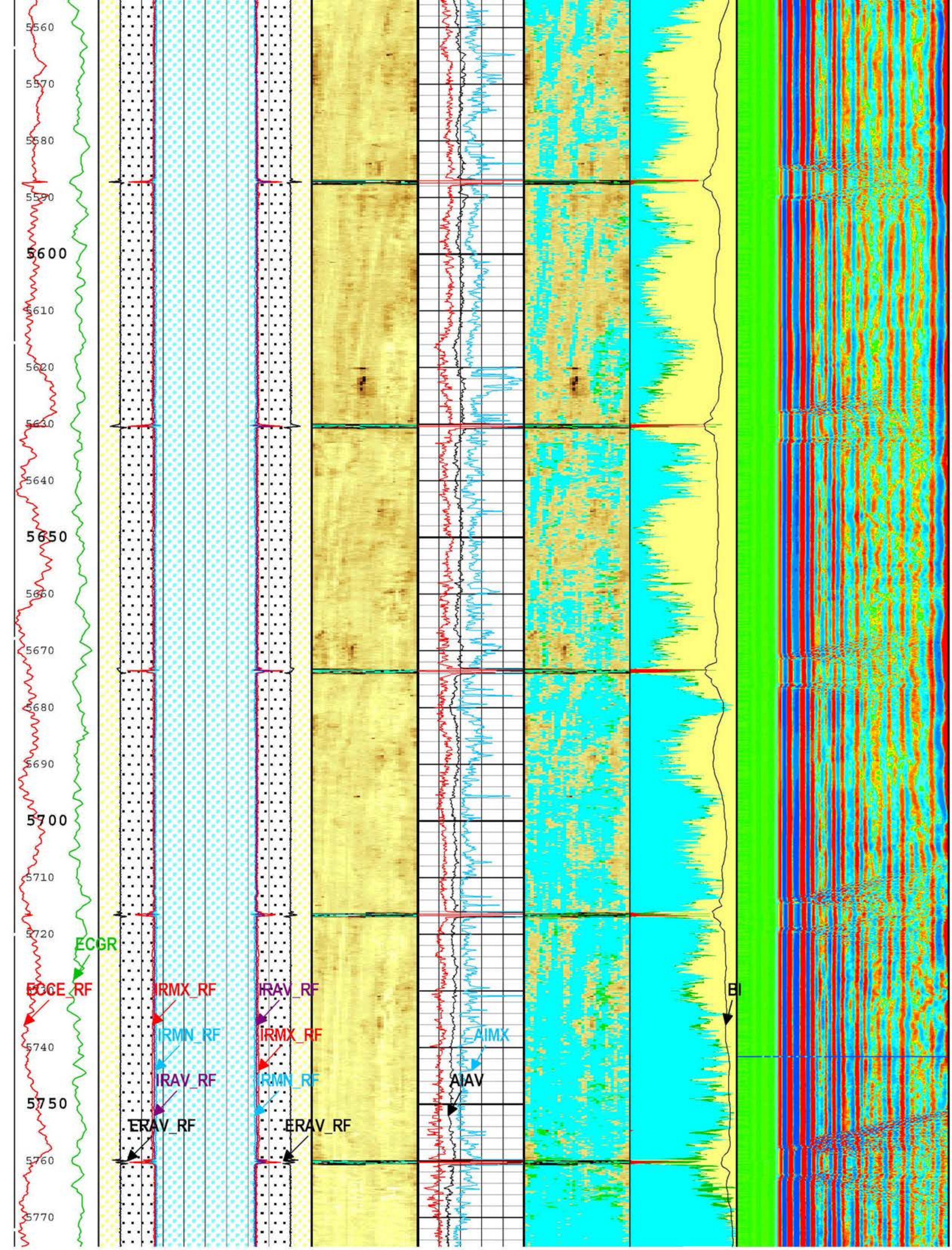
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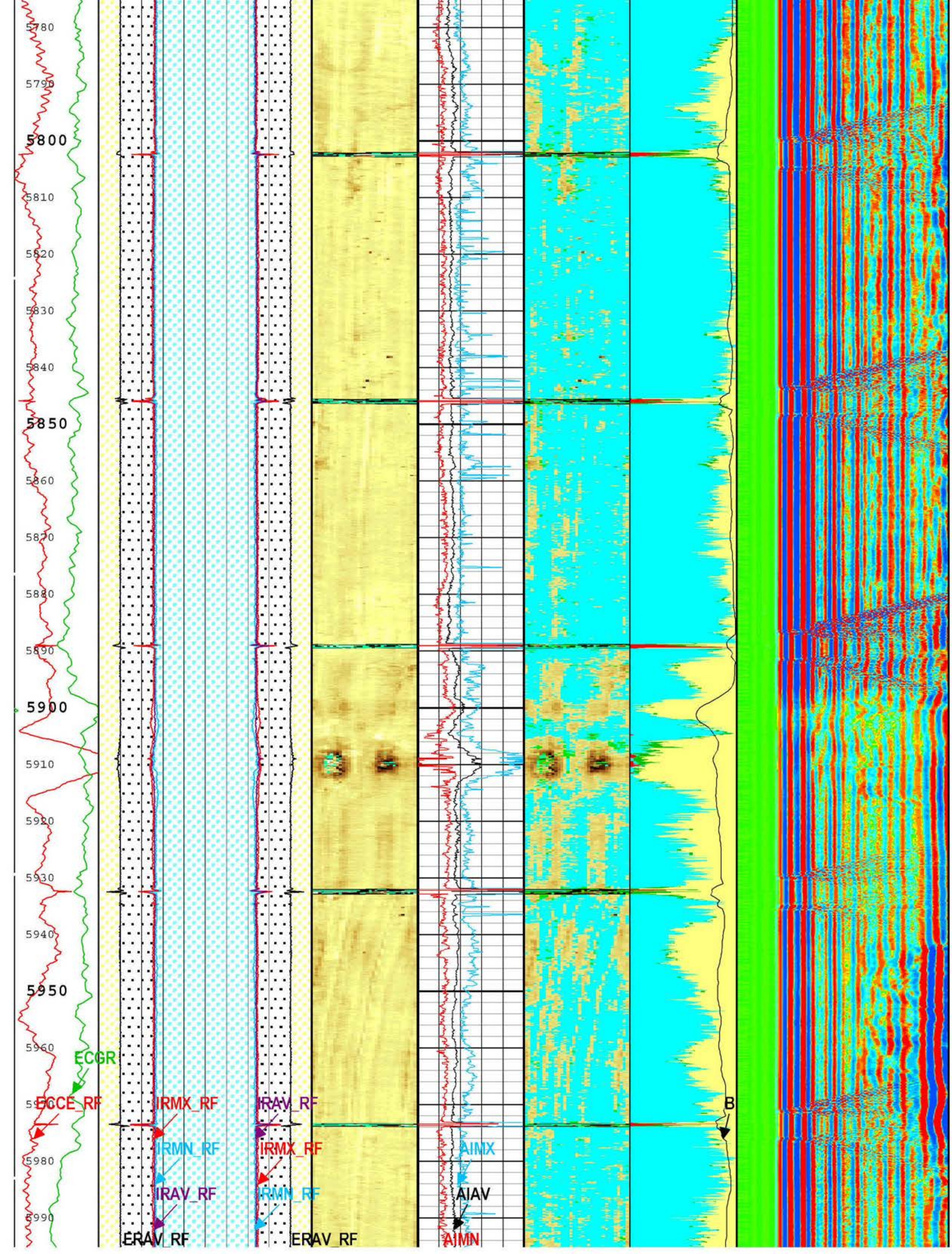
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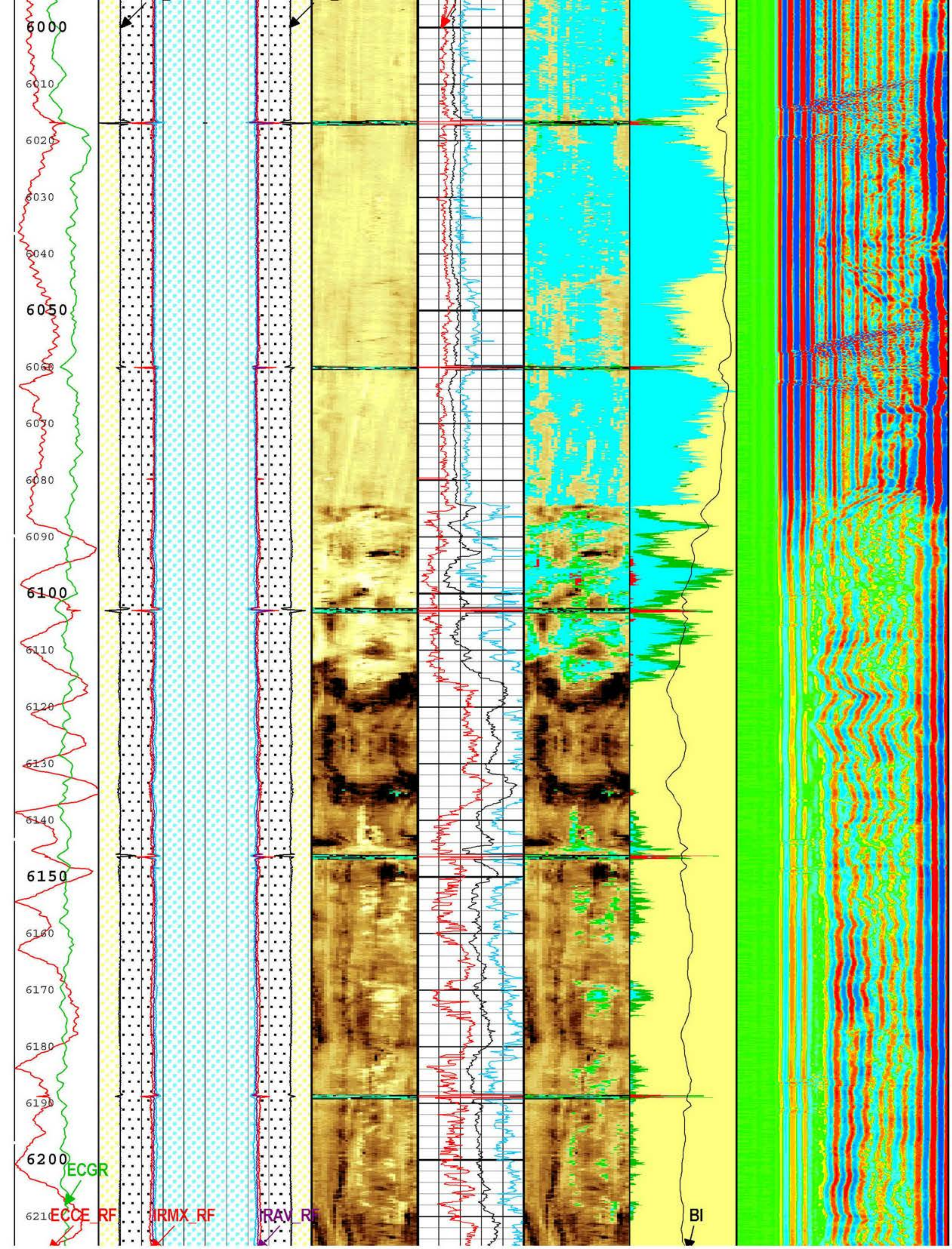
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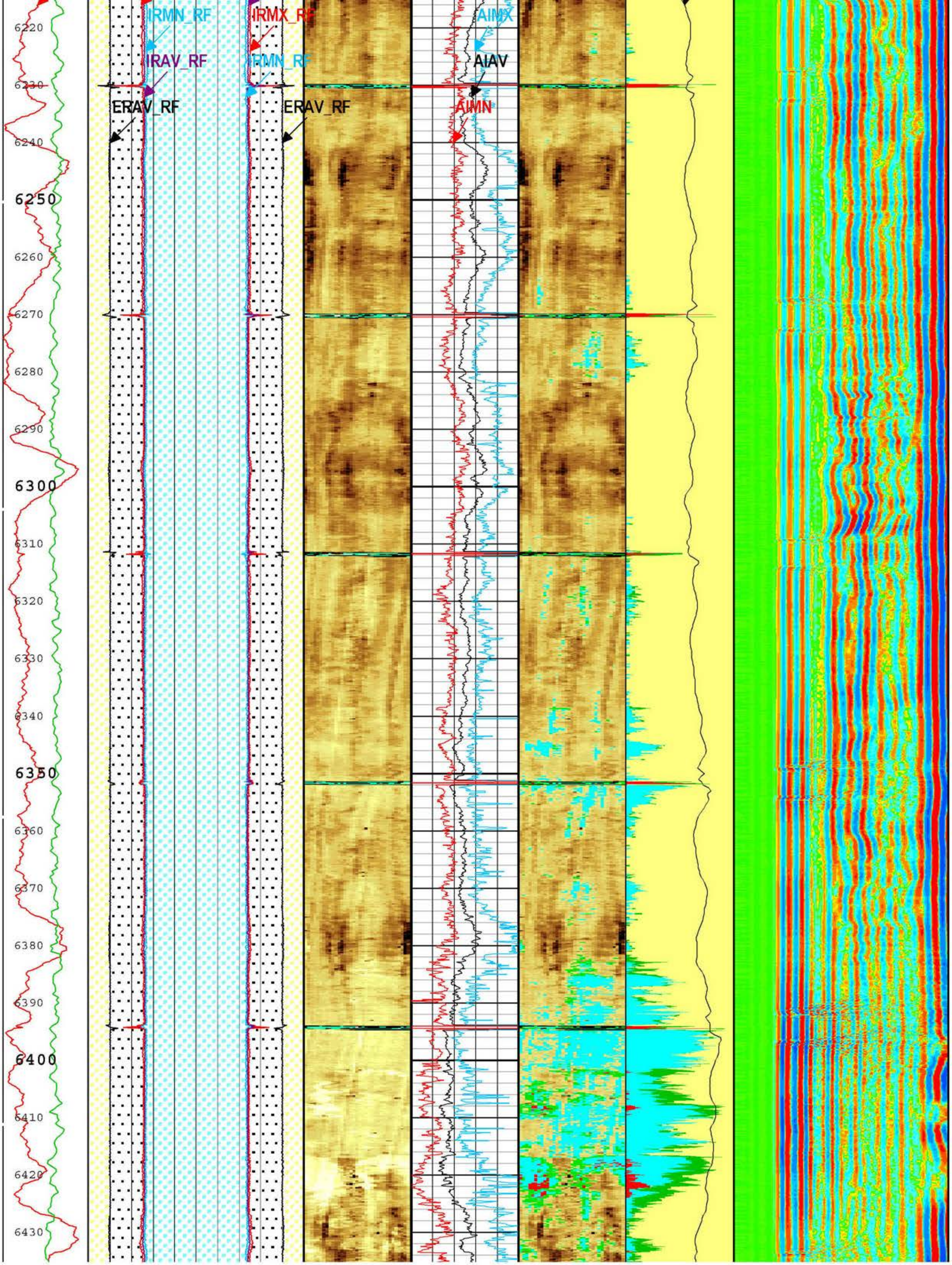
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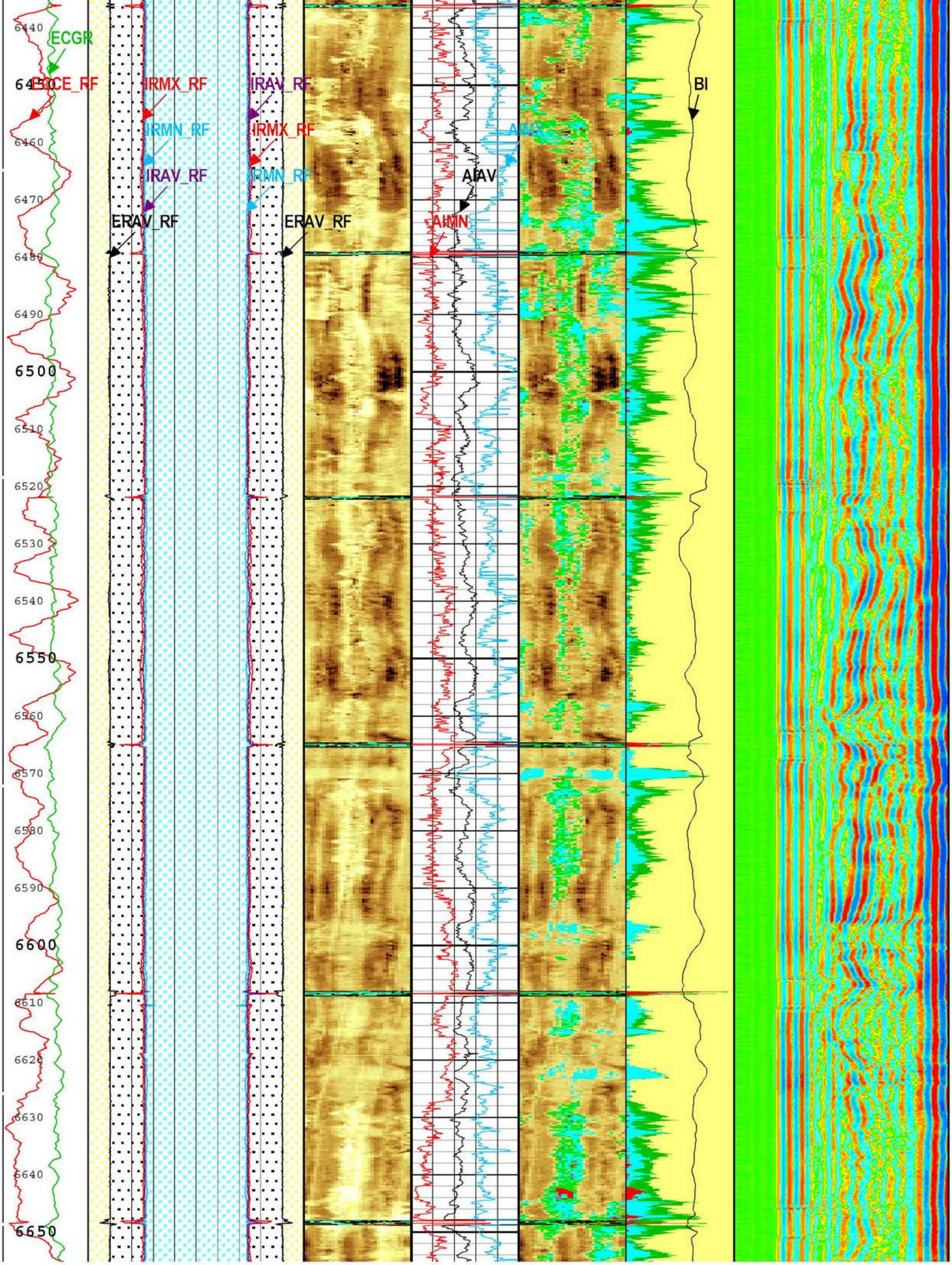
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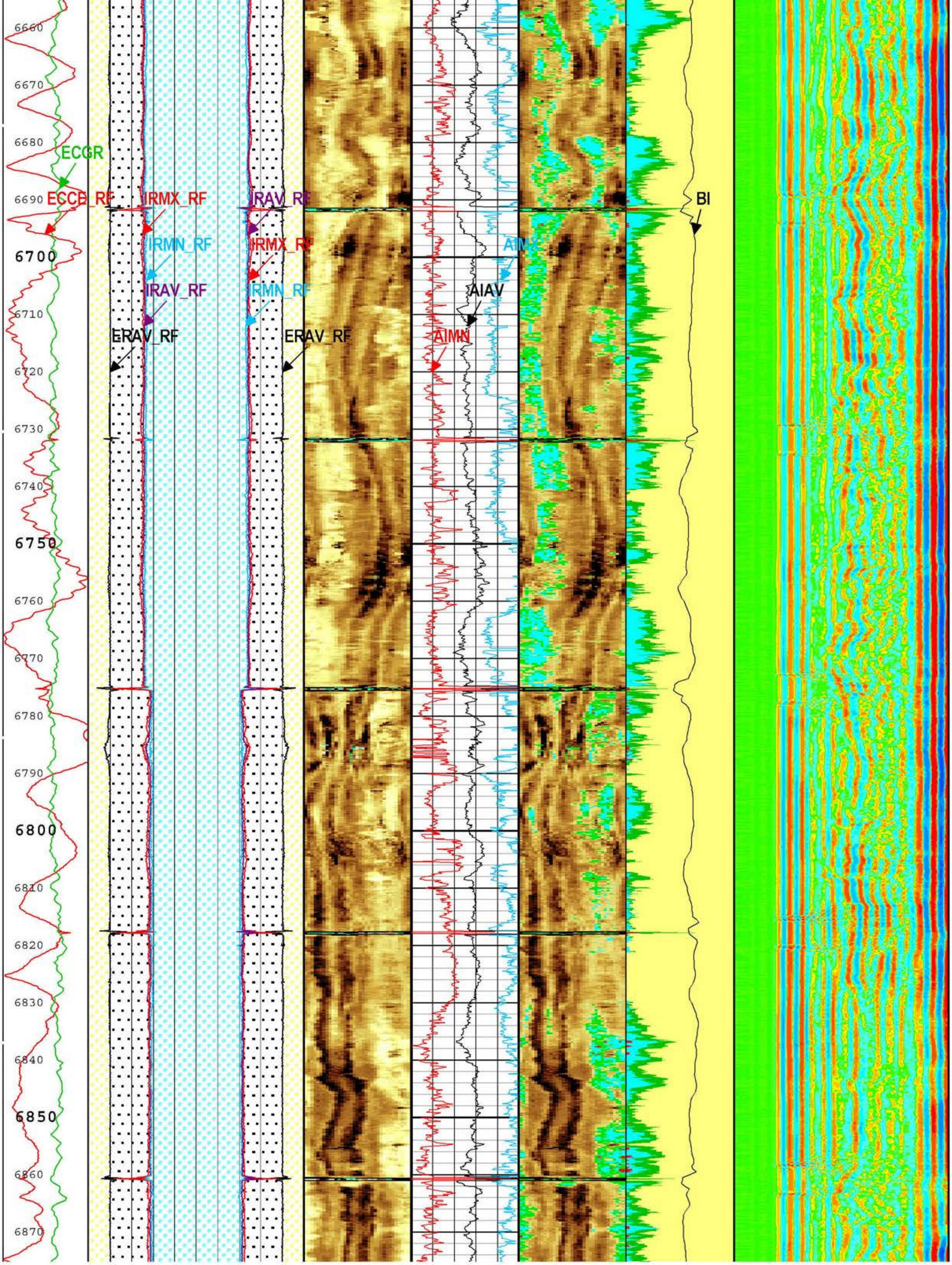
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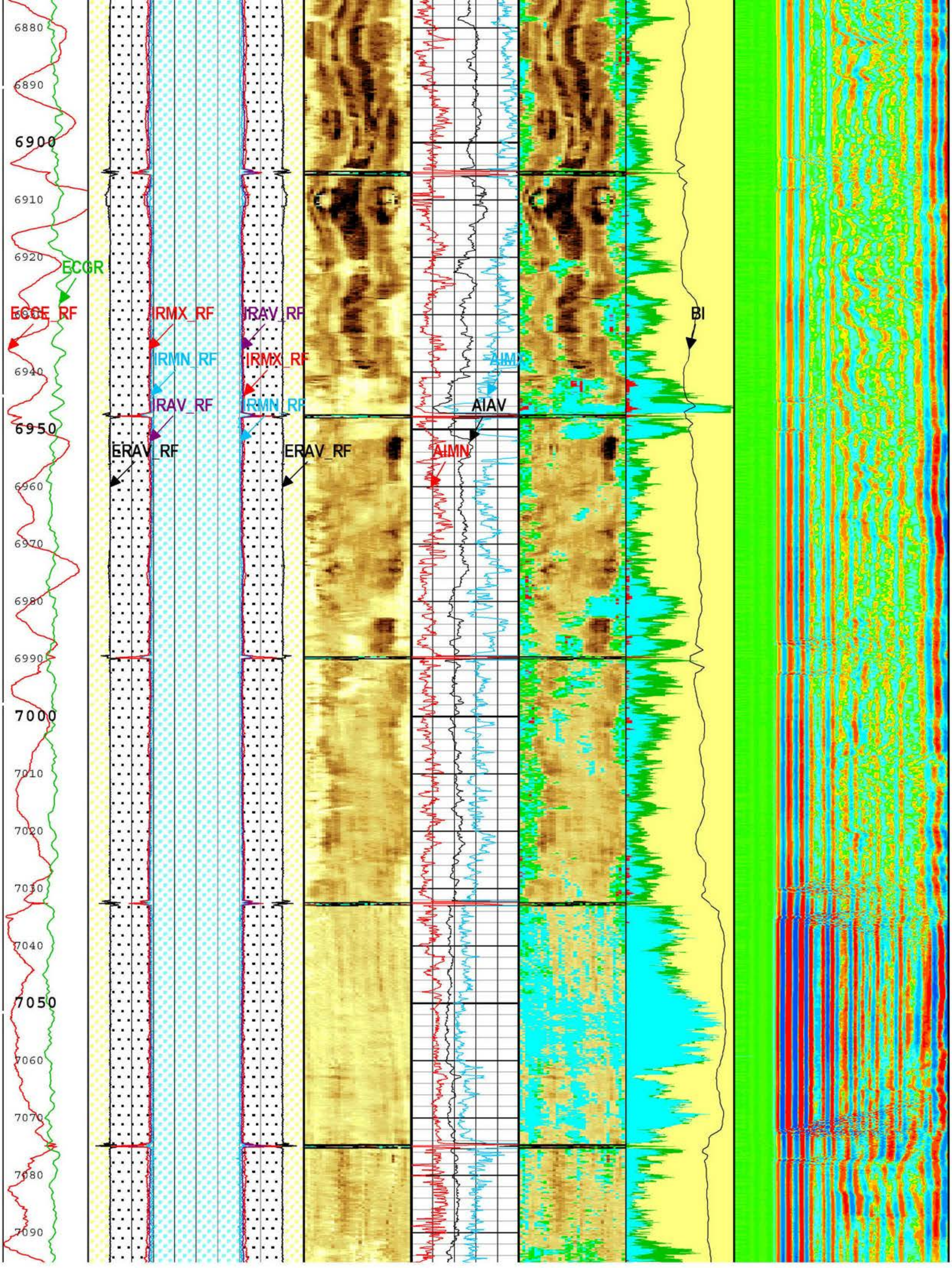
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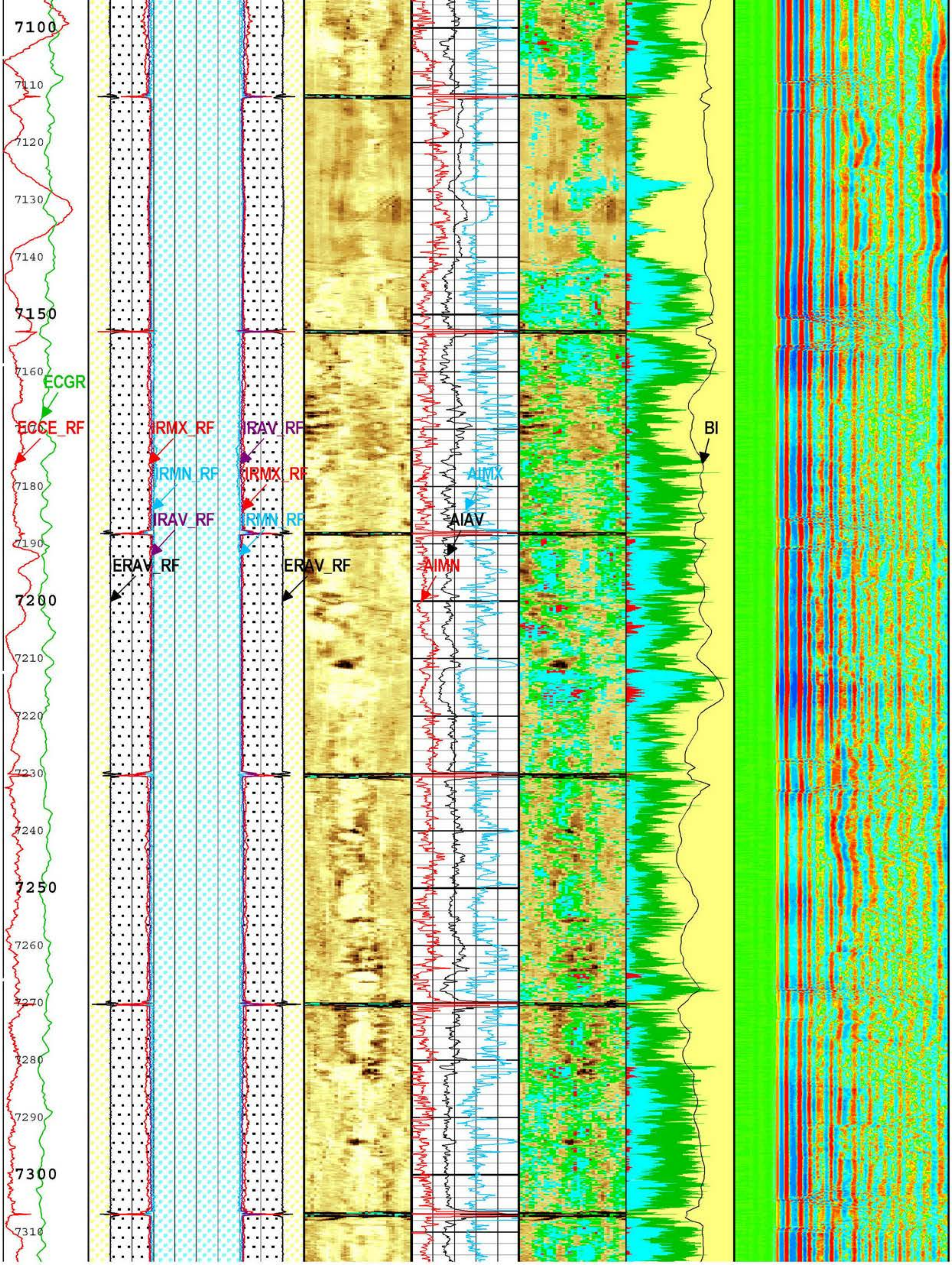
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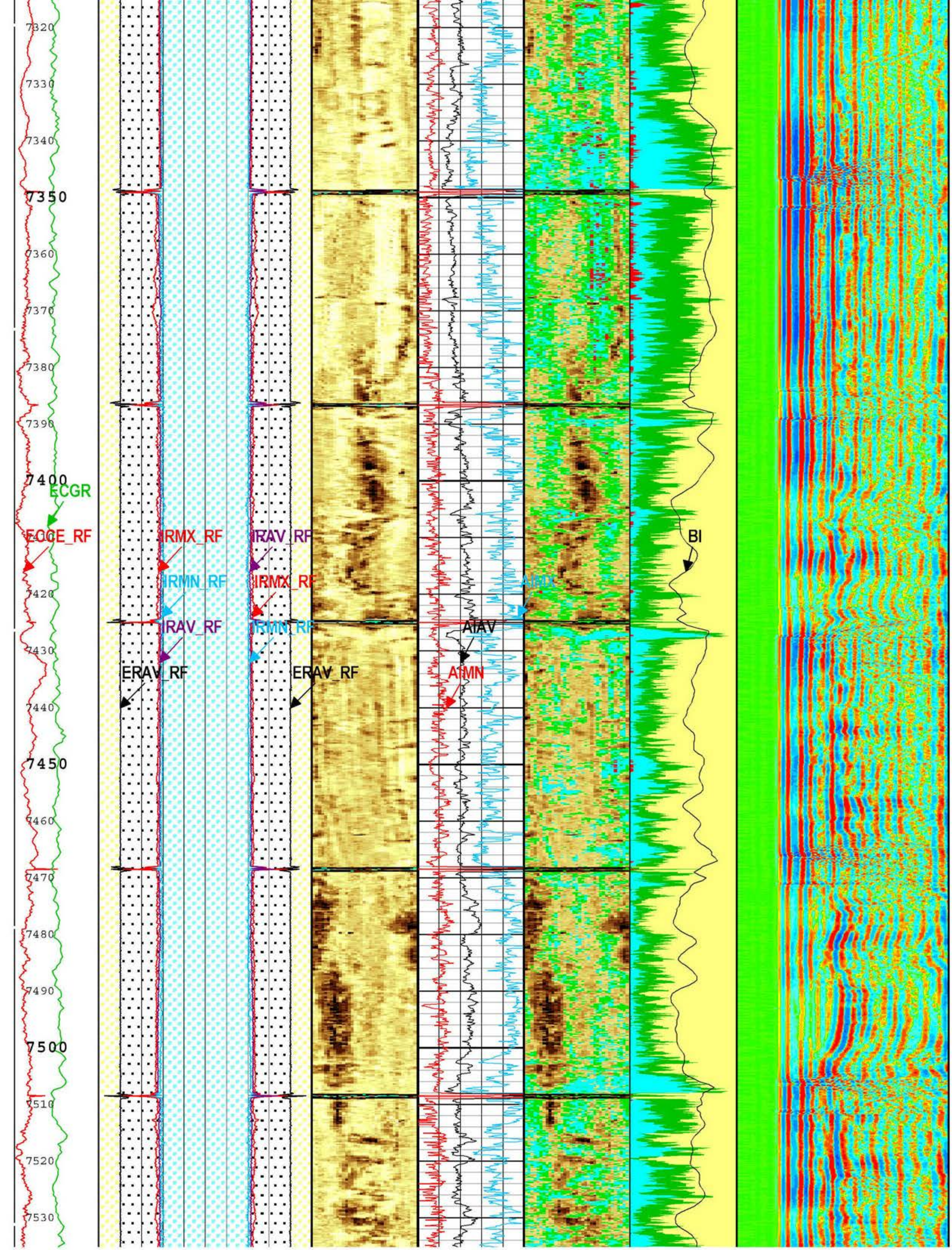
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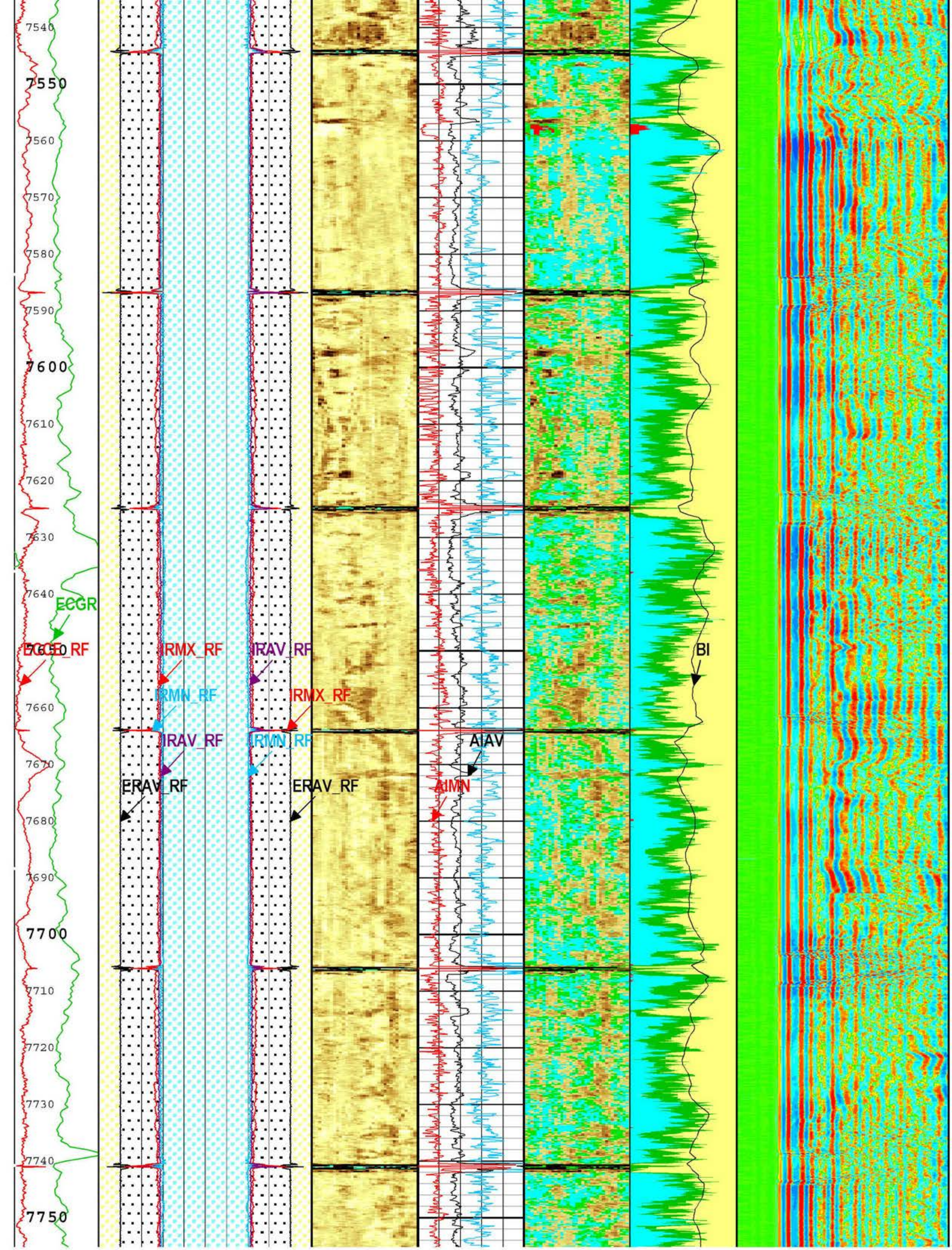
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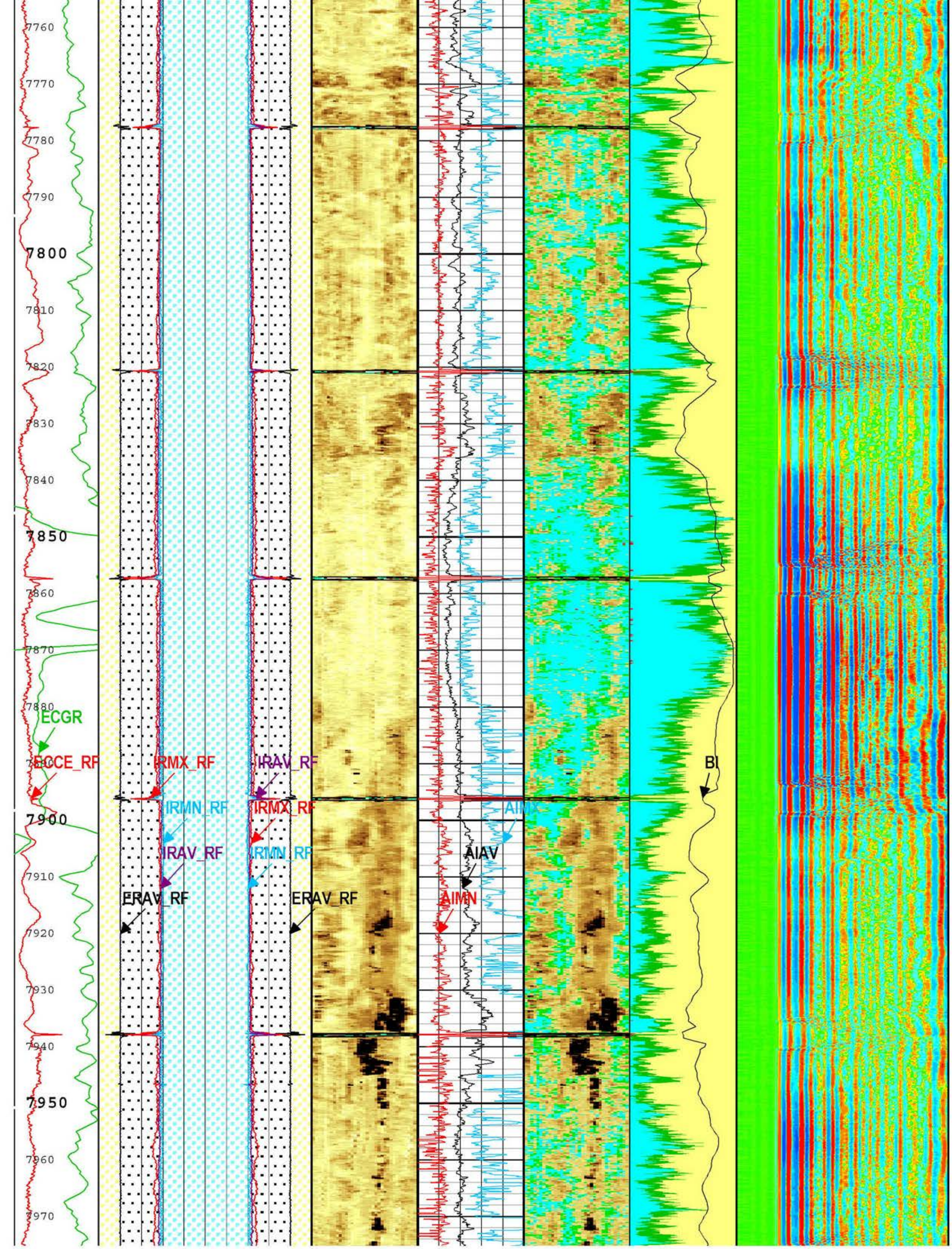
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AIAV
AIMN
BI
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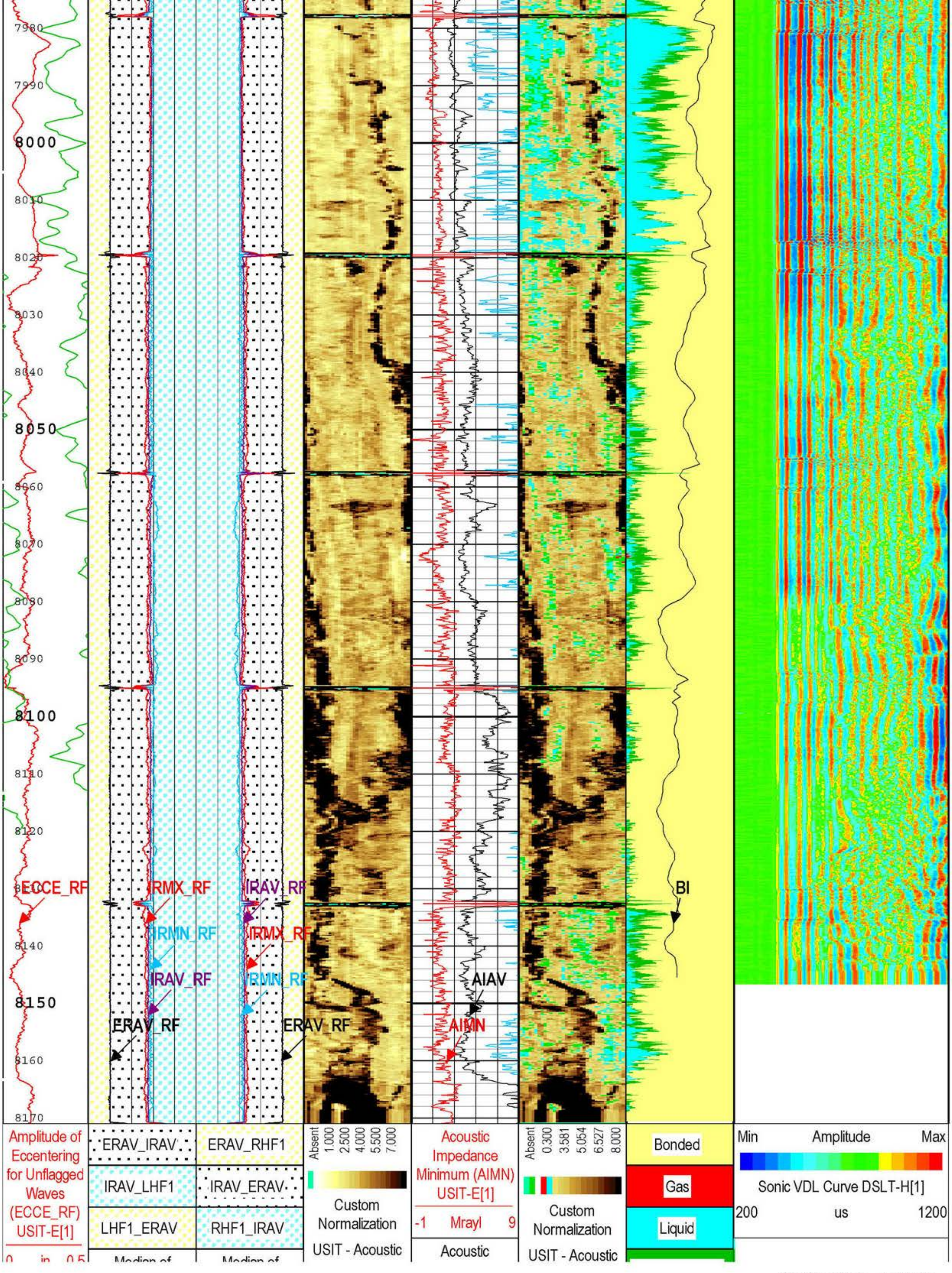
7970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ECCE_RF
IRMX_RF
IRAV_RF
IRMN_RF
IRMX_RF
IRAV_RF
IRMN_RF
ERAV_RF
ERAV_RF
AIAV
AIMN
BI
Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5
ERAV_IRAV
IRAV_LHF1
LHF1_ERAV
Median of
ERAV_RHF1
IRAV_ERAV
RHF1_IRAV
Median of
Absent 1.000 2.500 4.000 5.500 7.000
Custom Normalization
USIT - Acoustic
Acoustic Impedance Minimum (AIMN) USIT-E[1]
-1 Mrayl 9
Acoustic
Absent 0.300 3.581 5.054 6.527 8.000
Custom Normalization
USIT - Acoustic
Bonded
Gas
Liquid
Min Amplitude Max
Sonic VDL Curve DSLT-H[1]
200 us 1200

0 in 0.5

Gamma Ray (ECGR) HGNS[1]
0 gAPI 150

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7

Impedance (AIBK) USIT-E[1] (Mrayl)

Impedance Average (AIAV) USIT-E[1]
-1 Mrayl 9

Acoustic Impedance Maximum (AIMX) USIT-E[1]
-1 Mrayl 9

Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)

Micro-debonding

Bond Index (BI) DSLT-H[1]
1 0

TIME_1900 - Time Marked every 60.00 (s)

Description: USI VDL Cement Format: Log (LBV1_USI-VDL (DSLT) Cement 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth
Creation Date: 20-Oct-2016 14:28:02

Channel Processing Parameters

Two: Parameters

Parameter	Description	Tool	Value	Unit
AMSG	Auxiliary Minimum Sliding Gate	DSLT-H	140	us
ISSBAR	Barite Mud Presence Flag	Borehole	No	
BERJ	Bad Echo Rejection	USIT-E	On	
BHS	Borehole Status (Open or Cased Hole)	Borehole	Cased	
BILI	Bond Index Level for Zone Isolation	DSLT-H	0.8	
BS	Bit Size	WLSESSION	Depth Zoned	in
CASING_PRATIO	Casing Poisson Ratio	USIT-E	Standard Poisson Ratio	
CBLG	CBL Gate Width	DSLT-H	45	us
CBLO	Casing Bottom (Logger)	WLSESSION	8280	ft
CBRA	CBL LQC Reference Amplitude in Free Pipe	DSLT-H	62	mV
CDEN	Cement Density	HGNS-H	2	g/cm3
CMCF	CBL Cement Type Compensation Factor	DSLT-H	1	
CMTY(U-USIT_CEMT)	Cement Type	USIT-E	Regular Cement	
THNO	Nominal Casing Thickness - Zoned along logger depths	WLSESSION	Depth Zoned	in
DETE	Delta-T Detection	DSLT-H	E1	
DFD	Drilling Fluid Density	Borehole	9	lbm/gal
DFT	Drilling Fluid Type	Borehole	Water	
DTMD	Borehole Fluid Slowness	Borehole	206	us/ft
FCF	CBL Fluid Compensation Factor	DSLT-H	0.94	
FDII	FPM Data Interpolation Interval	USIT-E	0	ft
GCSE_DOWN_PASS	Generalized Caliper Selection for WL Log Down Passes	Borehole	BS	

GCSE_UP_PASS	Generalized Caliper Selection for WL Log Up Passes	Borehole	BS	
GOBO_CURR	Good Bond in Arbitrary Cement	DSLT-H	Depth Zoned	mV
GR_MULTIPLIER	Gamma Ray Multiplier	HGNS-H	1	
HEMA	Hematite Presence Flag	Borehole	No	
ICE_PROCESS	ICE Processing	USIT-E	Yes	
IMAR	Image Rotation	USIT-E	Off	
MAHTR	Manual High Threshold Reference for first arrival detection	DSLT-H	120	
MATT_CURR	Maximum Attenuation in Arbitrary Cement	DSLT-H	Depth Zoned	dB/ft
MCI	Minimum Cemented Interval for Isolation	DSLT-H	Depth Zoned	ft
MEAS_WLEN	Tcube Processing Window Length in Measurement Mode	USIT-E	Depth Zoned	us
MNHTR	Minimum High Threshold Reference for first arrival detection	DSLT-H	100	
MSA	Minimum Sonic Amplitude	DSLT-H	Depth Zoned	mV
MSA_CURR	Minimum Sonic Amplitude in Arbitrary Cement	DSLT-H	Depth Zoned	mV
MUD_N_FRP	Free Pipe Mud Normalization Factor	USIT-E	1.1	
MUD_N_THE	Theoretical Mud Normalization Factor	USIT-E	1	
NMSG	Near Minimum Sliding Gate	DSLT-H	285	us
NMXG	Near Maximum Sliding Gate	DSLT-H	950	us
NUMP	Number of Detection Passes	DSLT-H	2	
OPLEV	USIT Remove Flagged Data Level	USIT-E	OPT2	
RCOD	Reference Calibrator Outer Diameter	USIT-E	7	in
RCSO	Reference Calibrator Standoff	USIT-E	1.181	in
RCTH	Reference Calibrator Thickness	USIT-E	0.295	in
SDNV	Number of Vertical Samples used for Micro-debonding Computation	USIT-E	5	
SDTHOR	Acoustic Impedance STD Horizontal Threshold for Micro-debonding	USIT-E	0.5	Mrayl
SDTVER	Acoustic Impedance STD Vertical Threshold for Micro-debonding	USIT-E	0.3	Mrayl
SFAF	Sonic Formation Attenuation Factor	DSLT-H	3.25	dB/ft
SGAD	Sliding Gate Status	DSLT-H	Off	
SGCL	Sliding Gate Closing Delta-T	DSLT-H	130	us/ft
SGCW	Sliding Gate Closing Width	DSLT-H	25	us
SGDT	Sliding Gate Delta-T	DSLT-H	57	us/ft
SGW	Sliding Gate Width	DSLT-H	110	us
SLEV	Signal Level for AGC	DSLT-H	5000	mV
SOCN	Standoff Distance	HGNS-H	0.125	in
SOCO	Standoff Correction Option	HGNS-H	No	
TCUB	T^3 Processing Level	USIT-E	Loop	
THDH	Maximum Search Thickness (percentage of nominal)	USIT-E	Time Zoned	%
THDL	Minimum Search Thickness (percentage of nominal)	USIT-E	Time Zoned	%
HISC	Tool Position: Centered or Eccentered	HGNS-H	Eccentered	
U-USIT_DFSZ	Drilling Fluid Specific Acoustic Impedance	USIT-E	0.1	Mrayl
UFGDE	Fiberglass Density	USIT-E	1.95	g/cm3
UFGPS	Fiberglass Processing Selection	USIT-E	No	
UFGVL	Fiberglass Velocity	USIT-E	9678.48	ft/s
USI_FSOD	USIT USI Fluid Slowness Fits Casing Outer Diameter	USIT-E	0_OFF	
USI_FVEL_SEL	USI Fluid Velocity Selection	USIT-E	Automatic	
USI_ZMUD_SEL	USI Mud Impedance Selection	USIT-E	FreePipe Norm.	
THDP	Thickness Detection Policy	USIT-E	Fundamental	
VCAS	Ultrasonic Transversal Velocity in Casing	USIT-E	51.4	us/ft
VDLG	VDL Manual Gain	DSLT-H	5	
ZCAS	Acoustic Impedance of Casing	USIT-E	46.25	Mrayl

ZCMT	Acoustic Impedance of Cement	DSLT-H	6.8	Mrayl
ZCMT_NEAT	Acoustic Impedance of Cement in Neat Cement	DSLT-H	6.8	Mrayl
ZINI	Initial Estimate of Cement Impedance	USIT-E	-1	Mrayl
ZMUD	Acoustic Impedance of Mud	Borehole	1.48	Mrayl
ZTCM	Acoustic Impedance Threshold for Cement	USIT-E	2.6	Mrayl
ZTGS	Acoustic Impedance Threshold for Gas	USIT-E	0.3	Mrayl

TwoDepth Zoned Parameters

Parameter	Value	Start (ft)	Stop (ft)
BS	17.5	0	770
BS	12.25	770	6187
BS	11.75	6187	7421
BS	11	7421	8171
THNO	0.362	0	179
THNO	0.317	179	6774
THNO	0.362	6774	8171
GOBO_CURR	2.87	0	179
GOBO_CURR	1.87	179	6774
GOBO_CURR	2.87	6774	8171
MATT_CURR	11.82	0	179
MATT_CURR	13.39	179	6774
MATT_CURR	11.82	6774	8171
MCI	21.68	0	770
MCI	10	770	8171
MEAS_WLEN	22.5	0	179
MEAS_WLEN	19.62	179	6774
MEAS_WLEN	22.5	6774	8171
MSA	1.33	0	179
MSA	0.78	179	6774
MSA	1.33	6774	8171
MSA_CURR	1.33	0	179
MSA_CURR	0.78	179	6774
MSA_CURR	1.33	6774	8171

All depth are actual.

TwoTime Zoned Parameters

Pass Log[9]:Up

Parameter	Value	Start Time	Stop Time	Start Depth (ft)	Stop Depth (ft)
THDH	125	20-Oct-2016 09:51:44	20-Oct-2016 10:20:40	8171.38	6648.71
THDL	60	20-Oct-2016 09:51:44	20-Oct-2016 10:20:40	8171.38	6648.71

Pass Log[11]:Up

THDH	125	20-Oct-2016 10:26:34	20-Oct-2016 12:34:00	6648.71	113.27
THDL	60	20-Oct-2016 10:24:53	20-Oct-2016 12:00:23	6648.71	1633.75
THDL	70	20-Oct-2016 12:00:23	20-Oct-2016 12:34:00	1633.75	113.27

Pass Log[14]:Up

THDH	130	20-Oct-2016 12:53:24	20-Oct-2016 12:58:23	155.15	5.56
THDL	70	20-Oct-2016 12:53:24	20-Oct-2016 12:58:23	155.15	5.56

All depth are at tool zero.

Tool Control Parameters

Tool Control Parameters

Two: Parameters

Parameter	Description	Tool	Value	Unit
AGMN	Minimum Gain of Cartridge	USIT-E	-12	dB
AGMX	Maximum Gain of Cartridge	USIT-E	18	dB
DDEL	Digitizing Delay	DSLT-H	0	us
U-USIT_DDT5	USIC Downhole Decimation for T5 only	USIT-E	0_NONE	
DOT(DOS)	Distance between Opposite Transducer Faces	USIT-E	2.874	in
MODE	DSLT Acquisition Mode	DSLT-H	CBL	
RATE	DSLT Firing Rate	DSLT-H	15 Hz	
DTFS	DSLT Telemetry Frame Size	DSLT-H	536	
DWCO	Digitizer Word Count	DSLT-H	250	
EMXV	EMEX Voltage	USIT-E	Time Zoned	V
HRES	Horizontal Resolution	USIT-E	10 deg	
MOTOR_PROTECT	Motor Protection	USIT-E	On	
SDTH	Switch Down Threshold	DSLT-H	20000	
SGAI	Selectable Acquisition Gain	DSLT-H	x1	
SUTH	Switch Up Threshold	DSLT-H	1000	
TMUC	Type of Mud	USIT-E	BRI	
UACLV_PERM	Ultrasonic ACLV Permanent	USIT-E	No	
ULOG	Logging Objective	USIT-E	MEASUREMENT	
UMFR	Modulation Frequency	USIT-E	333333	Hz
USFR	Ultrasonic Sampling Frequency	USIT-E	500000	Hz
UPAT	USIT Emission Pattern	USIT-E	Pattern 500 KHz	
UWKM	USIT Working Mode	USIT-E	Uncompressed 10 deg at 1.5 in LF	
USIT_DEPTHLOG	Starting Depth Log for Ultrasonics	USIT-E	Time Zoned	ft
USSP	Ultrasonic Service	USIT-E	USI	
VRES	Vertical Resolution	USIT-E	1.5 in	
WINB	Window Begin Time	USIT-E	25	us
WINE	Window End Time	USIT-E	90	us
WMOD	Waveform Firing Mode	DSLT-H	Full	

TwoTime Zoned Parameters

Pass Log[9]:Up

Parameter	Value	Start Time	Stop Time	Start Depth (ft)	Stop Depth (ft)
EMXV	50	20-Oct-2016 09:51:44	20-Oct-2016 10:20:40	8171.38	6648.71

Pass Log[11]:Up

EMXV	60	20-Oct-2016 10:24:53	20-Oct-2016 11:05:14	6648.71	4600.07
EMXV	65	20-Oct-2016 11:05:14	20-Oct-2016 12:34:00	4600.07	113.27

Pass Log[14]:Up

EMXV	100	20-Oct-2016 12:53:24	20-Oct-2016 12:54:59	155.15	76.32
EMXV	110	20-Oct-2016 12:54:59	20-Oct-2016 12:57:44	76.32	16.88
EMXV	125	20-Oct-2016 12:57:44	20-Oct-2016 12:58:23	16.88	5.56

All depth are at tool zero.

Composite 1

Main Pass 5 IN = 100 FT

Composite Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[9]:Up	Up	6640.29 ft	8171.85 ft	20-Oct-2016 9:51:39 AM	20-Oct-2016 10:20:40 AM	ON	1.47 ft	No
Two	Log[11]:Up	Up	36.69 ft	6737.51 ft	20-Oct-2016 10:24:53 AM	20-Oct-2016 12:34:00 PM	ON	1.35 ft	No
Two	Log[14]:Up	Up	5.56 ft	155.15 ft	20-Oct-2016 12:53:24 PM	20-Oct-2016 12:58:23 PM	ON	1.96 ft	No

All depths are referenced to toolstring zero

Log

Company:Southern California Gas Company Well:Frew 4

Composite 1:S008

Description: USI Composite Format: Log (LBV1_USI Composite 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:19

TIME_1900 - Time Marked every 60.00 (s)

USIT Processing Flags (UFLG[0]) USIT-E[1]

1 - UFLG 1 Value within [0.0 - 1.5] - :	⬛	UTIM Error
2 - UFLG 2 Value within [1.5 - 2.5] - :	🟫	Pulse Origin Not Detected
3 - UFLG 3 Value within [2.5 - 3.5] - :	🟥	WINLEN Error
4 - UFLG 4 UFLG 5 UFLG 6 Value within [3.5 - 6.5] - :	🟦	Casing Thickness Error
5 - UFLG 7 UFLG 8 UFLG 9 Value within [6.5 - 10] - :	🟦	Loop Processing Error

Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5

Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8

Gamma Ray (ECGR) HGNS[1]
0 gAPI 150

Absent 1.500 3.500
Explicit Normalization
USIT - USIT Processing Flags (UFLG) USIT-E[1]

USIT Processing Flags (UFLG[0]) USIT-E[1]
1 5

Absent -4.799 -2.799 -0.800
Explicit Normalization
USIT - Amplitude of Unflagged Wave (AWBK_RF) USIT-E[1] (dB)

Minimum of Unflagged Wave Amplitude (AWMN_RF) USIT-E[1]
0 dB 75

Average of Unflagged Wave Amplitude (AWAV_RF) USIT-E[1]
0 dB 75

Maximum of Unflagged Wave Amplitude (AWMX_RF) USIT-E[1]
0 dB 75

ERAV
ERAV-IRAV
IRAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7

IRAV
ERAV
IRAV-ERAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7

Absent -0.051 -0.012 0.028 0.068
Explicit Normalization
USIT - Unflagged Internal Radii minus Median Internal Radius (IRBKM_RF) USIT-E[1] (in)

Minimum of Unflagged Casing Thickness (THMN_RF) USIT-E[1]
0.1 in 0.6

Nominal Casing Thickness (THNO) USIT-E[1]
0.1 in 0.6

Median of Unflagged Casing Thickness (THAV_RF) USIT-E[1]
0.1 in 0.6

Maximum of Unflagged Casing Thickness (THMX_RF) USIT-E[1]
0.1 in 0.6

Absent -0.051 -0.012 0.028 0.068
Explicit Normalization
USIT - Unflagged Casing Thickness minus Median of Unflagged Casing Thickness (THBKM_RF) USIT-E[1] (in)

Absent 1.500 3.500 5.500 7.500
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)

Ratio of Cement Measurements to Total (CEMR) USIT-E[1]
1 0

Micro-debonding Ratio (MDR) USIT-E[1]
1 0

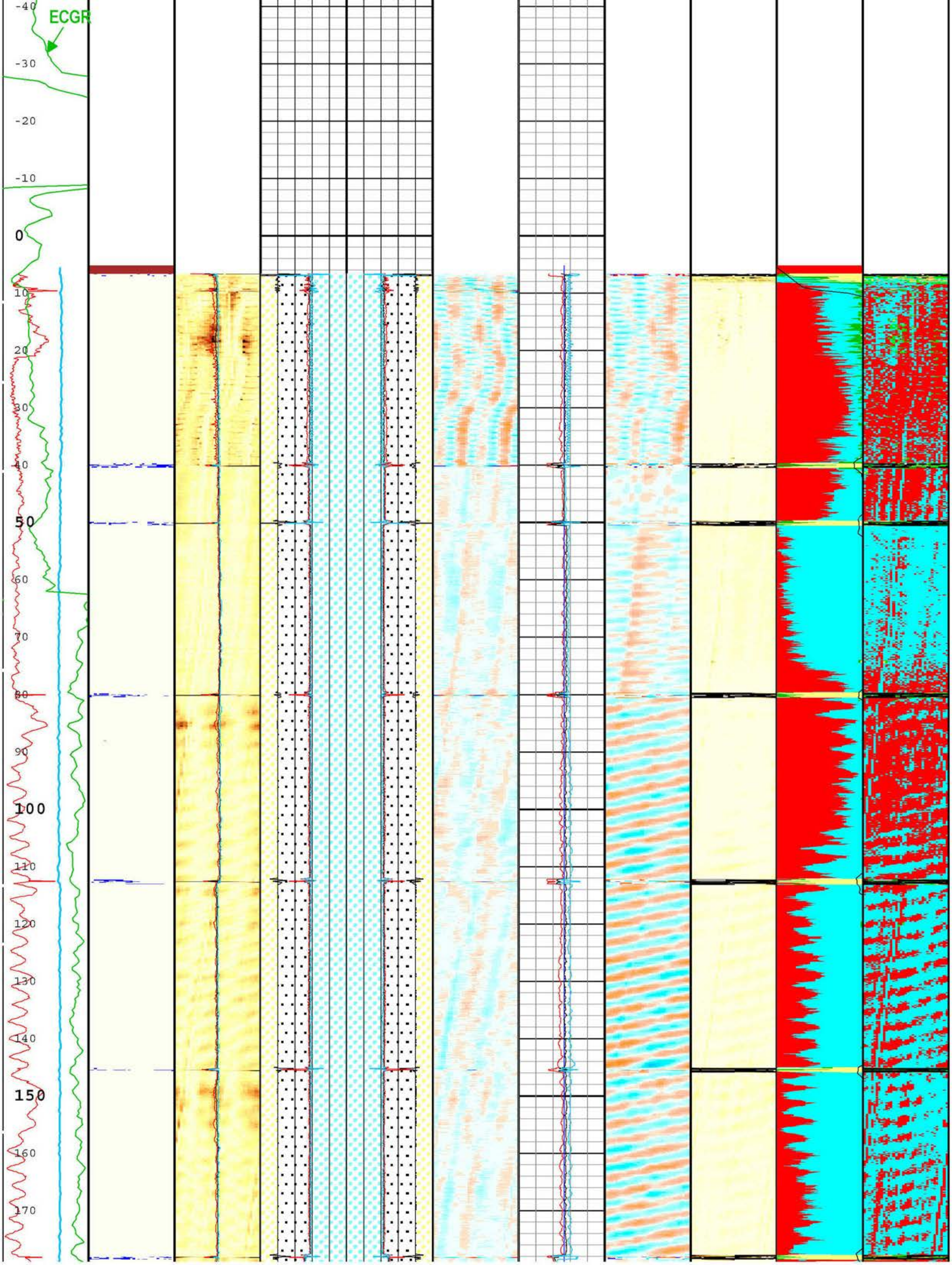
Ratio of Gas Measurements to Total (GASR) USIT-E[1]
1 0

Bonded
Gas
Liquid
Micro-debonding

Bond Index (BI) DSLT-H[1]
1 0

Absent 3.090 5.054 7.018
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)

