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1 **A Qualitative Assessment of Microclimatic Perturbations in a Tunnel**

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11 **Abstract**

12 Understanding microclimate dynamics in tunnels is important for designing and
13 maintaining underground facilities. For example, in the geological disposal of radioactive
14 materials, condensation of vapor should be minimized as it can accelerate waste package
15 corrosion and radionuclide release. While microclimate dynamics are known to be
16 dominated by the advection of heat and moisture, additional factors may also be
17 important, such as the presence of fractures or faults. We present a relatively inexpensive
18 method to assess microclimatic perturbations within a tunnel. By combining standard
19 temperature and relative humidity sensors with low-cost sensors designed to detect
20 changes in condensation, we monitored microclimate dynamics along a tunnel at the
21 proposed geological repository at Yucca Mountain, Nevada. We observed significant
22 differences in the pattern of condensation in a faulted zone relative to that of a nonfaulted
23 zone, suggesting that the microclimate dynamics of excavated cavities in fractured,
24 partially saturated rocks can be highly complex.

25 **Key Words**

26 Microclimate, Tunnels, Condensation, Evaporation, Fractured Rock , Monitoring
27 Techniques

28

29 **I. Introduction**

30 An understanding of microclimate dynamics in underground cavities is important for
31 applications ranging from the design of waste disposal facilities to the preservation of
32 artifacts or fauna in caves (de Freitas and Schmekal, 2003). In such environments,
33 typically having high humidity and containing partially saturated rocks, the microclimate
34 is dominated by advection of heat and moisture (De Freitas and Littlejohn, 1987), with
35 the thermal state being defined by the geothermal flux, thermal diffusion from the
36 surface, water circulation, and air exchange with the outside atmosphere (Crouzeix *et al*,
37 2003).

38 At the proposed geological repository for radioactive waste at Yucca Mountain,
39 Nevada, it is crucial to minimize exposure of waste containers emplaced in horizontal
40 tunnels (drifts) to water. The presence of in-drift water caused by seepage from the
41 surrounding rock mass or by condensation of vapor can accelerate waste package
42 corrosion and potentially enhance radionuclide dissolution, release and transport. It is
43 important to understand the microclimates that could develop in this fractured and faulted
44 rock environment, and the subsequent propensity for water condensation.

45 Yucca Mountain is located in the central portion of the southern Basin and Range,
46 which resulted from late Cenozoic extensional faulting (Piety, 1996). Key features in the
47 structural geology of the region include block-bounding faults, occurring every 1–4 km,
48 and intrablock faults (Stuckless and Dudley, 2002). Because the proposed geological
49 repository will include kilometers of horizontal tunnels, it will inevitably be intercepted
50 by sub near-vertical faults.

51 Here we present a relatively inexpensive technique for monitoring microclimate
52 dynamics along a tunnel. Using sensors designed to detect changes in water saturation
53 caused by condensation and evaporation, we were able to monitor in-drift microclimate
54 dynamics at higher temporal and spatial resolution than previously investigated (to our
55 knowledge). We observed significant differences between and within faulted and
56 nonfaulted zones. The complexity of the microclimate dynamics highlights the need for
57 such studies in designing facilities in fractured, partially saturated rocks.

58

59 **II. The Study Site**

60 The study was conducted over a period of 14 months, beginning in late 2001, in the
61 immediate vicinity of the Solitario Canyon Fault Zone (SCFZ) at Yucca Mountain
62 (Figure 1). The SCFZ, considered to be the laterally most continuous fault at Yucca
63 Mountain, is accessible ~300 m below ground surface through a 2.7 km long, 5 m
64 diameter tunnel, the Cross Drift (CD). The CD, excavated in 1998, is located entirely
65 within the Topopah Spring Tuff (Figure 1a). The eastern strand of the SCFZ begins at
66 Sta. 25+85, though the influence of the SCFZ on the surrounding rock extends to Sta.
67 25+00 in the form of shear intensity (Mongano et al., 1999). (“Sta.” indicates station and
68 is followed by distance in meters, with 25+85 indicating, for example, the location 2,585
69 m from the start of the CD).

