A European endeavor for optimizing Zonal Isolation, Drilling and Exploitation of EGS projects

THE ST2 BOREHOLE IN THE BEDRETTO UNDERGROUND LAB FOR GEOSCIENCES AND GEOENERGIES (BULGG):

ACTIVITIES CARRIED OUT IN THE FRAMEWORK OF THE GEOTHERMICA/ZODREX RESEARCH PROJECT

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Contents

1. Executive Summary

The present report aims to describe the ST2 borehole, and the successive activities carried out in the framework of the GEOTHERMICA/ZoDrEx research project. The content of the report is relevant to the work packages 2.1 (Characterization of the boreholes through logging and hydro-testing), 3.4 (Stimulation of various segments with different zonal isolation means) and 3.5 (Analysis of the data collected in WP 3.4 using analytical and advanced numerical models).

ST2 was drilled in July 2020 and it is part of an array of boreholes in the BULGG aiming to test methodologies and workflows to improve the development of geo energy projects in granitic rocks. Ten other long boreholes (100m to 400m) have been drilled in the vicinity of ST2 for monitoring or injecting purposes. ST2 is the second longest borehole of the array with a total length of 350m. Details on the position and geometry of ST2 are given in chapter 3.1 Borehole geometry and post-drilling condition.

The BULGG is located inside a granitic intrusion (The Rotondo granite) in the Gotthard massif in the Swiss Alps. Some general and specific geological considerations are described in this report (3 Characterization of the ST2 borehole) and a detailed structural analysis covering the whole BULGG is available in the report "Structural characterization of the Bedretto Underground Laboratory for Geoenergies (BULGG)".

A general overview of the activities carried out in ST2 is given in chapter 4 Summary of activities in the framework of ZoDrEx, indicating their chronological order as well as their respective depths. Carried out activities include hydrotests (chapter 5), notching (chapter 6), minifrac tests (chapter 7) and shear stimulations (chapter 8). The works carried out cover the bottom-most 100m of the borehole between depths 150m and 350m but the majority of activities were concentrated in the deeper 50m (300-350m).

Extensive logging was carried out before and after each one of the above listed activities. Logs acquired in a repetitive way at different stages of the project include spectral gamma ray, image logs (acoustic and optical televiewers) and fluid temperature and conductivity. Other logs acquired in a one-time basis are borehole GPR and full wave sonic. A campaign of flowmeter measurements was unsuccessful to define the flow rate in the borehole as well as the feeding zones from the formation and for that reason the results are not included here.

Examination of the logs before and after minifrac tests didn't reveal any significant effect on the borehole walls. The presence of natural fractures, observed mainly in the optical televiewer might explain the lack of new tensile fracturing associated to these tests.

Analyses of the acoustic televiewer logs revealed that the stimulation treatment carried out during November 2020 triggered shear displacement in at least 3 structures belonging to 3 different intervals (intervals 1, 2 and 5). This displacement is in the order of 2-5 mm and it is associated to deformation extending 20-50 cm away from the fractures. Details of this analysis can be found in chapter 8.1.4 Shear displacement on pre-existing fractures.

The evidence on the effectiveness of notching treatments to increase the probability of cross-borehole fractures is not conclusive. The almost omnipresent natural fractures and their response to injection might have masked the benefits expected from notching.

2. Conventions used in this report.

The official name of the Bedretto lab is the Bedretto Underground Lab for Geosciences and Geoenergies (BULGG). Bedretto lab and BULGG are used in this report interchangeably.

All depths in boreholes correspond to measured depth in meters unless stated otherwise. Image logs are loaded and interpreted in a "high side" reference system. This was necessary as ST2 is an inclined borehole and the reference to the North makes no sense. A High-side reference means that the horizontal axis in the logs represents the angle from the highest line in the borehole. This angle increases clockwise when looking towards the bottom of the borehole (Figure 1). The left, vertical axis of the log represents angle zero (aka. the high side).

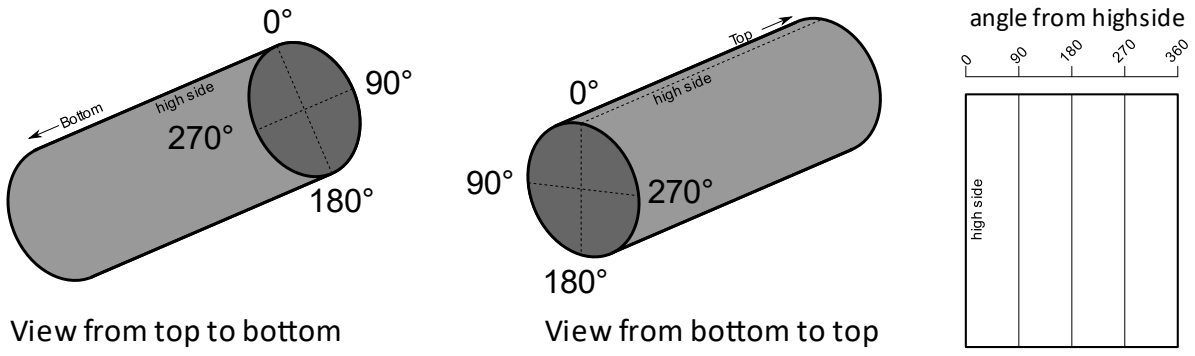


Figure 1. The "High side" of the borehole is the reference used in image logs from deviated wells. When unravelling the image log to display it in 2D, the high side (0°) coincides with the left border of the log. The angle increases clockwise when looking down the borehole.

Borehole orientations are given as azimuth (clockwise angle from north, 0°-360°) and inclination (angle from a vertical axis that is pointing down, 0°-90°). An inclination of 0° corresponds to a vertical borehole while 90° describes a horizontal borehole.

The orientation of planar elements (i.e faults & fractures) is given in strike (clockwise azimuth from north of a horizontal line in the plane) and dip (angle from the horizontal of a line perpendicular to the strike). A plane given as N50°/70° is oriented NE-SW and dips to the SE. A plane given as N230°/70° will also be oriented NE-SW but dips towards the NW.

3. Characterization of the ST2 borehole

3.1 Borehole geometry and post-drilling condition

ST2 was spudded on July 14th, 2020, and was completed on the 31st of July. It took approximately 6 days to drill the first 300m. A pause of 10 days in the drilling operations delayed the completion of the borehole. The final 50 m were drilled on July 31st (Figure 2).

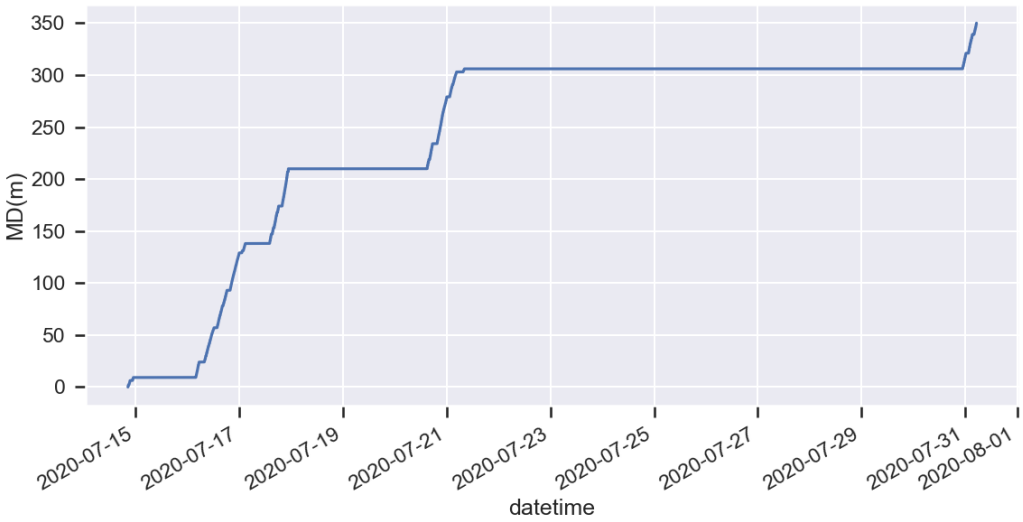


Figure 2 Drilling progress of ST2.

ST2's wellhead lies at tunnel coordinate (TM) 2065m. This is 15m NW of the MB1 wellhead. ST2 is the northernmost borehole in the Bedretto lab (Figure 3).

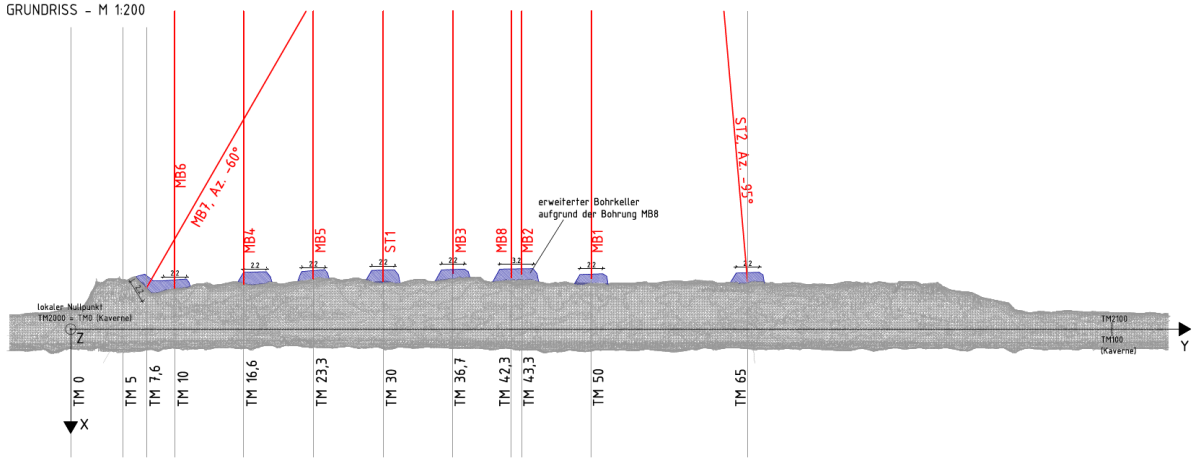


Figure 3. Diagram showing the disposition of well heads in the Bedretto Lab by March 2020. Taken from document from Zublin.

The inclination of the borehole diminishes from about 54° at the wellhead to approx. 40° at TD, meaning that the borehole gets steeper with depth. The azimuth is 222° at the wellhead and 227.5° at TD (Figure 4, Figure 5 and Figure 6).

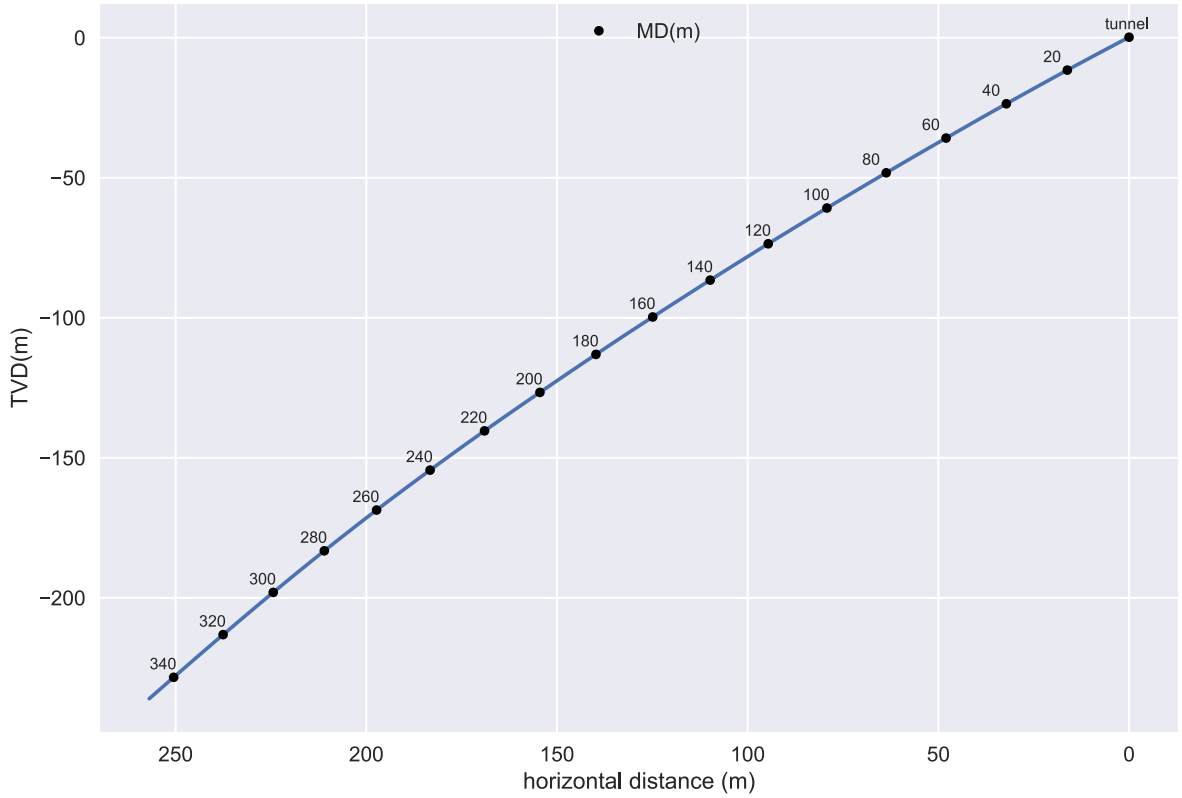


Figure 4. ST2 borehole path.

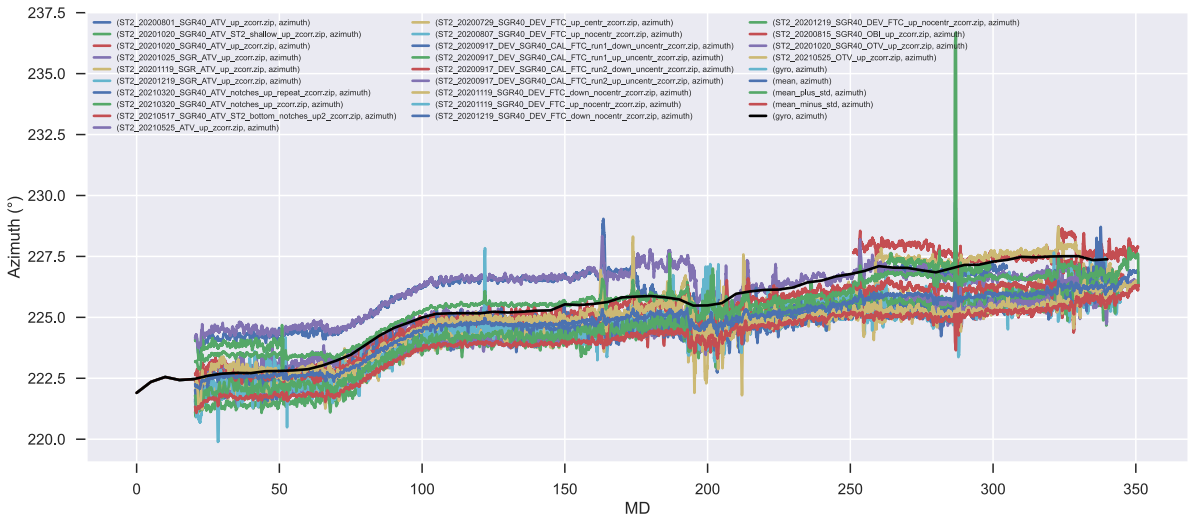


Figure 5. Azimuth (clockwise degrees from North) of ST2's path. Curves in color correspond to values from logging tools (ATV, OTV and DEV) with 2.21° added to correct for magnetic declination. The black curve is the gyro acquisition.

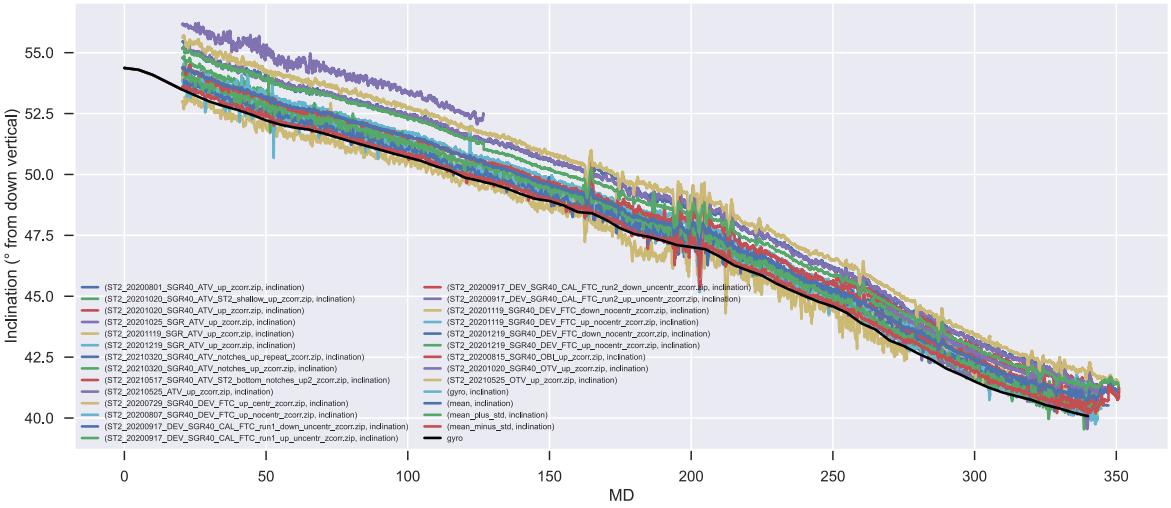


Figure 6. Inclination (degrees from a vertical pointing down) of ST2's path. Curves in color correspond to values from logging tools (ATV, OTV and DEV) while the black curve is the gyro acquisition.

The nominal diameter of the borehole is 8½ inches (below the conductor pipe). A non-calibrated caliper derived from the acoustic televiewer shows that the diameter is slightly wider at the top of the borehole (22.5cm instead of 21.6cm), and it diminishes with depth until it reaches the nominal value near TD (Figure 7). A regular borehole cross section can be observed between 50-160 m. Below 160m, regular cave-ins, breakouts and possible keyseats can be observed. Below 260m the cross section becomes relatively more regular although important irregularities in the borehole wall persist down to the TD.

Borehole breakouts are concentrated between 160-260m and 315-330m (Figure 7, Figure 8 and Figure 9). Figure 8 shows a rotation in the breakout's azimuth along the borehole depth. Zhang et al. (in press) describes in detail this rotation observed in ST2 as well as other boreholes in the BULGG.

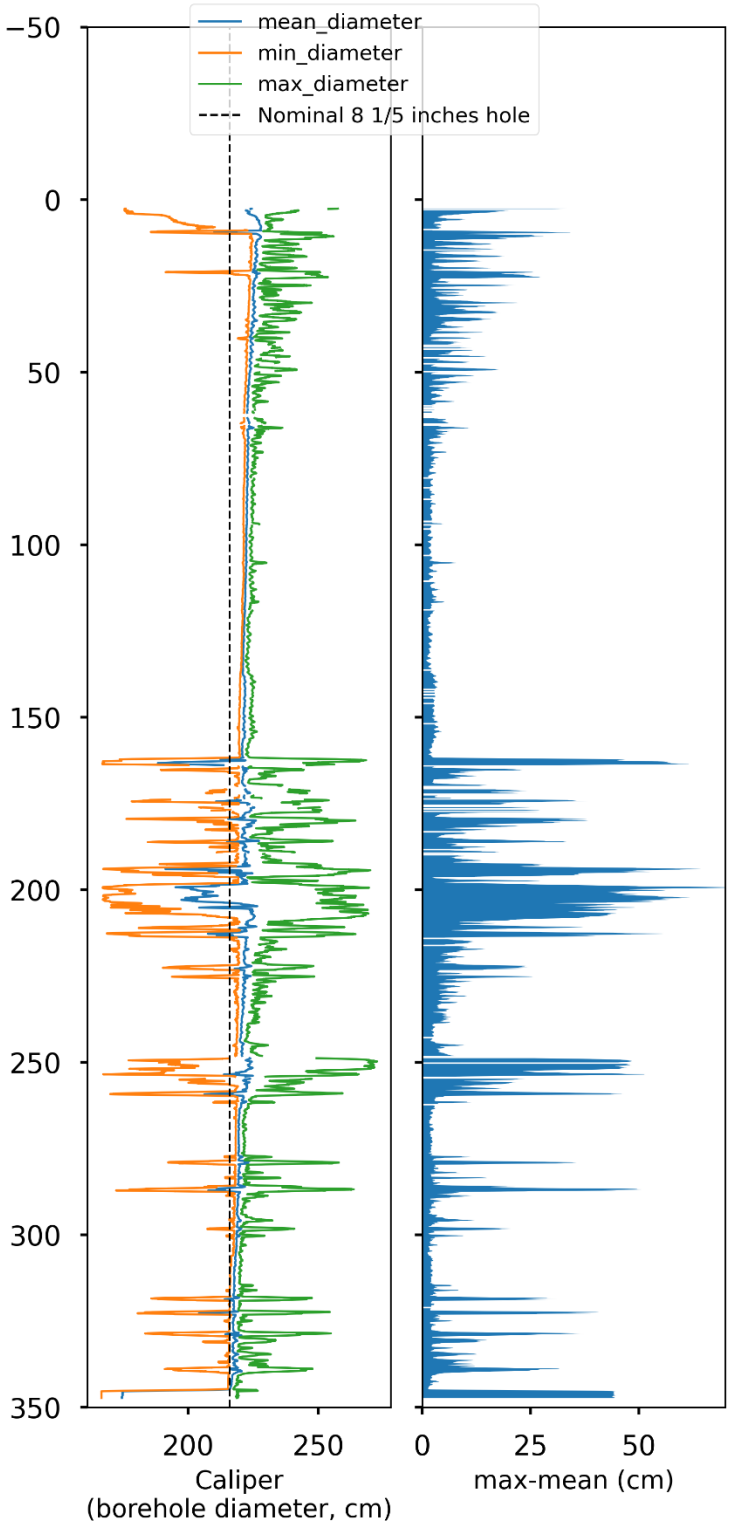


Figure 7. Caliper calculated from ATV log vs. Nominal diameter. The borehole gets narrower with depth. The section between 160 and 215m shows several cave ins. Sections with very low caliper values are certainly artifacts from the conversion of the acoustic signal.