Absent 2.599 4.563 6.527
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)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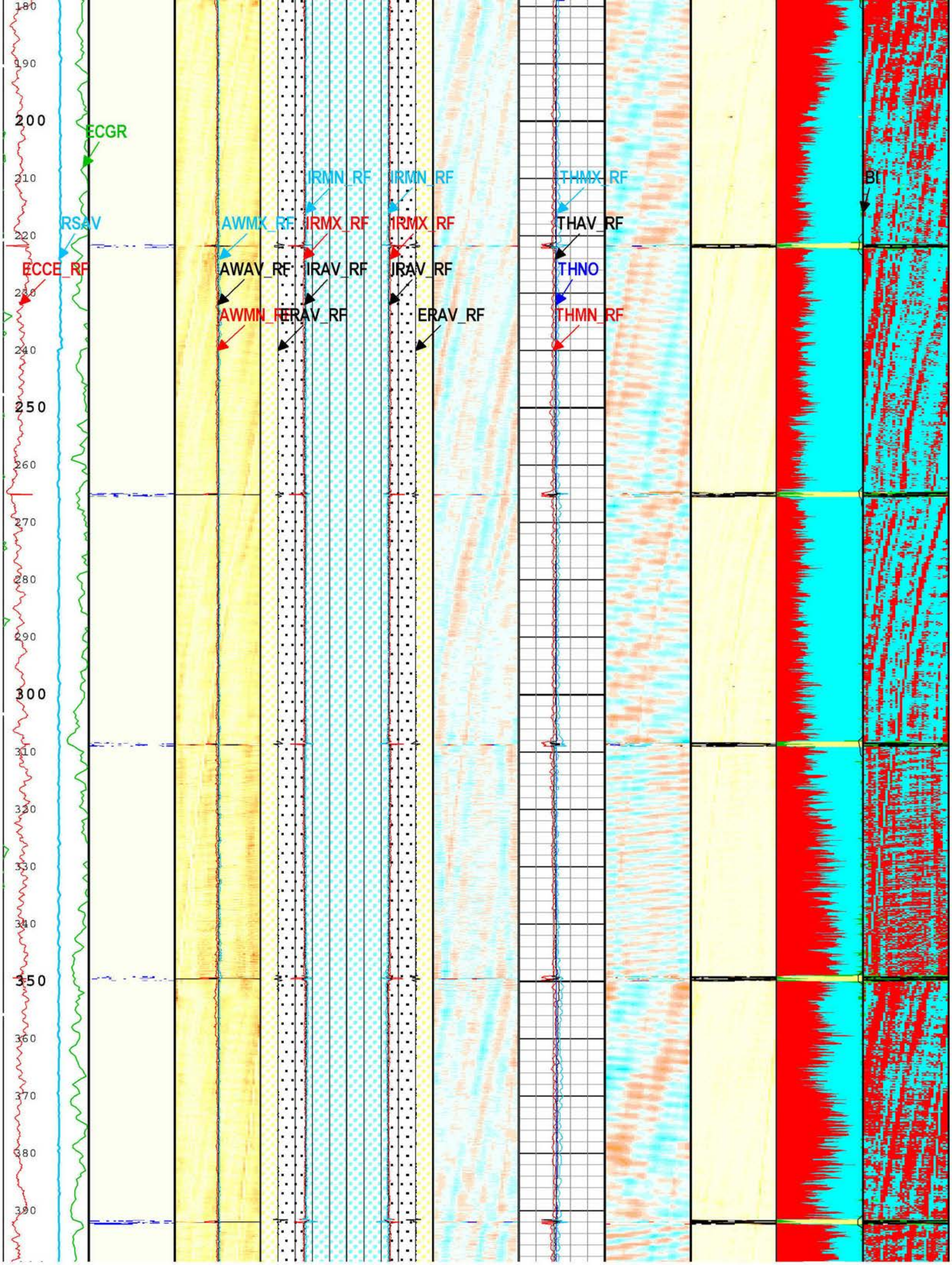
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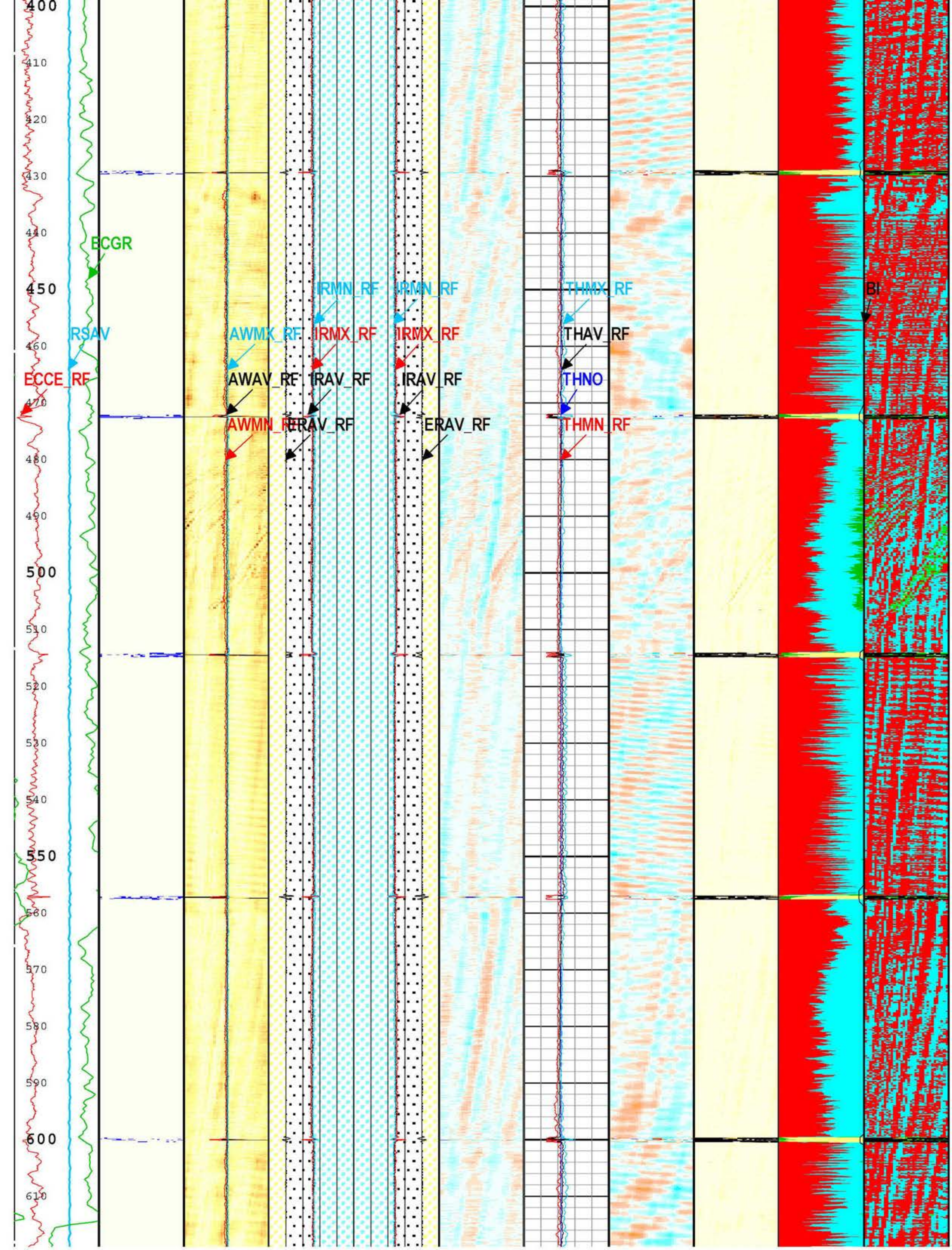
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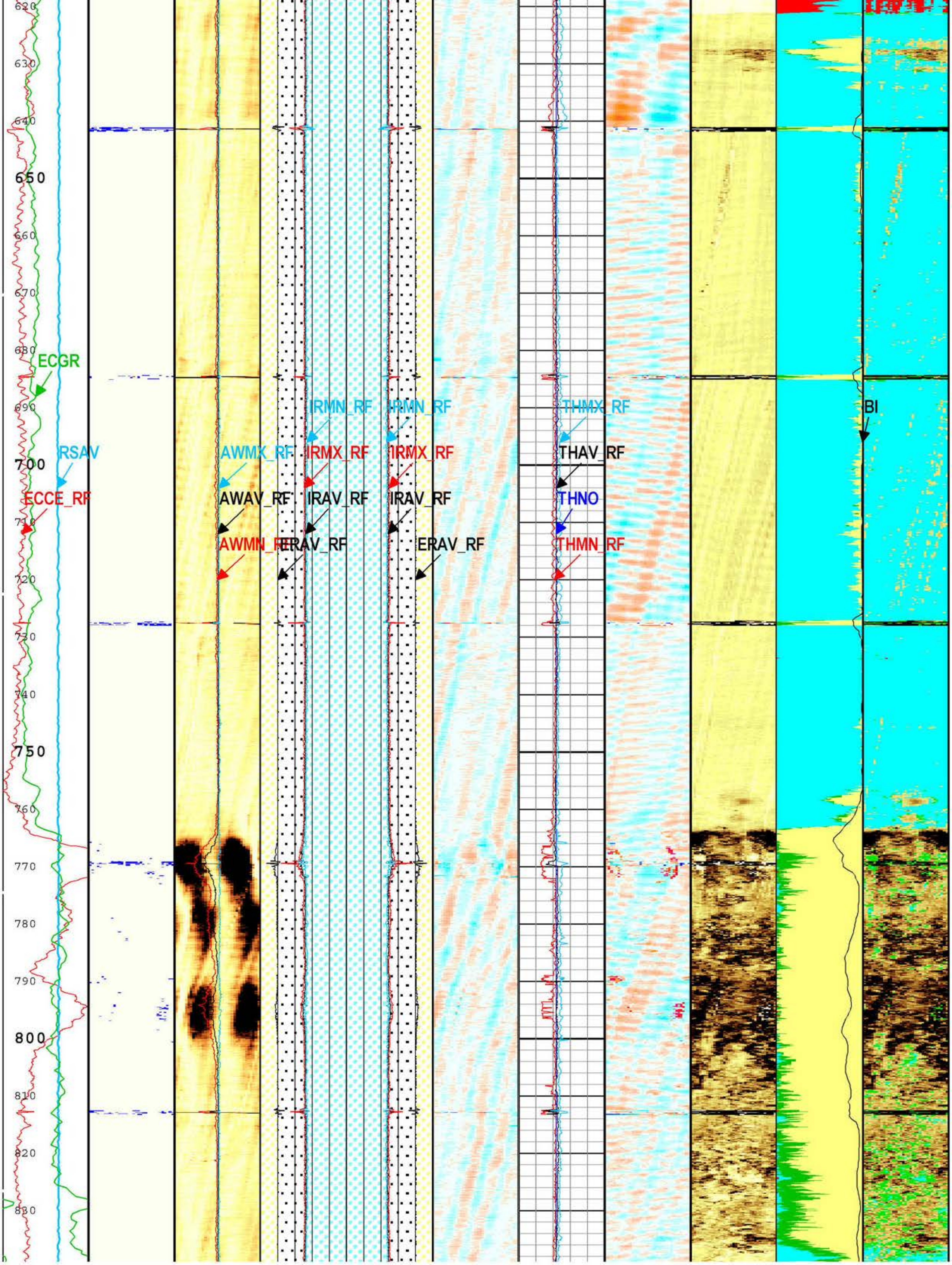
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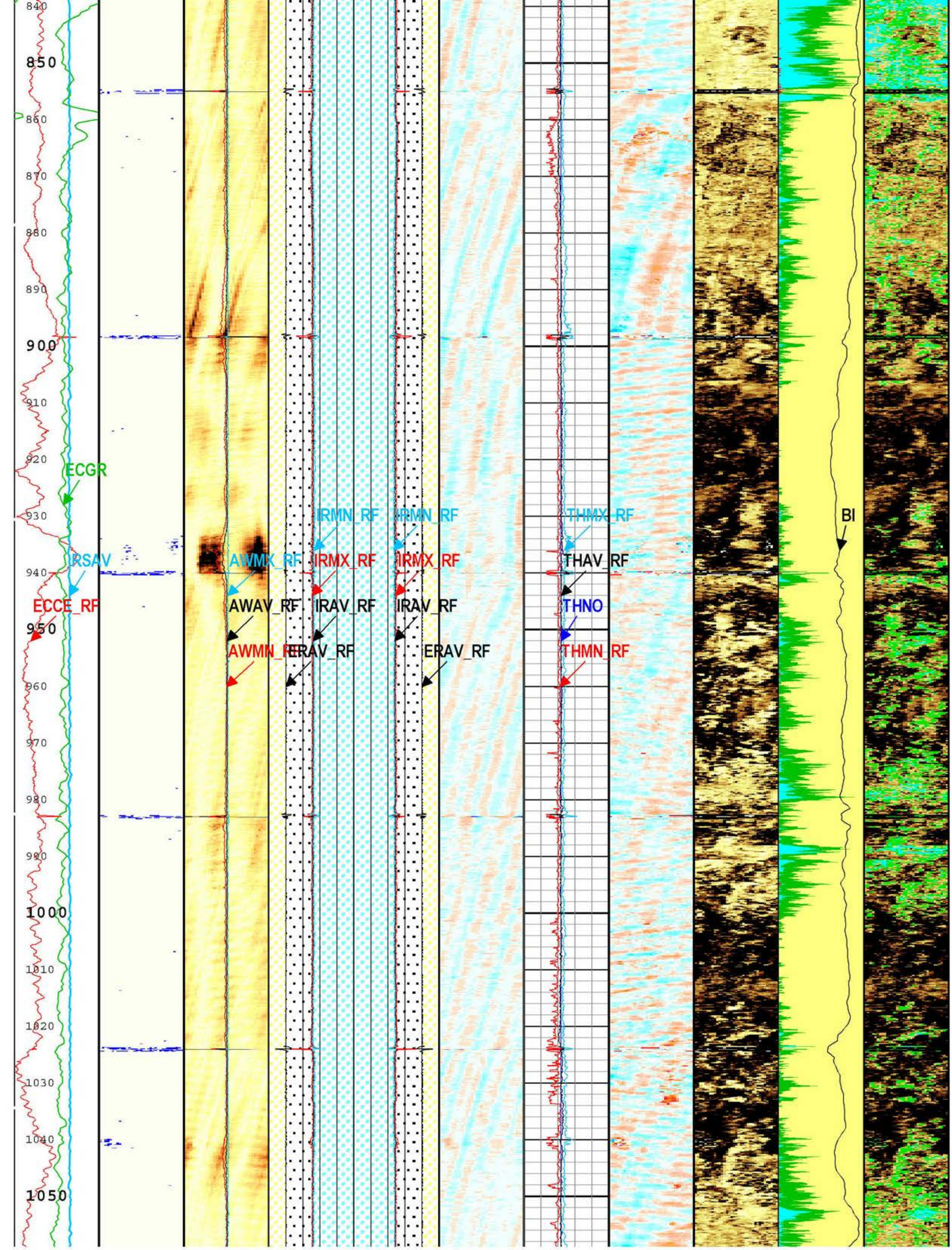
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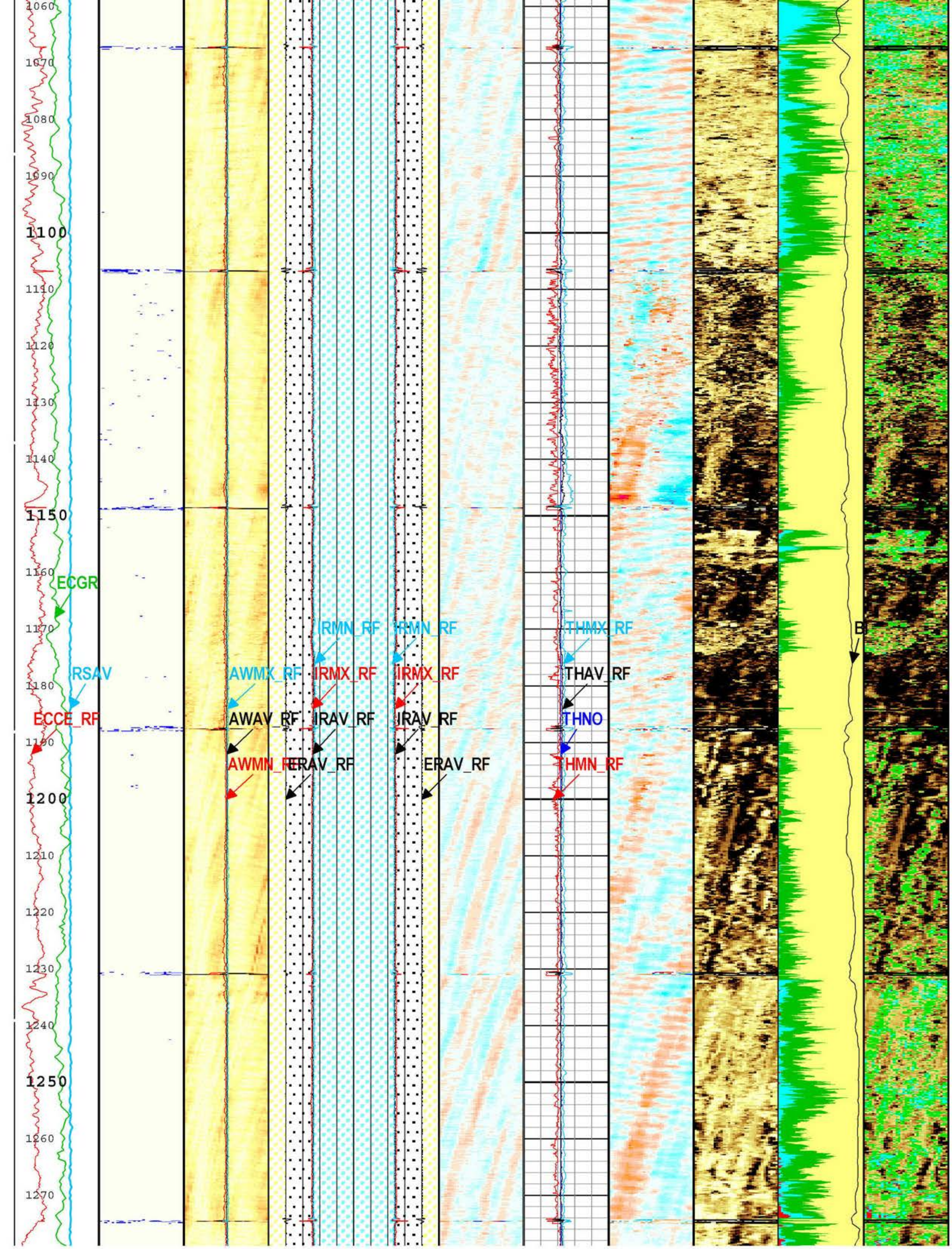
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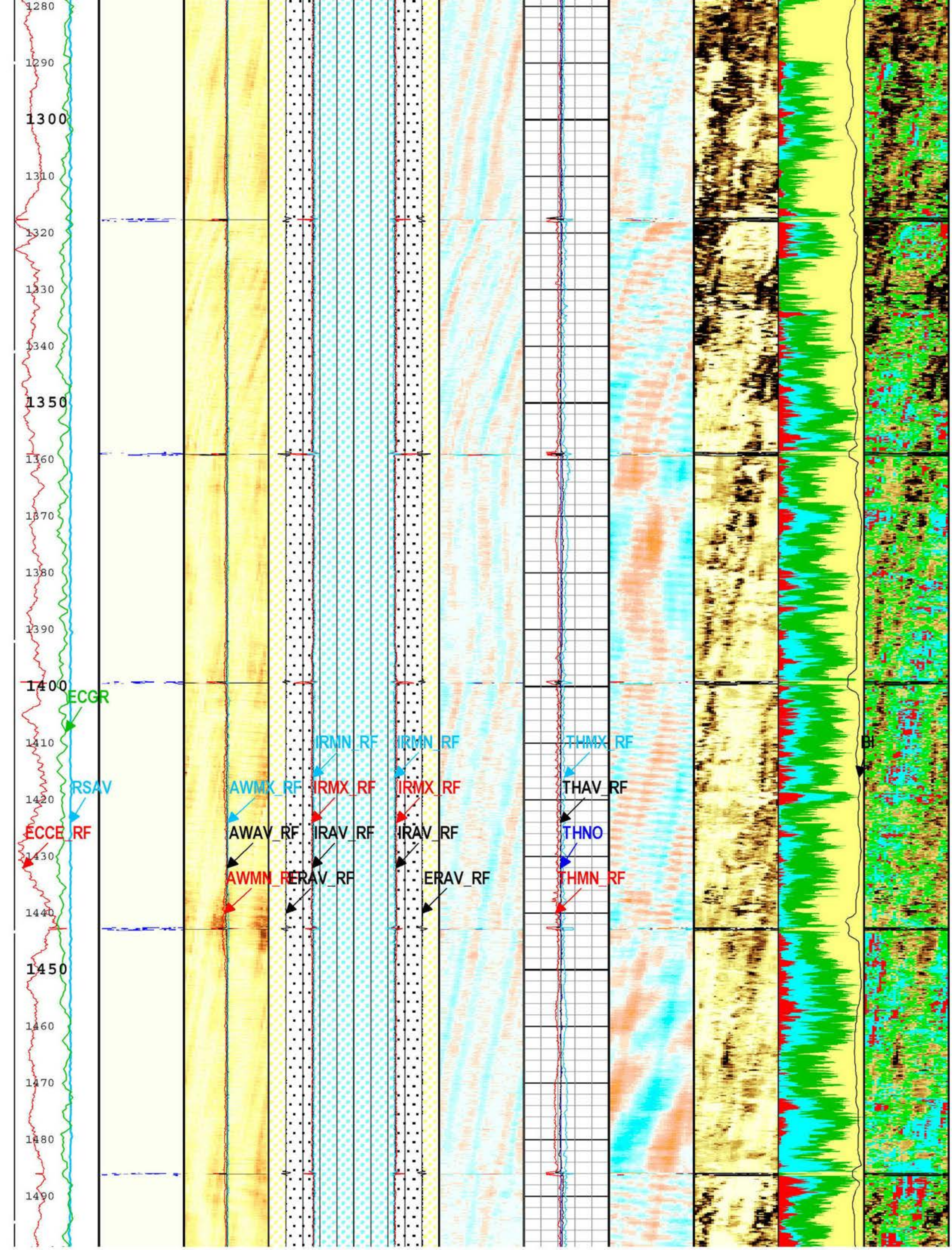
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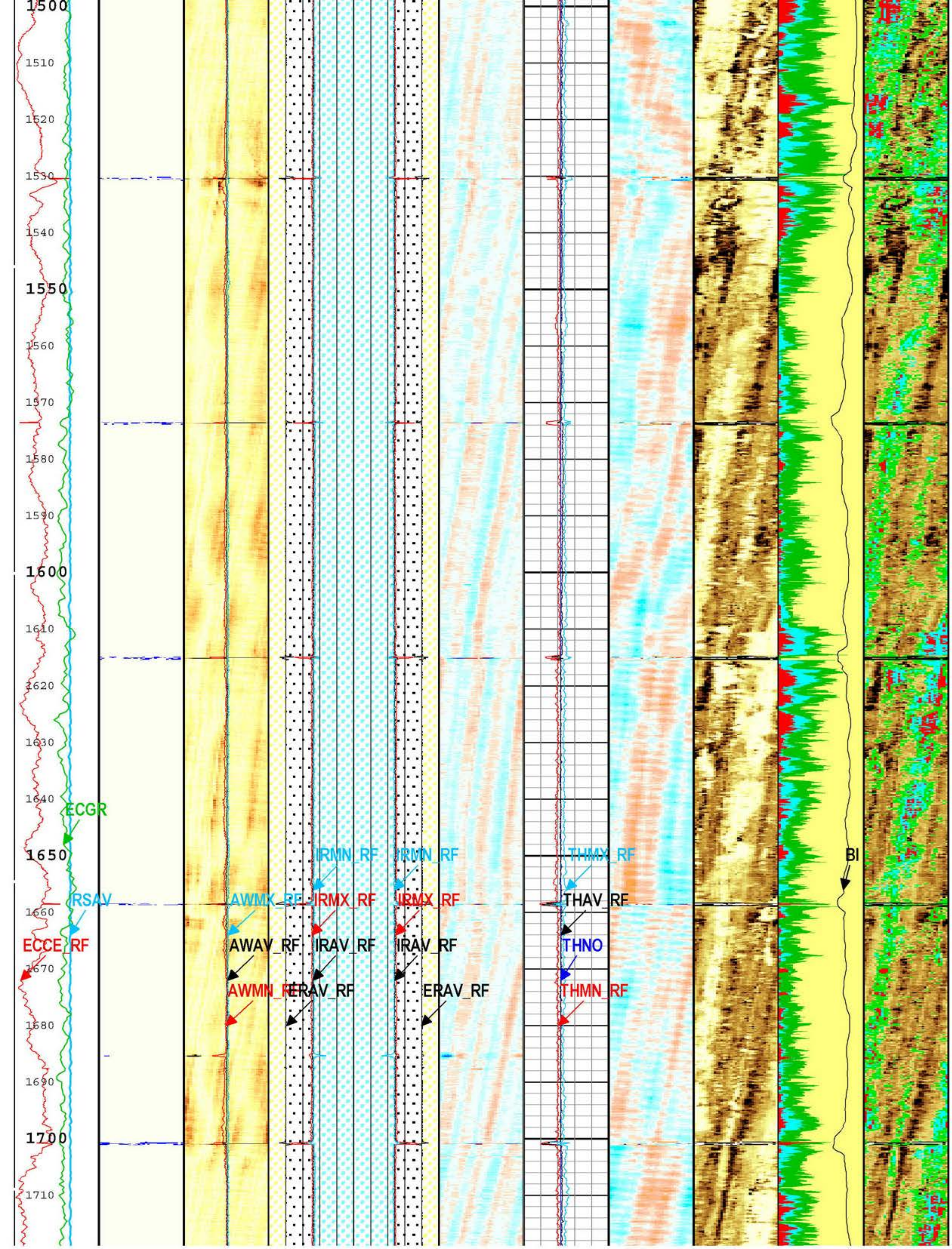
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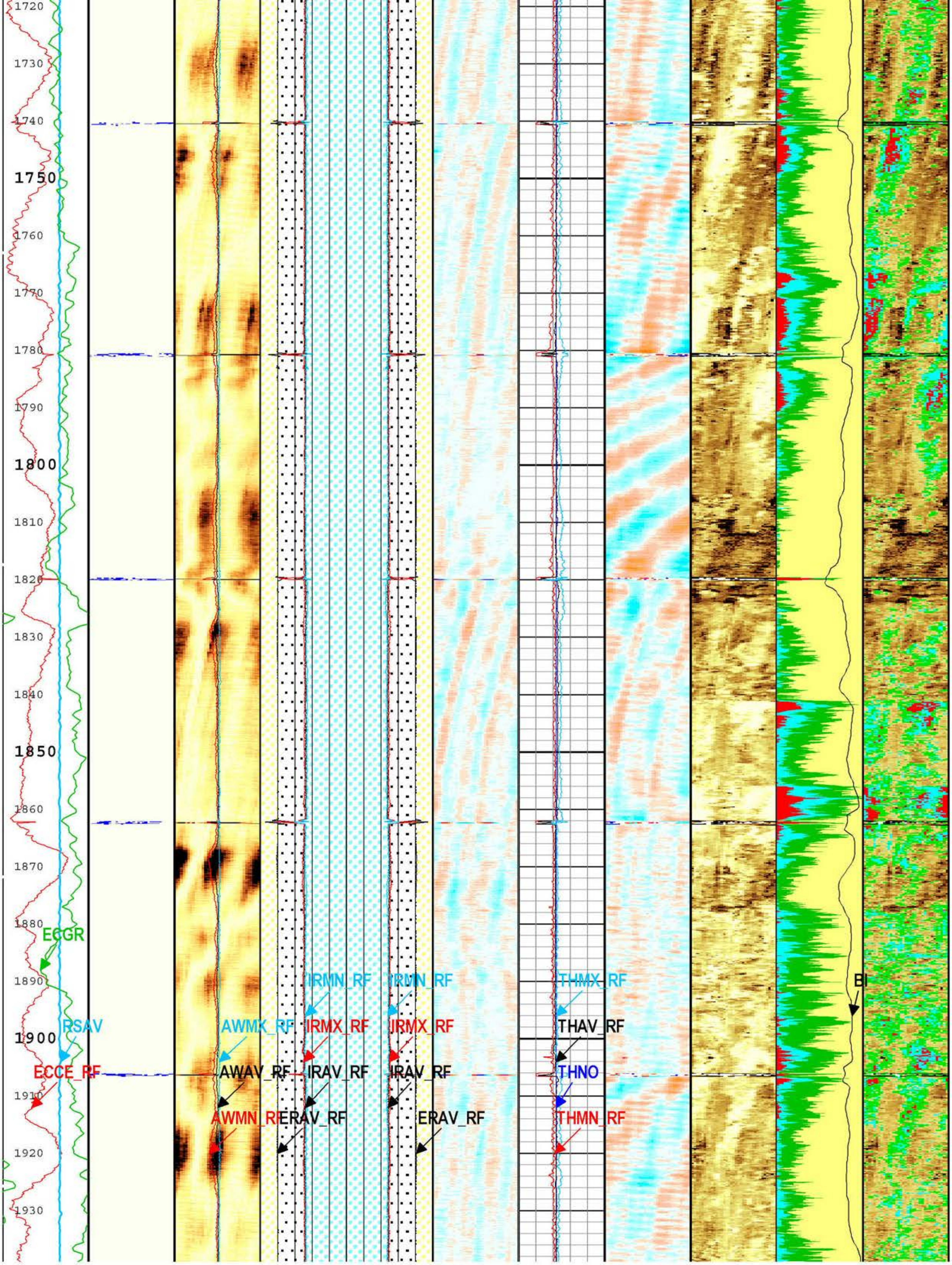
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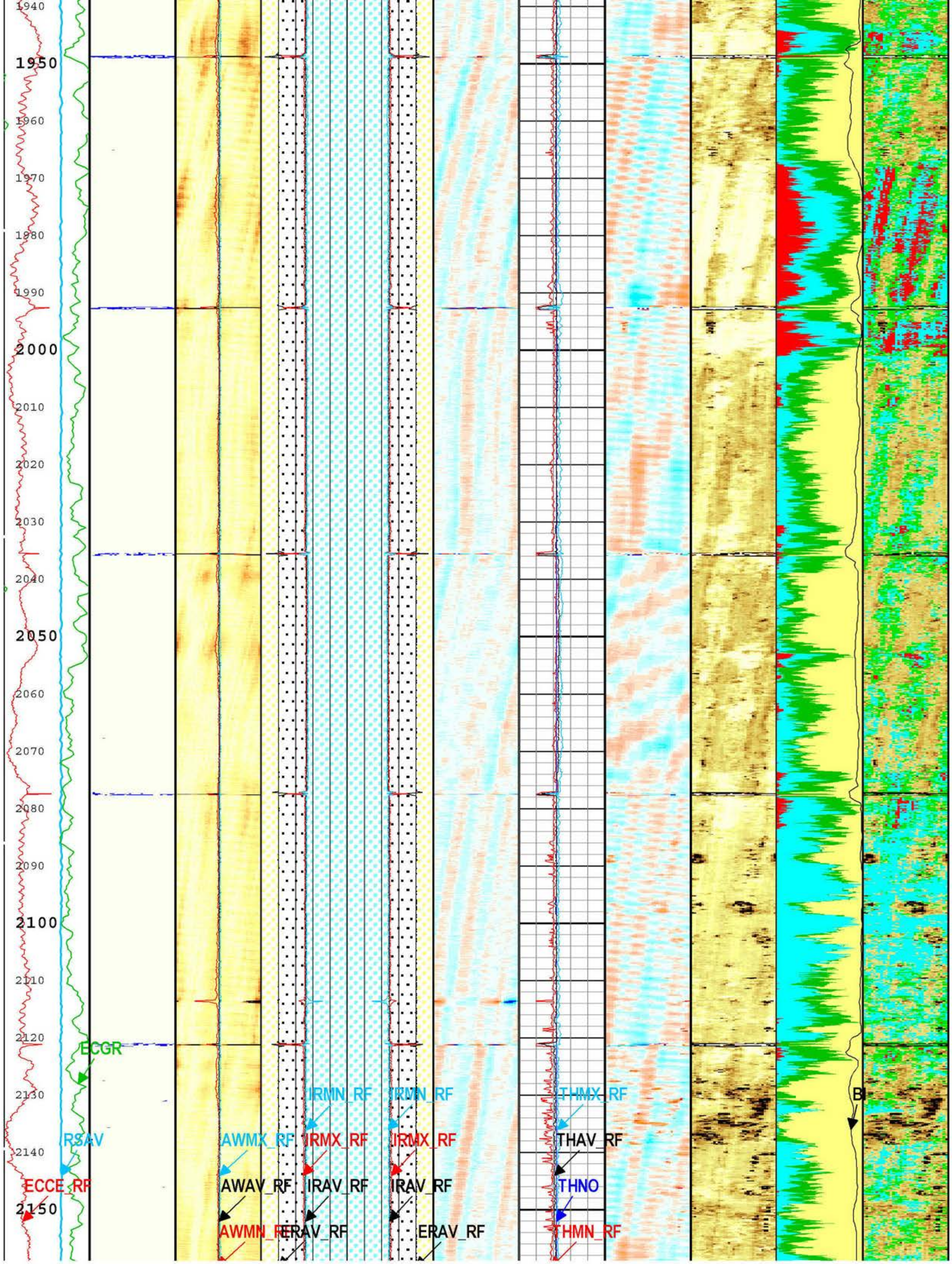
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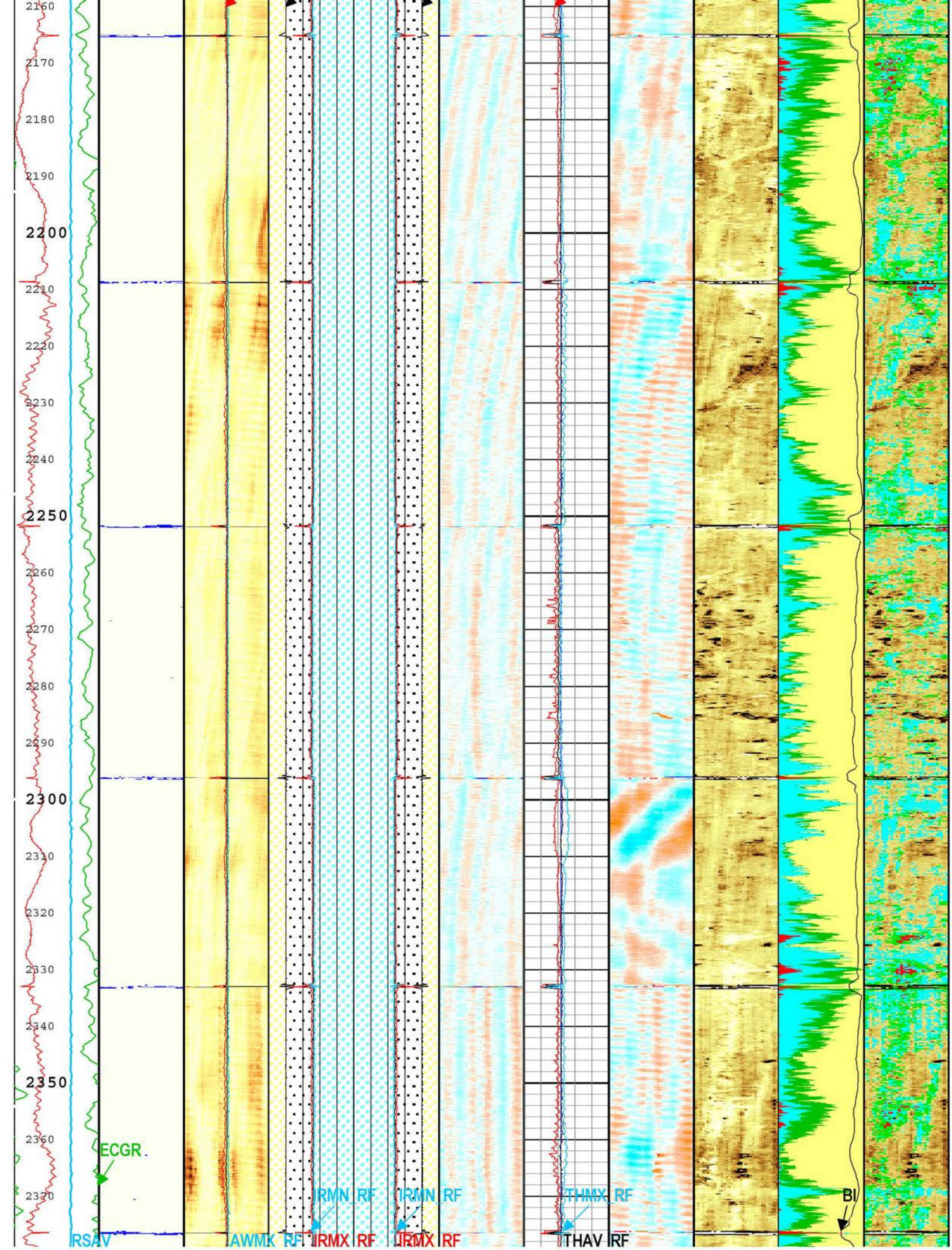
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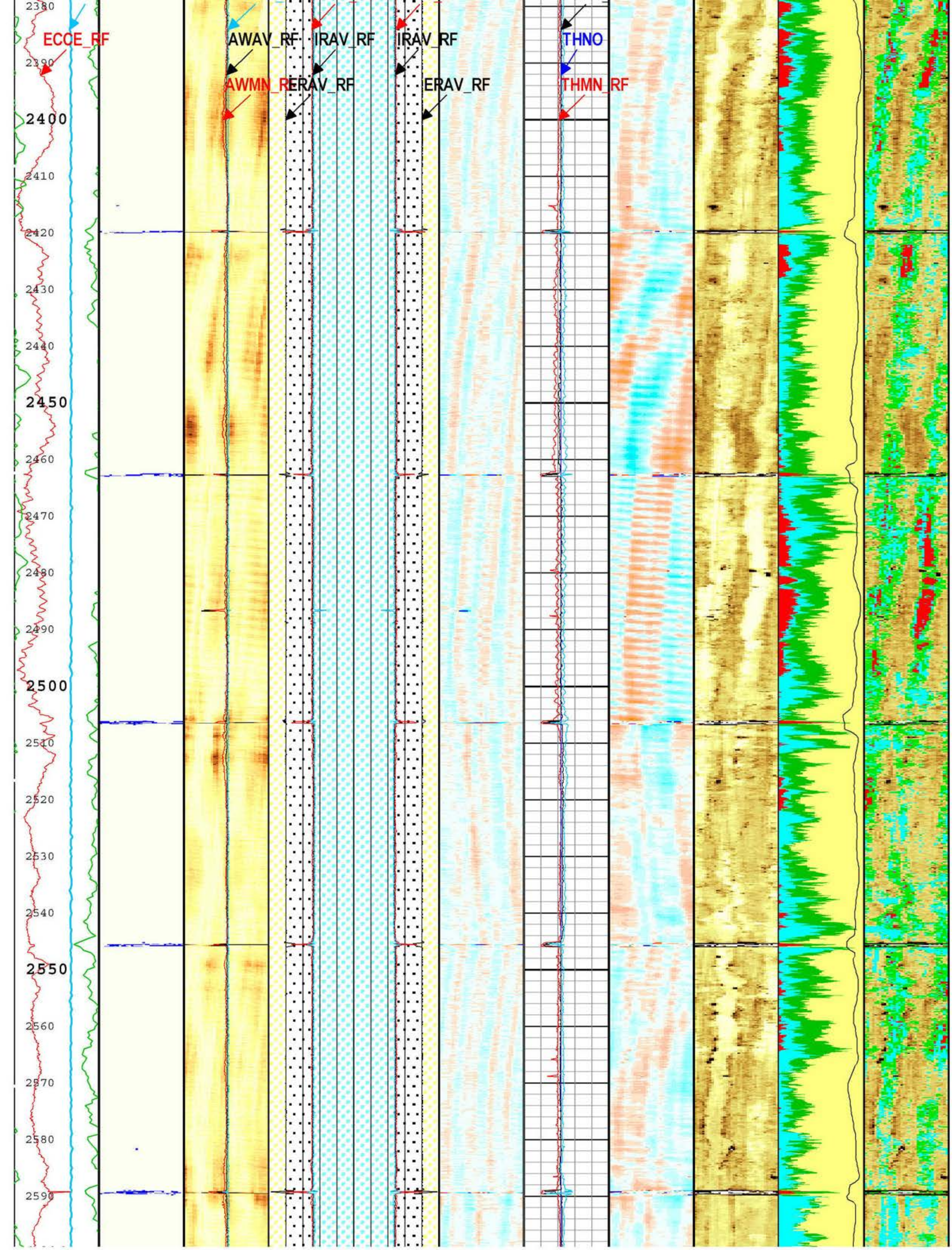
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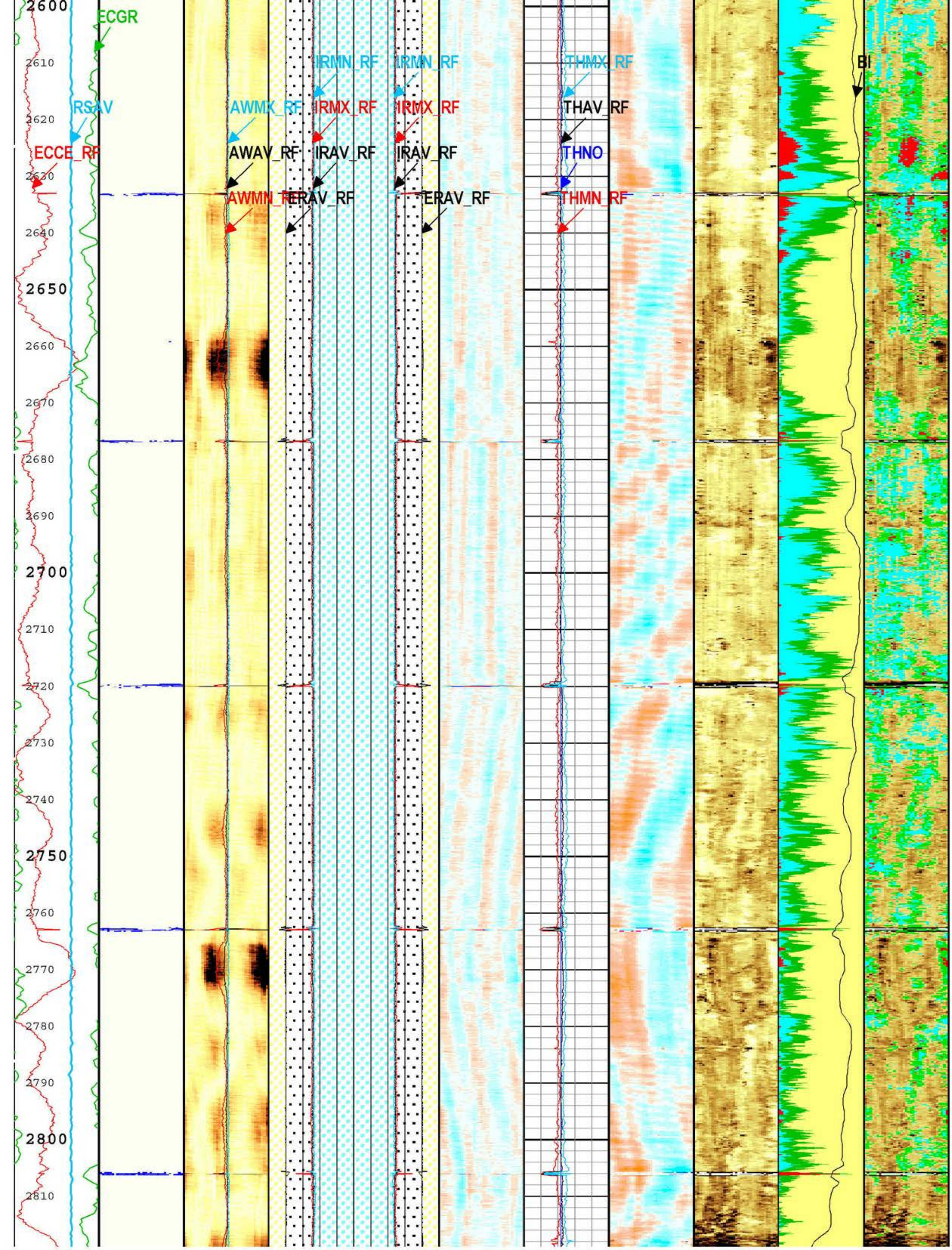
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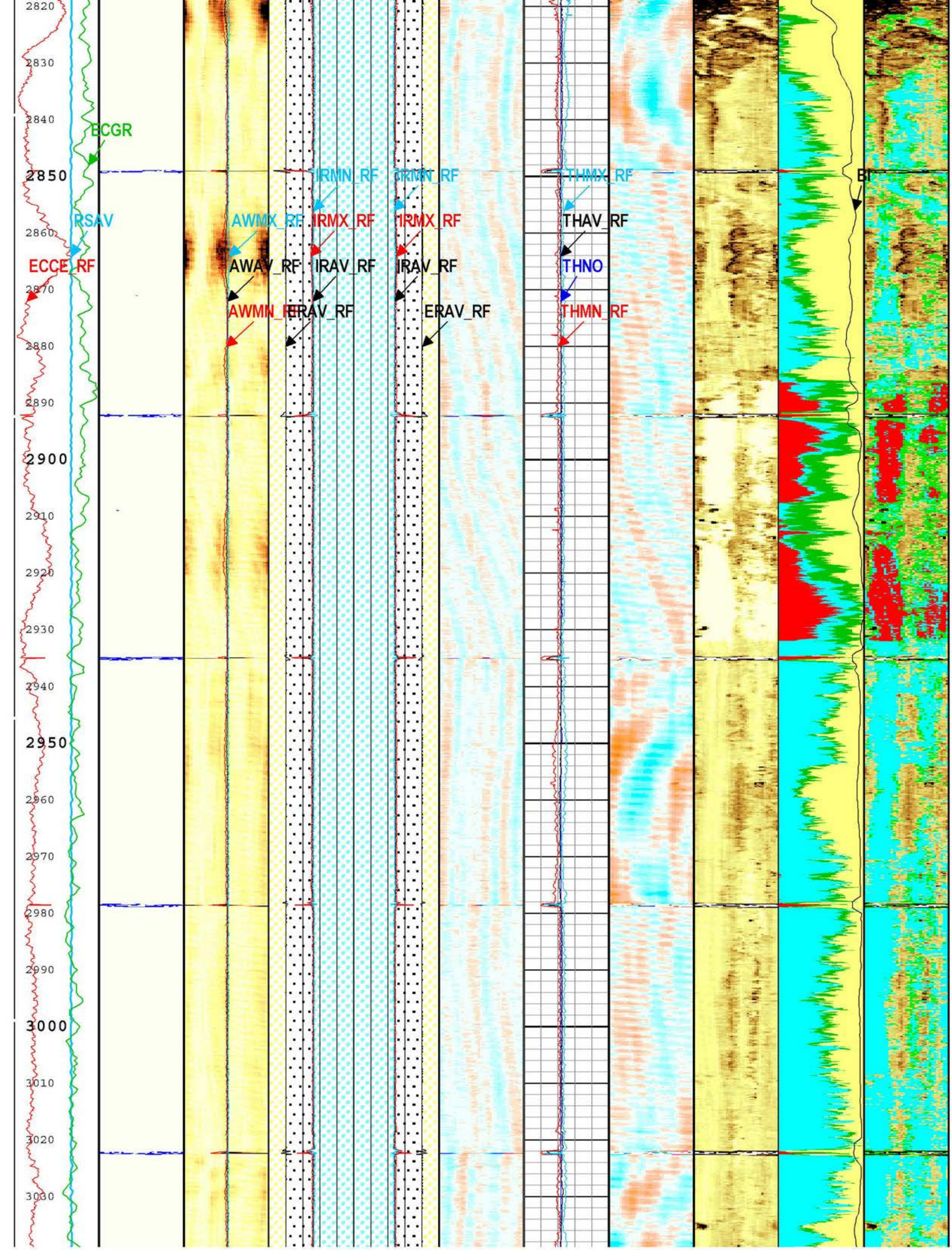
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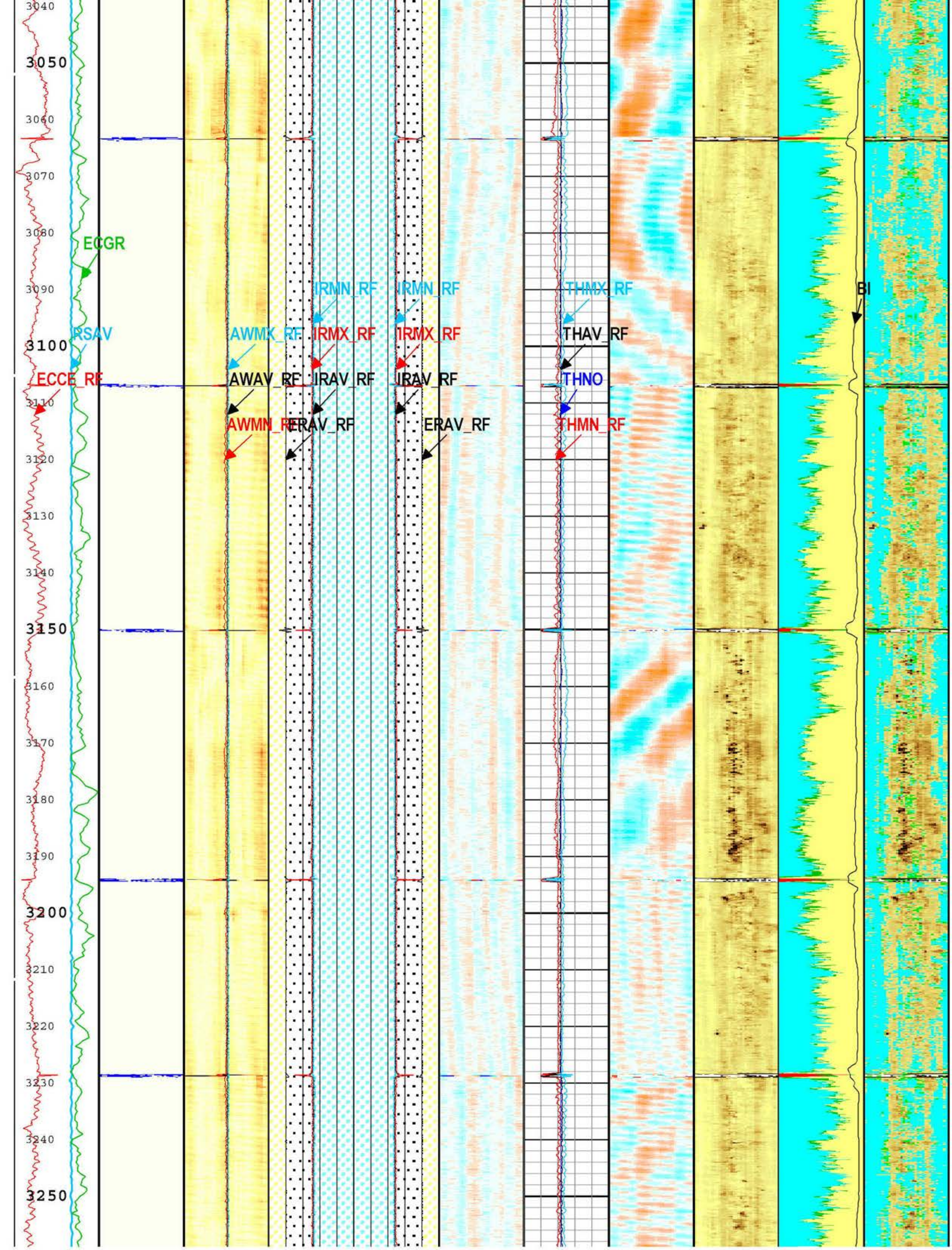
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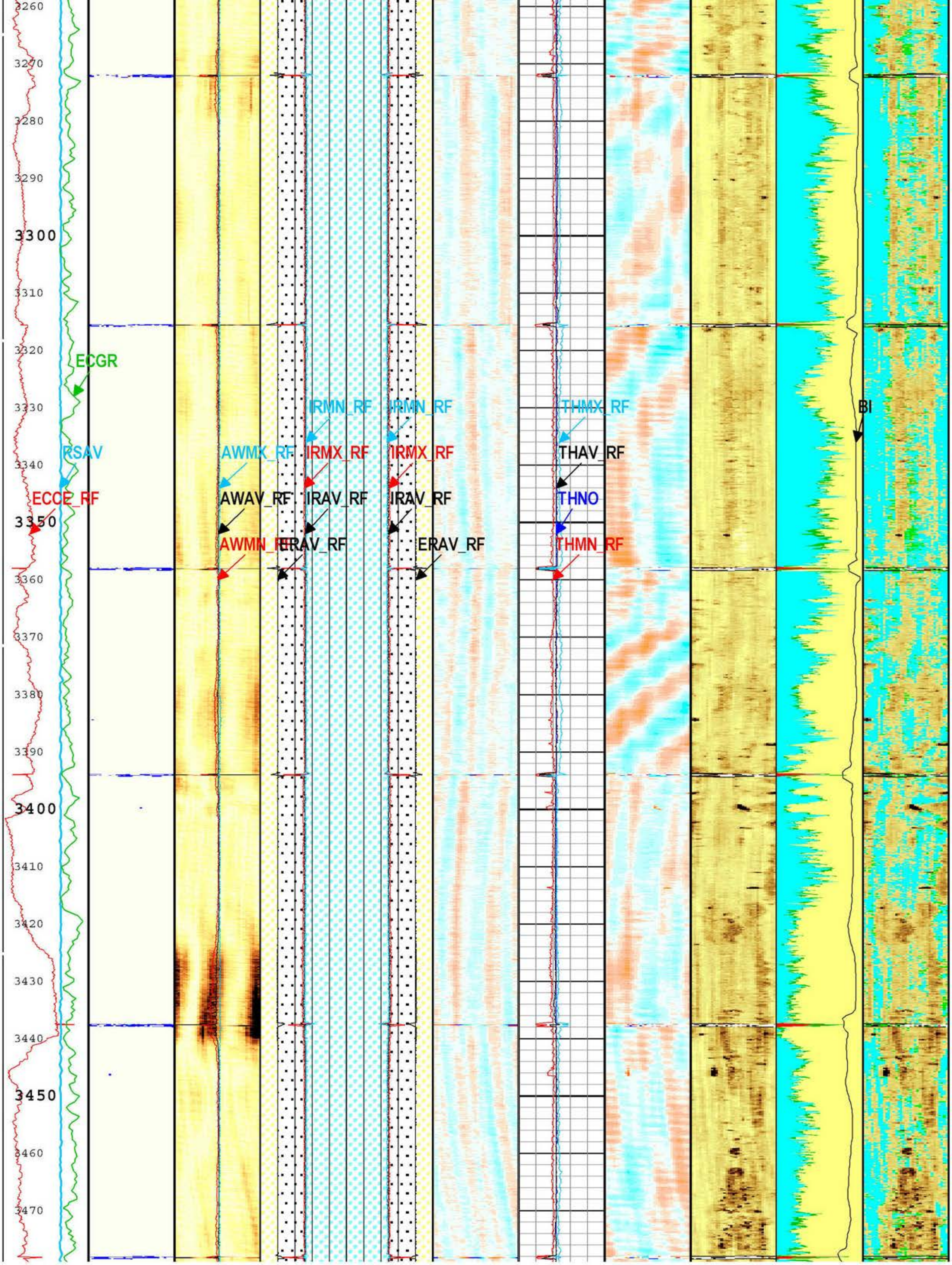
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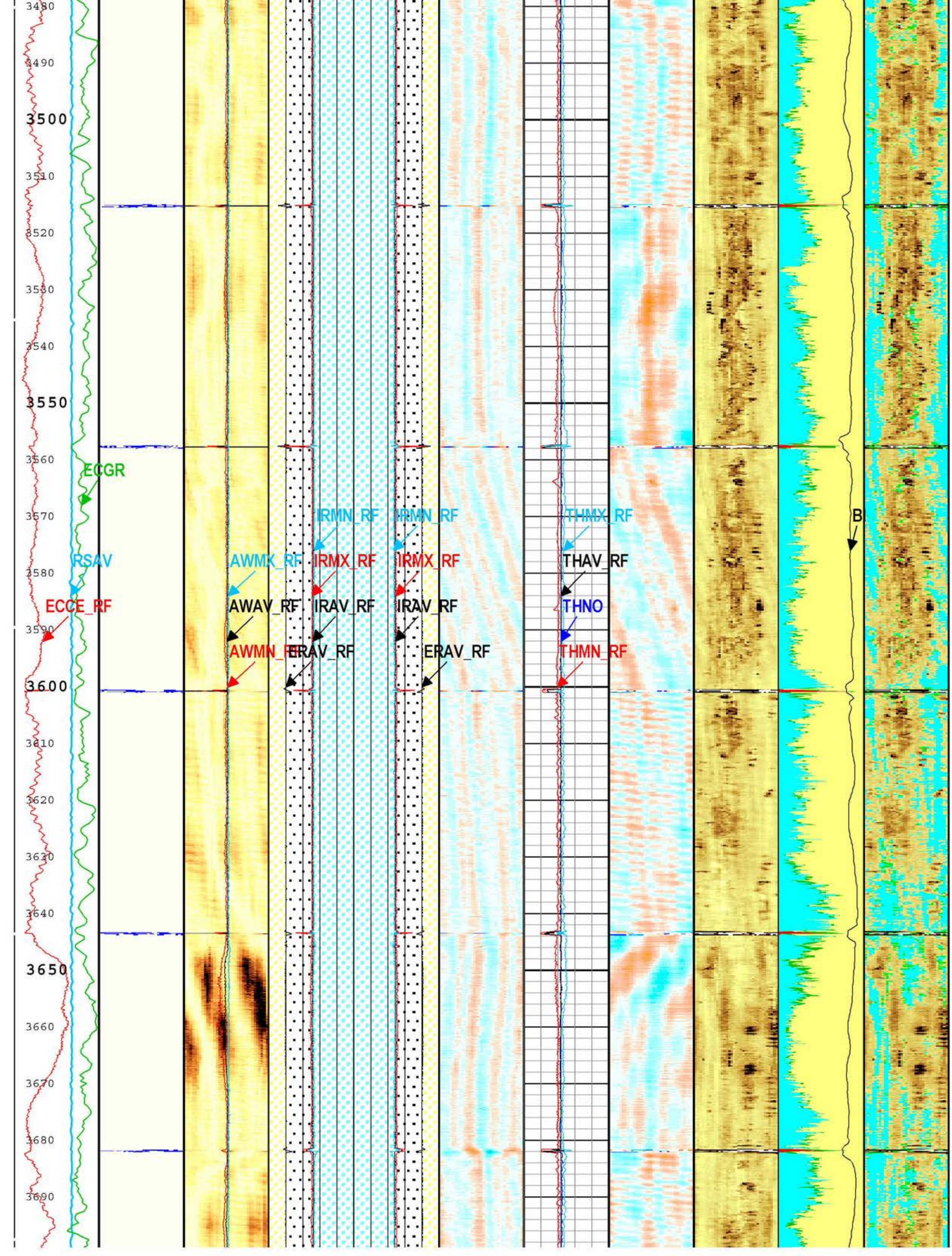
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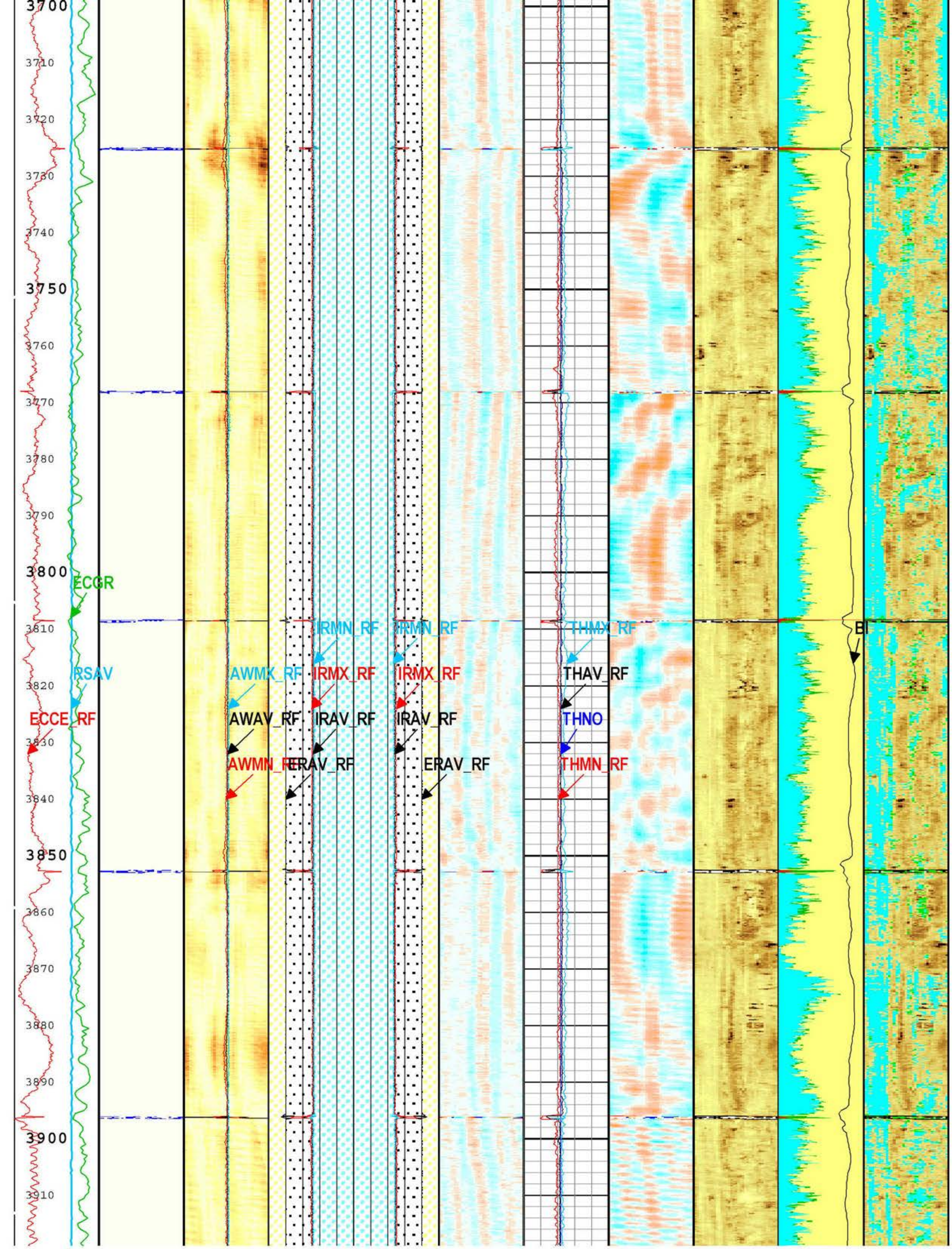
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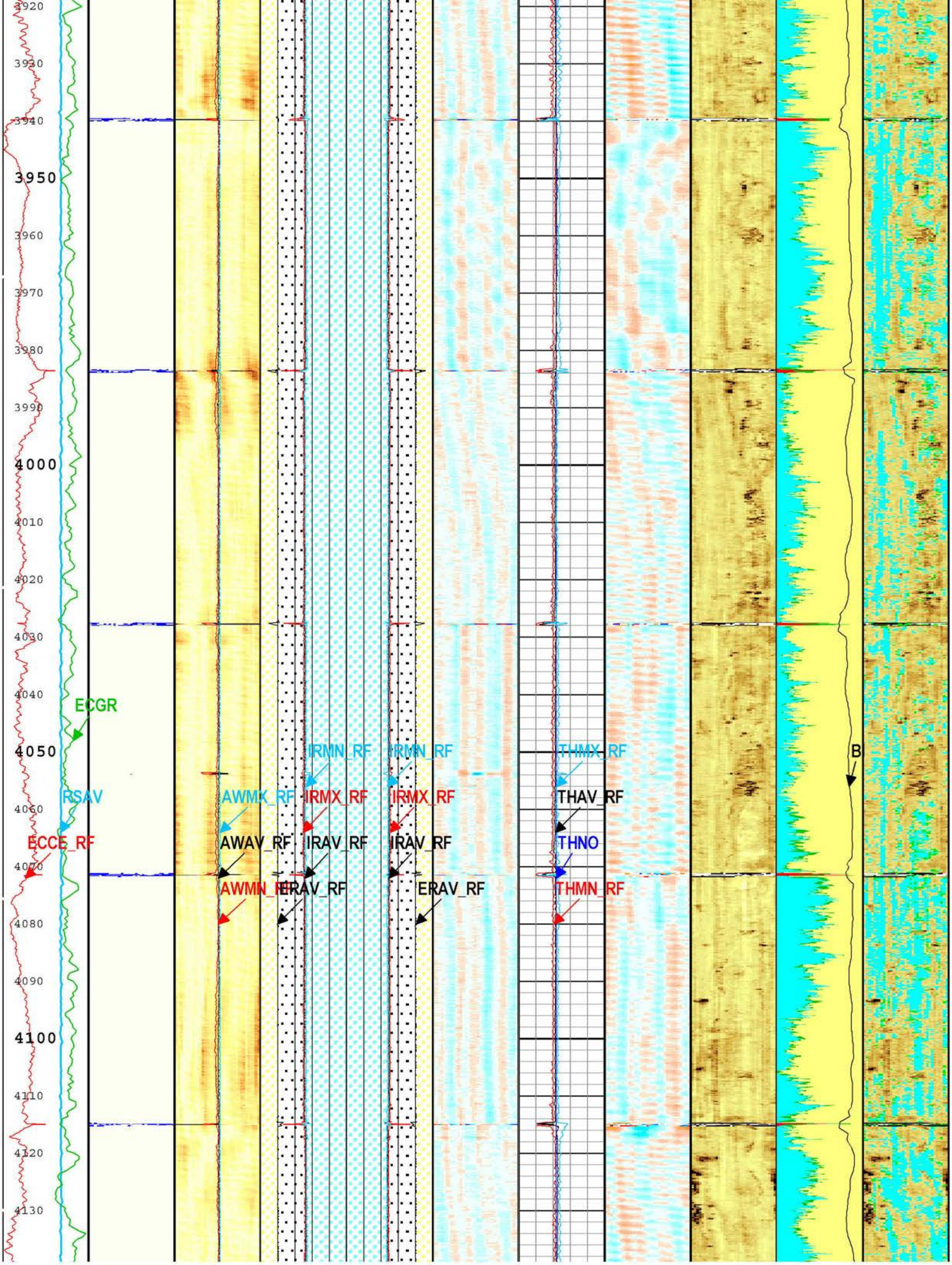
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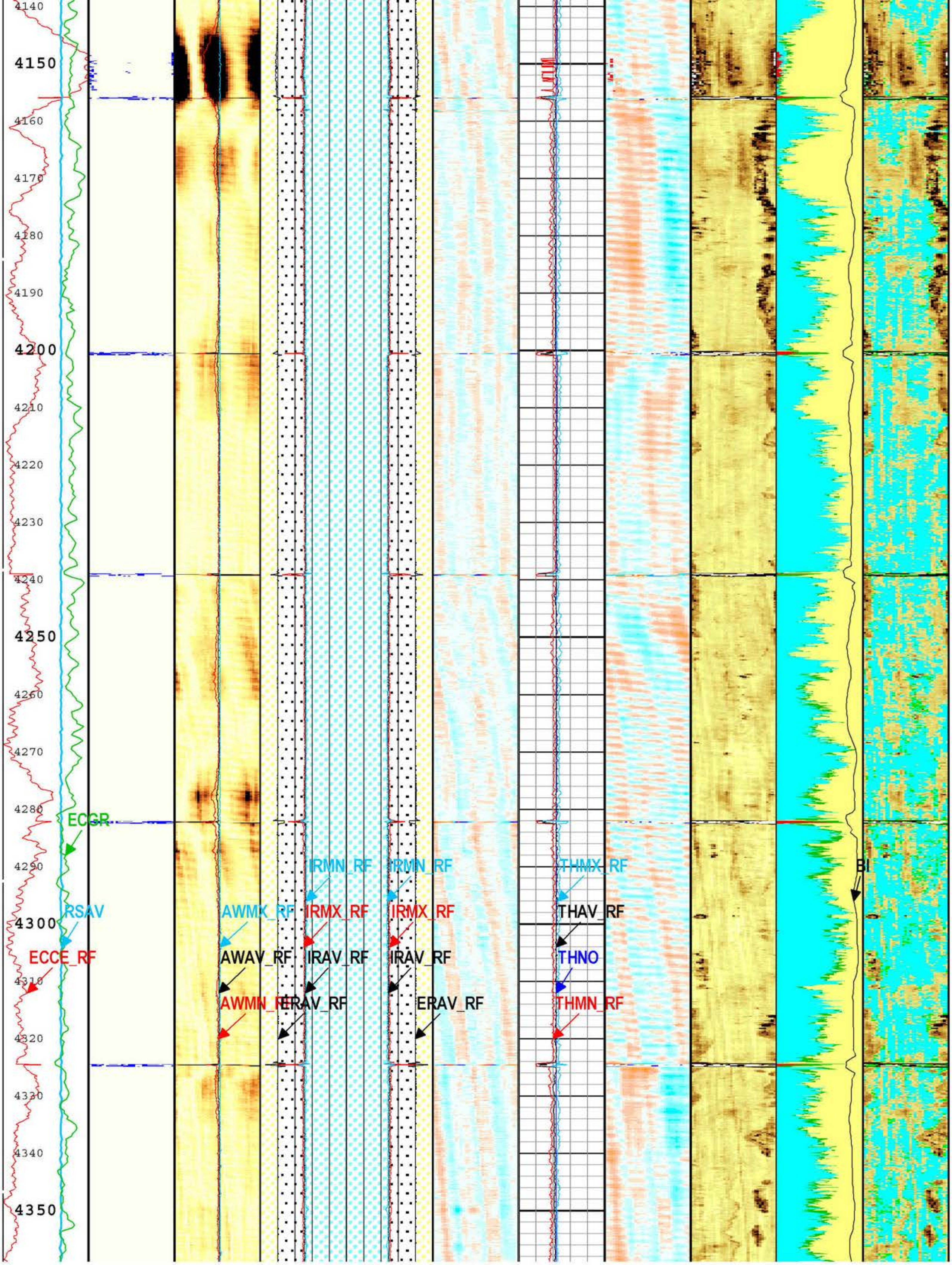
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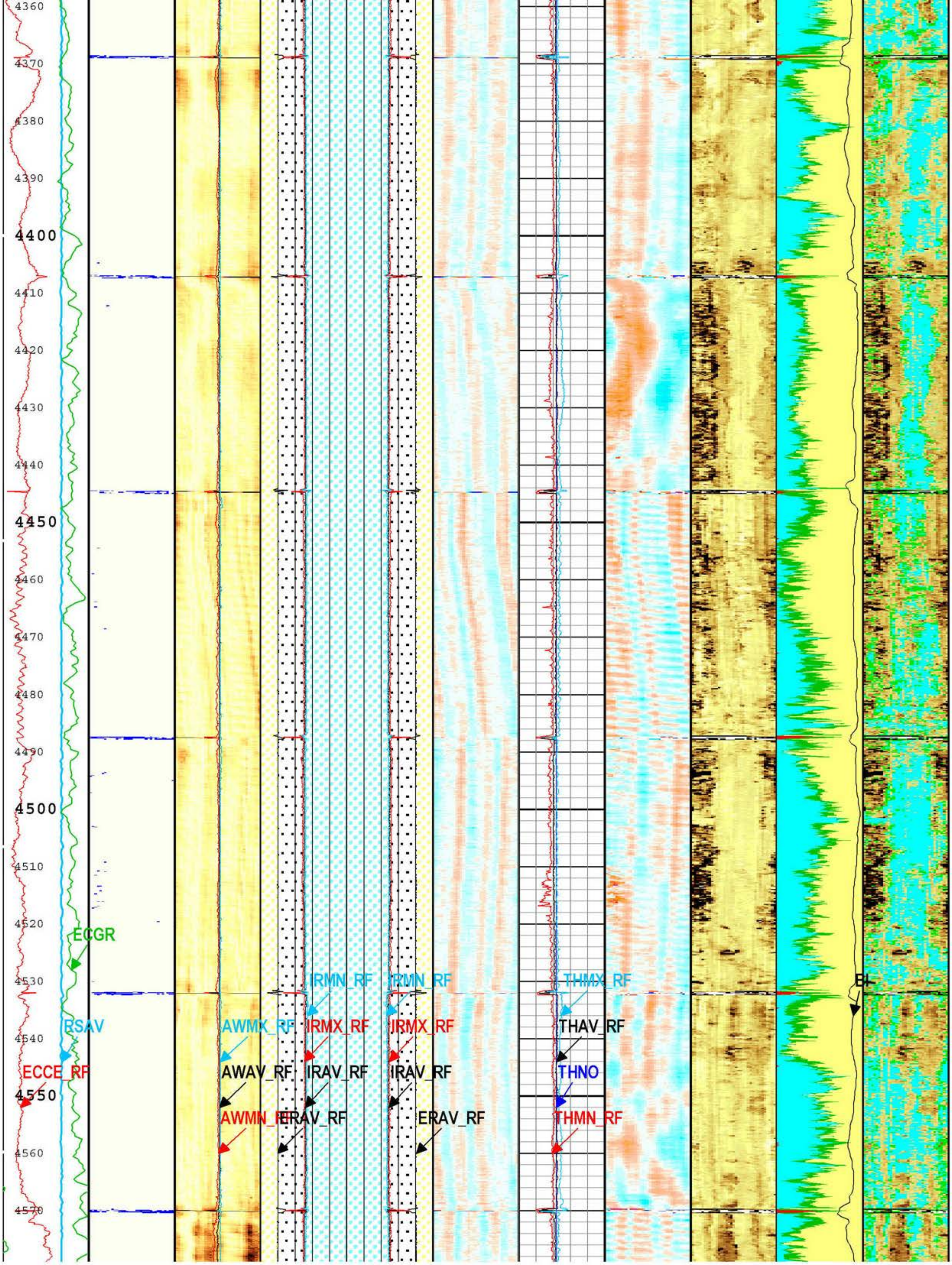
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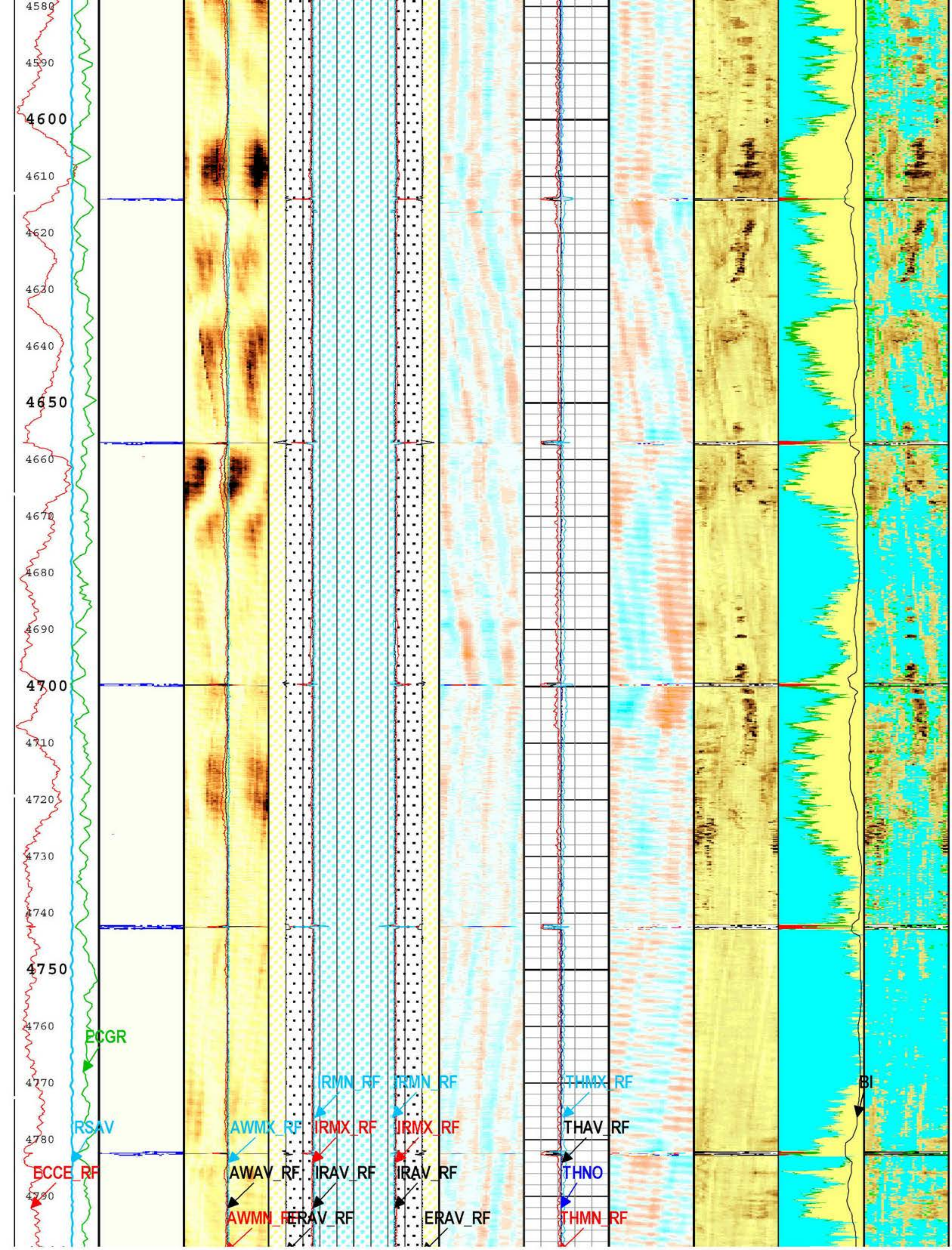
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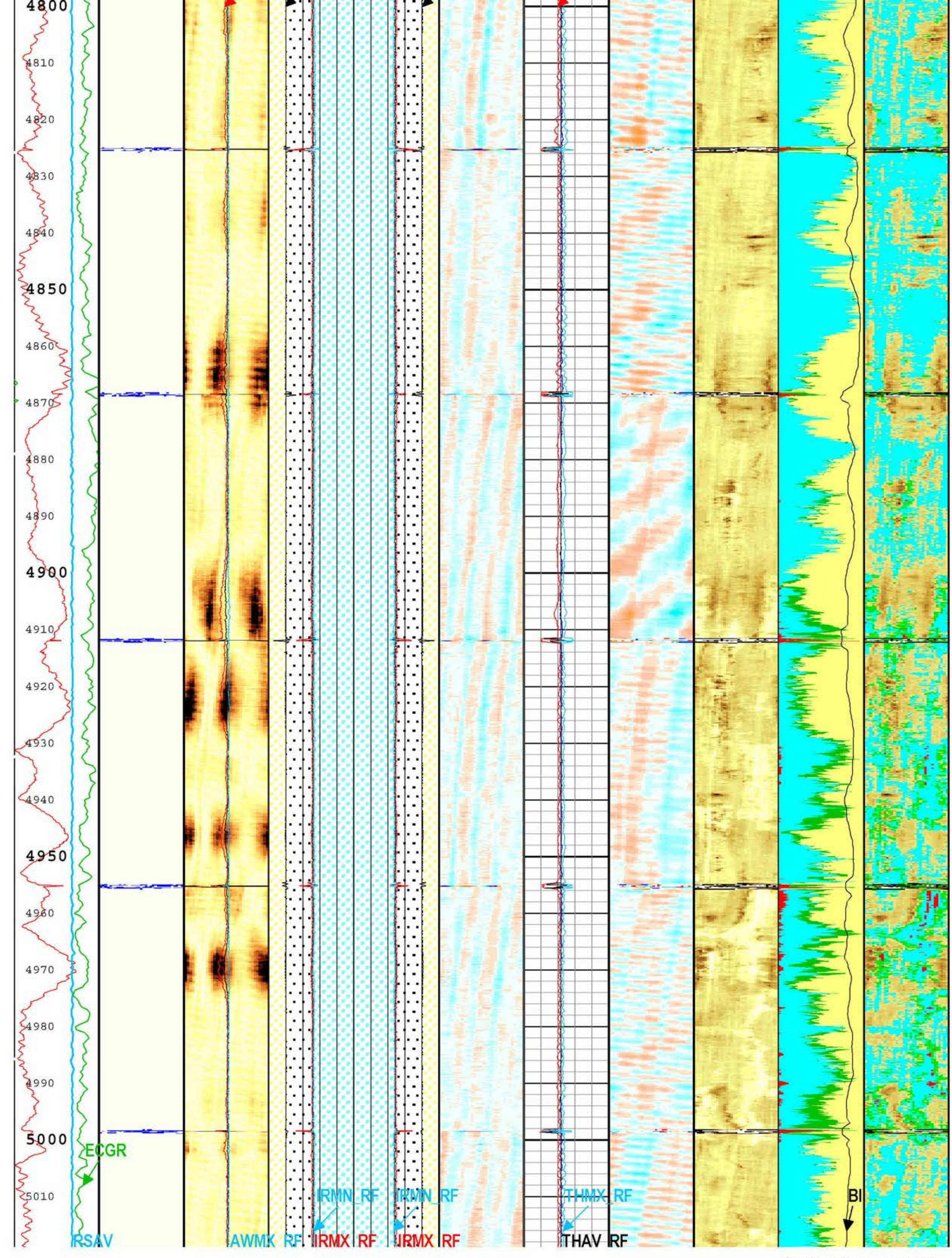
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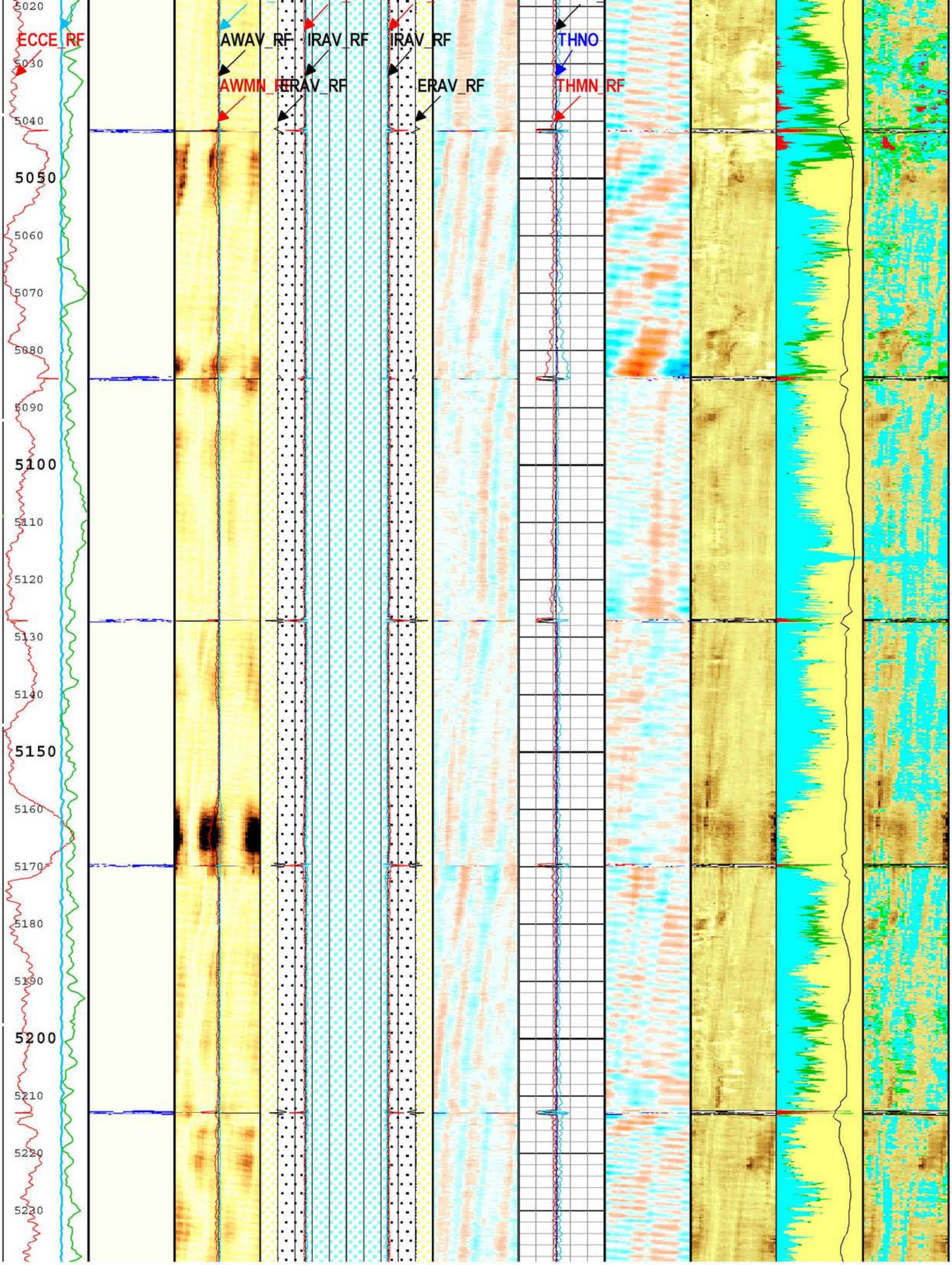
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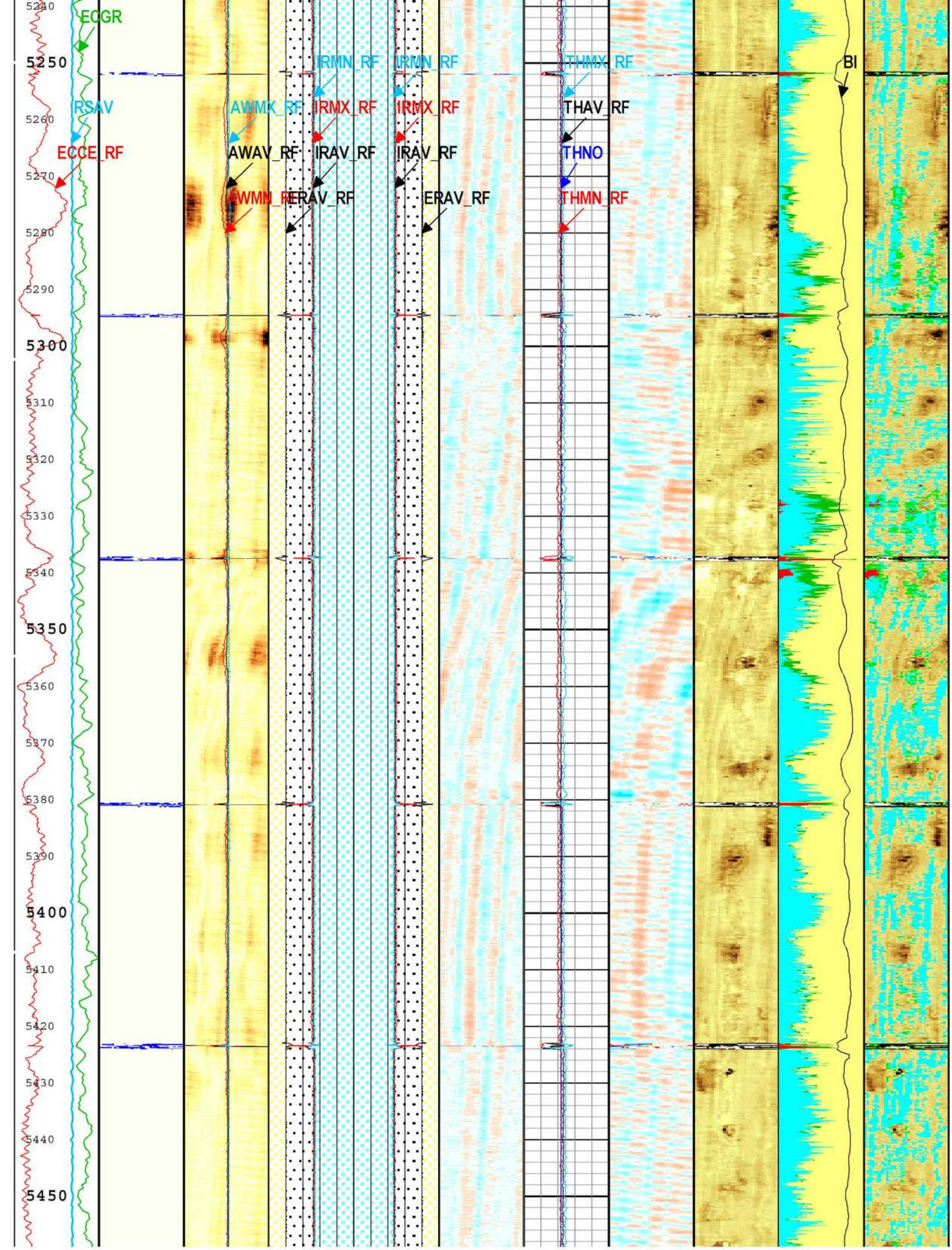
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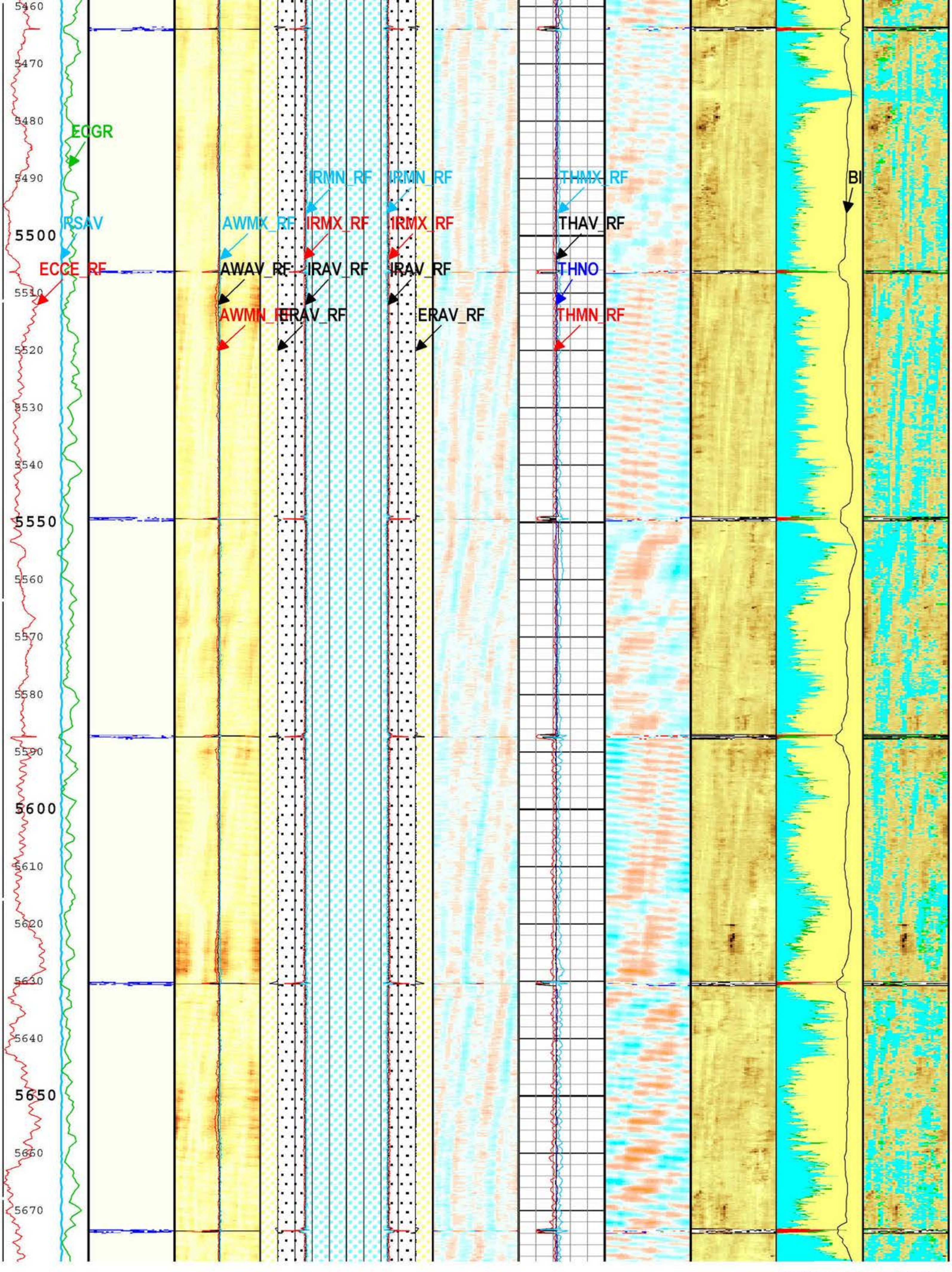
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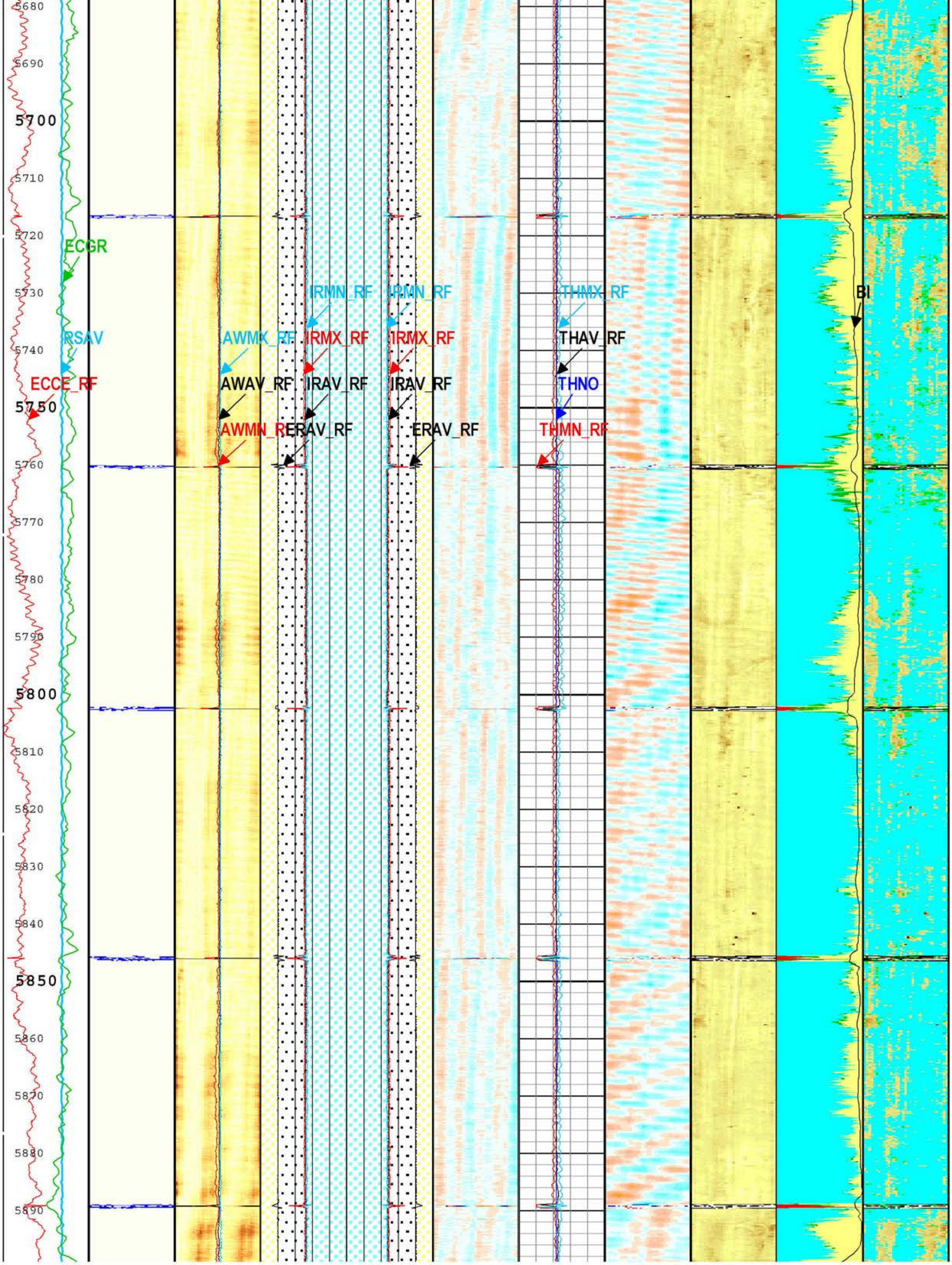
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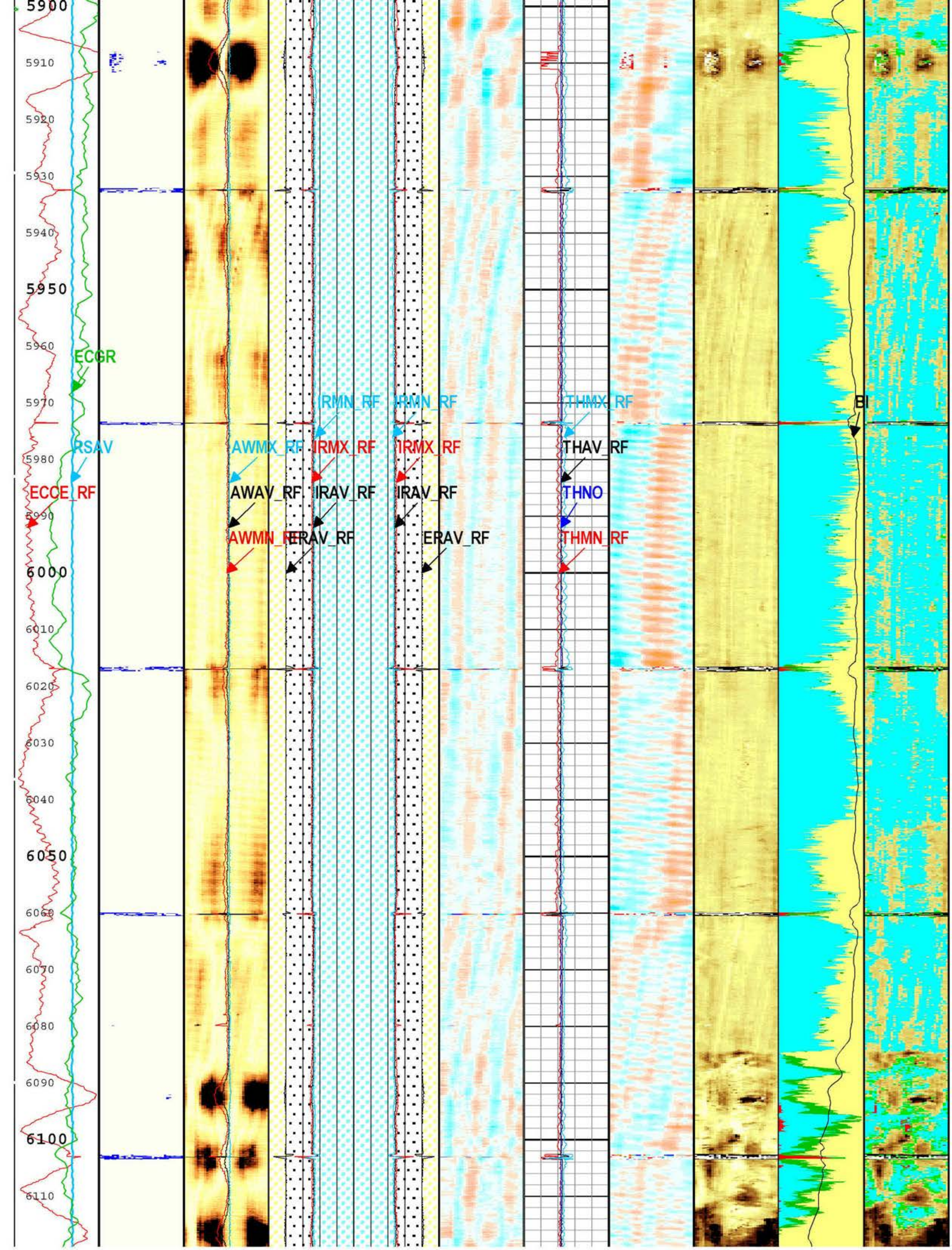
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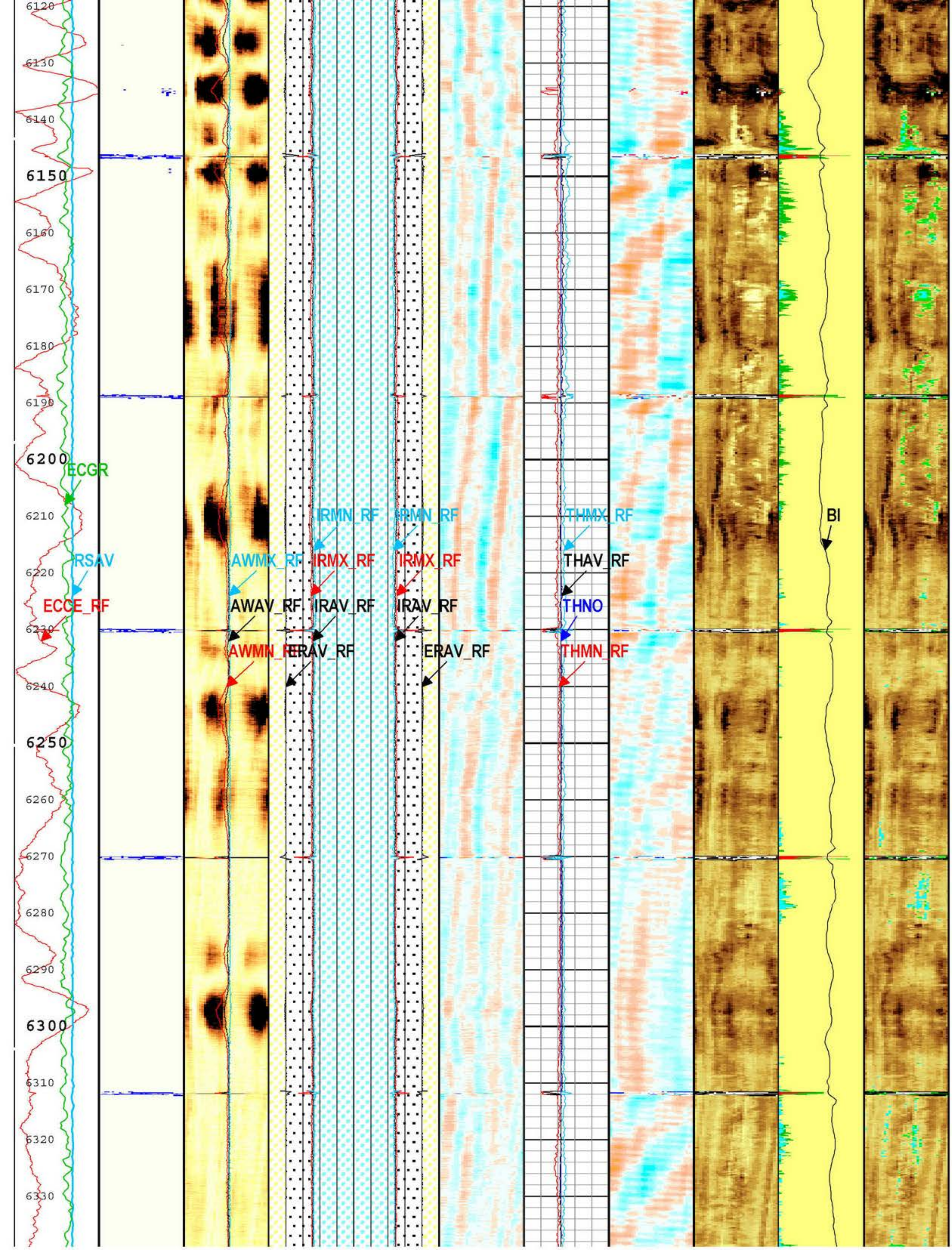
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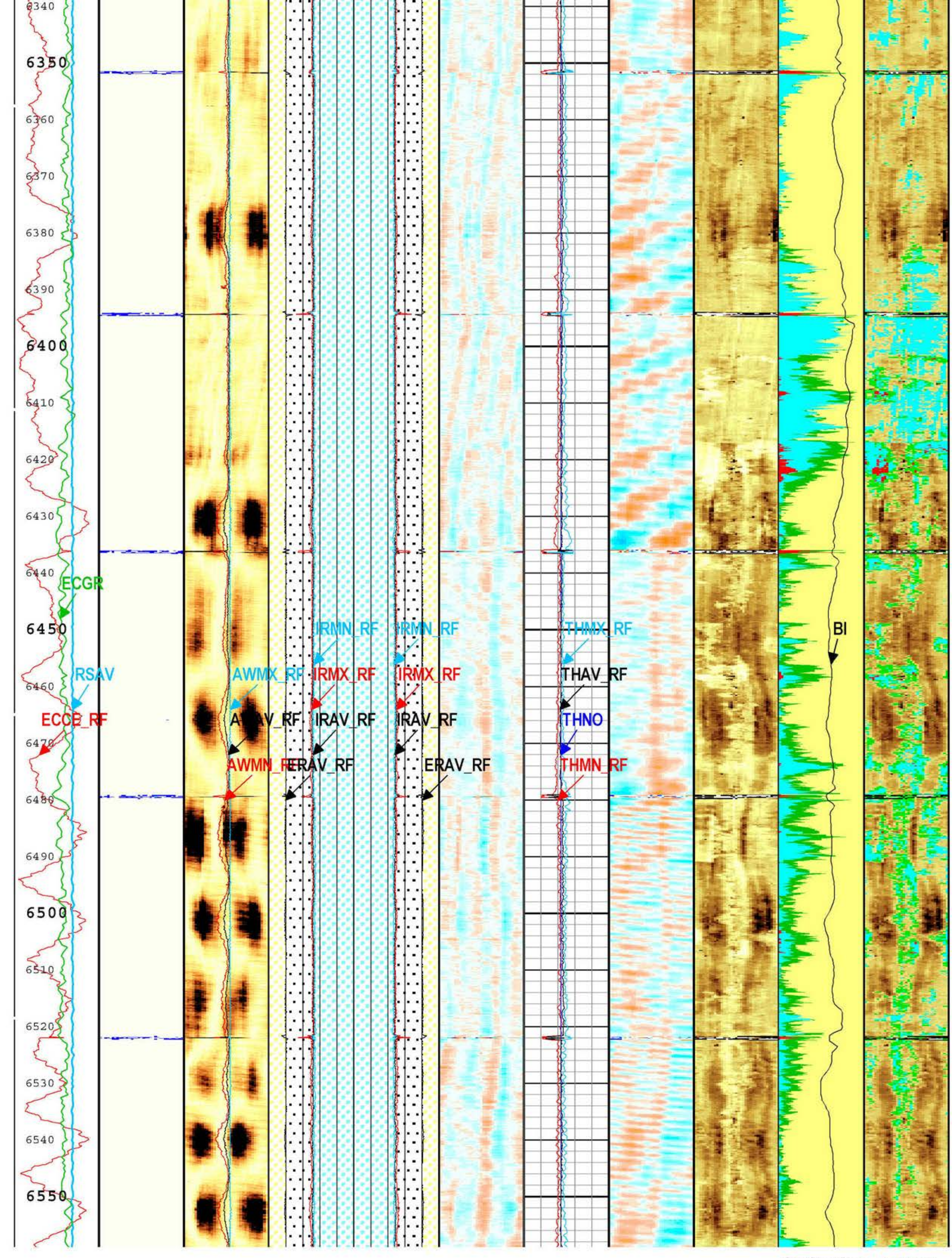
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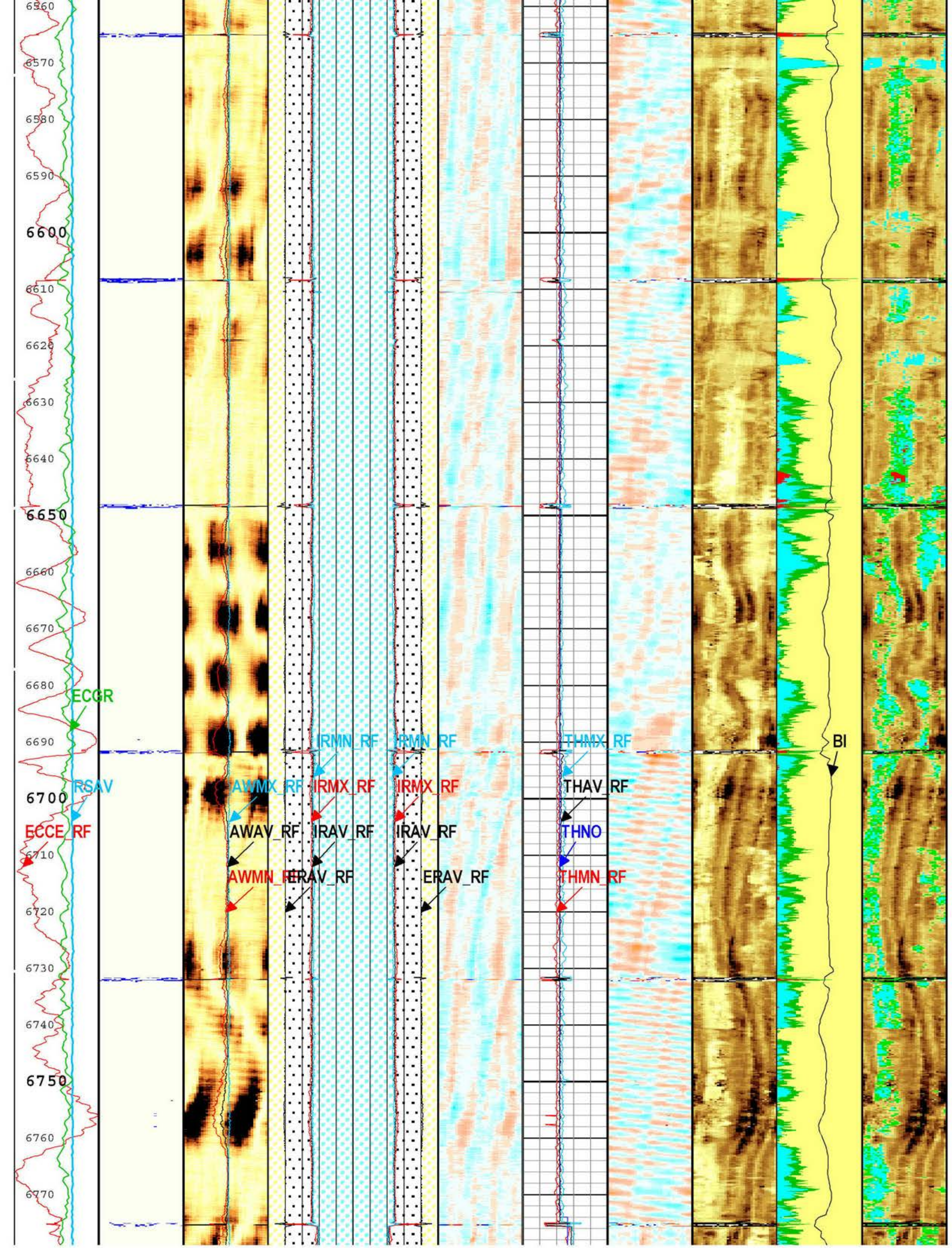
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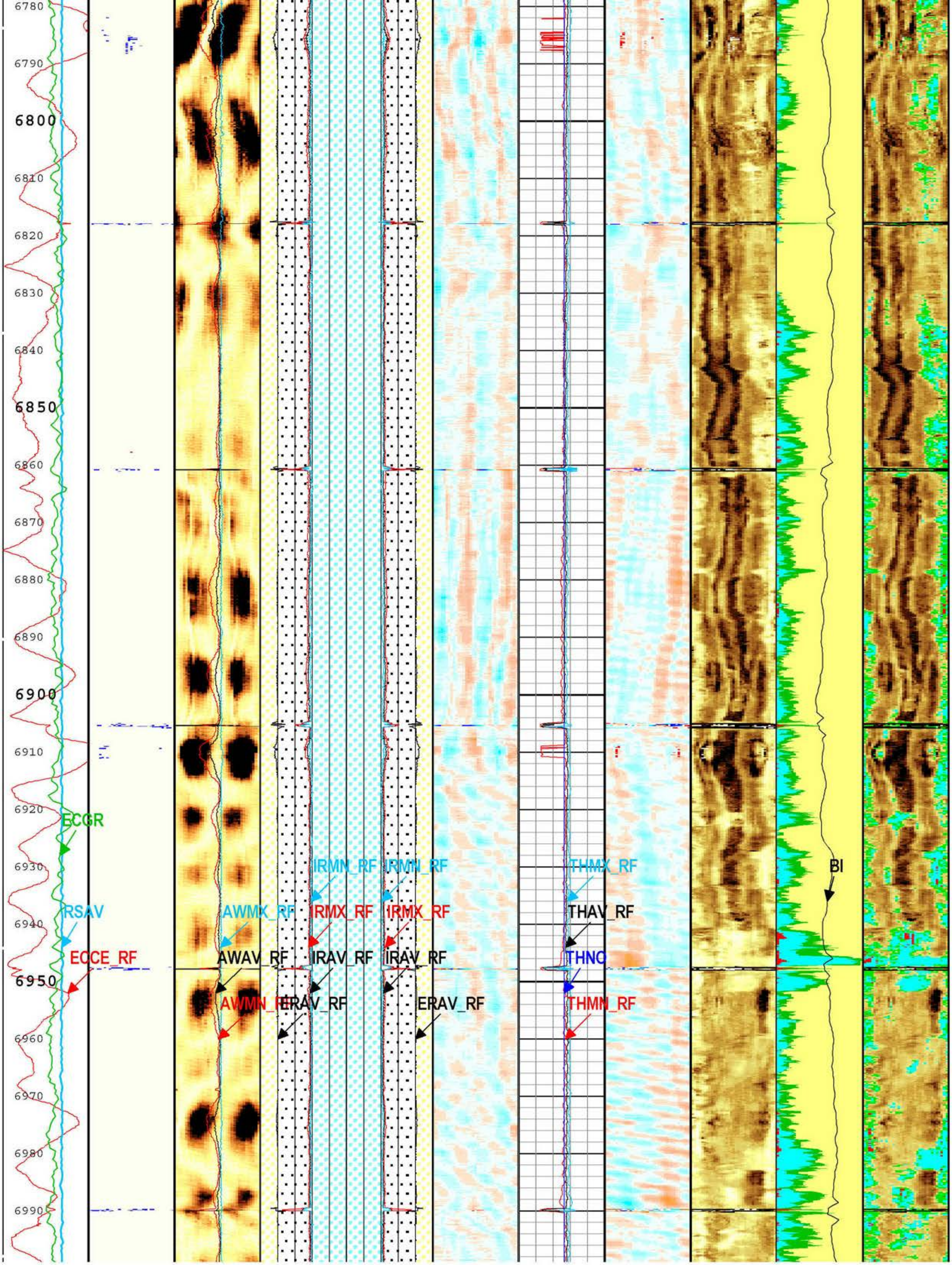
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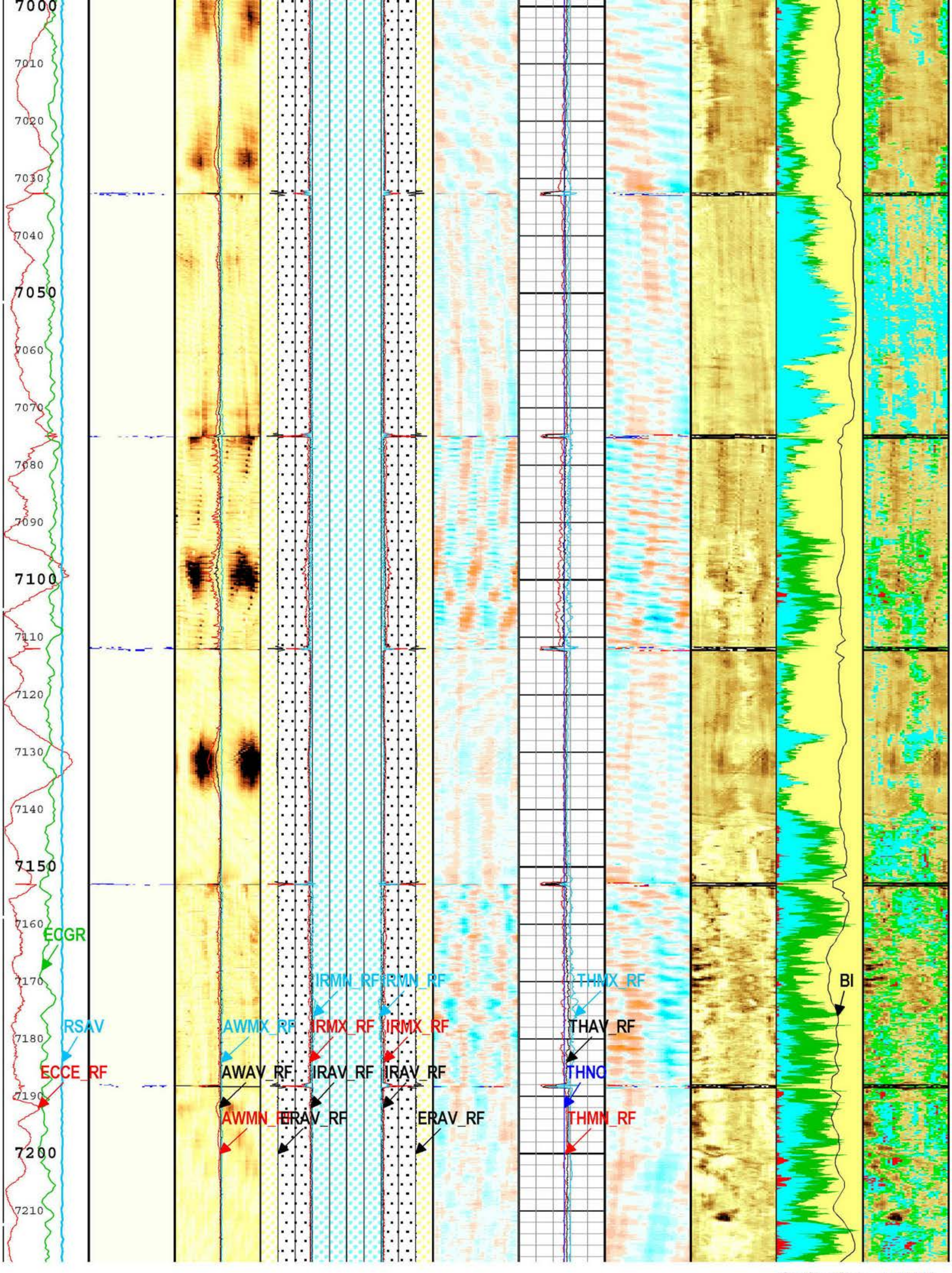
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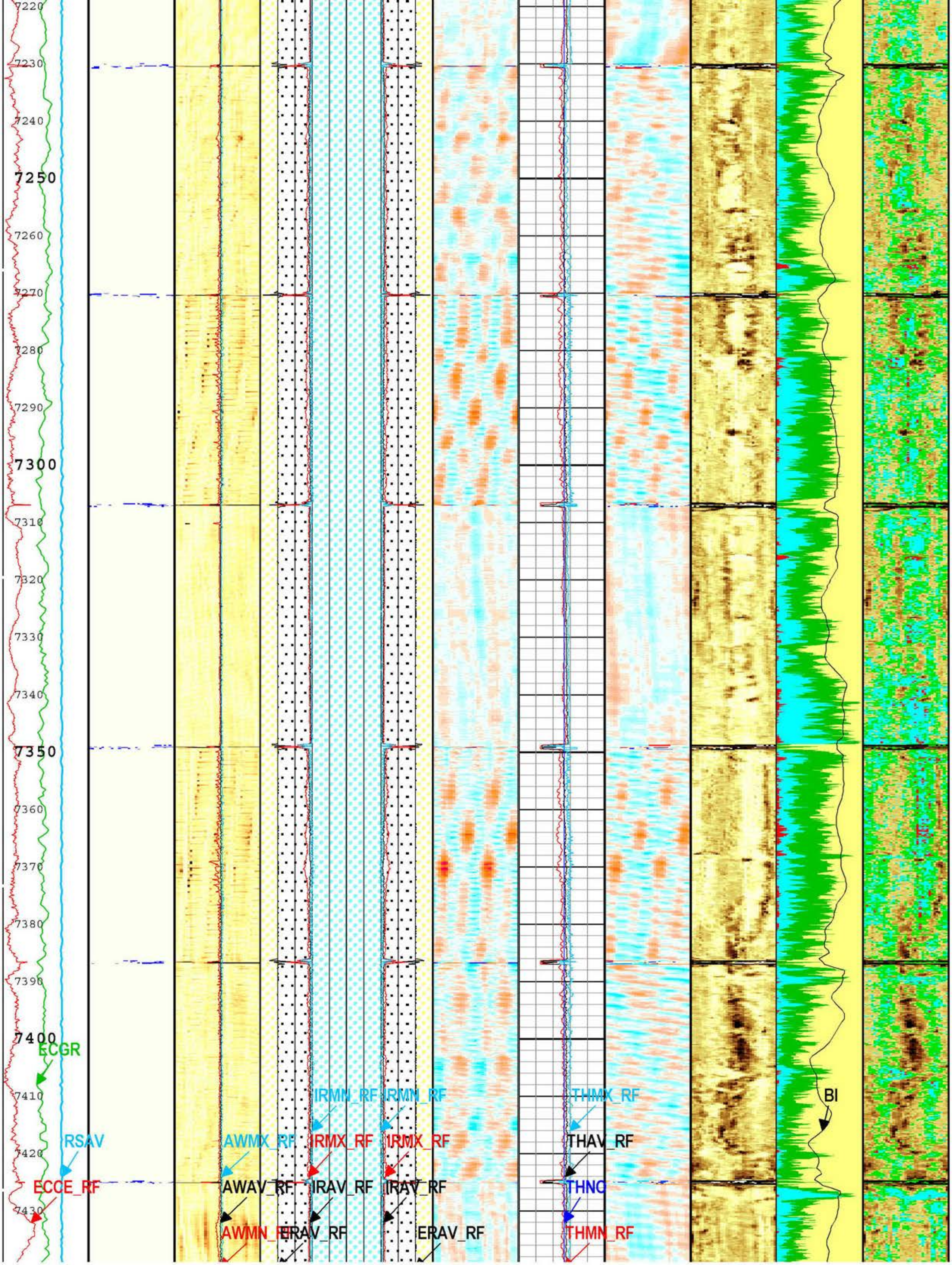
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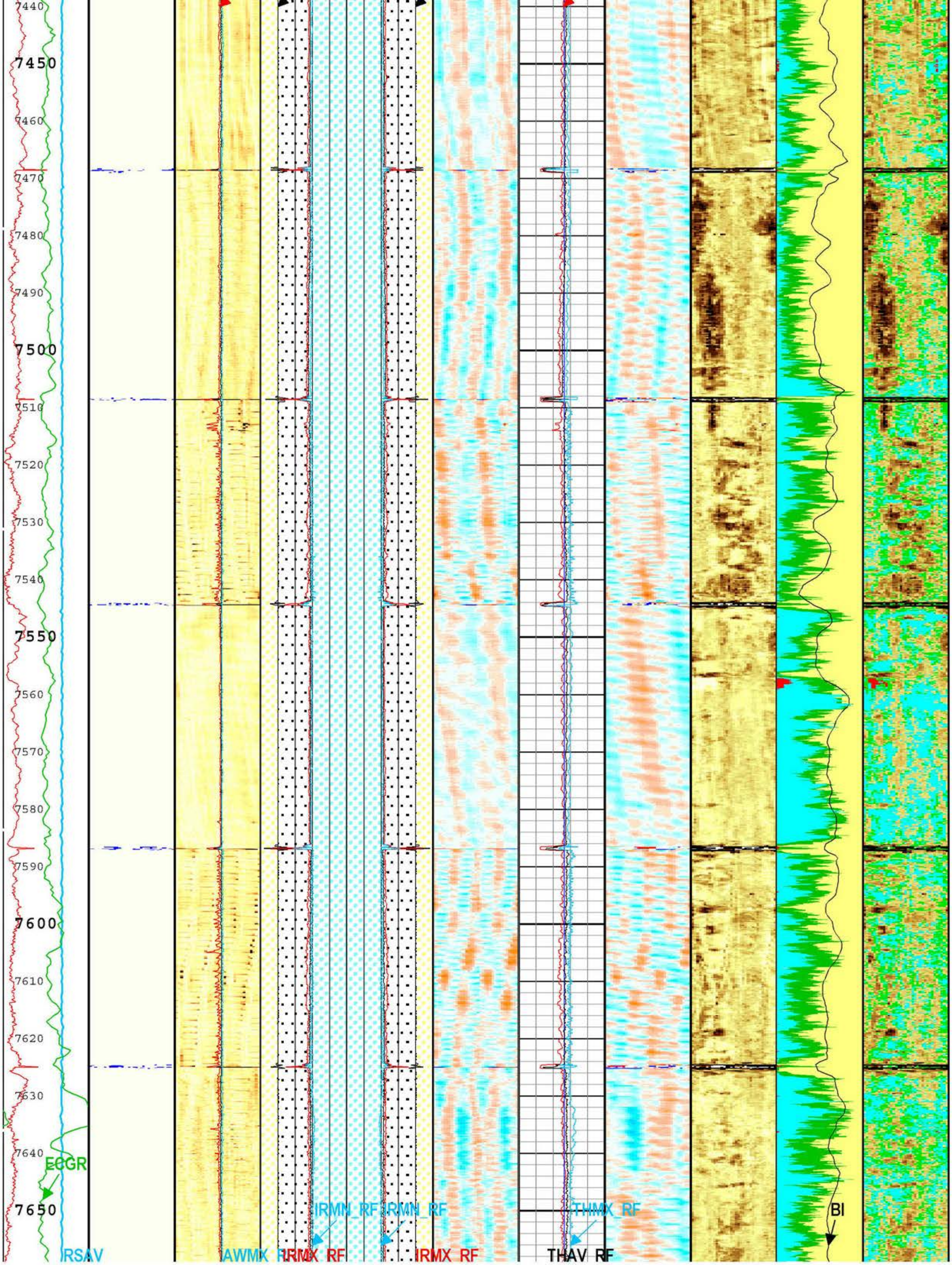
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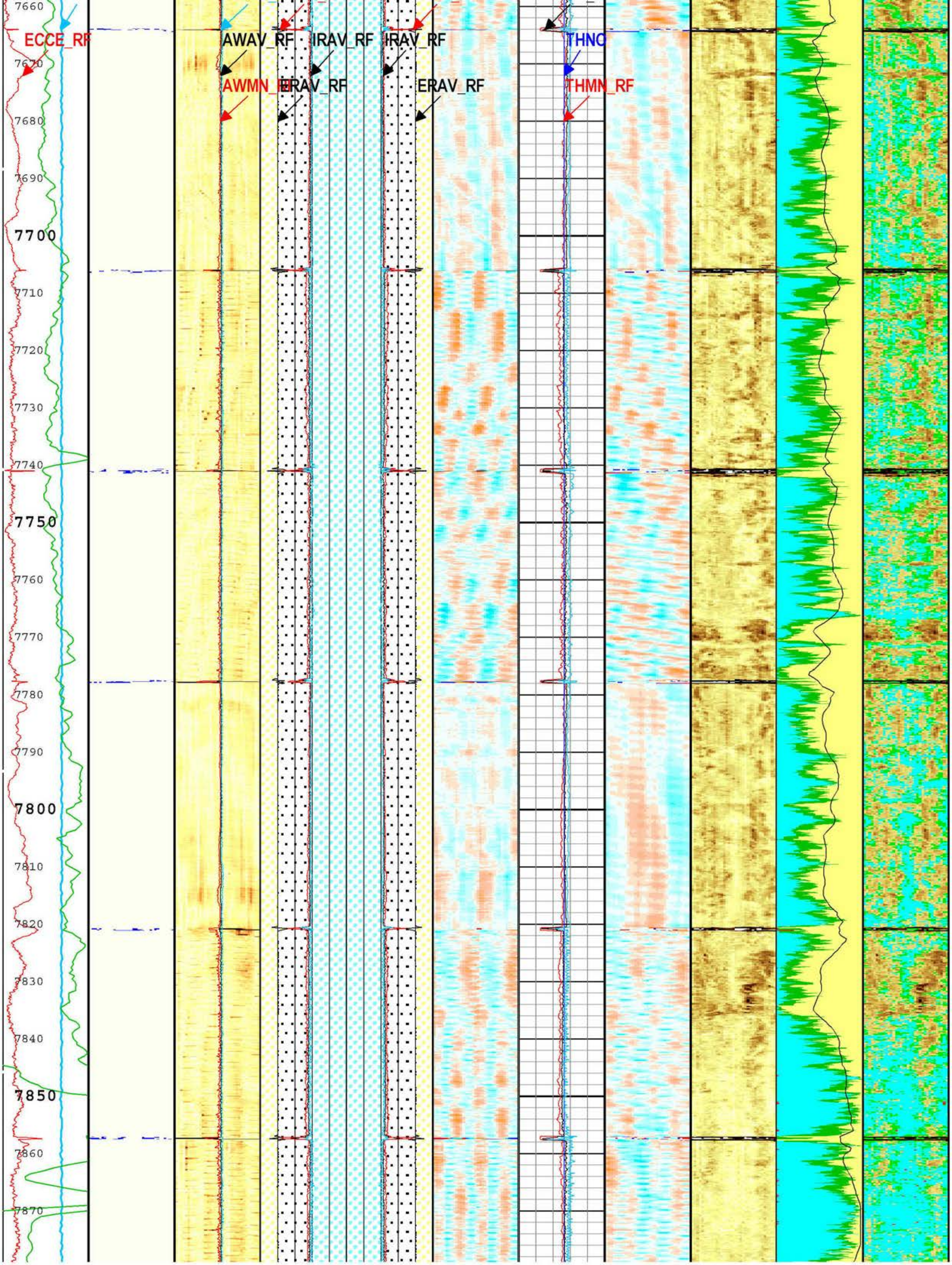
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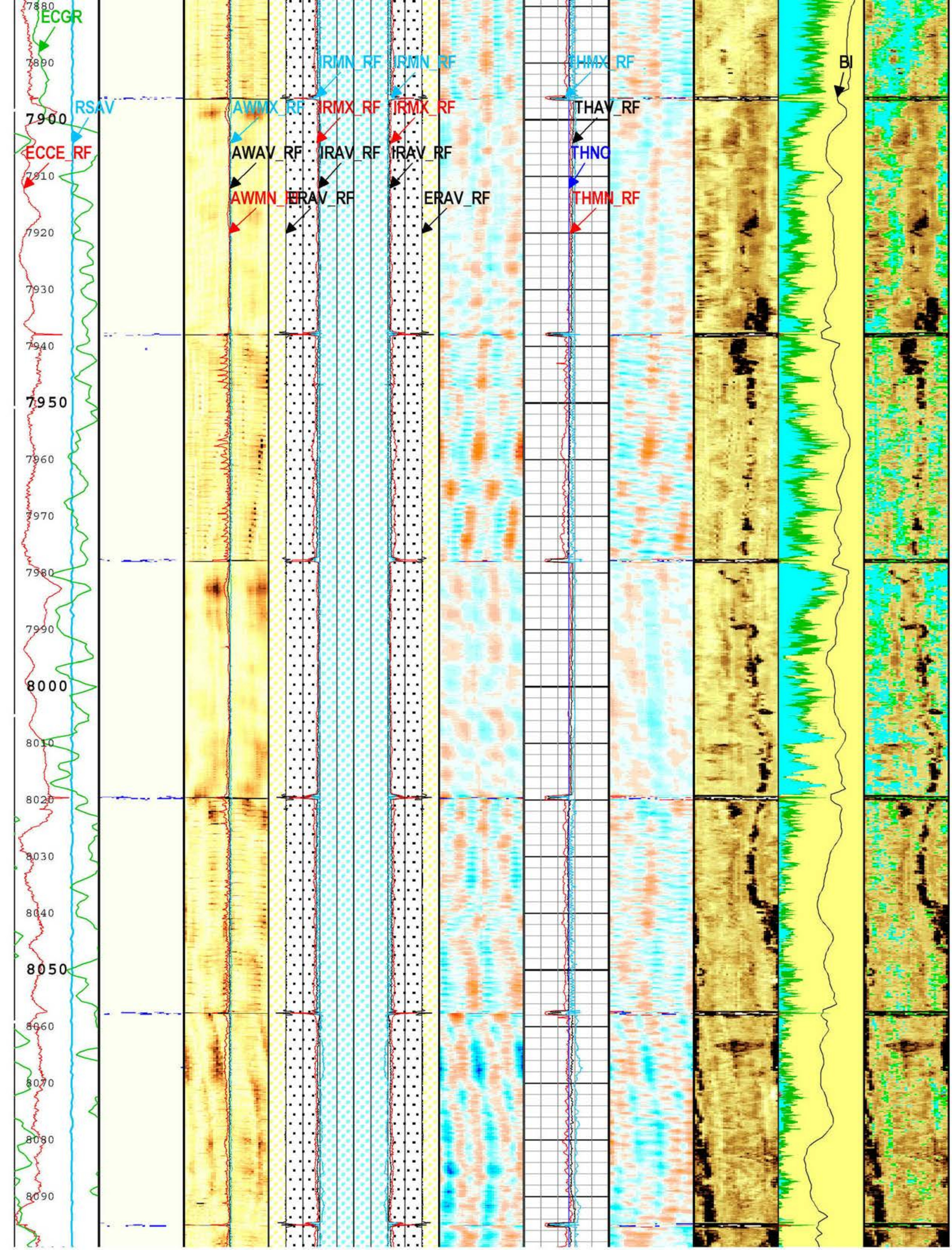
7880
ECGR
7890
IRMN_RF
IRMN_RF
THMX_RF
BI
RSAV
AWMX_RF
IRMX_RF
IRMX_RF
THAV_RF
7900
ECCE_RF
AWAV_RF
IRAV_RF
IRAV_RF
THNO
7910
AWMN_RF
ERAV_RF
ERAV_RF
THMN_RF
7920
7930
7940
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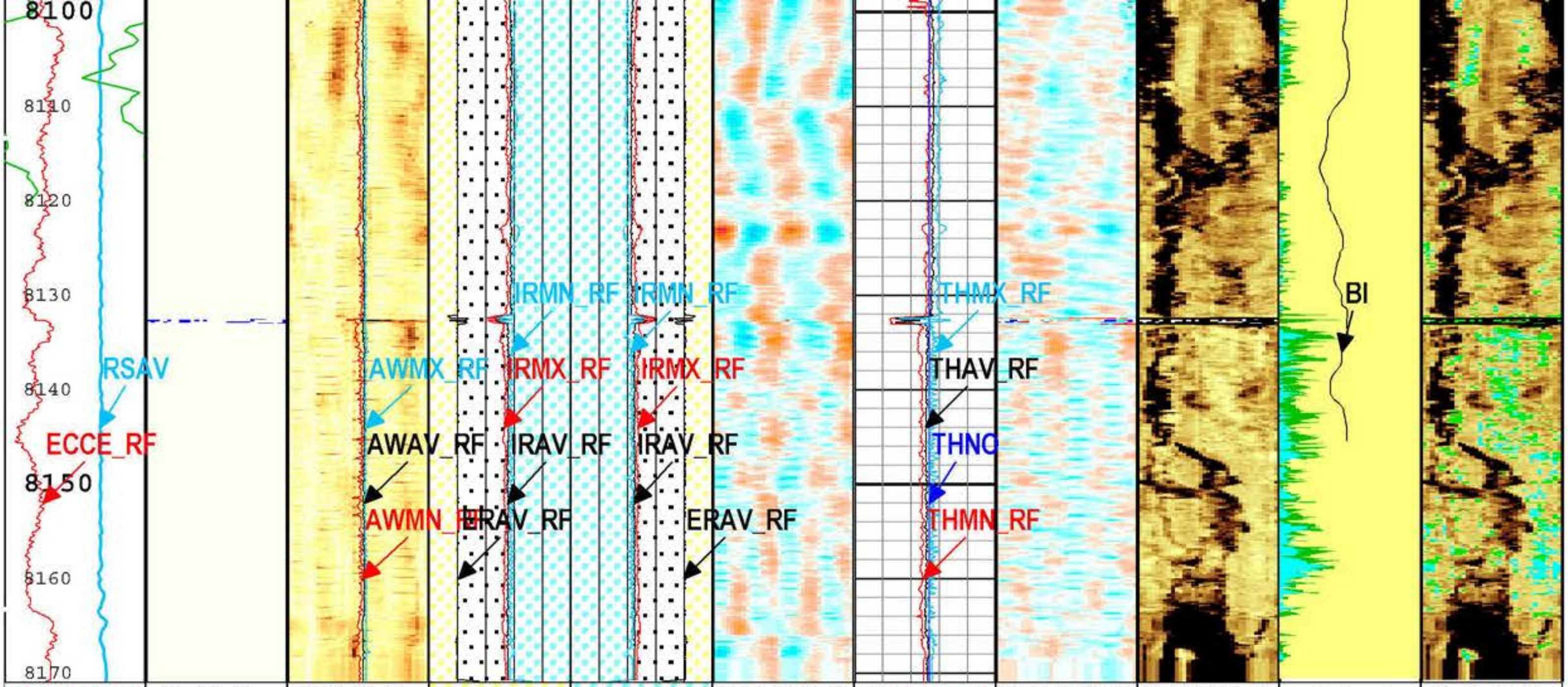


Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5

Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8

Gamma Ray (ECGR) HGNS[1]
0 gAPI 150

Absent 1.500 3.500
Explicit Normalization
USIT - USIT Processing Flags (UFLG) USIT-E[1]

USIT Processing Flags (UFLG[0]) USIT-E[1]
1 5

Absent -4.799 -2.799 -0.800
Explicit Normalization
USIT - Amplitude of Unflagged Wave (AWBK_RF) USIT-E[1] (dB)

Minimum of Unflagged Wave Amplitude (AWMN_RF) USIT-E[1]
0 dB 75

Average of Unflagged Wave Amplitude (AWAV_RF) USIT-E[1]
0 dB 75

Maximum of Unflagged Wave Amplitude (AWMX_RF) USIT-E[1]
0 dB 75

ERAV
ERAV-IRAV
IRAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7

IRAV
ERAV
IRAV-ERAV

Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7

Absent -0.051 -0.012 0.028 0.068
Explicit Normalization
USIT - Unflagged Internal Radii minus Median Internal Radius (IRBKM_RF) USIT-E[1] (in)

Minimum of Unflagged Casing Thickness (THMN_RF) USIT-E[1]
0.1 in 0.6

Nominal Casing Thickness (THNO) USIT-E[1]
0.1 in 0.6

Median of Unflagged Casing Thickness (THAV_RF) USIT-E[1]
0.1 in 0.6

Maximum of Unflagged Casing Thickness (THMX_RF) USIT-E[1]
0.1 in 0.6

Absent -0.051 -0.012 0.028 0.068
Explicit Normalization
USIT - Unflagged Casing Thickness minus Median of Unflagged Casing Thickness (THBKM_RF) USIT-E[1] (in)

Absent 1.500 3.500 5.500 7.500
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)

Ratio of Cement Measurements to Total (CEMR) USIT-E[1]
1 0

Micro-debonding Ratio (MDR) USIT-E[1]
1 0

Ratio of Gas Measurements to Total (GASR) USIT-E[1]
1 0

Bonded
Gas
Liquid
Micro-debonding

Bond Index (BI) DSLT-H[1]
1 0

Absent 3.090 5.054 7.018
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)

Absent 2.599 4.563 6.527
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)

USIT Processing Flags (UFLG[0]) USIT-E[1]

1 - UFLG 1 Value within [0.0 - 1.5] - : ■ UTIM Error
2 - UFLG 2 Value within [1.5 - 2.5] - : ■ Pulse Origin Not Detected

3 - UFLG 3 Value within [2.5 - 3.5] - :
4 - UFLG 4 UFLG 5 UFLG 6 Value within [3.5 - 6.5] - :
5 - UFLG 7 UFLG 8 UFLG 9 Value within [6.5 - 10] - :

🟥 WINLEN Error
🟦 Casing Thickness Error
🟦 Loop Processing Error

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Composite Format: Log (LBV1_USI Composite 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:19

Two

Cement Log 2 IN = 100 FT

Pass Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[6]:Up	Up	6845.38 ft	8162.42 ft	19-Oct-2016 2:46:42 PM	19-Oct-2016 3:11:08 PM	ON	2.05 ft	No

All depths are referenced to toolstring zero

Log

Company:Southern California Gas Company Well:Frew 4

Two: Log[6]:Up:S008

Description: USI Cement Format: Log (LBV1_USI Cement 7inch) Index Scale: 2 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:43

TIME_1900 - Time Marked every 60.00 (s)

ERAV_IRAV
IRAV_LHF1
LHF1_ERAV

ERAV_RHF1
IRAV_ERAV
RHF1_IRAV

Median of Unflagged External Radii (ERAV_RF) USIT-E
3.7 in 2.7

Median of Unflagged External Radii (ERAV_RF) USIT-E
2.7 in 3.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E
3.7 in 2.7

Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E
2.7 in 3.7

Gamma Ray (ECGR) HGNS-H
0 gAPI 150

Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E
0 in 0.5

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E
3.7 in 2.7

Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E
2.7 in 3.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E
3.7 in 2.7

Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E
2.7 in 3.7

Absent 0.500 1.500 2.500 3.500 4.500 5.500 6.500 7.500

Custom Normalization

USIT - Acoustic Impedance (AIBK) USIT-E

(Mrayl)

