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FLUID ELECTRICAL CONDUCTIVITY LOGGING IN BOREHOLE DGR-1 AT THE BRUCE SITE

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ABSTRACT
Fluid electrical conductivity (FEC) logging was conducted in the Silurian strata exposed in borehole DGR-1 at the Bruce site to identify the intervals that provide the most flow to DGR-1 so that those intervals could then be isolated for straddle-packer testing. The fluid left in the hole after drilling was replaced with Lake Huron water having a lower electrical conductivity than the water in the Silurian formations. Three sets of downward and upward FEC logging runs were performed, revealing five areas of pronounced inflow as well as other areas of lesser inflow.

RÉSUMÉ
Les diagraphies de conductivité électrique fluide (FEC) ont été conduite dans les strates siluriennes exposées dans le forage DGR-1 au site de Bruce pour identifier les intervalles qui fournissent la plupart d'écoulement à DGR-1 de sorte que ces intervalles aient pu alors être isolés entre double obturateur pour les tests hydrauliques. Le fluide dans le trou après forage a été remplacé avec de l'eau du Lac Huron ayant une conductivité électrique inférieure que l'eau dans les formations siluriennes. Trois ensembles de courses de diagraphie de haut en bas et ascendantes de FEC ont été exécutés, indiquant cinq niveaux producteurs aussi bien que d'autres niveaux de peu d'apport.

1 INTRODUCTION

Fluid electrical conductivity (FEC) logging was performed in borehole DGR-1 at the Bruce site near Tiverton, Ontario, Canada, 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). 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 1). While additional quantification of flow is possible from typical FEC (or hydrophysical) logging, the sole purpose of the FEC logging at the Bruce site 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 testing. In addition, the combination of FEC logging and straddle-packer testing will 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.

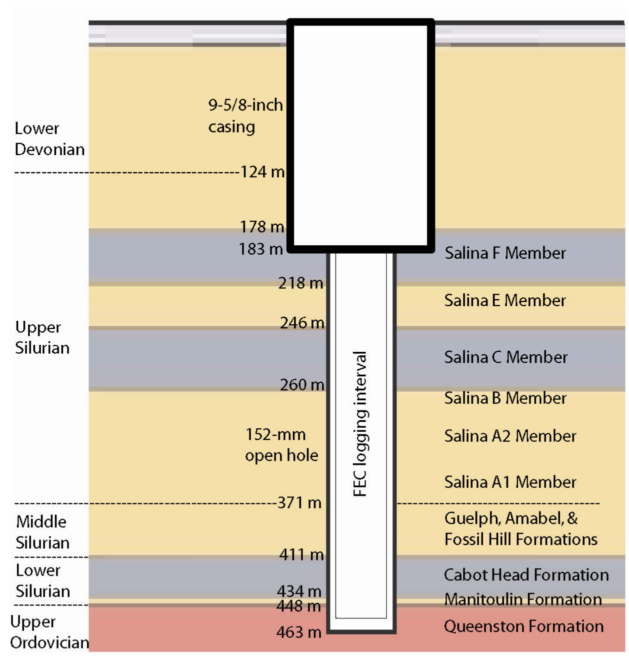

Figure 1. Stratigraphy and FEC logging interval in DGR-1 (all stratigraphic depths are preliminary).

2 FEC LOGGING

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. FEC logging may be performed under ambient (unstressed) or pumping conditions.

3 FEC LOGGING PROCEDURE

3.1 Fluid Emplacement

For the FEC logging in borehole DGR-1 at the Bruce site, the fluid left in the borehole after drilling was replaced with Lake Huron water having an electrical conductivity of approximately 800 microSiemens/ centimetre (μS/cm). In contrast, the waters in the Silurian formations being logged were expected to have FECs in excess of 100,000 μS/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 150 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 after 3-4 wellbore volumes had been flushed.

The hydraulic head in 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, with a flow rate at the wellhead of less than 1 L/min. Thus, a slight hydraulic gradient into the borehole was present during the logging.