153

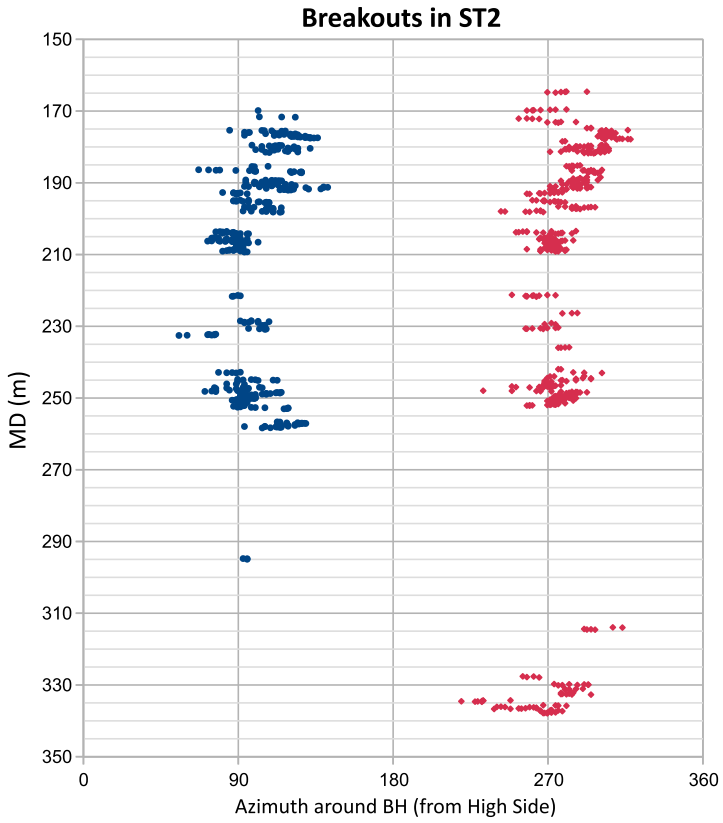
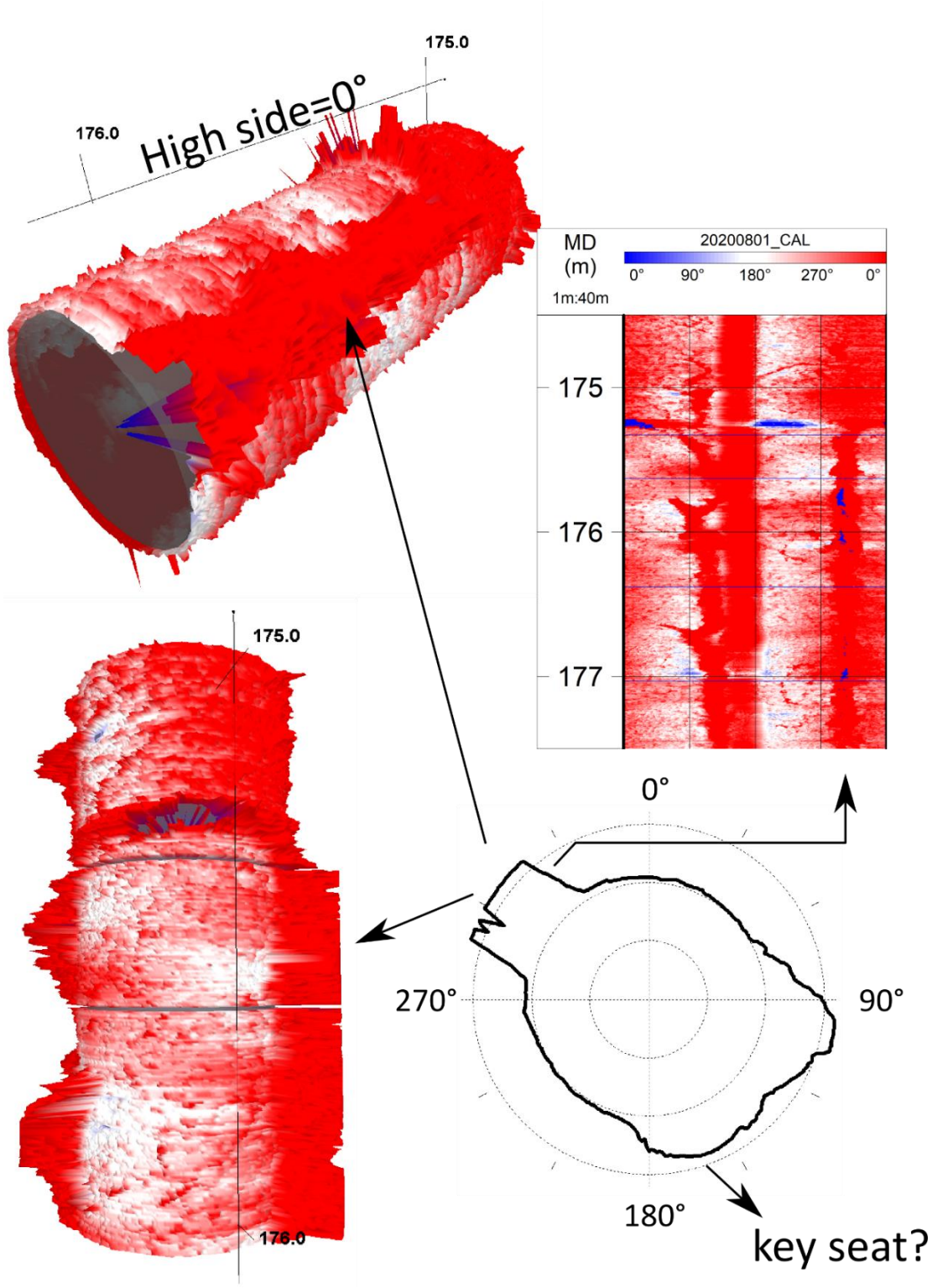


Figure 8. Borehole breakouts in ST2



156

157 *Figure 9. Calculated caliper, 3D reconstruction and cross section view of breakouts between 175 and*
158 *176 m MD. Breakouts are not exactly at 180° of each other. The breakout at around 100° rotates*
159 *with depth until it reaches approx. 130°. The breakout at 310° stays fixed.*

160

3.2 Lithology

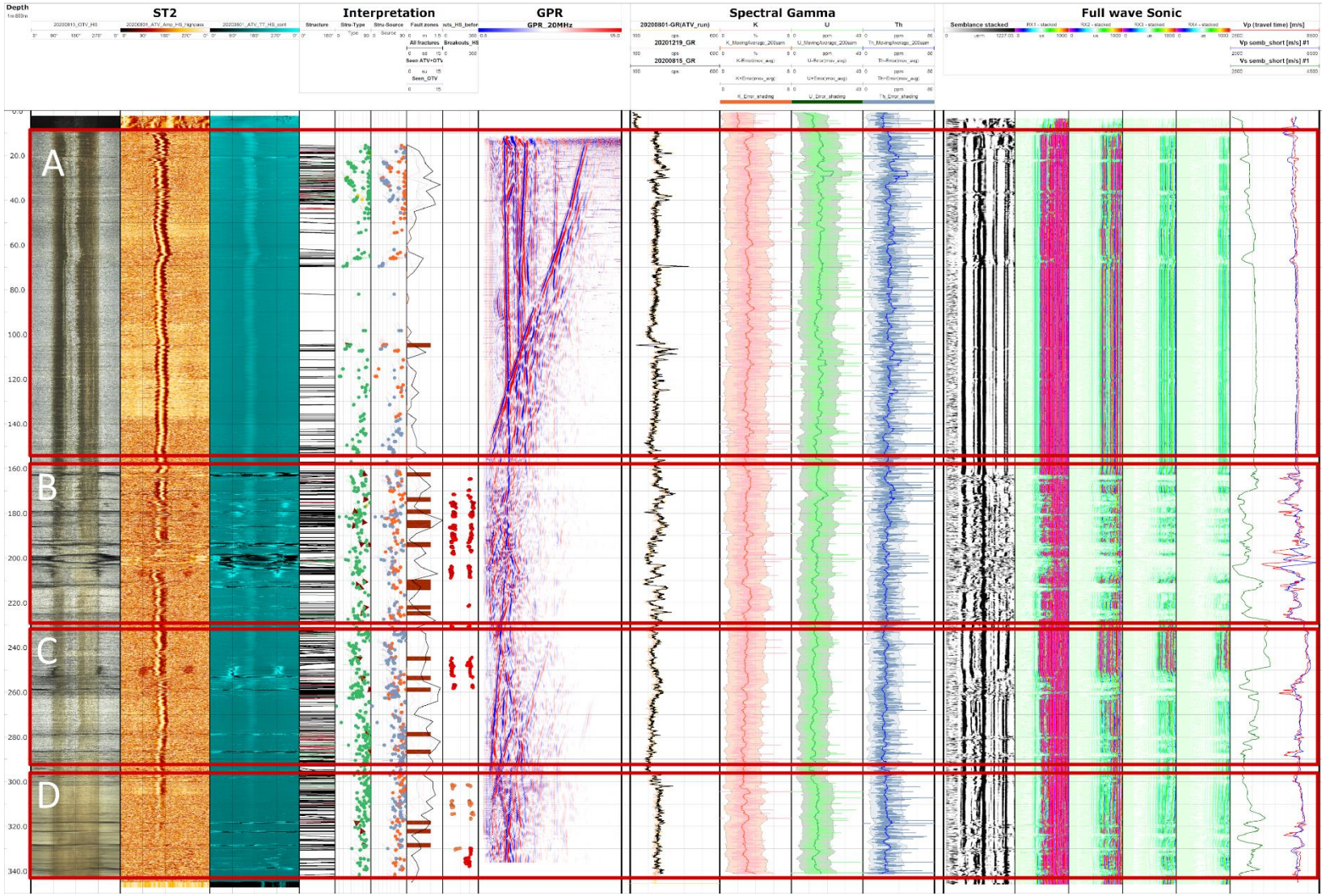
ST2, like all other boreholes in the Bedretto lab, was drilled through the Rotondo granite. The Rotondo granite is composed of 64.9% of feldspars, 29.9% quartz and 5.2% of mafic minerals (Debon & Lemmet, 1999). It presents a generally massive aspect with randomly distributed, large and easily visible crystals that, in general, lack any consistent direction. Foliated zones are present but are usually concentrated around individual shear (fault) zones.

Characterisation of the rock volume was carried out via core descriptions and an extensive campaign of wireline logging. Figure 10 shows the major sections identified through the logging data:

- Section A (0-155m): first section near the tunnel where fractures were identified in the Optical televiewer (OTV) but that for the most part lack an acoustic response in the Acoustic televiewer log (ATV). Spectral gamma ray (SGR) signal shows numerous peaks probably indicating lithological heterogeneities in this section. Vp and Vs on the contrary are relatively constant.
- Section B (155-230m): A high deformation section about 80m thick where multiple fault core zones are present and where the background fracture count increases considerably with respect to the rest of the borehole. Borehole breakouts form almost exclusively in this section. The SGR signal is more heterogenous and varies with higher frequency. Vp and Vs show also larger amplitude variations.
- Section C (230-300m): shows individual and “isolated” fault core zones with strong acoustic response intercalated with sections of low fracture count. Spectral gamma is more regular than in section B.
- Section D (300-350m): Towards the bottom of the borehole, the granite looks clearer in the OTV in comparison to the rest of the borehole. The total gamma ray shows a base level that is consistently higher than the sections above. These observations point to a section of the granite that is most probably richer in Feldspars. Structures in the shallowest 20m of this section have a smaller amplitude response than those towards the deepest 30m.

Except for some shallow hydrotests and notching between 150m and 300m, all other activities presented in this report were carried out in the deepest part of section C (275m-300m) or entirely in section D (300m-350m).

Figure 10 Next Page. Composite data log of ST2 with Optical televiewer (OTV), Acoustic televiewer (ATV), structural interpretation, borehole GPR, spectral gamma and full-wave sonic.



3.3 Structure

Structures were interpreted in the acoustic and optical televiewers (ATV and OTV) and were classified as either "generic fractures" or "fault zones". Other structure types were identified but can be considered here as negligeable because of their scarcity in the logs (e.g. quartz veins). A detailed analysis of the structure for the whole BULGG can be found in the report "Structural characterization of the Bedretto Underground Laboratory for Geoenergies (BULGG)" by R. Castilla.

Measured orientations concentrate mainly around strikes=N140°-150° and dips=40°-60°. Secondary directions include one concentrated around strike=N10°±5°, dip=90°±5° and a disperse one of SE-NW striking structures identified mainly in the OTV. Generic fractures can be found in all these 3 groups while most fault zone cores are only found in the NE-SW group dipping NW.

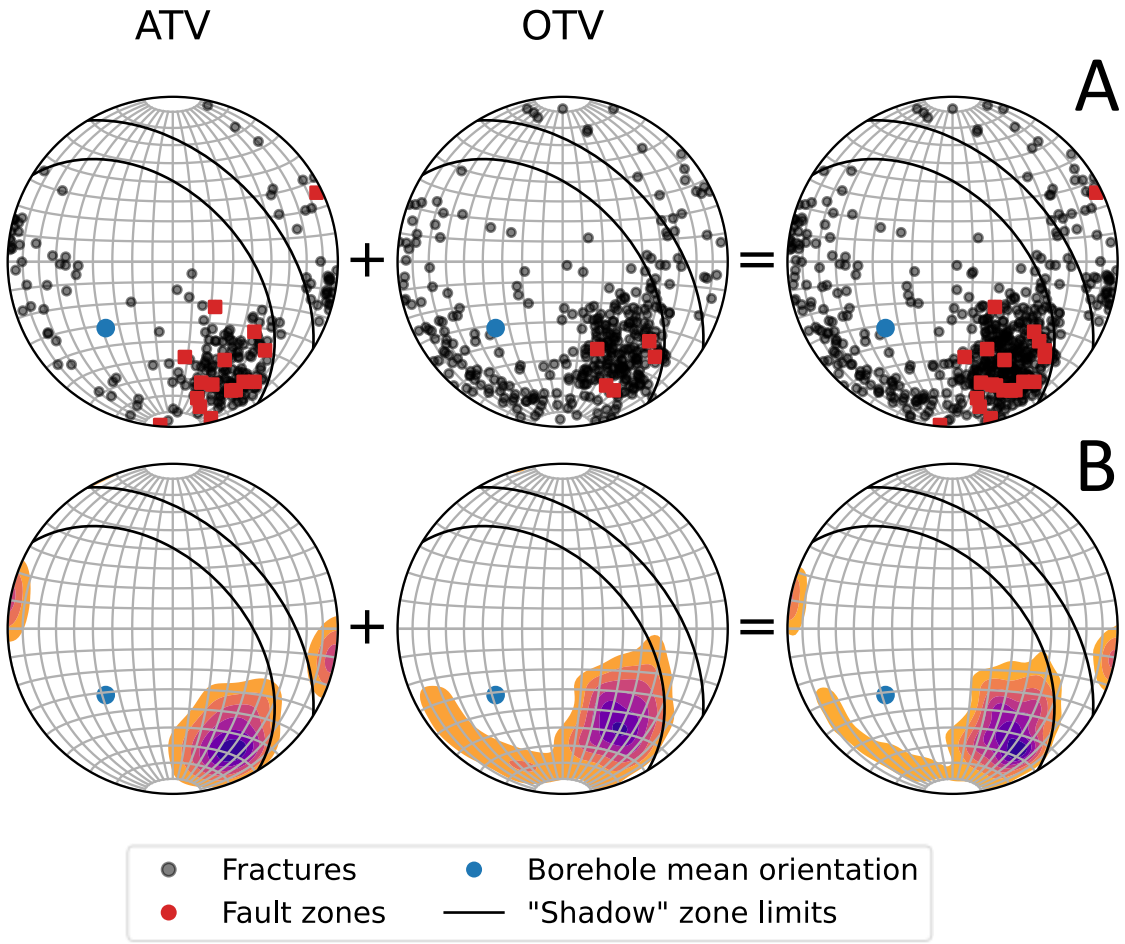


Figure 11. Structures interpreted in the televiewer logs. A) Poles to structure planes, B) Contours of pole density.

The region where under sampling of structures is expected to occur (aka "shadow zone") is indicated in Figure 11 by the area between two black polylines. This data gathering pitfall is common to all structural work and is formally known as the orientation bias. A correction, only relevant for quantitative workflows (e.g. construction of a DFN model) can be applied to correct the frequency/spacing of measured data. This correction is not useful for descriptive reports like the

present one. No reliable processing method exists to "populate" the shadow zone. The two polygons in Figure 11 mark the zone where planes forming less than 20° with the borehole axis would plot. This theoretical shadow zone fits well with the lack of data points in that area of the stereonets. For the qualitative and descriptive purpose of this report no correction of the orientation bias was deemed necessary.

The frequency of structures occurrence along the borehole is shown in Figure 12. Fault core zones are marked with a red square. The lithological subunits identified through the log integration (Figure 10) is shown as lightly colored rectangles. The total structure count curve ("All orientations" in Figure 12) mimics the count of structures in the NE-SW set (light blue curve). The NS set is only present at the shallow and deep ends of the borehole while SE-NW set is only present in the deepest 90m.

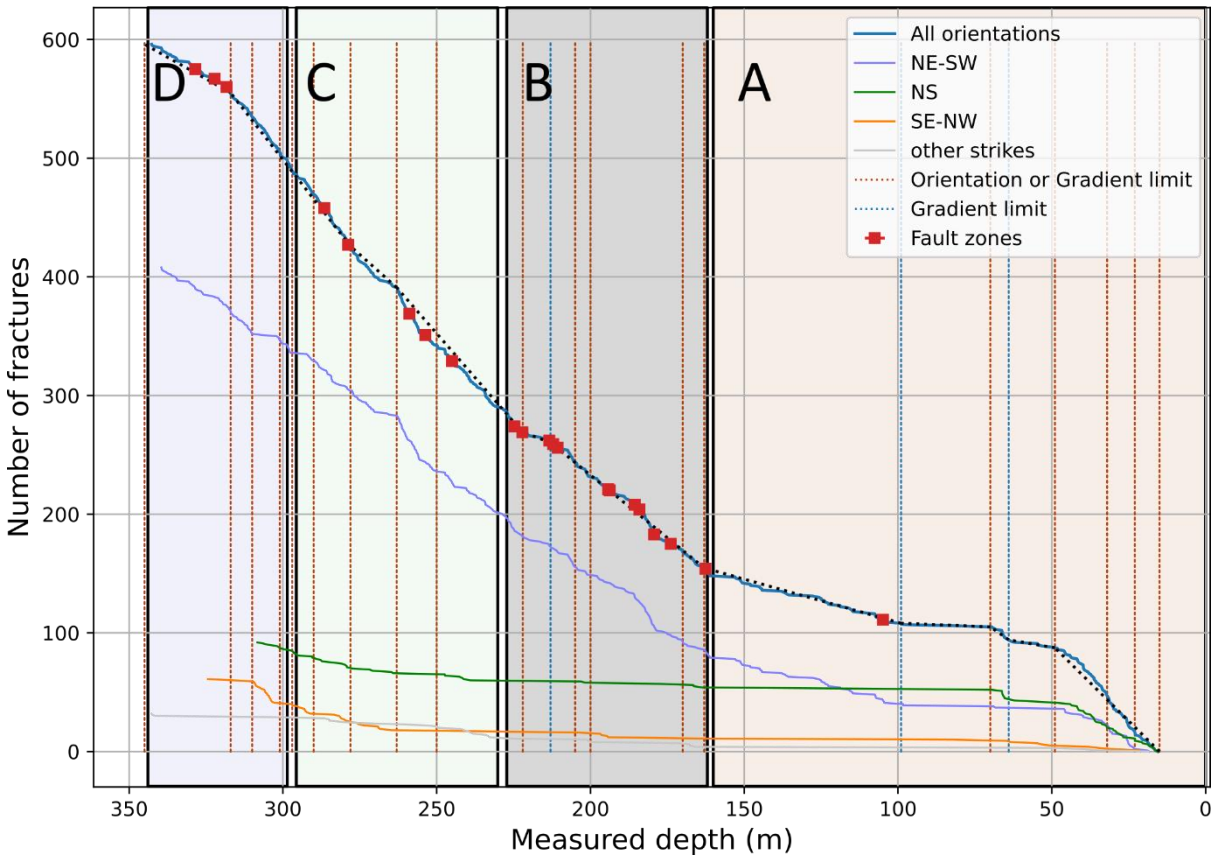


Figure 12. Structure frequency for the total population and detailed for each individual orientation set.

Fault zones identified in ST2 were correlated with those interpreted in other boreholes in the BULGG. A 3D view with the resulting fault surfaces is shown in Figure 13. All faults in ST2 connect up dip with other boreholes.

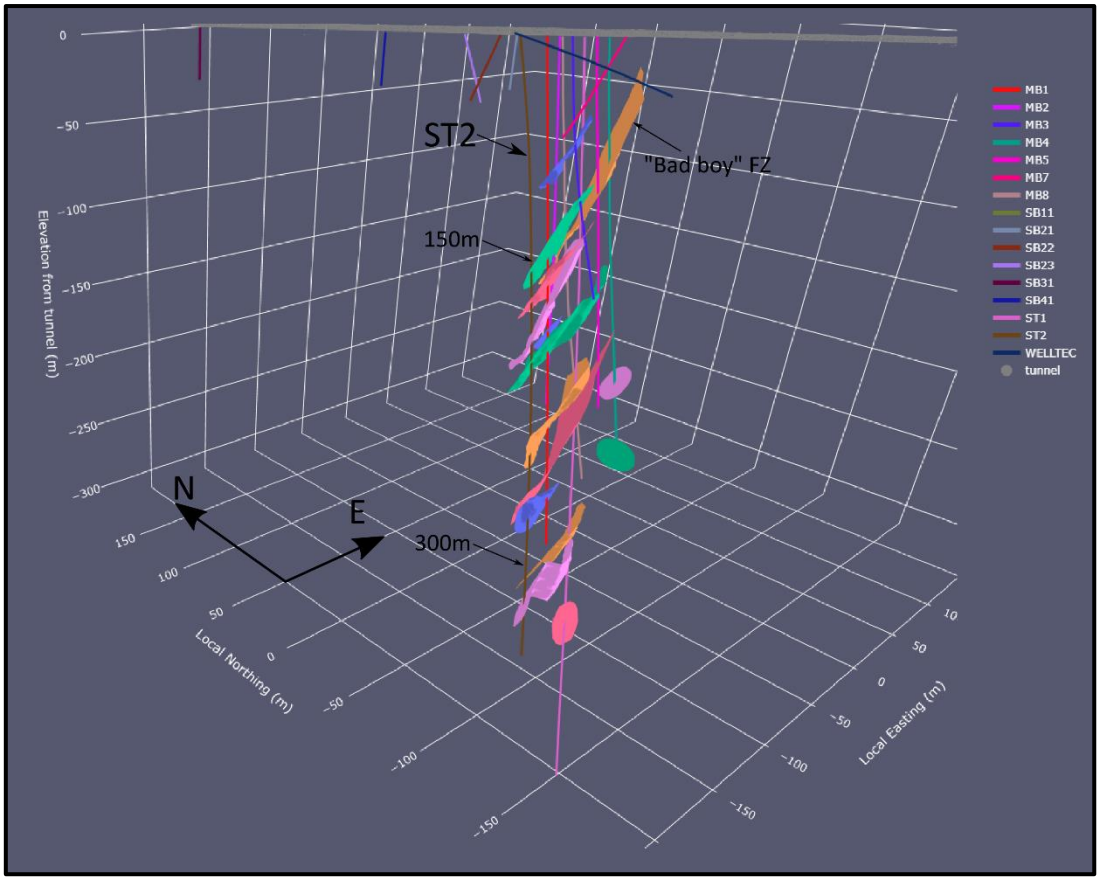


Figure 13.

3.4 Fluids

Fluid and conductivity of the fluid in the borehole were extensively monitored through logging (Table 1 and Figure 15). Comparison of a log acquired just before the final stage of drilling (29/07/2020) and another one run 1½ months after (17/09/2020), shows how the fluid n the borehole gets warmer with time meaning that the in-situ fluid is warmer than the circulated fluid during drilling. Conductivity shows changes in time as well, but they differ depending on the position in the borehole. Above 175m the fluid got slightly more conductive (i.e., salinity increased) with time while below the conductivity decreased significantly.

A temperature gradient was estimated using a rolling window of 2m on the September 17th log. An average gradient of about 11.5 °C/km was estimated with important anomalies around 175m, 215m and 285m (Figure 14). Smaller anomalies can also be seen at 40m and 305m. Simultaneous temperature and conductivity anomalies can be observed at 175m, 215m, 285m and 305m.