Acoustic Impedance Minimum (AIMN) USIT-E
-1 Mrayl 9

Acoustic Impedance Average (AIAV) USIT-E
-1 Mrayl 9

Acoustic Impedance Maximum (AIMX) USIT-E
-1 Mrayl 9

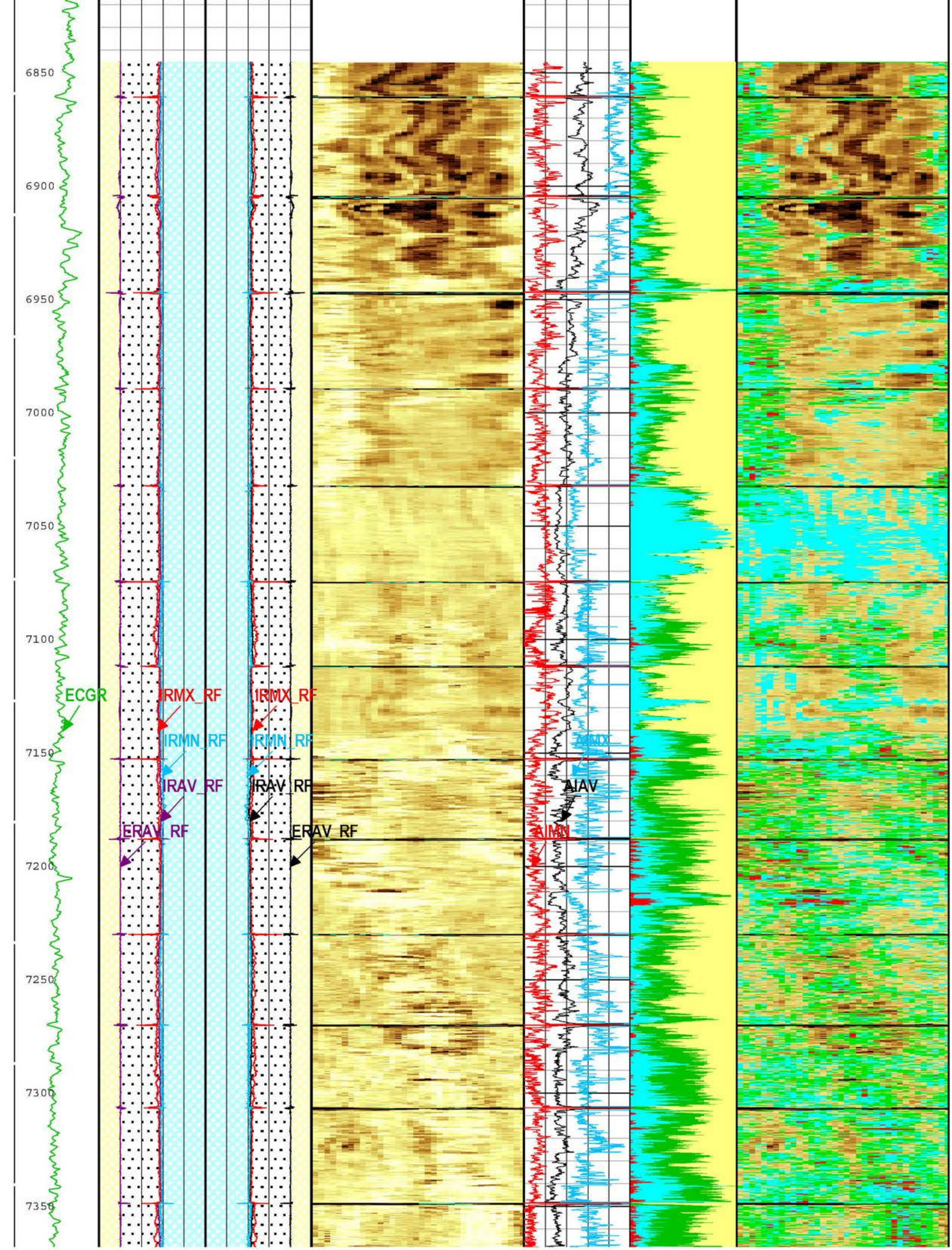
Bonded
Gas
Liquid
Micro-debonding

Absent -500.000 2.599 3.581 4.563 5.545 6.527 7.509

Custom Normalization

USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E

(Mrayl)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6900
6950
7000
7050
7100
7150
7200
7250
7300
7350
ECGR
IRMX_RF
IRMN_RF
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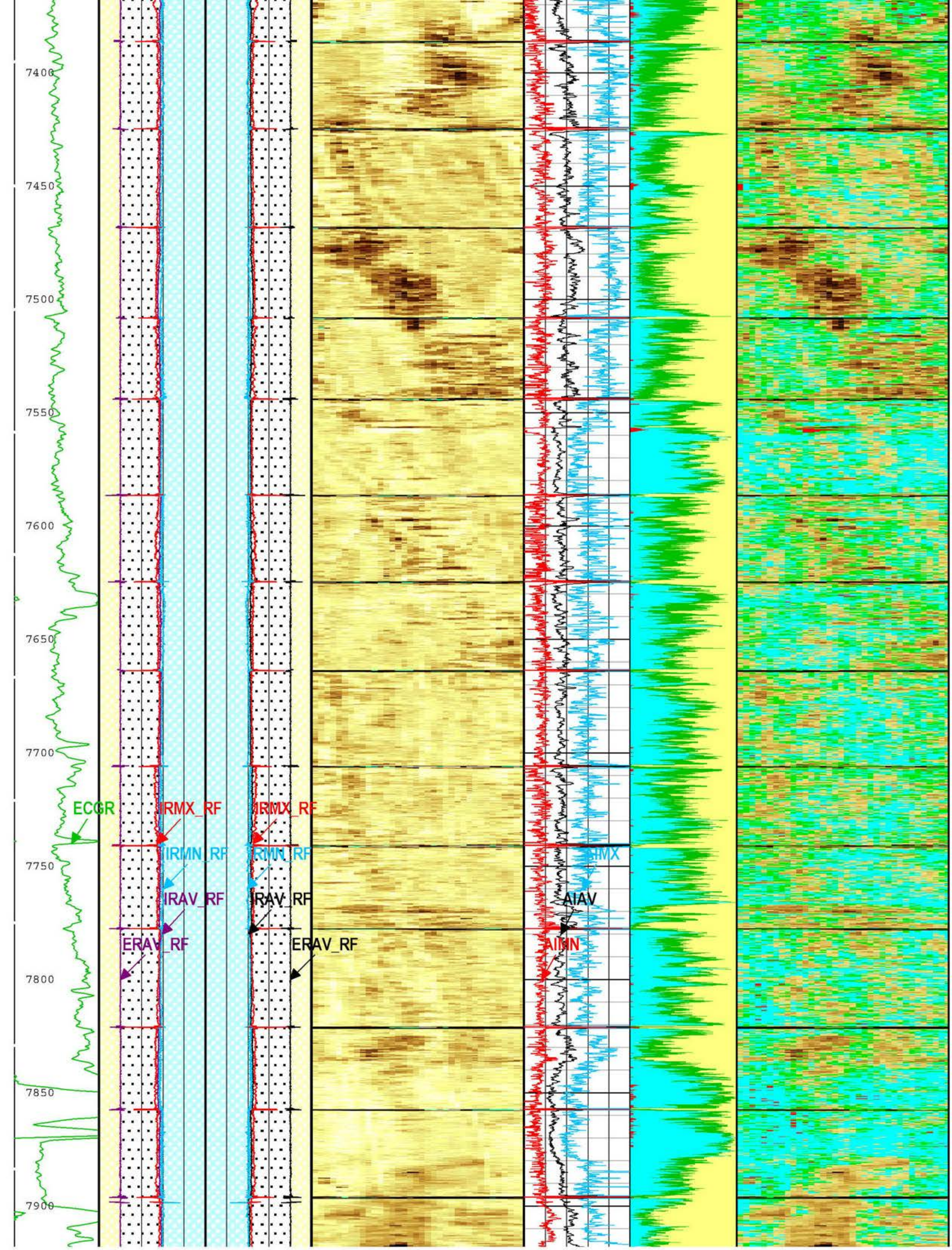
AIMX
AIAV
AIMN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IRMX_RF
IRMX_RF
7750
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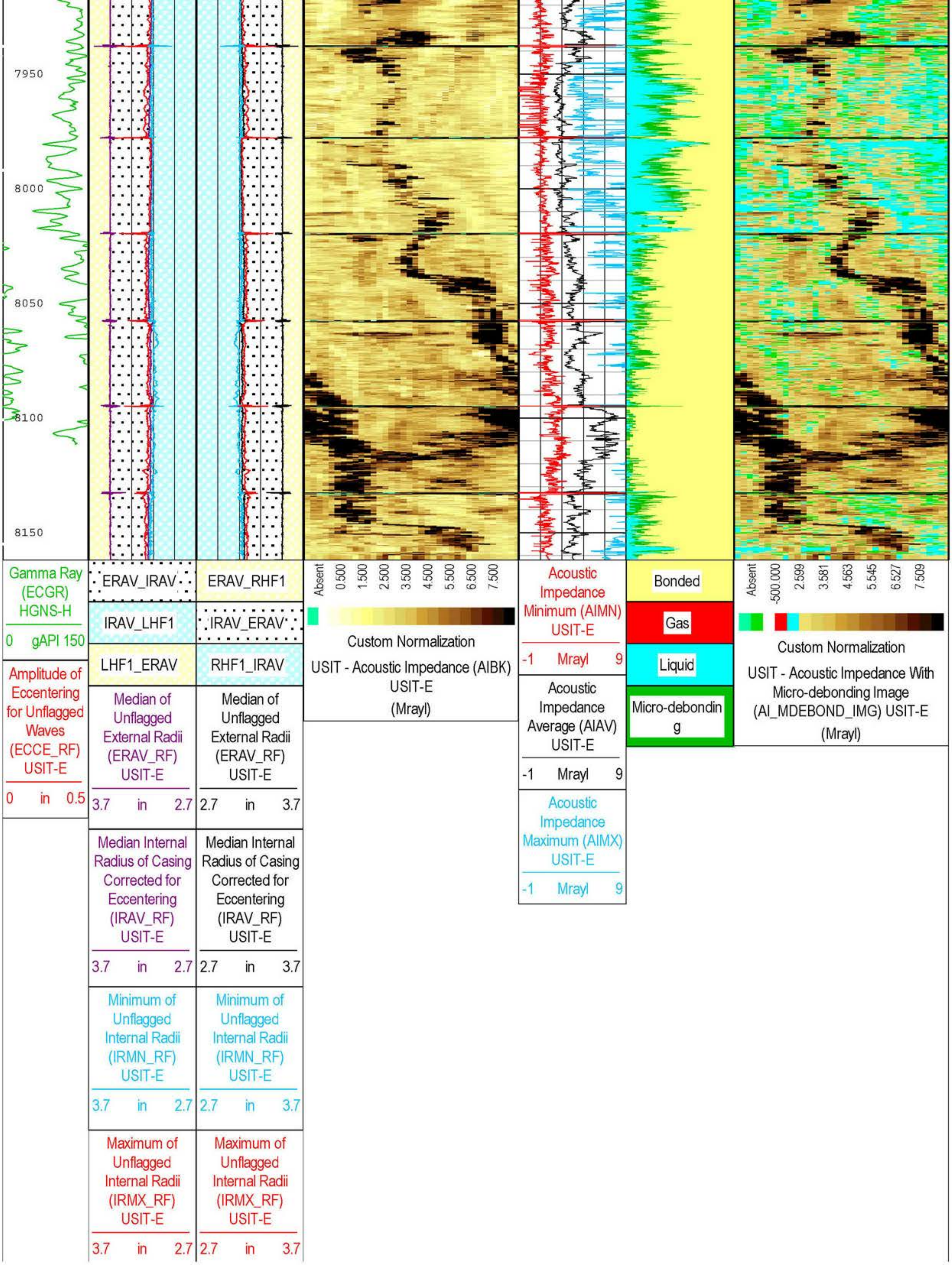
AIMX
IRAV_RF
IRAV_RF
AIAV
ERAV_RF
ERAV_RF
AIMN
7800
7850
7900


7950
8000
8050
8100
8150
Gamma Ray (ECGR) HGNS-H
0 gAPI 150
Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E
0 in 0.5
ERAV_IRAV
IRAV_LHF1
LHF1_ERAV
Median of Unflagged External Radii (ERAV_RF) USIT-E
3.7 in 2.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E
3.7 in 2.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E
3.7 in 2.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E
3.7 in 2.7
ERAV_RHF1
IRAV_ERAV
RHF1_IRAV
Median of Unflagged External Radii (ERAV_RF) USIT-E
2.7 in 3.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E
2.7 in 3.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E
2.7 in 3.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E
2.7 in 3.7
Absent 0.500 1.500 2.500 3.500 4.500 5.500 6.500 7.500
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E
(Mrayl)
Acoustic Impedance Minimum (AIMN) USIT-E
-1 Mrayl 9
Acoustic Impedance Average (AIAV) USIT-E
-1 Mrayl 9
Acoustic Impedance Maximum (AIMX) USIT-E
-1 Mrayl 9
Bonded
Gas
Liquid
Micro-debonding
Absent -500.000 2.599 3.581 4.563 5.545 6.527 7.509
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E
(Mrayl)

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Cement Format: Log (LBV1_USI Cement 7inch) Index Scale: 2 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:43

Composite 1

Corrosion 5 in = 100 ft

Composite Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[9]:Up	Up	6640.29 ft	8171.85 ft	20-Oct-2016 9:51:39 AM	20-Oct-2016 10:20:40 AM	ON	1.47 ft	No
Two	Log[11]:Up	Up	36.69 ft	6737.51 ft	20-Oct-2016 10:24:53 AM	20-Oct-2016 12:34:00 PM	ON	1.35 ft	No
Two	Log[14]:Up	Up	5.56 ft	155.15 ft	20-Oct-2016 12:53:24 PM	20-Oct-2016 12:58:23 PM	ON	1.96 ft	No

All depths are referenced to toolstring zero

Log

Company:Southern California Gas Company Well:Frew 4

Composite 1:S008

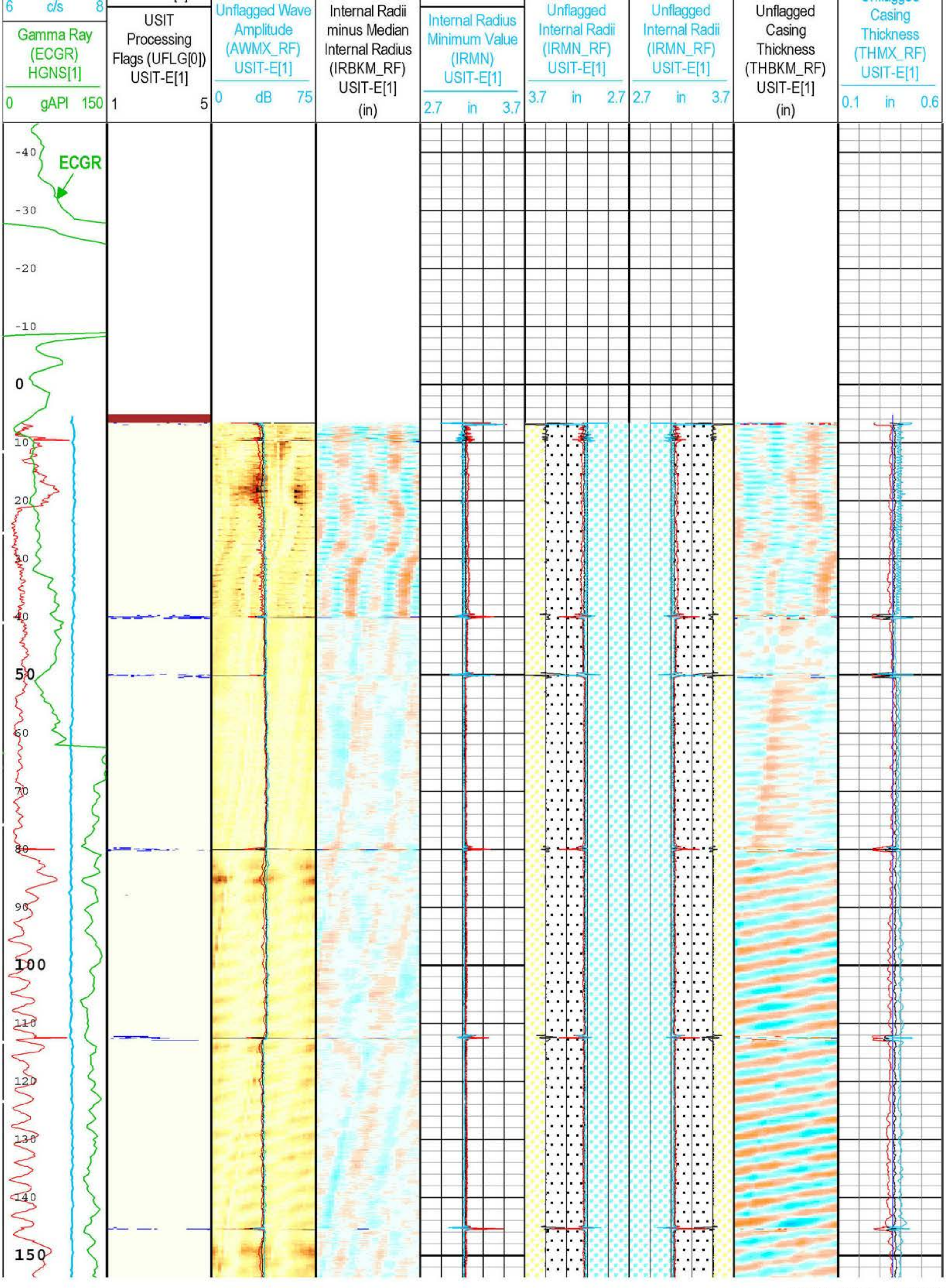
Description: USI Composite Format: Log (LBV1_USI Corrosion 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:48

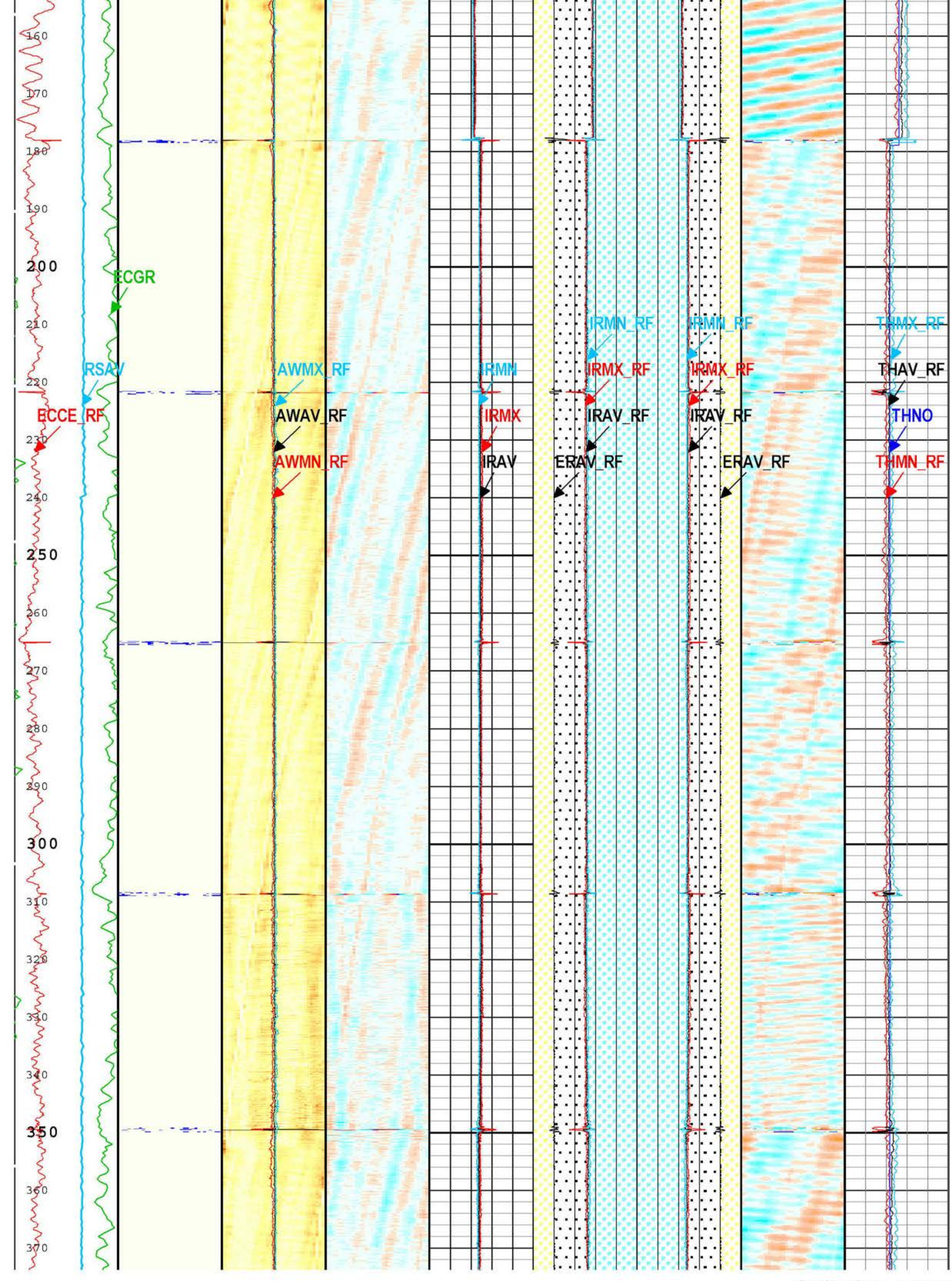
TIME_1900 - Time Marked every 60.00 (s)

USIT Processing Flags (UFLG[0]) USIT-E[1]

1 - UFLG 1 Value within [0.0 - 1.5] - :	⬛	UTIM Error
2 - UFLG 2 Value within [1.5 - 2.5] - :	🟫	Pulse Origin Not Detected
3 - UFLG 3 Value within [2.5 - 3.5] - :	🟥	WINLEN Error
4 - UFLG 4 UFLG 5 UFLG 6 Value within [3.5 - 6.5] - :	🟦	Casing Thickness Error
5 - UFLG 7 UFLG 8 UFLG 9 Value within [6.5 - 10] - :	▢	Loop Processing Error

Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1] 0 in 0.5 Motor Revolution Speed (RSAV) USIT-E[1]	Absent 1.500 3.500 Explicit Normalization USIT - USIT Processing Flags (UFLG) USIT-E[1]	Absent -5.200 -3.600 -2.000 -0.400 Explicit Normalization USIT - Amplitude of Unflagged Wave (AWBK_RF) USIT-E[1] (dB) Minimum of Unflagged Wave Amplitude (AWMN_RF) USIT-E[1] 0 dB 75 Average of Unflagged Wave Amplitude (AWAV_RF) USIT-E[1] 0 dB 75 Maximum of	Absent -0.059 -0.028 0.004 0.035 0.068 Explicit Normalization USIT - Unflagged	Internal Radius Averaged Value (IRAV) USIT-E[1] 2.7 in 3.7 Internal Radius Maximum Value (IRMX) USIT-E[1] 2.7 in 3.7	ERAV ERAV-IRAV IRAV Median of Unflagged External Radii (ERAV_RF) USIT-E[1] 3.7 in 2.7 Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1] 3.7 in 2.7 Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1] 3.7 in 2.7 Minimum of	IRAV ERAV IRAV-ERAV Median of Unflagged External Radii (ERAV_RF) USIT-E[1] 2.7 in 3.7 Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1] 2.7 in 3.7 Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1] 2.7 in 3.7 Minimum of	Absent -0.059 -0.028 0.004 0.035 0.068 Explicit Normalization USIT - Unflagged Casing Thickness minus Median of	Minimum of Unflagged Casing Thickness (THMN_RF) USIT-E[1] 0.1 in 0.6 Nominal Casing Thickness (THNO) USIT-E[1] 0.1 in 0.6 Median of Unflagged Casing Thickness (THAV_RF) USIT-E[1] 0.1 in 0.6 Maximum of Unflagged


6 c/s 8
Gamma Ray (ECGR) HGNS[1]
0 gAPI 150
USIT Processing Flags (UFLG[0]) USIT-E[1]
1 5
Unflagged Wave Amplitude (AWMX_RF) USIT-E[1]
0 dB 75
Internal Radii minus Median Internal Radius (IRBKM_RF) USIT-E[1] (in)
Internal Radius Minimum Value (IRMN) USIT-E[1]
2.7 in 3.7
Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7
Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7
Unflagged Casing Thickness (THBKM_RF) USIT-E[1] (in)
Casing Thickness (THMX_RF) USIT-E[1]
0.1 in 0.6
ECGR
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150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IRMX_RF
IRMX_RF
THAV_RF
ECCE_RF
AWAV_RF
IRMX
IRAV_RF
IRAV_RF
THNO
230
AWMN_RF
IRAV
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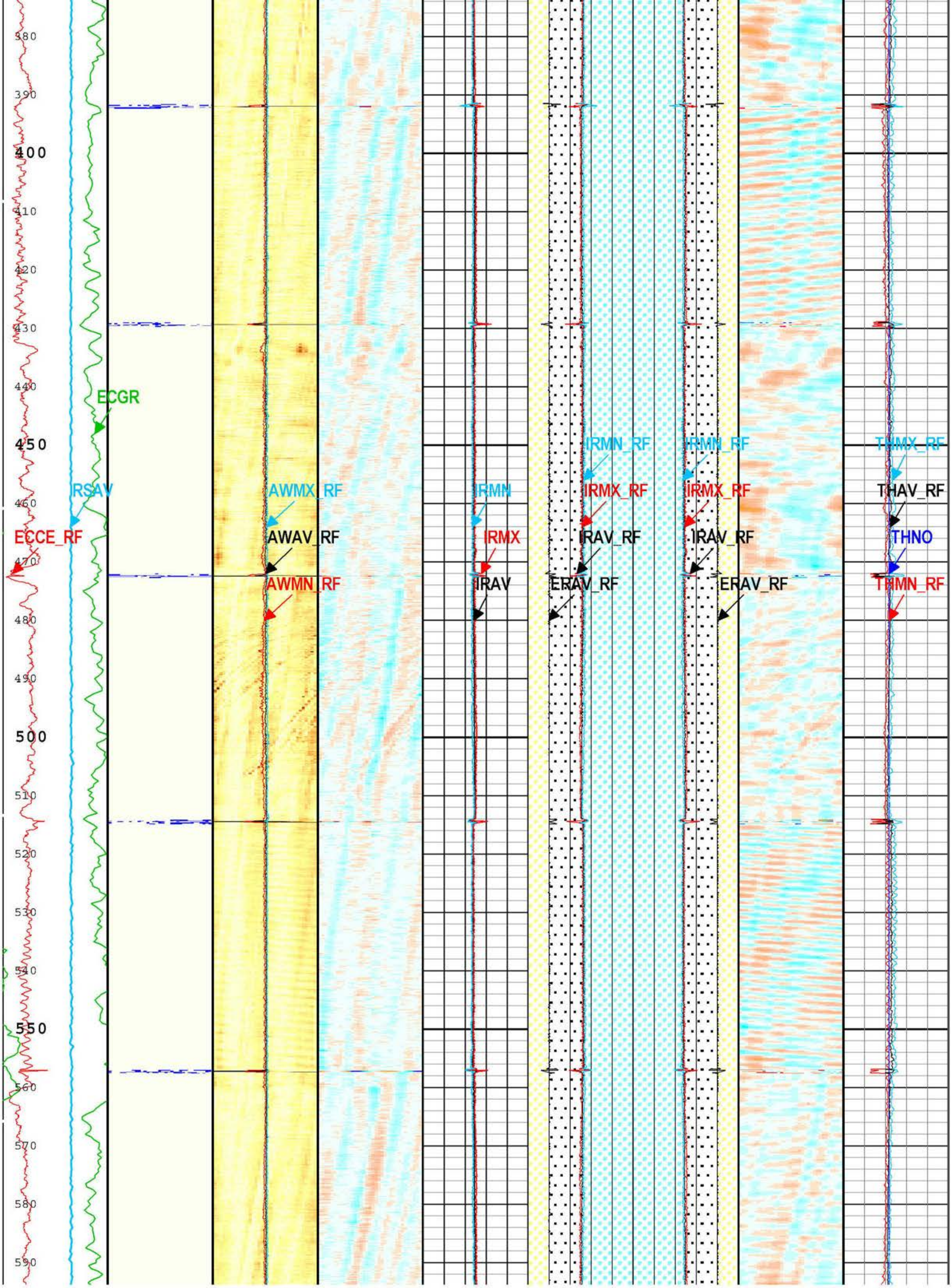
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ECGR
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RSAV
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ECCE_RF
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490
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520
530
540
550
560
570
580
590
AWMX_RF
AWAV_RF
AWMN_RF
IRMN
IRMX
IRAV
IRMN_RF
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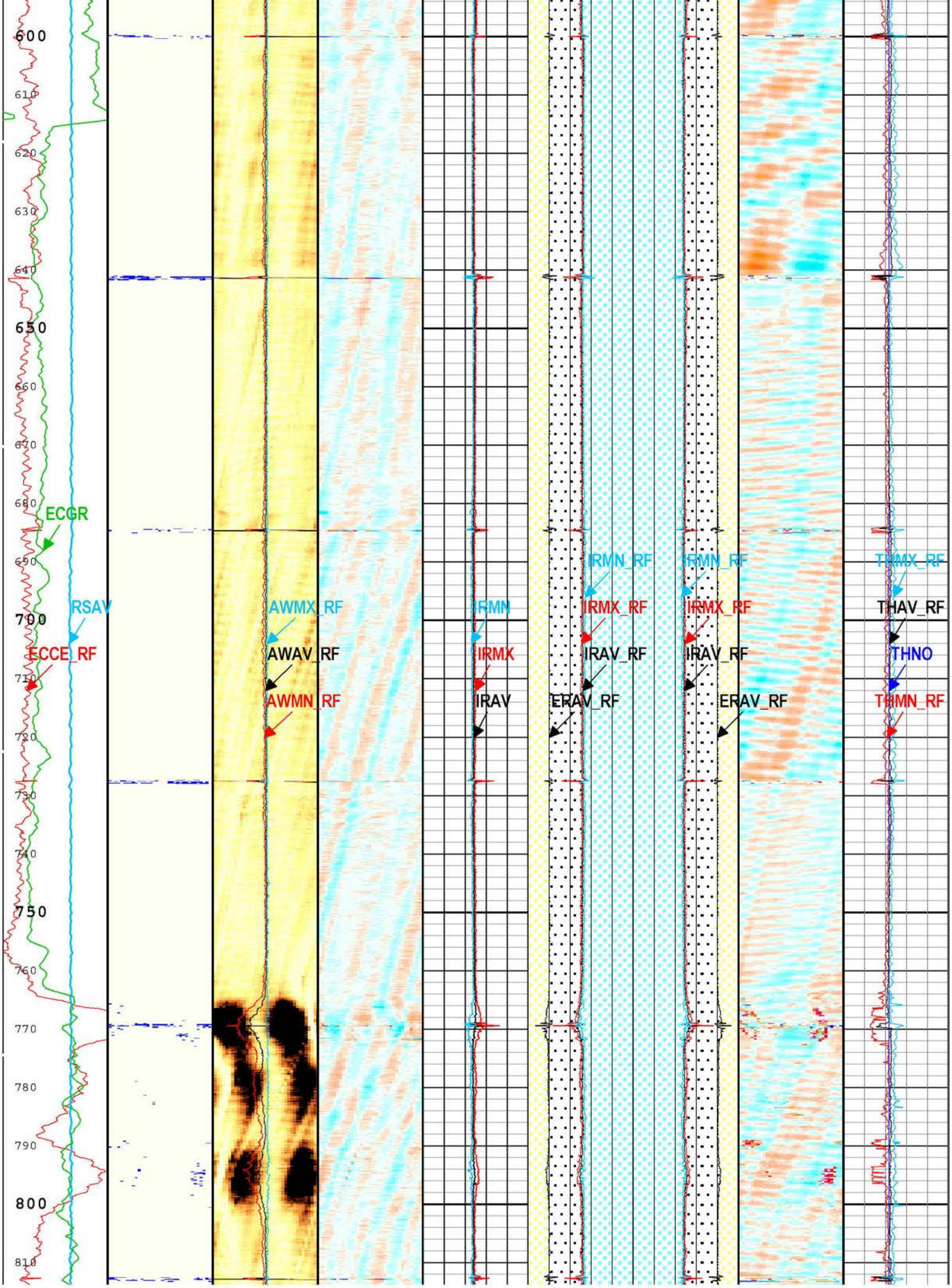
THMN_RF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810
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RSAV
ECCE_RF
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AWAV_RF
AWMN_RF
IRMN
IRMX
IRAV
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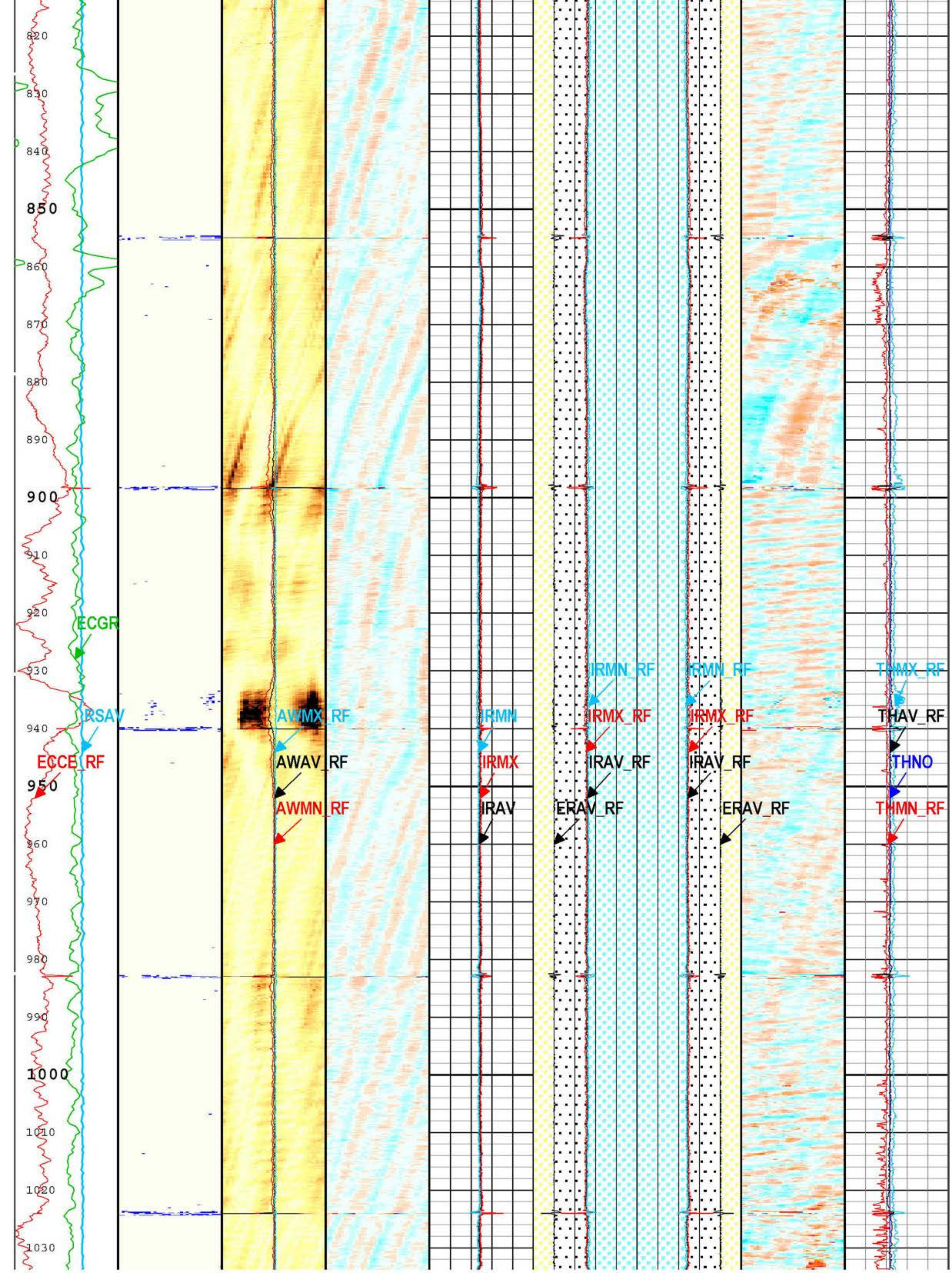
THMN_RF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ECGR
RSAV
ECCE_RF
AWMX_RF
AWAV_RF
AWMN_RF
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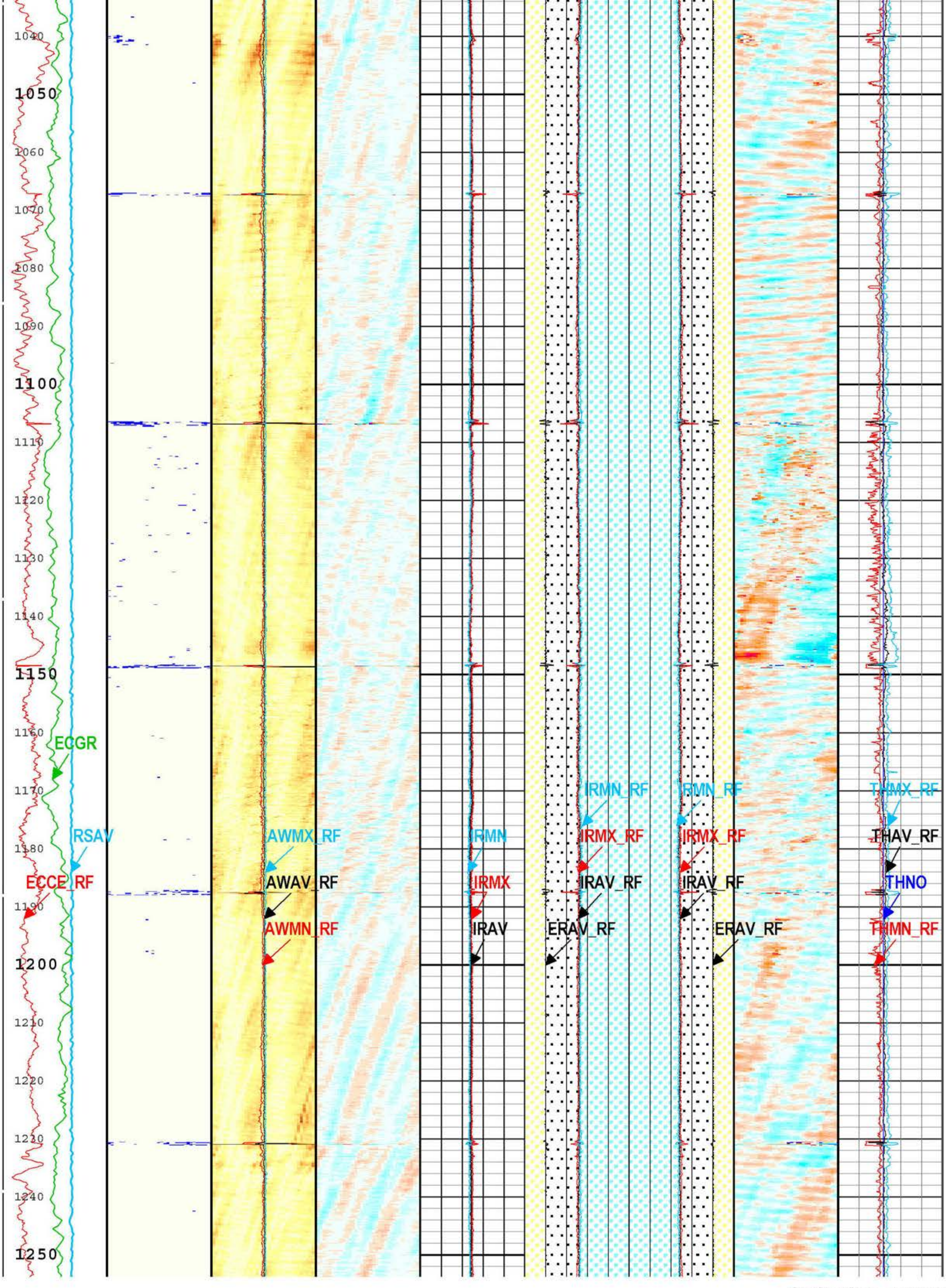
THMN_RF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1250
ECGR
RSAV
ECCE_RF
AWMX_RF
AWAV_RF
AWMN_RF
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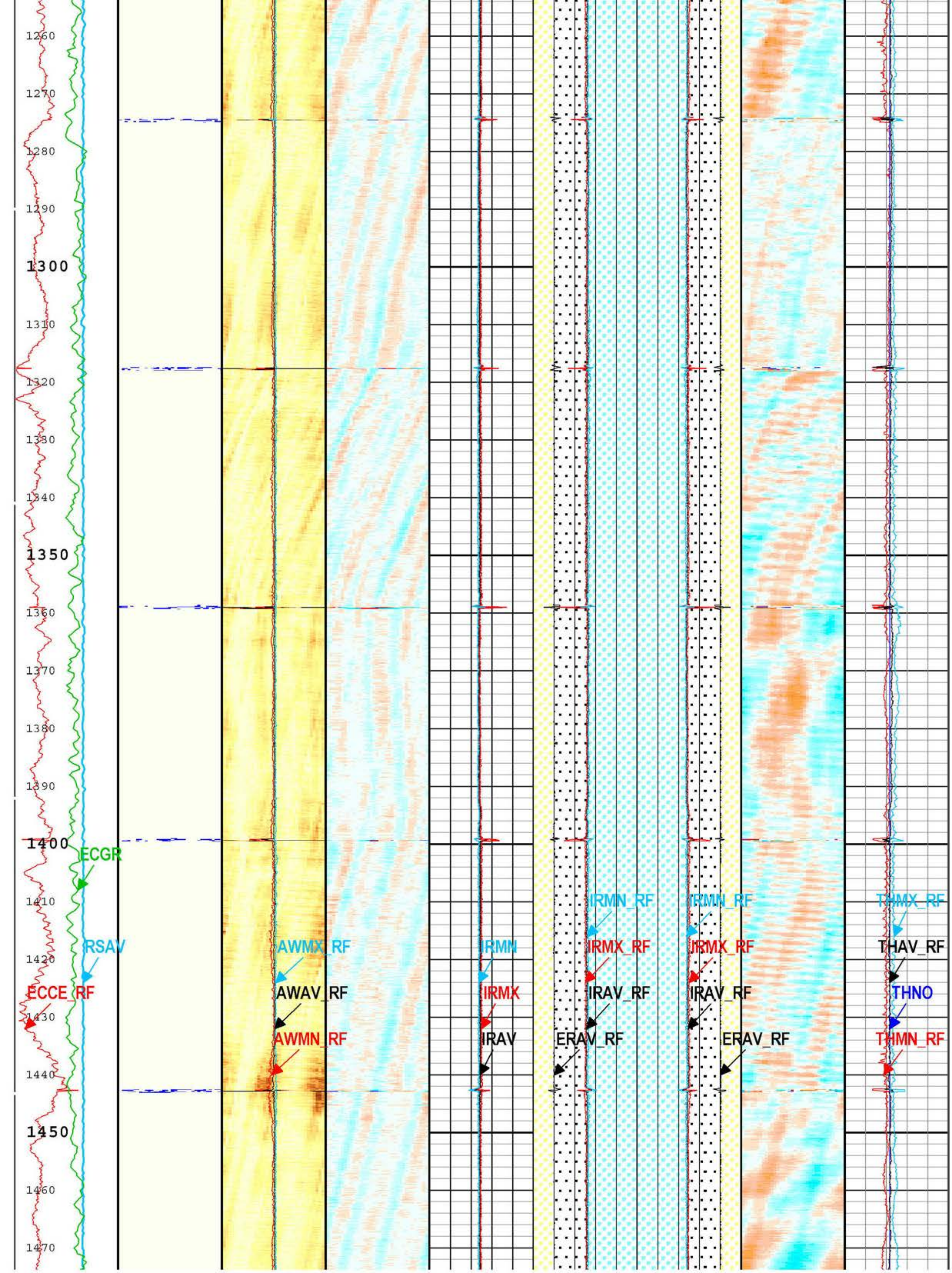
ERAV_RF
THMX_RF
THAV_RF
THNO
THMN_RF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AWMX_RF
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IRAV
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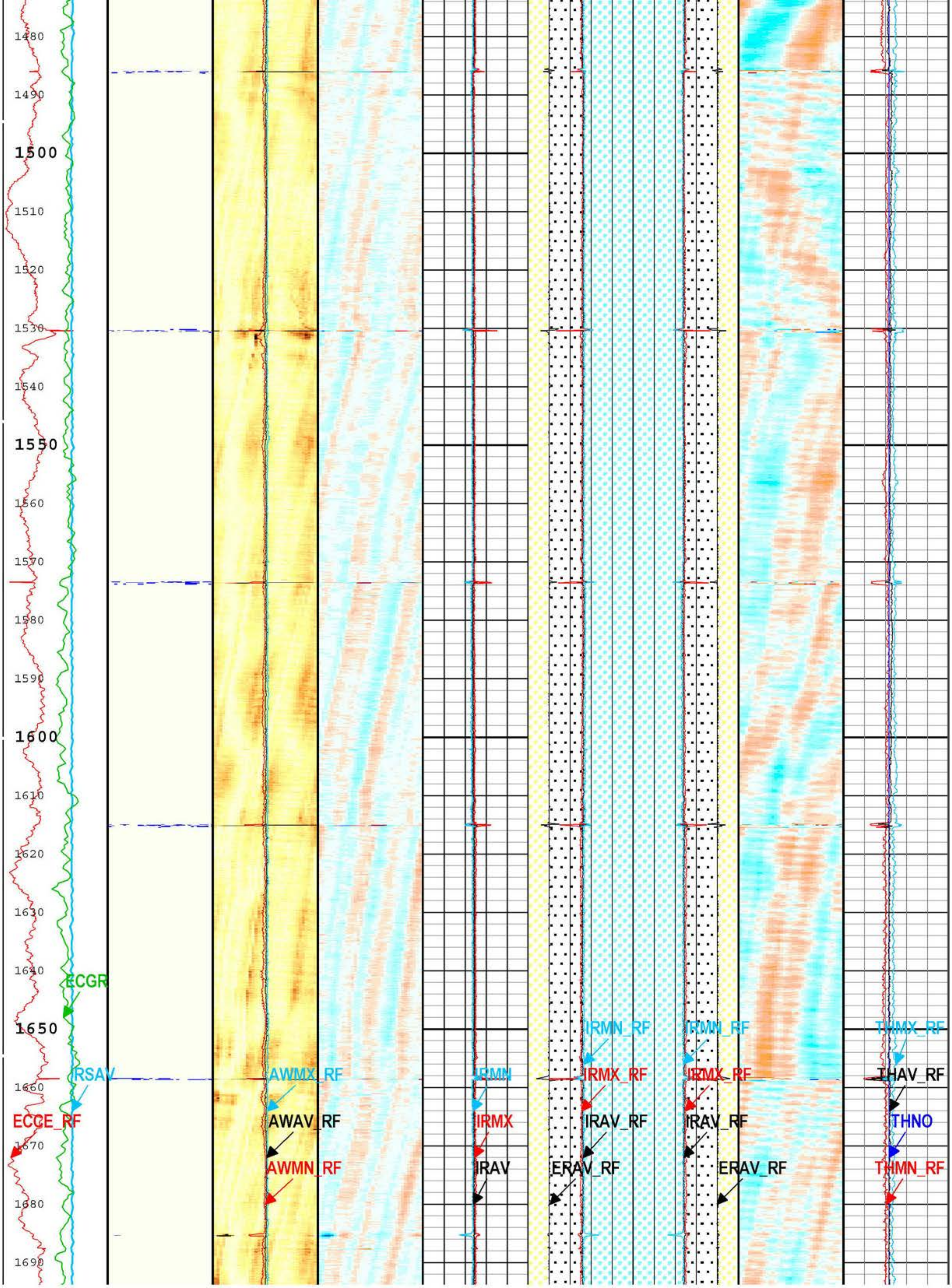