70

71 **III. Methods**

72 **a. Isolation of the CD from engineered ventilation**

73 During the six-month excavation of the CD, engineered ventilation was maintained
74 by a series of fans in a ~1 m diameter tube extending over the length of the tunnel which
75 drew air into the tube and transported it out of the tunnel. The impact of the engineered
76 ventilation on the in-drift microclimate and surrounding formation was substantial, and
77 thus had to be mitigated for this investigation, which was accomplished by isolating four
78 sections along the terminal section of the CD with steel doors, referred to as bulkheads, at
79 Sta. 17+63, 22+00, 25+03, and 26+00 (Figure 1b). The first two sections were outside the
80 SCFZ: between Sta. 17+63 and 22+00 (Section 1), and between Sta. 22+00 and 25+03
81 (Section 2). The third section (Section 3) was located between Sta. 25+03 and 26+00 and
82 included the eastern strand of the Solitario Canyon Fault. The fourth section (Section 4)
83 was located beyond Sta. 26+00 in a faulted zone between the eastern and western strands
84 of the Solitario Canyon Fault. This configuration allowed us to monitor microclimate
85 dynamics outside of (Sections 1 and 2) and within (Sections 3 and 4) the SCFZ.

86 On November 19, 2001, the ventilation was stopped in Sections 2-4 and these
87 sections were sealed by closing the last three bulkhead doors. One month later Section 1
88 was similarly sealed by closing the first bulkhead door and removing ventilation.
89 Sections 2-4 would remain sealed for 15 months, while Section 1 would for only 7
90 months. To remove artificial sources of heat, electrical power to the investigated region
91 was stopped, except for the 12 V batteries used to power the data loggers and sensors.

92 **b. Monitoring of in-drift microclimate in faulted and nonfaulted zones**

93 Humidity and temperature were measured (Model HMP45C, Campbell Scientific
94 Inc.) in the isolated Sections 1–4 of the CD, and just outside the isolated sections (at Sta.
95 15+00), where engineered ventilation remained active.

96 Electrical resistance probes (ERPs) were used to monitor changes in condensation
97 along 200 m of the drift at high spatial and temporal resolution. Working under the
98 principle that the water saturation of a material is inversely proportional to the electrical
99 resistance (Archie, 1942; Blasch et al., 2002), Salve et al. (2000) developed ERPs using
100 filter paper as the sensing element, such that the electrical resistance depended on the
101 amount of water adsorbed on the filter paper. Placed close to the floor of the tunnel and
102 exposed to the in-drift atmosphere, a total of 400 ERPs were installed at 0.5 m intervals
103 between stations 24+00 (in Section 2) and 26+00 (at the end of Section 3). To keep water
104 from pooling on or near the probes and influencing subsequent measurements, the ERPs
105 were mounted on the outer curved surface of PVC pipes that were sectioned length-wise.

106 The measurement system for the ERPs included four data loggers (Model CR10X,
107 Campbell Scientific Inc., Logan, Utah), each connected to several multiplexers (Model
108 A416, Campbell Scientific Inc., Logan, Utah). The data loggers and multiplexers were
109 placed in air-tight containers to prevent corrosion from the humid in-drift air. An internal
110 check of the measurement system was provided with precision resistors placed on the
111 measurement ports of the multiplexers and near some of the ERPs.

112 The ERP data were compared with data from co-located relative humidity (RH)
113 sensors (Model HMP 45C, Cambell Scientific). The relationship between these two data
114 types is as follows: an increase in relative humidity , as measured by the RH sensor,
115 causes an increase in condensation on (and thus water saturation of) the ERP filter paper,
116 resulting in a decrease in electrical resistance, as measured by the ERPs (and vice versa).
117 Figure 2 compares the ERP and RH response at two locations, focusing on the RH range
118 of 90%–100% (values below this are of less interest as they reflect conditions in which

119 humidity is unnaturally low due to the engineered ventilation). The relationship between
120 the two data types is as expected, with decreasing electrical resistance closely tracking
121 the increasing RH.

122

123 **IV. Observations**

124 **a. Temperature and relative humidity**

125 The temperature and RH measurements for Sections 1–4 are presented in Figure 3.
126 When ventilation was removed from Sections 2–4 in mid-November 2001, there was an
127 immediate, rapid decrease in temperature that persisted for ~1 week, followed by a
128 gradual decrease (Figure 3a). While the temperature was slightly higher (relative to
129 Sections 2–4) in Section 1, (this section was not isolated from ventilation effects until the
130 third week in December 2001), the pattern was similar as for the other sections. When the
131 first bulkhead door was opened in June 2002, the temperature in Section 1 immediately
132 increased. A more gradual increase was observed in Section 2 (measured at Sta. 23+45)
133 over the next five months. Temperatures in Section 4 (measured at Station 26+30)
134 consistently remained higher than in Sections 2 and 3 until November 2002, when some
135 sensors failed.

