

Technical Report

Title: *Fluid Electrical Conductivity Logging in Borehole DGR-1*

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1 Introduction

Fluid electrical conductivity (FEC) logging was performed in borehole DGR-1 at the Bruce site near Tiverton, Ontario, Canada (Figure 1) on May 9, 2007, as part of the Geoscientific Site Characterization Program for a proposed Deep Geologic Repository for low- and intermediate-level radioactive waste (Intera Engineering Ltd., 2006). The logging described in this Technical Memorandum was performed under Intera Test Plan TP-07-10 – DGR-1 FEC Logging (Intera Engineering Ltd., 2007a), prepared following the general requirements of the Project Quality Plan for DGR Site Characterization (Intera Engineering Ltd., 2007b). Borehole DGR-1 was drilled to a depth of 463 m below ground surface (bgs) into the upper part of the Upper Ordovician Queenston Formation. FEC logging was conducted over the Silurian formations between the bottom of the borehole casing (183 m bgs) and the Queenston Formation (Figure 2). The purpose of the FEC logging in DGR-1 was only to identify the intervals within each of the Silurian formations and members that provide the most flow to the borehole so that those intervals could then be isolated for straddle-packer testing, although additional quantification of flow is possible from typical FEC (or “hydrophysical”) logging. In addition, the combination of FEC logging and straddle-packer testing was intended to allow development of a continuous hydraulic conductivity profile over the length of the hole, and identify potential groundwater sampling zones and zones to be monitored by the Westbay system to be installed in the borehole.



Figure 1 Location of Bruce site (from OPG, 2005)

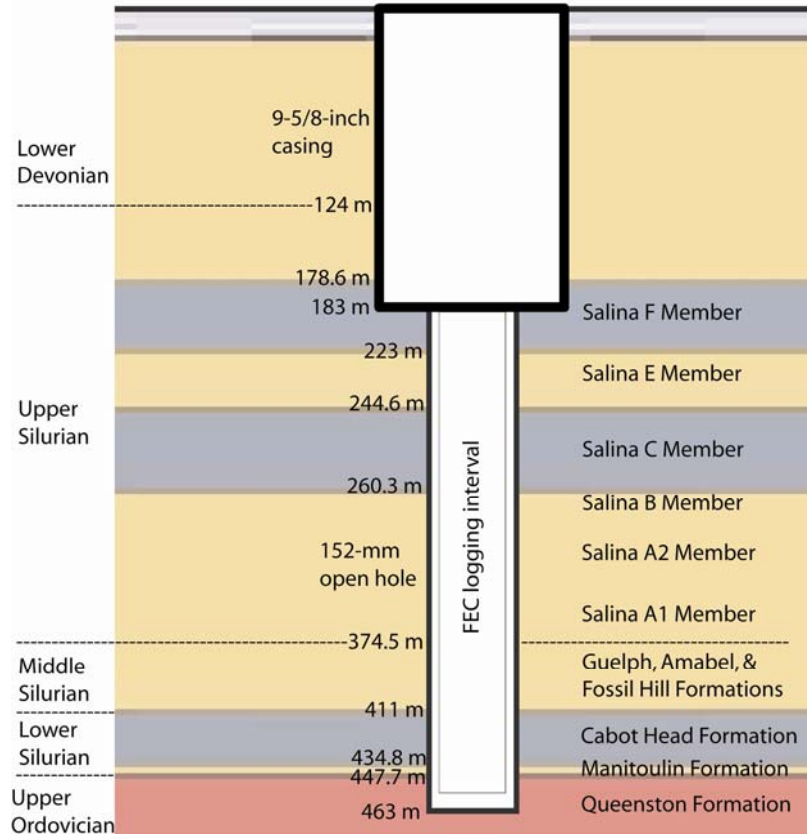


Figure 2 Stratigraphy and FEC logging interval in DGR-1

2 Background

FEC logging was developed for the radioactive waste program in Switzerland in the 1980s (Tsang et al., 1990), and has since been applied at the Waste Isolation Pilot Plant in the U.S. (Beauheim et al., 1997), the French underground research laboratory site at Bure (Andra, 2005), the Japanese Tono and Horonobe sites (Doughty et al., 2005), and numerous other types of sites (e.g., Pedler and Urish, 1988; Pedler et al., 1990; Evans, 1995). FEC logging entails replacing the fluid in a borehole with another fluid having an electrical conductivity that contrasts with that of the fluids in the formation(s) penetrated by the borehole. After fluid replacement has been completed, repeated logging runs are conducted over the length of the water column with an electrical conductivity probe to identify locations where the FEC of the water column is changing. The locations where the FEC changes represent places where water is either flowing into or out of the borehole. The changes in FEC detected during logging reflect the combined effect of two factors—the magnitude of flow (which is directly related to transmissivity and hydraulic gradient) and the FEC of the flowing water. Without independent measurement of the FEC of the flowing fluid and an estimate of the hydraulic gradient, changes in FEC cannot be directly related to transmissivity.

FEC logging may be performed under ambient (unstressed) conditions to identify the locations where water is flowing into (or out of) the borehole under natural gradients (possibly influenced by the borehole itself), or under stressed conditions with an induced high gradient into the borehole. The FEC logging described herein was performed with a slight gradient into the hole (described below) to identify the intervals within each of the Silurian formations and members that provide the most flow to the borehole so that those intervals could then be isolated for straddle-packer testing. Additional logging under pumping conditions was anticipated in the Test Plan, but was not undertaken.

3 Methodology

3.1 Fluid Emplacement

For the FEC logging in borehole DGR-1 at the Bruce site, the fluid left in the borehole after drilling, which had an electrical conductivity greater than 185,000 microSiemens/centimetre ($\mu\text{S}/\text{cm}$), was replaced with filtered and chlorinated Lake Huron water having an electrical conductivity of approximately 240 $\mu\text{S}/\text{cm}$. In contrast, the waters in the Silurian formations being logged were expected to have FECs in excess of 100,000 $\mu\text{S}/\text{cm}$. The fluid replacement was accomplished using a large oilfield “mud pump” to inject Lake Huron water at the bottom of the hole through 2-3/8-inch tubing at an approximate rate of 470 litres per minute (L/min), forcing the drilling fluid in the hole up and out of the hole into a frac tank. The FEC of the extracted water was monitored until its value stabilized at approximately 500 $\mu\text{S}/\text{cm}$ after approximately 45,000 L, or 3.5 wellbore volumes, had been flushed.

3.2 FEC Logging Sonde

The sonde used for the FEC logging was the RAS Hydrophysical™ proprietary logging tool (Figure 3). This tool represents the fourth and, at the time, latest generation of fluid logging sondes and has four separate channels (designated 2 through 5) for the measurement of FEC and temperature. The four sets of sensors are spread at 15.24-cm separations along the length of the tool and rotated 90 degrees from one another. FEC is measured with six-pole type sensors, and temperature is measured with thermistors. The sonde has fully digital telemetry with all analog-to-digital conversion performed downhole. The maximum FEC the sonde could measure was 20,000 $\mu\text{S}/\text{cm}$, which proved to be adequate as the maximum FEC measured was approximately 16,000 $\mu\text{S}/\text{cm}$. Pre- and post-logging calibration checks were performed as outlined in RAS TP 19 (Appendix B in Intera Engineering Ltd., 2007a).

3.3 Logging Runs

FEC logging began after the tubing used for fluid emplacement was removed from the hole, approximately 90 minutes after the end of emplacement. A total of six logging runs were completed, three downward and three upward. The vertical logging speed was approximately 8 m/min, and the four FEC/T sensors were read every 1-2 seconds. The downward runs discussed herein were completed at approximately 75-minute intervals. All of the logging runs were affected by unusual electrical noise downhole that also affected geophysical logs run earlier and transducer signals during hydraulic testing performed later. The noise was apparently related to the grounding network for the Bruce nuclear power station, and was later eliminated by reconfiguring that network. Because of differences in the signals and digitization of the thermistor and FEC data, the noise affected the thermistor data far more than the FEC data, making it useless for temperature compensation of the FEC data. Temperature compensation of FEC data typically increases the FEC value, but not the shape of an FEC log curve. The noise in the FEC data was more oscillatory in nature, and averaging over a seven-point moving window was found through trial and error to be adequate to smooth the data. The data from all four FEC channels from all downward and upward logging runs are shown in Appendix A. All channels provided qualitatively similar results, hence only the data from channel 2 will be discussed in detail.

3.4 Hydraulic Conditions During Logging

The hydraulic head in at least one of the Silurian formations, combined with the low density of the Lake Huron water compared to that of the natural fluids in the Silurian formations, caused DGR-1 to be in a flowing artesian condition after fluid replacement and during the FEC logging, with a flow rate at the wellhead of less than 1 L/min. Thus, a slight hydraulic gradient into the borehole from one or more formations was present during the logging. Whether or not a gradient out of the borehole into one or more other formations was present cannot be evaluated with the data available.