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1690
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IRSAV
ECCE_RF
AWMX_RF
AWAV_RF
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IRMN
IRMX
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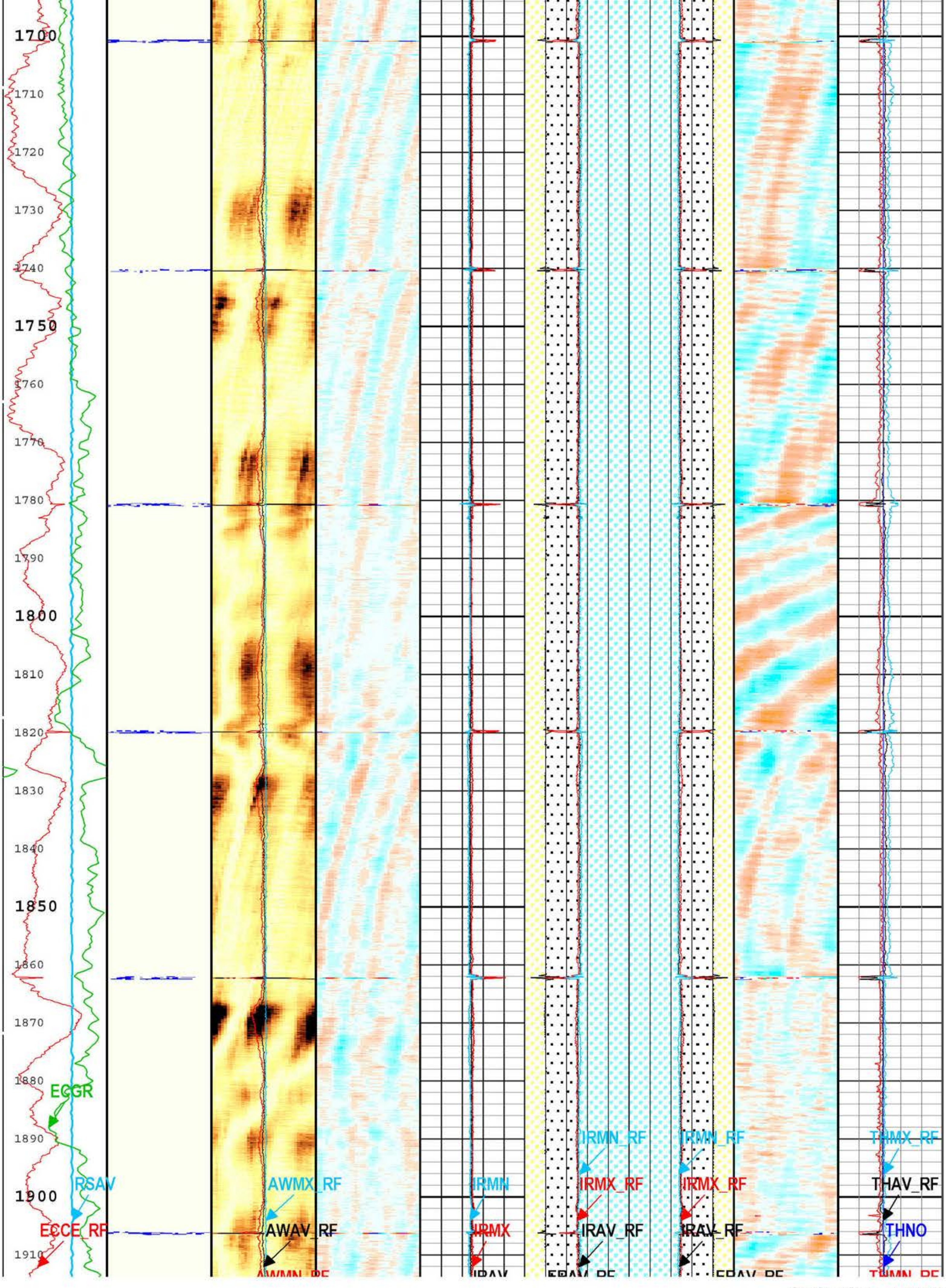
THMN_RF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ECGR
RSAV
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AWMX_RF
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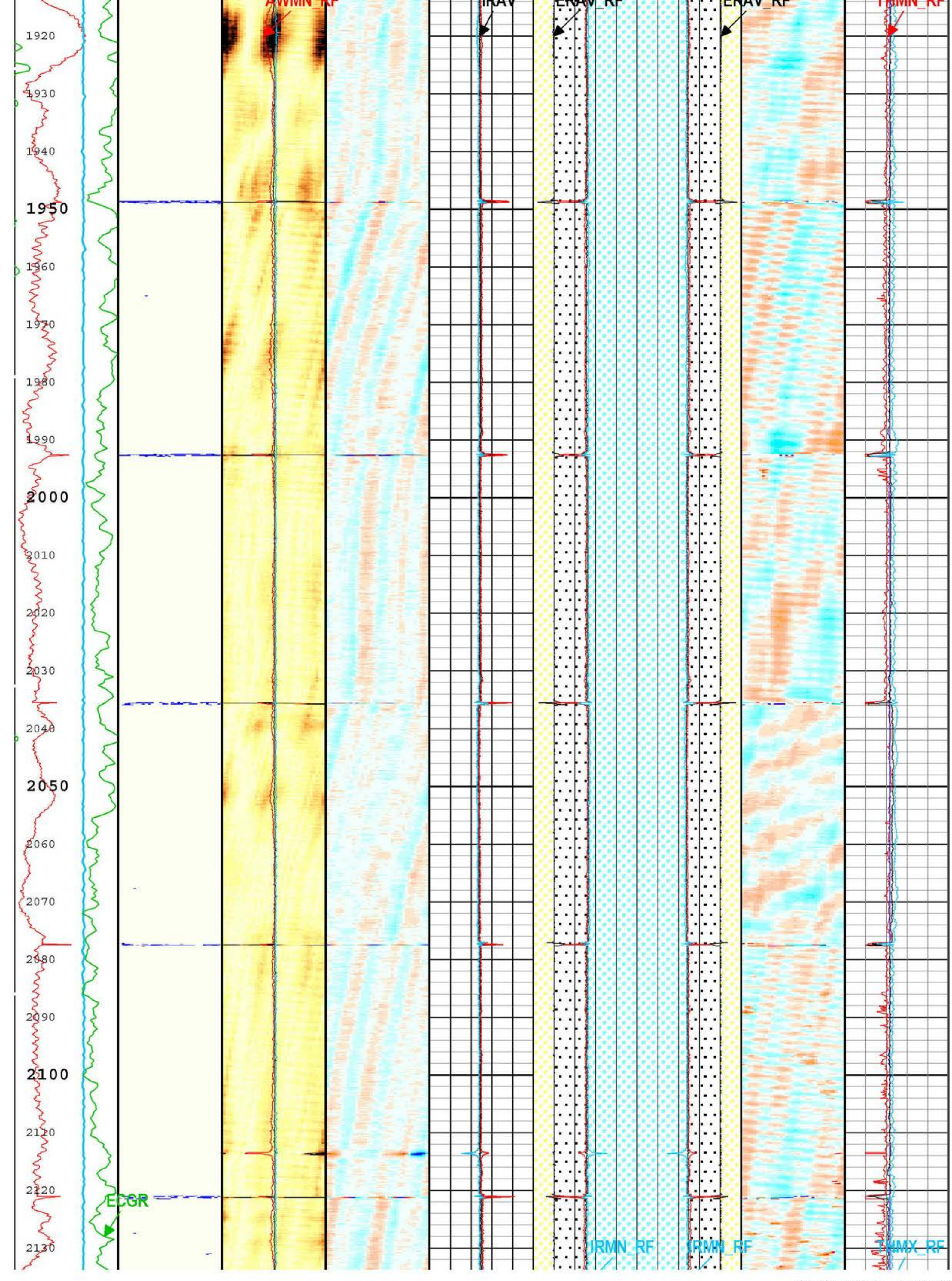
THMN_RF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TRMN_RF
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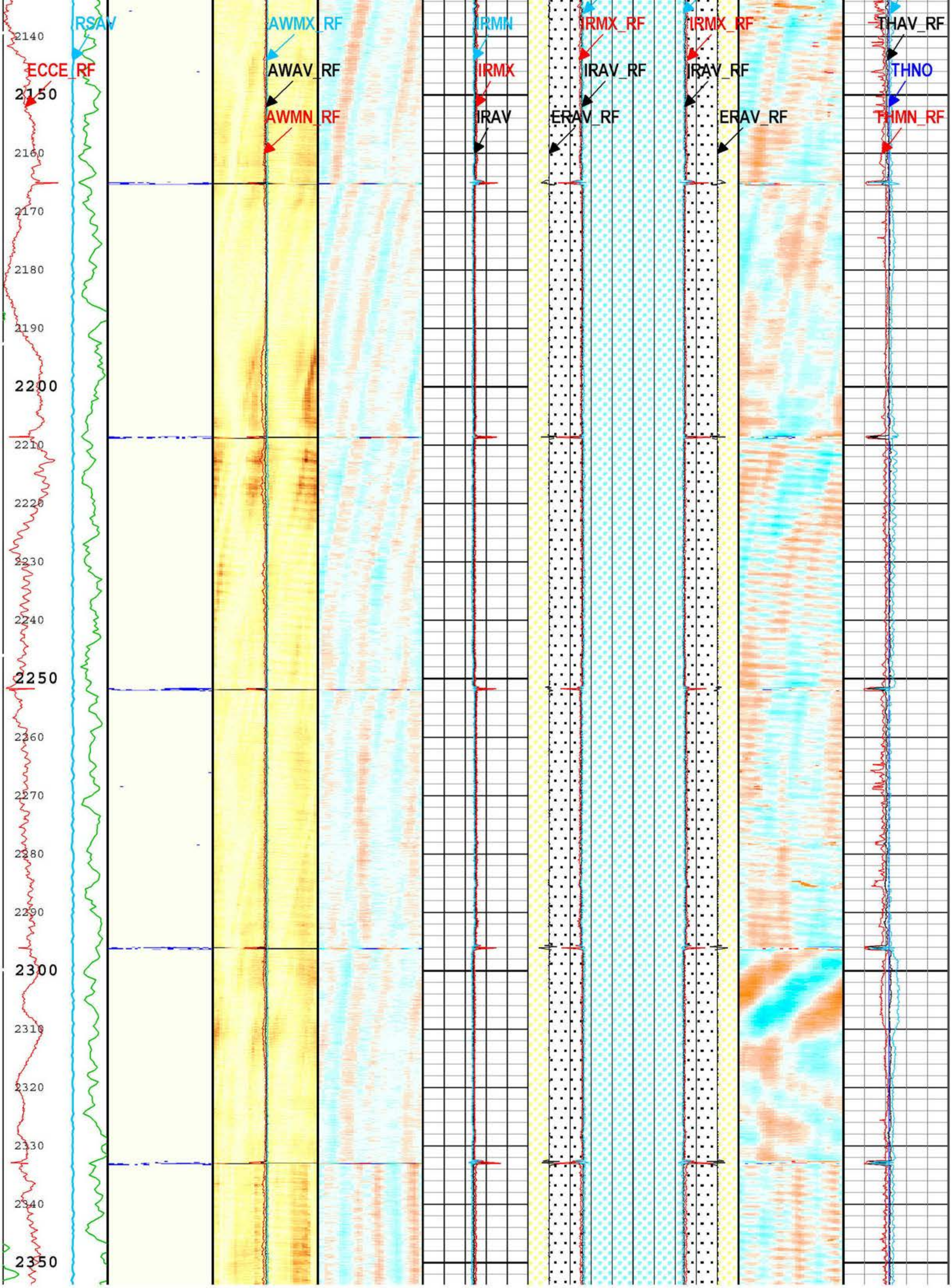
RSAV
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THAV_RF
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AWAV_RF
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AWMN_RF
IRAV
ERAV_RF
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THMN_RF
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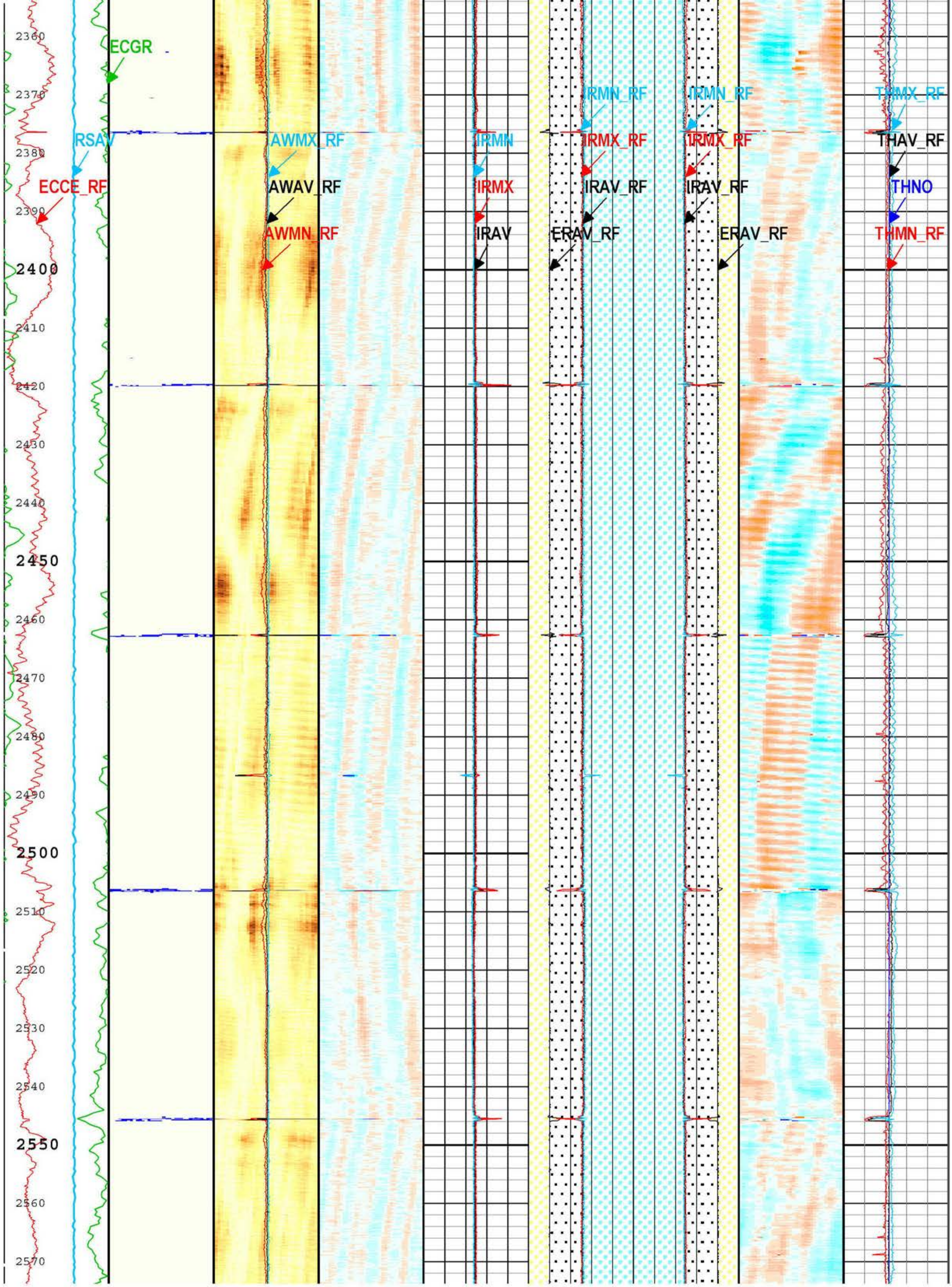
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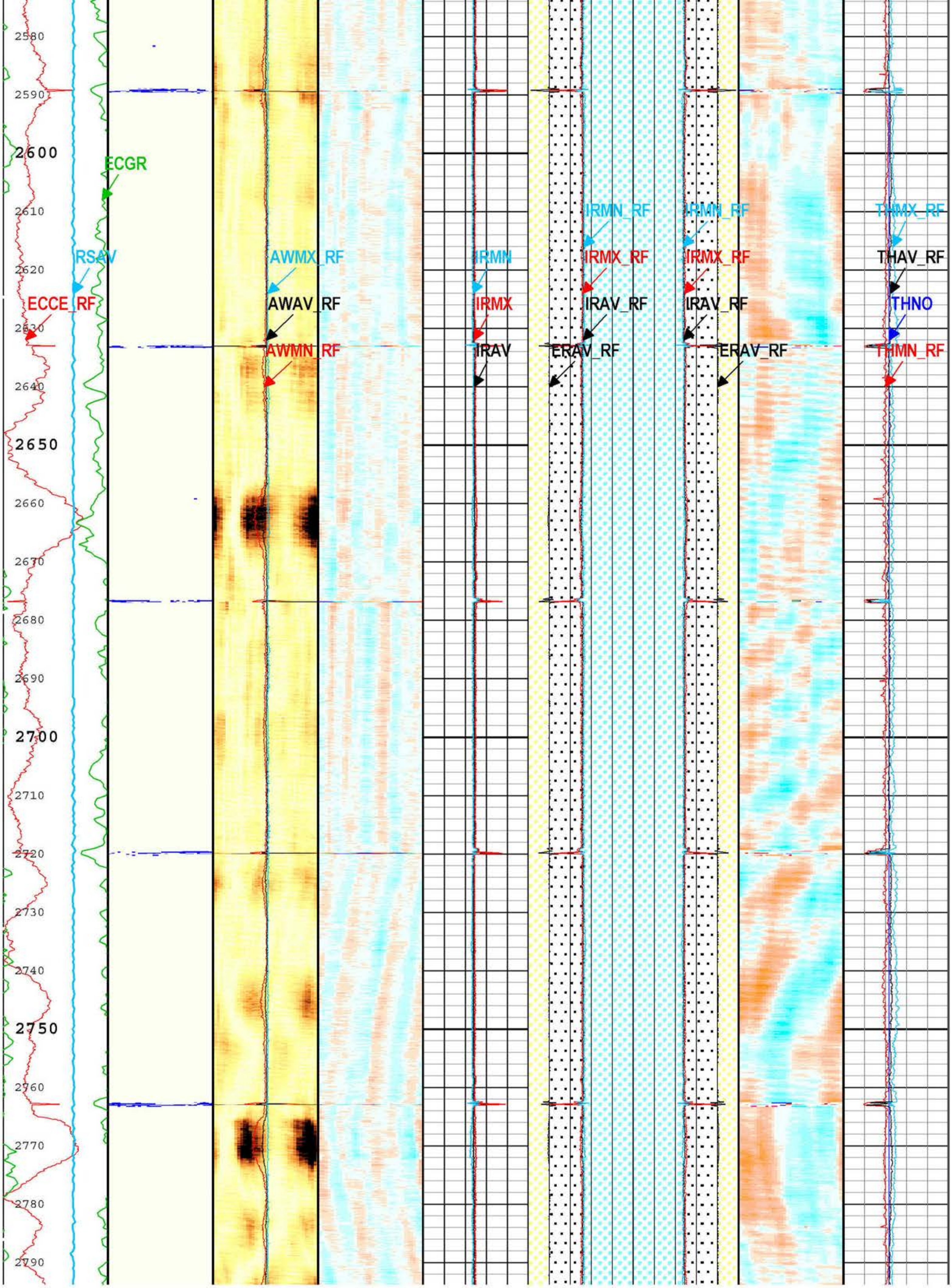
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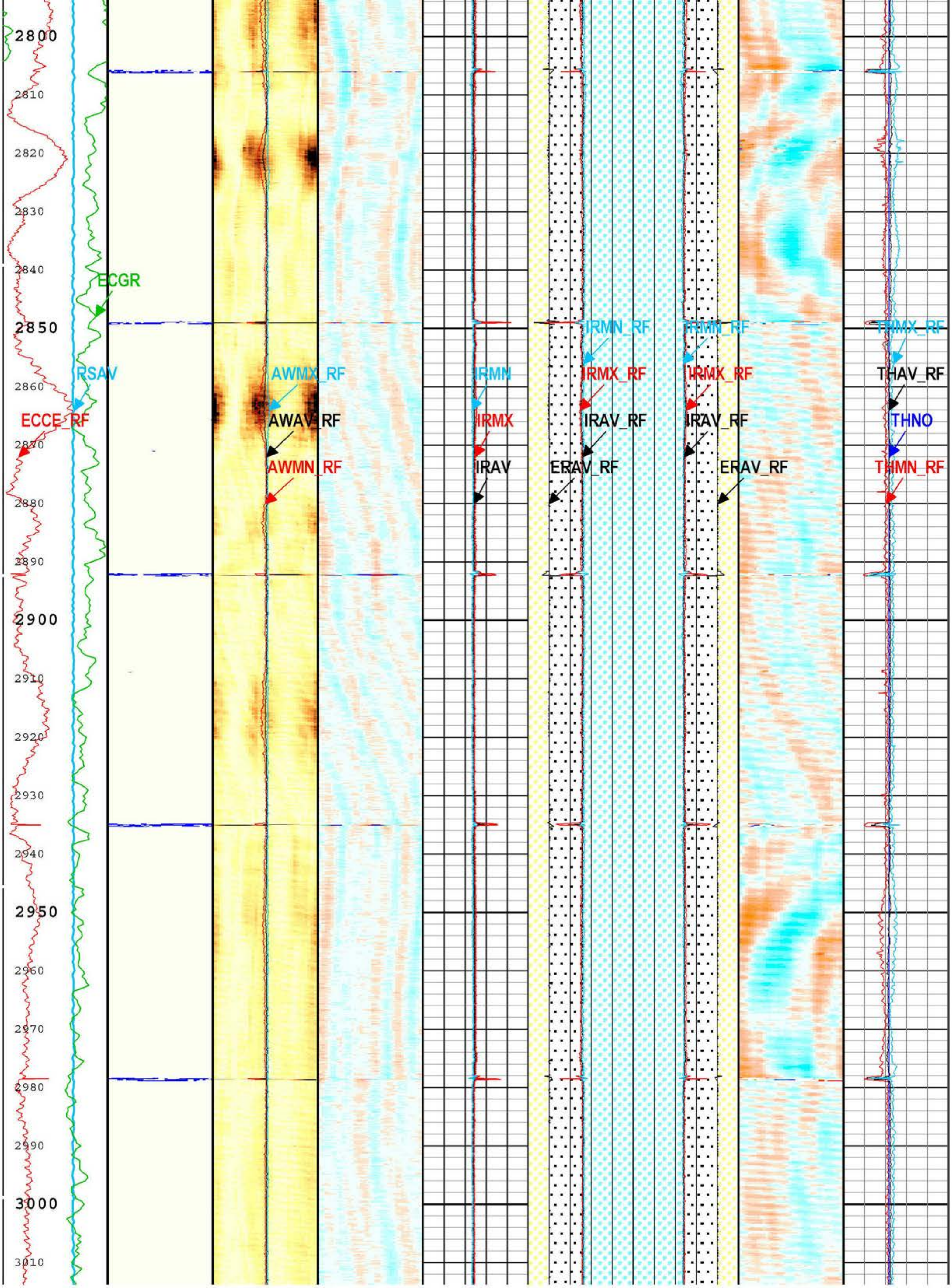
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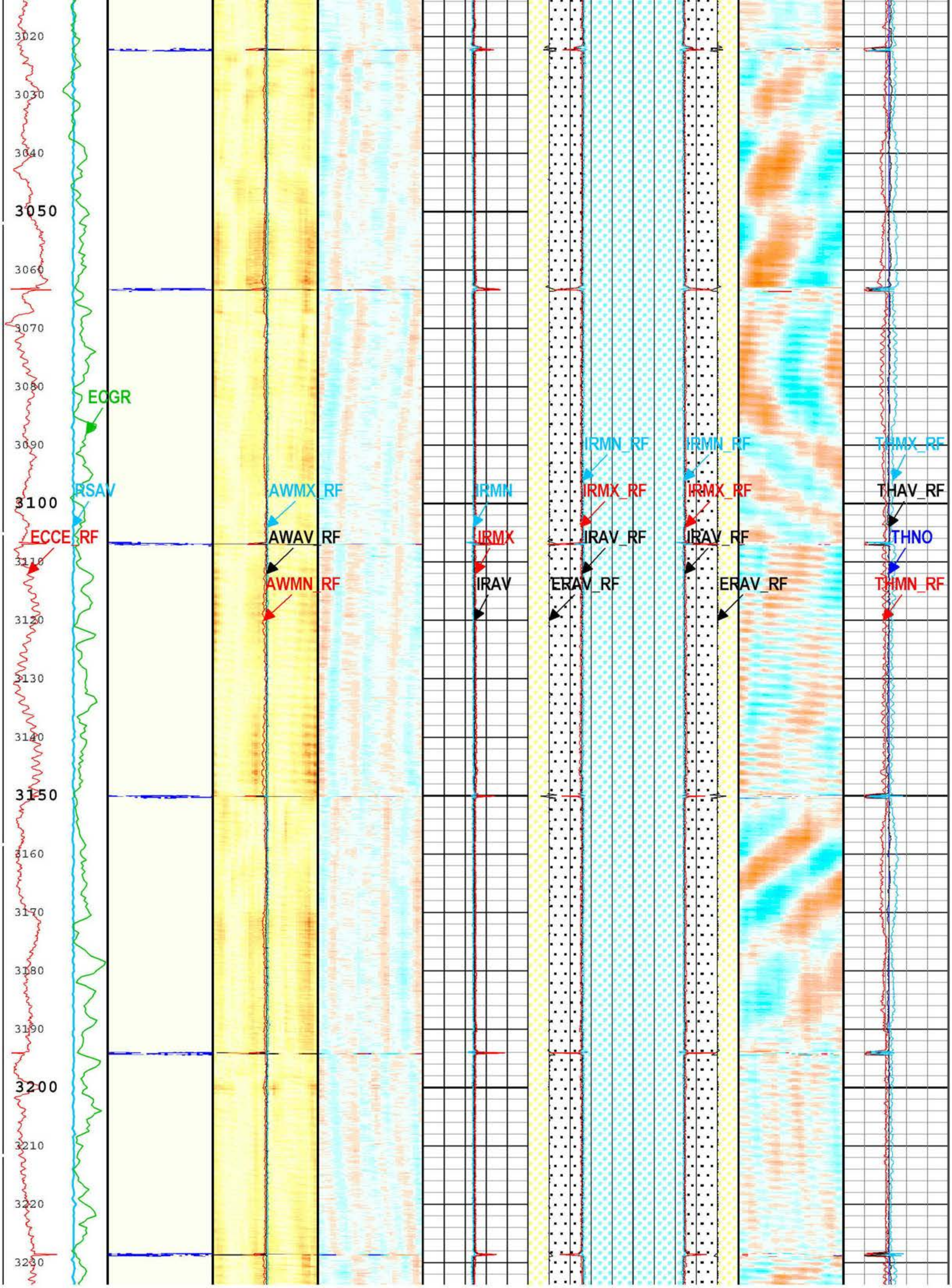
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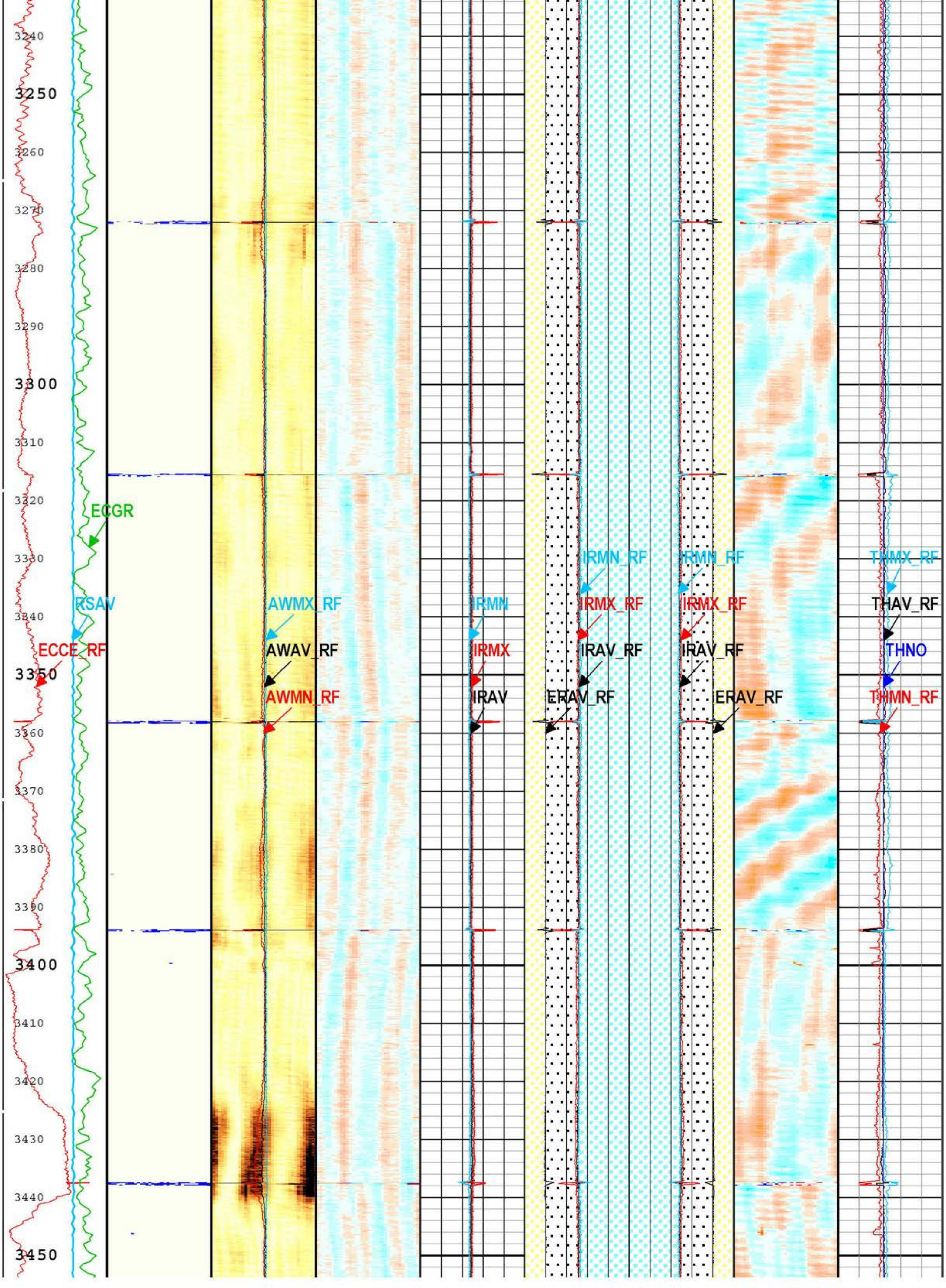
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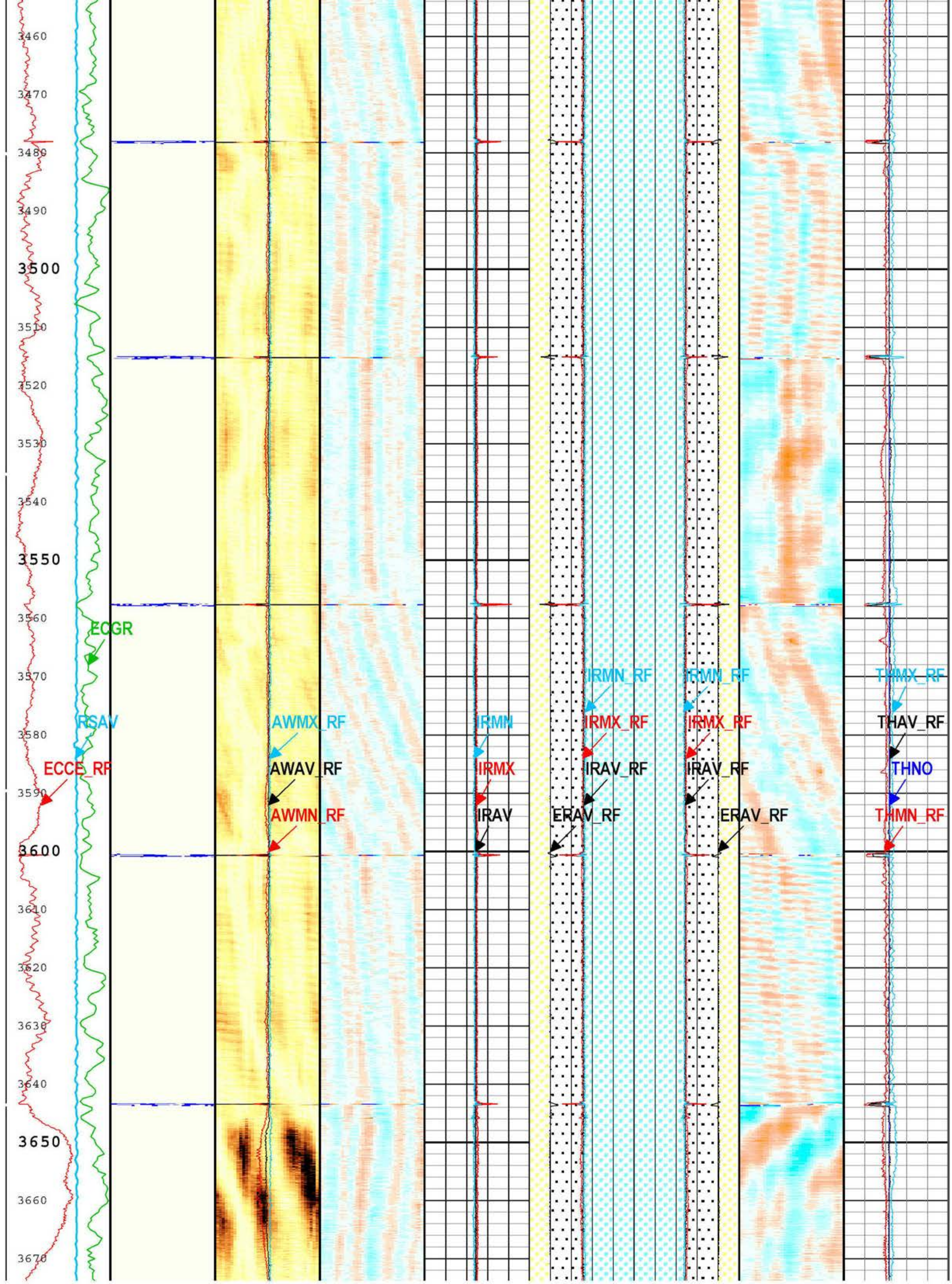
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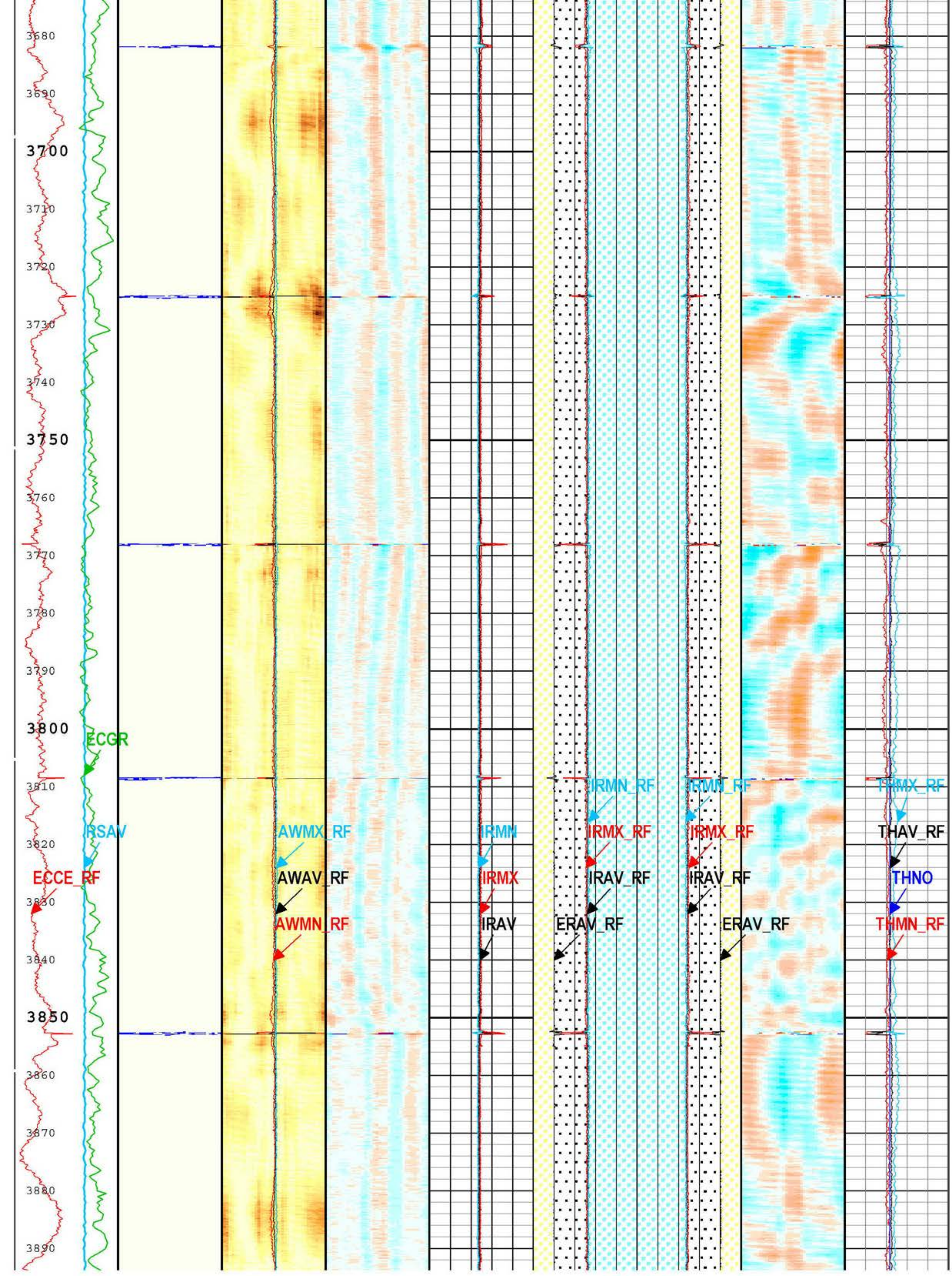
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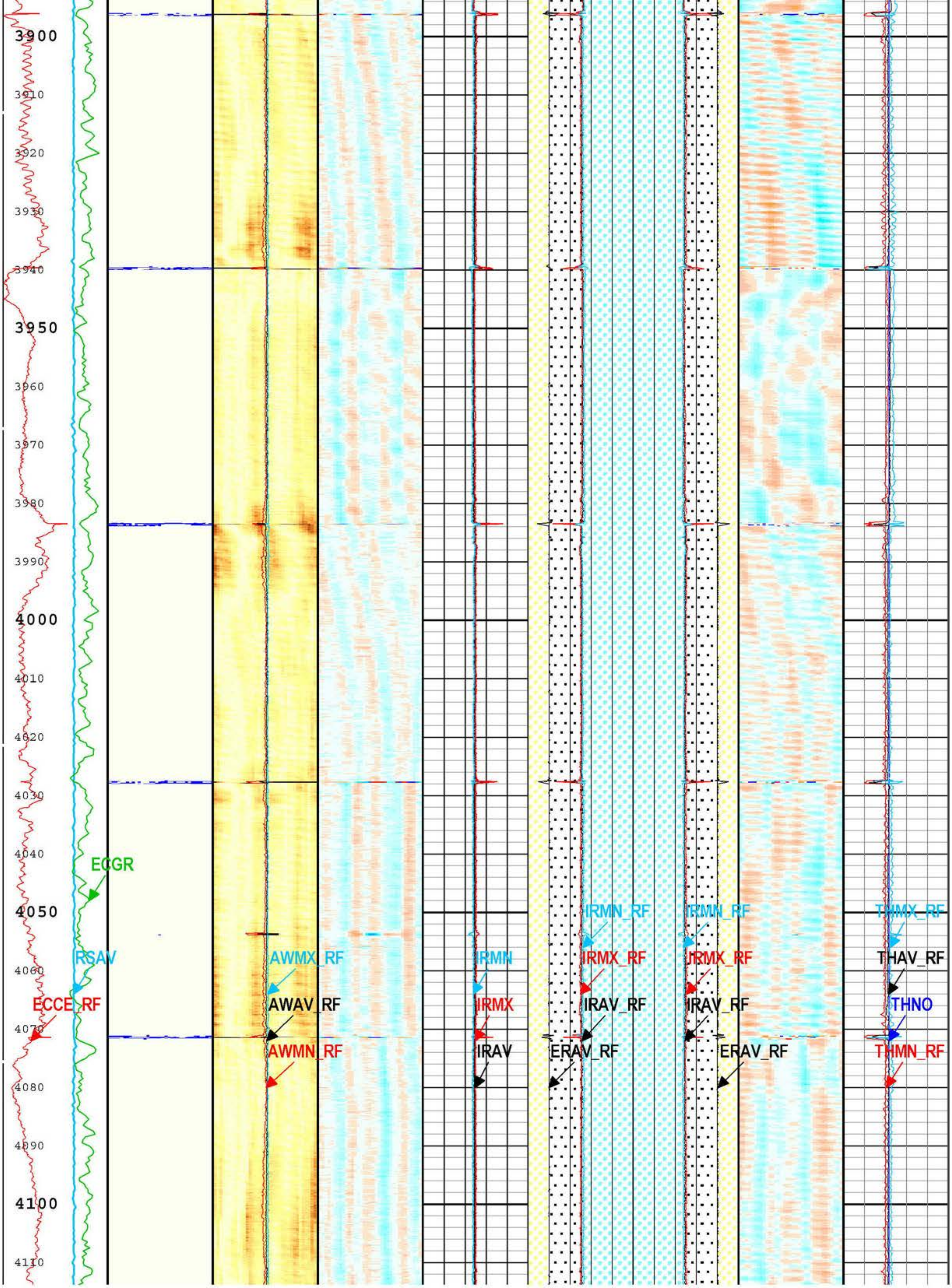
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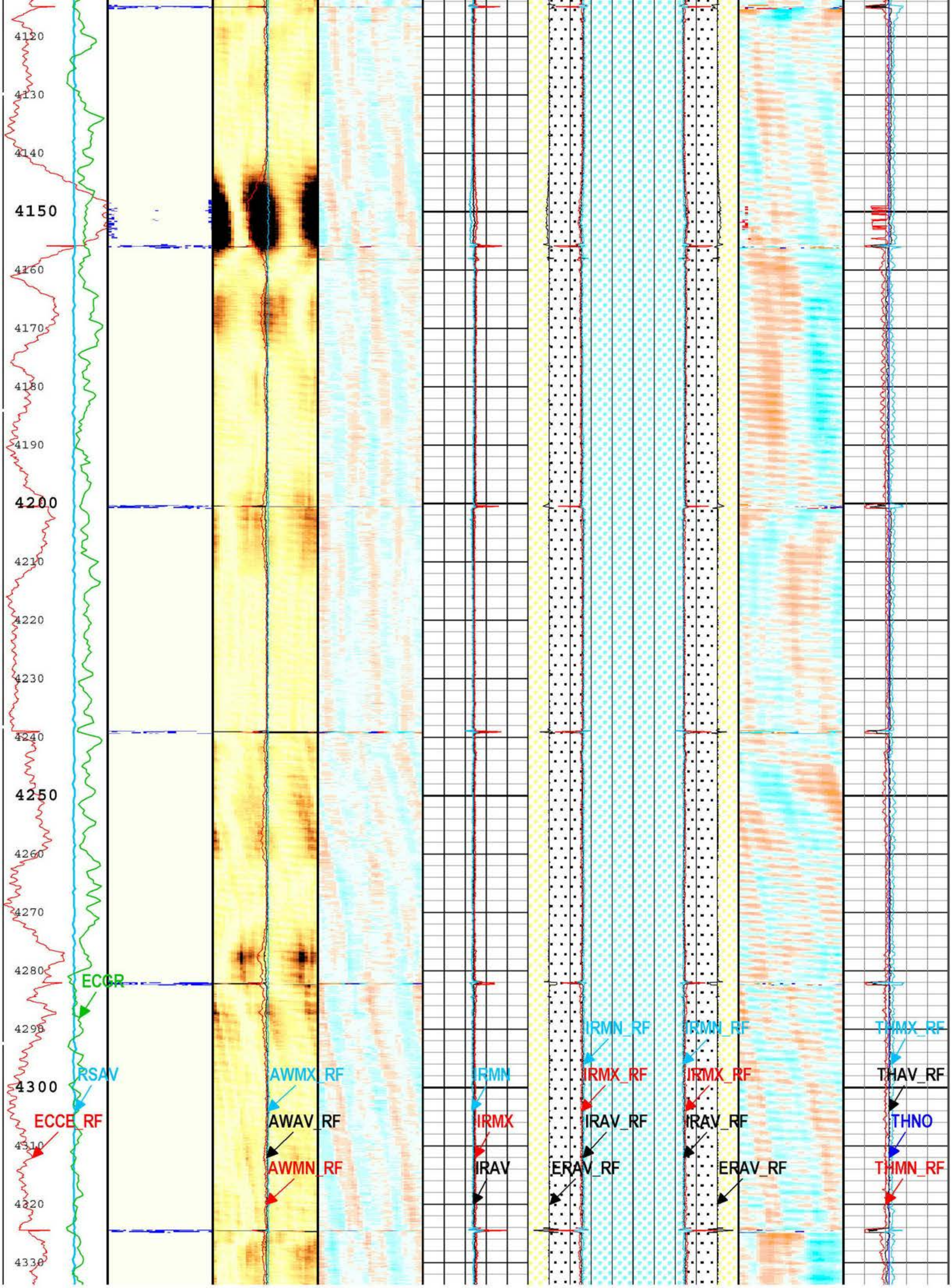
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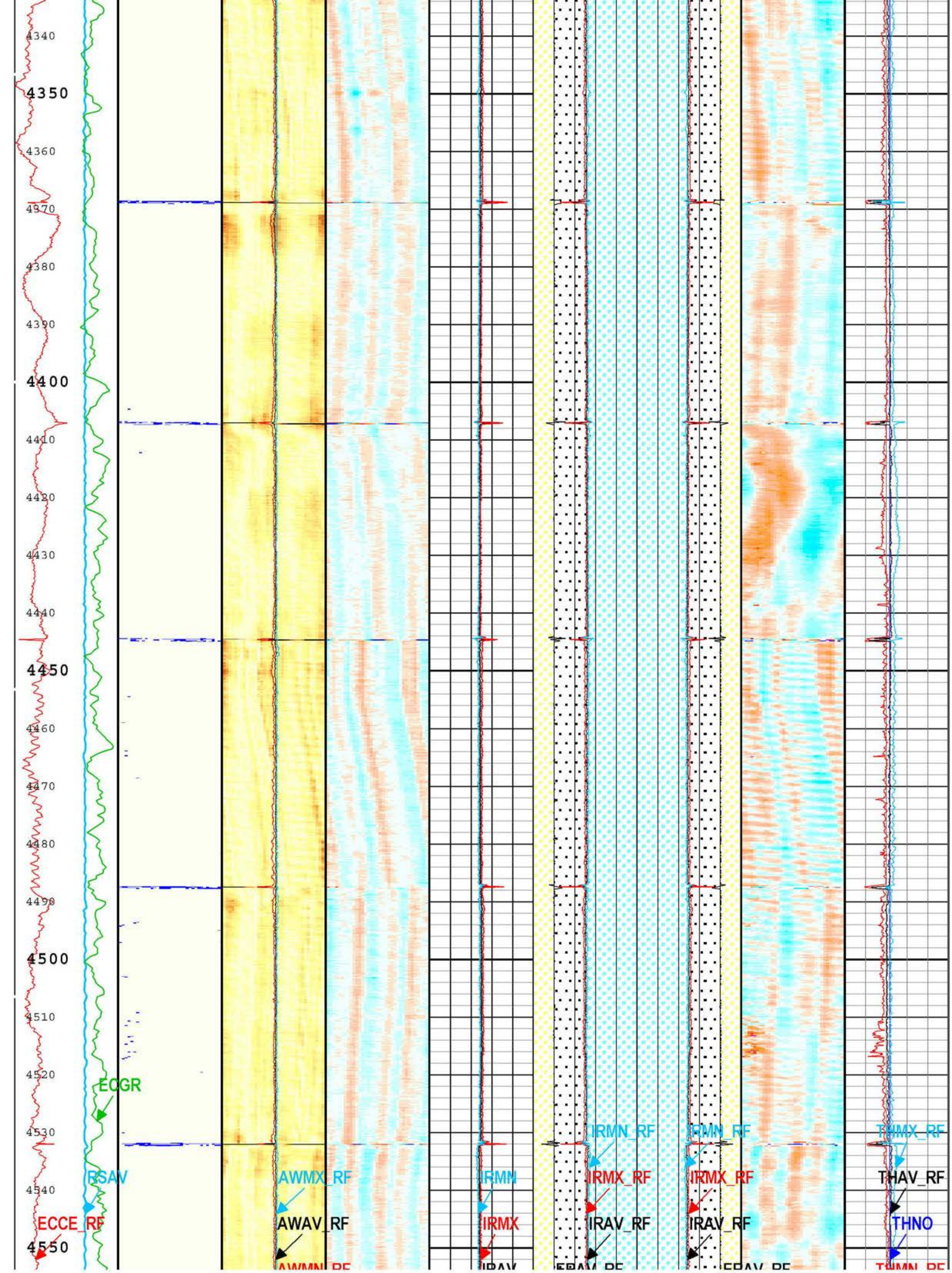
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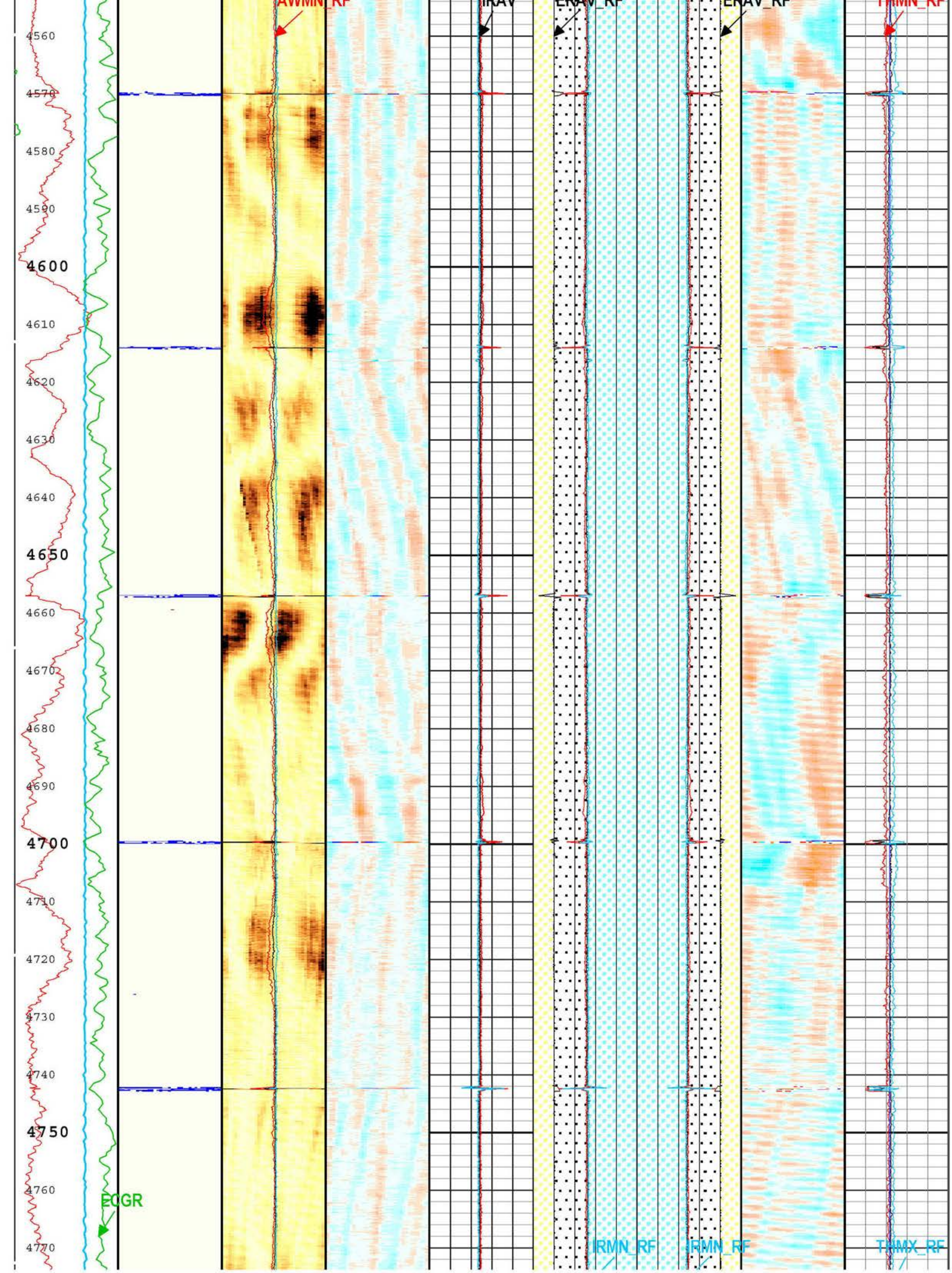
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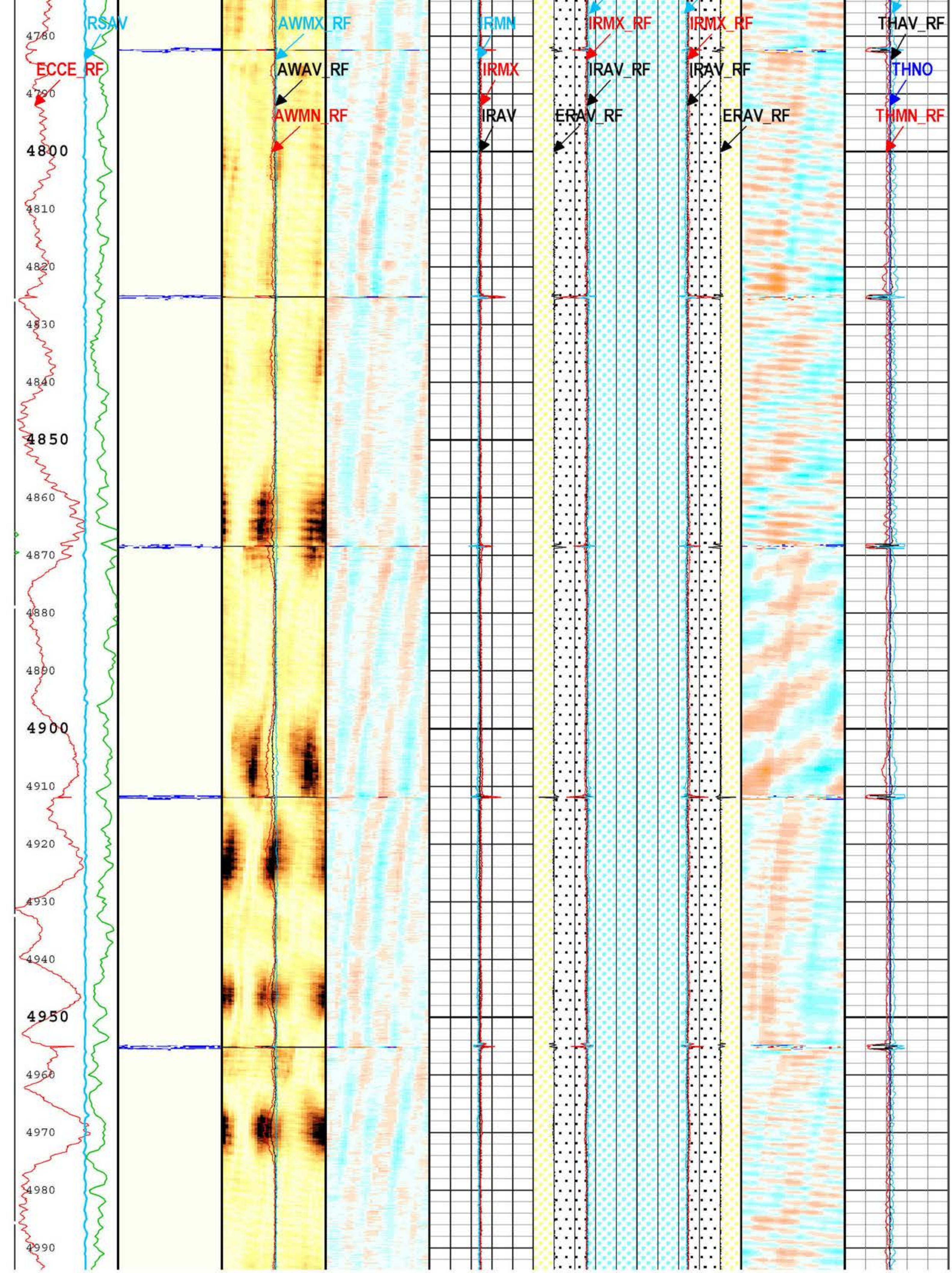
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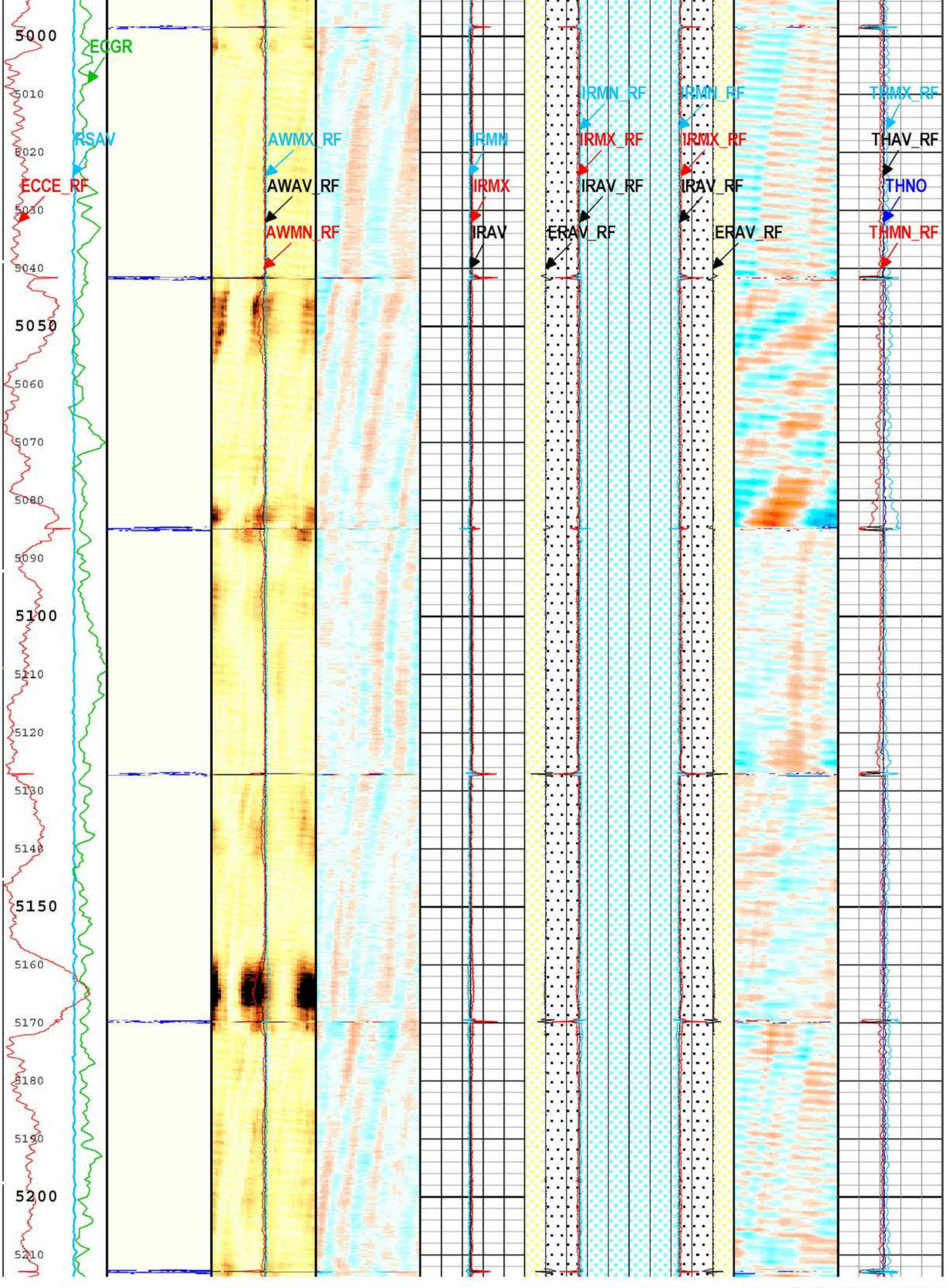
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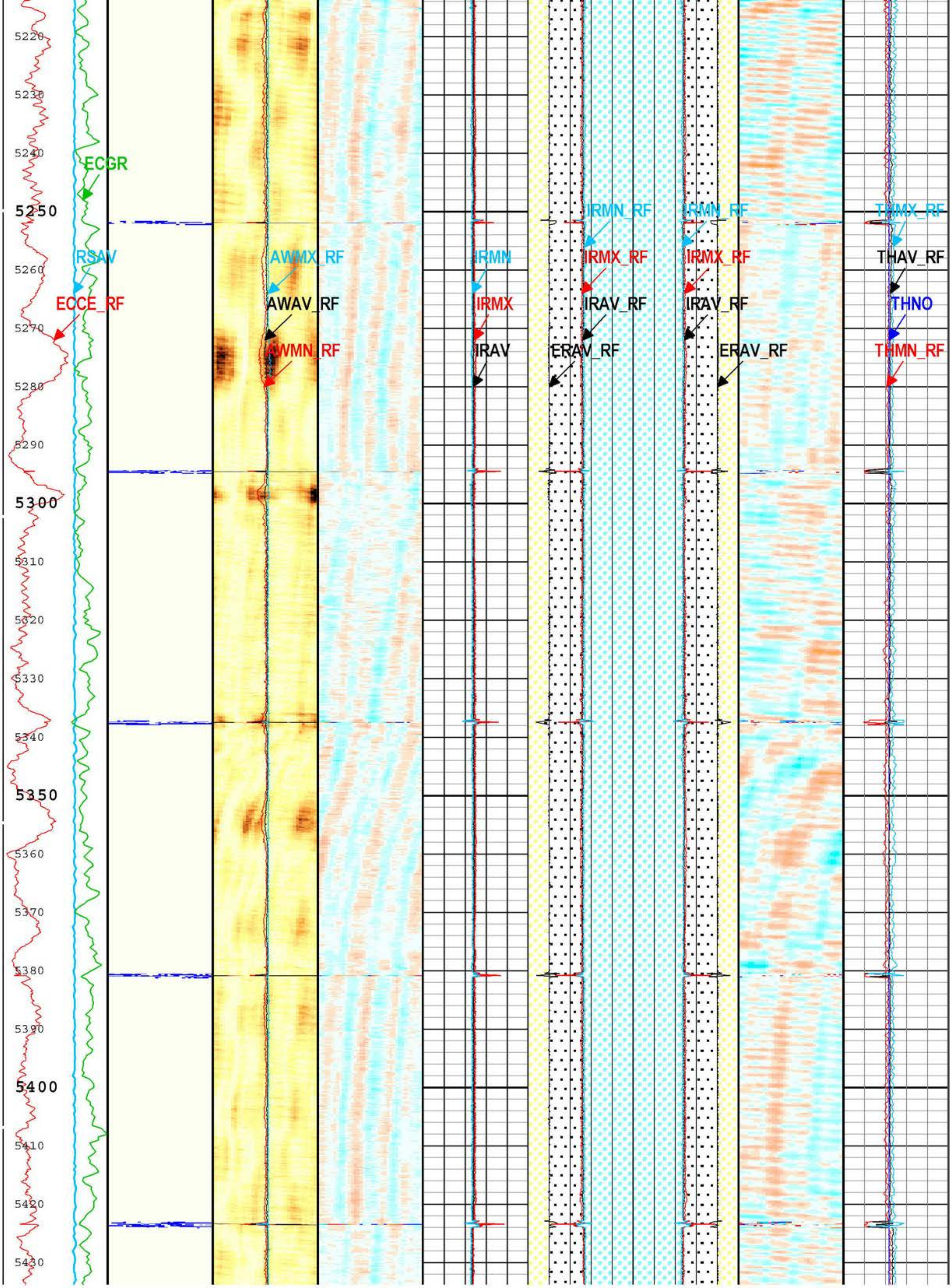
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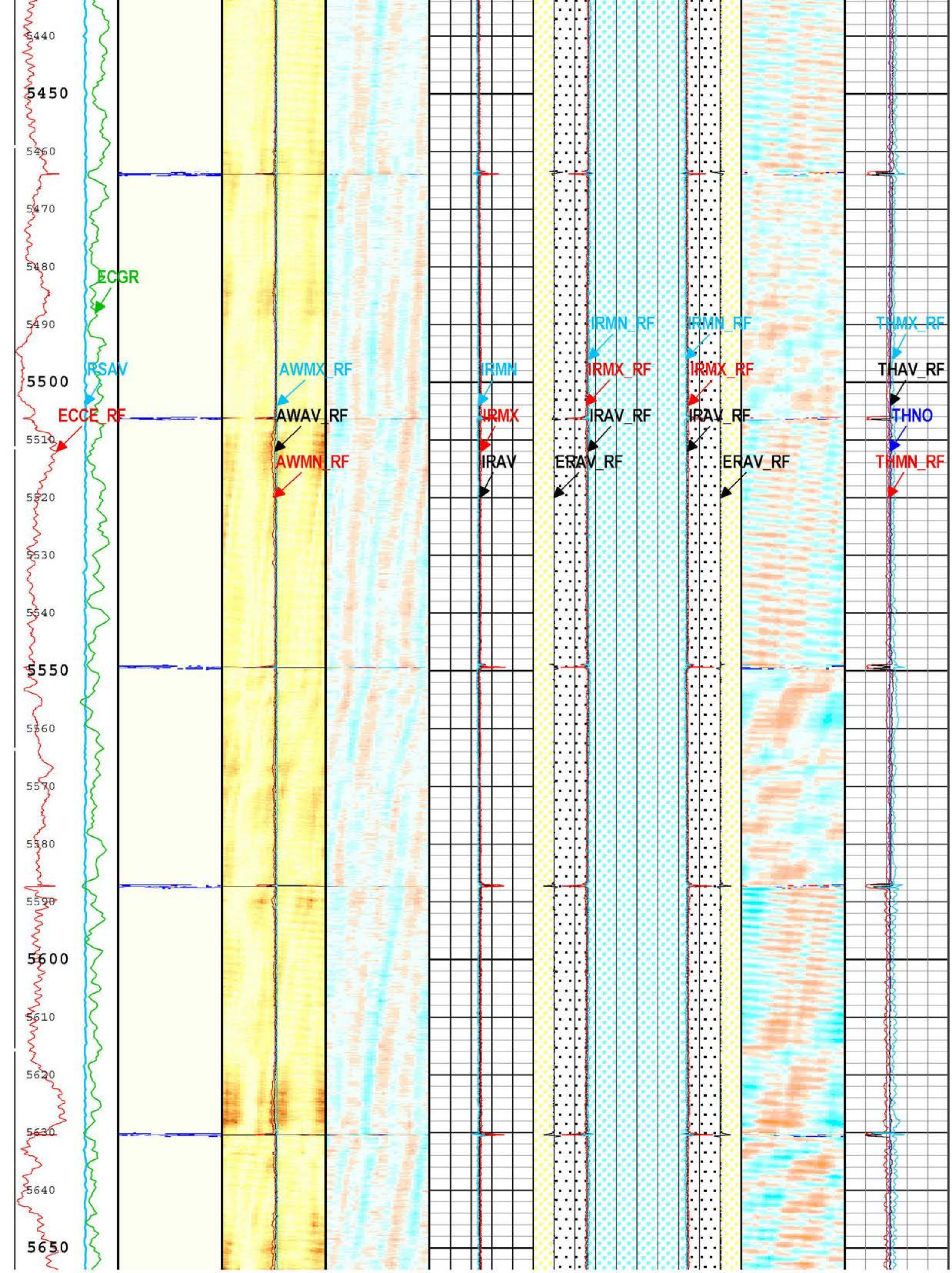
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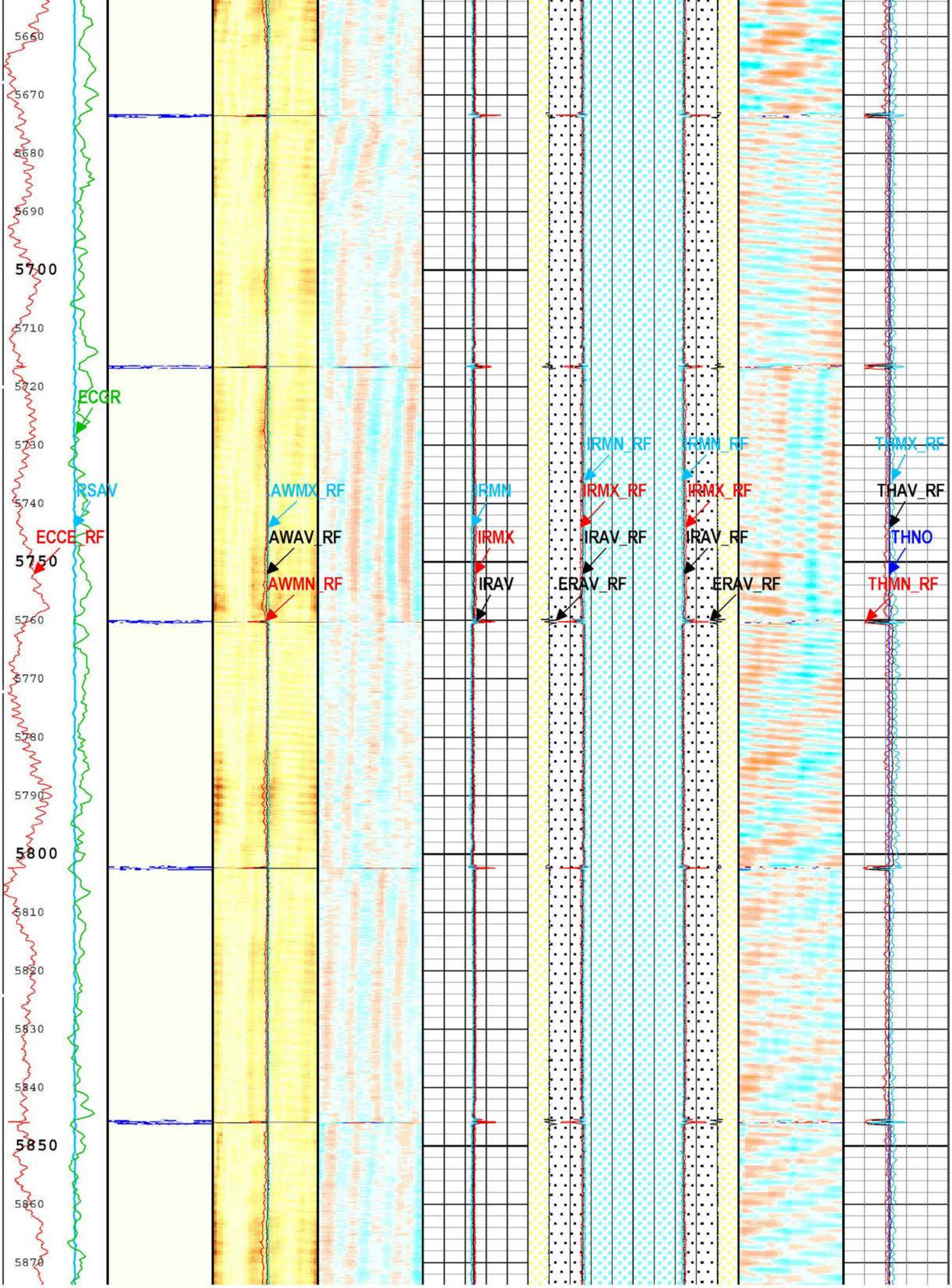
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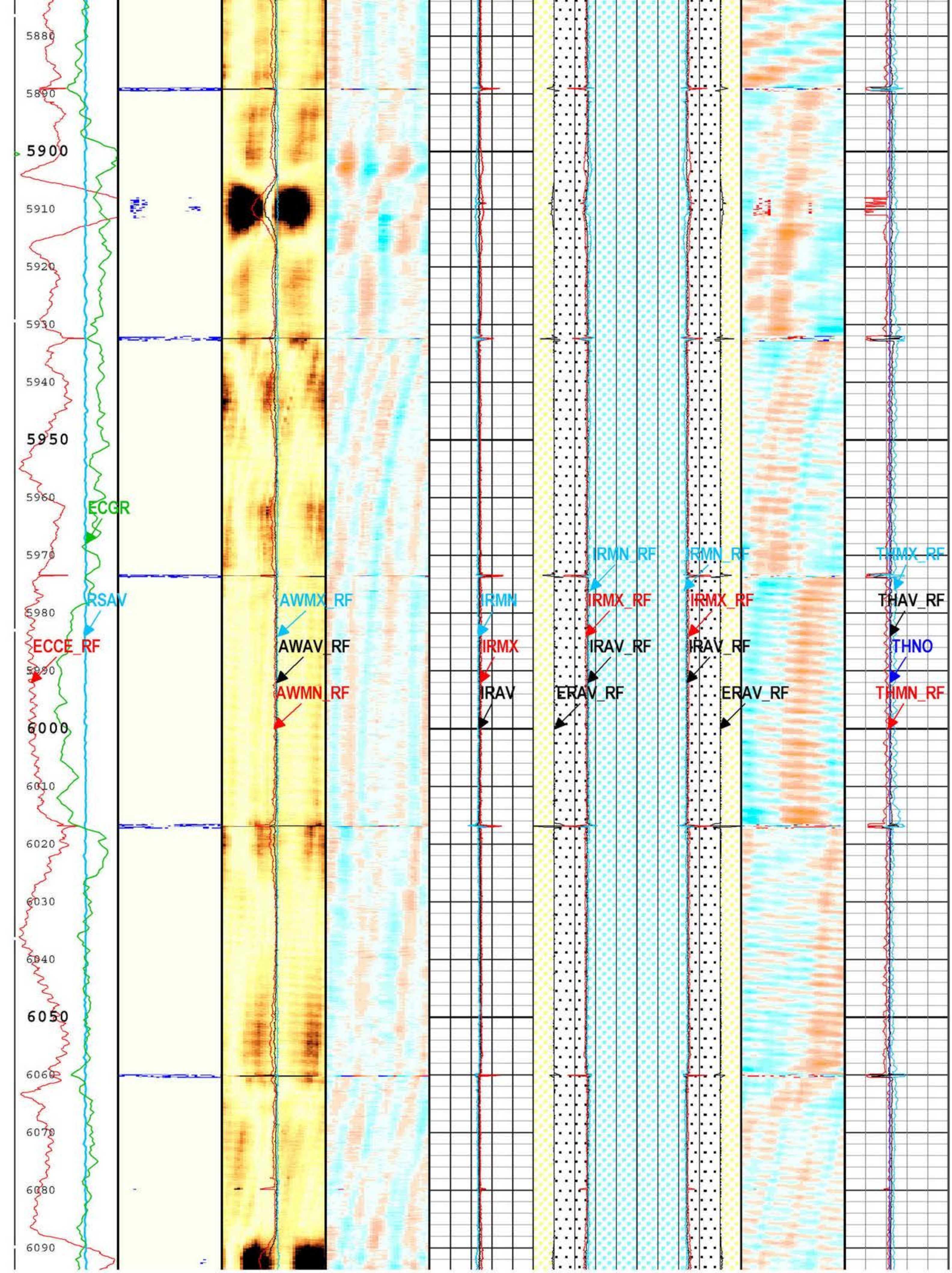
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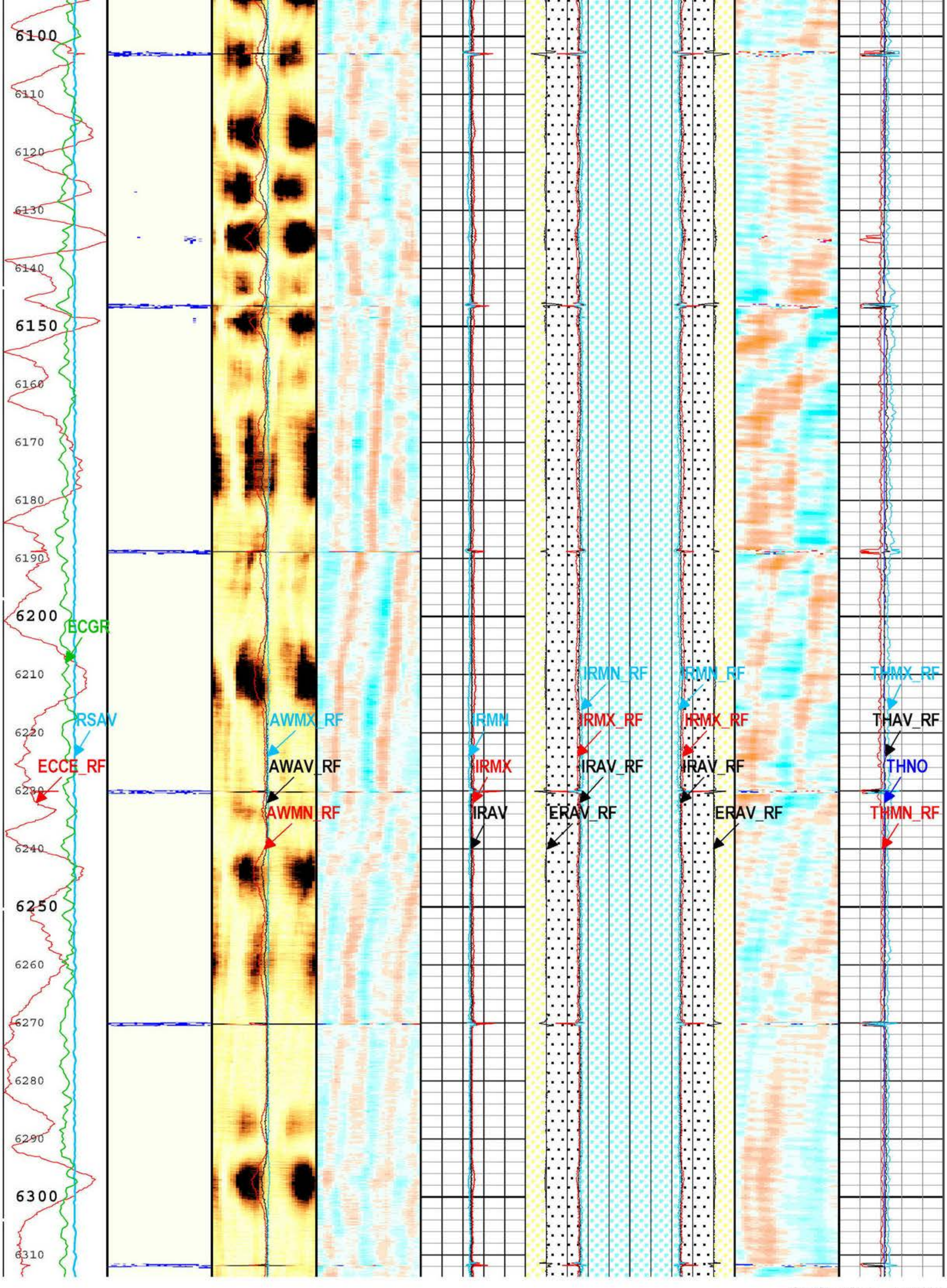
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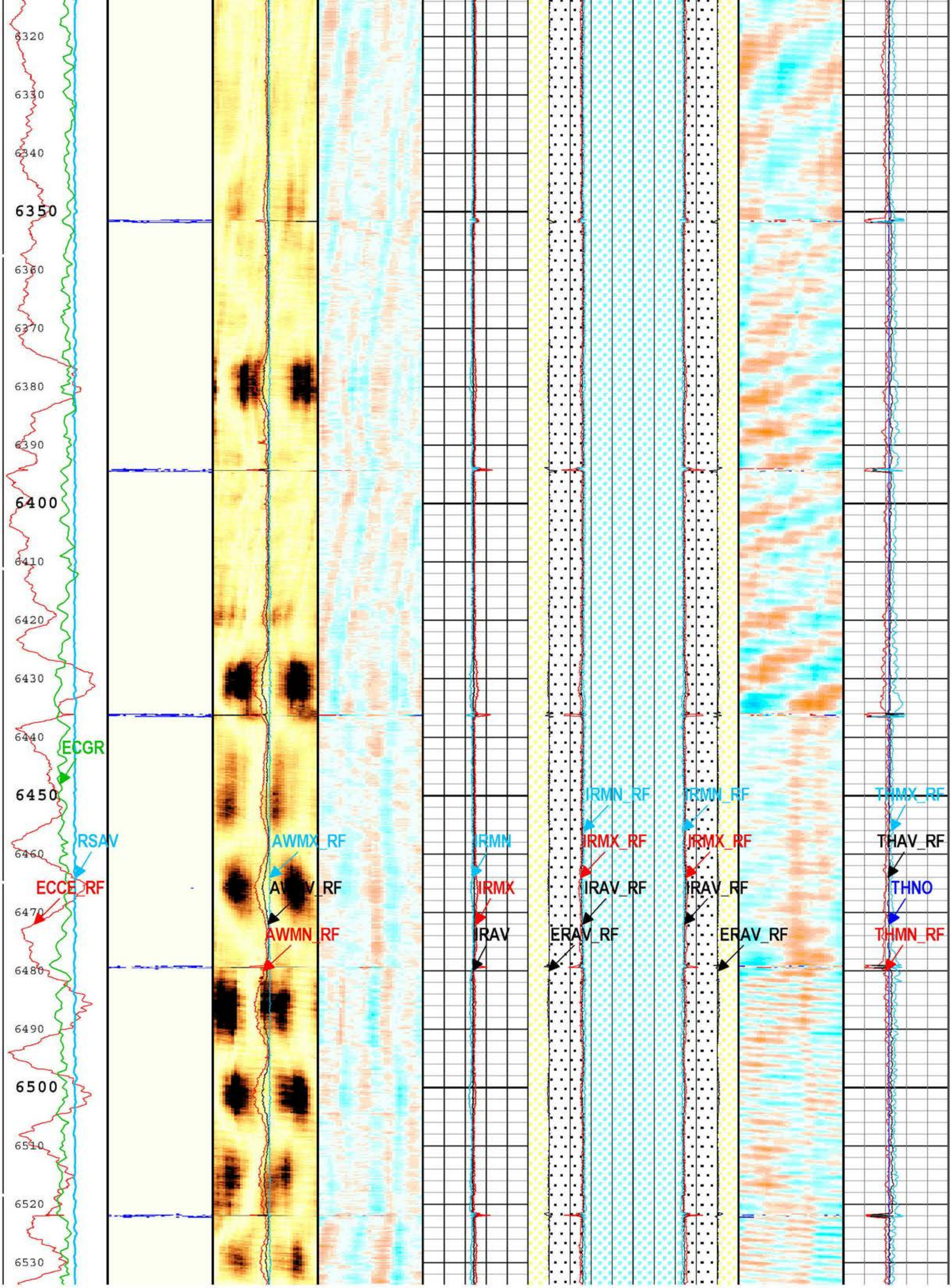
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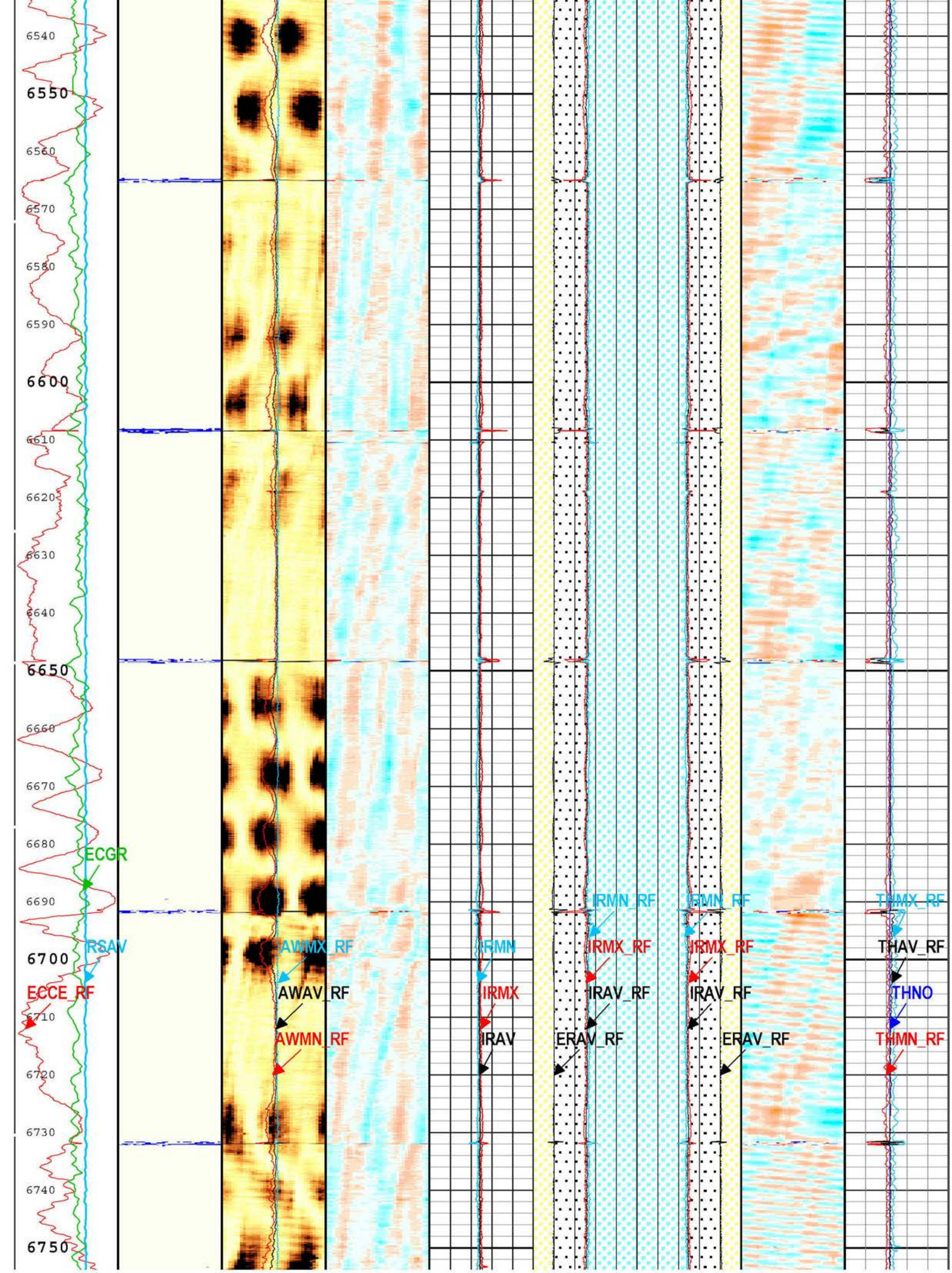
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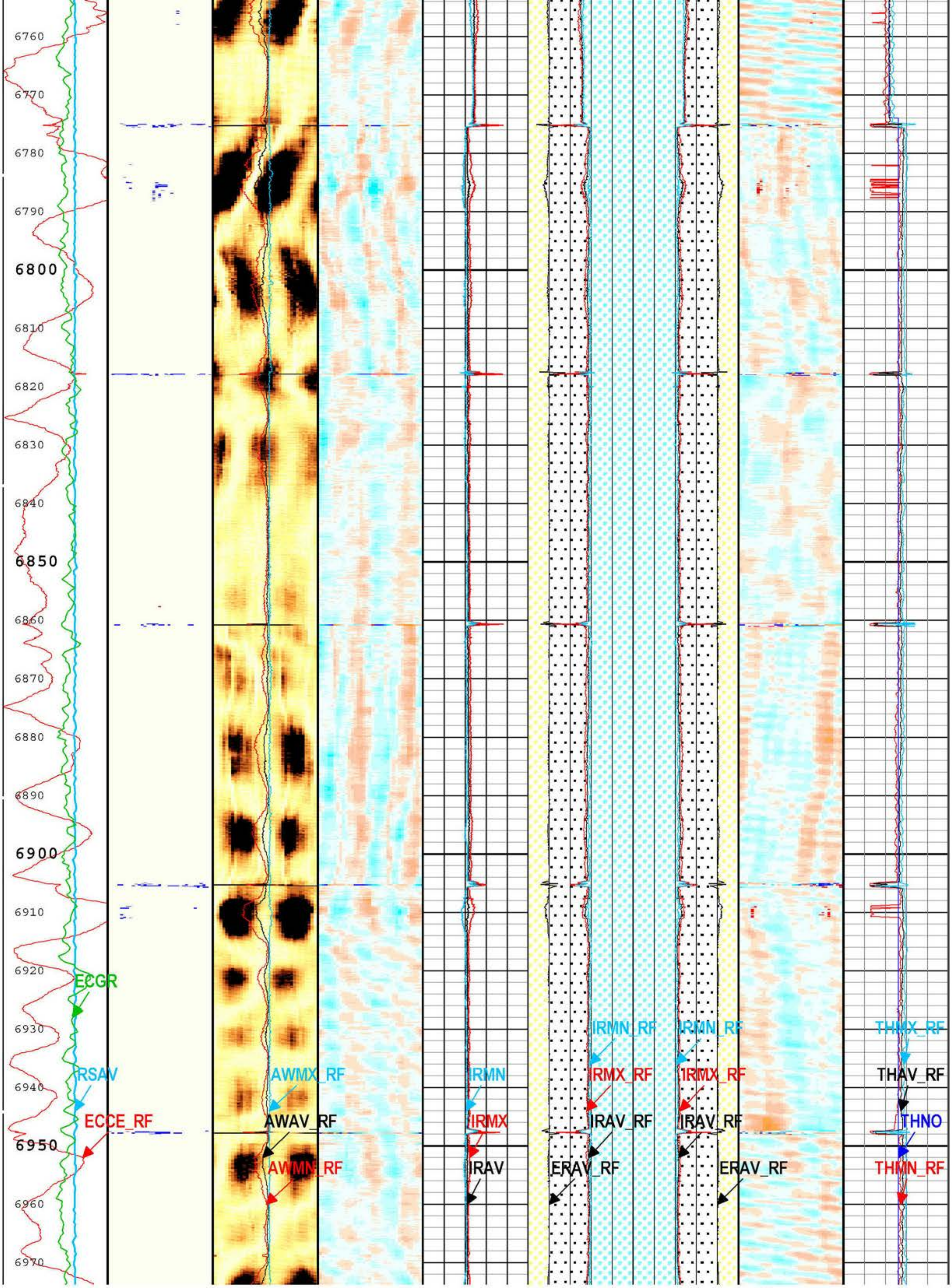
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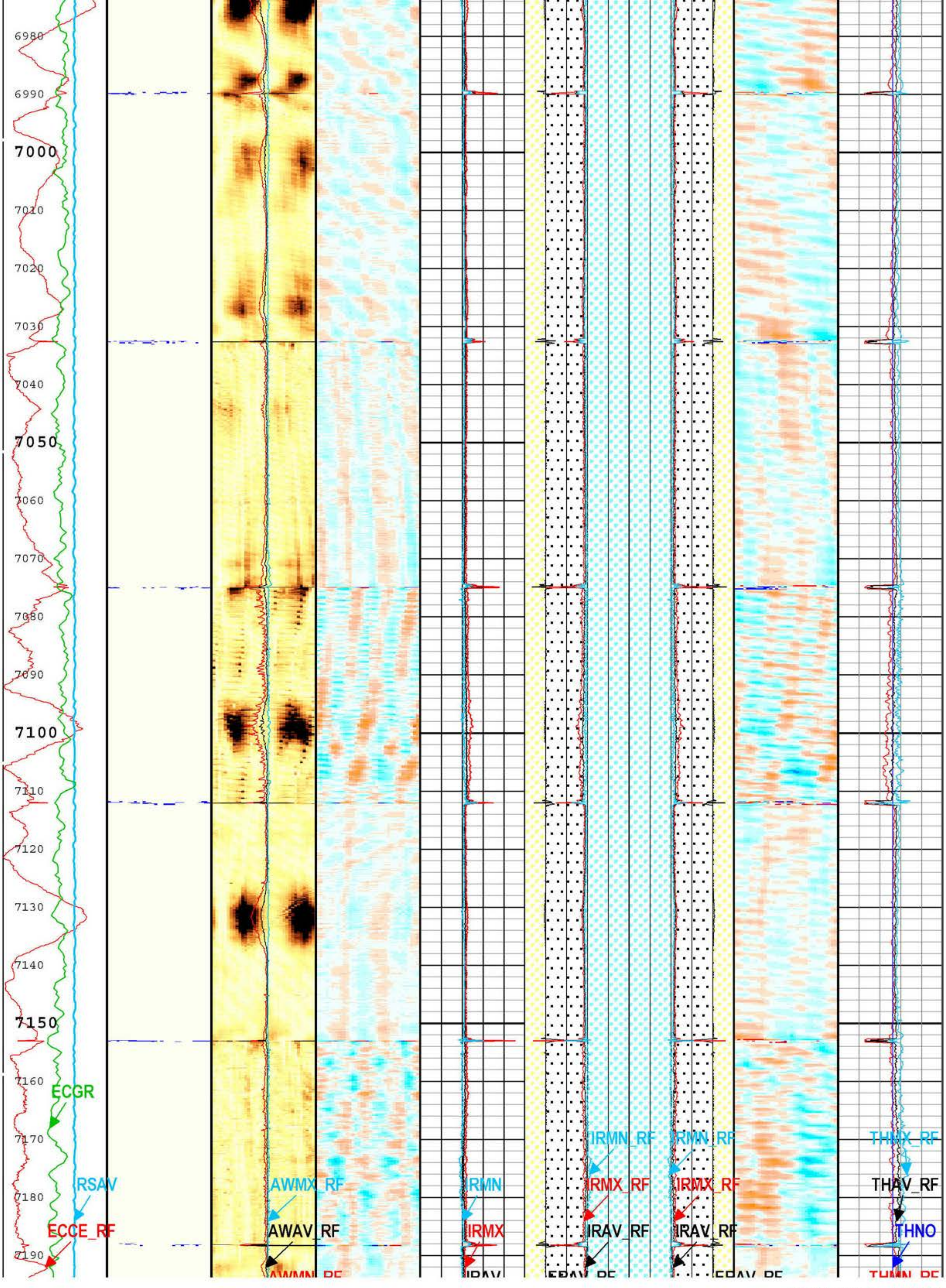
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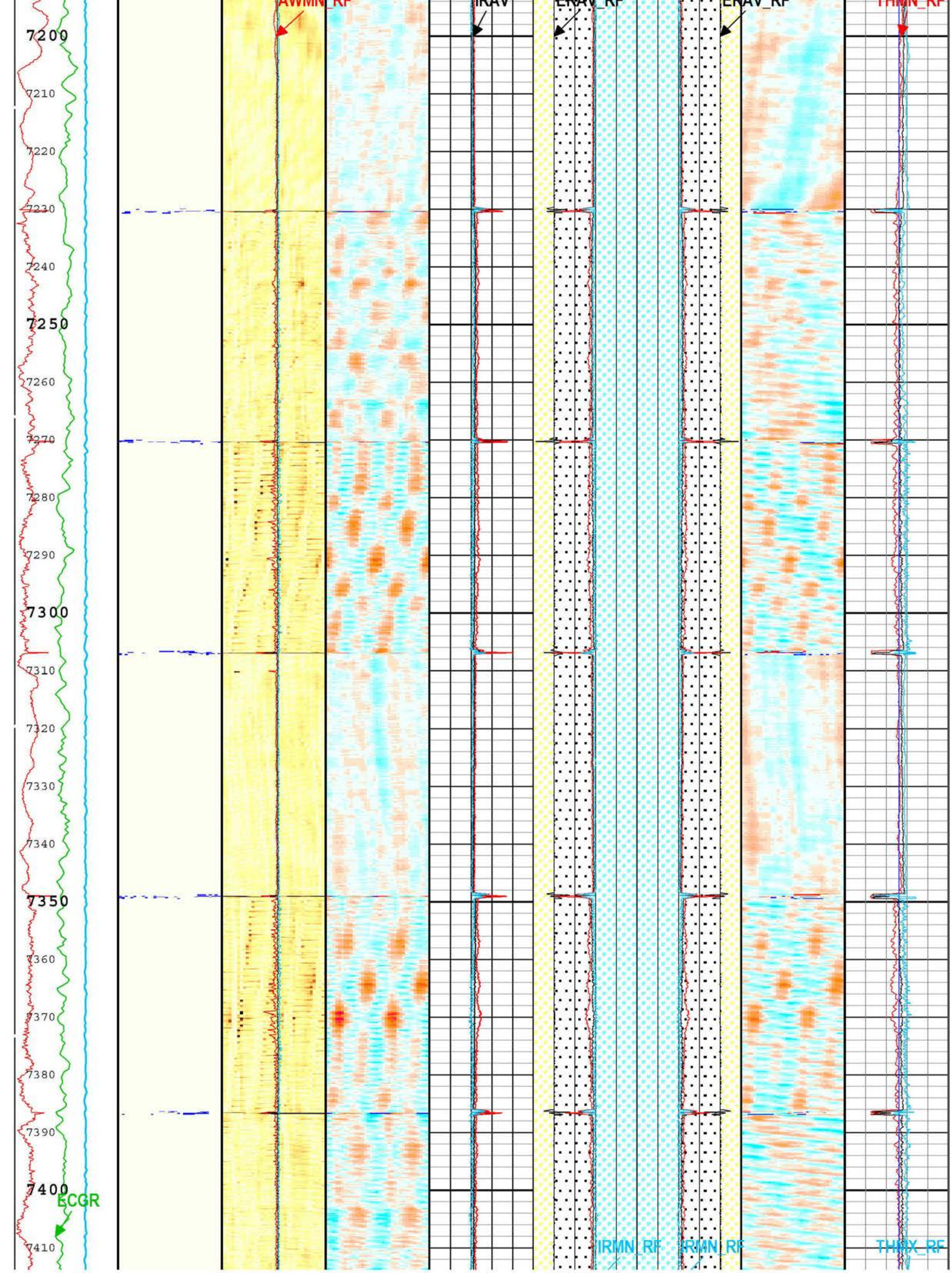
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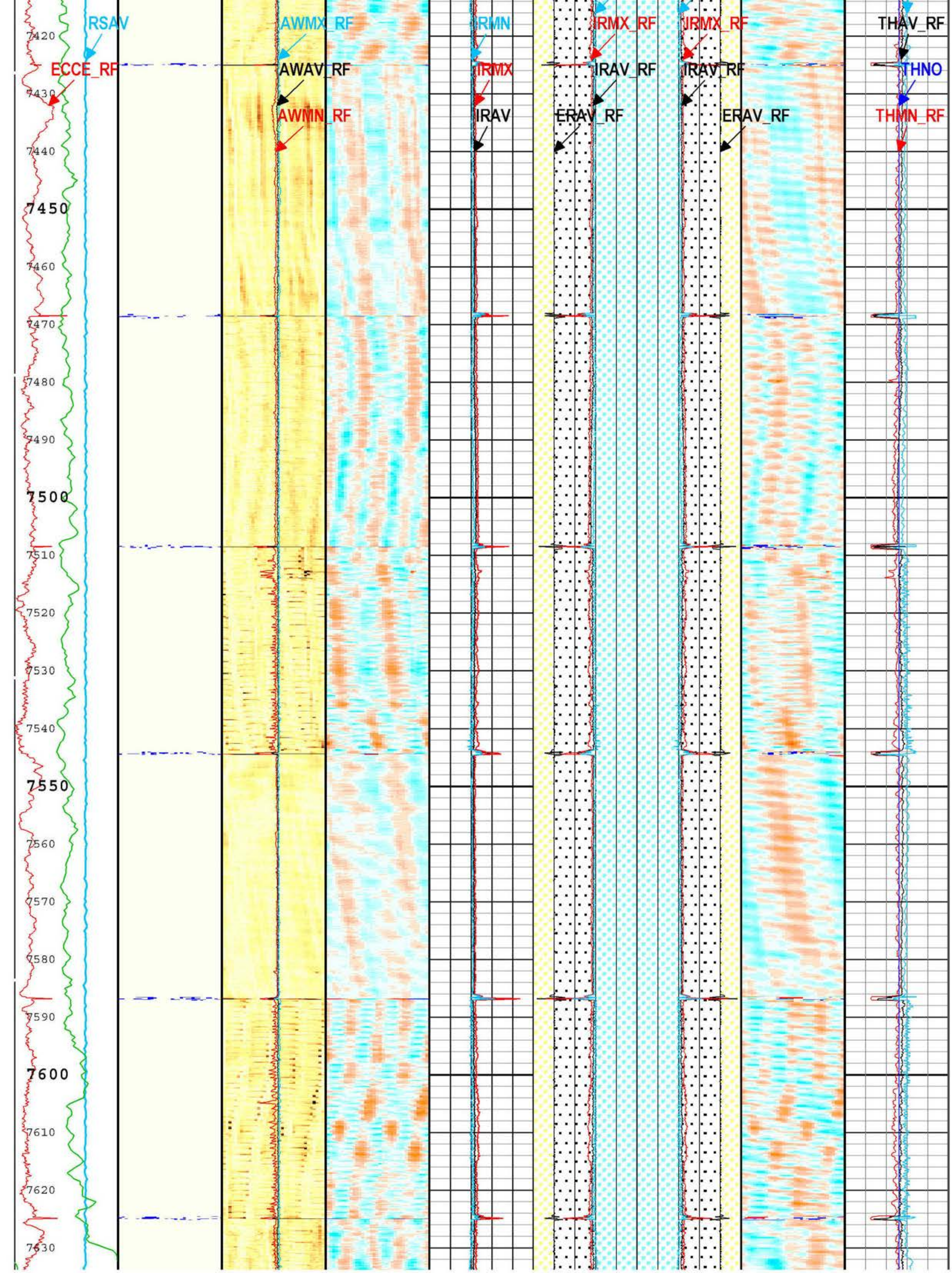
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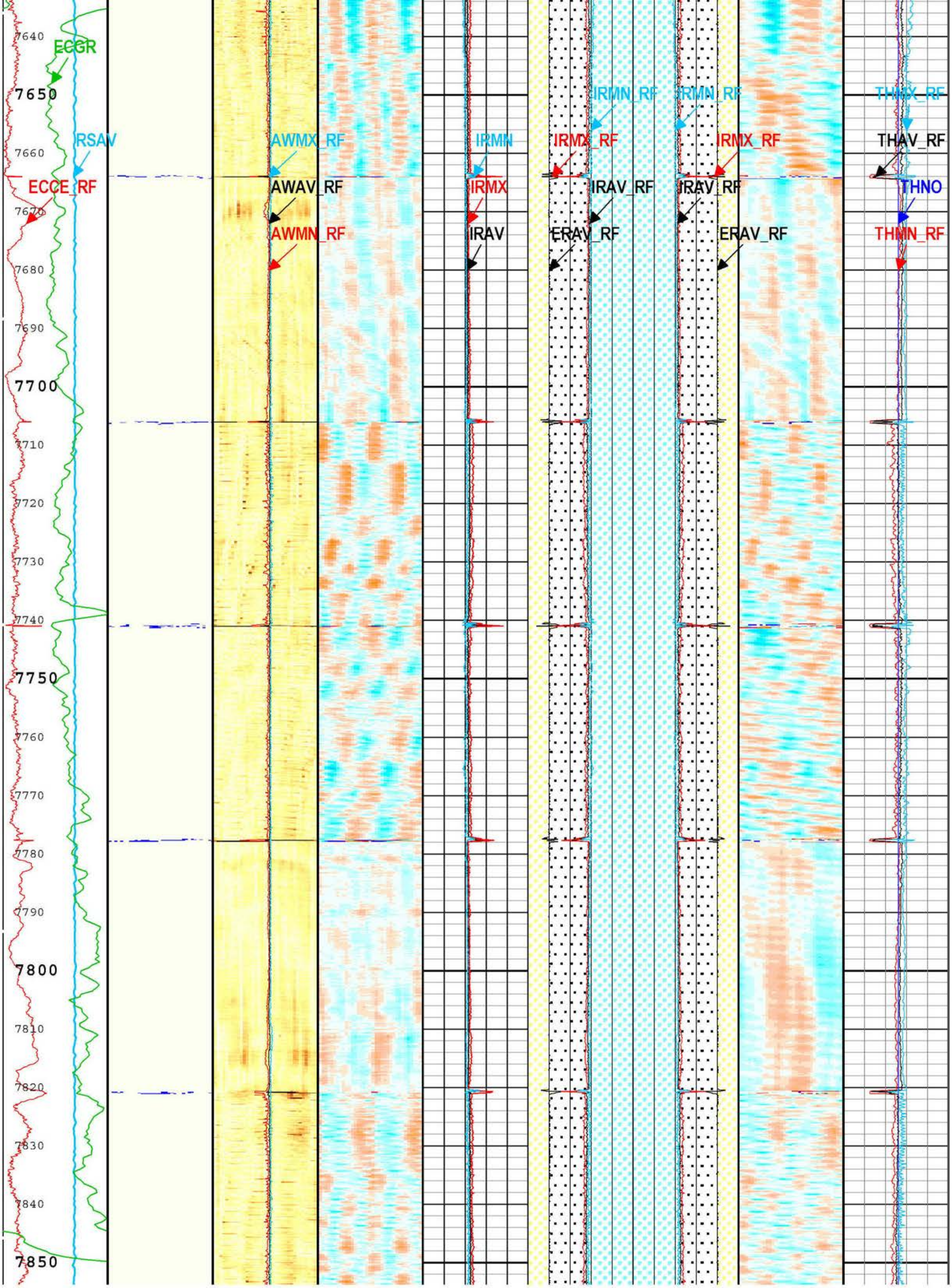
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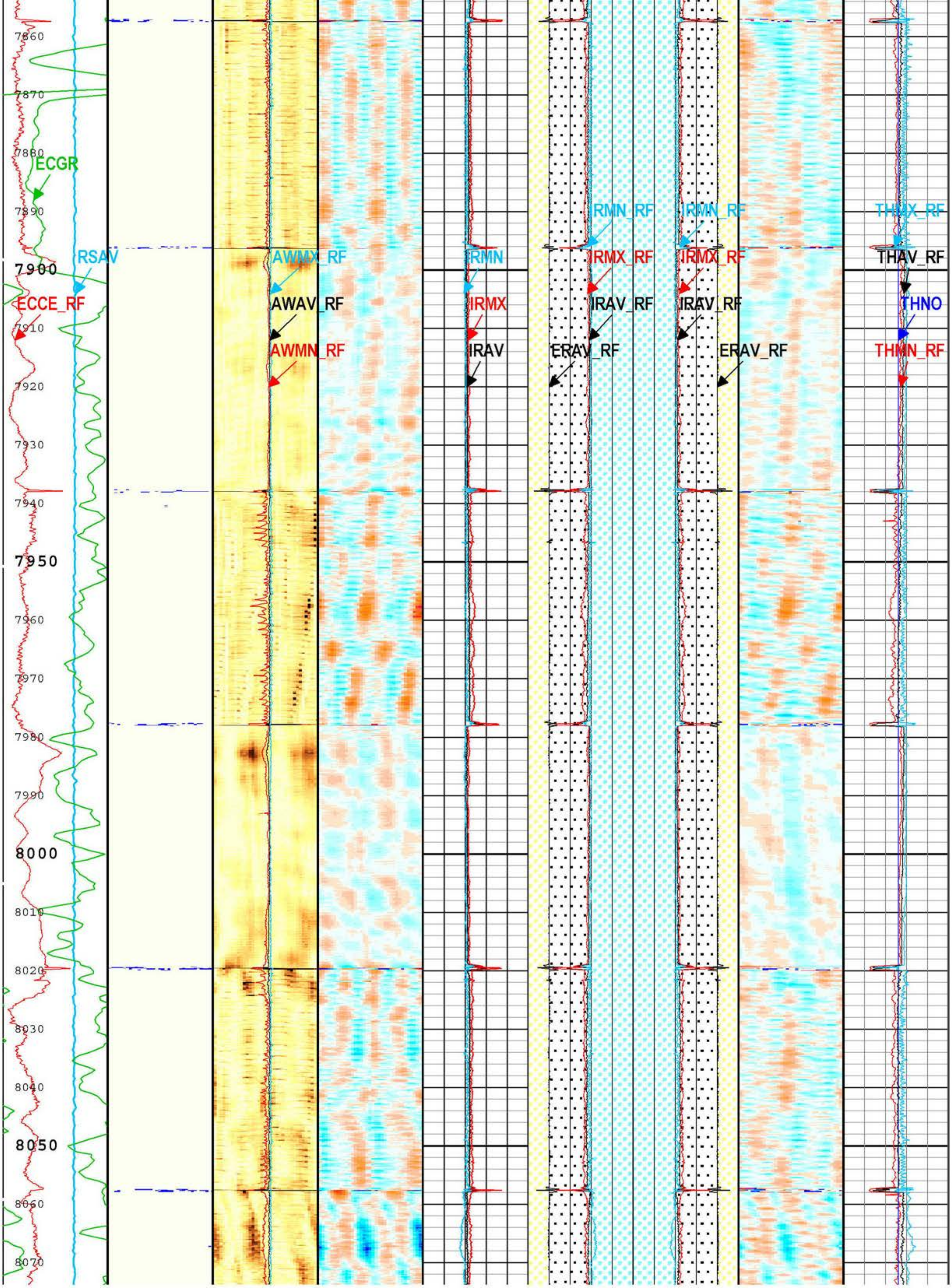
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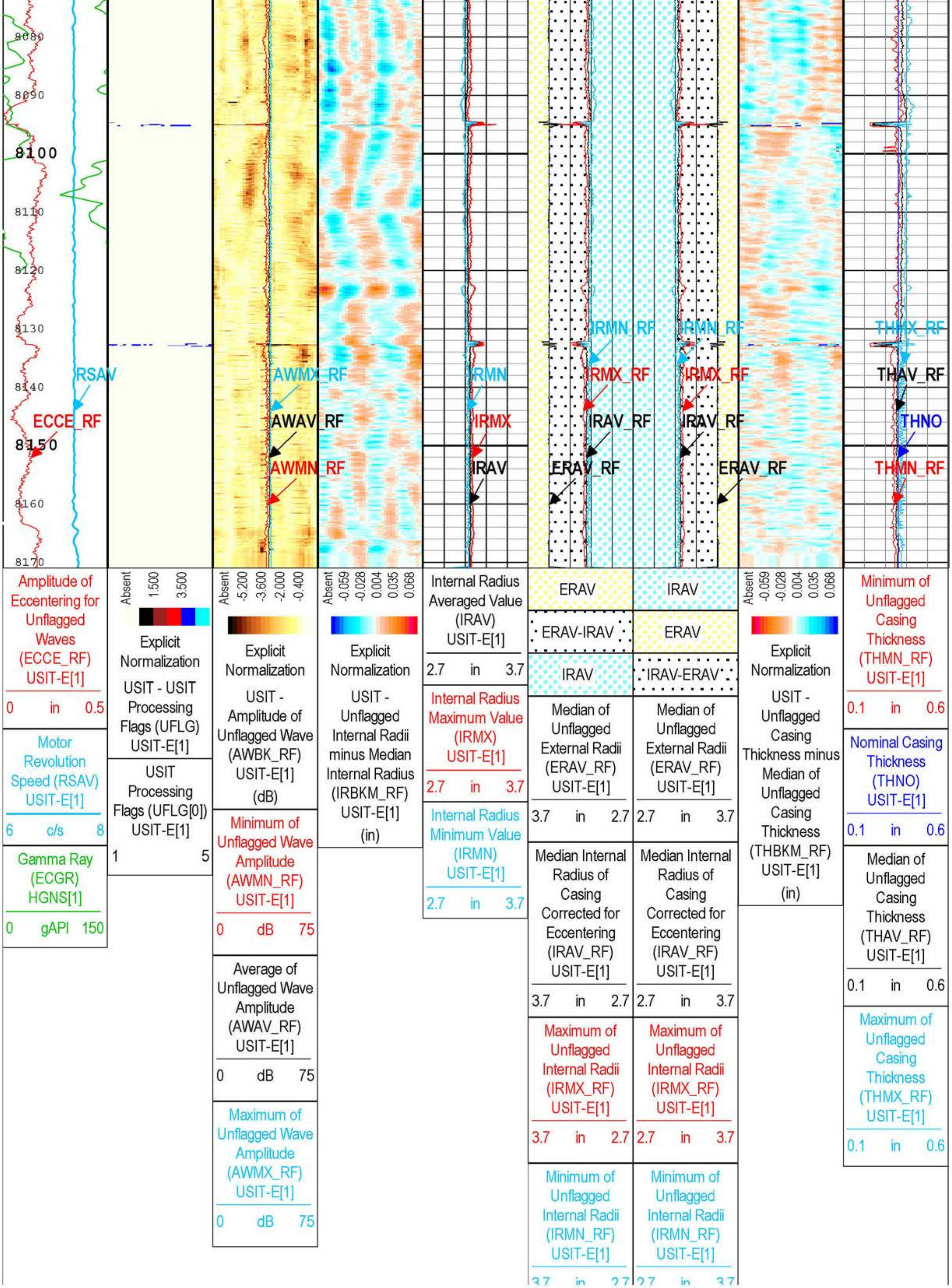
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THNO
THMN_RF
Amplitude of Eccentering for Unflagged Waves (ECCE_RF) USIT-E[1]
0 in 0.5
Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8
Gamma Ray (ECGR) HGNS[1]
0 gAPI 150
Absent 1.500 3.500
Explicit Normalization
USIT - USIT Processing Flags (UFLG) USIT-E[1]
USIT Processing Flags (UFLG[0]) USIT-E[1]
1 5
Absent -5.200 -3.600 -2.000 -0.400
Explicit Normalization
USIT - Amplitude of Unflagged Wave (AWBK_RF) USIT-E[1] (dB)
Minimum of Unflagged Wave Amplitude (AWMN_RF) USIT-E[1]
0 dB 75
Average of Unflagged Wave Amplitude (AWAV_RF) USIT-E[1]
0 dB 75
Maximum of Unflagged Wave Amplitude (AWMX_RF) USIT-E[1]
0 dB 75
Absent -0.059 -0.028 0.004 0.035 0.068
Explicit Normalization
USIT - Unflagged Internal Radii minus Median Internal Radius (IRBKM_RF) USIT-E[1] (in)
Internal Radius Averaged Value (IRAV) USIT-E[1]
2.7 in 3.7
Internal Radius Maximum Value (IRMX) USIT-E[1]
2.7 in 3.7
Internal Radius Minimum Value (IRMN) USIT-E[1]
2.7 in 3.7
ERAV
ERAV-IRAV
IRAV
Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
3.7 in 2.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
3.7 in 2.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
3.7 in 2.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
3.7 in 2.7
IRAV
ERAV
IRAV-ERAV
Median of Unflagged External Radii (ERAV_RF) USIT-E[1]
2.7 in 3.7
Median Internal Radius of Casing Corrected for Eccentering (IRAV_RF) USIT-E[1]
2.7 in 3.7
Maximum of Unflagged Internal Radii (IRMX_RF) USIT-E[1]
2.7 in 3.7
Minimum of Unflagged Internal Radii (IRMN_RF) USIT-E[1]
2.7 in 3.7
Absent -0.059 -0.028 0.004 0.035 0.068
Explicit Normalization
USIT - Unflagged Casing Thickness minus Median of Unflagged Casing Thickness (THBKM_RF) USIT-E[1] (in)
Minimum of Unflagged Casing Thickness (THMN_RF) USIT-E[1]
0.1 in 0.6
Nominal Casing Thickness (THNO) USIT-E[1]
0.1 in 0.6
Median of Unflagged Casing Thickness (THAV_RF) USIT-E[1]
0.1 in 0.6
Maximum of Unflagged Casing Thickness (THMX_RF) USIT-E[1]
0.1 in 0.6