136 RH measurements show that humidity in the four nonventilated sections began to
137 increase after the bulkhead doors were closed and ventilation was stopped (Figure 3b).
138 Similar to the temperature responses, there was an initial period of rapid change in RH,
139 followed by a slower rise after the first few weeks. In Section 1 (at Sta. 21+40), after the
140 section was sealed in December 2001, there were initially rapid changes in over a period
141 of two weeks, with values rising from ~10 to ~90%. In the following 5 months, the RH

142 continued to rise, but was interrupted at weekly intervals, likely affected by the adjacent
143 non-isolated section of the drift, for which ventilation was active from Monday through
144 Thursday and inactive from Friday through Sunday of each week. Deeper in the CD (in
145 Sections 2–4), the average RH response was almost identical in each section, with the RH
146 increasing rapidly to ~90% and then gradually toward 100%. The periodic disruptions in
147 RH observed in Section 1 were not observed in Sections 2–4.

148 Note that we observed no correlation between the barometric pressure (not shown)
149 and the temperature and RH data.

150

151 **b. Electrical resistance probes (ERPs)**

152 After the engineered ventilation was removed, ERP resistance values began to rapidly
153 decrease for a few months before reaching a relatively constant value (Figure 4a). The
154 decrease in the nonfaulted zone (Sta. 24+00 to 25+00) was generally faster than in the
155 faulted zone (Sta. 25+00 to Sta. 26+00). After the initial decrease, the resistance in the
156 nonfaulted zone remained mostly uniform at low values (i.e., indicating wetter conditions
157 with more condensation) compared to the faulted section with increasingly higher values
158 (i.e., indicating drier conditions with less condensation).

159 Within the nonfaulted section, small differences in the general pattern were noted
160 between January and August 2002, when the region between Sta. 24+00 and 24+20
161 remained drier than the rest of the nonfaulted zone. By September 2002, these differences
162 disappeared, but others began to emerge. For example near Sta. 24+35, there was a large
163 decrease over several meters which persisted until the end of monitoring. However, for

164 the remainder of this section (Sta. 24+40 to 25+00) the response was relatively uniform
165 following the initial decrease.

166 As in the nonfaulted section, there was no identifiable spatial trend in the faulted
167 section during the first few months. However, by April 2002, for a period of about two
168 months, the faulted section shows a trend going from lower to higher resistance (higher to
169 lower condensation) with increasing station number. This spatial pattern was interrupted
170 in early July 2002, when a substantially wetter zone developed abruptly between Sta.
171 25+65 and 25+75.

172 It is interesting to note that the sharp contrast in resistance on either side of the
173 bulkhead door at Sta. 25+03 suggests that the bulkhead door likely influenced the
174 microclimate in its vicinity.

175 The resistance profile is shown in Figure 4b for two times during the monitoring
176 period. Note that for the earlier time the spatial fluctuations are relatively minor, and a
177 trend of increasing resistance is seen in the faulted zone (Sta. 25+00 to 26+00). While the
178 later profile shows similarly mild fluctuations in the nonfaulted zone (except near Sta.
179 24+35), more extreme fluctuations are seen in the faulted zone.

180

181 **c. Precision resistors**

182 Measurements were also collected using standard resistors, referred to here as
183 “precision resistors,” to check that the measurement systems were functioning properly
184 (i.e., the resistance measured across these resistors was expected to remain constant and
185 be unaffected by the surroundings). An interesting, though unexpected observation was
186 made when changes were detected in the precision resistors.

187 Some of the precision resistors were placed in sealed containers and isolated from the
188 in-drift microclimates, while the rest were located alongside ERPs and thus were exposed
189 to the in-drift microclimates. The isolated resistors showed no significant changes during
190 the investigation (Figure 5a). However, the resistors exposed to the in-drift conditions
191 showed substantial changes that were similar in nature (but smaller in magnitude) to the
192 changes observed in the ERP data, with slightly less variability in the nonfaulted zone
193 (Figure 5b) than in the faulted zone (Figure 5c). It appears that the high humidity
194 conditions within the drift resulted in condensation that caused steady but non-uniform
195 corrosion of the precision resistors.