3.2 FEC Logging Sonde

The sonde used for the FEC logging was the RAS Hydrophysical™ proprietary logging tool (Figure 2). This tool represents the fourth and latest generation of fluid logging sondes and has four separate channels 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 μS/cm.

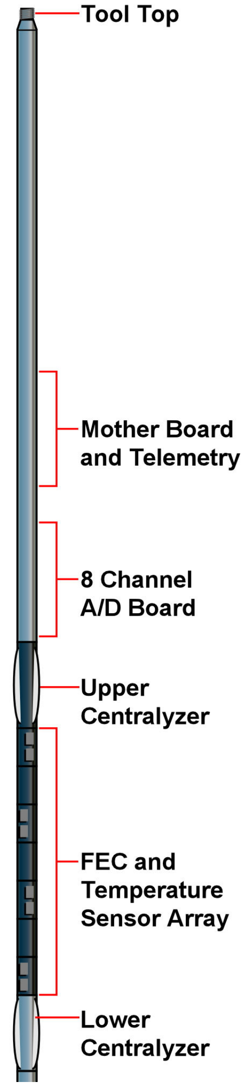

Figure 2. FEC logging sonde.

3.3 Logging Runs

FEC logging began after the tubing used for fluid emplacement was removed from the hole, approximately 1 hour 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.

4 LOGGING RESULTS

4.1 First Logging Run

Figure 3 shows the raw (not temperature-compensated) FEC values recorded on channel 4 of the DAS during logging run 1. Five major peaks, corresponding to fluid-inflow points, are evident in Figure 3. The three largest peaks, beginning at 323, 374, and 444 m (all depths are below top of casing (btoc), approximately one metre above ground) actually comprise multiple inflow locations. 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 waters entering the hole are not necessarily the same.

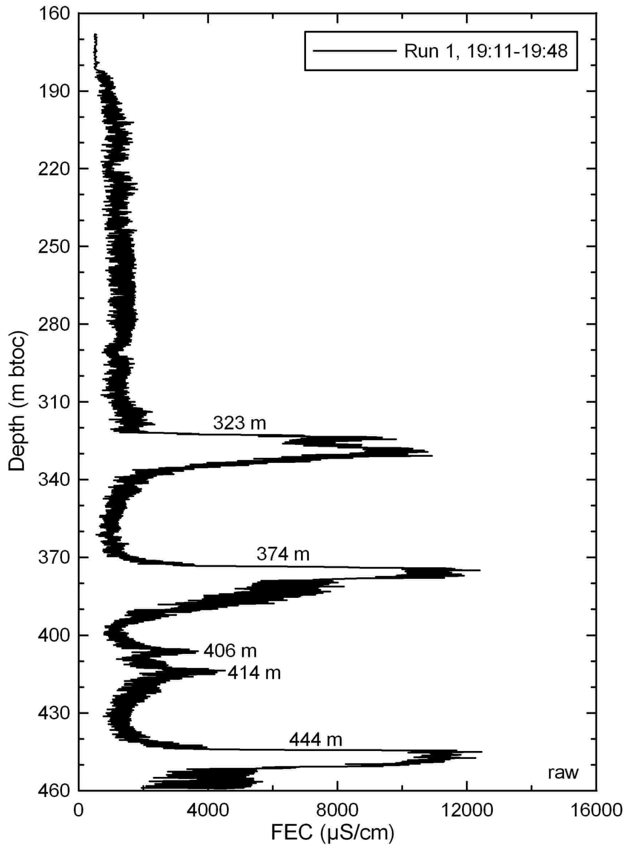

Figure 3. FEC data from run 1 in DGR-1, channel 4.

Figures 4, 5, 6, and 7 show the intervals from 310 to 340 m, 370 to 400 m, 400 to 430 m, and 430 to 460 m btoc, respectively, in more detail. Figure 4 shows one peak centered at approximately 324 m and a broader peak between approximately 328 and 331 m. This inflow zone appears to correspond to porous and vuggy dolostone recovered in core runs (CR) 115, 116, and 117 in DGR-1, which may be part of the A Member of the Salina Formation (not yet differentiated between A1 and A2).