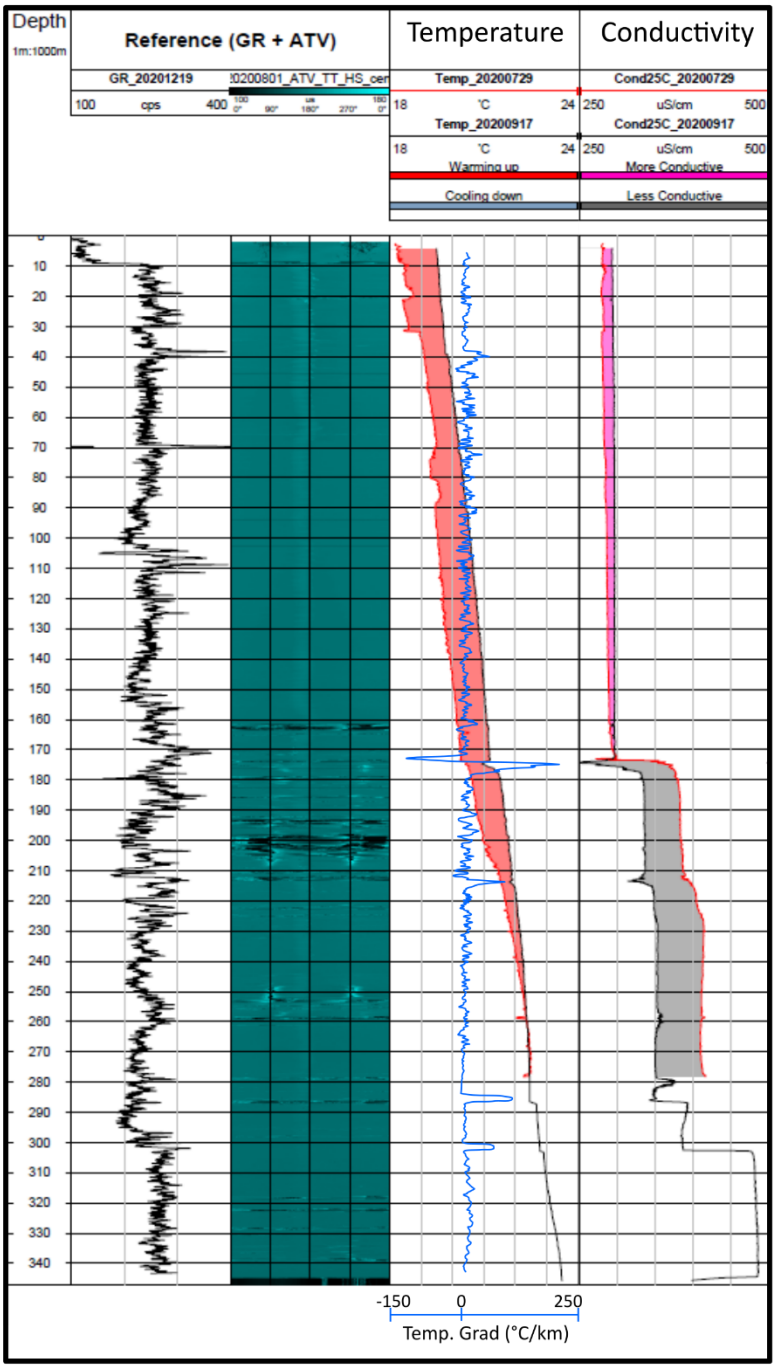


Figure 14. Temperature and conductivity logs acquired in ST2 towards the end of drilling (29/07/2020) and about 1½ months afterward (17/09/2020).

4. Summary of activities in the framework of ZoDrEx

Table 1 and Figure 15 show the history of activities carried out in ST2, from its drilling to the final stimulation in the framework of ZoDrEx. From spudding until the last stimulation, the works were conducted along 15 months. In this span of time, 14 intervals were the object of hydraulic tests, 20

minifrac tests were conducted and 18 intervals were stimulated by hydraulic injection. In addition, 4 notching campaigns were carried out on both, open hole and cased & cemented configurations. 25 televiewer logs were acquired (19 ATV and 6 OTV) in addition to 15 temperature and conductivity logs. The rock volume below 300m was the most repeatedly tested and stimulated

Table 1 Summary of operations carried out in ST2

Date	Borehole	Action
14/07/2020	ST2	Spud
29/07/2020	ST2	FTC
29/07/2020	ST2	FTC
30/07/2020	ST2	ATV
31/07/2020	ST2	End Drilling
01/08/2020	ST2	ATV
01/08/2020	ST2	ATV
05/08/2020	ST2	FTC
07/08/2020	ST2	FTC
15/08/2020	ST2	OTV
28/08/2020	ST2	Start Hydrotesting campaign
07/09/2020	ST2	End Hydrotesting campaign
14/09/2020	ST2	Start FO-DTS campaign
17/09/2020	ST2	End FO-DTS campaign
17/09/2020	ST2	FTC
17/09/2020	ST2	FTC
17/09/2020	ST2	FTC
17/09/2020	ST2	FTC
21/09/2020	ST2	Start Notching campaign
01/10/2020	ST2	End Notching campaign
01/10/2020	ST2	ATV
01/10/2020	ST2	OTV
12/10/2020	ST2	ATV
12/10/2020	ST2	OTV
16/10/2020	ST2	Start Mini-Frac campaign
17/10/2020	ST2	End Mini-Frac campaign
20/10/2020	ST2	ATV
20/10/2020	ST2	ATV
20/10/2020	ST2	OTV
20/10/2020	ST2	OTV
25/10/2020	ST2	ATV
09/11/2020	ST2	Start Stimulation campaign
19/11/2020	ST2	ATV
19/11/2020	ST2	ATV
19/11/2020	ST2	FTC
19/11/2020	ST2	FTC
30/11/2020	ST2	End Stimulation campaign
19/12/2020	ST2	ATV
19/12/2020	ST2	FTC
19/12/2020	ST2	FTC
10/03/2021	ST2	Start Notching campaign
18/03/2021	ST2	End Notching campaign
20/03/2021	ST2	ATV
20/03/2021	ST2	ATV
11/05/2021	ST2	ATV
11/05/2021	ST2	ATV
11/05/2021	ST2	ATV
11/05/2021	ST2	Start Notching campaign
17/05/2021	ST2	End Notching campaign
17/05/2021	ST2	ATV
17/05/2021	ST2	ATV
18/05/2021	ST2	Start Mini-Frac campaign
21/05/2021	ST2	End Mini-Frac campaign
21/05/2021	ST2	Start Re-Stimulation campaign
23/05/2021	ST2	End Re-Stimulation campaign
25/05/2021	ST2	ATV
25/05/2021	ST2	OTV
25/05/2021	ST2	Start Casing installation - Cementation
02/06/2021	ST2	End Casing installation - Cementation
20/07/2021	ST2	Start Notching campaign 1
30/07/2021	ST2	End Notching campaign 1
30/07/2021	ST2	FTC
30/07/2021	ST2	FTC
30/07/2021	ST2	FTC
13/09/2021	ST2	Start Notching campaign 2
02/10/2021	ST2	End Notching campaign 2
04/10/2021	ST2	Start Stimulation campaign
15/10/2021	ST2	End Stimulation campaign

ATV = Acoustic Televiewer; **OTV** = Optical televiewer

FTC = Fluid temperature & Conductivity

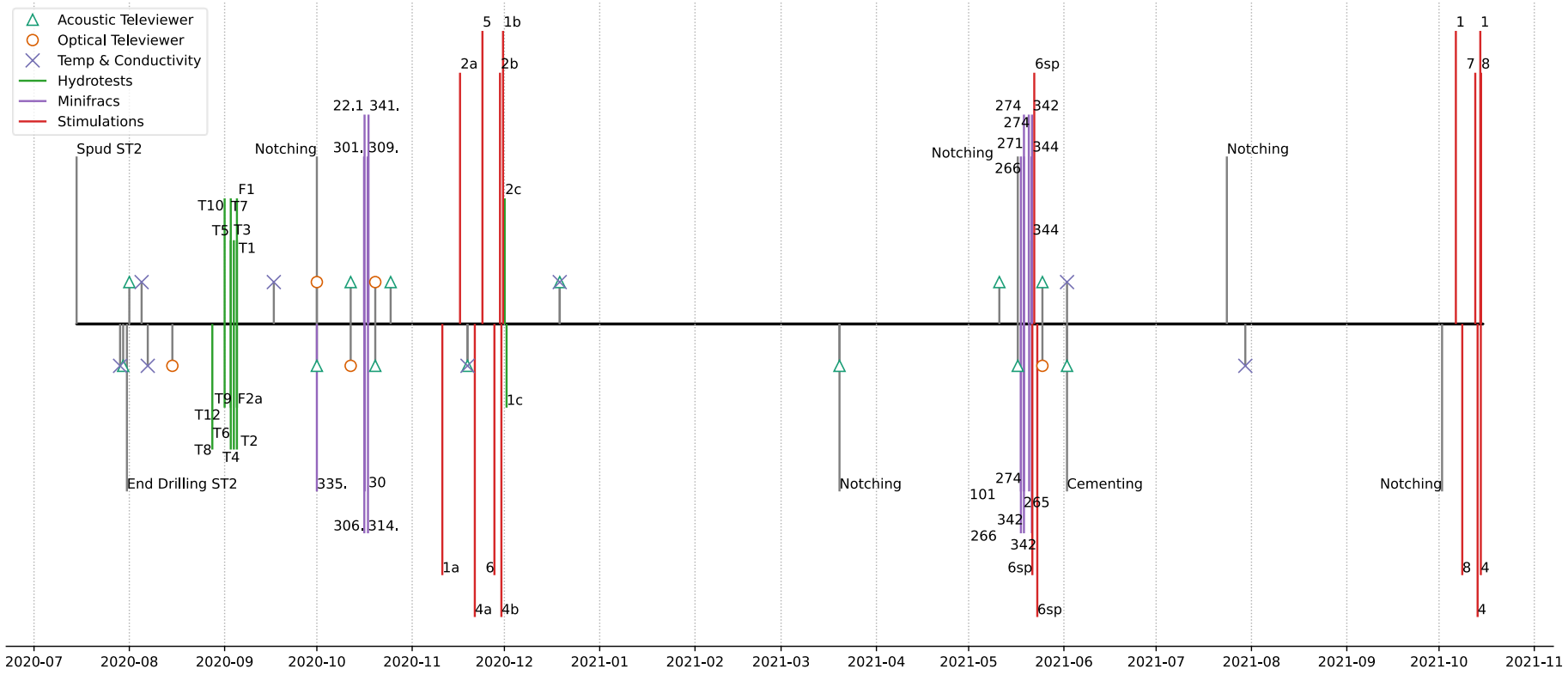


Figure 15. Timeline of operations on ST2

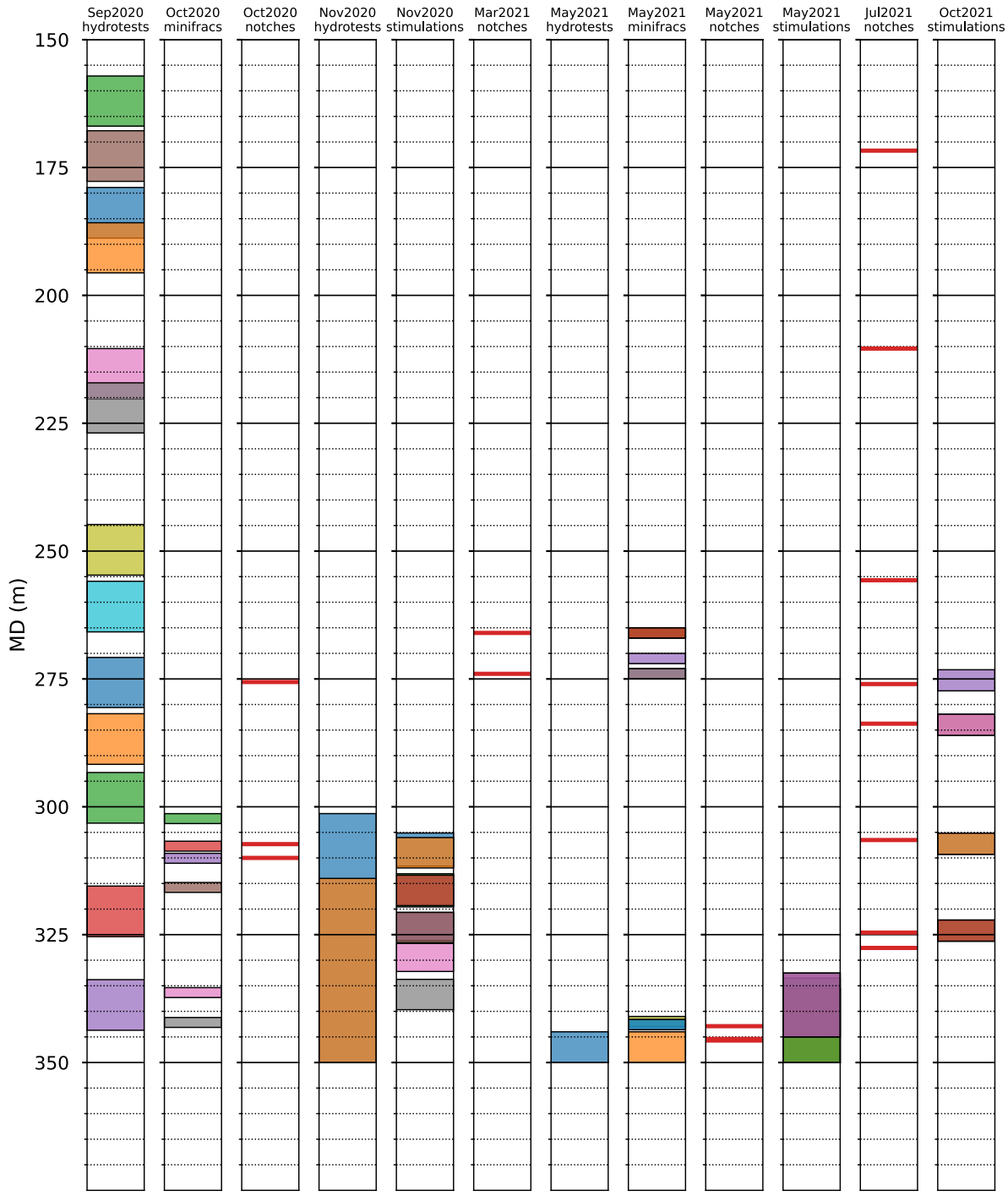


Figure 16. Depth intervals where different hydraulic tests, minifracs, stimulations and notching were carried out. Colors are random and are only intended to improve the readability of the plotHydraulic tests

5. Hydrotests

Formation pressure and flow rates were extensively measured in ST2 below 160m. A first campaign of measurements was carried out between August and September 2020, testing a total of 13 intervals (Figure 17 and Figure 16). A second set of measurements was carried out in December 2020 with a single packer setting to isolate the bottom section of the borehole (Figure 16). Detailed analysis of these tests is available in the ZoDrEx report "Evaluation of hydraulic tests in borehole ST2" by Meier et al.

Figure 17 shows the results of these hydraulic tests alongside the structural log and fault zone correlation with nearby wells. Three intervals stand out with important flow rates and estimated transmissibility:

1. T8: Flow=6.90 l/min; Transmissibility=7.7e-7 m2/s
2. T2: Flow=4.25 l/min; Transmissibility =1.7e-7 m2/s
3. T3: Flow =1.24 l/min; Transmissibility =1.6e-7 m2/s

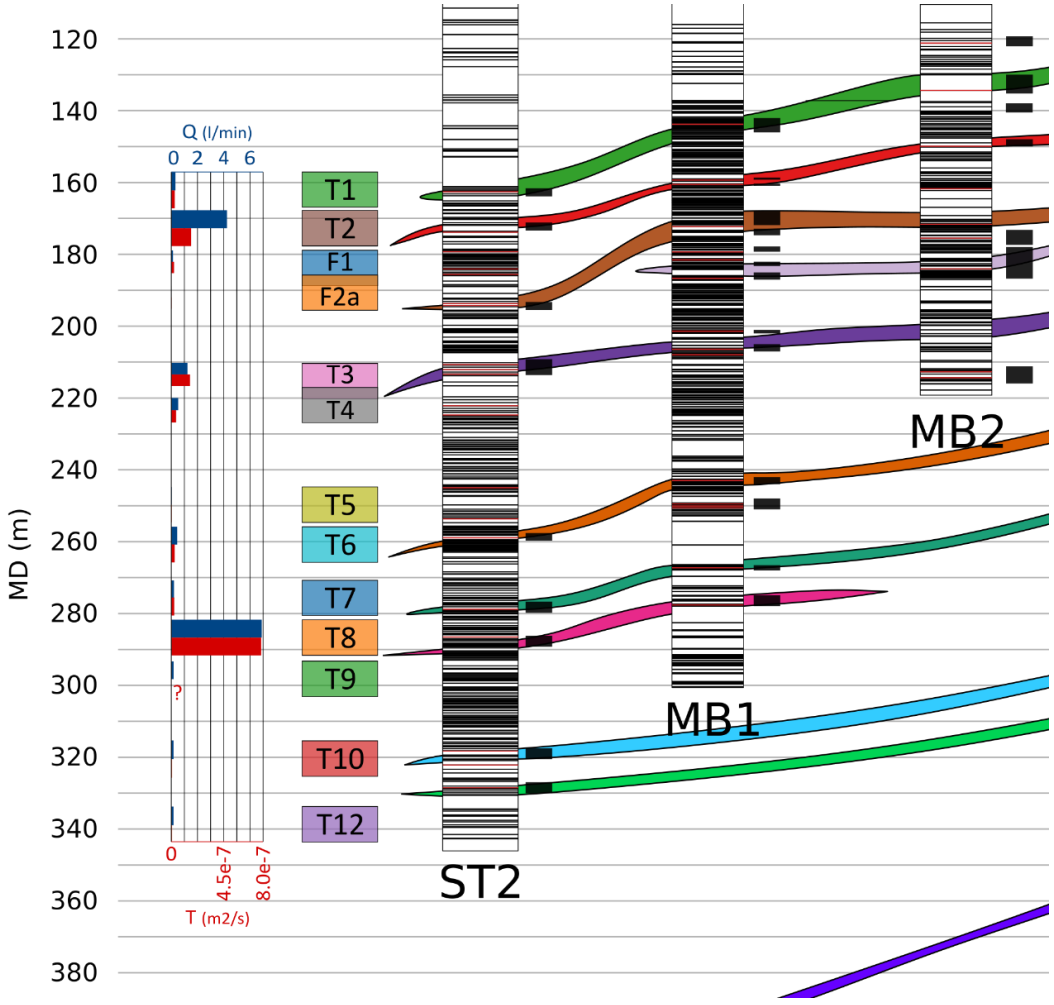


Figure 17. Hydraulic tests results and structural correlation between boreholes in the BULGG.

Important structures can be identified in each tested interval (Figure 18). There doesn't seem to be significant differences that could explain the variability in hydraulic properties in terms of thickness, orientation, or total number of structures. It is likely that the observed variability in hydraulic properties is linked to the way the structural network is connected beyond the borehole wall.

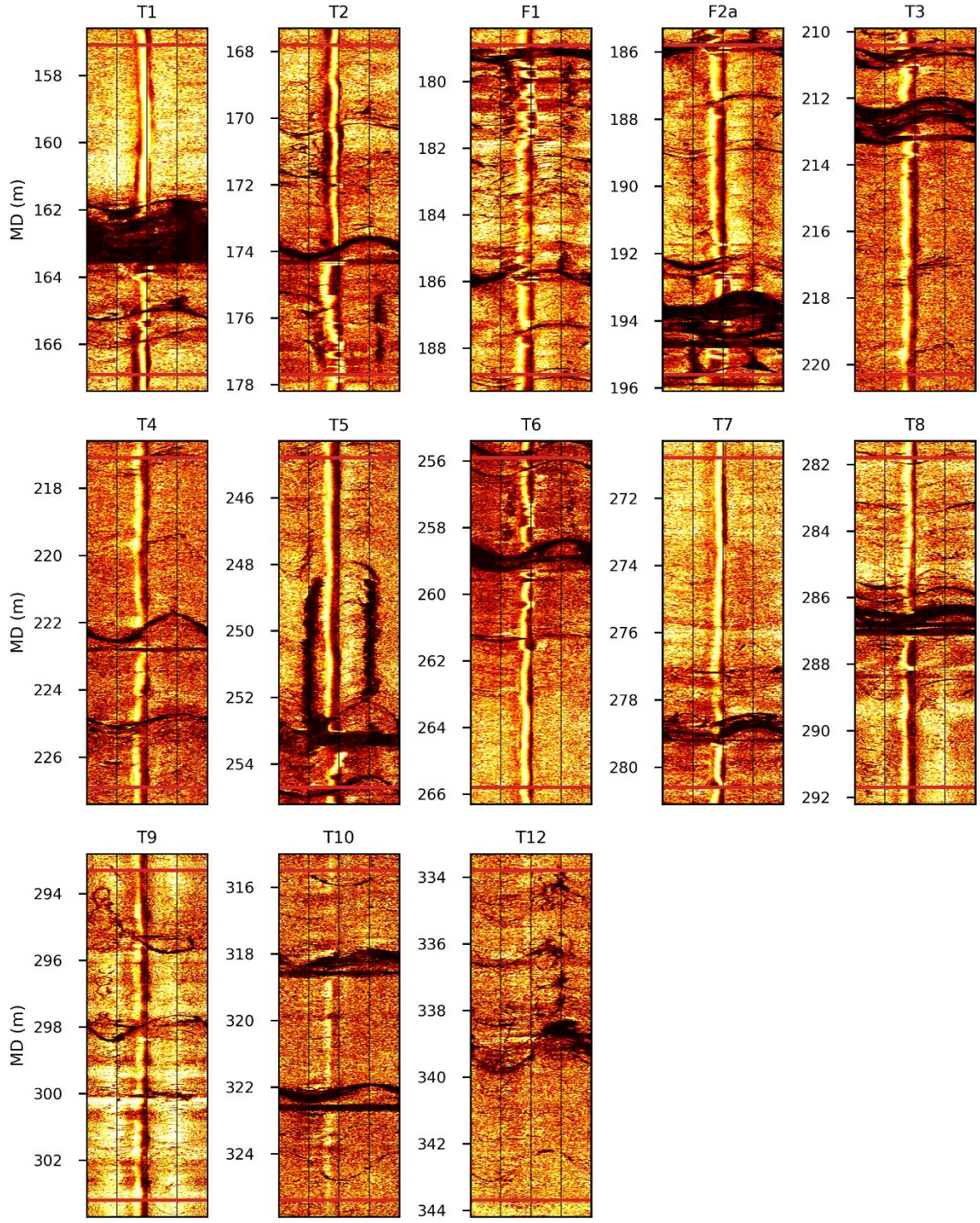


Figure 18. ATV log for each hydrotest interval.

6. Notching

Notches are micro-drills performed at the borehole wall. They show up as circular or elliptical shaped features in borehole images. In terms of acoustic signal, notches show a response similar to any other irregularity in the borehole wall (i.e. fractures, breakouts), that is longer travel times and lower amplitudes.

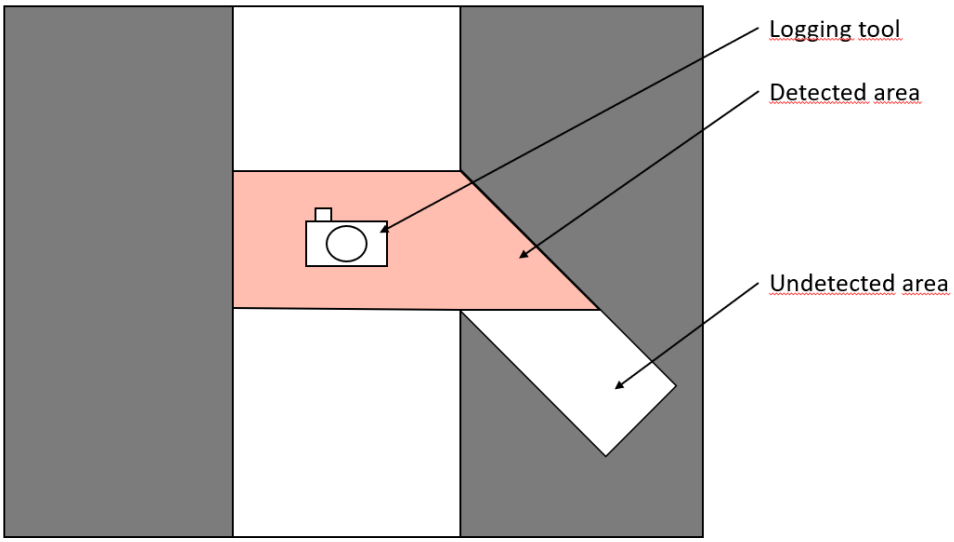
Notching of the borehole wall has several positive effects:

- It may help promoting transverse fractures during hydrofrac operations.
- Decrease near-wellbore tortuosity.
- Might help mitigate seismic risks by reducing the pressure required for breakdown

In the context of ZoDrEx, 4 notching campaigns were carried out with a total of 16 depths perforated (Table 2). Since the micro-drills are inclined at 60° with respect to the borehole axis, the imaging of notches by televiewer logs is limited to the first millimeters of the perforations (Figure 19). A 3D reconstruction (Figure 20) helps understand this factor that limits the capacity to evaluate the final geometry of each notch.