196

197 **V. Discussion and Conclusion**

198 When engineered ventilation is suppressed in excavated cavities that are thought to be
199 isolated from atmospheric dynamics, it is tempting to assume that a low-energy
200 environment with a stable internal microclimate exists (e.g., Freitas and Littlejohn, 1987;
201 Gamble et al., 2000). However, our observations suggest that in cavities located in
202 fractured/faulted rock, such as the CD at Yucca Mountain, the microclimatic regime is
203 dynamic and may vary unexpectedly from the assumed low-energy environment.

204 The following observations can be made from this study:

- 205 1. The ERP response suggests that there are changes in condensation patterns within
206 the drift over the large spatial scale (200 m) and long time frame (~14 months)
207 that we examine. Some areas of the drift are subject to greater amounts of
208 condensation than others.

- 209 2. There are significant differences in the microclimates of the faulted and
210 nonfaulted sections, with the faulted section showing greater variability.
- 211 3. Non-uniform corrosion of precision resistors (installed with the intent of
212 providing a check on the electronics) also suggests spatial variability in the in-
213 drift moisture dynamics.

214

215 While qualitative in nature—since we based our observations on trends seen in a
216 large number of ERPs that were not calibrated specifically to provide condensation or RH
217 estimates—the results of this study point to the need for detailed, quantitative
218 investigations of in-drift microclimates for designing or maintaining facilities in
219 fractured, partially saturated rocks.

220

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228

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254

254 **Figure Captions**

255 Figure 1. (a) Cross section of Yucca Mountain showing the geology of the formation
256 surrounding the Cross-Drift (CD). (b) Location of the four bulkhead doors used to isolate
257 sections of the drift from engineered ventilation. (c) Photograph of the Solitario Canyon
258 Fault in Section 3.

259 Figure 2. Comparison of in-drift electrical resistance probe (ERP) measurements with
260 relative humidity measurements made using commercially available probes (Model HMP
261 45C, Campbell Scientific). The insets depict expanded views over a time period of two
262 weeks.

263 Figure 3. (a) Temperature and (b) relative humidity measured at four locations in the CD.
264 The legend indicates the locations of the sensors along the drift. A drop in temperature
265 after December 6, 2002 in stations 23+45 and 25+55 results from the battery losing
266 adequate power.

267 Figure 4. Resistance measurements collected with ERPs from Sta. 24+00 to 26+00. (a)
268 Data collected at all times with color representing resistance (in $k\Omega$). (b) Resistance
269 profile at two times, as indicated by dashed lines in (a).

270 Figure 5. Precision resistor measurements (a) isolated in sealed containers, (b) open to the
271 in-drift atmosphere in the nonfaulted section, and (c) open to the in-drift atmosphere in
272 the faulted section.

Figure 1.