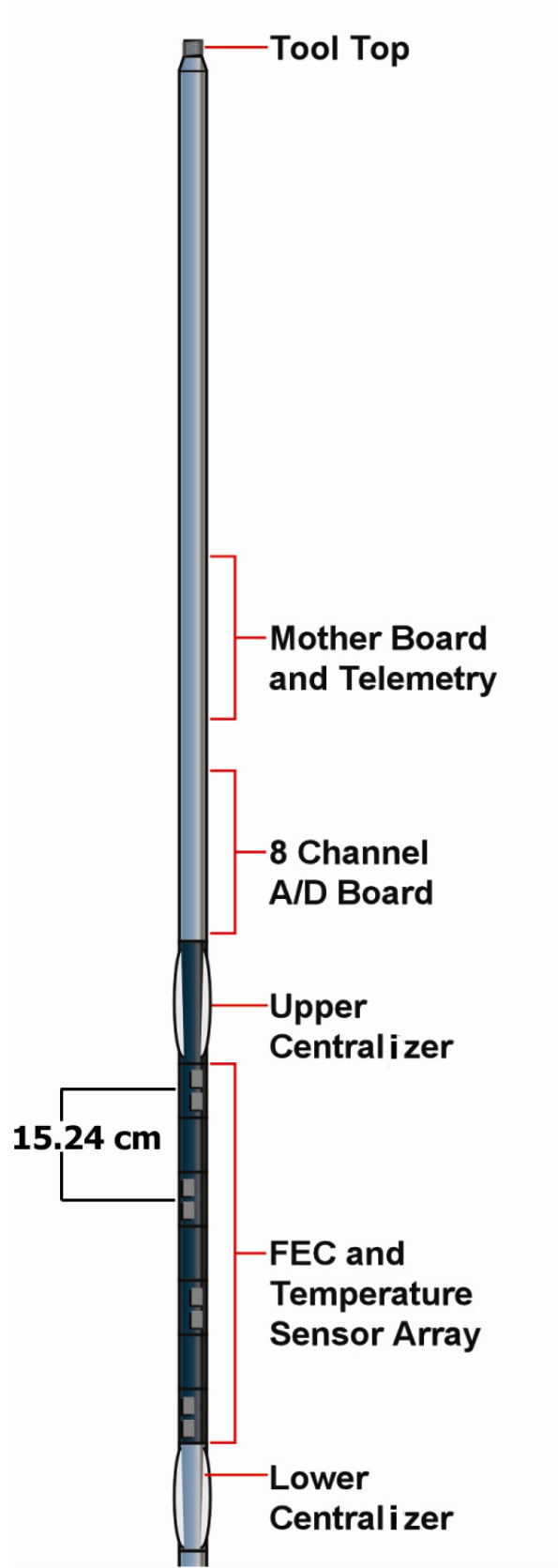


Figure 3 FEC logging sonde

4 Logging Results

4.1 First Logging Run

Figure 4 shows the smoothed FEC values recorded on channel 2 of the DAS during logging run 1, along with stratigraphic information from Intera Engineering Ltd. (2009). Five major peaks, corresponding to fluid-inflow points, are evident in Figure 4, with the three largest peaks beginning at 322, 373, and 443 m bgs. These peaks were produced by flow into the borehole between the time that the tubing used for fluid emplacement was removed (which lowered the head in the borehole) and the time of the first logging run (~90 minutes). Note that the magnitudes of the peaks cannot be presumed to correlate with the amounts of inflow at each location because the FEC of the formation water entering the hole at one depth is not necessarily the same as that of the water from a different formation entering at a different depth.

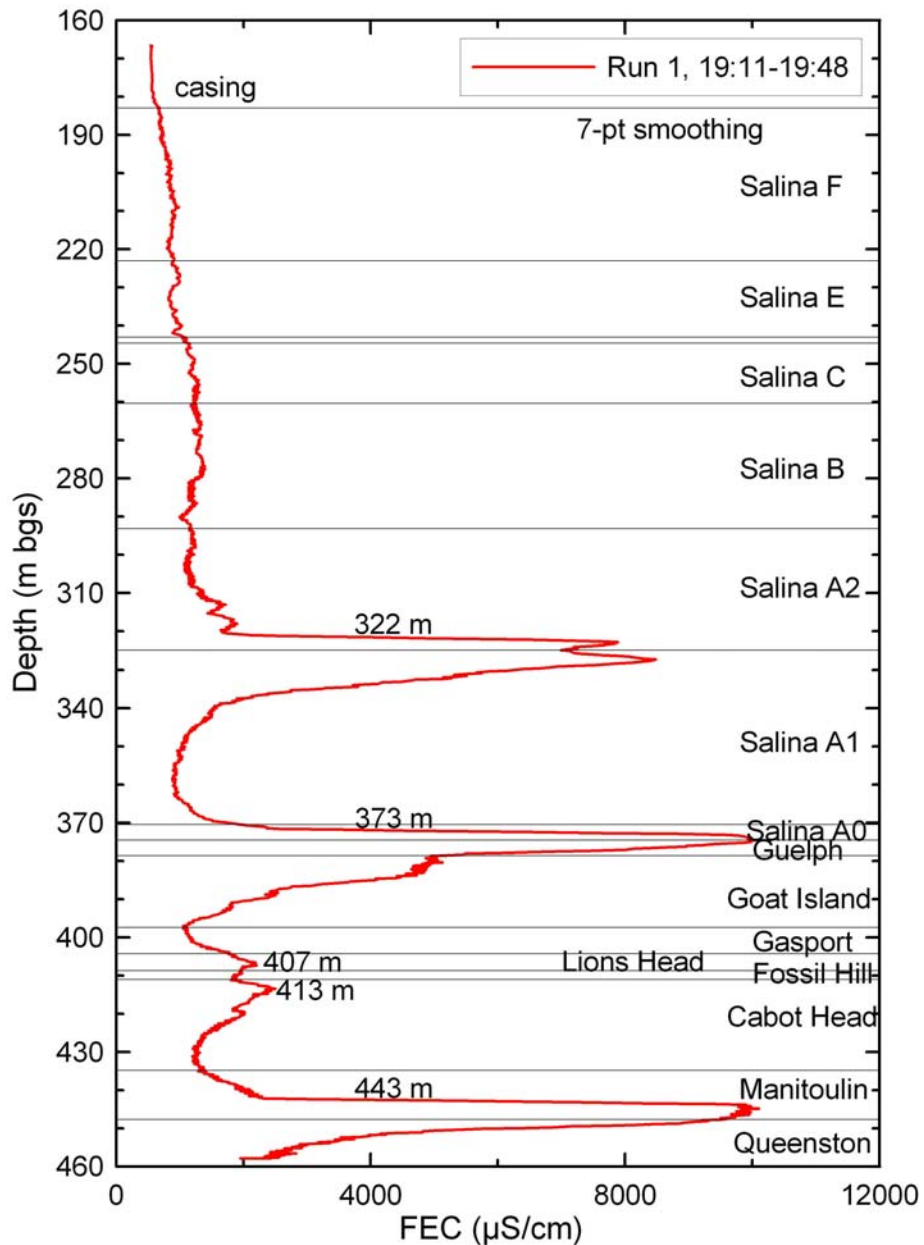


Figure 4 FEC data from run 1 in DGR-1, channel 2

The upper sides of the three major FEC peaks seen in Figure 4 are sharper and better defined than the lower sides. This is probably caused by density-driven downward flow of the high FEC water entering the borehole during the 90-minute period between the end of fluid emplacement and the beginning of FEC logging. Thus, the actual inflow points in the borehole are likely to be at or near the upper parts of the peaks.

Figure 5 shows the temperature data collected on channels 2 and 4 during the first downward logging run. The channel 2 data degraded significantly below approximately 345 m, and remained unusably noisy for the remainder of the logging runs. The data from channel 4 showed unaccountably high temperatures down to a depth of approximately 310 m, in sharp contrast to the slowly rising temperatures shown over the same interval by channel 2 (and by channel 4 in all subsequent runs). Below 310 m, however, the channel 4 temperature data clearly show the same three major and two minor peaks shown by the FEC data in Figure 4, although the lower two major peaks showed excessive noise, which increased over successive runs. Channels 3 and 5 provided no usable data at all.

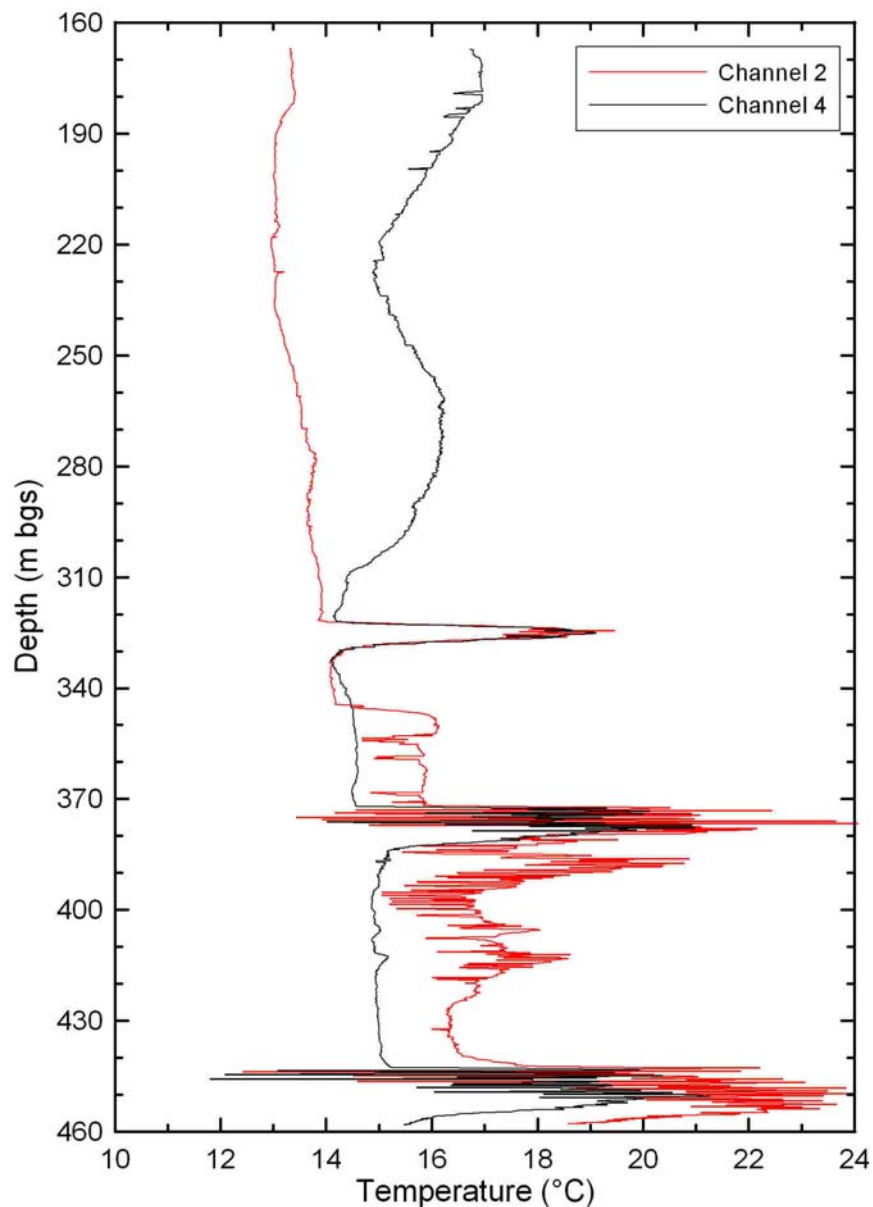


Figure 5 Temperature data from run 1 in DGR-1, channels 2 and 4

Figures 6, 7, 8, and 9 show the intervals from 310 to 340 m, 370 to 400 m, 400 to 430 m, and 430 to 460 m bgs, respectively, in more detail. Figure 6 shows one peak centered at approximately 323 m and a broader peak at approximately 327 m. These peaks appear to correspond to porous and vuggy dolostone recovered in core runs (CR) 115 and 116 in DGR-1, which are attributed to the lower evaporitic part of the A2 Unit of the Salina Formation and the upper carbonate part of the A1 Unit of the Salina. As mentioned above, the gradational falling (lower) limb of the FEC spike from approximately 328 to 336 m bgs was probably caused by density-driven downward flow.