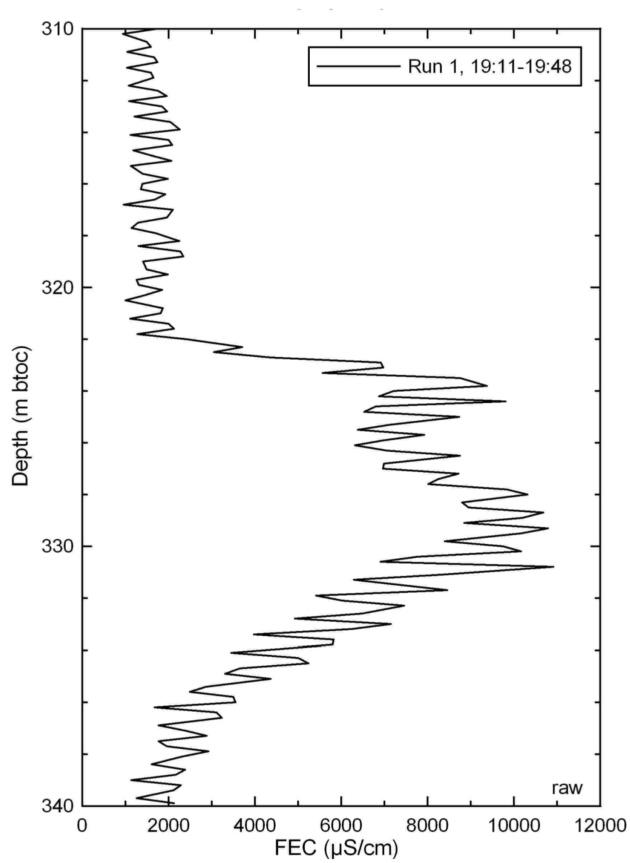

Figure 4. Run 1 FEC data for the interval from 310-340 m, channel 4.

Figure 5 shows a broad inflow zone from approximately 374 to 378 m btoc, with what may be a less significant, less well-defined inflow zone immediately below. The major inflow zone probably corresponds to porous and vuggy dolostone recovered in CR 132 and 133, thought to be from the upper Guelph Formation.

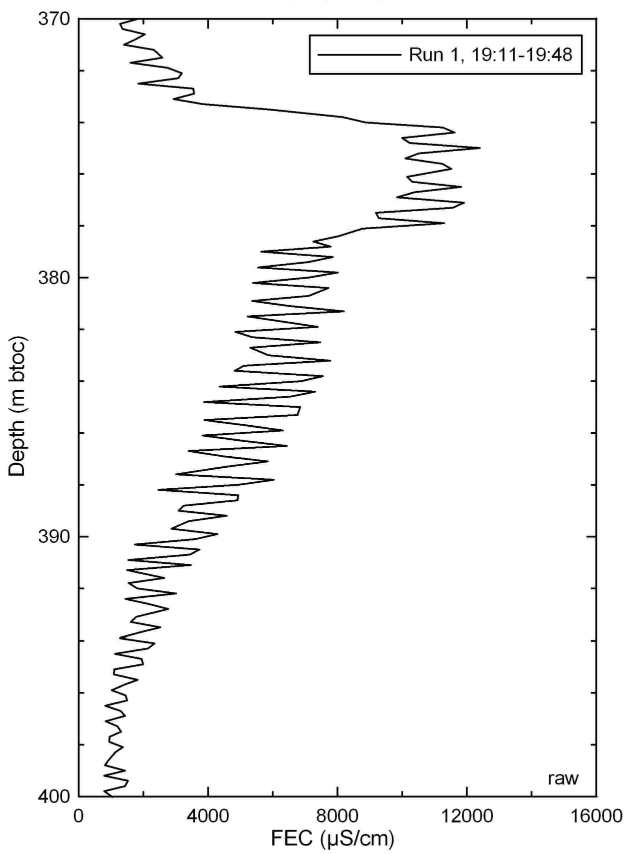

Figure 5. Run 1 FEC data for the interval from 370-400 m, channel 4.