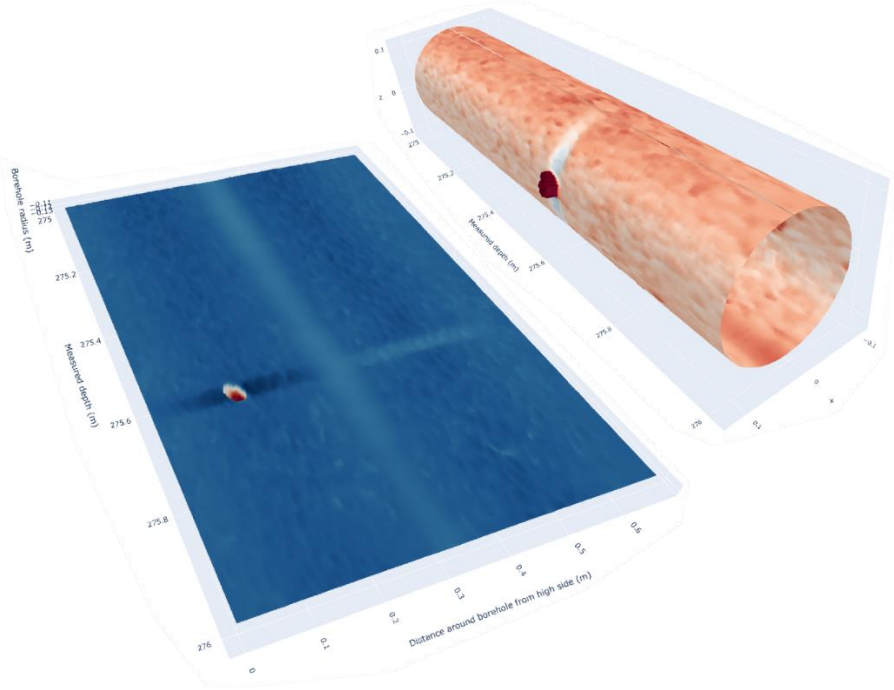
Table 2. Sumnmary of notching operations.

Notching		
Date	MD (meters)	Location (Degrees from the borehole high side)
01.10.2020	275.6	75°
	307.3	7°
	310.0	300°
20.03.2021	266.0	50°-70°-123°-170°257°
	274.0	132°-194°-238°260°320°
17.05.2021	342.9	33°-80°-340°
	345.4	115°-165°-205°-295°
	345.7	285°-340°
20.07.2021-02.10.2021	171.7	180°-270°
	210.4	270°-235°
	255.7	270°
	276	290°-270°
	283.75	305°
	306.5	250°
	324.6	272°
	327.6	unsuccessful



303

304 *Figure 19. Imaging of notches at oblique angle with borehole are incomplete. Image courtesy of*
305 *Niklas Geissler.*



306

307 *Figure 20. 3D reconstruction of ST2around 275m MD showing, partially, the notch at 275.6m. The*
308 *total length and complete geometry of the notch is obscured by the inclination of the perforation.*

309 6.1 October 2020

310 Three perforations were carried out at different depths in the borehole between 275m-310m. The 3
311 notches sit close to isolated natural fractures with limited acoustic response.

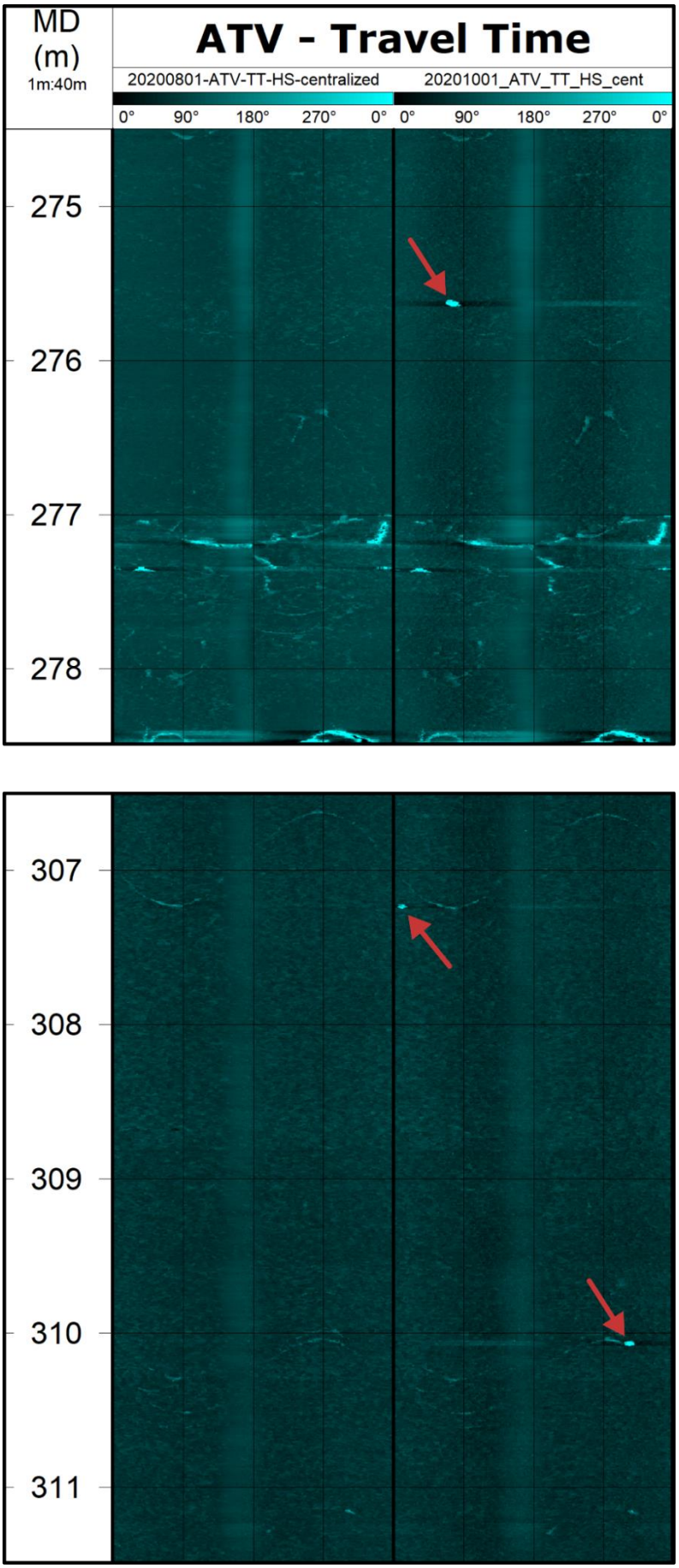


Figure 21. Examples of notching from October 2020 observed on ATV log (travel time).

6.2 March 2021

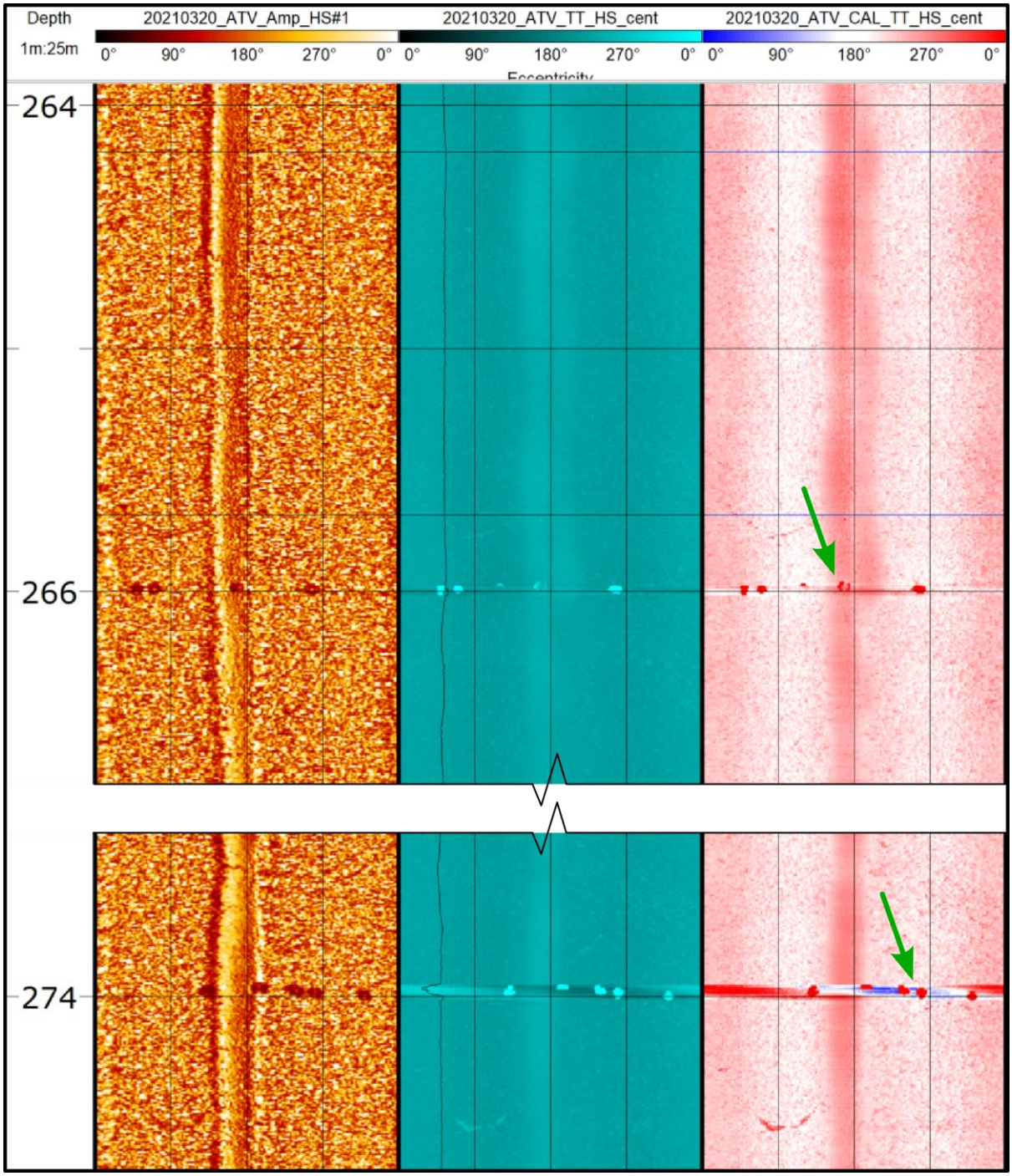


Figure 22. Result from notching operations carried out in March 2021.

6.3 May 2021

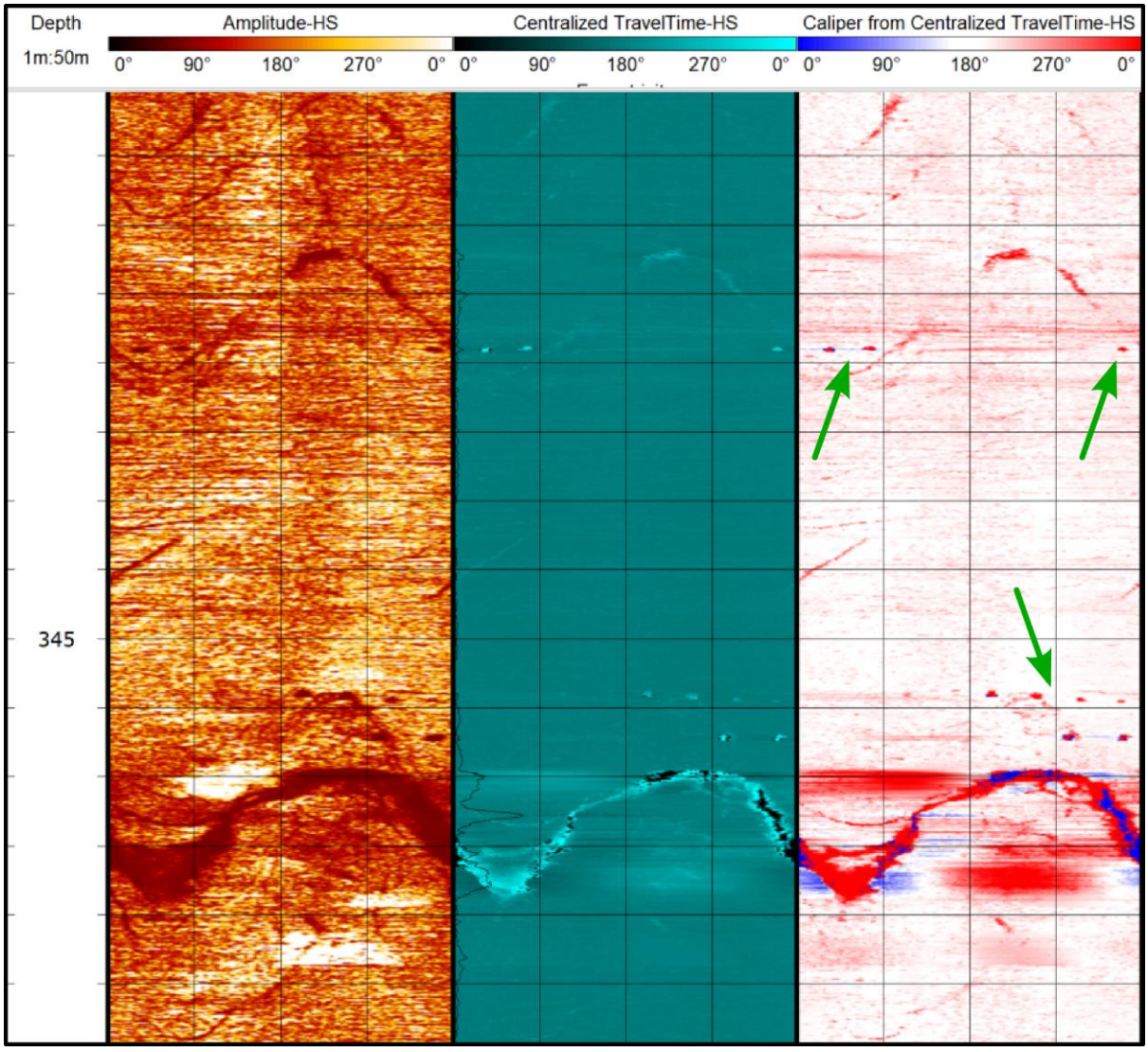


Figure 23. Result from notching treatment in May 2021

6.4 July-October 2021

A notching campaign through the cased and cemented borehole wall was carried out between July and October 2021. Seven depths were successfully perforated between 171-276m. All perforations are in the southern side of borehole between angles 180-305° from the high side (Figure 24).

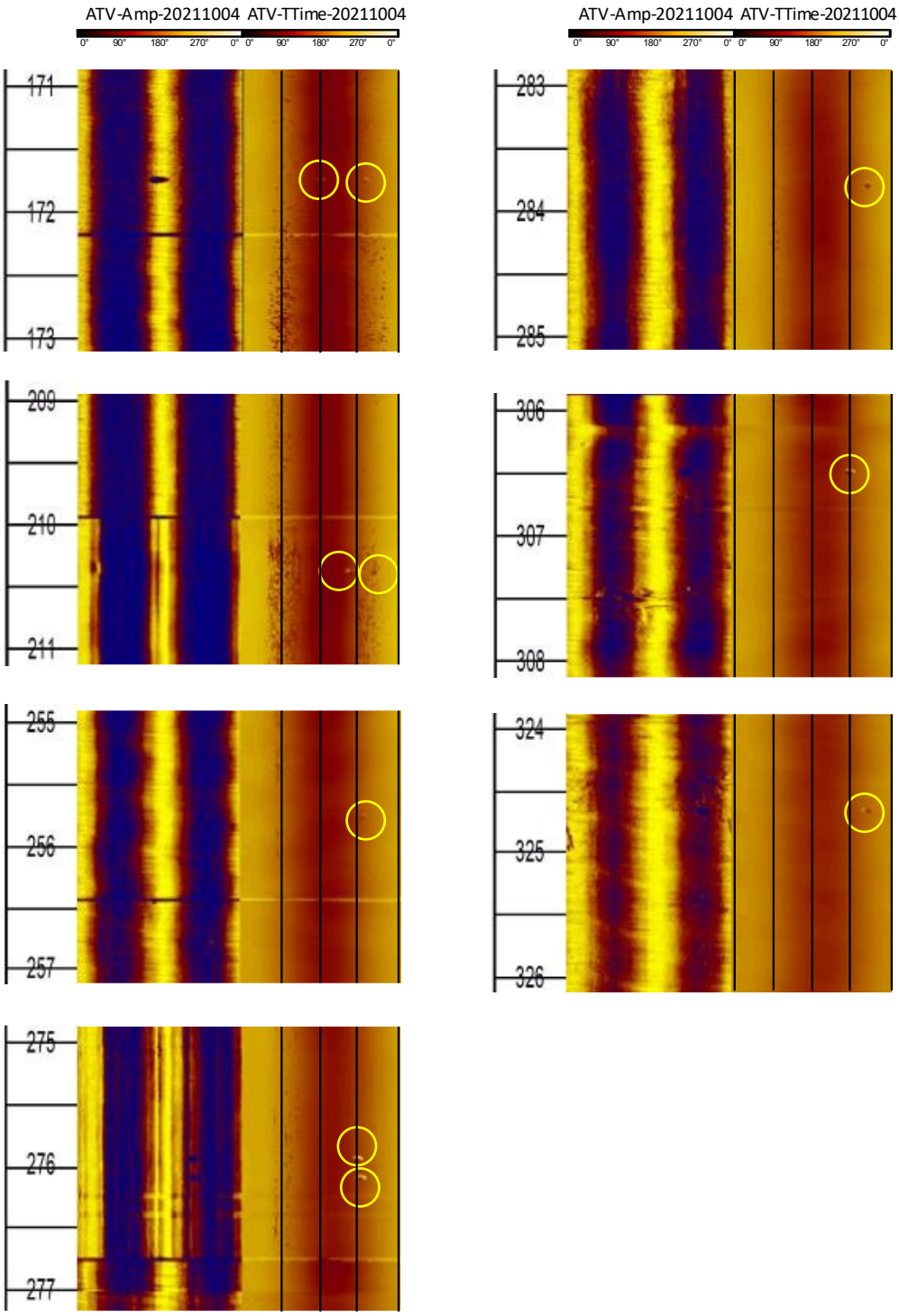


Figure 24. Notches through the casing drilled between July and October 2021.

A camera run allowed to check the depth of these notches and a match with fluid temperature and conductivity responses associated to the notching (). A certain mismatch exists between the depths shown in the camera runs, the ATV and the FTC logs. This mismatch is inherent to the logging process due to the different characteristics of the logging tools and the cables attached to them. In open hole conditions this mismatch is easily corrected, and all logs are corrected to match a unique

reference log. The lack of visible features in the cemented borehole wall makes this correction impossible so the depths mismatches persist.

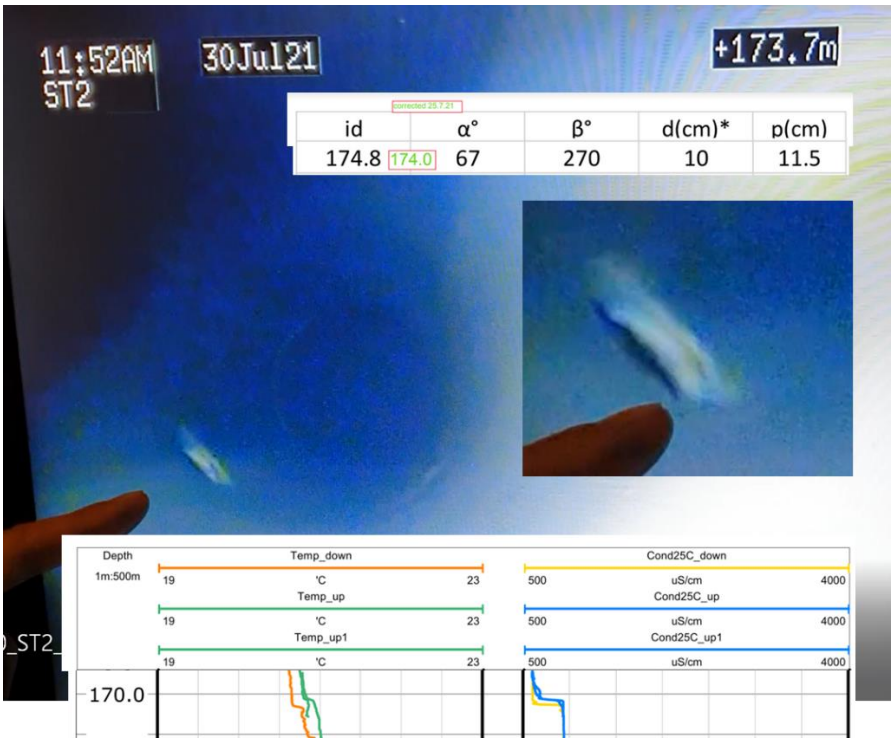


Figure 25. Notches listed in Table 2 at 171.7m.