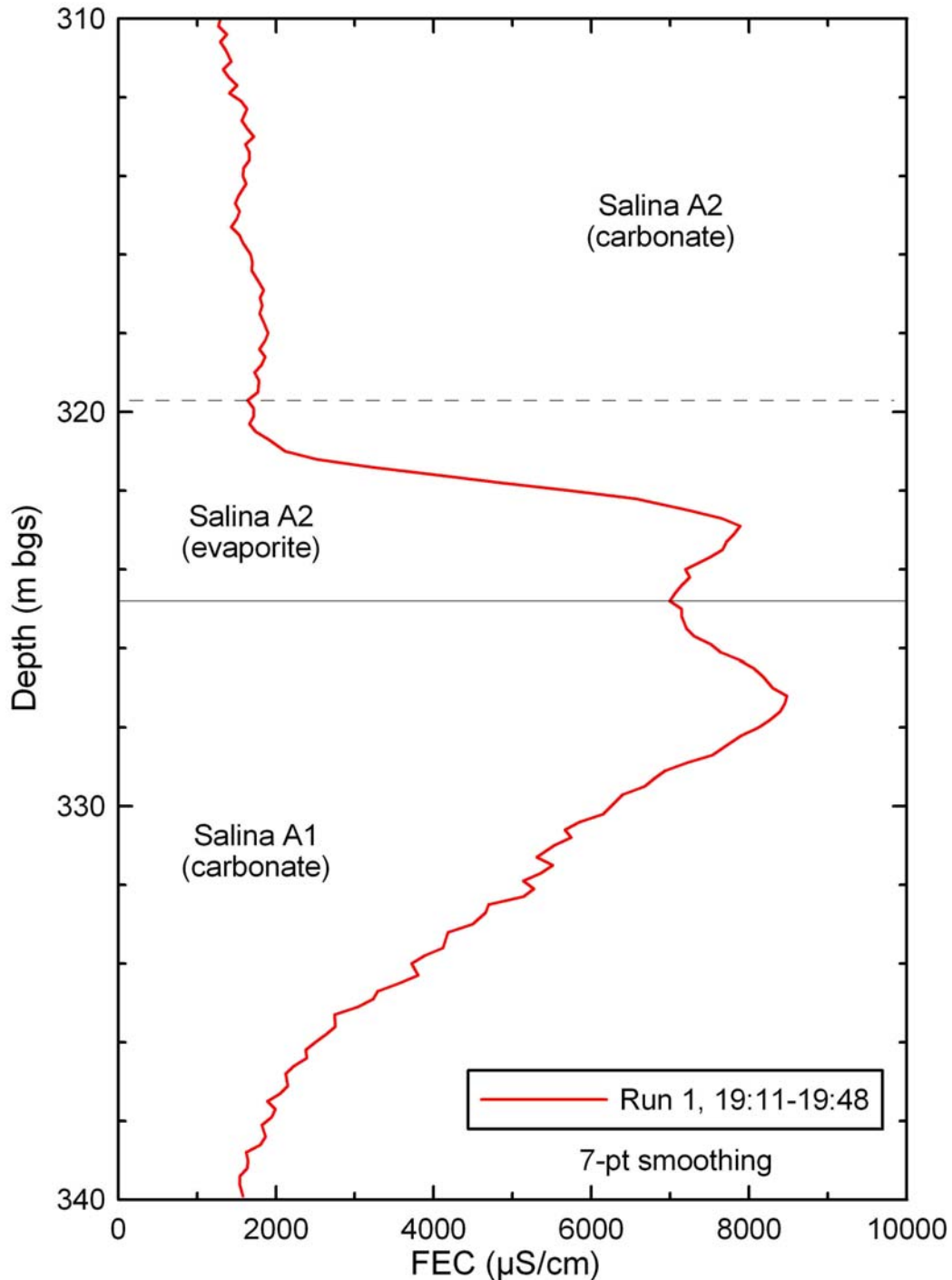


Figure 6 Run 1 FEC data for the interval from 310 to 340 m bgs, channel 2

Figure 7 shows a broad FEC signal from approximately 372 to 377 m bgs, with what may be a less significant, less well-defined inflow zone immediately below. The major inflow zone corresponds to porous and vuggy dolostone recovered in CR 132 and 133 from the lower part of the A0 Unit of the Salina Formation and the Guelph Formation (Intera Engineering Ltd., 2009).

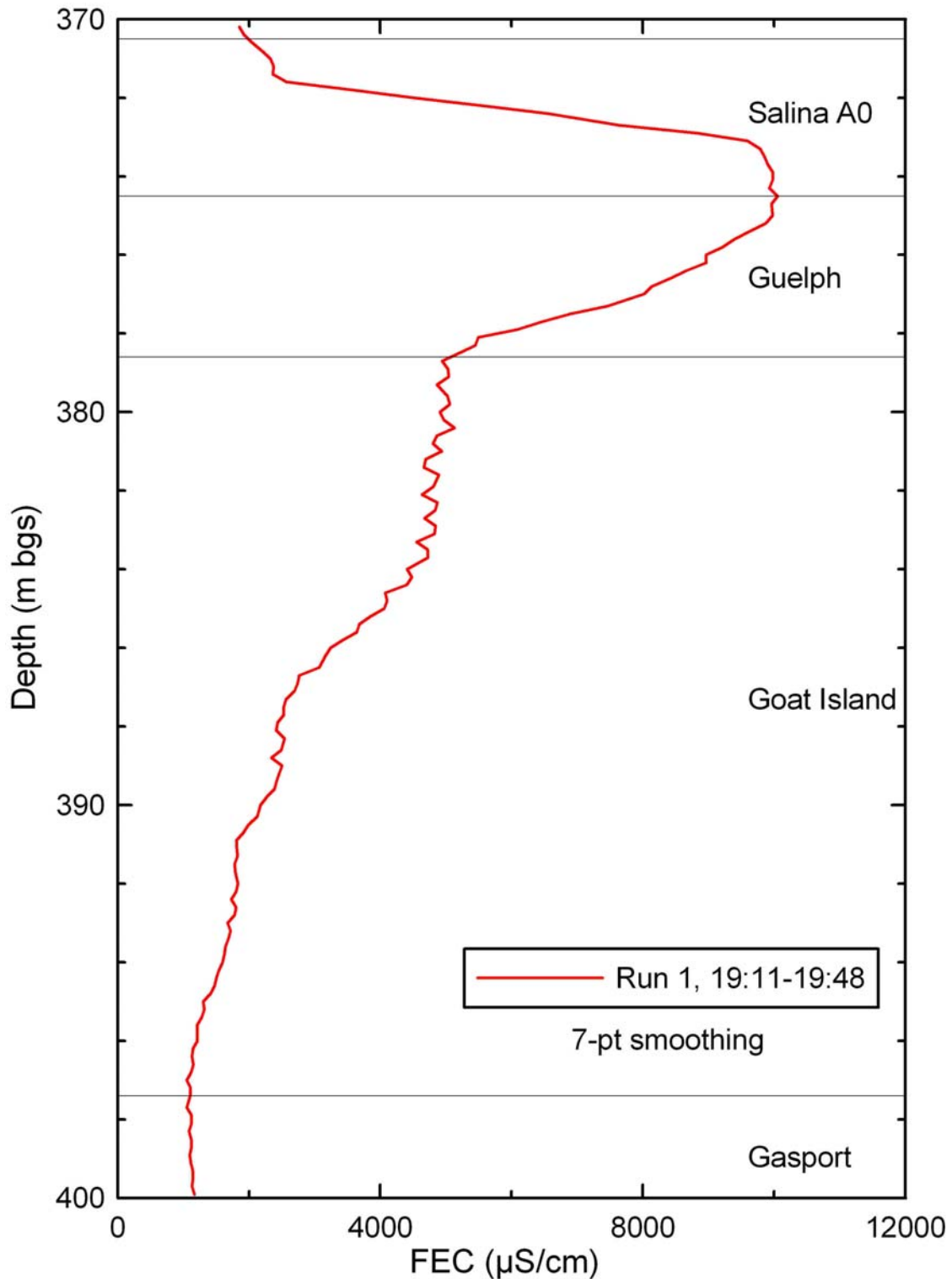


Figure 7 Run 1 FEC data for the interval from 370 to 400 m bgs, channel 2

Figure 8 shows the two FEC peaks centered on approximately 407 and 413 m bgs. The interval around 407 m corresponds to the middle part of the Lions Head Member of the Amabel Formation, and the interval around 413 m corresponds to the upper part of the Cabot Head Formation (Intera Engineering Ltd., 2009).