USIT Processing Flags (UFLG[0]) USIT-E[1]

1 - UFLG 1 Value within [0.0 - 1.5] - :	■	UTIM Error
2 - UFLG 2 Value within [1.5 - 2.5] - :	■	Pulse Origin Not Detected
3 - UFLG 3 Value within [2.5 - 3.5] - :	■	WINLEN Error
4 - UFLG 4 UFLG 5 UFLG 6 Value within [3.5 - 6.5] - :	■	Casing Thickness Error
5 - UFLG 7 UFLG 8 UFLG 9 Value within [6.5 - 10] - :	■	Loop Processing Error

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Composite Format: Log (LBV1_USI Corrosion 7inch) Index Scale: 5 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:28:48

Composite 1

USI Compressed Goodwin

Composite Summary

Run Name	Pass Objective	Direction	Top	Bottom	Start	Stop	DSC Mode	Depth Shift	Include Parallel Data
Two	Log[9]:Up	Up	6640.29 ft	8171.85 ft	20-Oct-2016 9:51:39 AM	20-Oct-2016 10:20:40 AM	ON	1.47 ft	No
Two	Log[11]:Up	Up	36.69 ft	6737.51 ft	20-Oct-2016 10:24:53 AM	20-Oct-2016 12:34:00 PM	ON	1.35 ft	No
Two	Log[14]:Up	Up	5.56 ft	155.15 ft	20-Oct-2016 12:53:24 PM	20-Oct-2016 12:58:23 PM	ON	1.96 ft	No

All depths are referenced to toolstring zero

Log

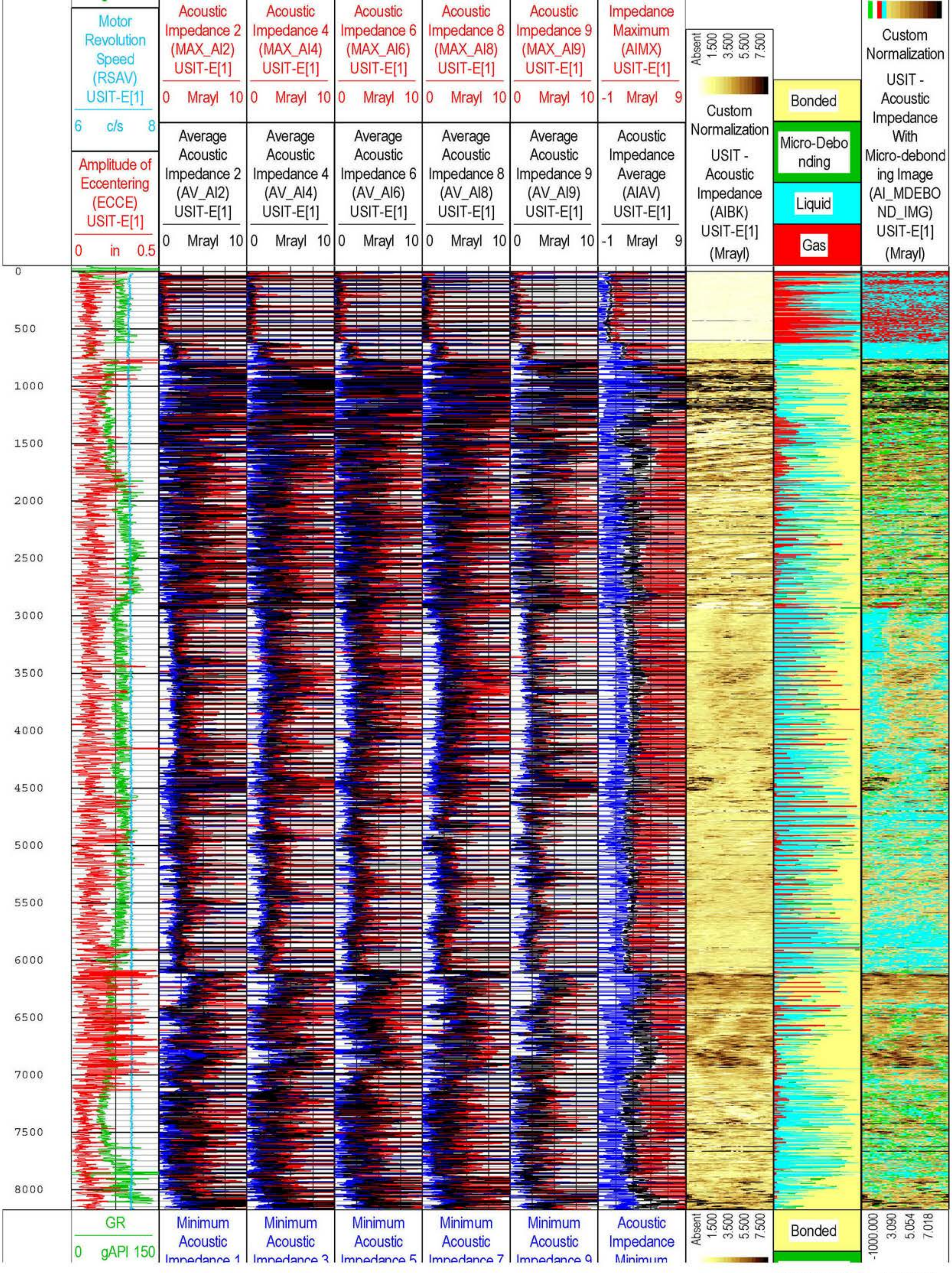
Company:Southern California Gas Company Well:Frew 4

Composite 1:S008

Description: USI Goodwin Format: Log (Import of USI Goodwin) Index Scale: 0.1 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:29:06

TIME_1900 - Time Marked every 60.00 (s)

	Minimum Acoustic Impedance 1 (MIN_AI1) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 3 (MIN_AI3) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 5 (MIN_AI5) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 7 (MIN_AI7) USIT-E[1] 0 Mrayl 10			
	Maximum Acoustic Impedance 1 (MAX_AI1) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 3 (MAX_AI3) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 5 (MAX_AI5) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 7 (MAX_AI7) USIT-E[1] 0 Mrayl 10			
	Average Acoustic Impedance 1 (AV_AI1) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 3 (AV_AI3) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 5 (AV_AI5) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 7 (AV_AI7) USIT-E[1] 0 Mrayl 10			
GR 0 gAPI 150	Minimum Acoustic Impedance 2 (MIN_AI2) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 4 (MIN_AI4) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 6 (MIN_AI6) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 8 (MIN_AI8) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 9 (MIN_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Minimum (AIMN) USIT-E[1] -1 Mrayl 9	-1000.000 3.090 5.054 7.018
	Maximum	Maximum	Maximum	Maximum	Maximum	Acoustic	


Motor Revolution Speed (RSAV) USIT-E[1]
6 c/s 8
Amplitude of Eccentering (ECCE) USIT-E[1]
0 in 0.5
Acoustic Impedance 2 (MAX_AI2) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 2 (AV_AI2) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 4 (MAX_AI4) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 4 (AV_AI4) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 6 (MAX_AI6) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 6 (AV_AI6) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 8 (MAX_AI8) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 8 (AV_AI8) USIT-E[1]
0 Mrayl 10
Acoustic Impedance 9 (MAX_AI9) USIT-E[1]
0 Mrayl 10
Average Acoustic Impedance 9 (AV_AI9) USIT-E[1]
0 Mrayl 10
Impedance Maximum (AIMX) USIT-E[1]
-1 Mrayl 9
Acoustic Impedance Average (AIAV) USIT-E[1]
-1 Mrayl 9
Absent 1.500 3.500 5.500 7.500
Custom Normalization
USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)
Bonded
Micro-Debonding
Liquid
Gas
Custom Normalization
USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
GR
0 gAPI 150
Minimum Acoustic Impedance 1
Minimum Acoustic Impedance 3
Minimum Acoustic Impedance 5
Minimum Acoustic Impedance 7
Minimum Acoustic Impedance 9
Acoustic Impedance Minimum
Absent 1.500 3.500 5.500 7.500
Bonded
-1000.000 3.090 5.054 7.018

Motor Revolution Speed (RSAV) USIT-E[1] 6 c/s 8	Impedance 1 (MIN_AI1) USIT-E[1] 0 Mrayl 10	Impedance 3 (MIN_AI3) USIT-E[1] 0 Mrayl 10	Impedance 5 (MIN_AI5) USIT-E[1] 0 Mrayl 10	Impedance 7 (MIN_AI7) USIT-E[1] 0 Mrayl 10	Impedance 9 (MIN_AI9) USIT-E[1] 0 Mrayl 10	Minimum (AIMN) USIT-E[1] -1 Mrayl 9	Custom Normalization USIT - Acoustic Impedance (AIBK) USIT-E[1] (Mrayl)	Micro-Debonding Liquid Gas	Custom Normalization USIT - Acoustic Impedance With Micro-debonding Image (AI_MDEBOND_IMG) USIT-E[1] (Mrayl)
Amplitude of Eccentering (ECCE) USIT-E[1] 0 in 0.5	Maximum Acoustic Impedance 1 (MAX_AI1) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 3 (MAX_AI3) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 5 (MAX_AI5) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 7 (MAX_AI7) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 9 (MAX_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Maximum (AIMX) USIT-E[1] -1 Mrayl 9			
	Average Acoustic Impedance 1 (AV_AI1) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 3 (AV_AI3) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 5 (AV_AI5) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 7 (AV_AI7) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 9 (AV_AI9) USIT-E[1] 0 Mrayl 10	Acoustic Impedance Average (AIAV) USIT-E[1] -1 Mrayl 9			
	Minimum Acoustic Impedance 2 (MIN_AI2) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 4 (MIN_AI4) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 6 (MIN_AI6) USIT-E[1] 0 Mrayl 10	Minimum Acoustic Impedance 8 (MIN_AI8) USIT-E[1] 0 Mrayl 10					
	Maximum Acoustic Impedance 2 (MAX_AI2) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 4 (MAX_AI4) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 6 (MAX_AI6) USIT-E[1] 0 Mrayl 10	Maximum Acoustic Impedance 8 (MAX_AI8) USIT-E[1] 0 Mrayl 10					
	Average Acoustic Impedance 2 (AV_AI2) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 4 (AV_AI4) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 6 (AV_AI6) USIT-E[1] 0 Mrayl 10	Average Acoustic Impedance 8 (AV_AI8) USIT-E[1] 0 Mrayl 10					

TIME_1900 - Time Marked every 60.00 (s)

Description: USI Goodwin Format: Log (Import of USI Goodwin) Index Scale: 0.1 in per 100 ft Index Unit: ft Index Type: Measured Depth Creation Date: 20-Oct-2016 14:29:06

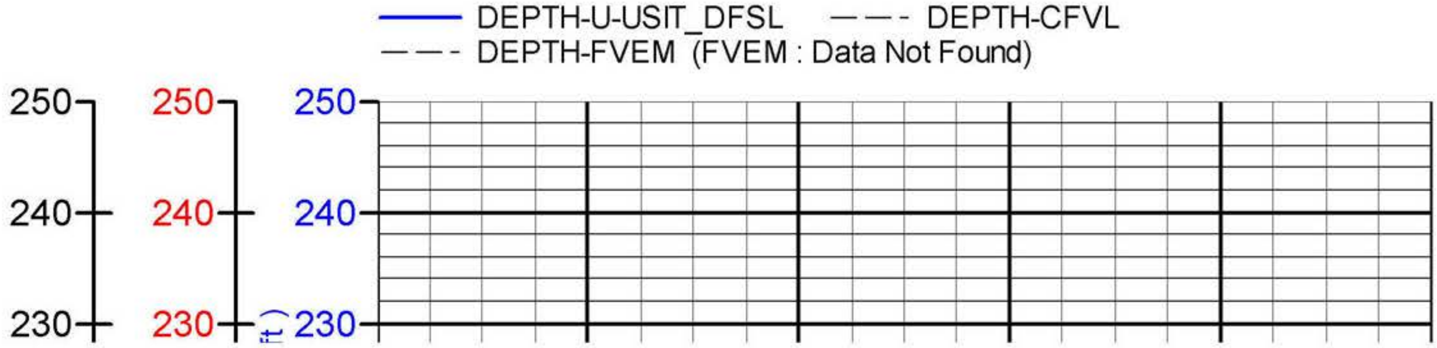
XYZ

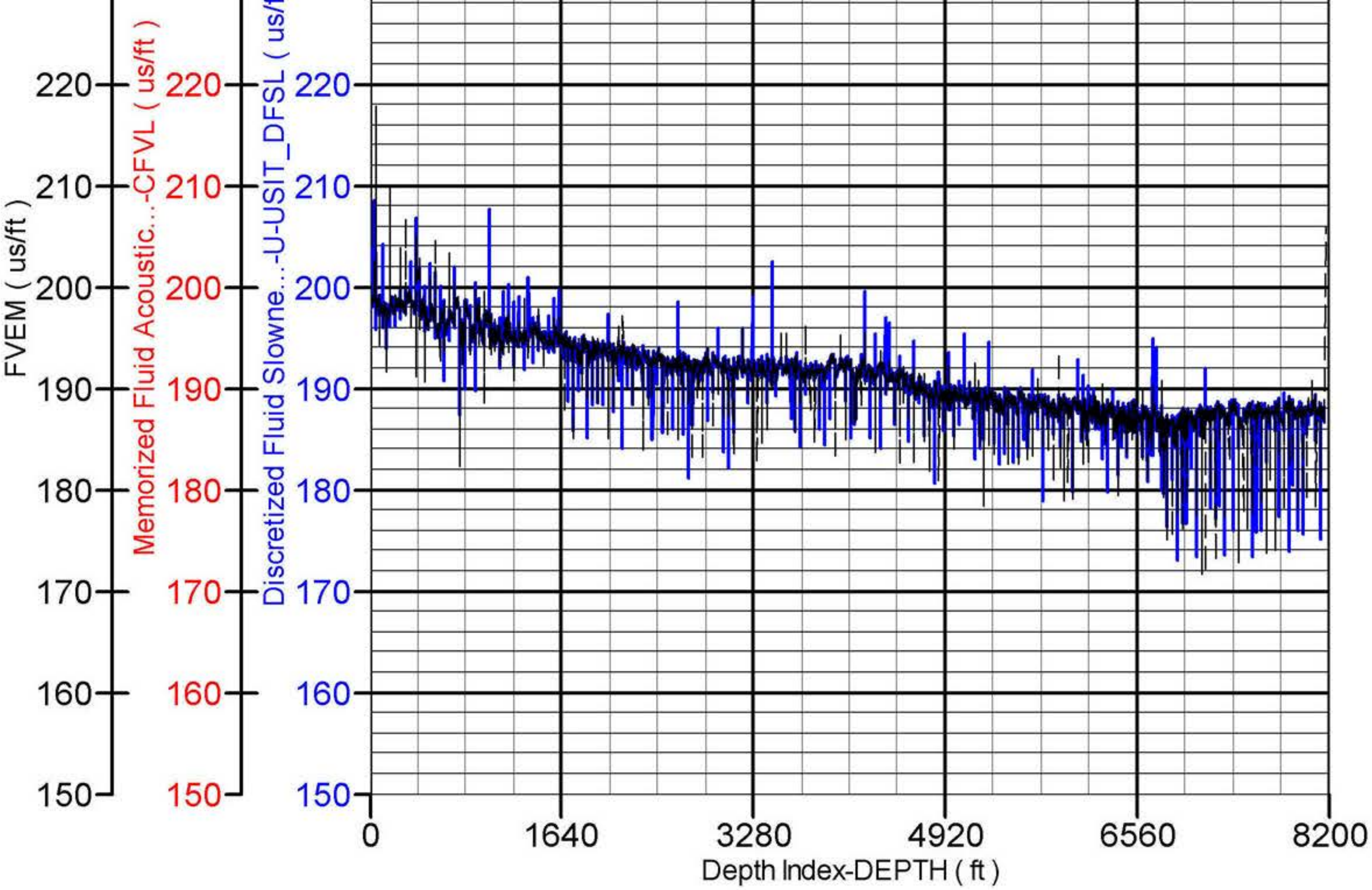
Company:Southern California Gas Company Well:Frew 4
Composite 1:S008

Fluid Acoustic Slowness vs Depth

2D Cross Plot

Index Range: From 5.25 to 8171.50 ft



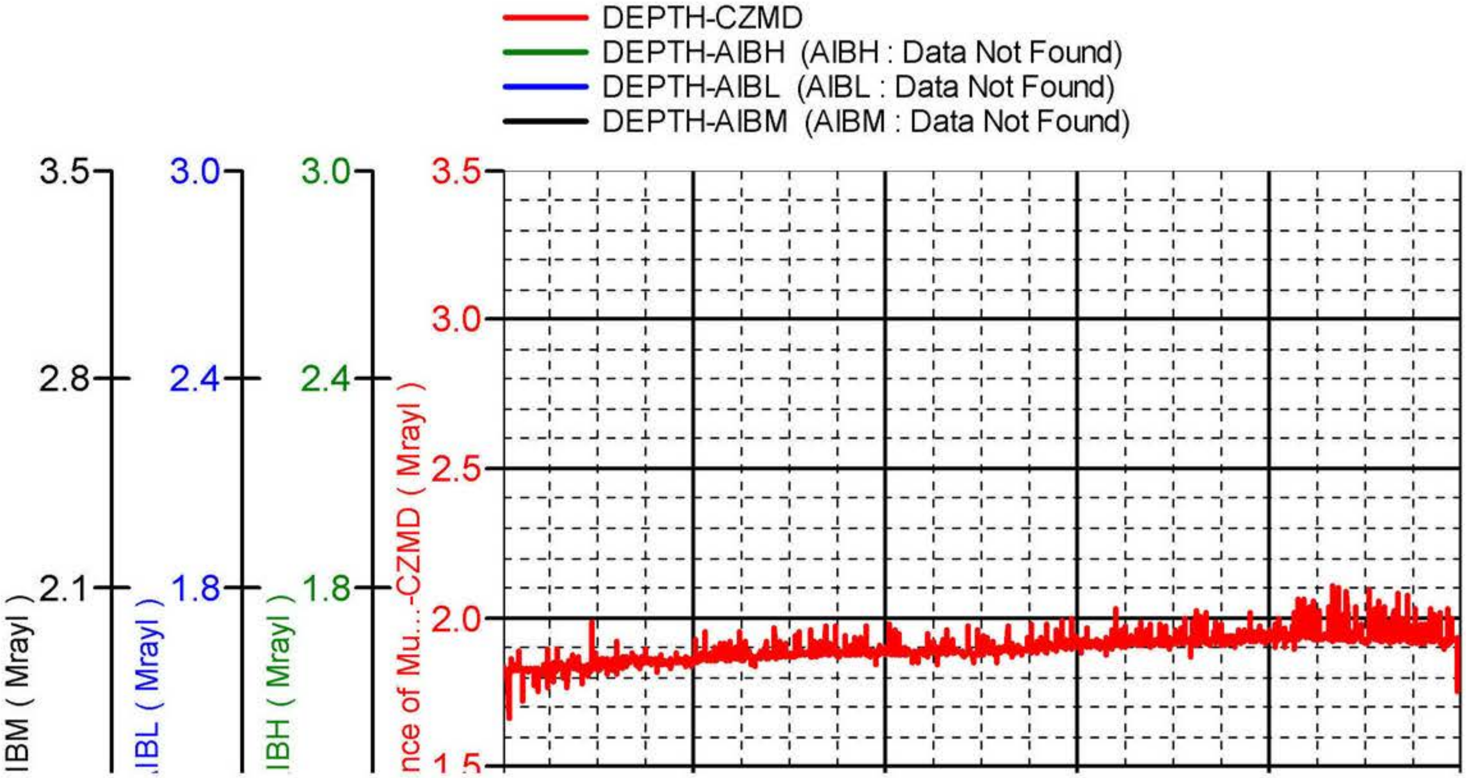


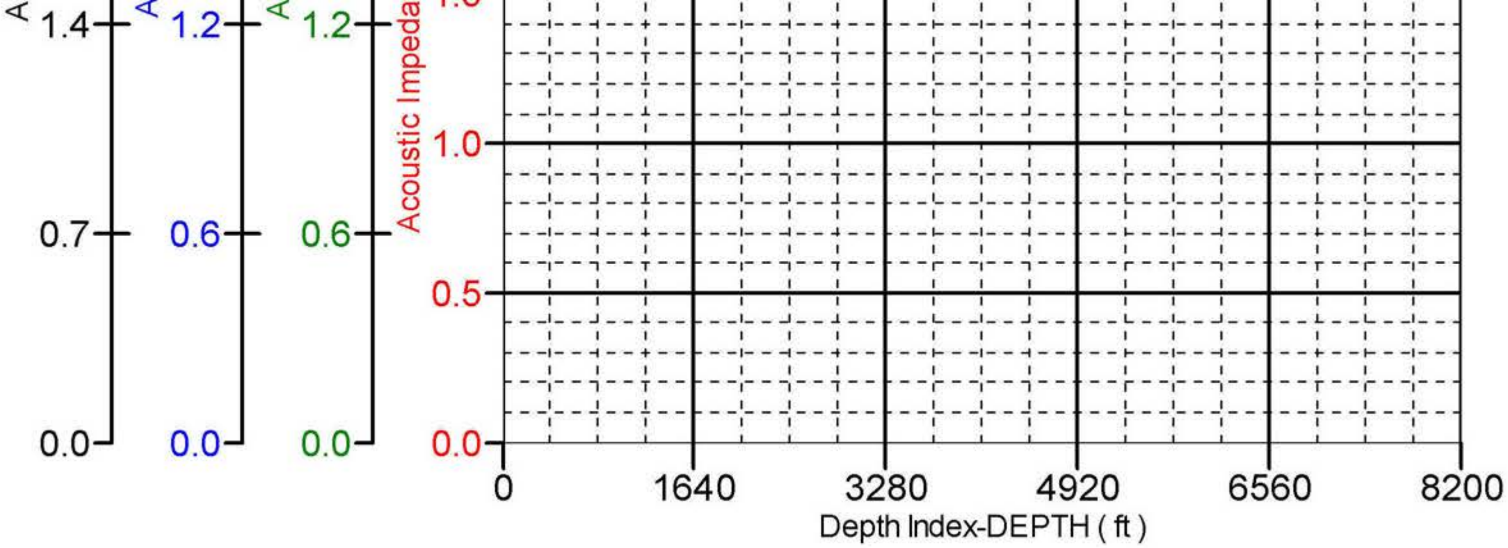
XYZ Company:Southern California Gas Company Well:Frew 4
Composite 1:S008

Theoretical Acoustic Impedance of Mud vs Depth

2D Cross Plot

Index Range: From 5.25 to 8171.50 ft





Company:	Southern California Gas Company	Schlumberger
Well:	Frew 4	
Field:	Aliso Canyon	
County:	Los Angeles	
State:	California	

Ultrasonic Imager

Ultrasonic Imager

Gamma Ray - CCL

7" casing

Ex. II - 25

Ex. II - 26

Due to the large file size, please view document DOGGR_03700761_Vertilog_1-17-1989 at the below publicly available website. The native file of this document is available upon request.

(https://secure.conservation.ca.gov/WellRecord/037/03700761/tifs/03700761_Vertilog_1-17-1989.tif) (accessed March 20, 2020) *file*

SOUTHERN CALIFORNIA

INTEROFFICE gas CORRESPONDENCE

COMPANY

R M Hijazi

TO M. E. Melton FROM R. M. Hijazi DATE Jan. 23, 1989

SUBJECT Casing Inspection Log and Pressure Test Results
SS-8 and SS-9, Aliso Canyon

Casing inspection logs (Vertilogs), recently run by Atlas Wireline Services, show three main areas of casing corrosion in Standard Sesnon 8 and no significant corrosion in Standard Sesnon 9.

There appears to be approximately 48% isolated metal loss in the casing in SS-8 at a depth of 3253' and approximately 45% metal loss at depths of 3314' and 3321'. Recent temperature surveys do not indicate anomalies at these depths. Both SS-8 and SS-9 were pressure tested to 1900 psi at the surface using 63 #/ft3 fluid in the hole. Neither of the two wells leaked.

RMH:hr

64-F

Ex. II - 27

MICROBIOLOGICALLY INFLUENCED CORROSION (MIC):

Methods of Detection in the Field

GRI Field Guide 1990

Microbiologically Influenced Corrosion (MIC):

Methods of Detection in the Field

GRI Report No. ~~88/0113~~ 90/0299 [revised 1991]

Gas Research Institute
Chicago, Illinois

GRI FIELD GUIDE 1991

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Acknowledgments

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Table of Contents

(Continued)

Purpose of This Guide

This guide is designed to help gas industry personnel determine whether or not the corrosion occurring at a particular site is microbiologically influenced corrosion (MIC) and to provide data useful to GRI's ongoing research program. It is useful for determining whether bacteria potentially capable of causing MIC are present in large numbers in fluid samples. Additionally, the data collected by users of this field guide are important in identifying the types of sites most susceptible to MIC and the effects of environmental factors and materials on MIC processes.

This version of the field guide primarily addresses external pipe corrosion and readily accessible internal corrosion sites and is the result of research funded by the Gas Research Institute and the collaboration of interested gas pipeline companies. Future guides will address monitoring of fluids, on-line monitoring methods, cathodic protection, and coatings. Continuing research by GRI will continue to focus on the development of practical and cost-effective methods of mitigating MIC in the gas industry.

Background Information

Microbiologically influenced corrosion is seldom attributed to the action of just one type of microorganism, but more often to the activities of several different organisms which form a community. Because microbial communities are common inhabitants in the environment, MIC is a problem in many industries.

A common type of MIC results in localized attack of carbon steels in the form of pitting, although some general attack takes place as well (see Figure 1). Some cases of severe pitting found under nodules formed at holidays in coatings have been attributed to MIC. Intact coatings may provide some protection against MIC; however, when holidays occur, corrosion often exists under the adjacent disbonded coating (see Figure 2).

Three types of evidence are used to estimate whether MIC is likely at a particular site: metallurgical, chemical, and biological. The GRI program has discovered that the presence of the metallurgical fingerprint is fairly definitive. Chemical and biological data are supportive, and are useful for estimating whether a potential for MIC exists in cases where only fluid samples are available or where corrosion has not progressed so that a metallurgical fingerprint is clearly defined.

The MIC of carbon steels usually has been attributed to sulfate-reducing bacteria (SRB). Recent evidence suggests that many other microorganisms, principally anaerobic and facultatively anaerobic bacteria, are also involved in the corrosion of carbon steel in part due to their ability to produce organic acids.

External Corrosion Site Samples

External samples are usually portions of the corrosion products on the outer surface of excavated pipe and include nodules, pit contents, and scale. Samples of soil or water on, or adjacent to, the pipe can also be tested for MIC-related organisms. However, bacteria are frequently found in soil whether or not corrosion is present. Therefore, a positive soil test for MIC-related microorganisms is not confirmation of MIC, but it is an indicator of the potential for MIC at that site.

Internal Corrosion Site Samples

Internal samples are usually water or other liquids obtained from inside pipes, separators, drips, or water dumps. Analysis of liquid samples does not always give an accurate assessment of MIC activities occurring at the pipe surface; rather, they are an indication of the potential for MIC and the effectiveness of treatments being applied. Refer to "Scoring Samples Other Than Corrosion Product" for procedures to be used with these samples. Installation of sidestream test loops is the best way to monitor sessile bacteria, internal corrosion, and treatment methods. In the event thata pipe is opened, samples of nodules, scale, pit contents, or biofilm material can be collected for analysis. These samples can be used in the following procedures.

How To Use This Guide

This guide is to be used by corrosion technicians during examination of a corrosion site. Data sheets are included for recording information and observations at the corrosion site. Corrosion characteristics and test results are assigned numerical values and then used to determine the probability that the corrosion is MIC.

For biological and chemical analyses, any brand of test kit capable of estimating numbers of SRB and acid-producing bacteria (APB) and chemical parameters is suitable. For purposes of providing GRI with a standarized data set, consistent with data previously collected for GRI, the use of MICKIT™ III-C and IV is encouraged but not essential. A set of detailed instructions is included in these test kits.

Read the entire guide and have materials ready before you begin sampling. Once the site is exposed, pit material or corrosion product should be collected and processed immediately.

Key Contacts

Address questions regarding the GRI program to:

Mr. Daniel Werner
Pipeline Operations Research
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631
(312)399-8306

Address additional questions and MICKIT requests to:

Dr. Dan Pope
Bioindustrial Technologies, Inc.
40200 Industrial Park Circle
Georgetown, TX 78626
(512)869-0580

To order additional Field Manuals, blank data forms, MIC videotape, or 1989 Annual Report contact:

Ms. Jane Wessels
Radian Corporation
8501 N. Mo-Pac Blvd.
P.O. Box 201088
Austin, TX 78720-1088
(512)454-4797

Other sources of information on MIC:

National Association of Corrosion Engineers
1440 South Creek Drive
Houston, TX 77084-4906
(713)492-0535

Materials Needed

These materials can be purchased separately or in kit form. As indicated earlier, GRI's data base has been developed using MICKIT™ III C test kit for acid-producing bacteria (APB) and sulfate-reducing bacteria (SRB) and MICKIT™ IV test kit for chemical analysis.

To test for APB and SRB

Depending upon the test kit used, it may include the following:

media for detection of APB and SRB
any standard SRB media (for detection of SRB)
ADS sample collection bottle
two 3-cc syringes with 21-gauge needles
alcohol spongette
1 sterile wooden sampling stick
1 cotton swab (for sampling biofilms)
styrofoam tray to hold and protect bottles

To test for chemical composition of corrosion product

Test kits should include:

3 normal HCl
sulfide indicator strips
Fe^{2+} indicator strips
Fe^{3+} indicator strips
sodium acetate
potassium oxalate
pH paper
deionized water
disposable sample cuvettes

Notes: These items can be purchased separately.
MICKIT III C and IV are trademarks of Bioindustrial Technologies, Inc.

Other equipment

Hand lens/field microscope (5X-60X)
Metal cleaning equipment
  spatula/pocket knife
  nylon brush (toothbrush)
  brass wire brush
  pit depth gauge
  sandblasting equipment (if available)
35-mm camera

When possible, take color photographs of the involved area (e.g., pit, nodule, debris, etc.) **before** and **after** sampling and cleaning.

Procedure for Determining MIC at Suspected Corrosion Sites

Prior to excavation, have kit in hand. Also measure pipe-to-soil potential before excavation.

The pipe should be excavated carefully to avoid disturbing the surface conditions at the sampling site. The coating around the suspected area of corrosion should be carefully removed using a knife or similar instrument. Sample contamination must be kept to a minimum; therefore, avoid touching the corrosion product or soil to be sampled with hands or tools other than those to be used in sample collection.

Once the site is exposed, pit material or corrosion product should be collected and processed immediately.

Fill out the Site Information Form as the required information becomes available. All of the information requested may not be available. Please provide as much as possible since this information will become part of the GRI MIC research program data base. The information provided will be coded and considered confidential and will not be reproduced with reference to company name or geographic location.

Three types of evidence are used to estimate whether MIC is likely at a particular site:

- metallurgical fingerprint (fairly definitive)
- biological (supportive), and
- chemical (supportive).

Determine whether nodules (discrete "buildup" of deposits) or aggregates of these are present at the corrosion site (see Figures 1, 2, and 11 for examples from field sites). If so, record the information on the GRI Summary Data Sheet (question no. 1). The Site Information Form and the Summary Data Sheet are shown on pages 28 and 29 of this handbook. A supply of these forms accompanies a copy of the field guide. Extra forms are available from Radian Corporation (c/o Jane Wessels), P.O. Box 201088, Austin, Texas 78720-1088 (512/454-4797).

After the proper incubation period, interpret the media reactions according to kit directions (see Figures 4 and 5). Record the number of bottles showing positive results for each type media on the Summary Data Sheet (question no. 2). For example, if four turbid MC media bottles and three black SRB media bottles were observed, you would record 4 and 3 on the Summary Data Sheet.

Observe metal and pit contents under the deposits. Record the results on the Summary Data Sheet (question no. 3).

An area that was scraped shiny should not be recorded as shiny metal.

Using the test kit for chemical analysis, determine the presence of carbonate, sulfide, calcium, iron and pH. Follow the directions included with the kit. Record the results on the Summary Data Sheet (question no. 4).

Any deposit remaining over or in the corrosion site should be carefully removed so as not to damage the metal surface. Follow the procedure below for cleaning the pipe surface.

Mechanical Removal

Start by removing the deposit using a clean spatula or pocket knife, being careful not to dig into the metal. After removing as much deposit as possible without damaging the metal, continue cleaning with a dry stiff brush (e.g., a nylon toothbrush).

Do not use a metal brush since it can damage the metallurgical pattern. If the dry brush does not completely remove the material, the deposit should be wetted and brushed again. Dry the area with a blast of compressed air or rub the area with the alcohol swab.

Additional Mechanical Cleaning

If the surface is not yet clean, a brass wire brush may be used. To limit the damage to the metallurgical picture, brush only in the direction of the length of the pipe.

Final Mechanical Cleaning

If the surface is not yet clean, use a light/blast type sandblast at low air pressure (75-125 psi). The sand used by GRI investigations for this purpose is:

Ottawa Industrial Sand
    Designation: F125 Mesh: AFS grain fineness 126; average mesh size 183.126
    Density: 103.5 lb/cu ft (compacted); 87.0 lb/cu ft (uncompacted)

Refer to Figure 6 for an example of typical surface deposit condition as excavated and after sandblasting.

The clean corrosion site should be examined first with the unaided eye and then using a low power (e.g., 5X to 60X) magnifying lens or microscope. Low-power hand microscopes can be obtained from Cole-Parmer, Radio Shack, and other distributors.

Compare the observed surface with those in Figures 7 to 13, which are examples of MIC. Record the results on the Summary Data Sheet (question no. 5).

1. Look for cup-type, scooped-out hemispherical pits on the flat surface of the pipe and craters up to 2 to 3 inches across. Sometimes the cup-type pits occur on the inside surface of the craters, as in Figures 7, 8, 11, 12, and 13. If present, record this on the Summary Data Sheet.

2. Look for the striation lines (contour lines) that run parallel to the length of the pipe, as in Figures 7, 9, and 10. If present, record the results on the Summary Data Sheet.

3. Look very carefully at the surface of the craters. Look for tunnels on the upstream and downstream surfaces of the craters. They should also run parallel to the length of the pipe, as in Figures 7 and 11 to 15. If present, record this on the Summary Data Sheet.

4. Are the tunnels in the direction that is parallel to the rolling direction of the pipe? If so, record this on the Summary Data Sheet.

Tally the results on the Summary Data Sheet (question no. 6), and use the scoring guide on the sheet to determine the probability that the corrosion is microbially related.

Scoring Samples Other Than Corrosion Product

Test results on samples of soils on or adjacent to the pipe and liquids (produced or process waters, hydrocarbons, etc.) should be viewed as indicators of the potential of MIC, since these samples are in contact with pipe surfaces. The only way to score the sample for the probability of MIC is by using bacterial culture and sulfide results. In general, positive results will occur for the presence of bacteria; however, the more bacteria present, the greater the potential exists for the development of MIC if the pipe is not properly coated, cathodically protected, or maintained. Record the data on the Summary Data Sheet in the section noted for samples other than corrosion product (question no. 7). Use the scoring system for samples other than corrosion product to help determine the potential for MIC. Subsequent field guides will address these samples in more detail.