Figure 6 shows the two FEC peaks centered on approximately 406 and 414 m btoc. The interval around 406 m is thought to correspond to the lower part of the Fossil Hill Formation, and the interval around 414 m is probably the upper part of the Cabot Head Formation.

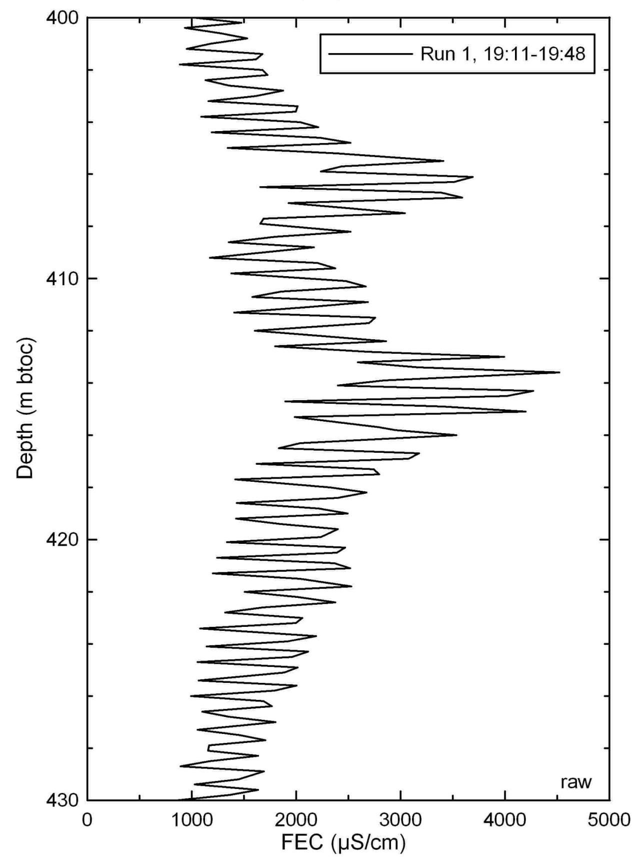

Figure 6. Run 1 FEC data for the interval from 400-430 m, channel 4.

Figure 7 shows a broad FEC peak from approximately 444 to 450 m btoc. This interval probably corresponds to the dolostone of the Manitoulin Formation recovered in CR 154 and 155.

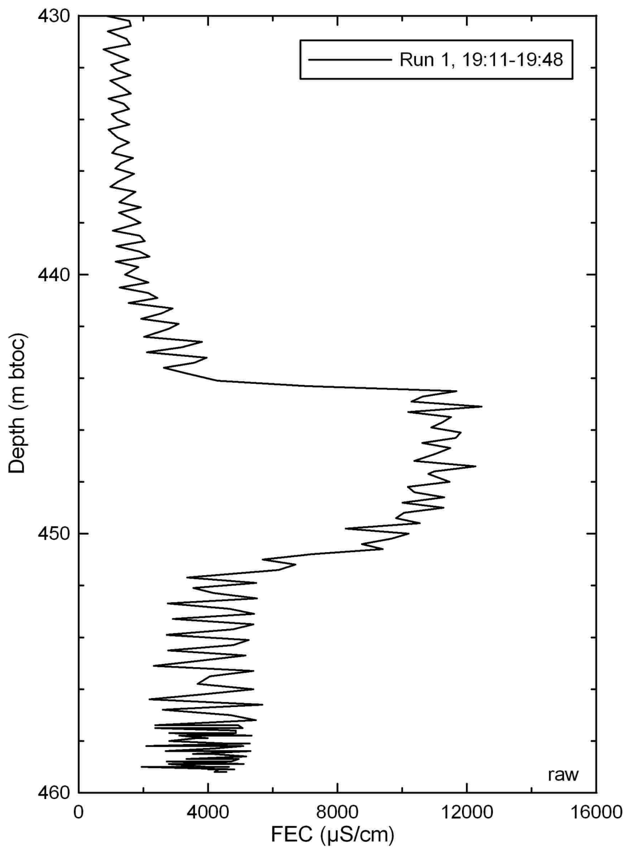

Figure 7. Run 1 FEC data for the interval from 430-460 m, channel 4.