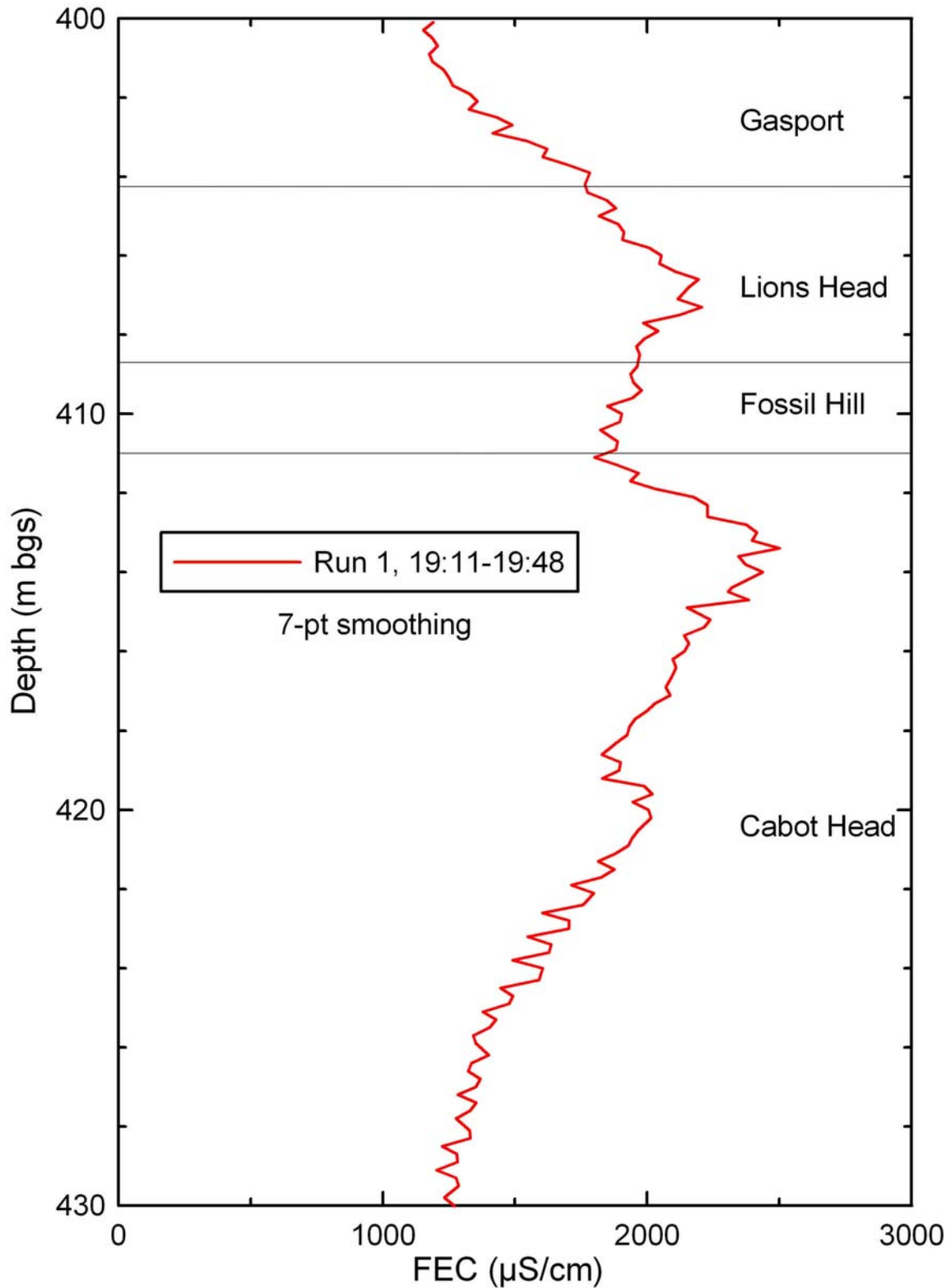


Figure 8 Run 1 FEC data for the interval from 400 to 430 m bgs, channel 2

Figure 9 shows a broad FEC peak from approximately 443 to 448 m bgs. This interval corresponds to the dolostone of the Manitoulin Formation recovered in CR 154 and 155 (Intera Engineering Ltd., 2009).

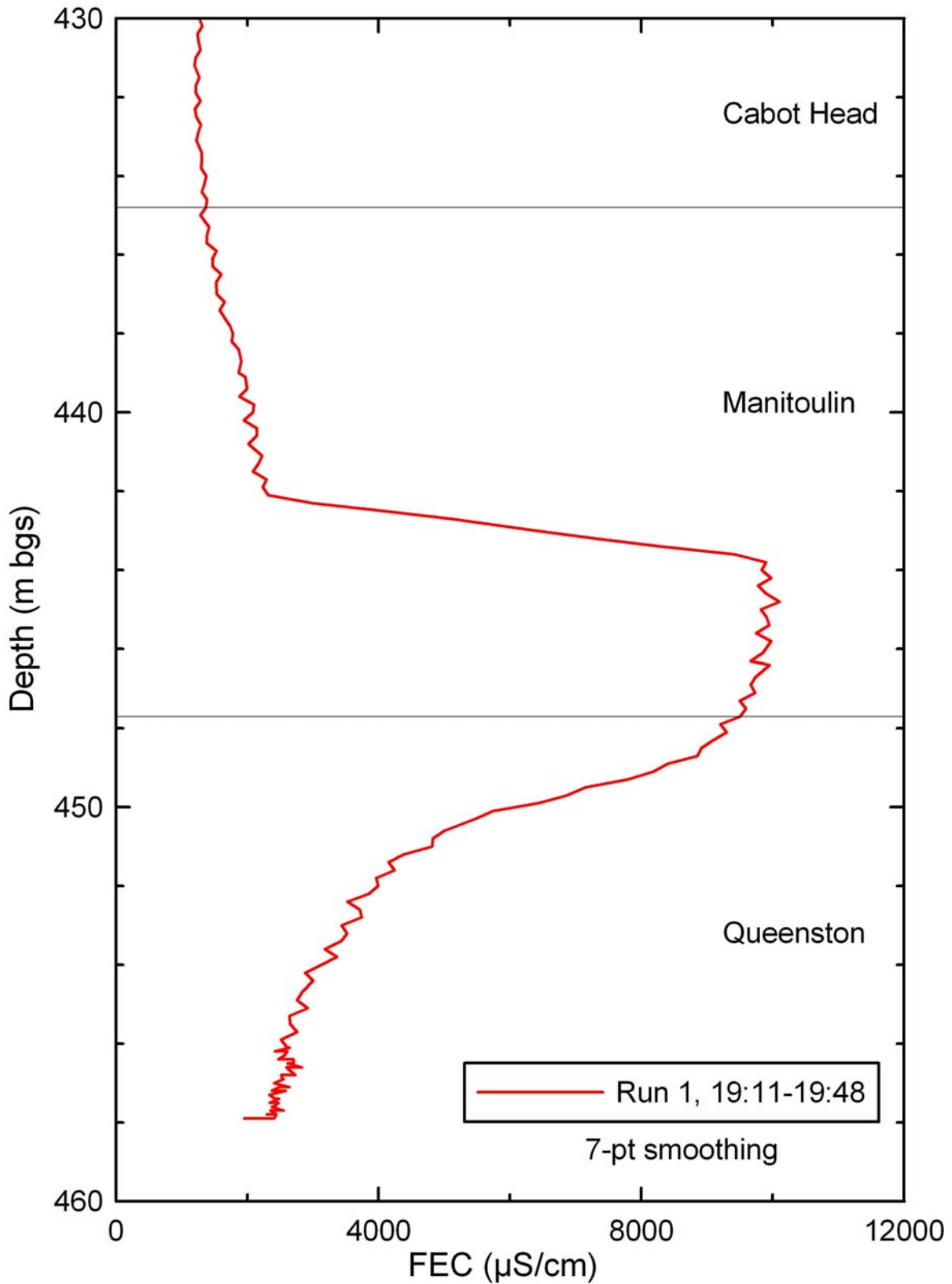


Figure 9 Run 1 FEC data for the interval from 430 to 460 m bgs, channel 2

4.2 Time Evolution of FEC Profiles

Whereas the first logging run served to identify the major inflow zones in DGR-1, the subsequent runs provided information on vertical flow in the borehole and zones of low, but non-zero, inflow. Figure 10 shows data from the three downward logging runs over the interval from 160 to 250 m bgs. The runs were conducted at approximately 75-minute intervals. The data have again been smoothed using a seven-point running average to remove the electrical noise observed during logging. The rate of increase in FEC varies with depth, but tends to be relatively uniform along specific zones, perhaps indicating low, evenly distributed inflow or possibly diffusion of solutes into the wellbore. A persistently low FEC zone is seen at approximately 220 m bgs (slightly more evident in the data from the other channels shown in Appendix A) exhibiting little change between subsequent runs. This observation may be indicative of an interval contributing very little water to the hole.

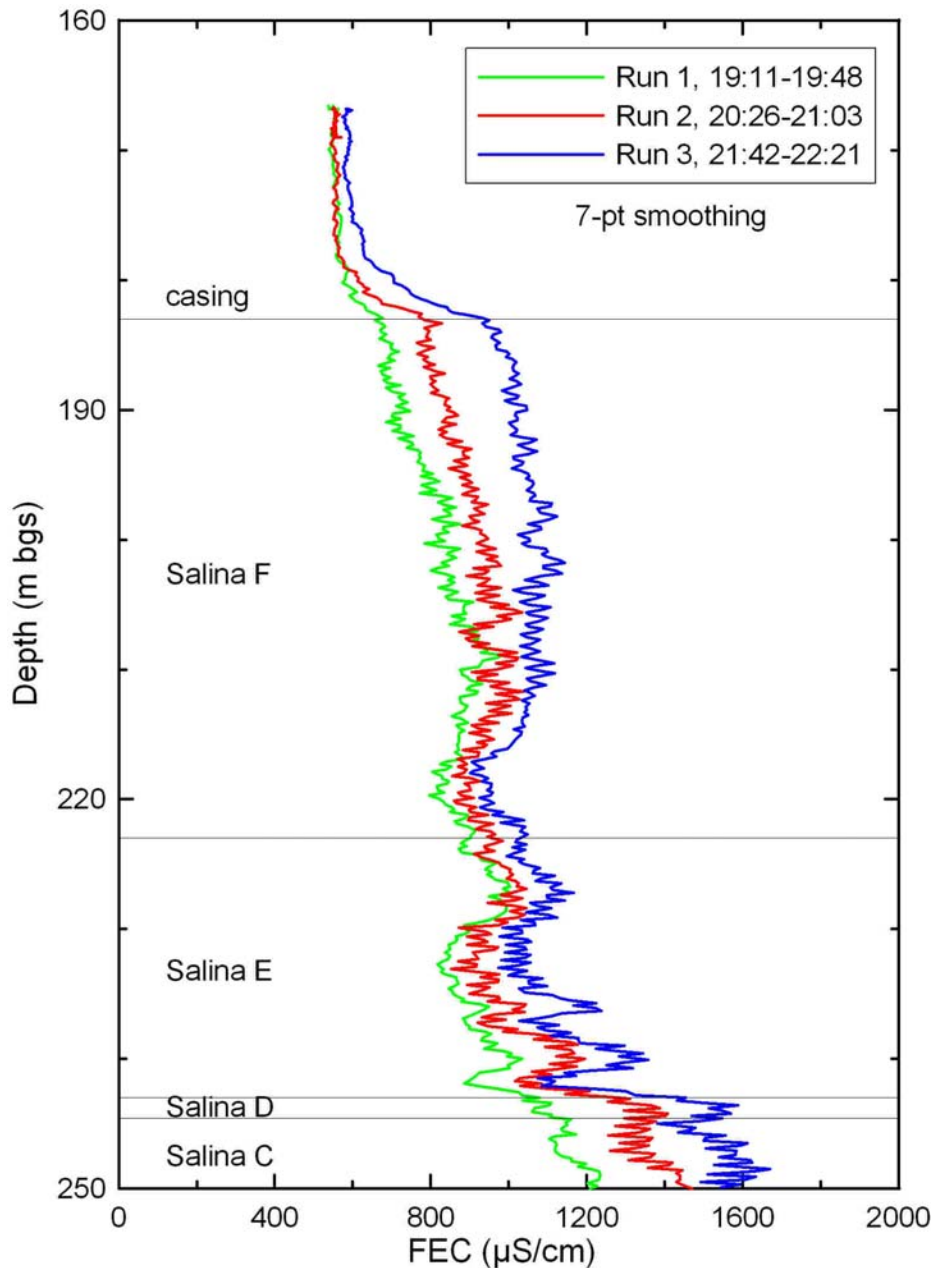


Figure 10 FEC data for the interval from 160 to 250 m bgs from all downward runs, channel 2

Figure 11 shows data from the three downward logging runs over the interval from 250 to 300 m bgs. As in the interval above, a slight increase in FEC with time is evident. Another persistently low FEC zone with little change between subsequent runs is seen at approximately 290 m bgs, which may reflect an interval contributing very little water to the hole.