Figure 1. Localized External Corrosion with Deposits, Pits, Craters and Some General Attack

Figure 2. Disbonded Pipeline Coating Associated with Localized External Corrosion

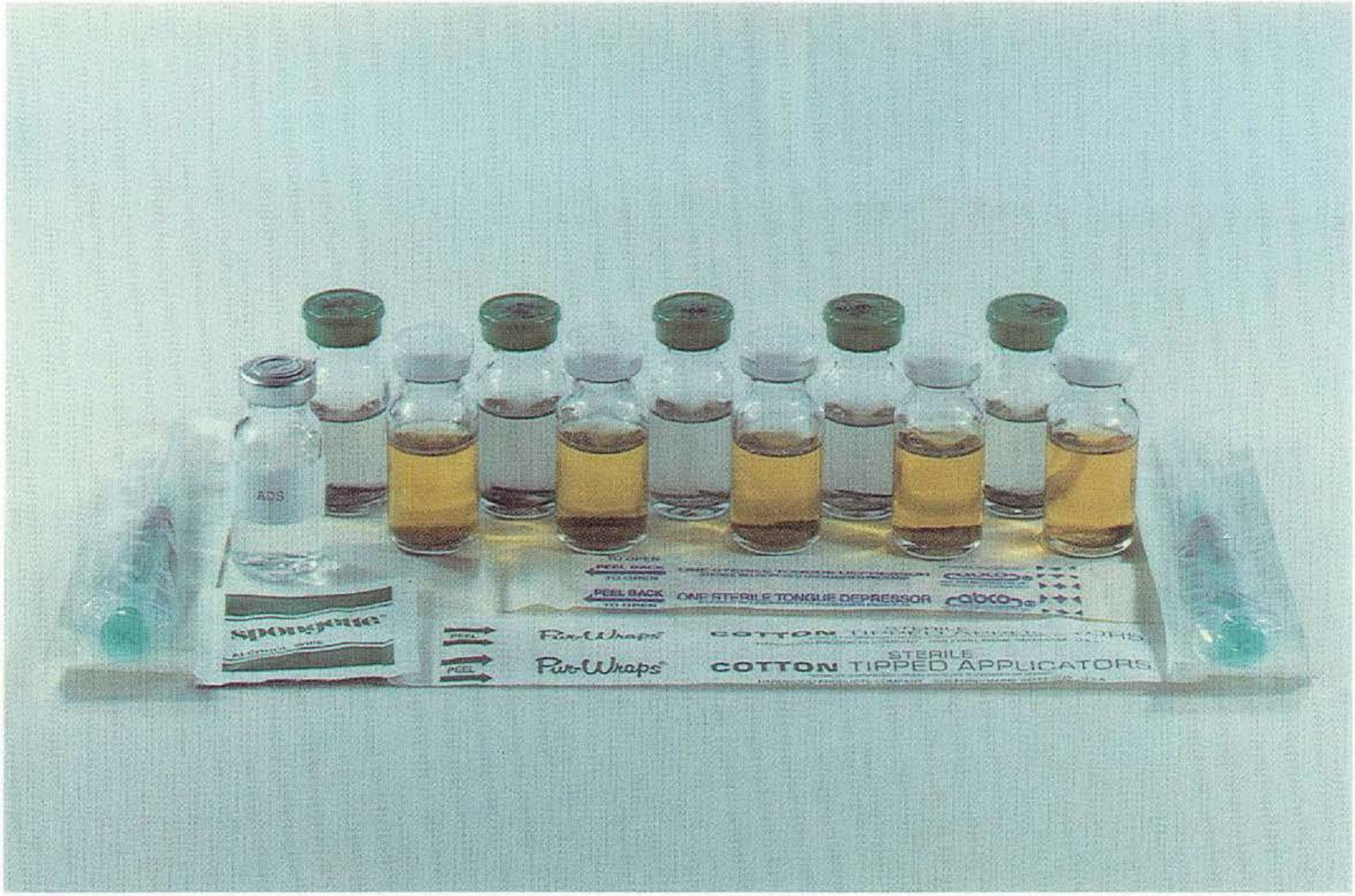

Figure 3. Example of a Biological Test Kit (shows MICKIT$^{\text{TM}}$ III C)

BLACK
Positive
for SRB

TURBID
Positive
for APB

UNINOCULATED

Figure 4. BTI-MC Media Reactions for SRB, APB, and Uninoculated

Figure 5. Media Reactions for APB, SRB, Anaerobes and Aerobes

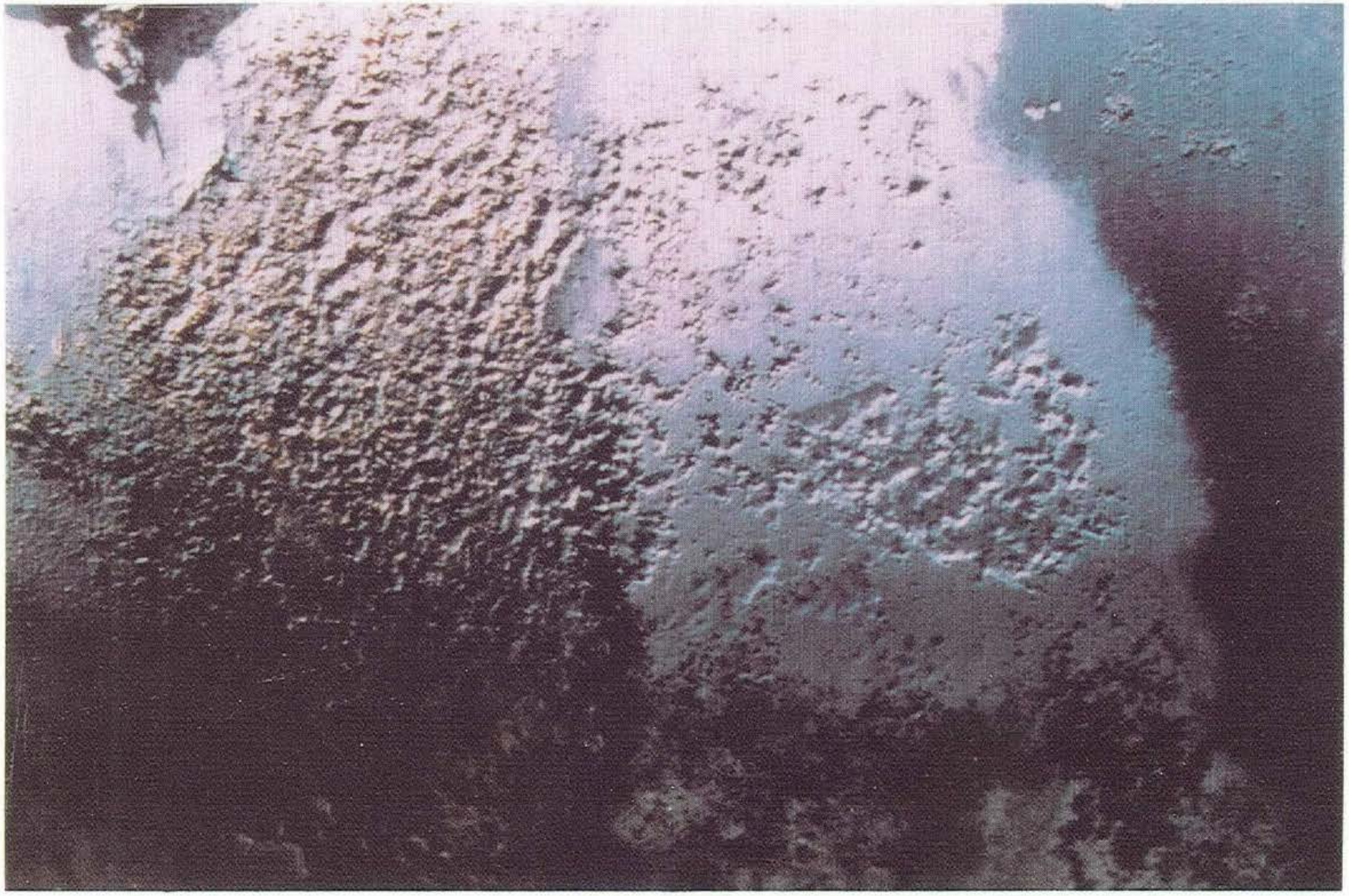

Figure 6. Condition of Pipe After Brush-blast Sandblasting

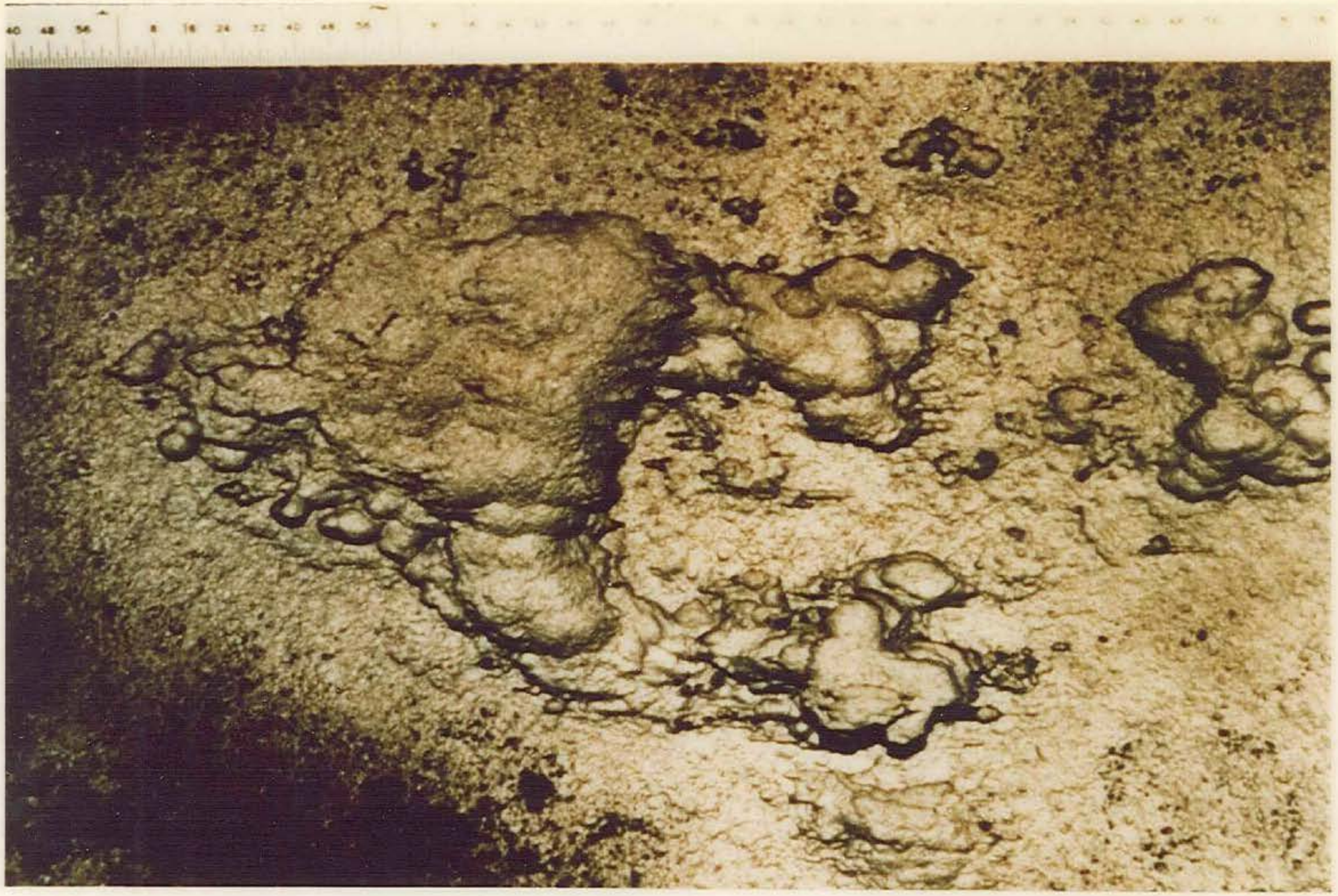

Figure 7. Close-up of Sandblasted Surface Showing MIC Pattern

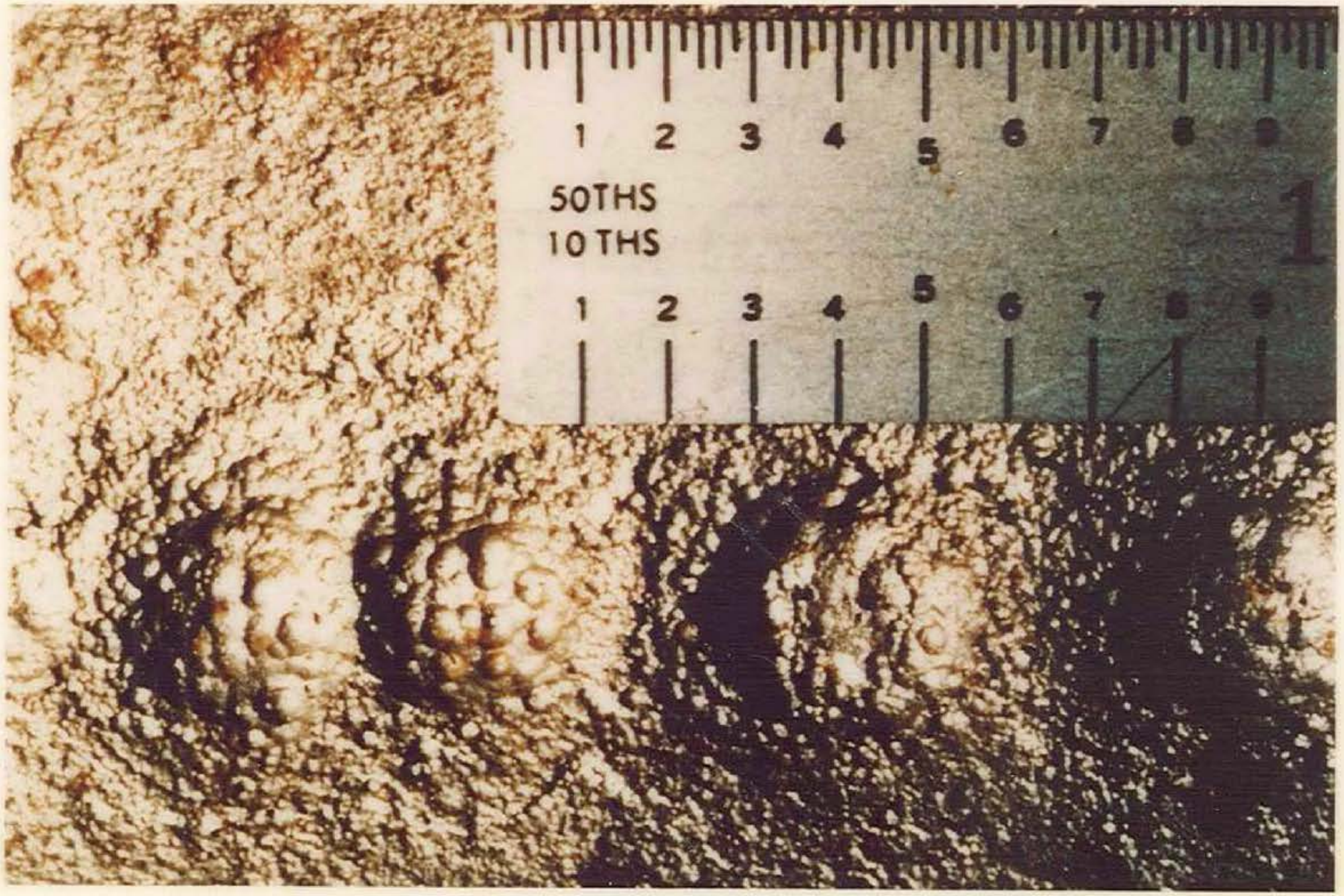

Figure 8. Cup-type Scooped Out Hemispherical Pits on Flat Surfaces with Craters in Pits

Figure 9. Corrosion Pits with Striations

Figure 10. Corrosion Pits with Striations

Figure 11. Surface Pit Showing Corrosion Product in Pit

Figure 12. Same Pit After Corrosion Product is Scraped Out

Figure 13 Same Pit After Cleaning with Nylon Brush (Note Cup-like Pits Inside Large Pit)

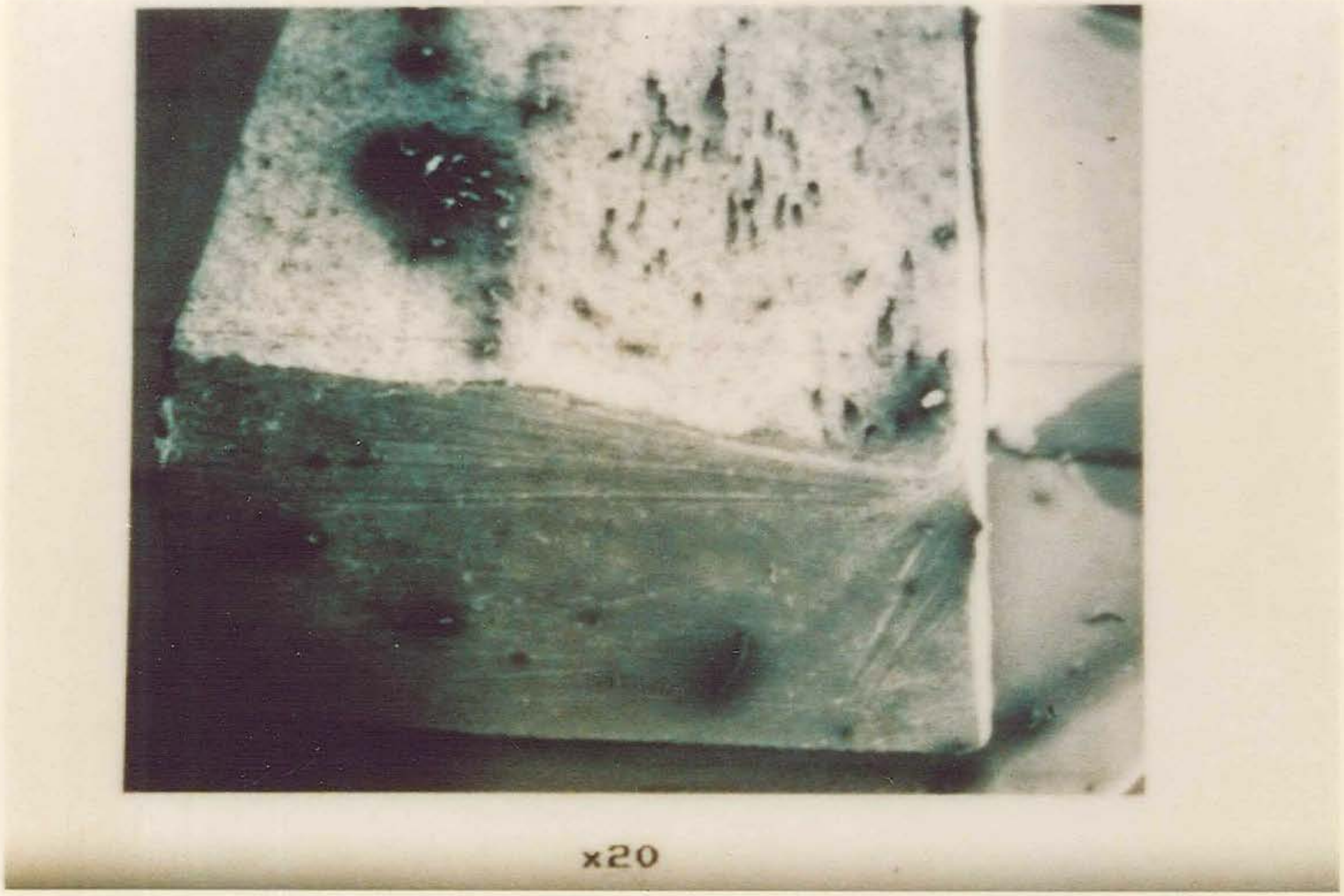

Figure 14. Cross-section of Pit Showing Tunnels (20X Magnification)

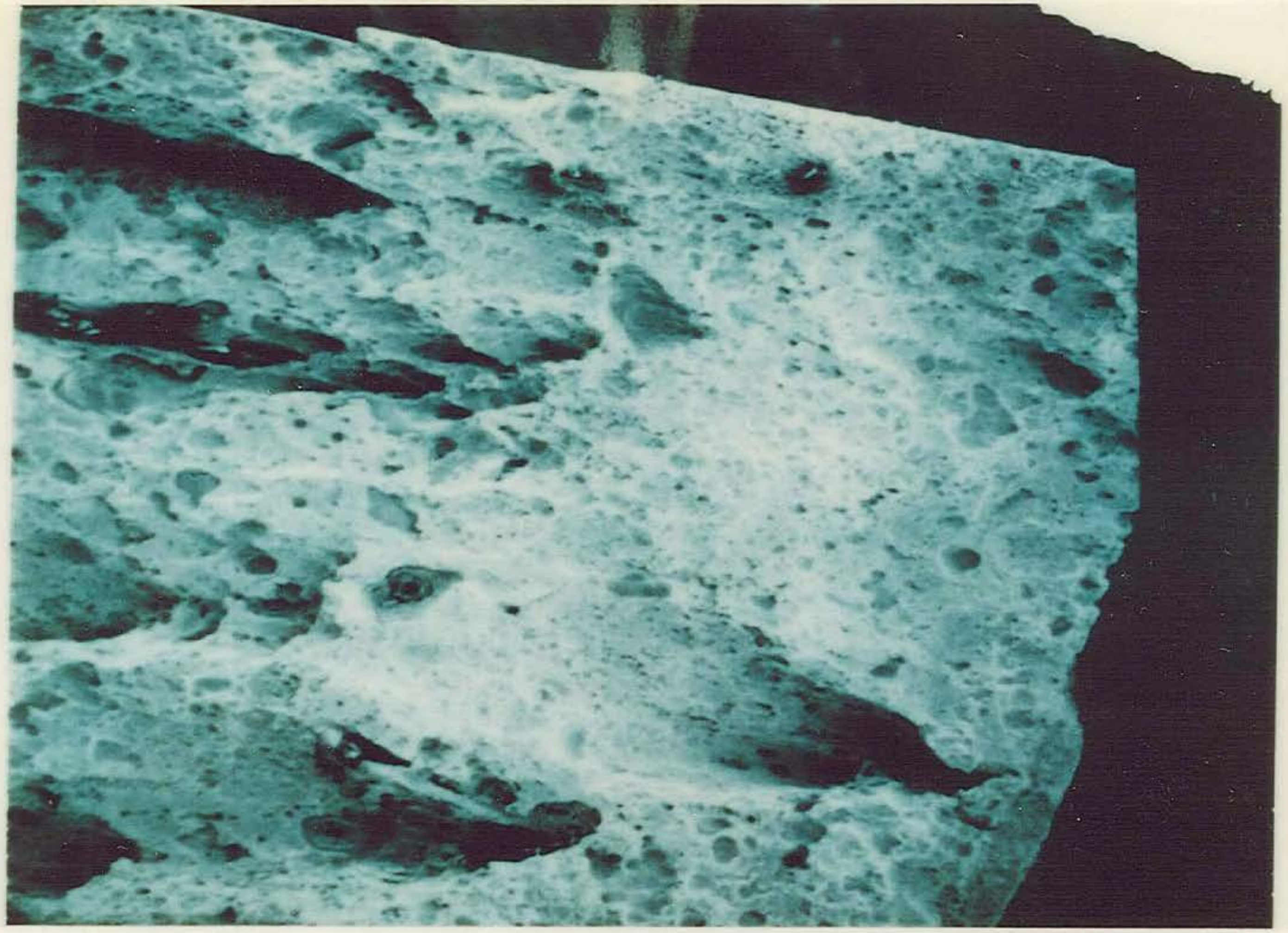

Figure 15. Close-up View of Tunnels (100X Magnification)

GRI SITE INFORMATION FORM

Provide as much information as possible.

Information Regarding Location and Company

Pipeline Company ______________________

Pipe location ______________________

State/County ______________________

Date inspected ______________________

Pipeline No. ______________________

Pipeline section No. ______________________

Information Regarding Pipe

Manufacturer ______________________

Age of pipe ______________________

Leak history ______________________

Wall thickness ______________________

Pipe grade ______________________

Specifications ______________________
(SMLS, ERW, DSAW)

Information Regarding Coating

Manufacturer ______________________

Type coating ______________________

Type recoating ______________________

Condition ______________________

Bond to pipe ______________________

Water under coating? ______________________

Information Regarding Soil and Site

Type terrain ______________________

Type soil ______________________

Soil resistivity ______________________

Soil pH ______________________

Pipe depth ______________________

Odor at site? ______________________

Moisture at pipe? ______________________

Other ______________________

Information Regarding Corrosion Site and Products

Pipe thickness ______________________

Color of sample ______________________

Length of pit family ______________________

Maximum pit depth ______________________

Information Regarding Storage and Production Sites

Formation ______________________

Iron in liquid ______________________

Other chem. info. ______________________

Biocide used ______________________

Other chemicals ______________________

pH of liquids ______________________

Manganese in liquid ______________________

Other chem. info. ______________________

Corrosion inhibitor ______________________

Other information ______________________

History of chemicals in use, if known ______________________________________

Additional comments ______________________________________

Send completed forms and request blank forms from:

Radian Corp.
8501 Mo-Pac Blvd.
P. O. Box 202088
Attn: Ms. Jane Wessels
(512) 454-4797

GRI SUMMARY DATA SHEET
Scoring Corrosion Samples

What media type did you use? (Results may differ between commerical types.)

Media Type	Formula Used	Company
MC		
APB		
SRB		

Question No.	Points	Score
1. Are deposits present?	Yes = 1	
Approximate number		
Approximate size		
2. Number of positive (turbid) bottles of MC media		
Number of positive (black) bottles of SRB or MC media		
Record the higher number of positive bottles above (0-5) (MC or SRB, not both)		
3. Are pit contents grey or black?	Yes = 1	
Is metal surface under the deposit shiny or black?	Yes = 1	
4. Calcium carbonate present? or	Yes = 0	
Iron carbonate present? or	Yes = 2	
Calcium and iron carbonate? and	Yes = 1	
Sulfide present?	Yes = 1	
5. Are cup-type pits present?	Yes = 1	
Are striation lines present?	Yes = 1	
Are tunnels present?	Yes = 5	
Are tunnels rolling direction?	Yes = 1	
Probability of MIC:	**Total Score**	

6. ≤6 Very unlikely   7-10 Likely   ≥11 Very likely

Scoring Samples Other Than Corrosion Products

7. A positive sulfide reaction?	Yes = 1	
Highest number of positive bottles in MIC or SRB media (not both!)		
	Total Score	

Probability of MIC:

<3 points
low probability

>3 points
high probability

Ex. II - 28

Biological Corrosion Failures

Thomas R. Jack, NOVA Chemicals Ltd.

MICROORGANISMS can directly or indirectly affect the integrity of many materials used in industrial systems. Most metals, including iron, copper, nickel, aluminum, and their alloys, are more or less susceptible to damage (Ref 1–3). Only titanium and its alloys appear to be generally resistant (Ref 4). This review focuses initially on the mechanisms of microbially induced or influenced corrosion (MIC) of metallic materials as an introduction to the recognition, management, and prevention of microbiological corrosion failures in piping, tanks, heat exchangers, cooling towers, and so on. Numerous reviews of MIC have appeared over the last decade (Ref 2, 5–12). Two recent publications (Ref 13, 14) present broader discussions of MIC, including a useful introduction to microbial problems seen with nonmetallic materials such as polymers, composites, concrete, glass, wood, and stone.

Viable microorganisms can be found over a surprisingly wide range of temperature, pressure, salinity, and pH (Ref 1). In the 1950s, pioneering work by Zobell isolated sulfate-reducing bacteria (SRB) that grew at 104 °C (219 °F) and pressures of 1000 bar from oil-bearing geological formations deep underground (Ref 15). Microbial communities exist in environments as diverse as subzero snowfields to deep ocean thermal vents. Halophiles evolved to live at extreme salinities turn pink the evaporation pans used to win salt from seawater. Sulfur-oxidizing bacteria create very acidic conditions ($\text{pH} < 1$) by producing sulfuric acid as an end product of their metabolism, while other microorganisms survive the opposite end of the pH scale. Given these examples, it should not be surprising that microorganisms have been implicated in the accelerated corrosion and cracking of a correspondingly wide range of industrial systems. For example, the involvement of thermophilic SRB in the severe intergranular pitting of 304L stainless steel condenser tubes in a geothermal electrical power plant operating at >100 °C (> 210 °F) has been reported (Ref 16). In another example, microbiological activity and chloride concentrated under scale deposits were blamed for the wormhole pitting of carbon steel piping used to transport a slurry of magnesium hydroxide and alumina at pH 10.5 (Ref 17).

Whatever the environmental conditions, microorganisms need water, a source of energy to drive their metabolism, and nutrients to provide essential building materials (carbon, nitrogen, phosphorus, trace metals, etc.) for cell renewal and growth. An understanding of these factors can sometimes help in failure investigations. Energy may be derived from sunlight through photosynthesis or from chemical reactions. The importance of photosynthetic metabolism is limited in the context of this article to above-ground facilities or submerged structures that receive sunlight. For closed systems and buried facilities, microbial metabolism is based on energy derived from oxidation reduction (redox) reactions. Under aerobic conditions, reduction of oxygen to water complements the metabolic oxidation of organic nutrients to carbon dioxide. Under anaerobic conditions, electron acceptors other than oxygen can be used. Figure 1 illustrates the range of pH and redox potential where anaerobic forms of microbial metabolism tend to be found (Ref 18).

Whatever the metabolism, electrochemical reactions catalyzed by enzymes provide energy for cell growth. Many of these reactions are not important under abiotic conditions, because they are kinetically slow in the absence of organisms. By promoting these reactions, microbes produce metabolites and conditions not found under abiotic conditions. In some cases, electrons released by the oxidation of metals are used directly in microbial metabolism. In other cases, it is the chemicals and conditions created by microbial activity that promote MIC. Secondary effects can also be important. These include such things as the biodegradation of lubricants and protective coatings designed to prevent wear or corrosion in an operating system, or the alteration of flow regimes and heat-transfer coefficients due to the biological fouling of metal surfaces.

Given the potential impact of MIC on a wide range of industrial operations, it is not surprising that microbiological effects are of significant concern in failure analysis and prevention. Microbially induced corrosion problems afflict water-handling operations and manufacturing processes in oil and gas production, pipelining, refining, petrochemical synthesis, power production, fermentation, waste water treatment, drinking water supply, pulp and paper making, and other industrial sectors. Microbially induced corrosion is also a concern whenever metals are exposed directly to the environment in applications including marine or buried piping, storage tanks, ships, nuclear waste containers, pilings, marine platforms, and so on.

Microbial Involvement in Corrosion

Corrosion involves the oxidation of metal atoms, *M*, in an anodic region with a loss of electrons to a complementary reduction reaction in a cathodic region elsewhere on the metal surface (Fig. 2). In the reduction reaction, an electron acceptor, *X*, receives the electrons given up by the oxidation process. The driving force for corro-

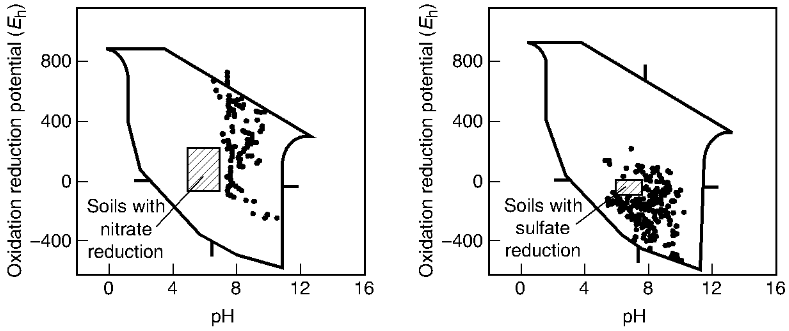

Fig. 1 The pH and oxidation reduction potential for growth of anaerobic bacteria able to reduce nitrate or sulfate (dots in plots) and for soils dominated by the microbial metabolism (boxes). Aerobic bacteria grow over a wide range of pH at E_h > 300 mV (normal hydrogen electrode). Source: Ref 19

sion is the free energy released by the overall chemical reaction resulting from combined cathodic and anodic half-reactions:

Anodic reaction $M \rightarrow M^{n+} + n \text{ electrons}$
Cathodic reaction $\underline{mX + n \text{ electrons} \rightarrow mX^{n/m-}}$
Overall corrosion reaction $M + mX \rightarrow M^{n+} + mX^{n/m-}$
(Eq 1)

where n, p, and m are integer values chosen to charge balance the equations based on the number of electrons given up by the metal being oxidized or taken up by the electron acceptor being reduced.

Because metals are good electrical conductors, the cathodic and anodic processes can occur at different locations on a metal surface exposed to a common electrolyte. Where anodes and cathodes frequently change location, general corrosion is seen, but when the anode becomes focused in one location, pitting results. In pitting, the rate of penetration is, to a large measure, a function of the relative size of the cathodic and anodic areas involved in the corrosion cell and is usually much higher than that seen for general corrosion.

The rate of metal loss is determined by the slowest, or rate-determining, step in the corrosion process. For example, where the availability of electron acceptor X is limiting, the corrosion rate depends on the transport kinetics for the arrival of X at the metal surface from the surrounding solution (Fig. 2). Where the availability of X is not a constraint, other processes may be rate limiting. For example, a buildup of primary reaction products such as M^{n+} on the anodic surface can polarize the anode, stifle the rate of metal oxidation, and limit the overall rate of corrosion by anodic polarization. Similarly, a buildup of primary cathodic reaction products, $X^{n/m-}$, can slow the overall process through cathodic polarization. A common example of this occurs under anaerobic conditions, where $X = H^+$. In this case, reduction of protons from the electrolyte leads to formation of atomic hydrogen on the metal surface. To escape the surface, atoms of hydrogen must combine to form molecular hydrogen that can then be lost to solution or enter the steel matrix, as shown in Fig. 3.

Byproducts of the various reactions involved may limit the corrosion process by altering the environment at the metal surface (Eq 2–6). For example, reduction of protons at the metal surface (Eq 3) raises the local pH. This can lead to the formation of insoluble deposits. The formation of ferrous carbonate on a steel surface by the sequence of events shown in Eq 2 to 6 provides one example. Precipitation of calcium or magnesium ions from the electrolyte as insoluble carbonates that can passivate a metal surface is another:

$$Fe \rightarrow Fe^{2+} + 2 \text{ electrons} \quad \text{(Eq 2)}$$

$$2H^+ + 2 \text{ electrons} \rightarrow 2H\cdot \text{ (cathodic hydrogen)} \quad \text{(Eq 3)}$$

$$H_2O \leftrightarrow H^+ + OH^- \quad \text{(Eq 4)}$$

$$OH^- + HCO_3^- \rightarrow CO_3^{2-} \quad \text{(Eq 5)}$$

$$CO_3^{2-} + Fe^{2+} \rightarrow FeCO_3 \quad \text{(Eq 6)}$$

Microorganisms accelerate corrosion by changing the nature or kinetics of the rate-controlling reaction or process. They can be directly involved in the electron transfer processes in the electrochemical cell represented by Eq 1 or be less directly involved through a number of mechanisms, including depolarization of the anode or cathode, disruption of passivating films, or rapid regeneration or provision of the electron acceptor, X.

Direct Involvement in the Corrosion Process

Corrosion Mechanisms Involving SRB. Perhaps the best-known mechanism of MIC involves corrosion cells generated and sustained on steel surfaces by the action of anaerobic SRB. These organisms reduce sulfate to sulfide in their metabolism and are commonly found in mixed microbial communities present in soils and natural waters. In industrial systems, biodegradable materials, such as some of the hydrocarbons found in oil and gas operations (Ref 20) or susceptible components of coating materials (Ref 21, 22), can provide a source of nutrients for microbial growth. Cathodic hydrogen formed on a metal surface (Eq 3) by active corrosion or by cathodic protection (CP) can specifically promote growth of organisms, including SRB that are able to use hydrogen in their metabolism (Ref 23). Severe corrosion cells develop as sulfide, produced by the microbial reduction of sulfate, combines with ferrous ions, released by the corrosion process, to produce insoluble black iron sulfides:

$$4Fe + SO_4^{2-} + 8H^+ \rightarrow FeS + 3Fe^{2+} + 4H_2O \quad \text{(Eq 7)}$$

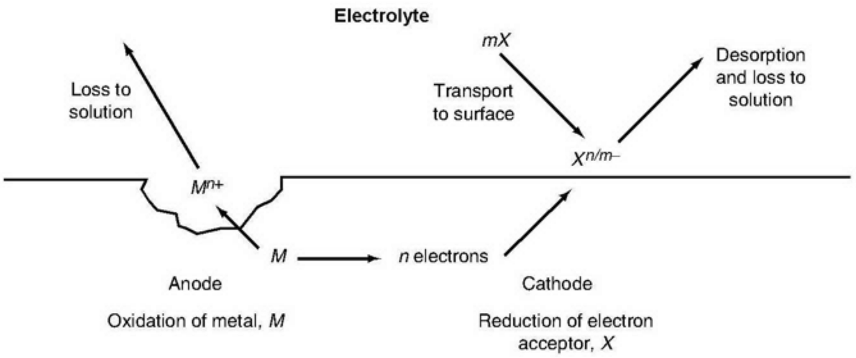

Fig. 2 Schematic diagram of a generic corrosion cell showing anodic oxidation of the metal (M) complemented by cathodic reduction of an electron acceptor (X). The corrosion rate can be controlled by the rate of arrival of X at the cathodic surface, a buildup of metal ions, M^+, at the anode, or a buildup of reduced oxidant, $X^{n/m-}$, at the cathode.

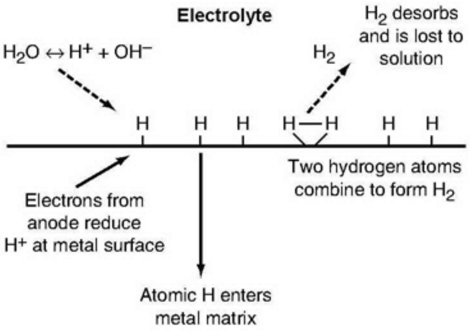

Fig. 3 Schematic diagram of the cathodic surface of an anaerobic corrosion cell in which H^+ is reduced to H on metal surface. The atomic hydrogen formed escapes the cathodic surface by combining to form molecular hydrogen, $2H \rightarrow H_2$, that desorbs from the surface or by entry as atomic hydrogen into the metal matrix.

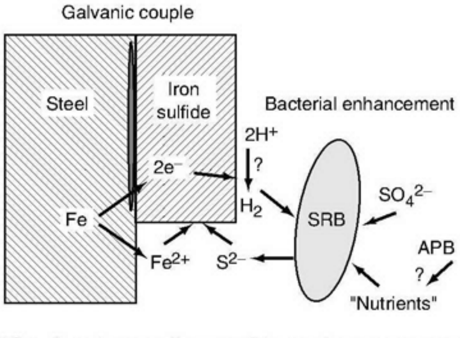

Fig. 4 Schematic diagram of the mechanism in an FeS corrosion cell created by the action of SRB. Iron sulfide sets up a galvanic couple with steel, sustained and extended by the further action of SRB. The bacteria use electrons from the corrosion process, possibly in the form of cathodic hydrogen, to reduce soluble sulfate. Enzyme assays for sulfate reductase and for hydrogenase have been developed as commercially available kits for assessing SRB activity in corrosion sites. The presence of specific iron sulfides is also used to identify this form of MIC. Acid-producing bacteria (APB) may have a role in providing nutrients to SRB, as suggested, and are often found in association.

Various versions of this MIC mechanism have been suggested (Ref 9). Figure 4 illustrates a plausible mechanism base on a galvanic couple formed between iron and iron sulfide sustained and extended by the active involvement of SRB. The way in which electrons are transferred from iron sulfide to the SRB, for example, is not well resolved. It may occur directly or via formation of cathodic hydrogen, as shown in Fig. 4, or by another reaction involving reduction of H_2S (Ref 6):

$$H_2S + \text{electron} \rightarrow HS^- + H\cdot \qquad \text{(Eq 8)}$$

Typical rates of metal loss for unprotected line pipe steel in an SRB/FeS corrosion scenario are 0.2 mm/year (0.008 in./year) for general corrosion and 0.7 mm/year (0.028 in./year) for pitting corrosion (Ref 24), but the corrosion rate observed depends on the concentration of FeS involved (Fig. 5). Consistent with the importance of this corrosion process in industrial facilities, commercial test kits have been developed for enumerating or assessing the activity of SRB in operating systems (Ref 25).

Formation of MIC corrosion cells involving iron sulfide need not be limited to the SRB. Reference 26 describes the corrosive action of bacteria isolated from oil production facilities that are able to reduce thiosulfate to sulfide. These organic-acid-producing organisms could generate a corrosion cell based on iron sulfide but would not show up in SRB assays based on sulfate reduction.

Corrosion by Microbially Produced Manganese (IV). Recent work has shown that microbially produced MnO_2 can corrode (Eq 9) steel, provided that contact is made with the metal surface (Ref 27):

$$Fe + MnO_2 + 4H^+ \rightarrow Fe^{2+} + Mn^{2+} + 2H_2O \qquad \text{(Eq 9)}$$

Although the scenario is somewhat more complex than suggested by Eq 9 and 10 there is evidence that marine biofilms help to sustain the corrosion process by the rapid regeneration of MnO_2 (Eq 10) (Ref 28). Manganese-oxidizing organisms have been implicated in the MIC of 304L stainless steel welds (Ref 29). Formation of manganic oxide ennobles the potential of stainless steel in natural waters (Ref 30). Ennoblement shifts the potential above the repassivation potential to the pitting potential for stainless steel and furnishes the increased cathodic current density needed to propagate nucleated corrosion sites:

$$O_2 + Mn^{2+} \xrightarrow[\text{microbial catalysis}]{} MnO_2 \qquad \text{(Eq 10)}$$

Other electron acceptors involved in microbial metabolism include oxygen, nitrate, iron (III), and carbon dioxide. All of these species could theoretically be involved as the electron acceptor, X, in the corrosion of metals (Eq 1) but evidence for direct MIC based on other electron acceptors is limited. A more general discussion of possible links between electrochemical reactions mediated in microbial metabolism and corrosion is provided in Ref 18.

Indirect Involvement in the Corrosion Process

Microorganisms can influence the corrosion process by a number of less direct mechanisms.

Depolarization Mechanisms. As previously noted, a buildup of hydrogen on the cathodic surface can stifle the corrosion process through cathodic polarization (Fig. 3). Microorganisms with hydrogenase enzymes are able to use hydrogen and have been widely cited as accelerating anaerobic corrosion through cathodic depolarization. Even though this concept has been challenged (Ref 6), commercial kits for hydrogenase activity are available for assessing MIC in practical applications (Ref 25).

Metabolites, such as organic acids produced by acid-producing bacteria (APB), may alleviate anodic polarization. Organic acids can form soluble chemical complexes with metal ions released by the corrosion process, reducing the buildup of M^{n+} on anodic surfaces. Figure 6 illustrates the damaging effect of trace levels of acetate (the conjugate base of the organic acid acetic acid) in the corrosion of steel exposed to carbon-dioxide-saturated brine. Acid-producing bacteria and organic acids at the levels shown in Fig. 6 have been identified in external corrosion sites in an extensive Gas Research Institute (GRI) program on pipeline MIC. Commercial kits and guides were produced for enumerating APB in field samples and for identifying related MIC sites (Ref 32, 33). Fungal production of organic acids has been implicated in the corrosion of posttensioned cables used in construction (Ref 34).

Production of Corrosive Metabolites. Other microbial metabolites have been recognized as agents of MIC. The many scenarios involving various sulfur species that are produced and consumed by microorganisms have been reviewed (Ref 35), and as-yet poorly described microbially produced phosphorus compounds in MIC have been implicated (Ref 11). It has been suggested that hydrogen peroxide produced in biofilms plays a role in the crevice corrosion of 304 and 316L stainless steel (Ref 36).

Alteration of Surface Environments to Create Concentration Cells. In many industrial water systems, colonization of metal surfaces by sessile microorganisms creates a new environment on the surface that may favor corrosion. During the colonization process, microbes from the aqueous phase quickly adhere to exposed steel surfaces and proceed to generate a slime made up of excreted extracellular polysaccharides (EPS). The slime envelops the organisms and creates a unique milieu for further development of microbial communities and possible MIC. The slime holds water, collects nutrients, and recruits other microbes as well as particulates and other debris from the liquid phase. Organisms in the biofilm are protected from direct exposure to biocides at dosages that would readily kill planktonic organisms freely suspended in the water phase. The metal surface is similarly shielded from doses of corrosion inhibitors added to the system.

Corrosion commonly occurs due to concentration cells established under the biofilm, where

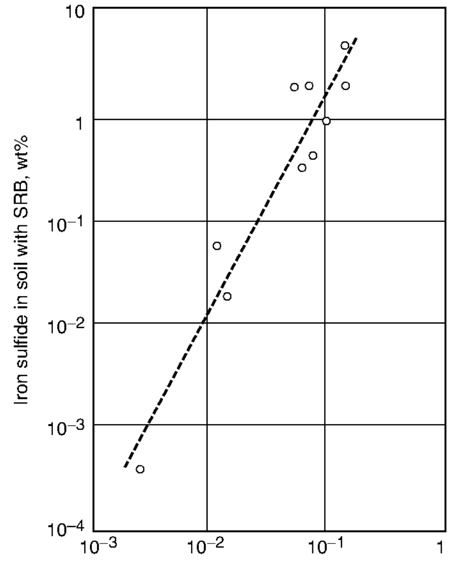

Fig. 5 Rate of corrosion of unprotected steel in biologically active soil as a function of iron sulfide present

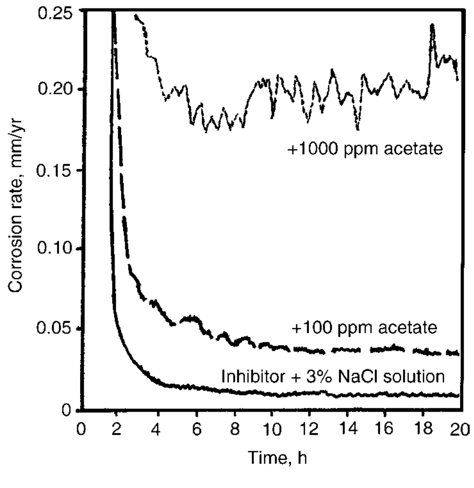

Fig. 6 Initial corrosion rates for steel exposed to carbonated 3% NaCl solution with 0, 100, and 1000 ppm acetate of 4, 9, and 18 mm/year (0.2, 0.4, and 0.7 in./year), respectively. This order is sustained after addition of 25 ppm of a corrosion inhibitor, despite a significant reduction in the corrosion rate in all cases. Source: Ref 31, reproduced with permission of National Association of Corrosion Engineers International

oxygen levels are depleted and metabolite (e.g., organic acid) concentrations may be high. Slime-forming organisms are a recommended target of monitoring programs for cooling water systems (Ref 37) as are iron- and manganese-oxidizing bacteria capable of laying down deposits of metal oxides on affected surfaces. Mobile anions such as chloride are attracted to the corroding surface under a biofilm and associated deposits by the release of positively charged metal ions. Concentration of chloride can accelerate the corrosion process further, especially in systems that rely on a passivating film on the metal surface to protect the underlying metal matrix from corrosion.

Alteration of Passivating Layers. Some metals are protected from corrosion by the formation of a passivating film of metal oxide or other insoluble deposits. It has been suggested that microbial acceleration of corrosion on copper is the result of incorporation of EPS into the copper oxide on the metal surface (Ref 38). This disrupts the passivating film and is accompanied by a reduction in pH due to metabolic activity. In a more complex example, 316L stainless steel exposed to a flowing microbial culture of *Citrobacter freundii* in the laboratory was selectively colonized at grain boundaries (Ref 39, 40). This led to the local depletion of chromium and iron content relative to nickel in the subsurface region of the superficial oxide. A coculture of *C. freundii* and the SRB, *Desulfovibrio gigas,* similarly selectively colonized grain-boundary regions and enhanced the local depletion of iron and the accumulation of sulfur. The authors of the study suggested that these changes weakened the oxide layer, predisposing the metal to a higher frequency of pitting due to attack by chloride. It has been noted that microorganisms can also produce organic acids and create conditions for formation of HCl or metal chlorides, including $FeCl_3$, under biofilms (Ref 2). These agents cause the passivating layer on stainless steel to fail, allowing pitting and crevice corrosion to proceed.

Massive failures due to pitting in water system components, such as utility condensers made of stainless steel, were identified as an MIC problem in the 1970s (Ref 6). Corrosion damage was ascribed to metastable sulfur oxyanions produced by SRB in the reduction of sulfate or formed in the oxidation of biogenic iron sulfide to elemental sulfur in oxygenated water (Ref 41). Sulfur oxyanions, such as thiosulfate and tetrathionate, have been shown to reduce the pitting potential of stainless steel and promote the localized corrosion of both stainless steels and nickel-base alloys (e.g., Inconels) with or without the presence of chloride (Ref 6, 41). One proposed mechanism involves the release of elemental sulfur by the disproportionation or reduction of thiosulfate anions at the metal surface. The elemental sulfur enhances the anodic dissolution process and accelerates pitting. Active SRB help to inhibit repassivation of the metal surface where chloride is present as a pitting agent.

Microbial Involvement in Environmentally Assisted Cracking

Environmentally assisted cracking (EAC) of susceptible materials under stress can be exacerbated by microbial activity. Potentially affected forms of EAC include sulfide-stress cracking (SSC), hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC), near-neutral pH stress-corrosion cracking (SCC), and corrosion fatigue. Accelerated corrosion and enhanced hydrogen uptake can increase the probability of cracking as well as subsequent crack growth rates.

Microorganisms can influence hydrogen uptake by a metal directly through the microbial production of hydrogen. Alternately, microbial activity can promote entry of cathodic hydrogen into the metal matrix through production of recombination poisons that prevent the formation and escape of molecular hydrogen from the metal surface (Fig. 3). Inside the steel, hydrogen concentrates in areas of stress, such as the plastic zone at the tip of a growing crack, or in areas of imperfection in the metal matrix, such as inclusions or grain boundaries. In the former location, hydrogen causes embrittlement of the metal and facilitates the cracking process in, for example, SCC (Ref 42). At imperfections, formation of molecular hydrogen can force voids to form in a metal matrix through a buildup of gas pressure. This can lead to macroscopic blistering and cracking within the steel matrix in the form of HIC or SOHIC. In general, these effects are of greater concern in higher-strength steels (Ref 43).

Only a modest amount of work has been done on the involvement of microorganisms in EAC relative to the potential importance of this topic. The HIC of high-tensile-strength hard-drawn steel wire used for prestressing concrete pipe on exposure to laboratory cultures of the hydrogen-producing anaerobe, *Clostridium acetobutylicum,* has been demonstrated (Ref 44). While this simple experiment demonstrates a principle, the real-world situation is likely to be more complicated due to competing effects, such as passivation of the metal surface and consumption of hydrogen by the mixed microbial population likely to be present.

Metabolites, such as hydrogen sulfide or thiosulfate, can act as poisons for the hydrogen recombination reaction and drive cathodic hydrogen into steel (Fig. 3). Sulfide can accelerate crack growth rates even at trace concentrations. Corrosion fatigue crack growth rates (per stress cycle) in RQT 701 steel exposed to seawater have been shown to increase with increasing levels of sulfide exposure in either biotic or abiotic environments (Ref 45). It has also been noted that hydrogen permeation through steel under CP in artificial seawater was greater for a mixed culture of bacteria producing 160 ppm of sulfide than it was for the same concentration of sulfide without bacteria. Attempts to demonstrate these effects more generally led to the conclusion that the microbial scenarios may involve inhibition of hydrogen permeation and crack growth as well as enhancement. Complex lab results have been reported on the enhanced permeation of hydrogen through carbon steel exposed to cultures of SRB isolated from oilfield waters (Ref 46). It was suggested that an initial enhancement in hydrogen flux caused by the bacteria was stifled for a time by formation of a protective iron sulfide (mackinawite) on the steel surface. Accelerated hydrogen permeation was later reestablished, an effect that the researchers attributed to production of additional sulfide and organic acids by the organisms disrupting the protective film.

In addition to corrosion and hydrogen effects, the buildup of certain microbial metabolites in an environment may also foster crack growth by EAC. One example is the production of high levels of CO_2 needed to sustain near-neutral pH SCC (Ref 42). This CO_2 may arise in SCC sites on buried pipelines through biological activity in the surrounding environment or be formed more directly by biodegradation of susceptible components in protective coatings or other materials used in construction of a facility (Ref 21).

Metabolic intermediates in the microbial oxidation and reduction of sulfur can also cause trouble (Ref 35). Metastable sulfur oxyanions (e.g., thiosulfate and tetrathionate) can promote severe intergranular stress-corrosion cracking (IGSCC) of sensitized austenitic stainless steels and nickel-base Inconel alloys at very low concentrations in acidic to slightly acidic solution (Ref 41). As noted previously, metastable sulfur oxyanions can be produced by microbial activity or by secondary oxidation of biogenically produced iron sulfides. One suggested mechanism for their role in IGSCC involves disproportionation of the oxyanion to release elemental sulfur in the acidified crack tip. This would enhance anodic dissolution of chromium-depleted grain boundaries, enabling accelerated cracking. In this case, promotion of crack growth results from enhanced corrosion at the crack tip rather than a hydrogen embrittlement effect.

General souring of an operating environment through the biological formation of hydrogen sulfide is a serious concern in the oil and gas sector. Significant concentrations of hydrogen sulfide require production facilities to be constructed for "sour service" to avoid integrity problems. Souring of oil and gas reservoirs during prolonged production or of gas storage caverns over time can threaten production infrastructure designed to handle "sweet" sulfide-free crude oil or gas. Consequently, control of in situ souring has attracted considerable effort (Ref 47).

Degradation of Protective Systems

Microbiological influence on the integrity of metal systems need not involve direct mediation of corrosion or cracking processes. In some situations, microbiological activity predisposes metals to integrity problems through degradation of protective systems, including corrosion inhibitors, coatings, CP, or lubricants.

Corrosion inhibitors are chemicals introduced into industrial systems to reduce the rate of metal loss. In some cases, these chemicals act as nutrients for MIC problems and are destroyed through biodegradation. In a long-term audit of water recycle systems in a large oilfield, failure costs were found to be inversely related to the residual concentrations of treatment chemicals used to control corrosion, as one would hope. The chemical treatment package included a filming amine corrosion inhibitor and ammonium bisulfite as an oxygen scavenger. Closer inspection of the data, however, showed that the residual concentrations of the oxygen scavenger correlated with measured corrosion rates, indicating that the ammonium bisulfite was actually being used as a nutrient by the SRB responsible for the corrosion observed. The microbial population had to be independently controlled by targeted biocide addition (Ref 48). This problem of conflicting effects by different additives is a common issue in the design of cost-effective chemical treatment programs.

As environmental concerns push treatment chemical suppliers to less toxic, biodegradable materials (see Ref 49 for an example), competition between biocides intended to reduce microbial populations and corrosion inhibitors that may feed them will become more common.

Protective Coatings. Buried structures and interior surfaces of tanks and piping are often protected by the application of protective coatings. While these coatings have improved over the years, many older coatings were susceptible to biodegradation in service. Microbial attack can be seen, for example, in some polyvinyl chloride (PVC) coatings. While the polymer itself remains relatively inert due to its large molecular size, biological degradation of plasticizers used to make the material flexible can occur (Ref 50). Loss of plasticizer in older PVC tape coatings on pipelines has led to embrittlement and coating failure in service. In a related example, the adhesive used to affix polyethylene tape coatings to line pipe has been found to be a source of nutrients for microbial sulfate reduction in external corrosion sites (Ref 21). Biodegradation of adhesive may contribute to the loss of adhesion seen when these coatings are exposed to biologically active soils (Ref 51). Coating failures of this sort block CP and have led to corrosion and SCC problems on operating pipeline systems (Ref 22, 42).

The modern trend to more environmentally friendly, safer materials also affects the formulation of paints and coatings used to protect industrial systems. This has raised concern that these changes will coincidentally result in a loss of resistance to microbial degradation for products in service (Ref 52). A conflicting strategy of adding more biocides to new formulations has been proposed.

Cathodic Protection. Buried or submerged structures and some interior surfaces in processing facilities are protected by imposition of an electrical potential that prevents oxidation of metal. This can be achieved through the use of sacrificial anodes or by an impressed current system. In either case, maintenance of a protective potential requires the provision of an adequate current density. Production of iron sulfides by active SRB can compromise CP potentials by draining current from exposed steel surfaces. Figure 7 shows the increase in current demand in a laboratory soil box with time as SRB active in the soil produce increasing quantities of electrically conducting iron sulfides around steel coupons at a fixed potential. An increased current demand has also been seen for stainless steel surfaces when a steady-state biofilm is present (Ref 53) and in lab experiments involving an anaerobic slime-forming APB (*Vibrio natriegens*) in pure culture (Ref 54). In the latter case, production of organic acids and exopolymers by *V. natriegens* affected the formation of calcerous scales that would normally seal the cathodically protected surface, reducing current demand. In locations where increased current demand cannot be met, the protective potential is lost. In the field, affected locations may show up as a local dip in close-interval-potential surveys.

Lubricants protect metal components from corrosion and wear in service. In some cases, these lubricants contain biodegradable hydrocarbons that support microbial growth where water is available and other conditions permit. Microbial growth is, in turn, often accompanied by the production of surfactants that stabilize water/oil emulsions. These extend the interface available for microbial activity and can be quite stubborn to break. The combined effect of biodegradation and emulsification can compromise the performance of lubricants, leading to failure of metal components (Ref 55). A case study involving the failure of bearings in a marine engine is given in Ref 56. Commercial kits are available to track microbial growth in lubricants and identify impending problems in large marine engines as well as other applications.

Failure Analysis

Although MIC is acknowledged to occur on a wide range of metals, most reported failure analyses have focused on iron, copper, aluminum, and their alloys. This is not surprising, given the importance of these metals in industrial applications.

Steel and Iron

Industry Experience. Failure analysis for steel and iron can begin with an assessment of the susceptibility of an operating system to MIC, based on industry experience. It appears that almost any system with free water present can host microbial activity, provided there is a source of nutrients and an absence of toxic material. In processing facilities, an increase in pressure drop or loss of flow through piping systems (Fig. 8) or a marked decline in the efficiency of heat exchangers are indicators of possible biological fouling. A history of failures due to unexpectedly high corrosion penetration rates may indicate MIC. Favored locations for failures include low spots where water can collect in piping, dead-end or shut-in piping, tank bottoms at the interface between liquid hydrocarbons and underlying water, or areas heavily fouled with surface deposits (Fig. 9). Microbially induced corrosion problems are found in refineries, cooling water systems, sprinkler water systems, oilfield water-handling systems, oil pipelines, and pulp and paper mills but are not recognized as a major issue in steam systems (Ref 57).

For external corrosion, past experience of susceptible metal surfaces exposed to a wide range of natural environments has led to a general understanding of where corrosive conditions, including MIC, can be expected to occur (Ref 58, 59).

For soils, corrosion rates for steel and iron have been correlated with the pH, oxidation reduction potential, resistivity, and water content of the soil as well as with the type of soil. Very dry soils that lack the electrolyte needed to support active corrosion cells are benign. Moist, aerobic soils, where oxygen can readily reach exposed steel, show corrosion rates typically in the range of 0.04 to 0.2 mm/year (0.002 to 0.008 in./year). Anaerobic soil environments, where oxygen is absent and where SRB have not precipitated extensive iron sulfide deposits, show intermediate corrosion rates of 0.002 to 0.01 mm/year (0.00008 to 0.0004 in./year). Where the focused action of SRB has exposed unprotected steel to extensive iron sulfide deposits, very high corrosion rates, >0.2 mm/year (>0.008 in./year), can be seen.

Attempts have been made to identify factors in soil environments that favor MIC by SRB for

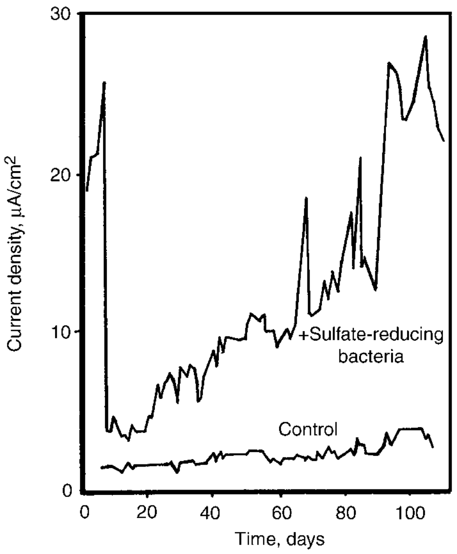

Fig. 7 Current demand needed to sustain a set CP potential increases with time for steel in soil as SRB produce increasing quantities of iron sulfide.

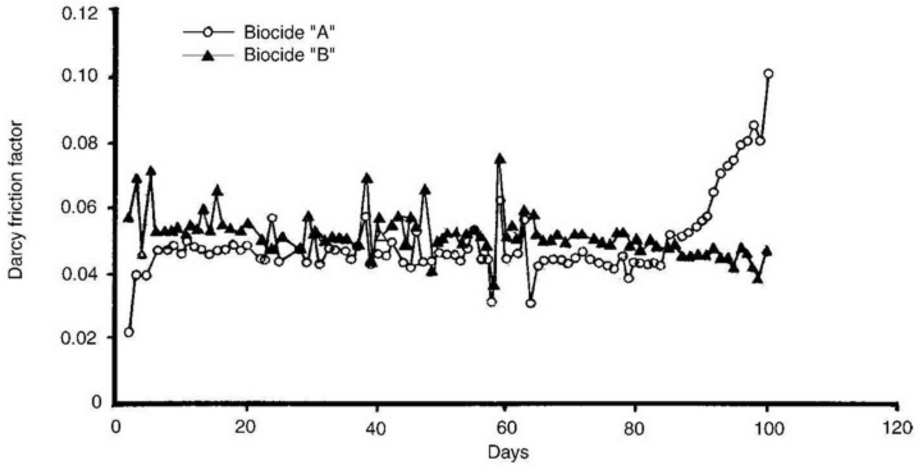

Fig. 8 Friction factors for flow through instrumented sidestreams under biocide treatment in an oilfield-produced water system can indicate biofouling. In this case, biocide "A" loses control of microbial fouling after 80 days, relative to biocide "B," in a comparison carried out in a field performance evaluation facility equipped with parallel test lines (see Fig. 14).

buried pipe (Ref 60, 61). Table 1 summarizes conditions that correlate with elevated SRB populations. Based on correlations of this sort, predictive models have been developed to prioritize maintenance activities in particular areas.

Anaerobic sediments in freshwater or marine environments generally host anaerobic microbial populations, including SRB that can create MIC problems. Guides have been developed at the University of Manchester Institute of Science and Technology to assess the potential risk of MIC due to SRB for sheet piling in sediments in ports and harbors and for design of CP systems on subsea pipelines (Ref 62).

Identification of MIC Sites. Possible MIC sites are often tentatively identified by the rapidity, severity, and localized nature of the corrosion. Confirmation is based on analysis of metallurgical damage, microorganisms, corrosion products, deposits, and environmental factors. There is no single approach to this problem, but a number of guides have been published (Ref 5, 7, 32, 33, 37, 63).

Guides for identification of internal and external MIC were developed through a major GRI program for natural gas pipelines. The guides provide a scorecard for the identification of MIC sites on mild steel, based on three types of evidence (Ref 32, 33):

- *Metallurgical:* appearance of the corrosion damage
- *Biological:* cell counts for SRB, APB, and general bacterial population
- *Chemical:* identification of corrosion products and other deposits

The metallurgical evidence is given the heaviest weighting, sufficient to pronounce MIC as being "very likely" in the absence of any other evidence from biological or chemical tests. Key features of the metallurgical fingerprint ascribed to MIC include corrosion pits composed of several smaller pits with hemispherical or cuplike appearance, striations in the direction of rolling in the steel pit bottom, and tunneling into the sides of the corrosion pit (Fig. 10). The guides provide appropriate photographs and methods for identification of these features. Biological analyses assess the number of viable SRB, APB, and anaerobic bacteria present. Chemical analysis of corrosion products has limited application in the scorecard and is more fully addressed later. Commercial kits have been developed for the analysis of the biological and chemical criteria used in the guides. Use of these tools is not confined to pipeline applications or soil environments. They are generally useful wherever the corrosion of carbon steel is observed (Ref 64).

A complementary approach to use of an MIC scorecard is based on the analysis of corrosion products and other deposits found on the corroded surface (Ref 20). This approach was developed for pipeline facilities suffering external corrosion (Ref 22). Qualitative chemical analysis can be done in the field to identify the presence of iron (II), iron (III), calcium, sulfide, and carbonate. Addition of acid to a sample can detect carbonate (by extensive bubble formation) and sulfide (by the odor of hydrogen sulfide or by its reaction with a color indicator such as lead acetate). Iron (II) and (III) can be detected in the resulting acid solution using standard ferricyanide and thiocyanate tests. Addition of a solution of oxalate to the test solution after buffering with excess sodium acetate yields a white precipitate if calcium is present. These qualitative chemical assays have been made available commercially in the form of a test kit through the GRI program noted previously. X-ray diffraction (XRD) analysis of crystalline material in corrosion products and associated deposits can provide more detailed insight (Ref 24). A summary of corrosion products indicating different corrosion scenarios is given in Table 2.

The presence of a hard, white, calcium carbonate scale is good evidence that effective CP potentials were achieved on metal surfaces where it is found. Identification of the very severe corrosion scenario due to iron sulfide corrosion cells developed by SRB can be made

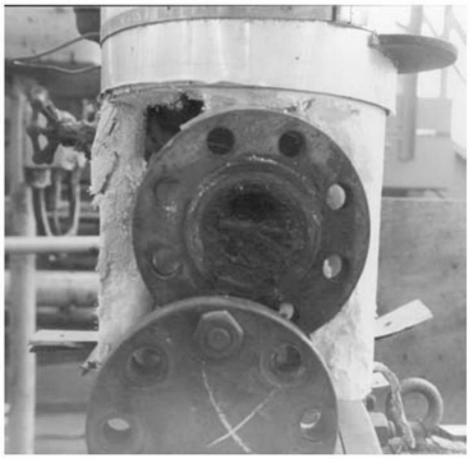

Fig. 9 Dead-end piping reveals extensive black deposits through an open flange in refinery piping.

Fig. 10 Microbially induced corrosion showing striations in the bottom and tunneling into the walls of overlapping pits, as described in Ref 32

Table 1 Factors correlating with sulfate-reducing bacteria (SRB) numbers for buried pipeline sites

Factor	Correlation coefficient	Range
Bacterial numbers (acid-producing bacteria)	0.829	$10^3 - 10^8$ cells/g wet soil
Total organic carbon in groundwater	0.645	0.05–1.2%
Soil resistivity	−0.642	500–30,000 Ω · cm
Soil water content	0.626	5–36%
Soil oxidation reduction potential	−0.545	−316 to 384 mV (CSE)
Sulfate in groundwater	0.455	0.3–200 mg/g wet soil
Clay	0.407	N/A

Note: CSE, copper-copper sulfate electrode. Source: Ref 60 based on analysis of corrosion products, as noted in Table 2. The observation of iron (II) sulfide in association with severe pitting or areas of significant metal loss in contact with dense, black corrosion products is definitive for this scenario. In some failure sites, extensive iron (II) sulfide present as a finely divided, black solid causes the general blackening of soil and corrosion deposits (Fig. 11). The additional presence of iron (III) suggests secondary oxidation has occurred, with potentially very serious corrosion consequences (Table 2) (Ref 24). In extreme cases, overlapping corrosion pits can lead to extensive areas of metal loss sufficient to cause pressurized piping or vessels to fail through rupture. This type of failure presents an inherently greater risk than formation of a leak due to perforation of the steel by isolated pitting.

Table 2 does not include corrosion scenarios due to APB. This possibility can be assessed using the methods described in the MIC field guides described previously or by analysis of deposits for organic acids.

A cryptic guide to the identification of corrosion in oil and gas operations offers two MIC scenarios (Ref 65). One, based on SRB, is identified by:

- Slope-walled pits within pits
- Attached SRB
- A source of sulfate

A second scenario, based on APB, is identified by:

- Steep-sided, sharp-edged, "fibery"-bottomed pits
- Attached APB
- Trace organic materials (presumably organic acids)

Reference 37 describes a wider range of tests and considerations for cooling water systems, and active and passive MIC scenarios are considered. In active scenarios, the organisms participate directly in corrosion processes. Microorganisms involved include SRB and acid producers. In this case, sulfur-oxidizing aerobic bacteria, such as *Thiobacilli,* that produce very acidic conditions and denitrifiers capable of reducing the pH to 3 are considered as well as the organic APB. Consideration of aerobic organisms is consistent with highly oxygenated environments found in cooling water circuits. Passive corrosion scenarios include underdeposit attack due to concentration cells set up under biofilms by slime-forming microbes or iron- and manganese-oxidizing bacteria (referred to as "metal depositors" by the researchers). Other organisms considered include algae that produce dense, thick mats of biomass on sunlit surfaces in cooling towers. These can foster underdeposit attack due to concentration cells and produce high levels of oxygen as well as nutrients for other organisms. In one case, ammonia released by the decay of algal biomass was blamed for SCC in a brass condenser.

The following four factors in the identification of corrosion as MIC were looked for (Ref 37):

- Presence of microorganisms or their byproducts
- Microbiologically unique corrosion morphology
- Specific corrosion products and deposits
- Compatible environmental conditions

The use of these factors for diagnosis of MIC scenarios in cooling water systems is addressed in Table 3.

Corrosion-Resistant Alloys of Steel

Microbially induced corrosion on stainless steel leads mostly to pitting or crevice corrosion failures. Statistical analysis of corrosion failures seen in once-through cooling systems on the Rhine River show that a disproportionate number occur in stainless steel systems relative to carbon steel. Estimates of MIC as a percent of total corrosion failures for stainless steel systems may be as high as 20% but are probably <10% (Ref 66).

Weldments in Stainless Steel. Most failures are associated with welds, because areas of joining tend to be inherently more susceptible to corrosive attack than the base material. Studies have shown that heat-tinted zones are especially vulnerable. These zones are created in a welding process where material above the scaling temperature is contacted by air. The result is a mi-

Table 2 Indicator minerals found as corrosion products in various corrosion scenarios seen in pipeline excavations and laboratory soil box tests

Corrosion scenario	Corrosion products (color, chemistry, mineral form)	Corrosion rate, mm/year
Simple corrosion processes		
Abiotic aerobic corrosion (O_2 is the electron acceptor, X, in cathodic reaction, Eq 2)	Yellow/orange/brown/black iron (III) oxides, including lepidocrosite, goethite, magnetite, maghemite, hematite	0.04–0.2
Abiotic anaerobic corrosion (H^+ as X in cathodic reaction, Eq 2)	Pasty or dispersed white iron (II) carbonate (siderite)	0.002–0.01
Anaerobic MIC (SRB with biotic iron sulfide as X, Eq 2)	Black, finely divided iron (II) sulfides, including amorphous iron sulfide, mackinawite, greigite	0.2 general 0.7 pitting
Secondary transformations involving MIC		
Aerobic → anaerobic MIC (SRB/"FeS")	Iron (II) sulfides, including marcasite and pyrite	. . .
Anaerobic MIC (SRB/"FeS") → aerobic	Elemental sulfur, iron (III) oxides + residual anaerobic corrosion products	2–5(a)

(a) This very high corrosion rate may not be sustained beyond the period of secondary oxidation of the anaerobic site.

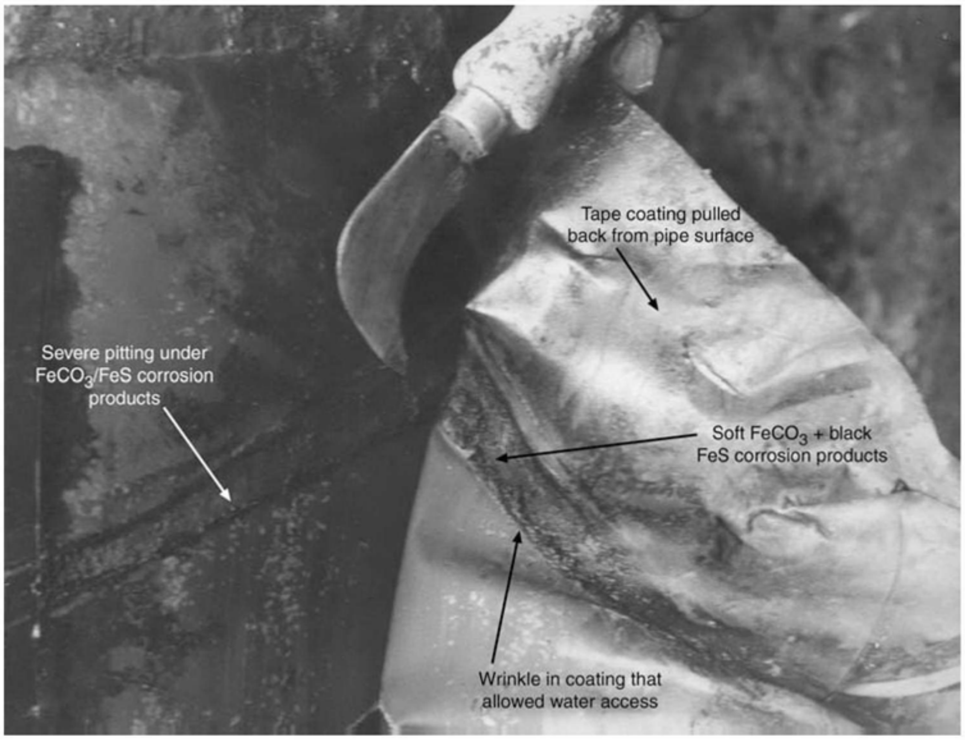

Fig. 11 FeS/SRB corrosion under disbonded polyolefin tape coating on a buried pipeline in a wet anaerobic location shows soft, black corrosion products rich in iron sulfides overlying severe pitting

gration of chromium into the surface scale, leaving underlying material depleted and susceptible to corrosion. Removing the heat-tinted scale and underlying surface by pickling, electrochemical cleaning, or mechanical grinding prevents corrosion damage with or without bacteria (Ref 67, 68) for 304L, 308L, or 316L material. It has been suggested that pickling is the most effective approach (Ref 69). Heat tinting can be avoided by use of an effective inert gas blanket in the welding procedure.

Microbially induced corrosion is perhaps the only mechanism that can perforate stainless steel piping in neutral aqueous service, such as river water cooling, in a matter of months (Ref 70). It is suggested that this may be due to the ratio of cathodic to anodic areas, where a single phase, for example, ferrite, is preferentially attacked relative to a large area of less susceptible material. Penetration rates of 17 mm/year (0.7 in./year) in United Numbering System (UNS) 30800 welds have been reported. Perforation of 316L stainless steel weldments in piping with 5.5 mm (0.2 in.) wall thickness in industrial water systems under intermittent flow in four months has been described (Ref 70).

Preferential attack of some sort is a common feature of MIC case studies (Ref 63, 70–73). Corrosion is often focused on the weld material or at the fusion line for the weld (Fig. 12a). Pit surfaces are often described as dendritic, consistent with preferential corrosion (Ref 63, 71–73), but the preferential attack of a single phase need not be a feature of MIC. From detailed study of UNS 30800 weld specimens, it has been concluded that either ferrite or austenite can be preferentially attacked, or they may corrode together, depending on a number of possible conditions (Ref 70). Abiotic attack by $FeCl_3$ solutions has been found to give similar effects to MIC, based on comparison of chemically degraded specimens with samples from identified MIC sites (Ref 70, 74). Preferential attack can also occur in a single phase, due to cold work effects on microstructure (Ref 70, 74).

As previously noted, microbially induced intergranular pitting and IGSCC can occur in sensitized stainless steels, where low chromium content at grain boundaries allows preferential dissolution (Ref 41). However, it has been found that transgranular pitting due to MIC in the heat-affected zone in socket-welded specimens of 304 stainless steel exposed to flowing lakewater (500 to 600 ppm chloride) over 6 to 18 months was not focused in sensitized areas (Ref 74). Instead, pitting occurred along deformation lines left by cold working of the metal during manufacturing. Annealing the material at 1150 °C (2100 °F) was suggested as a way to remove these features and increase resistance of the material to MIC. No pitting was seen in the base metal for either furnace-sensitized or girth-welded specimens of 304 or 316 stainless steel after similar exposure (Ref 74).

A number of trends seem apparent, based on past failure analyses:

- Microbially induced corrosion is often associated with stagnant, untreated water being left in piping over extended periods (Ref 63–72). It has been suggested that intermittent flow or low flow rates are most damaging (Ref 75).
- Damage often occurs at many welds in an affected section of piping. In one power plant cooling system using lake water, radiography indicated that 50% of the welds in 316L piping showed indications of deep MIC pitting (Ref 72).
- Pitting seems more prevalent in the bottom third of the pipe (Ref 63).
- Low pH or high chloride concentrations in the pit environment enhance attack (Ref 76).