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 8 shows data from the three downward logging runs over the interval from 300 to 350 m btoc. The data have been smoothed using a nine-point running average to remove the electrical noise seen in Figures 3 through 7. The high-FEC water entering the borehole between approximately 323 and 330 m is spreading both upward and downward in successive logs. The two inflow peaks also remain distinct as the “plume” spreads. Upward flow would be expected, given the flowing condition of the borehole. Downward flow could be caused by lower hydraulic head somewhere deeper in the hole, and/or by gravity causing the denser high-FEC water to sink.

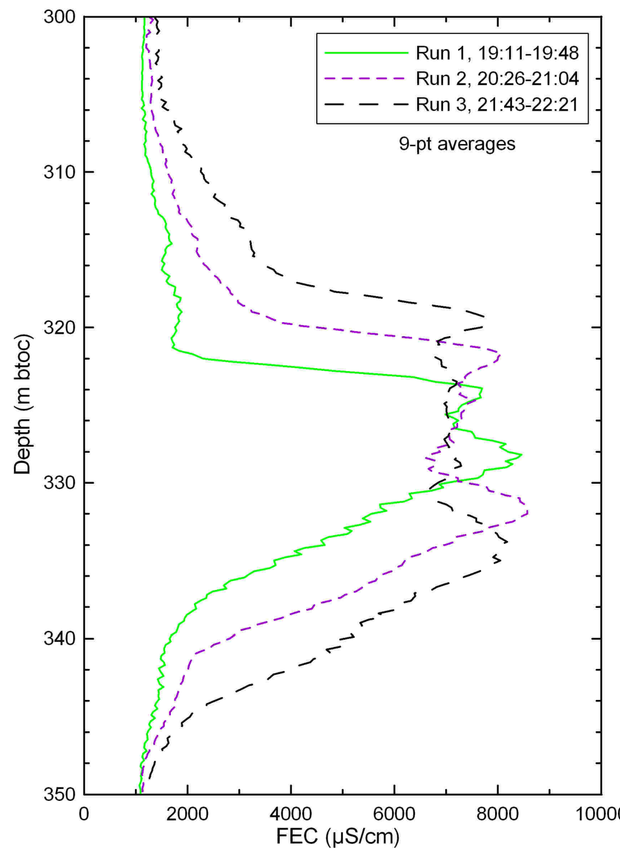

Figure 8. FEC data for the interval from 300-350 m from all downward runs with 9-point smoothing, channel 2.

Figure 9 shows the smoothed data from the three logging runs over the interval from 350 to 460 m btoc. The major peaks beginning at 374 and 444 m spread primarily downward, with little evidence of upward flow. The two smaller peaks at approximately 406 and 414 m 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 the interval from 323 to 330 m, and/or that they are contributing relatively less fluid (although possibly with higher FEC) to the borehole than the higher zone. The downward spreading is most likely a density effect (and possibly mixing caused by movement of the logging sonde), because of the absence of any obvious outflow point from the hole, which would appear as a horizon across which the FEC rapidly transitioned back to the baseline (Lake Huron water) level. The straddle-packer testing that will follow the FEC logging will provide the data needed to determine the vertical hydraulic gradients in the borehole.