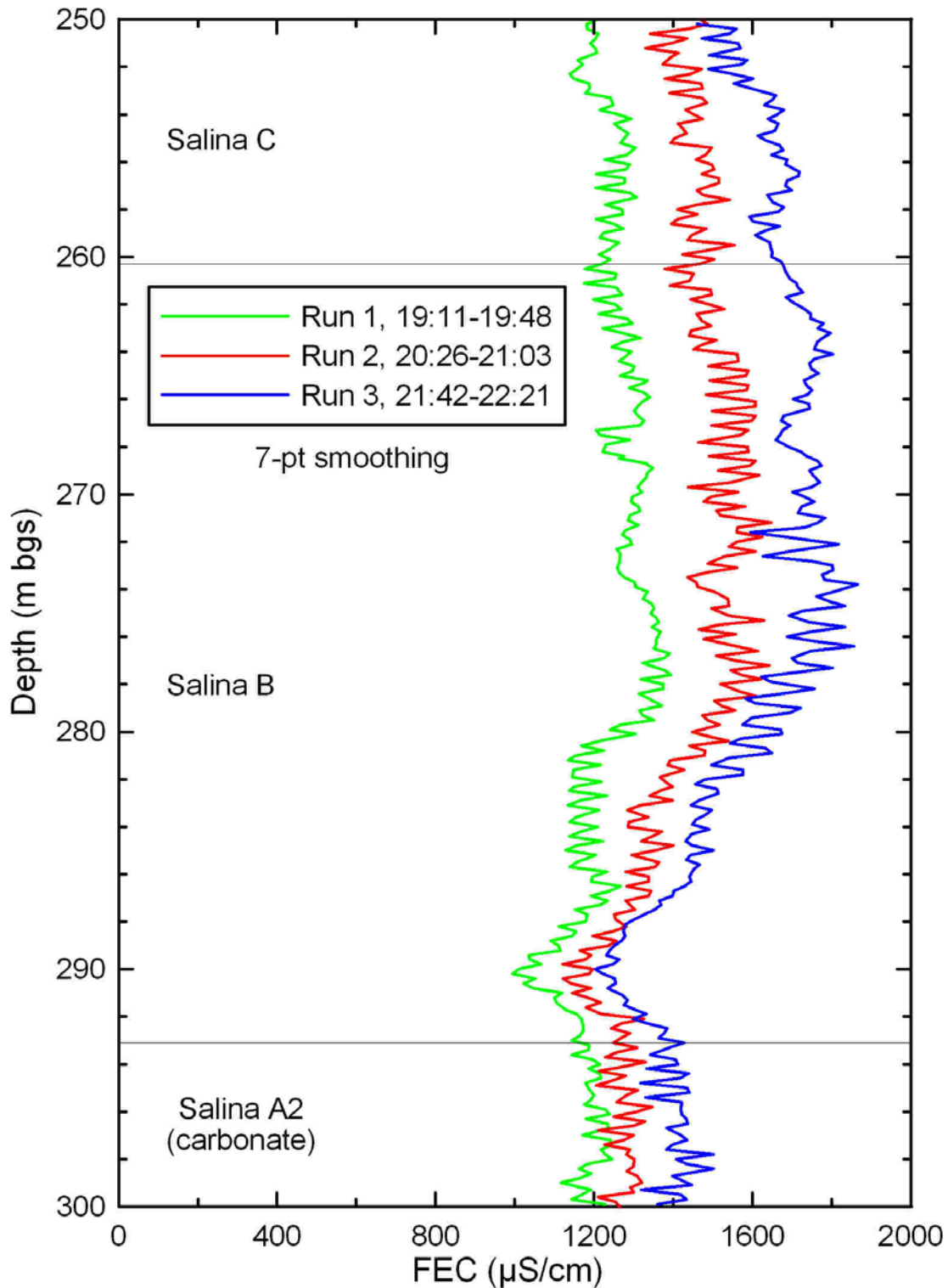


Figure 11 FEC data for the interval from 250 to 300 m bgs from all downward runs, channel 2

Figure 12 shows data from the three downward logging runs over the interval from 300 to 350 m bgs. The high-FEC water entering the borehole between approximately 323 and 327 m bgs is spreading both upward and downward in successive logs. Upward flow would be expected, given the flowing condition of the borehole. Downward flow is probably due to gravity causing the denser high-FEC water to sink. Somewhat surprisingly, the two inflow peaks themselves appear to be migrating. More typically, an FEC peak would simply spread around a fixed point. The data from channels 3 and 5 (Appendix A) show an intermediate third peak developing in runs 2 and 3 that appears to maintain a position between approximately 324 and 326 m bgs. These observations suggest some variability in the flow from this zone.

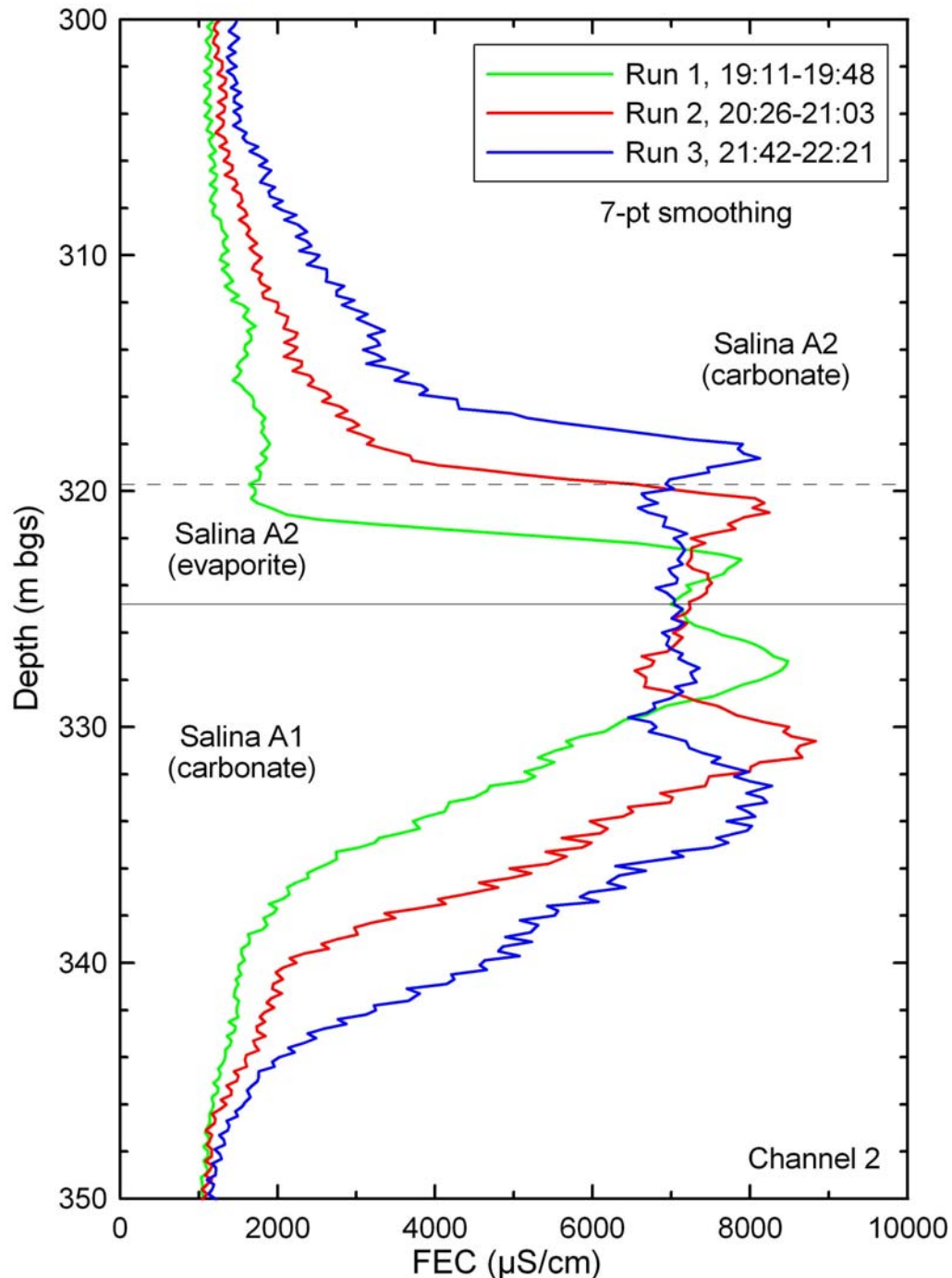


Figure 12 FEC data for the interval from 300 to 350 m bgs from all downward runs, channel 2

Figure 13 shows the smoothed data from the three logging runs over the interval from 350 to 400 m bgs. By the time of run 2, there is a suggestion of separate peaks from the lower A0 unit of the Salina and the Guelph. Little can be concluded about the lower potential inflow zone suggested by the run 1 log from approximately 378 to 384 m bgs in the upper Goat Island Formation because the high-FEC fluid from the overlying zone appears to have sunk through this lower zone by the time of runs 2 and 3.