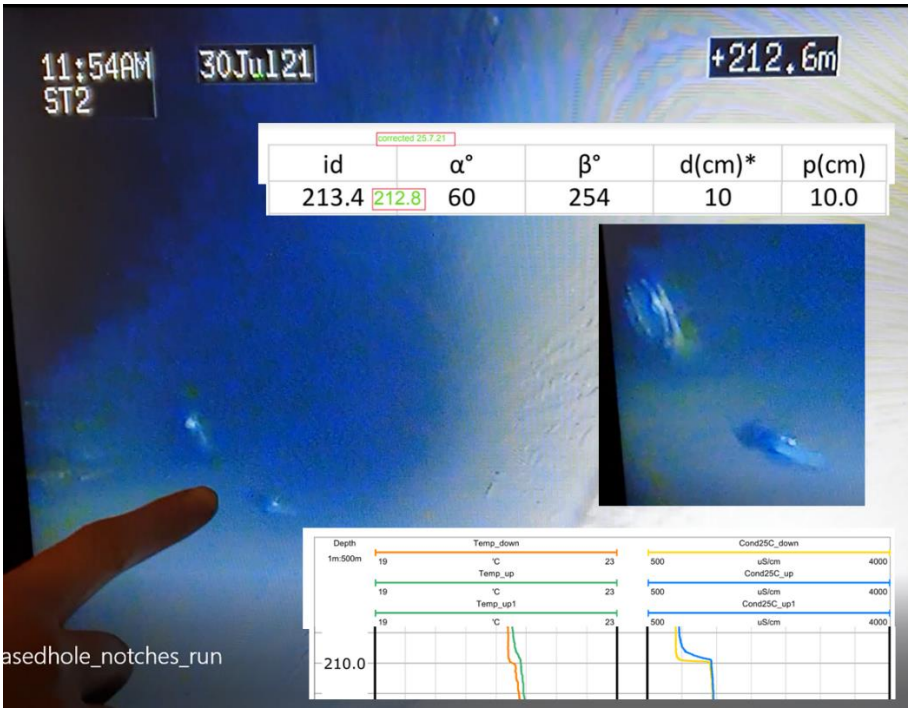
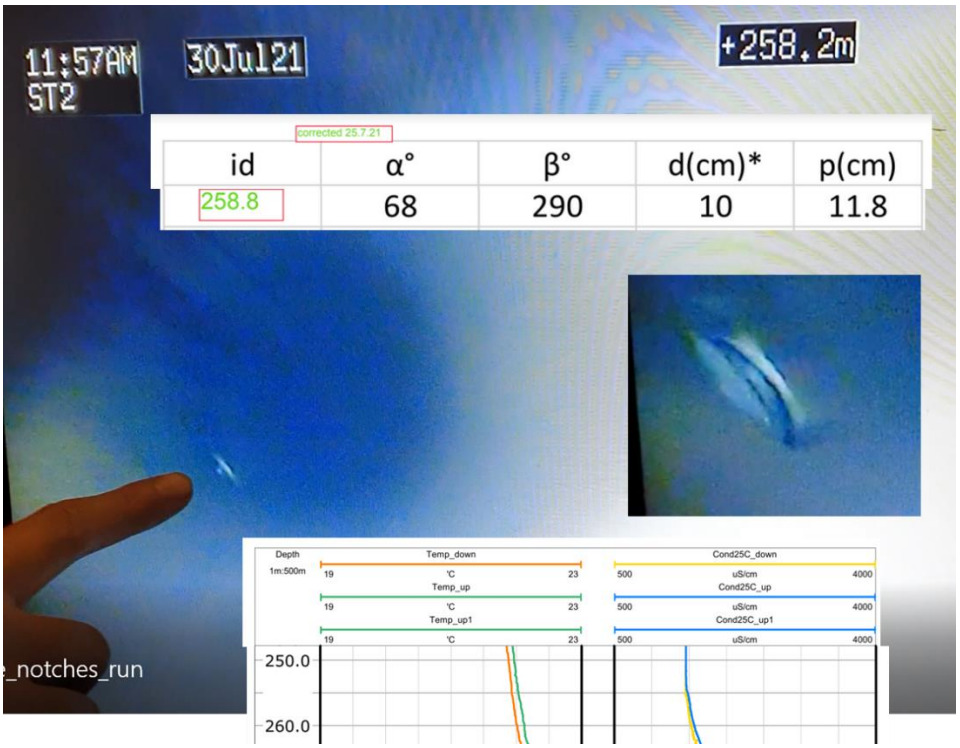
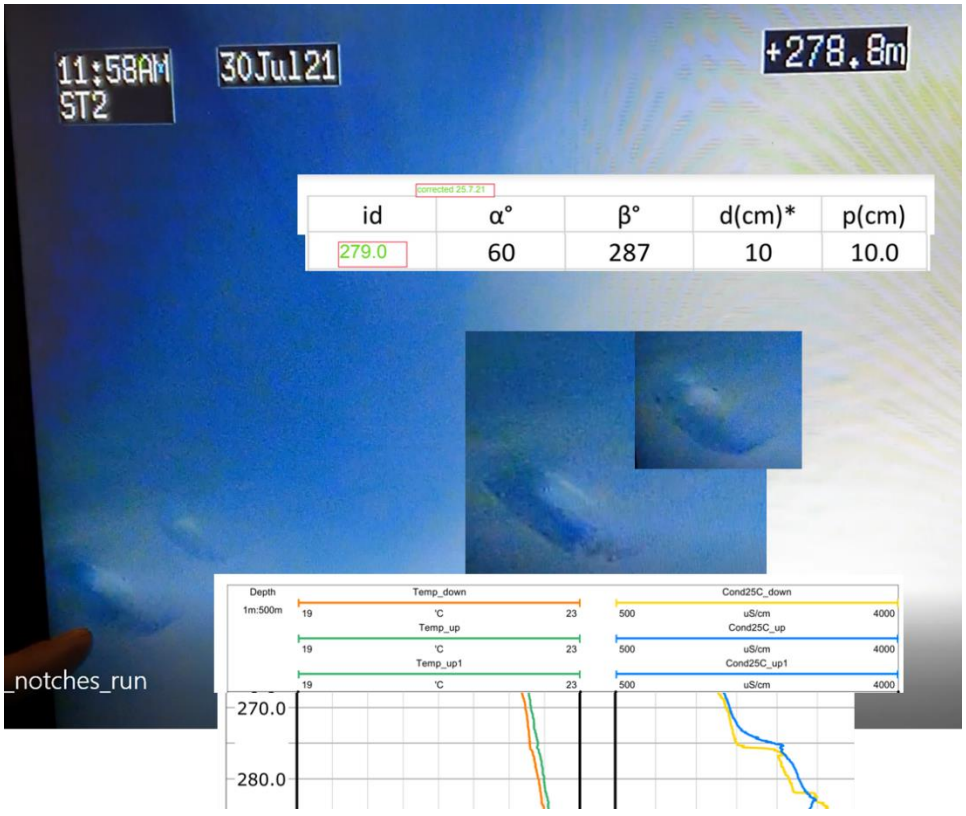


Figure 26. Notches listed in Table 2 at 210.4m.



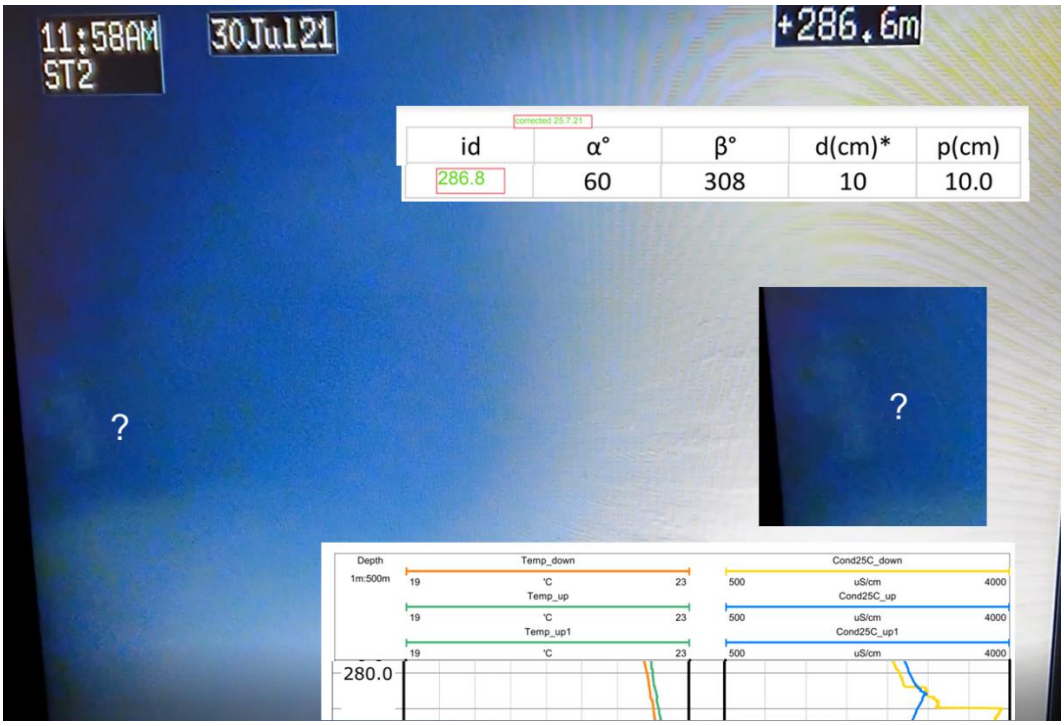
335

336 *Figure 27. Notches listed in Table 2 at 255.7m.*



337

338 *Figure 28. Notches listed in Table 2 at 276m.*



339

340 *Figure 29. Notches listed in Table 2 at 283.75m.*

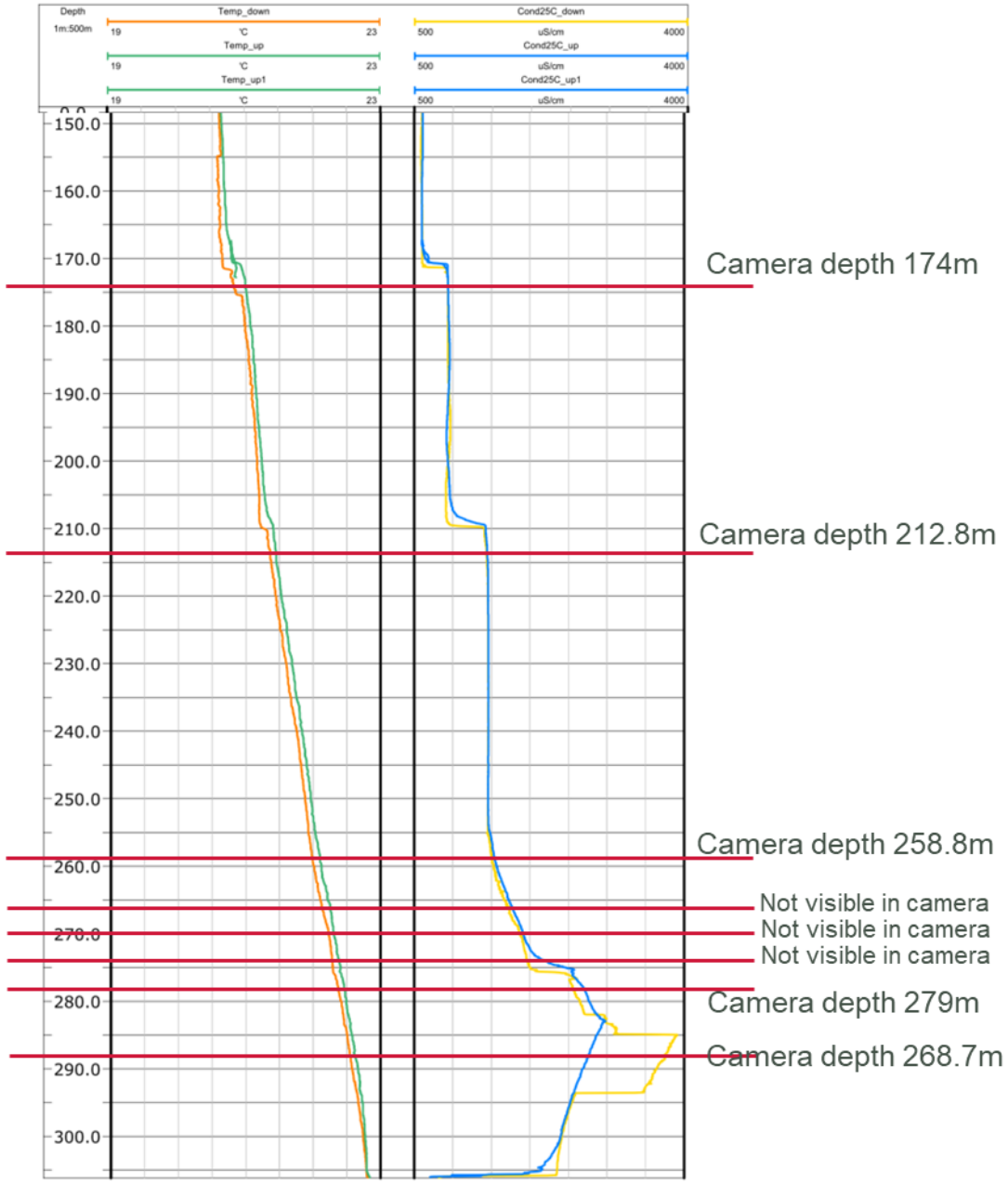


Figure 30. Summary of notches identified in the camera run and the associated fluid temperature and conductivity response.

7. Minifracs – October 2020

Minifrac tests were carried out in 8 intervals along ST2. No tensile fractures were identified on image logs acquired after the tests. OTV logs show that all minifracs were done in intervals with pre-existing natural fractures that, for most of them, lack of any clear amplitude signal (i.e. they don't show up in ATV logs). So, despite their original "tight" state, the minifrac tests most probably managed to jack these structures instead of creating new tensile fractures (Figure 31 to Figure 37).

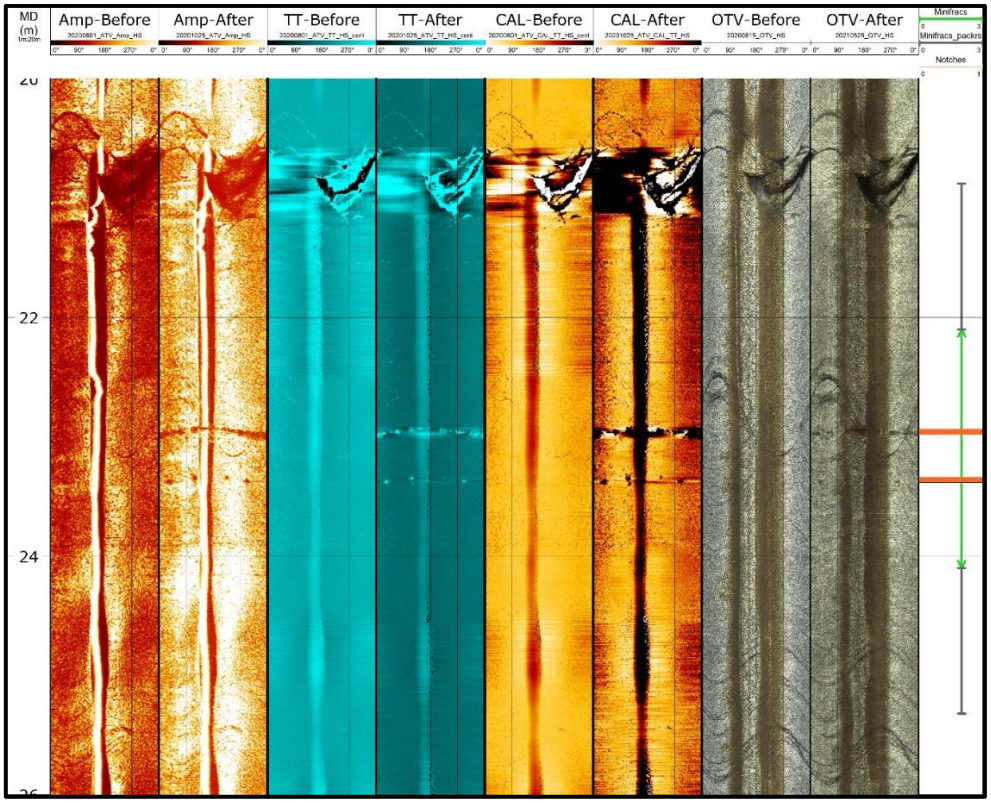


Figure 31. Interval 22.1-24.1m.

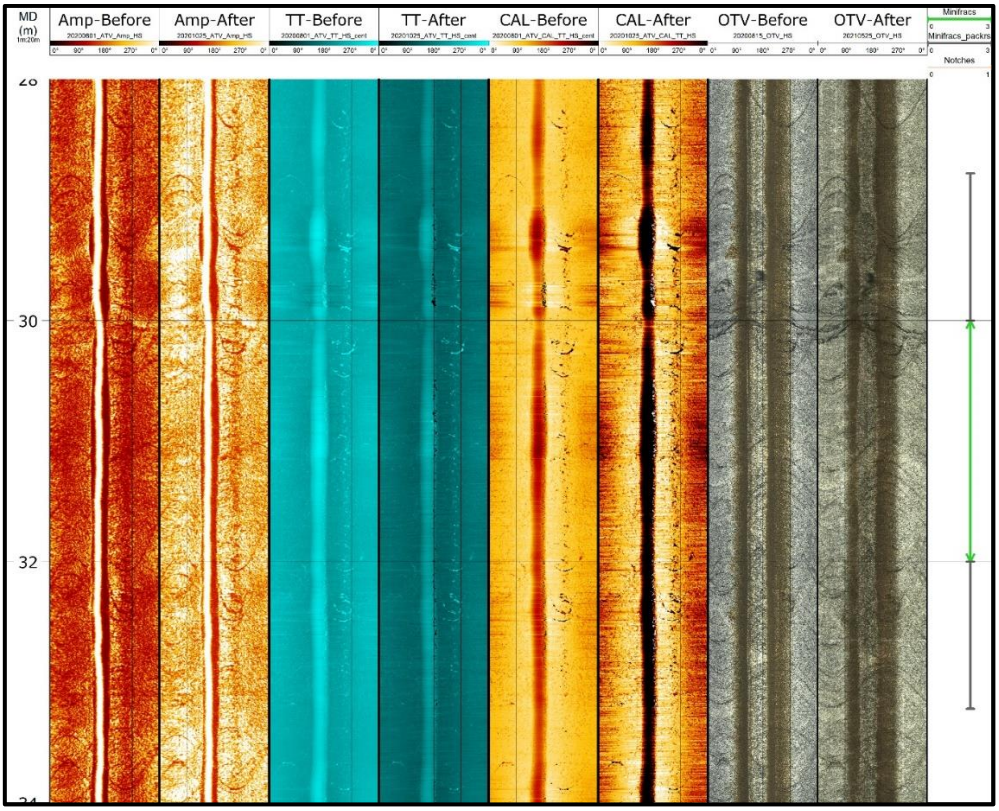


Figure 32 Interval 30-32m

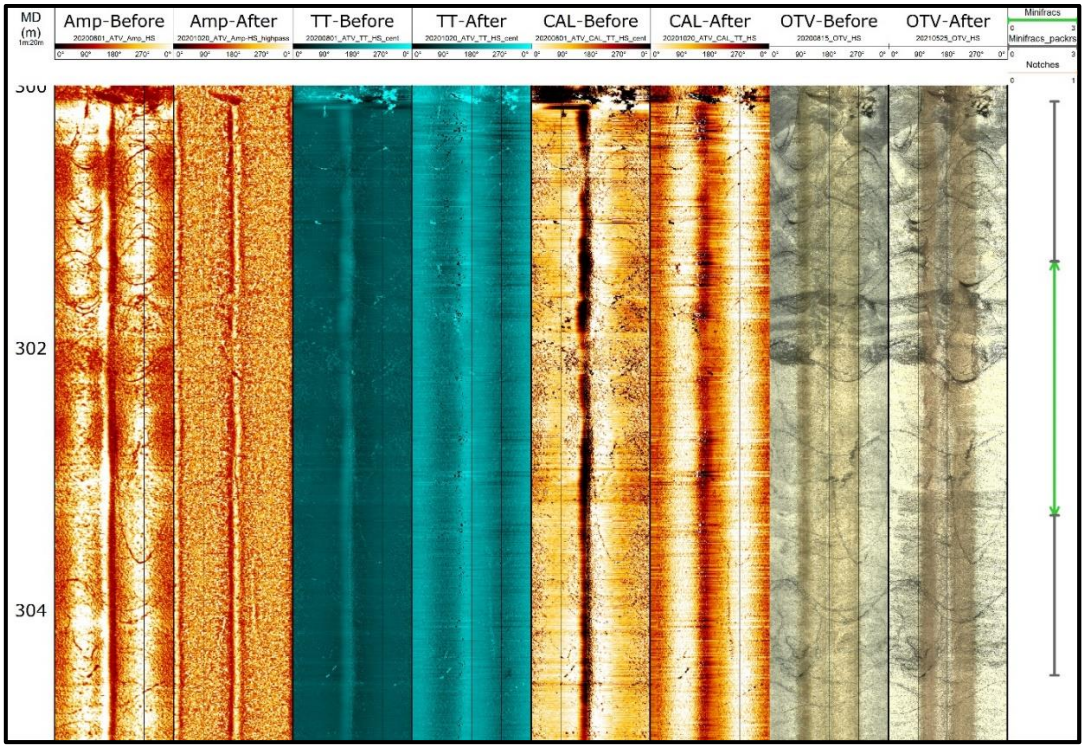


Figure 33. Interval 301.3-303.3m

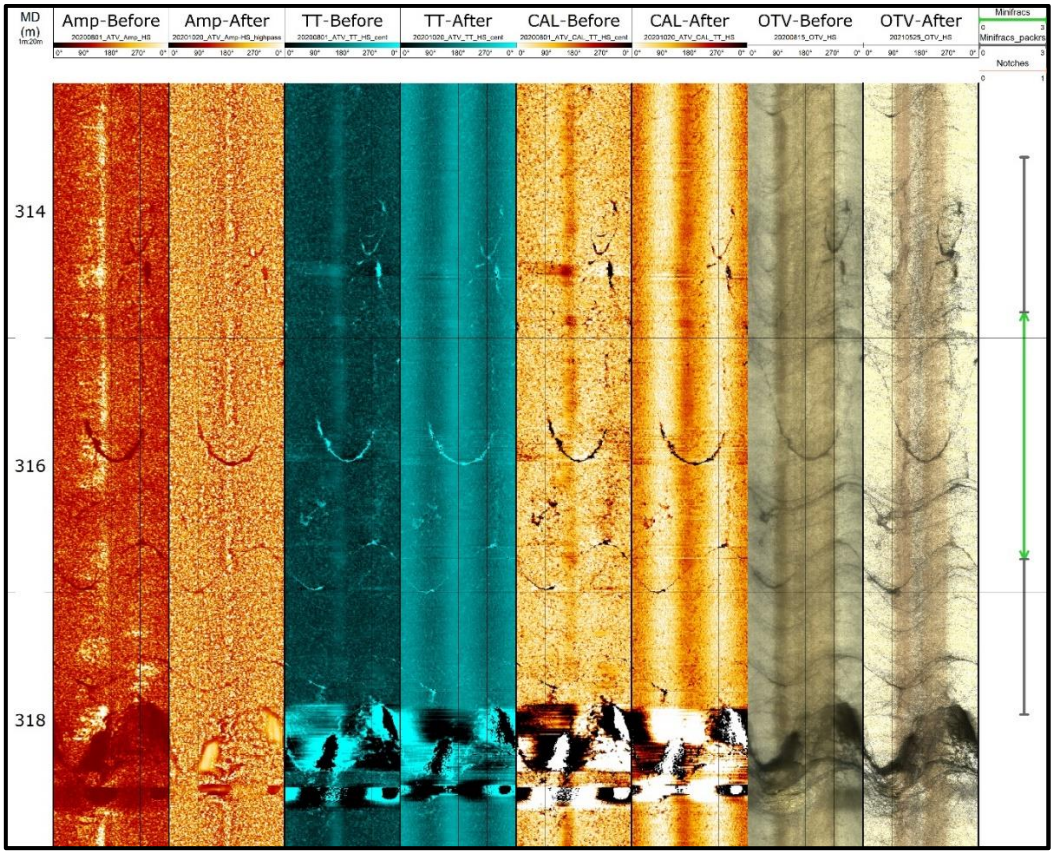
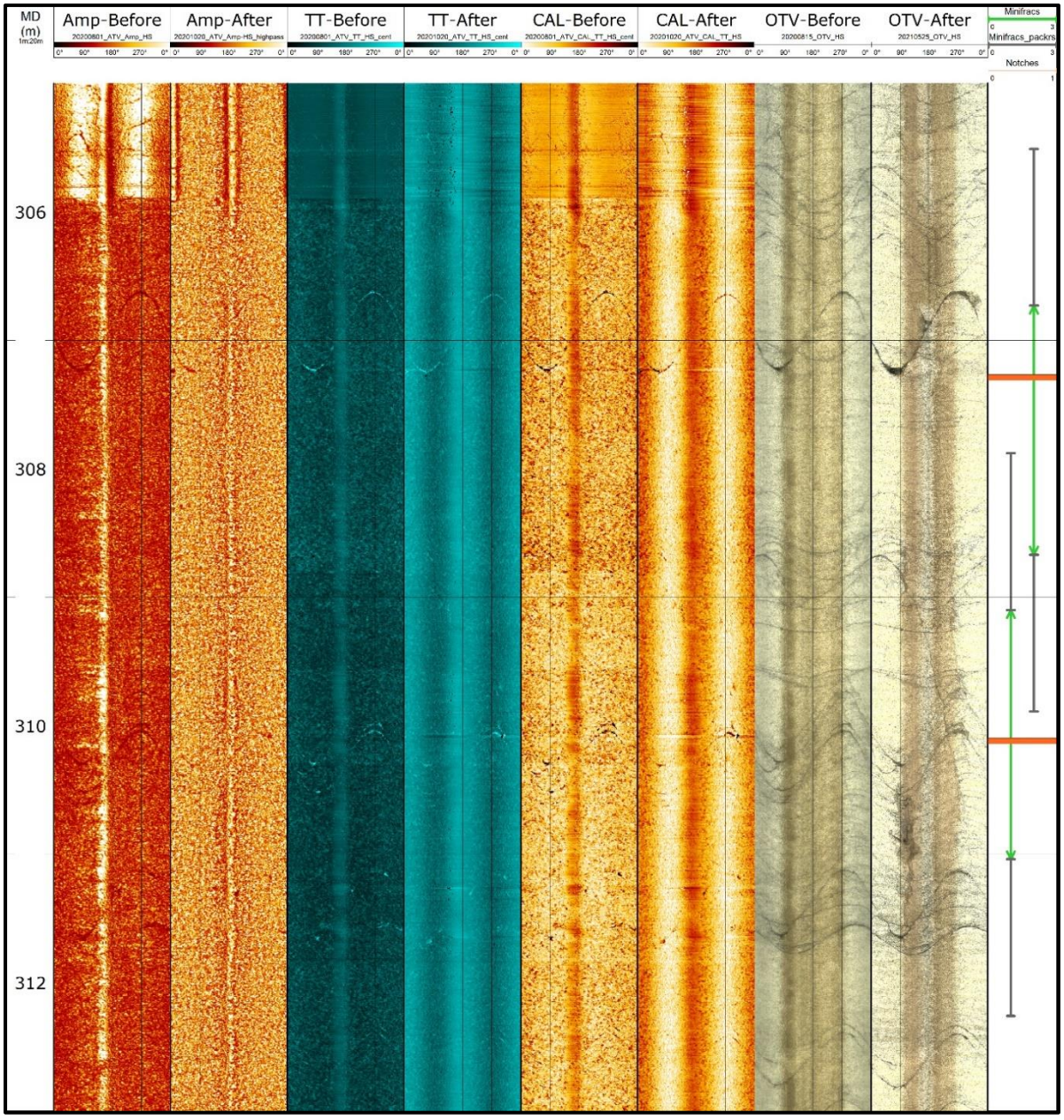