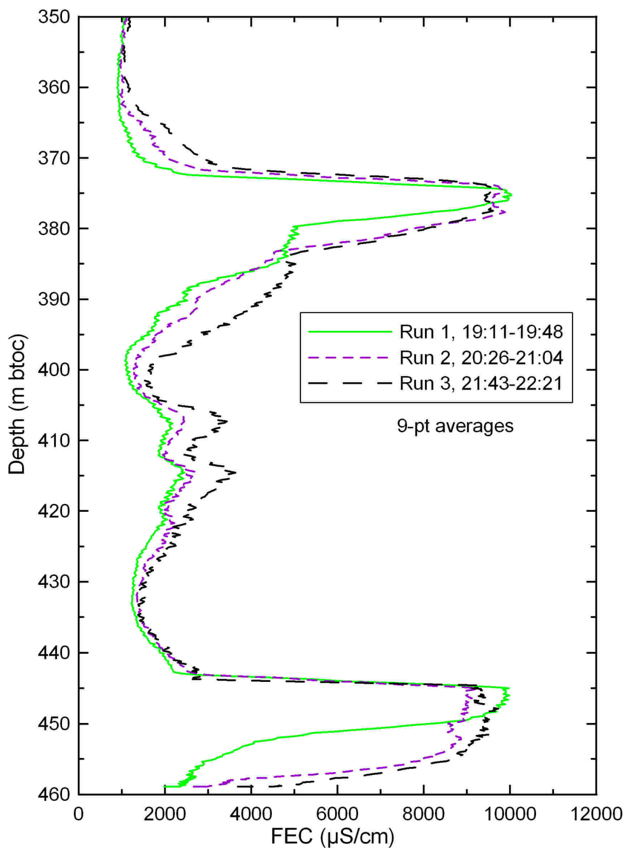

Figure 9. FEC data for the interval from 350-460 m from all downward runs with 9-point smoothing, channel 2.

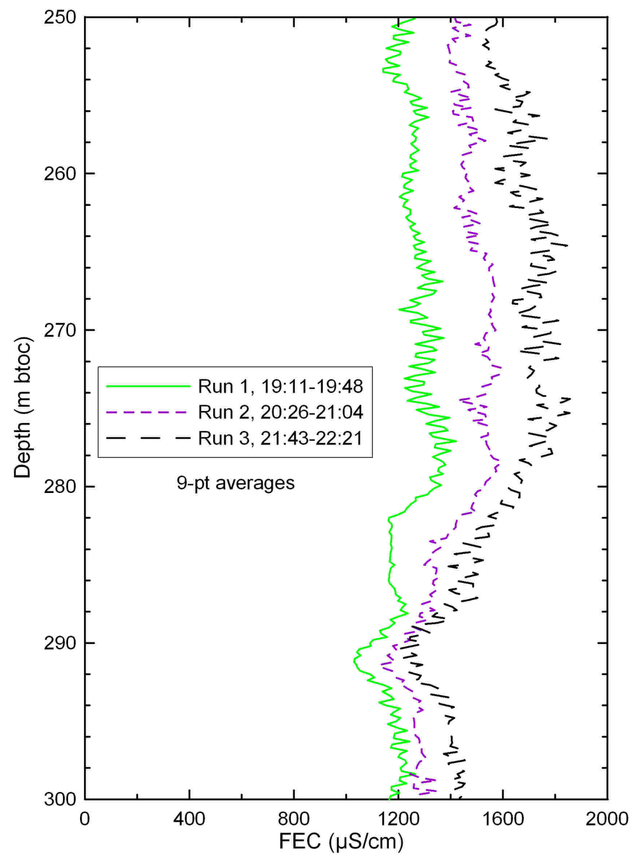

Figure 10. FEC data for the interval from 250-300 m from all downward runs with 9-point smoothing, channel 2.

Figure 10 shows the smoothed data from the three downward logging runs over the interval from 250 to 300 m btoc, which more or less typifies the portions of the hole that did not show pronounced inflow The FEC clearly increases relatively uniformly with time over the interval from approximately 250 to 280 m, perhaps indicating low, evenly distributed inflow. A persistent low-FEC zone is seen at approximately 291 to 292 m, which may reflect an interval contributing very little water to the hole. A similar zone is seen at approximately 220 m in Figure 3.

5 SUMMARY AND CONCLUSIONS

FEC logging was conducted over the Silurian interval from 183 to 460 m 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 800 µS/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 323 to 331 m btoc 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. Possible very small inflows were noted over much of the rest of the hole.

ACKNOWLEDGEMENTS

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