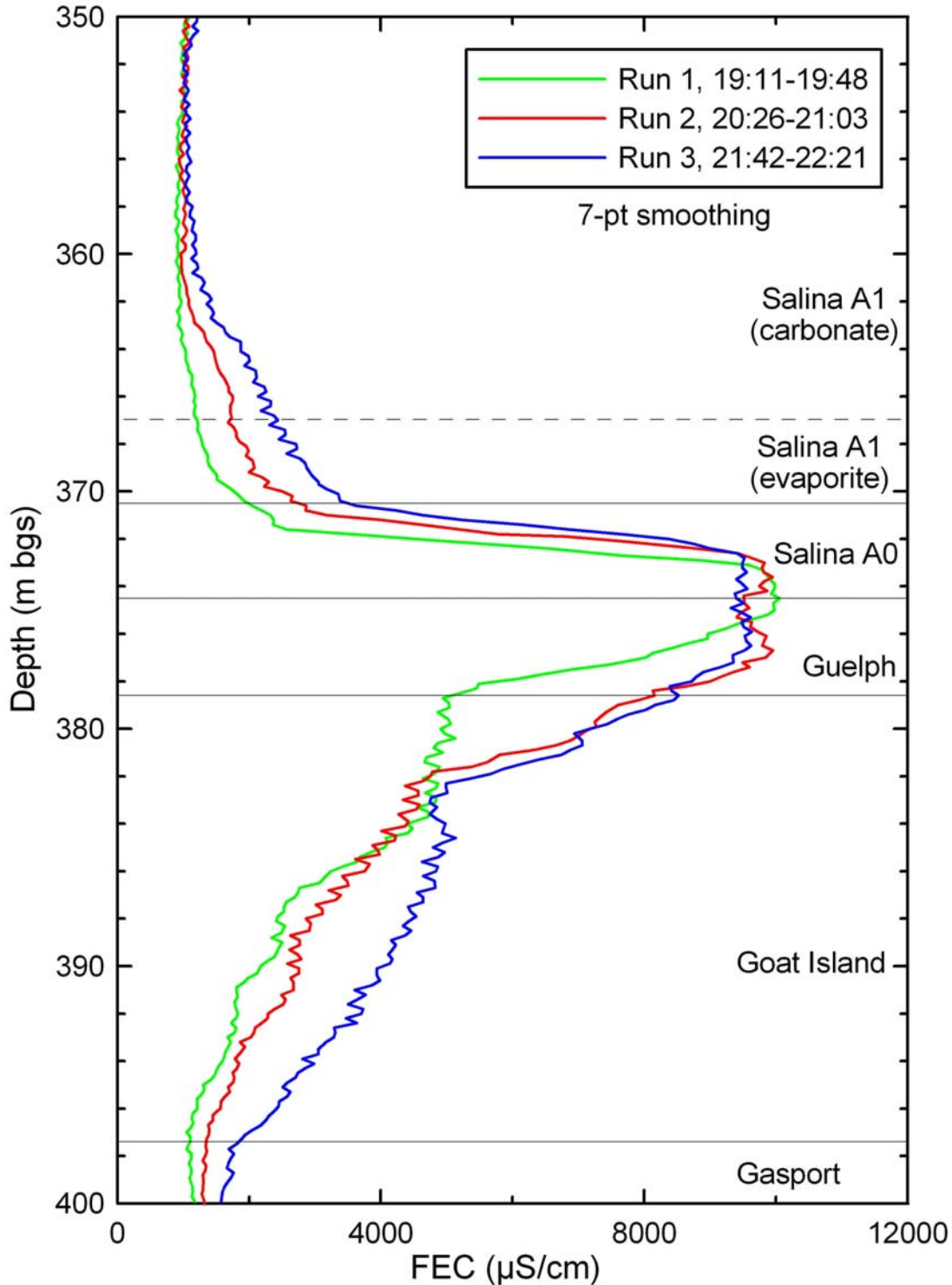


Figure 13 FEC data for the interval from 350 to 400 m bgs from all downward runs, channel 2

Figure 14 shows the smoothed data from the three downward logging runs over the interval from 400 to 430 m bgs. The two small peaks at approximately 407 and 413 m bgs became more noticeable as time progressed. The absence of apparent upward flow from these inflow zones may indicate that the hydraulic head is higher in overlying intervals of the borehole, and/or that they are contributing relatively less fluid (although possibly with higher FEC) to the borehole than higher zones. The downward spreading is most likely a density effect (and possibly mixing caused by movement of the logging sonde).

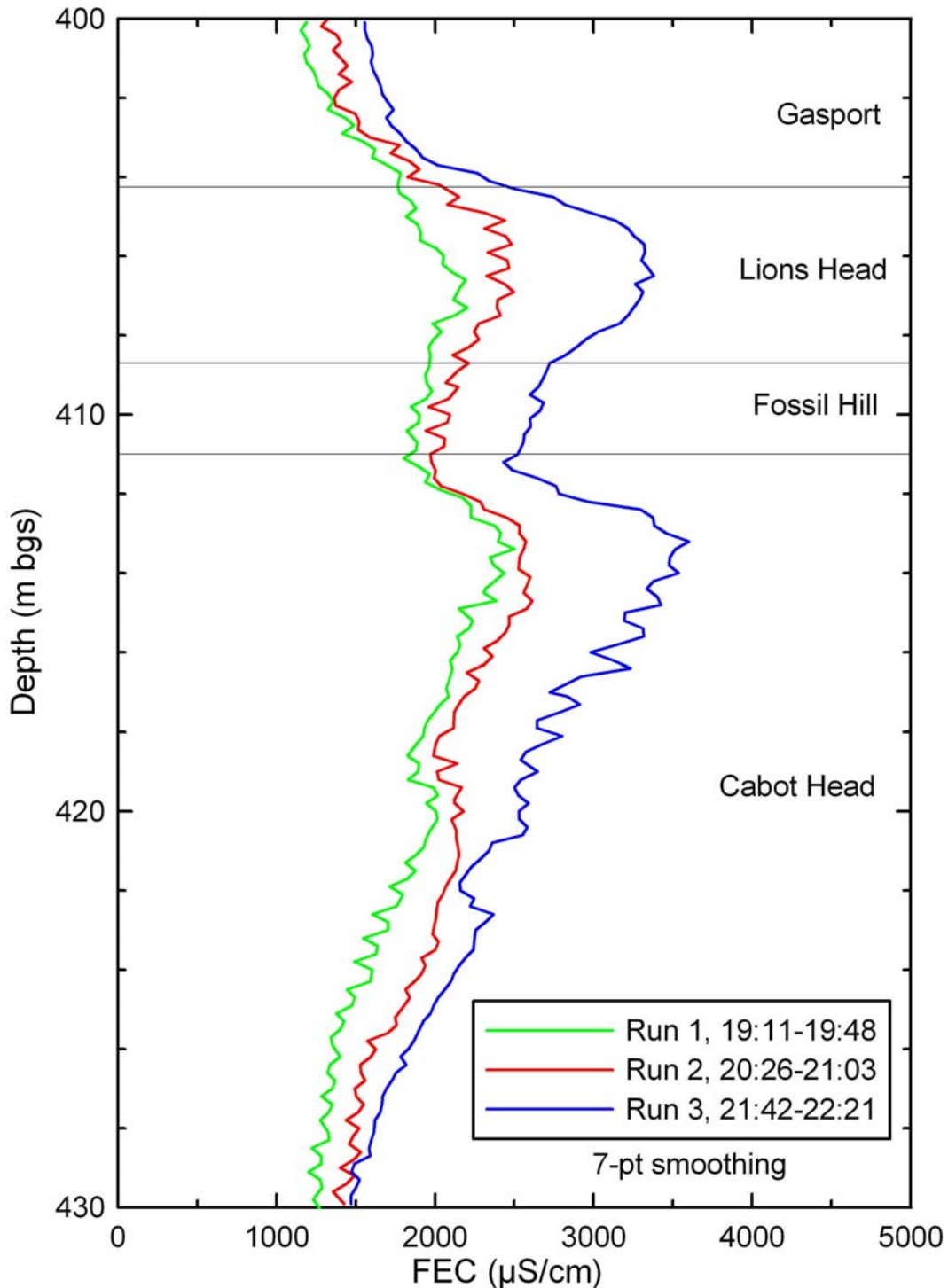


Figure 14 FEC data for the interval from 400 to 430 m bgs from all downward runs, channel 2

Figure 15 shows the time-series FEC data over the interval from 430 to 460 m bgs. The major peak beginning at 443 m bgs spread primarily downward, with little evidence of upward flow. The considerably greater downward extent of the high-FEC fluid in runs 2 and 3 compared to run 1 suggests significant gravity-driven downward movement. It also suggests that the actual inflow zone could be much thinner than the run 1 data indicate, given that two hours had already elapsed between the time fluid emplacement ended and the run 1 data over this interval were collected.

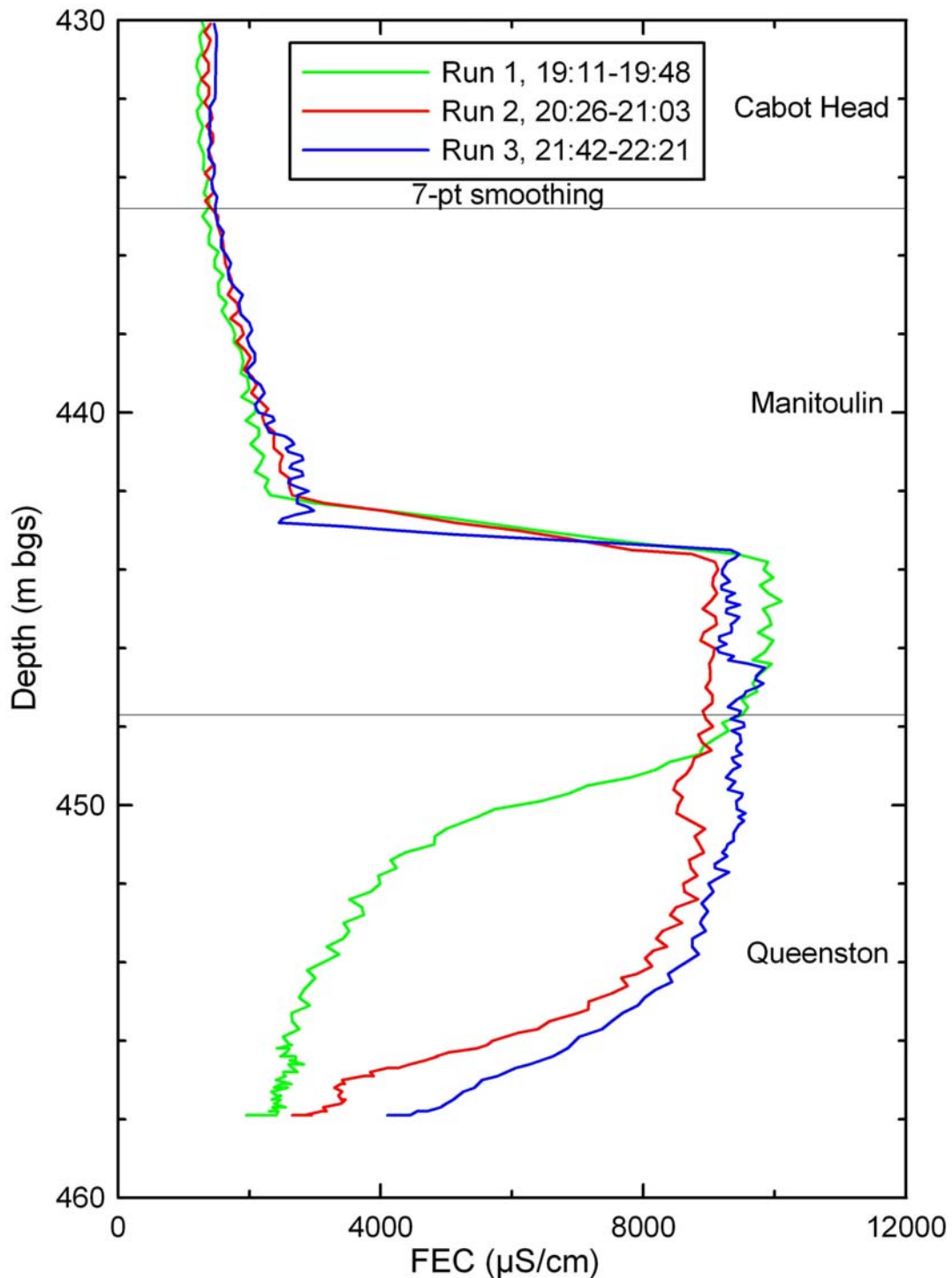


Figure 15 FEC data for the interval from 430 to 460 m bgs from all downward runs, channel 2

5 Correlation with Hydraulic Testing

The results of the FEC logging were used to select intervals for straddle-packer hydraulic testing as described by Beauheim et al. (2007). The 11 intervals tested and average preliminary values of hydraulic conductivity obtained by dividing the inferred value of transmissivity obtained by Intera Engineering Ltd., (2008) by the interval thickness are shown along with the FEC data in Figure 16. Hydraulic conductivity does not correlate perfectly with the magnitude of FEC because, as mentioned above, the FEC of the formation water entering the hole at one depth is not necessarily the same as that of the water from another formation entering at a different depth, and the hydraulic gradient into the borehole is likely different at different depths. The actual hydraulic conductivity of each flowing feature is also certain to be higher than the average hydraulic conductivity of the entire straddled interval. Nevertheless, the two zones of highest hydraulic conductivity were clearly identified by the FEC logging.