Figure 34. Interval 314.8-316.8m



358

359 *Figure 35. Intervals 306.7-308.7m and 309.1-311.1m*

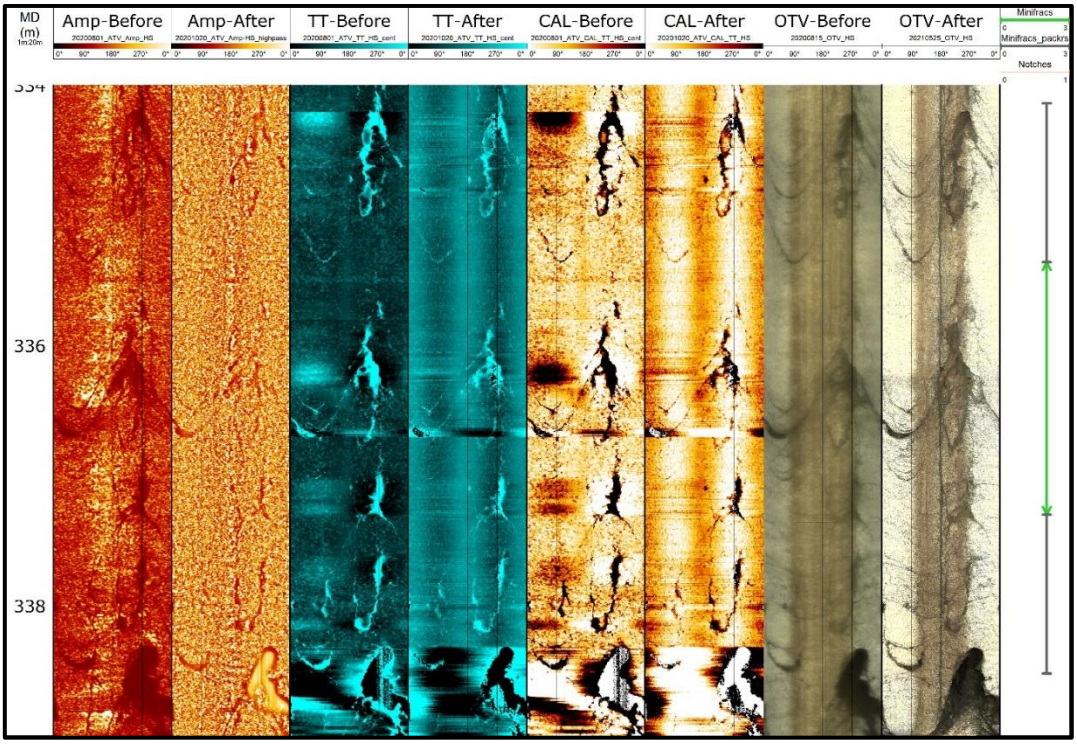


Figure 36. Interval 335.3-337.3m

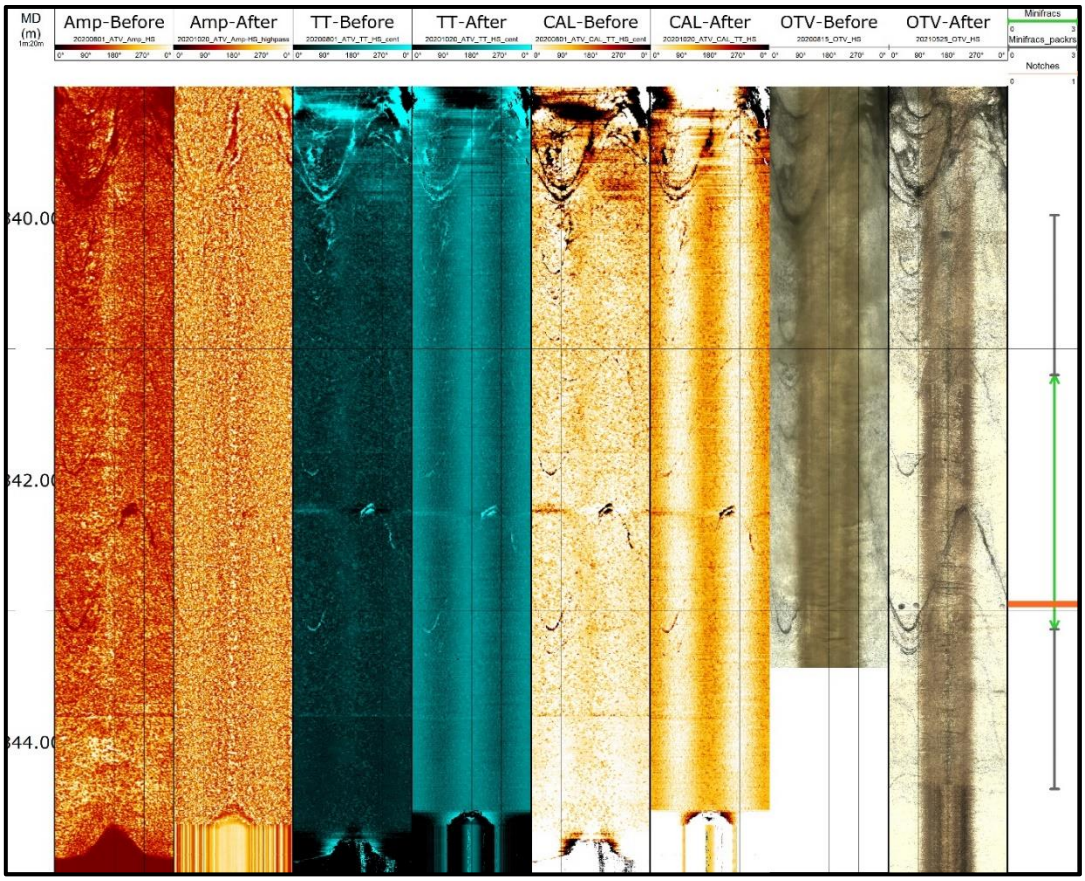


Figure 37. Interval 341.1-343.1m

8. Stimulations

Three stimulation campaigns were carried out in ST2 in the framework of ZoDrEx. (Table 3).

The first set of stimulations was carried out in November 2020 in open hole conditions and with a double packer system. The stimulated intervals are located between 305m and 340m. A second stimulation campaign in May 2021 was carried out also in open hole conditions but this time with a single packer to isolate the bottom of the borehole between 332m and 350m.

The third stimulation campaign took place in October 2021 in the cemented and cased borehole and through perforations done between July and October 2021 (see section 6.4). The intervals stimulated during this last campaign are located between depths 275m and 325m.

374 *Table 3 Summary of stimulation campaigns*

Stimulation Campaign	interval id	Packers					Interval			Datetime	
		Upper		Lower		length	top	base	length	start	end
		top	base	top	base						
Nov2020	1a	303.63	305.13	311.61	313.11	1.5	305.13	311.61	6.48	10/11/2020 19:25:06.0	15/11/2020 21:38:00.0
	2a	311.6	313.1	319.58	321.08	1.5	313.1	319.58		16/11/2020 13:38:54.0	19/11/2020 00:29:00.0
	4a	319.2	320.7	326.18	327.68	1.5	320.7	326.18	5.48	21/11/2020 09:01:10.0	23/11/2020 11:58:43.0
	5	325.22	326.72	332.2	333.7	1.5	326.72	332.2		23/11/2020 20:33:59.0	25/11/2020 21:37:55.0
	6	332.52	333.74	339.68	340.9	1.22	333.74	339.68	5.94	27/11/2020 18:06:42.0	29/11/2020 12:45:38.0
	2b	312.16	313.38	319.32	320.54	1.22	313.38	319.32		29/11/2020 13:34:43.0	29/11/2020 23:14:54.0
	4b	319.4	320.62	326.56	327.78	1.22	320.62	326.56		30/11/2020 00:31:43.0	30/11/2020 12:40:55.0
	1b	304.8	306.02	311.96	313.18	1.22	306.02	311.96		30/11/2020 13:22:13.0	30/11/2020 23:20:40.0
May2021	6sp	331.02	332.52			1.5	332.52	350	12.48	21/05/2021 17:32:00.0	23/05/2021 13:48:00.0
Oct2021	1						305.16	309.29	4.13	06/10/2021 11:20:30.0	08/10/2021 12:06:00.0
	8						281.9	286.03		08/10/2021 13:54:43.0	12/10/2021 17:56:00.0
	7						273.2	277.33		12/10/2021 19:21:00.0	13/10/2021 11:15:00.0
	4						322.15	326.28		13/10/2021 13:33:00.0	14/10/2021 08:40:00.0
	1						305.16	309.29		14/10/2021 10:01:36.0	14/10/2021 12:55:00.0
	4						322.15	326.28		14/10/2021 14:02:00.0	14/10/2021 15:00:00.0
	8						281.9	286.03		14/10/2021 16:27:30.0	15/10/2021 07:13:00.0

375

8.1 November 2020

8.1.1 Intervals

Five intervals were stimulated during the November 2020 campaign (i.e. 1, 2, 4, 5 and 6). Three of these intervals were re-stimulated during the same campaign (1, 2 and 4). Figure 38 and Figure 39 show the before-vs.-after amplitude values from the ATV images for each interval.

Differences between the before and after versions of the ATV are observed in the intervals 1a and 2a where some natural, pre-existing fractures are more visible in the after version of the log. New breakout-like features also appear in the after images of the 1a interval with some further differences after the re-stimulation as it can be seen in the after version of the 1b interval. The effects of the stimulation, observed in intervals 1, 2 and 5 are described and analyzed further in detail in the subchapter "8.1.4. Shear displacement on pre-existing fractures"

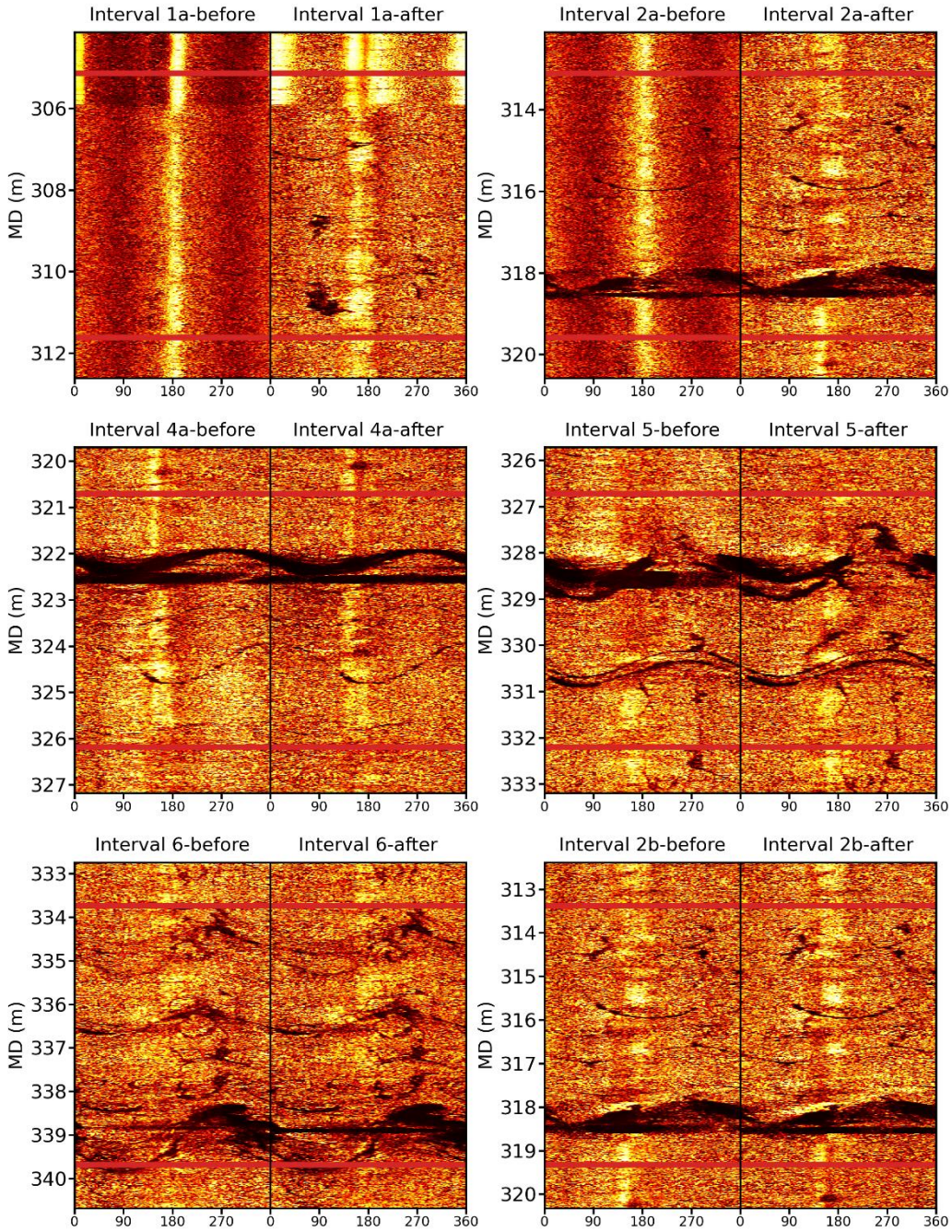


Figure 38. Before vs. After ATV amplitude logs of intervals stimulated in November 2020.

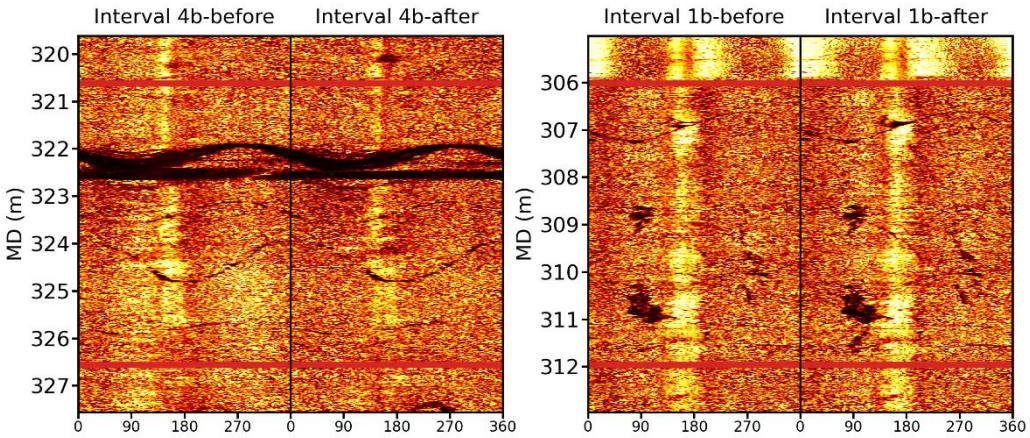


Figure 39. Continuation from Figure 38. Before vs. After ATV amplitude logs of intervals stimulated in November 2020.

8.1.2 Fluid Temperature & Conductivity

Two FTC logs are compared in Figure 40, corresponding to runs before the stimulation (September 17th), and after the end of the stimulation (December 19th).

The fluid temperature increased above 334m while it decreased below. The temperature gradient remains largely unchanged except for the disappearance of the temperature anomaly at 303m and the appearance of new ones between 326m-334m. The significant cooling of the water column below 329m is probably due to the backflow of injected water from interval 6 after the end of the stimulation.

The correspondent conductivity anomaly at 303m was also smoothed out after the stimulation. In general, conductivity decreased in the whole interval with important changes in the trend at 308m, 326m and 330m. Conductivity values below 330m are equivalent to those above 308m. This shows the salinity decrease only affected the one between intervals 1 and 5 when the December 19th log was run.

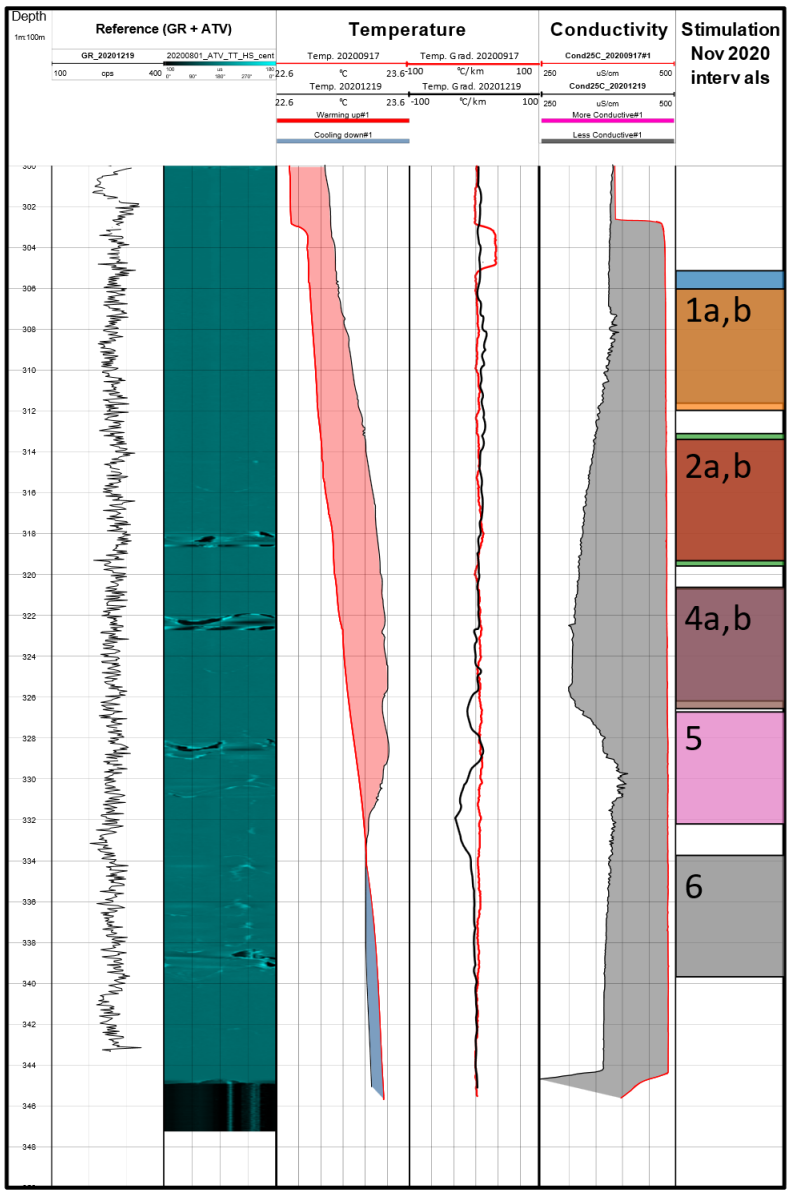


Figure 40. Fluid temperature and conductivity before and after the November 2020 stimulation.

8.1.3 Newly formed Breakouts

New breakouts are observed in ATV logs between 300-315m MD after the November 2020 stimulation campaign. It is not entirely clear if these breakouts formed as a consequence of the stimulation treatments or by wearing of the borehole due to the rubbing of logging tools and packer systems.

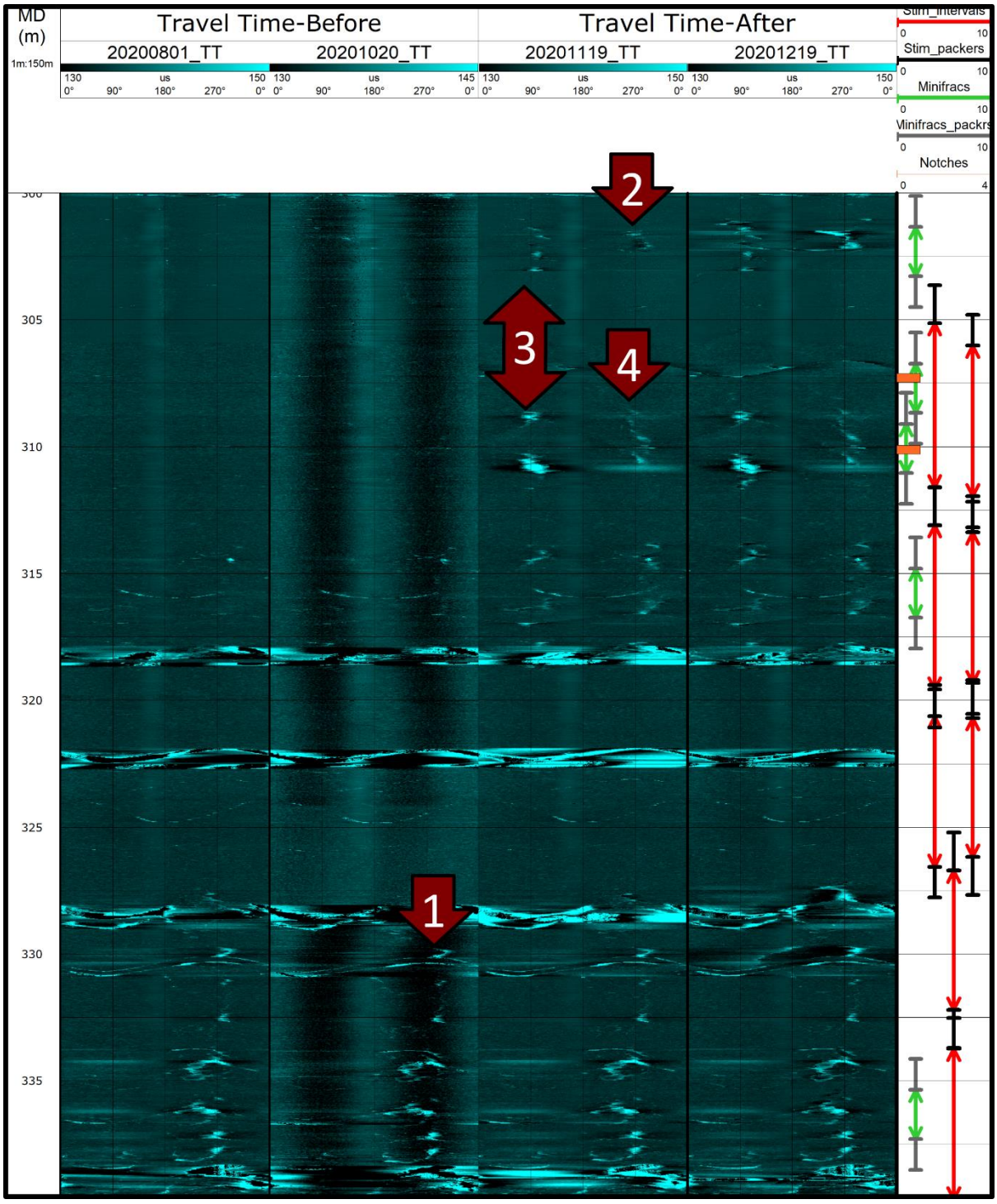


Figure 41. Four different ATV logs, two pre-stimulation (August and October 2020), one during stimulation (November 2020) and one post stimulation (December 2020). Pre-existing breakouts (1) vs. new breakouts created during the stimulation carried out in November 2020 (2-4). New BOs concentrate in the upper stimulated intervals. At this scale of observation, new BOs are not necessarily located near the biggest natural fractures. Instead, they seem to locate around smaller fractures reactivated by the stimulation.