It has been noted that higher alloying in weld combinations seems to improve resistance to MIC (Ref 76). This observation is supported by a systematic laboratory study of stainless steel (304, 316L, and 317L) and Ni-Cr-Mo (alloy 625) alloy weldments cleaned of surface thermal oxides (Ref 77); however, later work on as-received welds showed that thermal oxides produced during the welding process can obscure this dependence. In all cases, exposure of specimens to lake water augmented by active SRB reduced the polarization resistance of the alloys relative to sterile controls. This was true even for alloys with 9% Mo content; however, no documented corrosion failures due to MIC in alloys with 6% Mo or more could be found to support the idea

Table 3 Factors for the diagnosis of MIC scenarios in cooling water systems

Microorganism (metabolite)	Corrosion morphology	Specific corrosion products and deposits
Active MIC		
Sulfate-reducing bacteria (sulfide)	Clustered hemispherical pits on stainless steel, Carpenter 20, aluminum, carbon steel. Rare on titanium. Copper poorly defined Very irregular pit surface in less noble metals	Metal sulfides present Voluminous, brown, friable tubercles of iron (III) oxides over pit
Acid producers (lower-pH organic acids for acid-producing bacteria)(a)	Corrosion is localized, moderate Striations in steel under tubercles, as for preferential acid dissolution of microstructure in rolling direction	None stated
Passive MIC		
Slimers (gelatinous mass with high microbial numbers)	General corrosive attack under slime Pitting if SRB present	Rusting may color surfaces brown

(a) Acid producers are often associated with SRB but outnumber them in this case. Organisms such as *Clostridia, Thiobacillus,* and *Nitrobacter* are cited as potential acid producers. Source: Ref 37

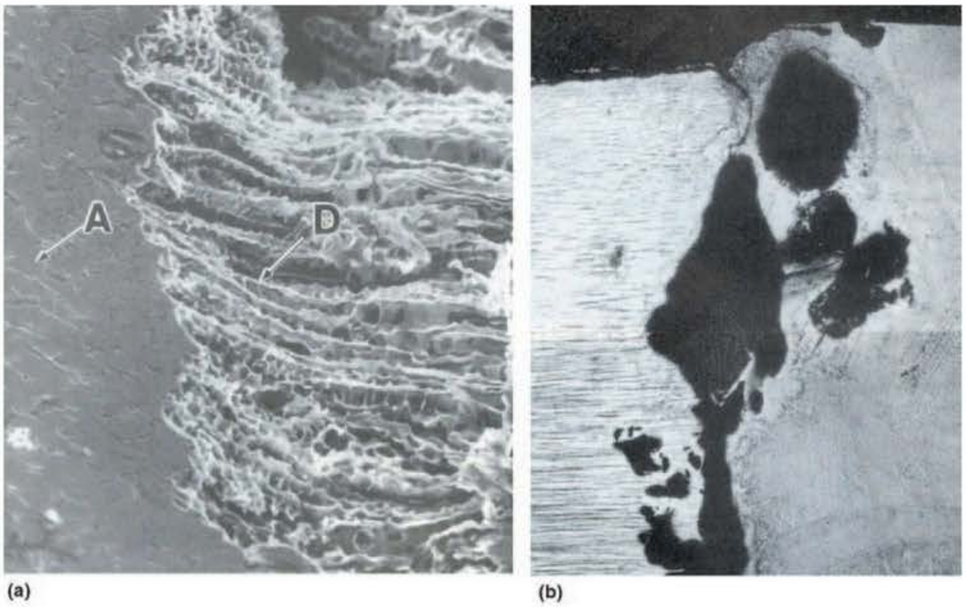

Fig. 12 MIC of stainless steel weldments. (a) MIC showing a surface view of interdendritic attack at the fusion line of a stainless steel weldment. "A," nondentritite; "D," dendrite. (b) Cross section of MIC at a stainless steel weldment showing extensive corrosion of weld metal and fusion line, with a relatively small opening at the bold surface. Source: Ref 71. Reproduced with permission of National Association of Corrosion Engineers International

that elevated molybdenum content can provide added resistance to corrosion damage (Ref 2).

It was recommended that failure analysis for stainless steel cooling systems include biological analysis of associated water and deposits, chemical analysis of water, and radiography of welds (Ref 63). Microbially induced corrosion in pitting at weldments in stainless steel was identified by (Ref 74):

- The combination of bacteria present and morphology of pits
- Corrosion features with small surface openings leading to bulbous cavities in the steel matrix at welds
- The absence of other agents that could account for the attack

While SRB in mixed populations are a favorite for laboratory studies, and sulfides are often found in associated deposits on affected metal surfaces in the field, the microbiology found in case studies tends to be complex. A wide range of organisms can be present, especially in cooling systems drawing on natural waters. All sorts of bacteria were found to be present in once-through cooling systems using untreated river water, including sulfur oxidizers, iron oxidizers, iron reducers, SRB, nitrogen oxidizers, and denitrifiers (Ref 66). Aerobes, anaerobes, SRB, and APB were reported to be present in slimes and nodules on the metal surface (Ref 74). The presence of iron oxidizers and slimers for MIC problems in UNS S30800 stainless steel welds has been cited (Ref 69), while *Gallionella* in characteristic MIC pits has been specifically identified (Ref 63). Enhanced numbers of manganese-oxidizing bacteria have been noted in deposits formed on corroded welds in 304L stainless steel specimens exposed to Lake of Constance water in lab studies (Ref 29).

Surface deposits in nine case studies (Ref 63, 66–68, 72) contained iron, silicon, and sulfur in >75% of the samples analyzed (Fig. 13). Manganese, chromium, and aluminum were also frequently found (>50% of samples), but more soluble ions, such as chloride and potassium, were detected in less than half the samples.

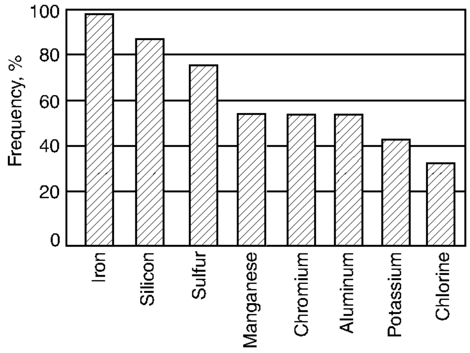

Fig. 13 Most commonly found elements in nine deposits from MIC sites in stainless steel cooling water systems (expressed as percent of deposits showing element). Source: Ref 63, 66, 71

At least two sorts of surface deposits were reported. Most of the surface of service water piping receiving lake water was covered by a tightly packed, black, slimy deposit that had a high content of manganese and iron, with trace sulfide, silicon, and aluminum present (Ref 72). No corrosion was reported under these deposits. Rust-colored deposits found in a small area (6.5 cm^2) at the weld were rich in chromium and iron, with sulfur, chlorine, aluminum, and silicon in smaller concentrations. This rust-colored deposit covered the opening of an extensive corrosion cavity in the underlying metal (Fig. 12b). This is a unique form of pitting associated with MIC in weldments in stainless steel. The cavity openings are often associated with rust-colored stains on the surface metal or with rust-colored deposits rich in iron and manganese (Ref 63, 66).

Radiography or destructive testing of field specimens reveals the large cavities to be a series of pits branching off one another to give a bulbous and irregular void volume sometimes associated with tunneling in the direction of rolling along stringers of ferrite or austenite (Ref 63, 74). This form of pitting is focused on weld metal or the fusion line, with wall perforation occurring through a second small opening on the opposite metal surface. The frequent observation of sulfide in associated surface deposits (Fig. 13) implies that SRB are commonly involved at some stage, but iron-oxidizing bacteria, particularly *Gallionella,* found in the pits have come to be associated with this corrosion morphology. *Gallionella* oxidize Fe^{2+} to Fe^{3+} in their metabolism, leading to the formation of characteristic rust-colored deposits. The acidity of the hydrated ferric ion produced decreases the pH of the local environment. Whether *Gallionella* initiate pitting or are attracted to the anodic area by the release of ferrous ions through a previously existing anaerobic corrosion process is not clear. The latter seems more likely. Once iron-oxidizing organisms are established, reduction in the pH of the corrosion pit and concentration cells established by the buildup of iron (III) oxide deposits help to drive the corrosion process.

Literature reports identify several possible MIC scenarios on stainless steel weldments. Table 4 summarizes the organisms and features that may be useful in failure analysis.

Stainless Steels. Corrosion-resistant alloys can suffer MIC failures in the body of the material not associated with welds. Numerous reports of pitting and crevice corrosion due to MIC have been noted for austenitic (304, 304L, and 316L) stainless steels (Ref 2).

Microbially induced corrosion has been described in underdeposit corrosion in heat exchangers cooled with lake water in tubes made of American Iron and Steel Institute (AISI) type 304L stainless steel and nickel alloys (UNS N08800, N08025, and N08028) (Ref 78). Pitting was found under calcite (calcium carbonate) deposits after one year for N08800 and 304L, while deep pits were found after three years for molybdenum-containing alloys N08025 and N08028. Failure analysis found that microorganisms played a key role in the degradation process. Anaerobic methanogens promoted deposition of calcium carbonate, setting the stage for crevice corrosion. Oxygen introduced with flow on startup then oxidized biogenic sulfides produced by SRB during periods of stagnation, when anaerobic conditions prevailed. Formation of thiosulfate through oxidation stabilized metastable pitting in the affected alloys, promoting corrosion even at low chloride levels. It has been suggested that the same mechanism was responsible for perforation of 316 stainless steel weldments (Ref 71).

Elemental mapping of deposits in and around the pits that formed under the calcite deposits showed:

- High levels of nickel, iron, and sulfur around the pit
- Chromium as the major metal component in the pit
- Chlorine at low levels or not at all

The calcite scale overlying corrosion stains on the metal surface was etched and contained enhanced levels of iron, nickel, and chromium derived from the corrosion process (Ref 78).

An example of MIC in martensitic stainless steel under severe service conditions has been described (Ref 79). Rapid corrosion under a thick, slimy, jellylike deposit on stainless steel (UNS S40300) drive chain systems in clarifiers in a wastewater treatment plant led to 40% metal loss in the first year of operation. The steel had

Table 4 MIC scenarios that may play a role in the corrosion of weldments in stainless steel

MIC by	Mechanism	Indicators	Ref
Manganese oxidizers	Ennoblement of stainless steel potential due to MnO_2	Elevated manganese-oxidizing organisms, manganese, and possibly chloride in deposits	29, 30
SRB primary	Sulfides, SRB facilitate chloride attack in anaerobic systems	Dark-colored corrosion products, with iron sulfide, chloride, and a high ratio of Fe^{2+}/Fe^{3+}; near-neutral pH	71
SRB secondary oxidation	Pitting stabilized by thiosulfate formed by oxidation of sulfides	Cyclic anaerobic, aerobic conditions; surface of corrosion products in pit oxidized red, orange, or brown	71
Iron-oxidizing bacteria	Decrease of pH by oxidation of Fe^{2+} to Fe^{3+} in pits	Red/orange corrosion products rich in Fe^{3+}; iron-oxidizing organisms such as *Gallionella;* pH acidic	63

SRB, sulfate-reducing bacteria

been tempered for wear resistance at the cost of reduced corrosion resistance. Components made of 304L substituted into service in the unit corroded at half the rate of 403 but were subject to unacceptable levels of wear. The gray outer layer of the slime was rich in silicon and oxygen, with carbon, sulfur, and chlorine present in decreasing amounts. The dark-black inner layer showed major amounts of sulfur, chromium, and oxygen. Sulfate-reducing bacteria, APB, slime formers, and pseudomonads were all identified in samples of water and slime. High levels of biogenic hydrogen sulfide were generally present in the water phase, but the atmosphere over the fluid in the clarifiers was aerobic. This led to proliferation of sulfide- and sulfur-oxidizing organisms (*Thiothrix* and *Beggiatoa*) at the interface, producing very acidic local conditions for exposed components of the chain system. The high chloride content of the wastewater (up to 200 ppm) was also an issue. Given the extreme operating environment created, in part, by microbial activity, finding materials able to offer a reasonable service life at an acceptable cost remains a challenge.

Copper and Its Alloys

Copper is widely used in a variety of applications, because it is relatively low-cost, strong, and corrosion resistant. In addition, it conducts heat and electricity well and is readily formed, machined, and joined. Copper and brasses (copper and zinc alloys) are used, for example, in electrical wiring, water piping, architectural applications, heat exchangers, condensers, bearings, and valves, while bronzes (silicon, tin, and aluminum-amended copper) are used in bearings, impellers, pumps, screens, and special-purpose tubing. Cupronickel alloys are used in heat exchanger tubing and ships.

Copper is more-or-less susceptible to MIC in all its forms; however, copper-base alloys do show significant resistance to biofouling (Ref 80). Copper-nickel alloys, in particular, are used in marine applications, because of their resistance to both fouling and corrosion. Resistance to biofouling appears to be based on the slow release of toxic copper ions.

Elevated production of slime by microbial biofilms that develop on copper and its alloys suggests that EPS acts as a binding agent for copper ions that would otherwise inhibit microbial growth (Ref 81). The EPS exopolymers tend to be acidic and contain functional groups that bind metal ions. This capability has been linked to the formation of copper concentration cells under biofilms, the transport of metal ions away from the corroding surface, and variations in potential on the underlying surface (Ref 82). Incorporation of EPS in the oxide surface film that normally protects copper and its alloys from corrosive attack is a key reason for the occurrence of MIC in potable water systems (Ref 38). While EPS may bind the metal ions released by corrosion, it also allows an influx of mobile anions to balance the buildup of positive charge at the corroding surface. Chloride and other aggressive anions can be concentrated under biofilms, leading to disruption of passive films that would otherwise protect the metal surface.

Concentration cells set up under biofilms and production of corrosive metabolites, such as reduced pH, organic acids, and anaerobic sulfide, can lead to corrosion of copper and copper alloys. Copper is susceptible to pitting, especially in acidic media where oxidants are present. In alkaline media, production of ammonia or ammonium salts can promote SCC.

Sulfide production by SRB is one of the most potent MIC scenarios. Sulfate-reducing bacteria can become established during long periods of stagnation or in periods of intermittent flow in water systems (Ref 75). Copper sulfides deposited in the protective film by bacterial activity are rapidly oxidized when a flow of oxygenated water is introduced into the system, resulting in exposure and corrosion of the underlying metal. Failure analysis can be based on identification of specific copper sulfides formed as corrosion products. These include digenite (Cu_9S_5), spionkopite ($Cu_{39}S_{28}$), chalcocite (Cu_2S), and covellite (CuS). It is thought that digenite, formed initially, undergoes subsequent transformation to chalcocite, the most characteristic corrosion product for sulfate-reducing bacteria MIC scenarios (Ref 80). Djurleite ($Cu_{1.96}S$) formed in a SRB scenario may deposit as a passivating film, but this is likely to lack the mechanical stability needed to provide lasting protection to the metal surface in most industrial situations (Ref 2). The biogenic origin of the sulfide in MIC scenarios on copper has been supported by stable isotope analysis showing enrichment of ^{32}S in the corrosion products relative to the sulfate present in solution (Ref 35).

Pitting morphology can also provide a key to the identification of MIC in failure analysis. Two forms of pitting have been identified with MIC in potable water systems (Ref 80). One of these has been dubbed "pepper-pot pitting." In this form of damage, a conical cap of gray corrosion products (copper sulfate and cupric oxide) overlies a cluster of pits. Sulfides are present in some pits, and biofilms rich in EPS are invariably seen. In the second morphology identified with MIC, hemispherical pits are filled with crystalline cuprous oxide, with chloride often present at the metal surface. A tubercle over these pits is composed of pale-green basic copper sulfate carbonate ($Cu(OH)_x(SO4)_y$) and blue $Cu(OH)_2 \cdot CaCO_3$. Tubercles are covered by an outer layer of black cupric oxide, in some cases. Biofilm materials are seen associated with the original metal surface and with the tubercle.

Example 1: MIC of Brass Piping. A failure of buried brass (92% Cu, 8% Zn) piping used to carry drinking water in wet clay soil after less than two years service was attributed to MIC (Ref 83). Excavation showed the presence of soil blackened by deposition of sulfides and high numbers of SRB around the pipe. The external pipe surface showed a loss of zinc consistent with selective leaching of this metal from the alloy, and the groundwater contained appreciable levels of chloride that may have assisted in the breakdown of the passivating film protecting the metal surface.

A comparison was done of the corrosion failure of power station condenser tubing cooled by seawater for two copper alloys, an aluminum brass alloyed with arsenic (UNS C68700, ASTM B111, or CuZn20Al Deutsche Industrie-Normen (DIN) 17660), and a cupronickel 70-30 alloy with iron added (C71500, ASTM B111, or CuNi30Fe DIN17665) (Ref 84). Both kinds of tube had identical dimensions and had seen similar service, with failure occurring by perforation from internal pitting under sediment deposits. The presence of $Cu_{2-x}S$ in the corrosion products implicated MIC by SRB as the cause of failure, but this occurred more rapidly in the cupronickel alloy. The copper sulfide was close to stoichiometric Cu_2S on the aluminum brass but enriched in sulfur on the cupronickel tube. In the latter, large spherical pits were seen, with perforation taking the form of large, round holes. In the aluminum brass, big elliptic pits were seen, with small holes perforating the tube wall. These differences were attributed to differences in the pitting mechanism for the two alloys.

Alloy Cu-10%Ni (UNS C70600) is used extensively for condenser tubing in seawater applications, because it offers good corrosion resistance at reasonable cost. In polluted, brackish waters, however, severe localized corrosion has led to failures within three years of service. An investigation of MIC in these systems used online monitoring techniques and found elevated numbers of SRB in both the water phase (10^7 cells mL^{-1}) and in a surface biofilm (10^5 cells mL^{-1}) (Ref 85). A chlorination treatment intended to control the microbial problem destabilized the protective oxide film on the metal surface and made matters worse.

Example 2: SCC of Admiralty Brass Condenser Tubes. Microbes initiated SCC failures in admiralty brass condenser tubes in a nuclear plant cooled by freshwater (Ref 86). About 2500 tubes had to be replaced over a span of six years' operation. Analyses were carried out for microorganisms, water chemistry (for both intake and outfall), and corrosion products in the operating system and on test coupons exposed to the operating environment. Nitrate-reducing bacteria from the lakewater used in cooling were found to produce high levels of ammonia (5.8 mg/L) when established in biofilms. Ammonia levels at the metal surface were 300 times higher than background levels in the lake water. Copper amine complexes were identified in the surface deposits, and nitrate and oxygen in the incoming water were considered as accelerating factors for the cracking process.

Aluminum and Its Alloys

Aluminum is the third most abundant metal in the crust of the earth and second only to iron in

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Ex. II - 29

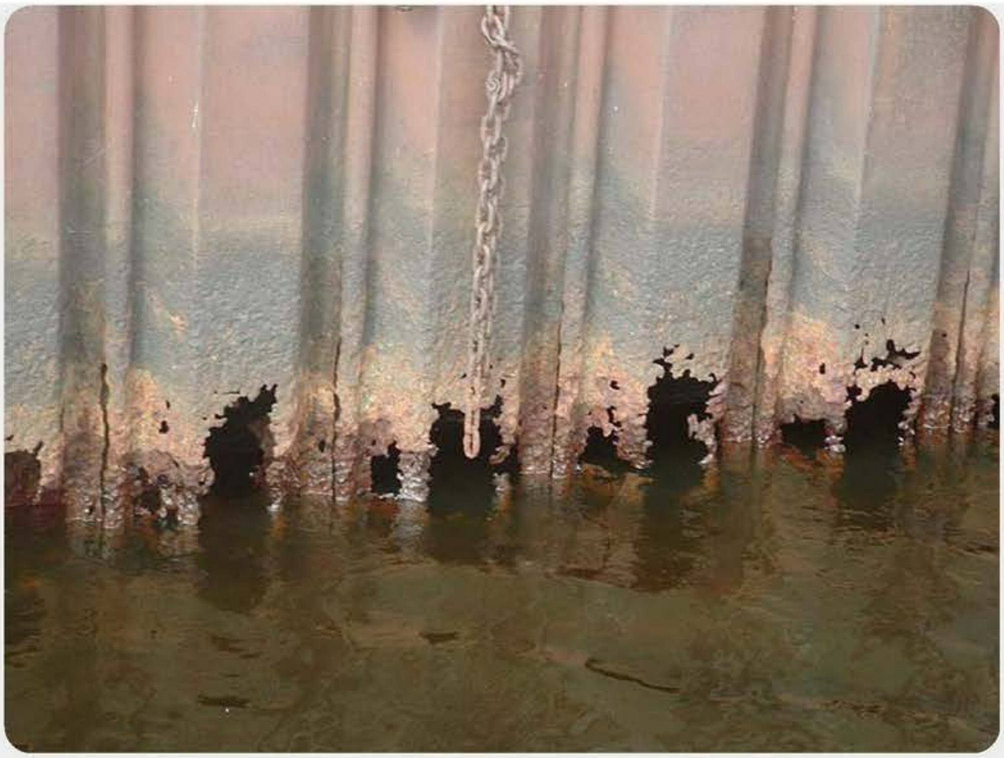
MP MATERIALS PERFORMANCE

Home / A Closer Look at Microbiologically Influenced Corrosion

Materials Selection & Design Chemical Treatment

A Closer Look at Microbiologically Influenced Corrosion

By *Kathy Riggs Larsen* on 7/29/2015 2:11 PM



MIC of pilings in the Duluth Superior Harbor in Duluth, Minnesota. Photo courtesy of Gene Clark, University of Wisconsin Sea Grant Institute.

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Microbiologically influenced corrosion (MIC) refers to corrosion caused by the presence and activities of microorganisms—microalgae, bacteria, and fungi. While microorganisms do not produce unique types of corrosion, they can accelerate corrosion reactions or shift corrosion mechanisms. Microbial action has been identified as a contributor to rapid corrosion of metals and alloys exposed to soils; seawater, distilled water, and freshwater; crude oil, hydrocarbon fuels, and process chemicals; and sewage. Many industries and infrastructure are affected by MIC, including oil production, power generation, transportation, and water and waste water.[1]

To better understand MIC and the corrosion threats it poses to pipelines, vessels, and structures, *Materials Performance* asked several NACE International members and others from industry, government, and academia to comment on the impact of MIC and challenges faced when identifying and mitigating MIC. Panelists are Richard Eckert and Torben Lund Skovhus with Det Norske Veritas (DNV); Gary Jenneman with ConocoPhillips; Sylvie Le Borgne with the Metropolitan Autonomous University at Mexico City; and Jason S. Lee and Brenda J. Little, FNACE, with the U.S. Naval Research Laboratory. (See their biographies in the sidebar, "Meet the Panelists.")

MP: How does MIC impact structures, vessels, and pipelines?

Le Borgne: The first reports of MIC are from the nineteenth century. Most of the studies have been in relation to metallic materials. However, other materials such as concrete, plastics, and new materials or coatings increasingly used nowadays should be included. MIC affects a variety of structures, vessels, and pipelines by directly or indirectly influencing the overall corrosion process, and is usually estimated to account for 20% of the total cost of corrosion. Due to the complexity of systems involving microorganisms, it is generally difficult to precisely quantify the influence of MIC to the overall corrosion process.

Microbial ecology studies have clearly demonstrated that microbes can survive and be active in a wide variety of environments including many man-made structures and environments. Systems where MIC is especially important include hydrocarbon and fuel (gas and liquid) transmission and storage systems, as well as hazardous materials transport and storage structures. These systems provide adequate environmental conditions and substrates for microbial development, and the participation of microorganisms in corrosion has been clearly demonstrated and MIC failures documented. Utilities such as drinking water and sewer systems also provide adequate conditions for MIC development. However in such systems, MIC has often been underestimated, as has been corrosion in general.

Eckert and Skovhus: MIC typically manifests itself as localized (i.e., pitting) corrosion—with wide variation in rate, including rapid metal loss rates—both internally and externally on pipelines, vessels, tanks, and other fluid handling equipment. Despite advances in the understanding of MIC, it remains difficult to accurately predict where MIC will occur and estimate the rate of degradation. MIC can occur as an independent corrosion mechanism or in conjunction with other corrosion mechanisms. These characteristics present challenges to implementing effective corrosion management of engineered systems in which MIC is an applicable threat.

Jenneman: Although the techniques to identify MIC are nonstandard and subject to interpretation, the places where we suspect MIC to occur experience rapid pitting, usually at interfaces where solids such as scale, wax, and or other solids can settle out or precipitate. Areas downstream of welds, where cleaning pigs have difficulty removing deposits, as well as dead legs, low-velocity areas, and tank bottoms where solids and bacteria/biofilms can accumulate, are particularly susceptible to attack. Often this pitting is very isolated, with one hole surrounded by a number of shallower pits. Pitting rates range from a few mpy to >250 mpy.

Lee: MIC in itself is not a unique corrosion mechanism; rather it produces conditions that increase the susceptibility of materials to corrosion processes such as pitting, embrittlement, and under deposit corrosion (UDC). MIC can result in orders of magnitude increases in corrosion rates. The most devastating issue regarding MIC is its general lack of predictability—both spatially and temporally.

Little: In almost all cases MIC produces localized attack that reduces strength and/or results in loss of containment.

MP: What are the current techniques used to identify MIC?

Le Borgne: Current techniques to identify MIC after it has occurred or when it is suspected are based on detecting and identifying the (causative/present) microorganisms; examining the damaged material (pit morphologies), and analyzing the corrosion products in search of biogenic structures. Concerning the detection and identification of microorganisms, the traditionally used techniques generally involve culture techniques with already prepared media tests kits to detect the growth of specific microorganisms known to participate in MIC in specific environments, such as sulfate-reducing bacteria (SRB), acid-producing bacteria, nitrate-reducing bacteria, or iron-reducing bacteria.

These kits are relatively easy to use although they need some basic laboratory expertise; the samples are inoculated directly in the field immediately after the sample has been collected. These kits also have the advantage of detecting only active bacteria, even in very low numbers. However, these kits can be rather unspecific and allow the growth of other types of microorganisms. Some years ago, genetic techniques had been proposed to allow a better detection and identification of microorganisms in MIC. These techniques need special expertise. Careful sampling is needed to avoid contaminations as these techniques are extremely sensitive and the samples must be transported and stored under special conditions to avoid degradation of the nucleic acids.

Following total DNA extraction from the samples, the total content and identity of virtually all the microorganisms present can be determined by different methods, from genetic fingerprints to pyrosequencing. When DNA is the starting material for these analyses, all the microorganisms, whether dead or alive, are detected. It cannot be determined which microorganisms were metabolically active when the sample was taken. RNA extraction from environmental samples is very challenging and is not a routine technique.

Lee: Advancements in molecular microbiology provide numerous methods to determine which ones are there, how many there are, and what they are doing. Metallurgical sectioning and microscopy provide information about material composition, corrosion morphology, and spatial relationships between microorganisms and sites of corrosion. Multiple techniques are used to determine the electrochemical properties of materials exposed to biologically active media. Surface science and crystallography provide the chemical and structural identity of corrosion products.

Jenneman: It is recommended when trying to justify MIC as a contributing or root cause of corrosion that the following lines of evidence be examined:

1. Biological: In this case we will chemically characterize the water for essential microbiological nutrients (e.g., organics, nitrogen, phosphorus) and perform microbiological testing, if possible, to determine if the environment can support growth and activity. We will use culture-based and molecular methods to determine the types/numbers of microorganism present if good samples are available. Other physical properties (temperature, pH, ionic strength) of the environment will also be checked and evaluated.

2. Chemical: In this case we work with corrosion engineers who will look at water chemistry, gas analyses, corrosion models, etc. to determine if abiotic mechanisms such as carbon dioxide (CO_2) corrosion can explain the corrosion.

3. Metallurgical: In this case both microbiologists and corrosion engineers will examine corrosion products (using x-ray fluorescence [XRF] and x-ray diffraction [XRD]) and pit locations/morphology, as well as determine maximum pit depth using surface profilometry to determine if parameters are consistent with MIC and/or other mechanisms

4. Operational: Many operational conditions and changes can influence the likelihood for MIC, e.g., low-velocity/stagnant conditions, pigging frequency, types of pigs, biocide usage, rapid failures, changes in temperature, introduction of oxygen, and upward trending of bacteria. All of these available lines of evidence and facts are then weighed to determine if MIC is the root cause or a contributing factor.

Eckert and Skovhus: MIC is identified by evaluating the physical conditions, chemical composition, microbiology, and metallurgy of the susceptible component or system. The integration of this data is what ultimately determines the extent to which MIC may be contributing to the observed corrosion. Therefore, the techniques used to identify MIC are varied and cross-disciplinary and require expertise in materials, corrosion, microbiology, chemical treatment, and asset operations. Although microbiological conditions are only one piece of the MIC puzzle, the counting of viable bacteria has historically received the most emphasis. Serial dilution using liquid culture media, despite its limitations, has been the predominant method used to identify viable bacteria.

The type (formulation) of the culture medium and incubation temperature determines the numbers and types of microorganisms that will grow. Since no culture medium can approximate the complexity of a natural environment, liquid culture provides favorable growth conditions for only about 1 to 10% of the natural microbiological population under ideal circumstances. Further, some microorganisms are incapable of growth in typical liquid media (e.g. some Archaea). While these factors bias culture-based results, serial dilution results are still useful for monitoring general trends of growth in some systems.

Molecular microbiological methods (MMM), long used in health care and forensics, have gained popularity in the analysis of microbiological corrosion and are now included in a number of NACE standards and publications, including TM0194-2004,[2] 3T199, [3] TM0212-2012, [4] and the forthcoming revision of TM0106-2006.[5] MMM require only a small amount of sample (liquid, biofilm, solid) with or without live microorganisms. After genetic materials are extracted from the sample, assays are specific and render a more accurate quantification of various types of microorganisms than culture tests. Molecular techniques that are finding increased use include quantitative polymerase chain reaction (qPCR), denaturing gradient gel electrophoresis (DGGE), and fluorescent in situ hybridization (FISH).

Little: Despite the limitations of liquid/solid culture techniques, it is my opinion that most industries use some form of culture to establish a most probable number (MPN) of viable organisms. Relating MPN to the likelihood of MIC is a questionable practice that can only be reliable in limited applications. NACE TM0212-2012 describes microscopic analyses, chemical assays, and molecular methods for evaluating MIC. Most of the research in MIC testing is related to molecular techniques that identify and quantify microorganisms. It is not clear that molecular techniques have provided a more accurate tool for predicting the likelihood of MIC. These techniques may provide a tool for assessing mitigation strategies. Microorganisms do produce mineralogical fingerprints that can be used to identify MIC. In many cases, MIC is assumed when there is no obvious cause of corrosion.

MP: What are the challenges faced when establishing MIC as the probable cause of corrosion?

Eckert and Skovhus: Since microorganisms are ubiquitous, and some are capable of life in even the most extreme environments, the greatest challenge is determining the degree to which MIC contributes to corrosion in conjunction with other relevant corrosion mechanisms. For example, biofilms that increase MIC susceptibility in pipelines often occur where the fluid velocity is continuously low enough to promote water accumulation and solid particle deposition. Deposit or sediment buildup may also allow UDC mechanisms, such as concentration cells, to occur.

Distinguishing the relative contributions of the biofilm and concentration cells, for example, may be difficult depending on the information available to the investigator. The second challenge is effectively collecting and integrating corrosion, microbiological, chemical, operational, design, mitigation, and metallurgical data to determine the predominant corrosion mechanisms that are present. Corrosion threat assessment for MIC should be conducted in view of all other applicable corrosion mechanisms for the asset. Identifying the predominant corrosion mechanisms supports the establishment of mitigation measures that are likely to have the greatest benefit.

Finally, establishing MIC as the probable cause of corrosion in a failed component may be particularly difficult since the failure event itself is likely to have altered the conditions that caused the corrosion damage. Careful sample preservation and field sample collection from representative undamaged areas can aid in forensic corrosion investigations. The identification of MIC as a damage mechanism should not be based solely on the presence, number, or type of microorganisms on a corroded component.

Lee: MIC is a very subtle study. Rarely can a case of suspected MIC be confirmed without evidence from multiple analysis techniques and sciences. The presence of microbes alone does not prove the existence of MIC. Microorganisms exist throughout the environment. The greatest challenge is proving that microorganisms actually influenced the electrochemical properties of the system. In addition, higher numbers of microorganisms does not necessarily mean increased likelihood of MIC. Molecular techniques are required to detect the individual activities of each microbe species. A system baseline of normal operating conditions, where predictable corrosion occurs (e.g. uniform corrosion of carbon steel [CS] in freshwater), is required for comparison with suspected MIC cases.

Jenneman: There are really no definitive tests or accepted standardized methodologies that can be applied to directly implicate MIC as the probable cause. It is often determined through a process of deduction of the facts and elimination of other mechanisms. Therefore a challenge is to develop standardized tests and approaches that can be widely accepted by the industry. However, MIC is a complex problem involving various aspects of materials science, electrochemistry, and microbiology that necessitates the involvement of scientists and engineers from various disciplines to take on this challenge. Also, the potentially large number of microbial types and activities involved challenges us to develop better mechanistic understandings of how these microorganisms and activities influence corrosion processes.

Little: MIC does not produce a unique corrosion morphology, making it impossible to identify MIC without specific testing.

Le Borgne: Challenges include the nature of the collected samples and whether they are from biofilms or bulk water. Only microorganisms in biofilms influence the corrosion process, although these microorganisms proceed from the surrounding bulk liquid phase. The number of corrosive or potentially corrosive microorganisms detected in the bulk water is not related to the intensity of the attack. Live microorganisms may not be detected in the samples, but dead organisms that participated in the attack or influenced the corrosion process are present on the surface of the material and in the corrosion products.

The microorganisms may act as consortia and not as isolated organisms, which may complicate the diagnosis and interpretation of the data. Different techniques are available for studying and diagnosing MIC. These analyses are generally performed in parallel and a multidisciplinary approach is necessary and might not always be easy to manage. There must be a link between the microbiological studies, the pit morphologies, and the composition of the corrosion products in order to clearly establish MIC as a corrosion mechanism, which may contribute from 0 to 100% in a corrosion process.

MP: Are current identification technologies adequate or is additional research necessary to develop more effective methods to identify MIC?

Little: The identification tools that can be used to determine that MIC has taken place appear to be adequate. There are recent refinements in sample preparation and fixation for more accurate molecular analyses. However, there are few tools/technologies for predicting MIC before it occurs.

Eckert and Skovhus: Current technologies, when used in combination with each other, can usually provide adequate information to assess and characterize MIC. Since MIC must typically be diagnosed using a combination of data (chemical, microbiological, metallurgical, operational, etc.), no single technology or tool can reliably identify MIC in all cases. Many operators have used extended coupon analysis to collect chemical, microbiological, and corrosion data from one sample point with much success.

The integration of results from MMM with other corrosion information is one area where additional research is needed to take advantage of the vast amount of information provided by genetic technologies. Researchers and asset owners are both continuing to find new insights resulting from collaboration between corrosion/materials professionals and microbiologists. Distinguishing the effect of MIC in combination with other abiotic external corrosion mechanisms on buried metallic structures and the influence of cathodic protection (CP) potentials more negative than -850 mV are other areas that deserve further attention and additional research—the pipeline industry would benefit from additional engineering guidance in this area.

Lee: Additional research is needed in development of a link between biological activity and corrosion rate. Real-time monitoring of corrosion rate and microbiology currently is not available. Lab-on-chip devices being developed are promising for use in microbiological monitoring programs, but academic disagreements still exist on which microbial markers are most important. Corrosion sensors have also become more sophisticated, but still lack the ability to be used in prediction of long-term corrosion susceptibility.

Le Borgne: Many identification technologies are available to provide a complete description of systems where MIC might have occurred. Some of these techniques require specific expertise and do not give an immediate response. However, more research is required in order to develop portable devices or online/remote sensors to detect MIC. The development of international standards and actualized protocols and programs that take the peculiarities of each system into account and allow the determination of risk factors is also needed to prevent MIC before it occurs in different facilities.

Jenneman: Better methods are definitely required to identify MIC. The traditional culture testing is very slow and does not give a very complete picture of the microbial communities involved in the corrosion. The newer molecular methods (e.g., DGGE, qPCR, and metagenomic sequencing) are gaining more widespread use and may eventually replace culture testing as costs decrease and availability of these technologies to oilfield end users increases. They do have the advantage of providing a faster and more complete picture of the microbial communities, but they currently require highly skilled professionals to perform the testing and interpret the results.

There are currently no accepted standards by which these tests are performed and no accepted models to help the end user interpret the results. These tests are typically outsourced to specialized laboratories and require the end user to understand the potential pitfalls of sampling, preservation, procedural nuances, and interpretation of results. There are currently industry-sponsored programs aimed at applying genomic technologies to better understand and identify MIC.

MP: When MIC is established as the corrosion mechanism, what are the mitigation and monitoring strategies typically used? Are these strategies effective?

Eckert and Skovhus: Common strategies for internal MIC mitigation in oil and gas pipelines include maintenance pigging and chemical treatment. Depending upon the pigging frequency and pig design, maintenance pigging can be effective in removing deposits/biofilm that promote MIC. A further benefit of removing deposits is increasing the effectiveness of chemical treatment by allowing the chemical to reach the exposed metal surface. Chemical treatment is typically performed using corrosion inhibitors (some with the added benefit of a biocidal tendency), biocides, and combinations of these chemicals. External MIC on buried structures and pipelines is more challenging to diagnose and mitigate properly, since nearly all soils are naturally rich with microbiological activity.

Furthermore, CP and an external coating are essentially the only mitigation options for external corrosion (including MIC) on direct buried pipe. Pipeline industry guidelines often call for applied potentials more negative than -850 mV when MIC is suspected; however, additional research is needed in this area to validate the effectiveness of more negative potentials in consideration of other parameters that influence external corrosion of buried structures. Regardless of the type of system, monitoring the effectiveness of MIC mitigation measures must include corrosion monitoring in addition to any microbiological monitoring that is performed, since ultimately the goal of mitigation is to control corrosion. Often MIC mitigation programs are focused on measuring microbial numbers, types or activity, which can be helpful in optimizing mitigation but is not a replacement for corrosion monitoring.

Little: Accelerated low water corrosion (ALWC) of CS in saline waters is a form of MIC most often attributed to microorganisms in the sulfur cycle (i.e., SRB and sulfur-oxidizing bacteria). Both CP and coatings have been effective in preventing ALWC.

Jenneman: Biocides are still the chemicals of choice when mitigating MIC; however, biocides usually need to be combined with a mechanical or chemical cleaning program to enhance their effectiveness, especially if the biofilms and corrosion are already firmly established. Biocides are comprised of both oxidizing and non-oxidizing chemicals. Both can be effective, but the environment and metallurgy will often dictate the choice. Other strategies are possible, including the injection of biostats or inhibitors. We have found that some low-toxicity film-forming corrosion inhibitors can inhibit MIC development in model laboratory flow cells.

Other tactics include developing new chemicals and surfaces (e.g., nanomaterials) that will not allow bacteria to attach and form biofilms, or destroy microorganisms on contact. In addition, application of natural chemicals can interfere with the quorum sensing capacity that microbial communities rely on to form mature biofilms, potentially rendering them less corrosive. Unfortunately, much of the testing to evaluate these techniques is targeted at controlling the microbes themselves and not the corrosion.

Testing that simply addresses the reduction of microbial populations without addressing the changes in corrosiveness is insufficient. To determine the effectiveness of these strategies, it is necessary to have effective monitoring and inspection strategies. Monitoring can be used to examine effectiveness of the mitigation strategy to deliver the chemicals, control microbiological growth, and reduce corrosiveness of the environment; however, monitoring is only as good as the locations selected and samples collected, as well as the analyses performed.

Le Borgne: The main problem associated with the use of chemicals is the adaptation capacity of microorganisms that allow them to develop resistance mechanisms and, in some cases, the ability to biodegrade these products. Constant injection of chemical products is necessary. Recently, the injection of nitrate in oilfields has been described as an effective technique to control MIC by SRB; however, the long-term effects of this manipulation of the environment have not been evaluated. Strategies based on the use of bacteriophage to control specific bacterial populations have also been proposed. These strategies, as well as their long-term effects, have to be tested.

MP: When selecting materials for new construction and/or predicting material lifetime, is MIC a consideration?

Lee: In my experience, often times MIC is not a consideration in materials selection. Certain materials have been shown to not be susceptible to MIC (e.g. titanium and high Ni-Cr alloys), but these alloys are often cost prohibitive. In the last 20 years, MIC has gained traction in industrial, commercial, and military sectors. The result of unexpected failures due to MIC has increased the attention of MIC and its consideration in material selection. While many sectors are hiring corrosion scientists and engineers to deal with increased failure concerns, MIC still lags behind in consideration in the field of corrosion.

Le Borgne: To my knowledge, it is rarely considered, at least in the systems I have been involved in. MIC is not usually taken into account until it occurs and few reports deal with prevention and the assessment of risk factors associated with MIC. If such information could be systematized and proper documentation of MIC failures cases organized, then MIC could be taken into account in materials selection. Standardized protocols and test methods are also needed to test for MIC of materials under laboratory conditions and norms must be established.

Jenneman: Yes. In some cases, particularly where the risks (e.g., dead legs and low-velocity sections) and consequences are high (e.g. oil and gas lines), we have changed from CS to corrosion resistant alloys (typically duplex stainless steels [SS]) as a means to mitigate the impact of MIC. I cannot say this will be effective in all cases, but we have seen good results in some instances thus far. Also, the application of fusion-bonded epoxies to tank bottoms and the use of non-metals (e.g., glass-reinforced epoxy [GRE] or high-density polyethylene [HDPE]) for low-pressure water lines can be effective strategies to combat MIC.

More research is needed on the effect of MIC in non-austenitic, high-alloyed SS and non-metallic coatings to qualify them for use in various MIC environments. Unfortunately, to my knowledge, there are currently no reliable mechanistic MIC models that can be used to predict material lifetimes in CS or SS.

Little: Certainly, reports of ALWC as a global problem in saline waters has forced design engineers and insurers to question the probability of MIC in specific locations and to plan accordingly.

Eckert and Skovhus: The threat of MIC needs to be considered in the design of new projects to enable monitoring and mitigation for managing MIC during the operational stage of the asset. More importantly, designing to reduce the potential for conditions that would promote MIC (e.g. dead legs, low velocity) should be part of the development process. Materials selection should be based upon the anticipated operating conditions through the life of the asset and the intended design life.

Few metallic materials commonly used for engineered structures exhibit complete resistance to MIC, therefore material selection is usually based primarily on other engineering requirements for the project. While a number of models have been proposed to rank the susceptibility of a system to MIC, widely accepted models for reliable prediction of MIC corrosion rates have yet to be developed, and in fact may remain elusive due to the vast range of conditions under which MIC can occur.

MP: Recent research has demonstrated new MIC-based corrosion mechanisms. Has this new information changed the approach to managing MIC?

Lee: The traditional understanding of MIC involves the formation of a biofilm that provides a niche for corrosive microorganisms to proliferate. Recent research has demonstrated that metal surfaces alone can produce redox, oxygen, and nutrient gradients without an established biofilm. Many mitigation and monitoring strategies operate under the assumption of a substantial biofilm presence and treat accordingly.

Little: The list of microorganisms that can influence corrosion and the causative mechanisms is constantly growing. Recent research has, in general, demonstrated the metabolic flexibility of causative organisms. Most recently it has been demonstrated that some bacteria can accept electrons for iron (iron is the electron donor). However, it is not clear that increased understanding has translated into increased predictability.

Eckert and Skovhus: Research continues to confirm that MIC does not occur by any single, exclusive mechanism, and that various microbial consortia in different environments have established novel ways to use the energy sources available to them. The increased knowledge of microorganisms in industrial systems brought about by application of genetic methods has resulted in new understanding, and at the same time raised new questions about how the activities of specific microorganisms contribute to corrosion. Increased knowledge of the ways in which microorganisms influence corrosion through both biotic and abiotic processes will ultimately lead to improved mitigation and monitoring strategies and technologies. However, even with improved understanding of MIC mechanisms, development and implementation of innovative MIC management technologies will take time.

Jenneman: The recent revelations of the ability of certain SRB and methanogens to directly use electrons from metallic iron prior to the formation of molecular hydrogen is indeed opening our eyes to the different ways in which microorganisms can influence corrosion and to the need to expand our approaches and methods when looking for these causative agents of MIC. We need to better understand how these microorganisms accomplish this and how to detect their presence and control their activity. Their presence and potential activity can also impact how we currently manage and formulate the risks to our pipelines and facilities.

Le Borgne: To my knowledge it has not changed the approach yet, at least in the systems I have been involved in. It will probably take some time until this new knowledge is incorporated and taken into account in the field.

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MEET THE PANELISTS:

Richard Eckert

Richard Eckert is a principal engineer—corrosion management at Det Norske Veritas (U.S.A.), Inc., in Dublin, Ohio. He has been involved with pipeline corrosion/failure investigation and forensic corrosion engineering for over 30 years. A NACE member for more than 20 years, Eckert has a B.S. degree in engineering metallurgy from Western Michigan University, is a NACE-certified Senior Internal

Corrosion Technologist, and currently serves as chair of the NACE Books Committee, vice chair of the NACE Publications Committee, and is a member of the NACE Institute Certification Commission. He is chair of NACE Task Group (TG) 254. Eckert received the NACE Presidential Achievement Award in 2004.

Gary Jenneman

Gary Jenneman is a principal scientist within the Global Production Excellence group of ConocoPhillips in Bartlesville, Oklahoma, where he has worked for the past 26 years. Jenneman has held various technical and supervisory positions in the areas of corrosion and oilfield microbiology. He holds a Ph.D. in microbiology from the University of Oklahoma and has 12 U.S. patents and numerous publications in the areas of microbiologically enhanced oil recovery, MIC, reservoir souring, and biodesulfurization. As a NACE member, he has served on various NACE technical committees and panels over the past 15 years.

Sylvie Le Borgne

Sylvie Le Borgne is a professor researcher in the Department of Process and Technology at the Metropolitan Autonomous University at Mexico City, Mexico. Some of her research interests are in environmental microbiology, biocorrosion, and biodeterioration, as well as other topics in the area of biotechnology. She has been directly involved in petroleum biotechnology from 1999 to 2005. She was a recipient of the Carlos Casas Campillo prize in 2004, given by the Mexican Society of Biotechnology and Bioengineering to young researchers under 36 years old.

Jason S. Lee

Jason S. Lee has worked as a materials engineer since 2001 at the U.S. Naval Research Laboratory, Stennis Space Center, Mississippi. A NACE member since 1999, Lee has chaired numerous MIC technical symposia and is currently vice chair of Technology Exchange Group (TEG) 187X. His research for the Navy focuses on the basic science aspects of MIC, computational corrosion modeling, improved fundamental understanding of the localized corrosion, and electrochemistry of metals and alloys exposed to marine environments. Lee received his B.S. degree in chemistry and cellular/molecular biology from the University of Michigan, and his M.S. and his Ph.D. degrees in materials science and engineering from the University of Virginia.

Brenda J. Little, FNACE

Brenda J. Little, is a senior scientist for marine molecular processes at the Naval Research Laboratory (NRL), Stennis Space Center, Mississippi. At NRL, she has worked on MIC projects for the Department of Transportation and the U.S. Army

Corps of Engineers, and has served as a consultant to NASA. In addition to her accomplishments in basic research, Little also works on U.S. Navy assets to identify and control MIC. Her research has been used to determine the cause of corrosion failures in weapons systems, seawater piping systems, storage tanks, and other U.S. Navy equipment.

Torben Lund Skovhus

Torben Lund Skovhus is project manager at Det Norske Veritas (DNV GL) in the Corrosion Management & Technical Advisory Group in Bergen, Norway. For almost 10 years he has been working with DTI Oil & Gas as a consultant and oil field microbiologist for oil and gas operators and chemical vendors worldwide. He is an author of more than 30 technical and scientific articles related to molecular biology, oil field microbiology, corrosion management, reservoir souring, and MIC. He is the editor of three books and the founder of the International Symposium on Applied Microbiology and Molecular Biology in Oil Systems (ISMOS). He has a M.S. degree in biology and a Ph.D. from the Microbiology Department at University of Aarhus, Denmark. A NACE member, he is the chair of NACE TEG 286X. "mod A?BR g

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PUBLIC ADVOCATES OFFICE RESPONSES TO SOUTHERN CALIFORNIA GAS COMPANY'S FIRST SET OF DATA REQUESTS

Order Instituting Investigation into SoCalGas' Practices and Operations of the Aliso Canyon Storage Facility and the Uncontrolled Release of Natural Gas, I.19-06-016

Data Request No: SoCalGas-CalAdvocates-01

Date of This Request: January 9, 2020

Response Date: January 24, 2020

GENERAL OBJECTIONS

The Public Advocates Office provides the following Responses (Responses) to Southern California Gas Company's (SoCalGas) First Set of Data Requests to the Public Advocates Office dated January 9, 2020 (SoCalGas DR 1). Questions from SoCalGas DR 1 are reproduced below, followed by Public Advocates Office Responses, solely for ease of reference. The Public Advocates Office does not adopt or admit any question or any portion of any question as correct or true. The Public Advocates Office reserves the right to supplement, clarify, revise, or correct any or all of the Responses and objections herein, and to assert additional objections or privileges, in one or more subsequent supplemental response(s). Responses pertaining to questions of law or legal conclusions have been prepared with the assistance of counsel.

The Public Advocates Office objects to each data request to the extent it mischaracterizes Public Advocates Office Opening Testimony.

The Public Advocates Office objects to each data request to the extent it is overly broad, unduly burdensome, or not reasonably calculated to lead to the discovery of admissible evidence.

The Public Advocates Office objects to each instruction, definition, and data request to the extent that it seeks information or documents protected from disclosure by the attorney-client privilege, attorney work product doctrine, or any other applicable privilege.

The Public Advocates Office objects to each instruction, definition, and data request as overbroad and unduly burdensome to the extent it seeks documents or information that are readily or more accessible to SoCalGas from SoCalGas's own files, from documents or information in SoCalGas's possession, or from documents or information that SoCalGas previously produced to the Public Advocates Office. Responding to such requests would be oppressive, unduly burdensome, and unnecessarily expensive, and the burden of responding to such requests is substantially the same or less for SoCalGas as for the Public Advocates Office. All such documents and information will not be produced.

The Public Advocates Office incorporates by reference every general objection set forth above into each specific response set forth below. A specific response may repeat a general objection for emphasis or some other reason. The failure to include any general objection in any specific response does not waive any general objection to that request.

DATA REQUESTS AND RESPONSES

YOU allege on page 5 of YOUR PREPARED TESTIMONY that had "SoCalGas management acted in accordance with recommendation from its staff, corrosion issues for SS-25 could have been identified, monitored, and remediated decades prior to the Leak." YOU further allege on page 9 of YOUR PREPARED TESTIMONY that had "SoCalGas' management properly administered the program, the corrosion issues on SS-25 would have been timely identified." With these references in mind, please answer the following:

Question 1

Please identify the earliest date that YOU contend SoCalGas could have identified "corrosion issues" in SS-25.

Response to Question 1

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation of its wells contrary to Public Utilities (PU) Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office Opening Testimony (Opening Testimony), pages 3-5, which states:

> In 1988, SoCalGas began a program to perform casing integrity logs (known as Vertilog) and hydrostatic pressure testing on 20 candidate wells, including SS-25….
>
> Vertilog logging inspections were [ultimately] performed on only seven of the 20 wells, which did not include SS-25. Moreover, only five of the seven logged wells have surviving records. Of the five wells with surviving records, each included corrosion indications of at least 20 percent loss in wall thickness, with one well having an indication of over 60 percent loss in wall thickness….

> … Given the condition of the inspected wells (as indicated by the 20 percent or greater corrosion rate and the subsequent remediation), a prudent manager would have inspected the remaining 13 candidate wells to ensure the absence of similar integrity issues. SoCalGas' management, however, failed to undertake a timely inspection of these wells, including SS-25, and consequently failed to identify and address corrosion issues. (Footnotes omitted)

Please also see Blade Report Root Cause Analysis of the Uncontrolled Hydrocarbon Release from Aliso Canyon (Blade Report), Volume 4, at page 2, which states: "There is no way to know what an inspection of the SS-25 casing would have shown in 1988, but it is possible that corrosion was present and detectable, and steps could have been taken to avoid the leak in 2015."

The Public Advocates Office contends that corrosion issues in SS-25 could have been identified as early as 1988 if SoCalGas had fully implemented its proposed 1988 Vertilog and hydrostatic pressure testing program.

Question 2

Please identify all tools available in or around 1988 that were capable of detecting corrosion on the outer diameter of casings in gas storage wells.

Response to Question 2

The Public Advocates Office objects to this question as vague and ambiguous, particularly as to the phrase "tools." The Public Advocates Office also objects to this question on the ground that SoCalGas attempts to shift the burden of investigation of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Pressure testing was an available method of identifying the integrity of casings in gas storage wells in 1988. (*See* Blade Report, page 197, Section 4.6.1: "Section 1724.10(j)(1): MIT Part 1. Prior to commencing injection operations, each injection well must pass a pressure test of the casing-tubing annulus to determine the absence of leaks." SS-25 was pressure tested in 1973, 1976, and 1979.) Please also see Opening Testimony, page 6, which states: "…SoCalGas could have proceeded with testing the integrity of the 13 remaining wells through pressure testing, as originally proposed in the 1988 Interoffice Memo. While SoCalGas may have originally planned for the pressure testing to identify leaks at casing collars, pressure testing would also have assessed the mechanical integrity of the wells." (Footnotes omitted).

Question 3

Please identify the minimum amount of corrosion or metal loss that YOU contend would necessitate remediation.

Response to Question 3

The Public Advocates Office objects to this question as vague and ambiguous, particularly as to the phrase "necessitate remediation." The Public Advocates Office also objects to this question on the ground that SoCalGas attempts to shift the burden of investigation of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

There is no minimum amount of corrosion or metal loss that should necessitate remediation; instead, once the wellbore is proven to be found in a corrosive environment, such a finding would "necessitate immediate remediation." Thus, once SoCalGas found that its wells had come in contact with the corrosive environment, SoCalGas should have taken action to remediate any corrosion issues. As to SS-25 specifically, despite knowledge that its wells existed in a corrosive environment, SoCalGas performed no wall thickness inspections or any other corrosion remediation measures from the time when Vertilog results in similar wells showed corrosion issues in 1988 until the leak occurred on October 23, 2015.

Question 4

Please identify all LAWS in effect as of 1988 that required gas storage operators to perform Vertilog testing of casings in gas storage wells.

Response to Question 4

The Public Advocates Office objects to this question on the ground that information responsive to this question is equally available and is known, or should be known, to SoCalGas. The Public Advocates Office further objects that this question calls for a legal conclusion. As this question pertains to questions of law or legal conclusions, it has been prepared with the assistance of counsel.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

PU Code Section 451 states: "Every public shall furnish and maintain such adequate, efficient, just, and reasonable service, instrumentalities, equipment, and facilities … as are necessary to promote the safety, health, comfort, and convenience of its patrons, employees, and the public."

YOU allege on pages 8-9 of YOUR PREPARED TESTIMONY that:

> Using an assumption that the production casings of each well would have had 0 percent Outer Diameter (OD) penetration (wall thickness loss) at the time they were installed and the percentage of OD Penetration found by the Vertilog results in 1988, it is possible to estimate a localized linear corrosion rate in units MPY. From the results in Table 1, the wells given Vertilog inspections had a corrosion rate from 1.4 to 4.6 MPY.39 Given the almost 5 MPY corrosion rate and an existing wall thickness loss exceeding 60 percent, the wall thickness would be reduced to 80 percent in as few as 14 years, or by 2002. [Footnote 40 omitted] … SoCalGas failed to perform this basic corrosion rate calculation with the 1988 Vertilog results, leaving SoCalGas' management uninformed and unable to assess the risk of casing failure events.

Footnote 39 provides the following citation:

> In an open water system, a corrosion rate of around 1 MPY is normal. Having corrosion rate of around 10 [MPY], you should take action. Corrosion rates of 20 MPY and above, you should be concerned, as the corrosion is "eating" the metal rather fast. Merus Oil and Gas, https://www.merusonline.com/mpy-milsper-year/.

With this reference in mind, please answer the following:

Question 5

Please describe YOUR basis, including any supporting literature or analysis, for assuming a "linear" rate of corrosion to estimate the rate of metal loss.

Response to Question 5

There are several assumptions that can be made for the corrosion rate of Aliso Canyon's production casings (i.e., linear, exponential, logarithmic). The assumption of a linear rate of corrosion is the most conservative estimate for this corrosion rate assessment that still fits the data presented by the Blade Report. Please see Blade Report, pages 123-124:

> The failure occurred through a patch of corrosion. This patch of corrosion was characterized by striated grooves, and the ends of the groove had a sharp 'V' shape. Further, these grooves consisted of grooves within, almost fractal in nature. Examination of the ends of the grooves revealed tunnels that began at the emds pf the groove and that penetrated parallel to the groove into the metal. One sample revealed the formation of multiple parallel tunnels that aligned and developed into grooves.
>
> … Many of these descriptions of corrosion deposits have been identified in literature as caused by MIC. The literature data were generated from controlled experiments with deliberate exposure to microbes.

> …
>
> The SS-25 well was originally constructed as an oil well with the 7 in. production casing. The top of the cement on the 7 in. casing was around 7,000 ft and above the cement was drilling fluid. Based on the available data, this fluid would have had a pH ranging from 10.5 to 12.5 at the time of well construction.… The drilling fluid either leaked off or was displaced with ground water over time.
>
> … The microbiological organisms grew in population and caused physio-chemical reactions that likely caused the corrosion process to occur. The corrosion rates would have been quite low, on an average of 5 to 10 mpy. This is expected because, as corrosion occurs, a scale is formed on steel surface and there is no mechanism of removal of this scale. Any further corrosion requires mass transfer through the scale. The corrosion rates are anticipated to be low in a relatively stagnant environment.…

A logarithmic corrosion rate would best fit an environment where most of the corrosion occurs immediately after the production casing comes in contact with the corrosive environment. The Blade Report finds that a period of time must have passed while the high pH drilling fluid was displaced before microbes could begin corroding the casing. A logarithmic assumption, therefore, does not match the data put forth by the Blade Report, so it was rejected.

An exponential corrosion rate may have been a reasonable fit for the corrosion occurring on the production casing. Corrosion as a process is a function of the surface area of the production casing in contact with the corrosive aqueous environment. As more of the surface of the casing is corroded and more "grooves and tunnels" appear, more surface area of the production casing comes in contact with the corrosive environment. This leads to more corrosion, which in turn increases the surface area by creating more grooves and tunnels. This corrosion of the outer diameter of the production casing therefore fits an exponential corrosion rate.

However, an issue with assuming an exponential corrosion rate is that in order to accurately document the nature of the corrosion, at least three data points are needed to fit the curve. Since SoCalGas has provided proof of only one wall thickness examination on its wellbores in their more than 60-year lifespan (Vertilog testing in 1988), there is not enough data to accurately estimate the exponential nature of the corrosion. Had SoCalGas performed other regular wall thickness measurement inspections, those data points may have better fit an exponential rate of corrosion to the wellbores.

As a result, the only available assumption is a linear local approximation of corrosion, which is a conservative estimate given the lack of data taken by SoCalGas. With the one wall thickness measurement in 1988 (for 7 of the 20 prioritized wells), and an assumption that the production casing was placed into the ground with a 0% Wall Thickness loss, it is possible to approximate a constant rate of corrosion while the casing was in the ground. This linear assumption balances the exponential growth of surface area in contact with the corrosive environment with Blade

Report's explanation of "scale formation" on the steel, which could have slowed corrosion of previously exposed casing.

It is important to note that this assumption would overestimate corrosion early in the lifespan of the production casing and underestimate the corrosion late in the corrosion's lifespan. However, by the time 60% Wall Thickness loss had been identified by Vertilog testing of similar casings, linear approximation would have been the conservative estimate. As time went on, actual corrosion rate would likely be a much larger MPY ("Mils Per Year") corrosion rate than the available linear assumption. The Blade Report accounts for this issue when it estimates the corrosion rate as "an average of 5 to 10 mpy."

Question 6

Please state all facts supporting YOUR assumption that the corrosion of SS-25 occurred in a linear fashion.

Response to Question 6

Please see Public Advocates Office's response to Question 5.

Question 7

Assuming the accuracy and reliability of YOUR corrosion rate calculation for Porter 37 (4.5 MPY as of 1988), what remedial action(s), if any, do YOU contend SoCalGas should have taken in or around 1988 respecting well Porter 37?

Response to Question 7

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Opening Testimony, page 9, which states: "Given the poor condition of the inspected wells, it would have been prudent for SoCalGas management to confirm that the remaining 13 wells did not also have compromised integrity. SoCalGas management failed to do so. Instead it claimed that continued Vertilog inspections would not have achieved SoCalGas' intended purposes of the 1988 program. Even if this claim is correct, SoCalGas' management could still have confirmed the integrity of the remaining 13 wells through other measures, such as pressure testing, as SoCalGas had originally proposed."

Please also see the Blade Report, page 219:

> When a failure of some component in a system occurs, it is not uncommon to conduct a failure analysis depending on the severity of the failure and its consequences. The purpose of the failure analysis is to determine why it happened, how to prevent its recurrence, and, of equal importance, determine if it was because of an isolated problem or if it was a potentially systemic problem. If the problem appears to be systemic, then a risk assessment is commonly done to determine the likelihood of the failure occurring elsewhere, what the potential consequences might be, and how tolerable the risk is. With this understanding of the nature of the problem and potential risks, existing procedures can then be changed or new ones developed to monitor and mitigate the risks.
>
> … Blade's review of the Aliso Canyon well files shows that 40% of the wells had casing failures (leaks, tight spots, parted casing) with an average of 2 failures per well (99 failures in 49 wells).
>
> … Despite this, there is no evidence that SoCalGas conducted a formal failure analysis or follow-up risk assessment on any of the casing failures to determine why they occurred. Nor was there an investigation of the reasons for, and the potential consequences of, the corrosion.

Question 8

Assuming the accuracy and reliability of YOUR corrosion rate calculations for Porter 46 (1.4 MPY as of 1988), what remedial action(s), if any, do YOU contend SoCalGas should have taken in or around 1988 respecting well Porter 46?

Response to Question 8

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office's response to Question 7.

Question 9

Assuming the accuracy and reliability of YOUR corrosion rate calculations for Standard Sesnon 8 (3.0 MPY as of 1988), what remedial action(s), if any, do YOU contend SoCalGas should have taken in or around 1988 respecting well Standard Sesnon 8?

Response to Question 9

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office's response to Question 7.

Question 10

Assuming the accuracy and reliability of YOUR corrosion rate calculations for Standard Sesnon 9 (1.5 MPY as of 1988), what remedial action(s), if any, do YOU contend SoCalGas should have taken in or around 1988 respecting well Standard Sesnon 9?

Response to Question 10

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office's response to Question 7.

Question 11

Assuming the accuracy and reliability of YOUR corrosion rate calculations for Frew 4 (4.6 MPY as of 1988), what remedial action(s), if any, do YOU contend SoCalGas should have taken in or around 1988 respecting well Frew 4?

Response to Question 11

The Public Advocates Office objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office's response to Question 7.

Question 12

Assuming that as of 1988 SS-25 had a "normal" corrosion rate of "around 1 MPY," as cited in footnote 39 of YOUR PREPARED TESTIMONY, what remedial action(s), if any, do YOU contend SoCalGas should take taken?

Response to Question 12

The Public Advocates Office objects to this question as it mischaracterizes the Opening Testimony. The Public Advocates Office further objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Question 12 mischaracterizes the findings of the Blade Report, which determined the corrosion rates to have been 'an average of 5 to 10 mpy." (Blade Report, page 124.) Further, please see Public Advocates Office's response to Question 7.

Question 13

Please identify all LAWS in effect as of 1988 that required gas storage operators to perform corrosion rate calculations for gas storage wells.

Response to Question 13

The Public Advocates Office objects to this question on the ground that information responsive to this question is equally available and is known, or should be known, to SoCalGas. The Public Advocates Office further objects that this question calls for a legal conclusion. As this question pertains to questions of law or legal conclusions, it has been prepared with the assistance of counsel.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

PU Code Section 451 states: "Every public shall furnish and maintain such adequate, efficient, just, and reasonable service, instrumentalities, equipment, and facilities … as are necessary to promote the safety, health, comfort, and convenience of its patrons, employees, and the public."

YOU allege on page 11 of YOUR PREPARED TESTIMONY that: "[t]he fact that SS-25 was not cathodically protected, replaced, or taken out of service prior to the Leak meant that the corrosion was unmitigated." With this reference in mind, please answer the following:

Question 14

Do YOU contend that SoCalGas should have applied cathodic protection to SS-25?

Response to Question 14

The Public Advocates Office objects to this question as it mischaracterizes the Opening Testimony. The Public Advocates Office further objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

If cathodic protection were applied to SS-25 prior to the invasion of groundwater, the resulting corrosion would not have occurred. Please also see the Blade Report, page 215: "For the 7 in. casing to have corroded, it must have been in direct contact with an environment that allowed the corrosion mechanism to exist, and a corrosion protection mechanism must have been absent. Cathodic protection systems, for example, are commonly used to protect pipelines from corrosion and are sometimes used on surface casing strings. While a cathodic protection system would have provided corrosion protection to the 11 3/4 in. casing, it would not have protected the 7 in. casing inside the 11 3/4 in. casing"

Question 15

Do YOU contend that cathodic protection would have prevented the SS-25 LEAK?

Response to Question 15

The Public Advocates Office objects to this question as it mischaracterizes the Opening Testimony. The Public Advocates Office further objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

Please see Public Advocates Office's response to Question 14.

YOU allege on page 11 of YOUR PREPARED TESTIMONY that:

> PU Code Section 451 mandates SoCalGas to operate its wells in a manner that promotes the safety and health of the public. This may include, for example, taking proactive actions to prevent a gas leak by carrying out technical analyses, inspecting of testing the wells (e.g., for well corrosion, for the strength of the well casing to withstand high pressure, etc.). Had SoCalGas taken such preventative measures in due time, it may have been able to prevent the SS-25 failure, which resulted in negative consequences to the health and safety of the public. However, SoCalGas failed to do so.

(Internal footnotes omitted). With this reference in mind, please answer the following:

Question 16

Please identify all LAWS in effect at the time of the LEAK that required gas storage operators to carry out "technical analyses" as used in the above passage from YOUR PREPARED TESTIMONY.

Response to Question 16

The Public Advocates Office objects to this question on the ground that information responsive to this question is equally available and is known, or should be known, to SoCalGas. The Public Advocates Office further objects that this question calls for a legal conclusion. As this question pertains to questions of law or legal conclusions, it has been prepared with the assistance of counsel.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

PU Code Section 451 states: "Every public shall furnish and maintain such adequate, efficient, just, and reasonable service, instrumentalities, equipment, and facilities … as are necessary to promote the safety, health, comfort, and convenience of its patrons, employees, and the public."

Question 17

Please identify all LAWS in effect at the time of LEAK that required gas storage operators to "inspect[] or test[] the wells (e.g., for well corrosion, for the strength of the well casing to withstand high pressure, etc.)" as used in the above passage from YOUR PREPARED TESTIMONY.

Response to Question 17

The Public Advocates Office objects to this question on the ground that information responsive to this question is equally available and is known, or should be known, to SoCalGas. The Public Advocates Office further objects that this question calls for a legal conclusion. As this question pertains to questions of law or legal conclusions, it has been prepared with the assistance of counsel.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

PU Code Section 451 states: "Every public shall furnish and maintain such adequate, efficient, just, and reasonable service, instrumentalities, equipment, and facilities … as are necessary to promote the safety, health, comfort, and convenience of its patrons, employees, and the public."

Question 18

Do YOU contend that Public Utilities Code section 451 imposes a STRICT LIABILITY standard of liability?

Response to Question 18

The Public Advocates Office objects to this question on the ground that information responsive to this question is equally available and is known, or should be known, to SoCalGas. The Public

Advocates Office further objects that this question calls for a legal conclusion. As this question pertains to questions of law or legal conclusions, it has been prepared with the assistance of counsel.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

The language of PU Code Section 451 speaks for itself.

YOU allege on pages 15-16 of YOUR PREPARED TESTIMONY "seven incidents involving missed compliance actions on surveys and inspections done for SS-25." The dates of these seven alleged "missed compliance actions range from the year 2000 through 2013." With this reference in mind, please answer the following:

Question 19

Did any of the seven surveys or inspections for SS-25 document any anomalies regarding the condition of SS-25?

Response to Question 19

The Public Advocates Office objects to this question as vague and ambiguous, particularly as to the phrase "anomalies regarding the condition of SS-25." The Public Advocates Office also objects to this question as it mischaracterizes the Opening Testimony. The Public Advocates Office further objects to this question on the ground that SoCalGas attempts to shift the burden of investigation and maintenance of its wells contrary to PU Code Section 451. The Public Advocates Office further objects to the question on the grounds that this question is unduly burdensome in that it requires the Public Advocates Office to gather and analyze all the information that is or was in SoCalGas's sole possession and control. The Public Advocates Office further objects that information responsive to this question is in SoCalGas's sole possession and control.

Subject to and without waiver of the foregoing objections, the Public Advocates Office responds as follows:

The information available from the seven incidents involving missed compliance by SoCalGas is insufficient to make any conclusion regarding the actual condition of SS-25. Only two of the seven surveys or inspections are specific to SS-25. The remaining five surveys or inspections pertain to a group of wells, which include, but do not speak specifically to, SS-25.

END OF DATA REQUESTS AND RESPONSES

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