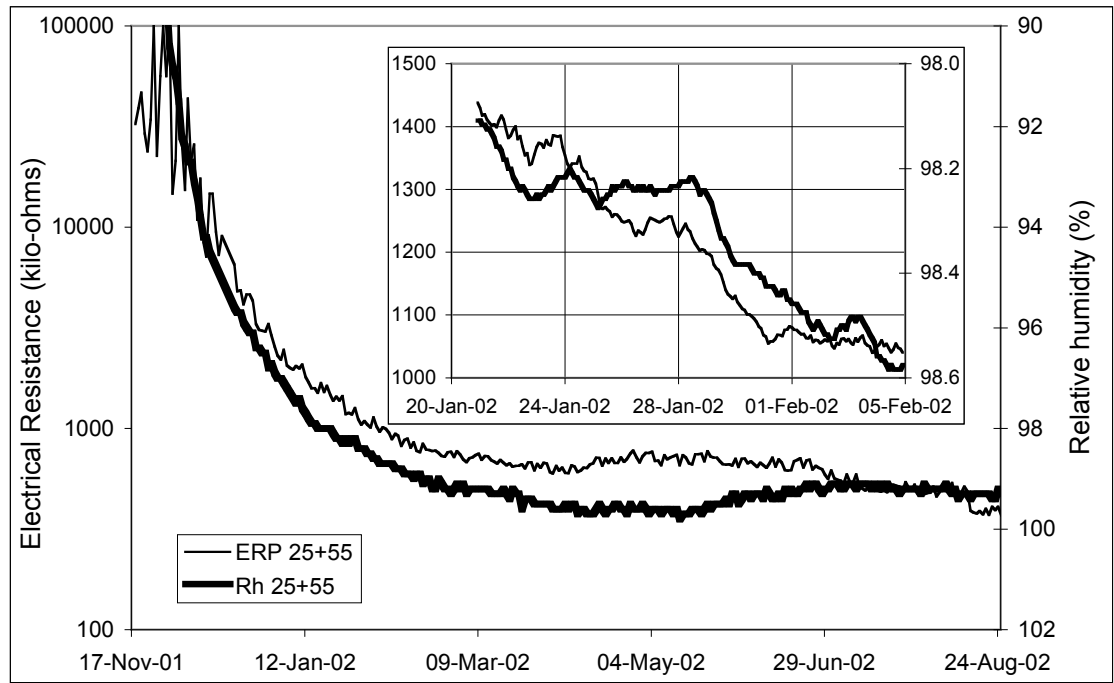
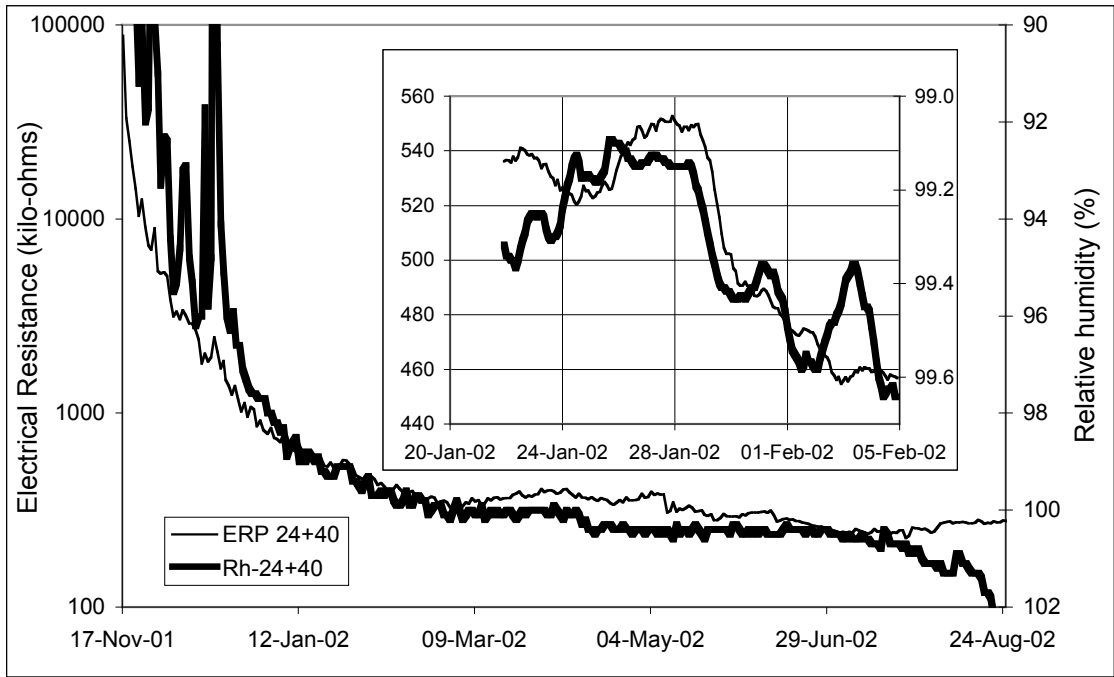


Figure 2.