8.1.4 Shear displacement on pre-existing fractures

The travel time of the acoustic signal, measured during the ATV acquisition, allows the 3D reconstruction of the borehole wall surface. This estimated 3D "caliper" was used here to identify and analyze the potential changes in the borehole wall induced by the shear stimulation campaigns of October 2020 and May 2021. A shear displacement along a structure intersecting the borehole (Figure 42A) will reduce and increase the distance between the borehole wall and the borehole axis in different places along the fracture as shown by the synthetic 3D caliper in Figure 42B. Figure 42C shows a real natural fracture in ST2 where the same pattern of cyclic caliper variation along the fracture can be observed.

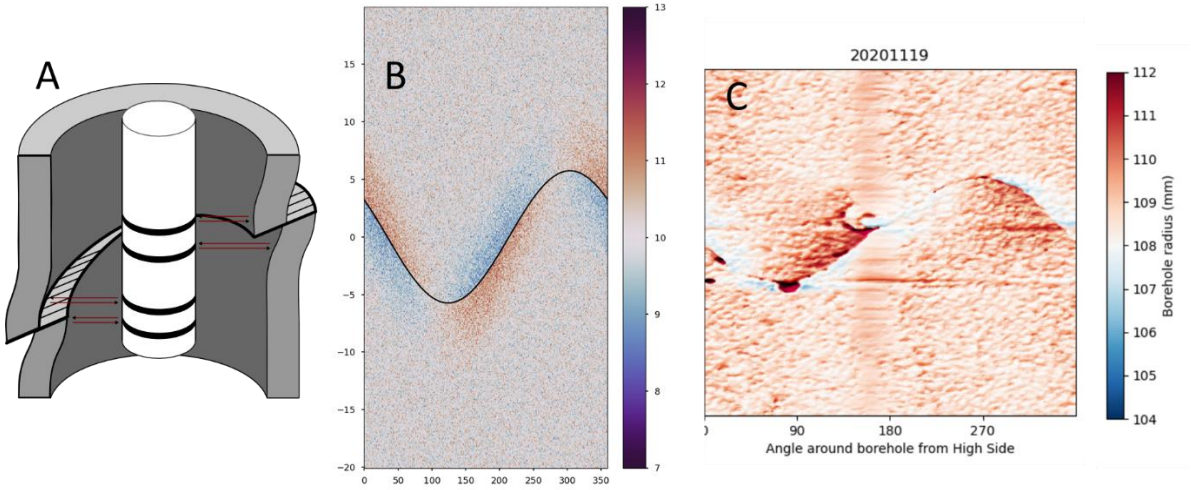


Figure 42 A) Sketch showing how a constant shear displacement vector applied on a fracture affect the distance between the borehole wall and the borehole axis. B) Synthetic simulated case with a fracture and an arbitrary shear displacement vector. Blue zones (decreased distance) intercalate with red zones (increased distance) along the fracture. C) A real case from ST2s showing a similar pattern as in B.

The comparison of ATV logs from before and after the stimulation allowed us to confirm that the observed effect was caused by the shear stimulation (Figure 43).

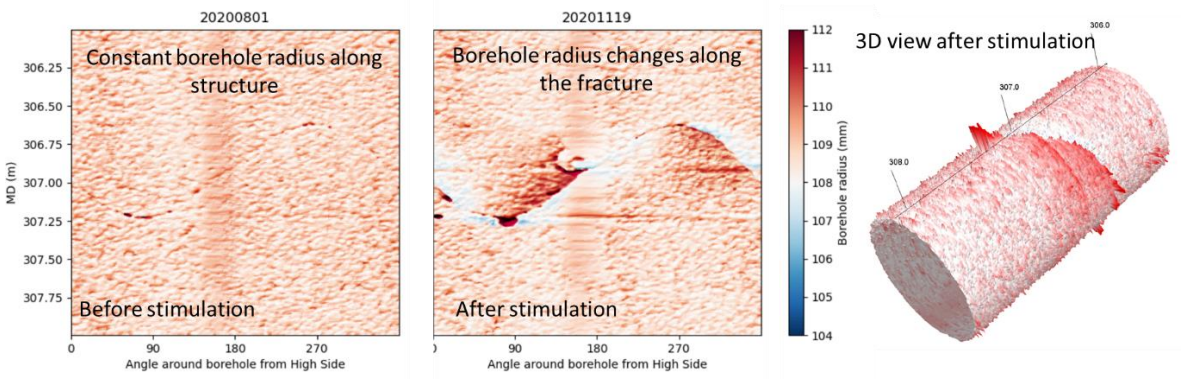


Figure 43. Example of sheared structure after stimulation. This structure can be found in interval 1a and 1b in Figure 38.

The amplitude of the shear displacement was the biggest after the 1st stimulation as shown in Figure 44. The re-stimulation carried out shortly afterwards didn't bring much of a change in the shear displacement.

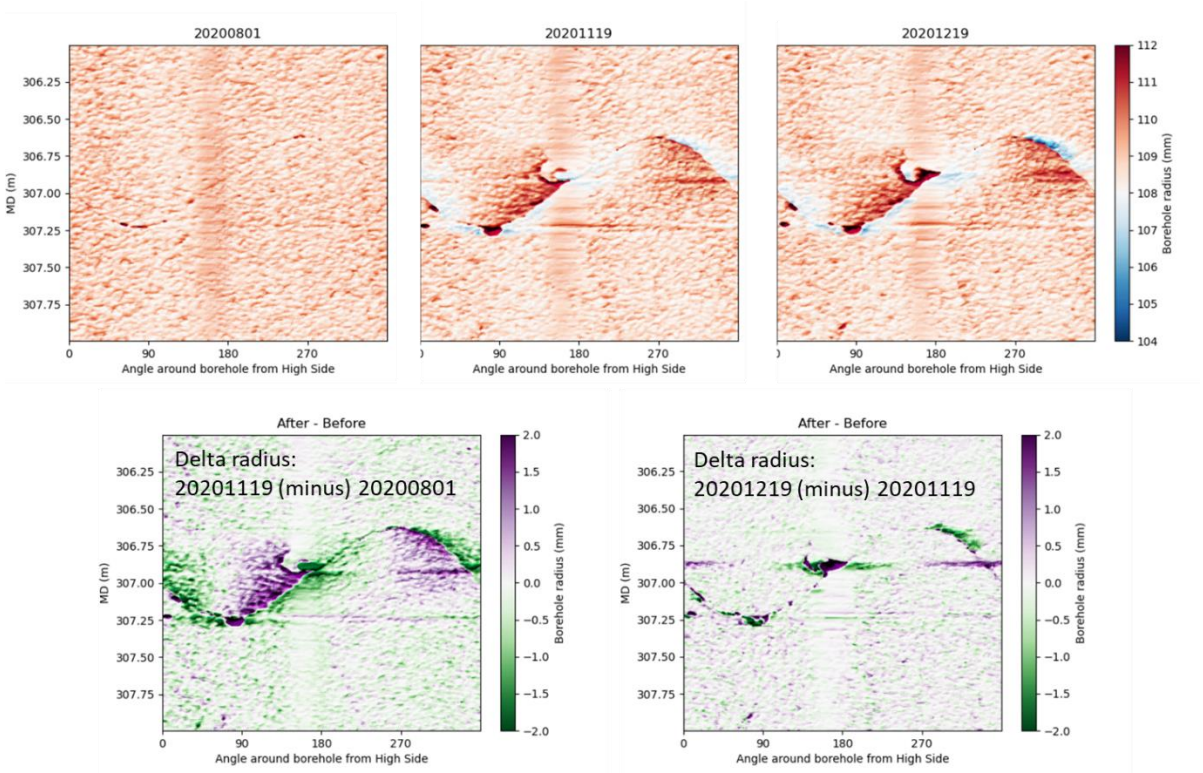


Figure 44. Sequential development of the deformation. Most displacement takes place in the 1st stimulation.

The identified displacement can be directly measured in the 3D caliper log at different places along the fracture (Figure 45). Maximum displacements of 5 mm could be measured. The zone affected by this deformation can extend up to 50cm away from the fracture.

The above-described shear displacement was identified in 3 different structures along ST2 in intervals 1, 2 and 5 (Figure 46). In each case, displacements between 1-5 mm were measured. The respective displacement vectors indicate that the shear sense was normal. This is at odds with the theoretical reverse displacement vector predicted when applying the stress state for the BULGG assessed in short boreholes in the vicinity of the tunnel (Ma et al., 2019) (Figure 47).

The three fractures with shear displacement share the common characteristic of being relatively simple structures that express as thin, linear features in the image logs. The lack of observed shear displacement in other intervals does not mean that it didn't take place, but rather that other structures are too complex, and the borehole wall is too perturbed by the drilling around these more complex fractures.

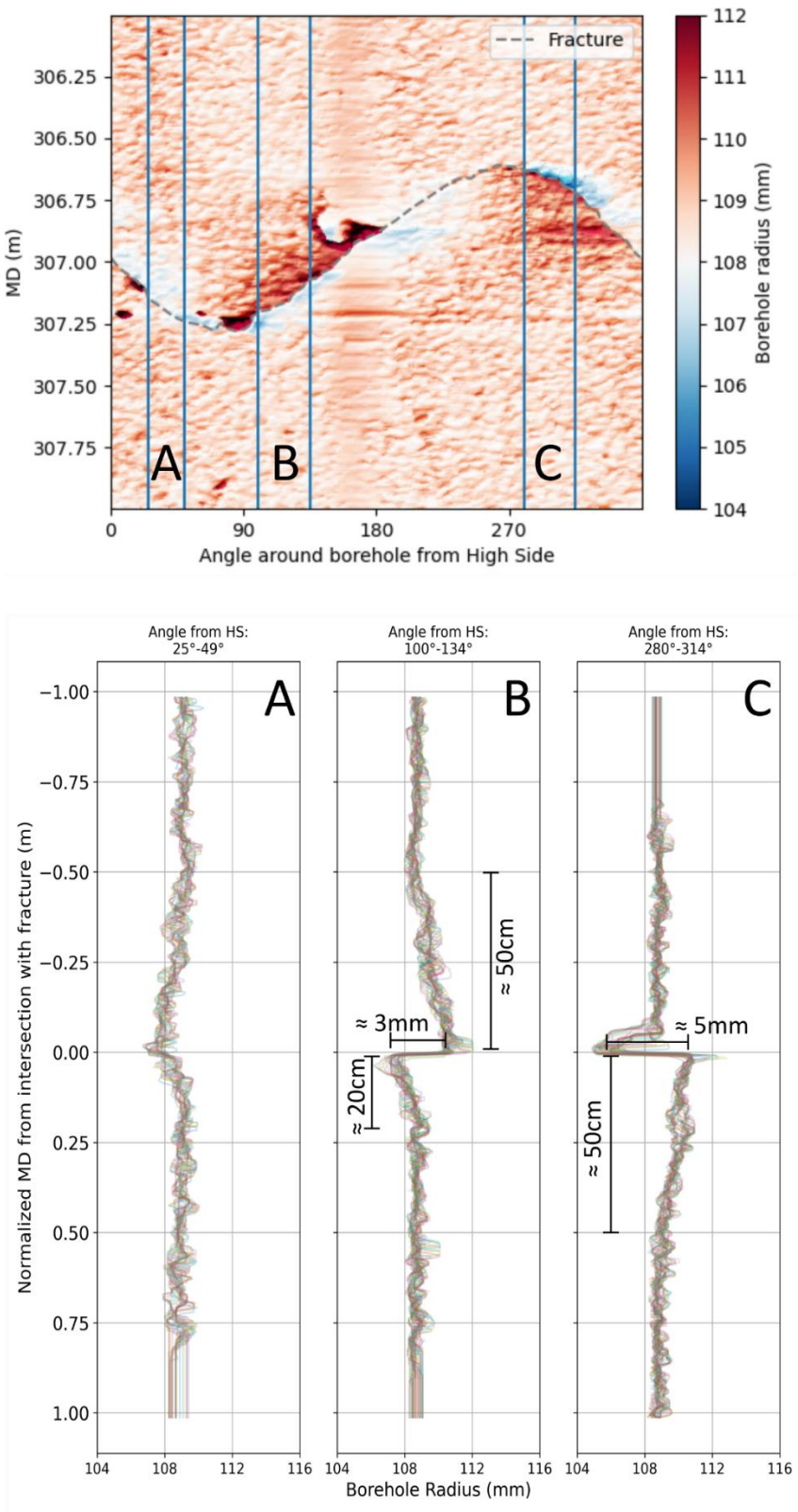


Figure 45. 3D caliper profiles across a fracture reactivated during the stimulation. Displacements of up to 5mm could be detected on acoustic logs. The effects of displacement can be seen as far as 50cm away from the fracture.

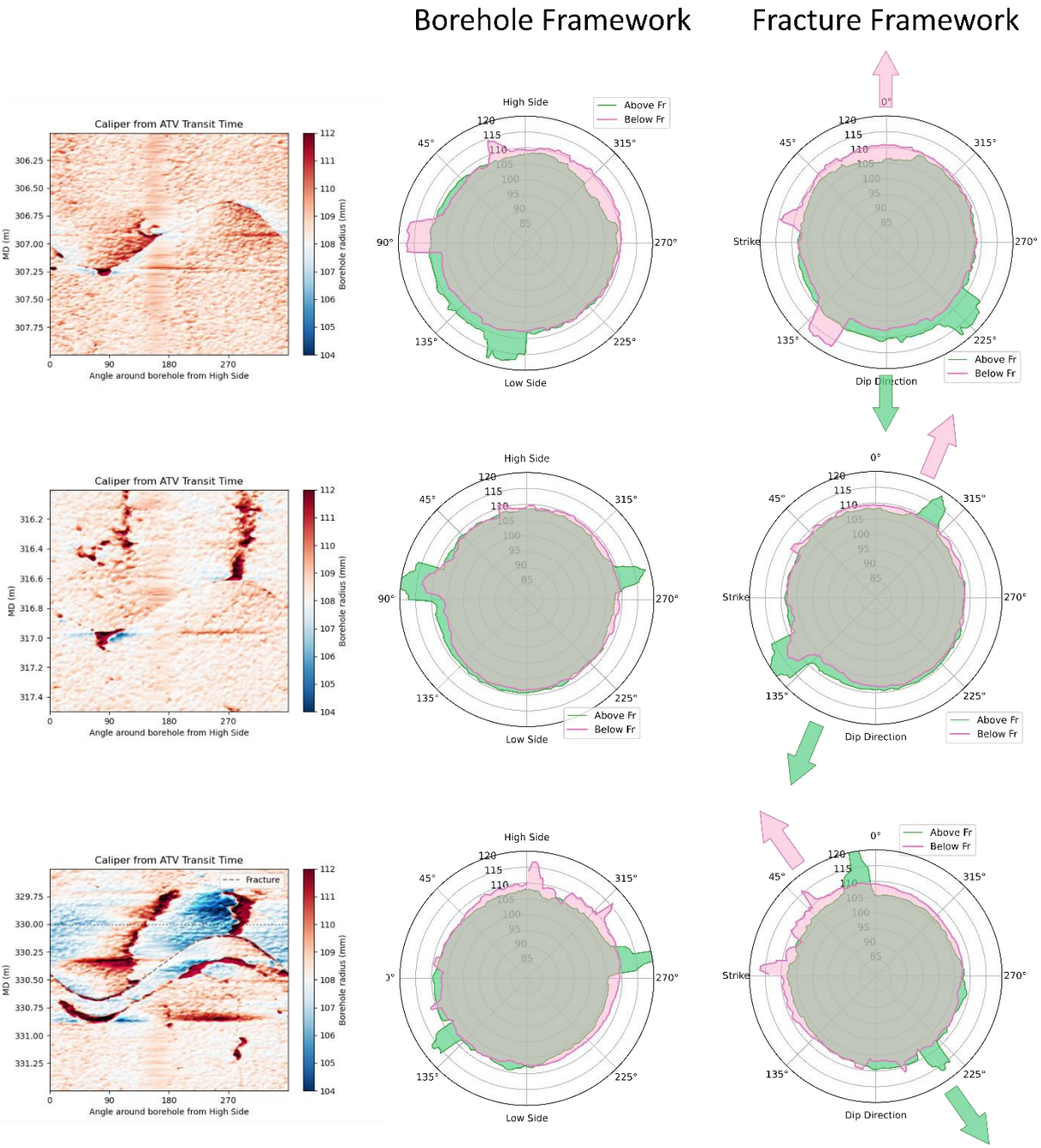


Figure 46. Three structures showing shear displacement after stimulation. In all cases the compartment above the fracture subsided. Each fracture is located in 3 different intervals (1, 2 and 5)

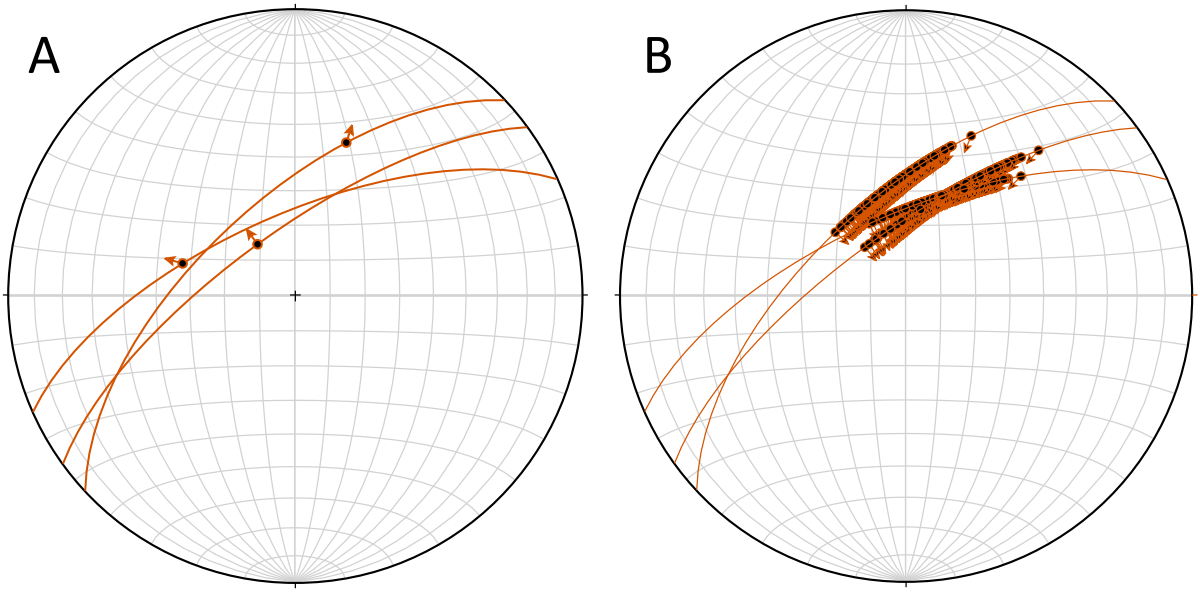


Figure 47. Stereonet showing the 3 fracture planes where shear displacement was identified in ST2. A) The measured directions of the respective displacement vectors, B) Theoretical displacement vectors with the stress state from Ma et al. (2019).

8.1.5 Influence of notching on stimulation results

Interval 1 had been perforated in October 2020 with 2 notches prior to the stimulation. These notches are clearly observed in ATV logs at 307.3m and 310m (Figure 21). A third notch was done at 275.6m but no stimulation was performed at this depth. It is difficult to assess whether these notches had an influence in the outcome of the stimulation. On one hand, the notch at 307.3 m is adjacent to the fracture where a shear displacement was measured after the stimulation (see 8.1.4 Shear displacement on pre-existing fractures), but on the other hand 2 other fractures with shear displacement lacked of any perforation nearby prior to the stimulation.

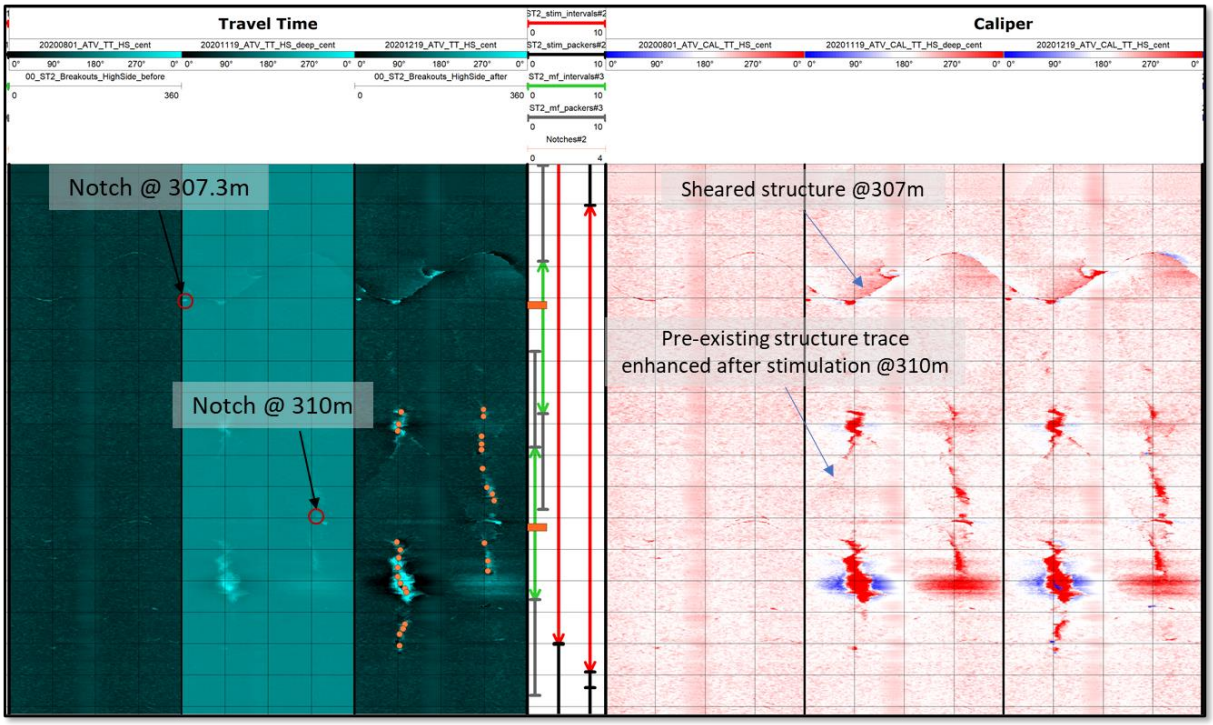


Figure 48. Sheared structures at 307m and 310m MD coincide with notching locations.