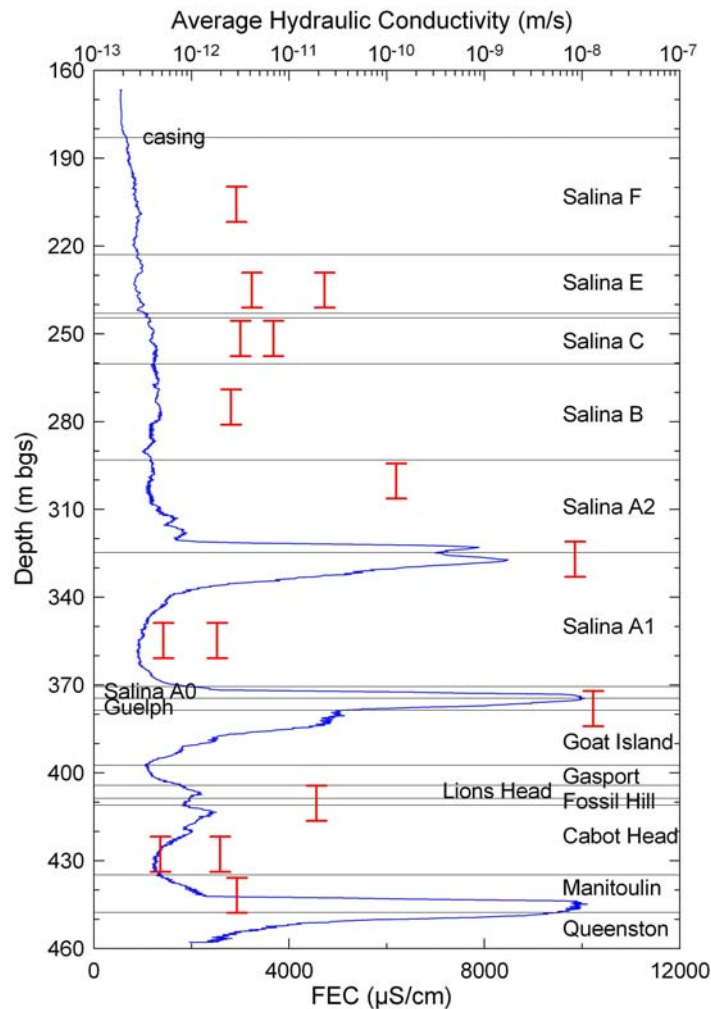


Figure 16 Comparison of average hydraulic conductivities inferred from straddle-packer hydraulic tests with FEC data

The zone with the third highest average hydraulic conductivity ($\sim 1\text{E}-10$ m/s), however, in the upper A2 Unit of the Salina, was not detected by the FEC logging. As the FEC of the water in this unit is not likely to be as low as that of Lake Huron water, the most probable explanation for the absence of an FEC peak from this unit is that no hydraulic gradient existed from this unit into the borehole. Testing under a higher induced gradient into the borehole, as originally planned, might have revealed the presence of this zone of relatively high hydraulic conductivity.

The greatest surprise was the very low average hydraulic conductivity, $\sim 3\text{E-}12$ m/s, associated with the pronounced FEC peak in the lower Manitoulin Formation. The most probable explanation for this peak is that the lower Manitoulin water must be particularly saline, so that very little of it has to enter the borehole to cause a significant change in FEC.

The two lower magnitude FEC peaks in the Lions Head Member of the Amabel Formation and the upper Cabot Head Formation correlate with the interval having the fourth highest average hydraulic conductivity, $\sim 2\text{E-}11$ m/s. All other tested intervals had average hydraulic conductivities of $\sim 4\text{E-}12$ m/s or less, consistent with the absence of any notable FEC peaks.

6 Data Quality and Use

The FEC data described in this Technical Memorandum are adequate for their intended purpose, which was to guide the selection of intervals to be tested using a straddle-packer tool. The data quality was adversely affected by the unusual electrical noise that was encountered in the borehole, which prevented FEC compensation for temperature and necessitated averaging the FEC data over a sliding seven-point window. This seven-point window represents approximately 1.3 m along the borehole, causing a reduction in the resolution of the depths at which changes in FEC occur. More pronounced FEC peaks, and probably identification of the relatively permeable section of the upper A2 Unit of the Salina, could have been achieved by logging with a larger hydraulic gradient into the borehole.

7 Summary and Conclusions

FEC logging was conducted over the Silurian interval from 183 to 460 m bgs in borehole DGR-1 at the Bruce site. The purpose of the FEC logging was to identify the intervals within each of the Silurian formations and members that provide the most flow to DGR-1 so that those intervals could then be isolated for straddle-packer hydraulic testing. Prior to logging, the drilling fluid that had been left in the borehole was replaced with Lake Huron water having an FEC of approximately 240 $\mu\text{S/cm}$, leading to flowing artesian conditions at the wellhead. Three sets of downward and upward FEC logs were run, identifying three major and two minor discrete inflow zones in the borehole. Water entering the hole at the upper major inflow zone from approximately 322 to 330 m bgs appears to be moving both upward and downward in the hole. Water entering at the other inflow zones appears to be moving primarily downward, probably because it has a higher density than the Lake Huron water in the hole. The majority of the borehole showed very small increases in FEC with time, indicative of very little advection or possibly some diffusion of solutes into the borehole.

The results of the FEC logging were used to select intervals for straddle-packer hydraulic testing. Comparison of the average hydraulic conductivity values inferred from the hydraulic tests with the FEC data shows that the FEC logging clearly identified the two zones of highest hydraulic conductivity in the borehole. One zone of relatively high hydraulic conductivity ($\sim 1\text{E-}10$ m/s) in the upper A2 Unit of the Salina Formation was not detected by the FEC logging, probably because of the absence of an adequate hydraulic gradient from this zone into the borehole. The pronounced FEC peak observed in the lower Manitoulin Formation more likely represents highly saline water than high hydraulic conductivity. The majority of the borehole that showed little increase in FEC with time appears to have an average hydraulic conductivity of $\sim 4\text{E-}12$ m/s or less.

Future FEC logging for the DGR project at the Bruce Site should employ a higher hydraulic gradient into the borehole than was established for the logging in DGR-1. This will allow better definition of the zones of highest hydraulic conductivity, and may also allow more relative differentiation of zones having hydraulic conductivities less than $1\text{E-}11$ m/s.

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APPENDIX A
FEC DATA FROM ALL CHANNELS, ALL RUNS

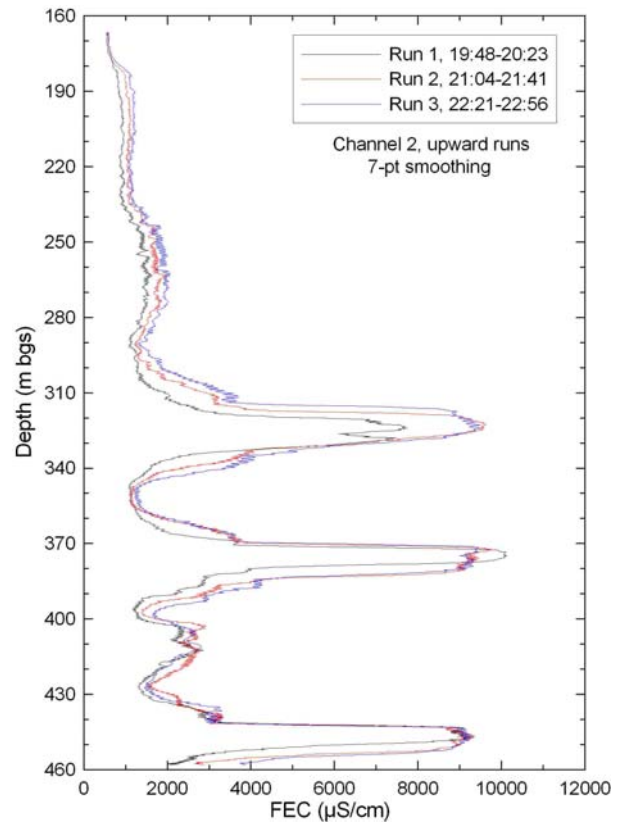
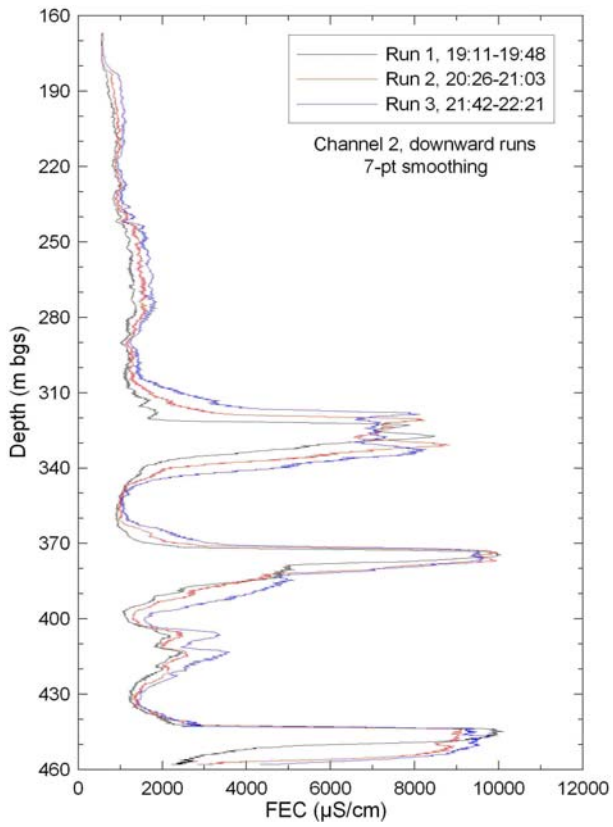