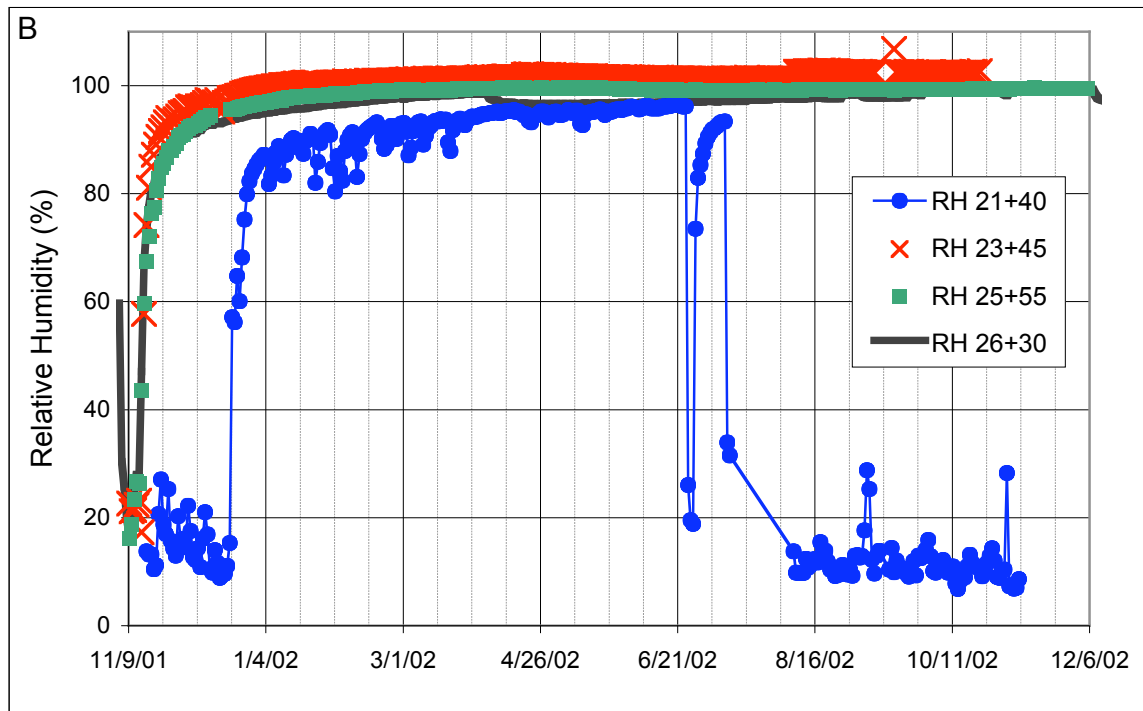
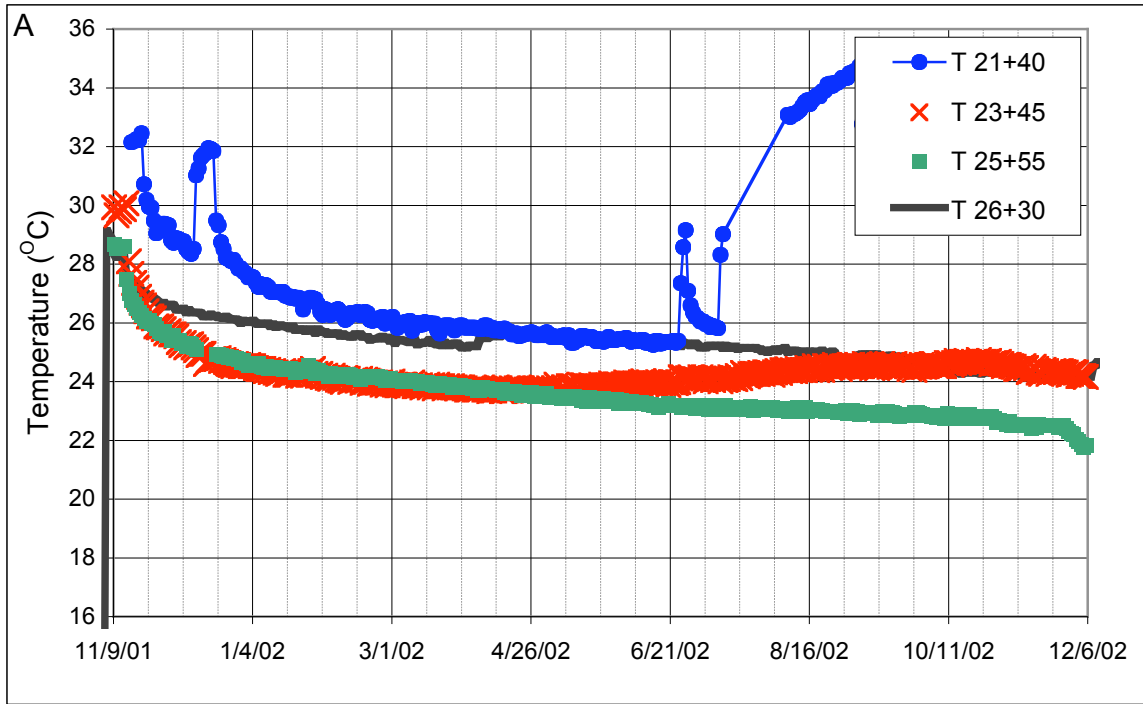


Figure 3.