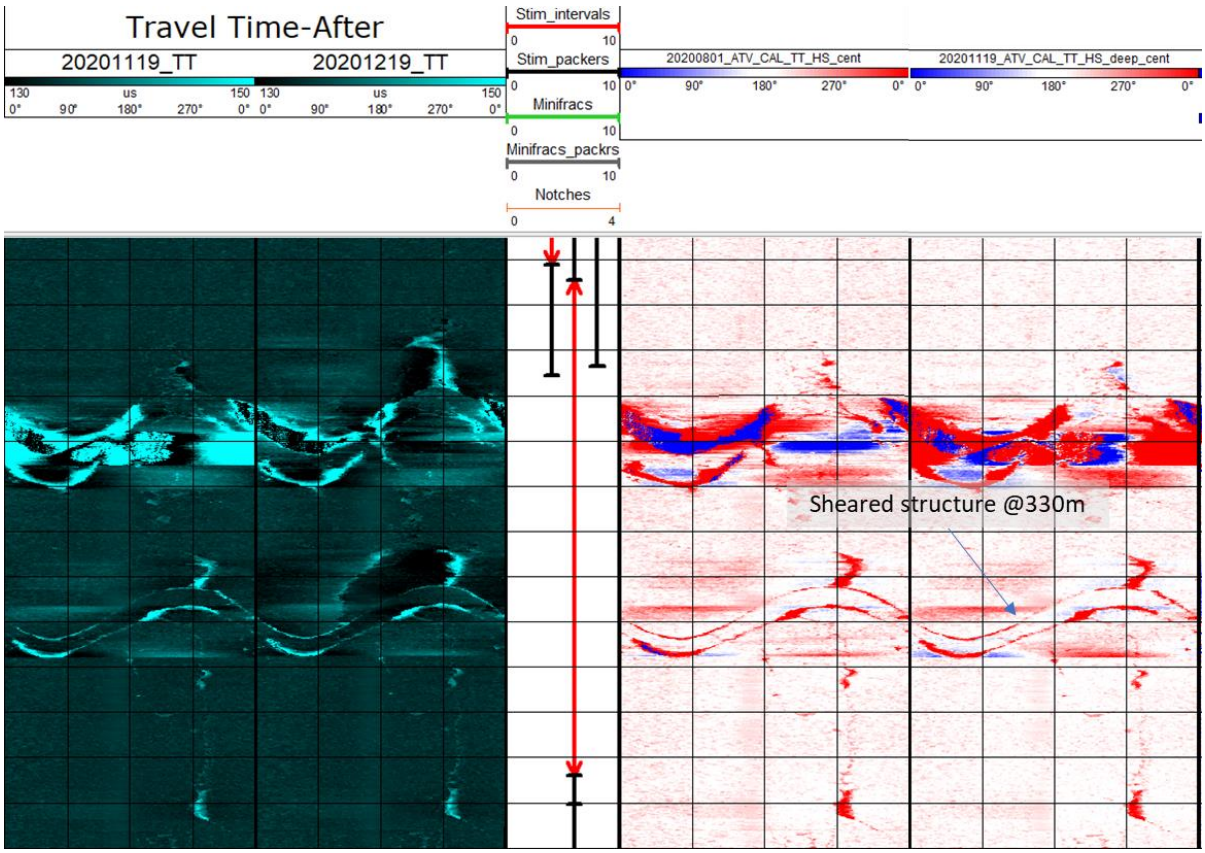


Figure 49. Sheared structures at 330m MD is not associated to any notching location.

8.2 May 2021

8.2.1 Intervals

In May 2021 the bottom of the borehole was stimulated by isolating the section below 332.5m. Figure 50 shows the before-vs-after ATV log of this interval. No clear evidence of changes can be observed in the ATV log.

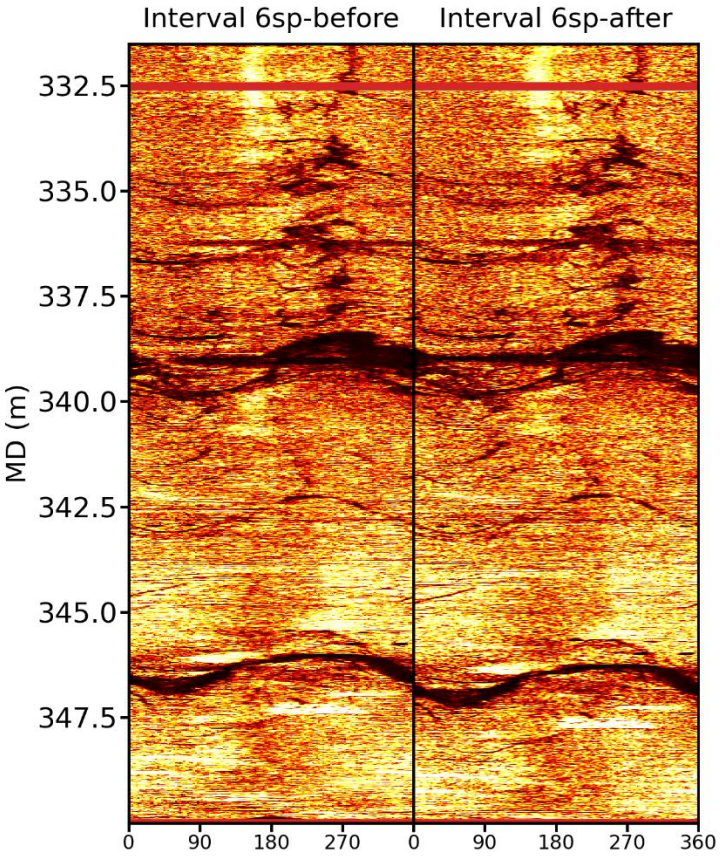


Figure 50. Interval stimulated in May 2021.

8.3 October 2021

8.3.1 Intervals

The last stimulation campaign carried out in ST2 took place in October 2021 after the borehole was cased & cemented and perforations were done at different depths. Logs were not run after this set of stimulations because no effect is expected to be seen in the cemented borehole wall. Figure 51 show the ATV logs for each stimulated interval and the places where notching was performed prior to the stimulation.

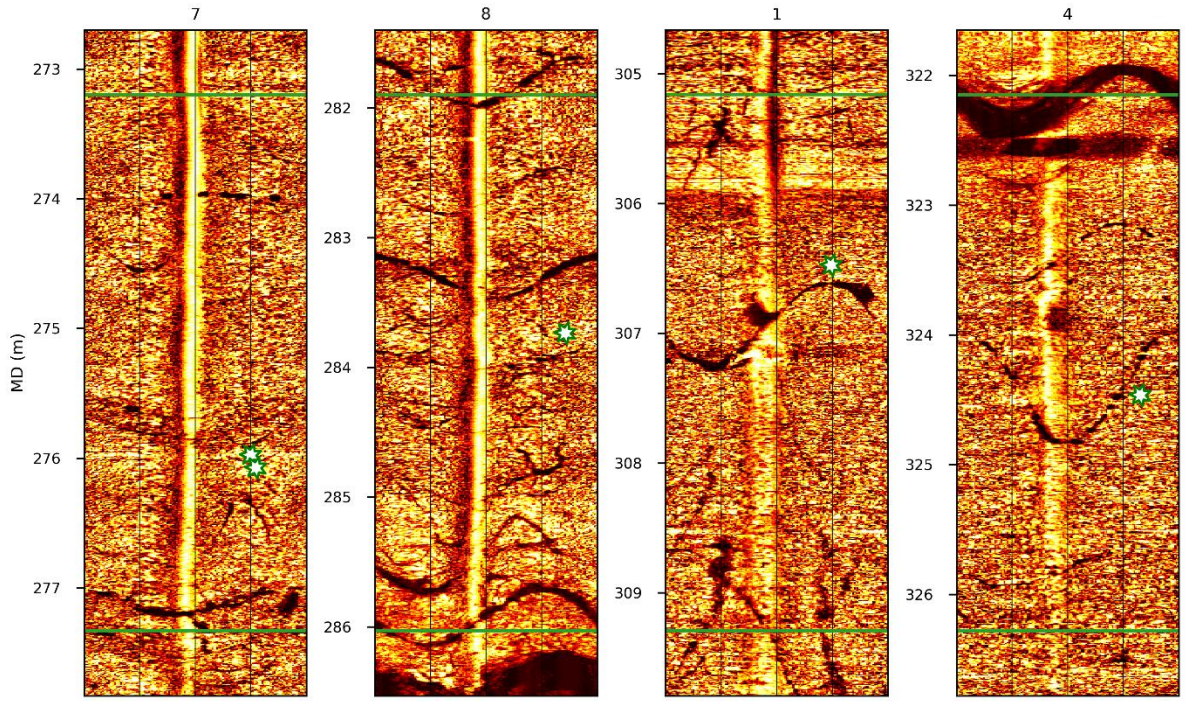


Figure 51. Intervals stimulated during the October 2021 campaign. Green stars mark the places where notches were perforated in the casing.

9. References

Zhang, S., K. Broeker, R. van Limbor, X. Ma, in press, In situ stress variations around reservoir-scale fault zones.

Ma, X., N. G. Doonechaly, M. Hertrich, V. Gischig, G. Klee, 2019, Preliminary in situ stress and fracture characterization in the Bedretto Underground Laboratory, Swiss Alps: implications on hydraulic stimulation, 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019), Foz do Iguassu, Brazil, September 13-18, 2019.

10. Annexes

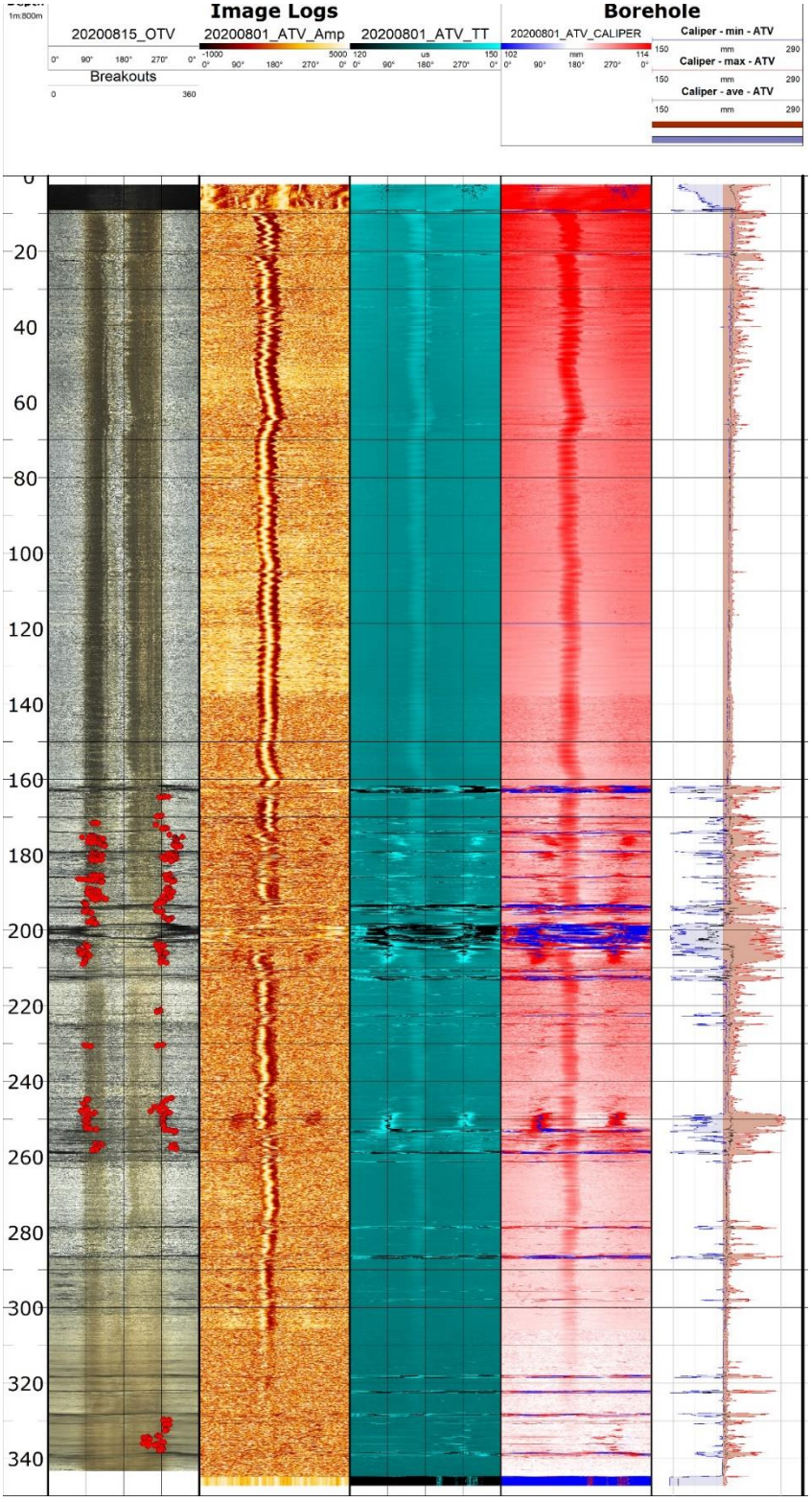


Figure 52. Image logs (OTV & ATV), breakouts (red points) and caliper calculated from acoustic travel time in ST2 after drilling. Breakouts and washouts form inside intervals of strong deformation (presence of fault zones and increased fracture frequency). Sections with small amounts or no brittle fractures do not develop breakouts.

10.1 Stimulation November 2020 – Full borehole logs

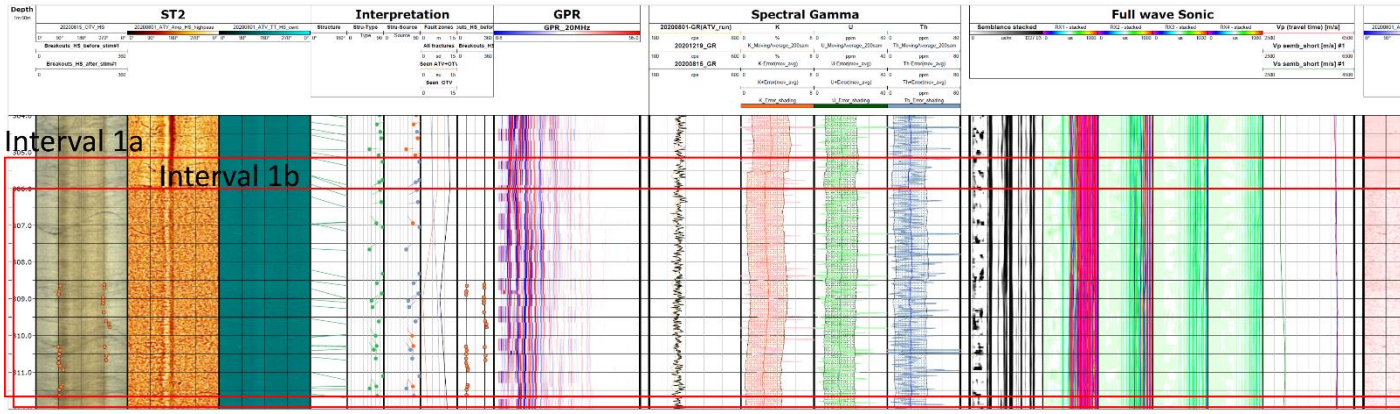


Figure 53. Stimulation-November 2020. Intervals 1a and 1b.

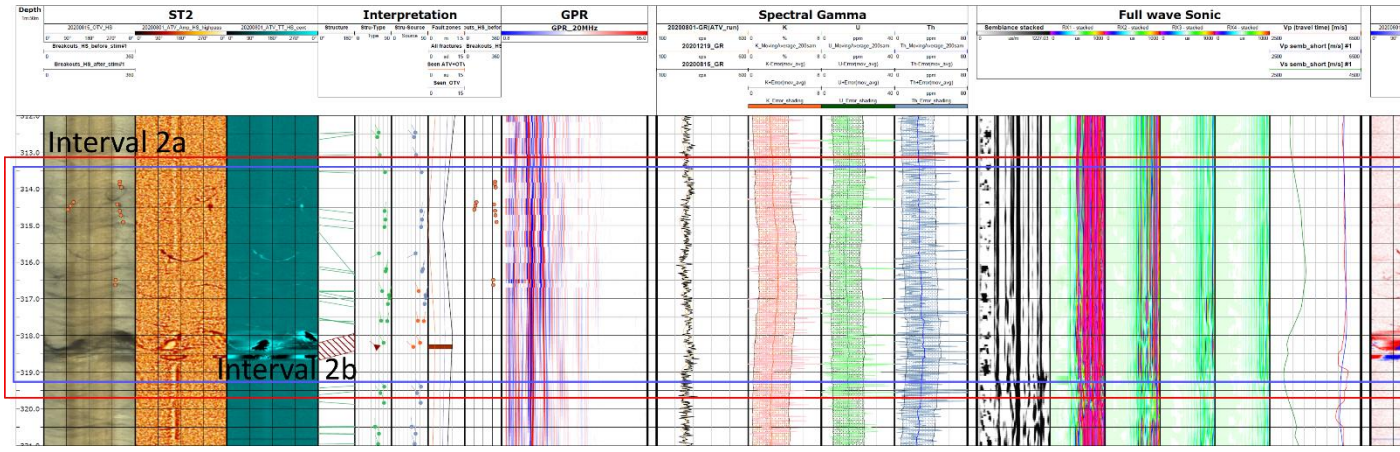


Figure 54. Stimulation-November 2020. Intervals 2a and 2b.

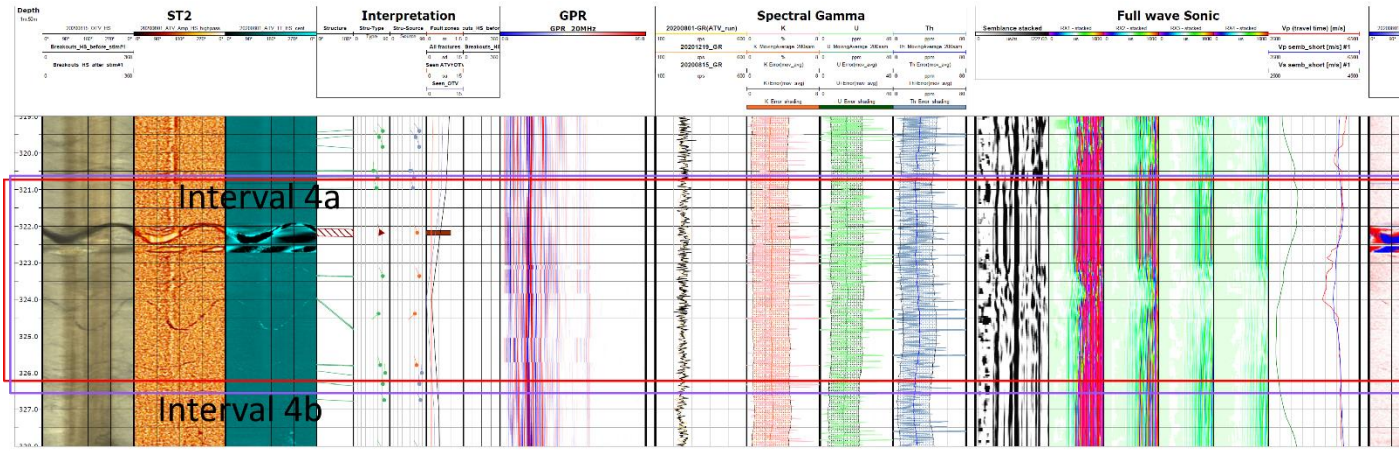


Figure 55. Stimulation-November 2020. Intervals 4a and 4b.

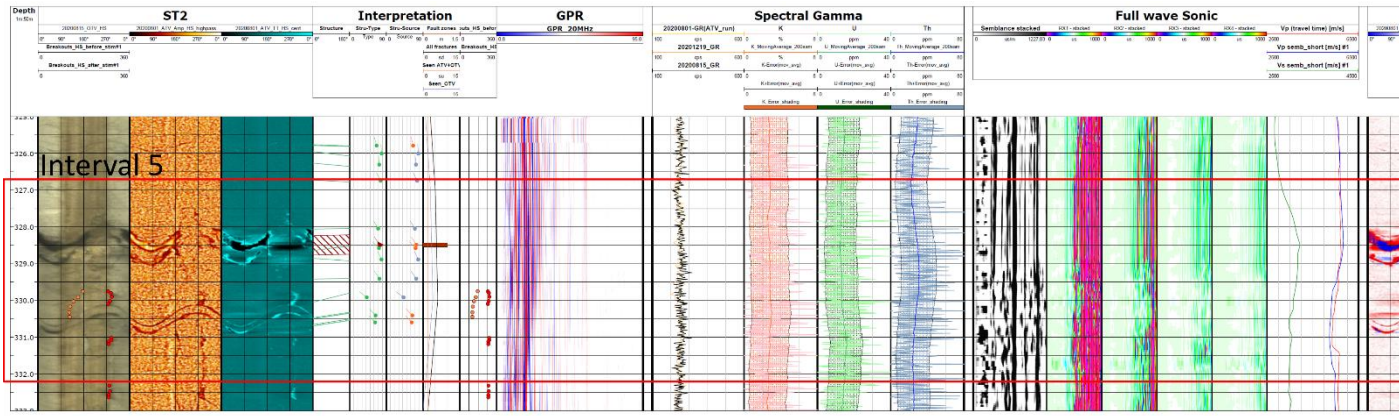


Figure 56. Stimulation-November 2020. Interval 5.

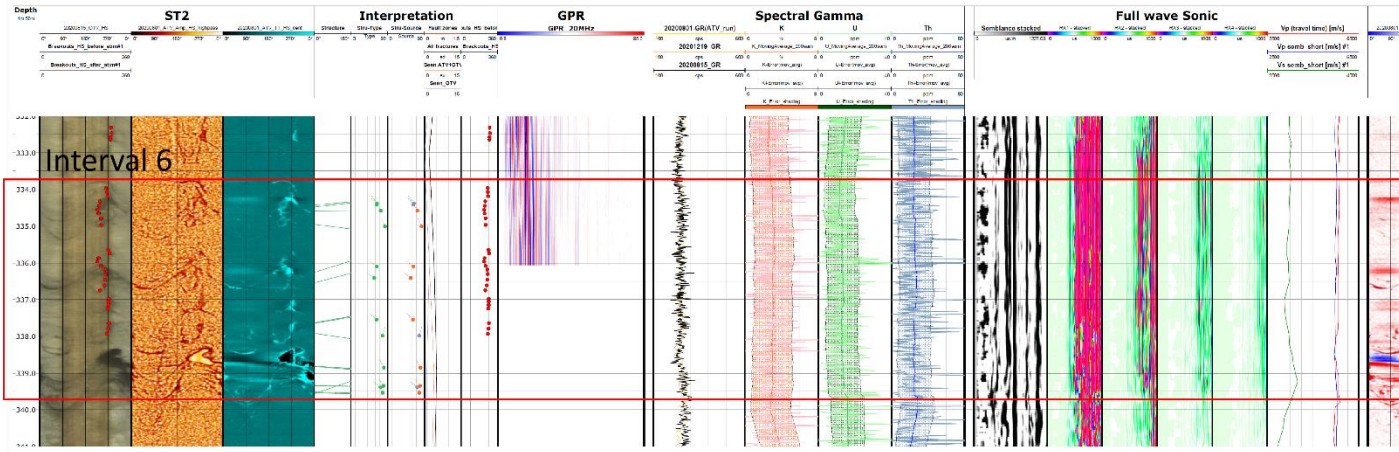


Figure 57. Stimulation-November 2020. Interval 6.

523