Figure A-1 Channel 2 FEC data from downward and upward logs

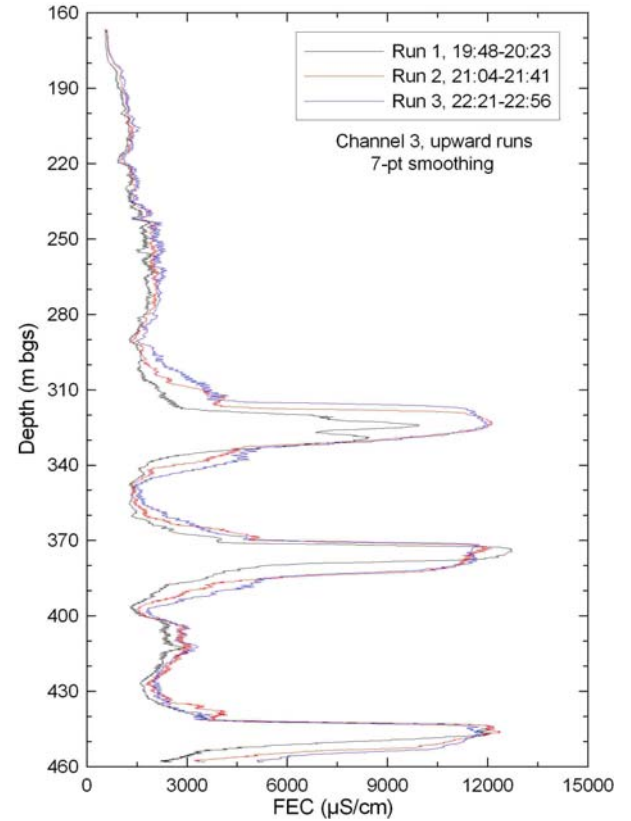
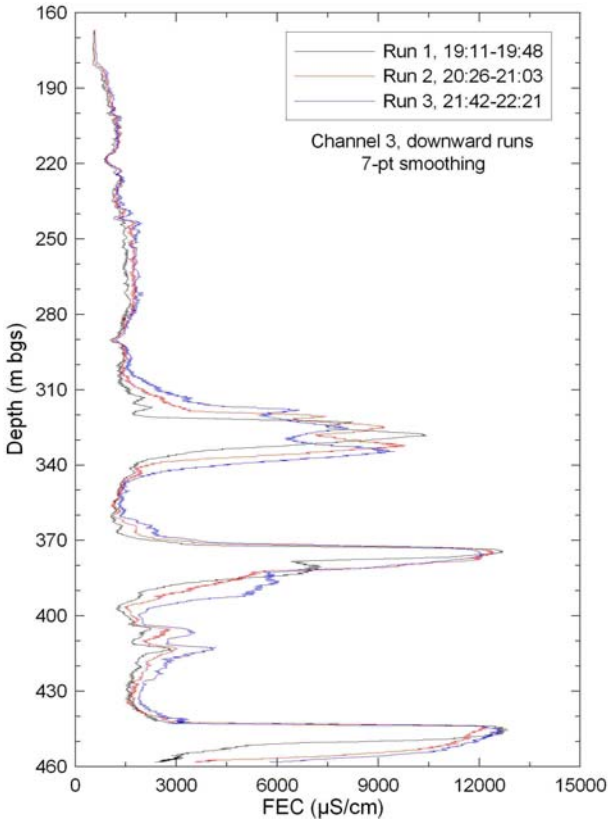


Figure A-2 Channel 3 FEC data from downward and upward logs

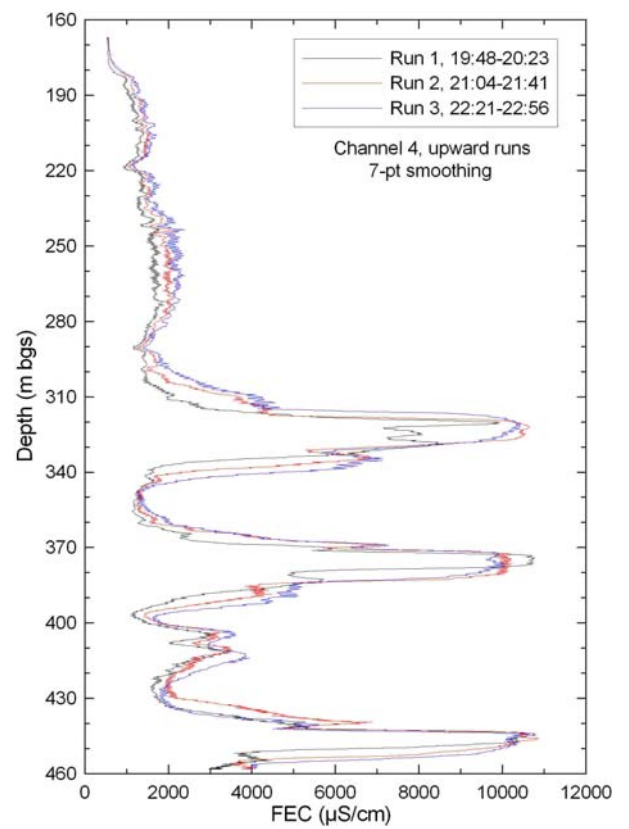
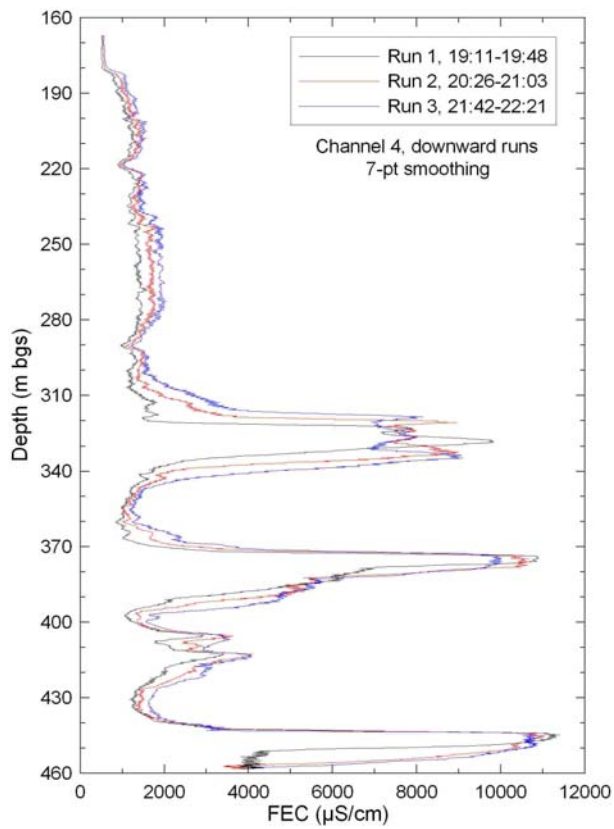


Figure A-3 Channel 4 FEC data from downward and upward logs

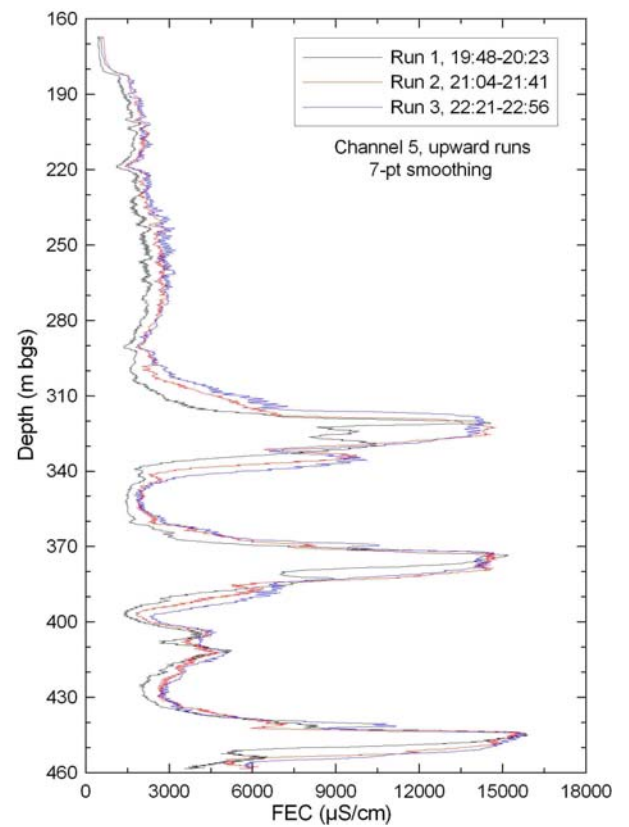
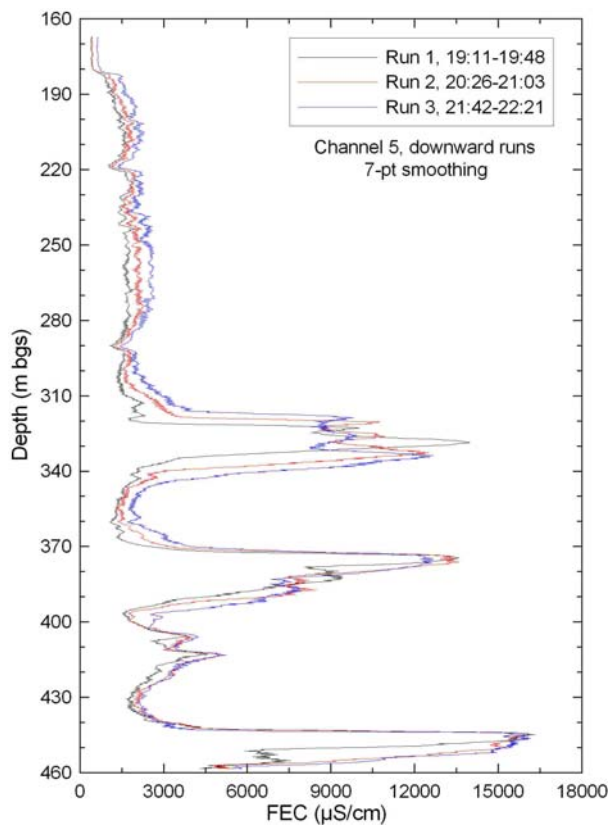


Figure A-4 Channel 5 FEC data from downward and upward logs