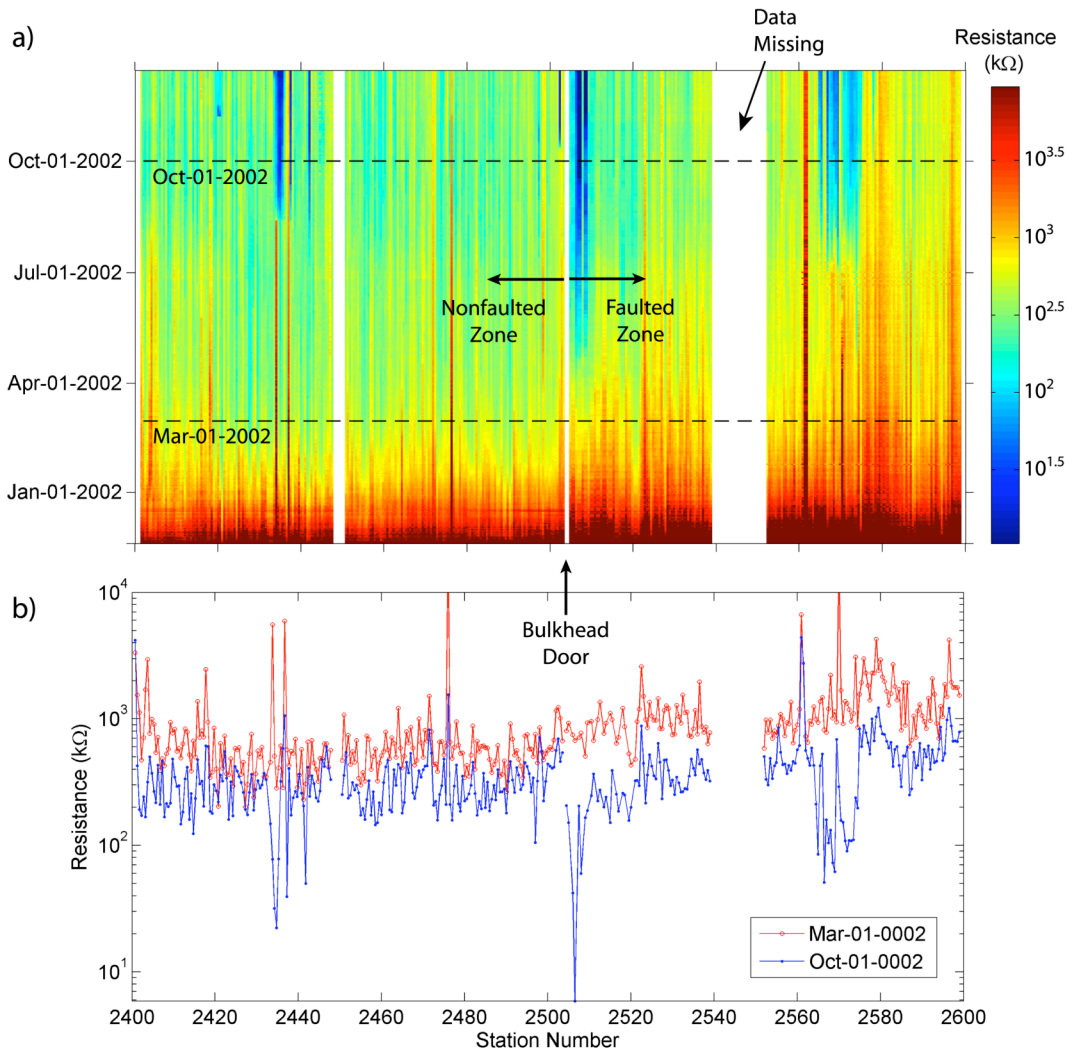


Figure 4.

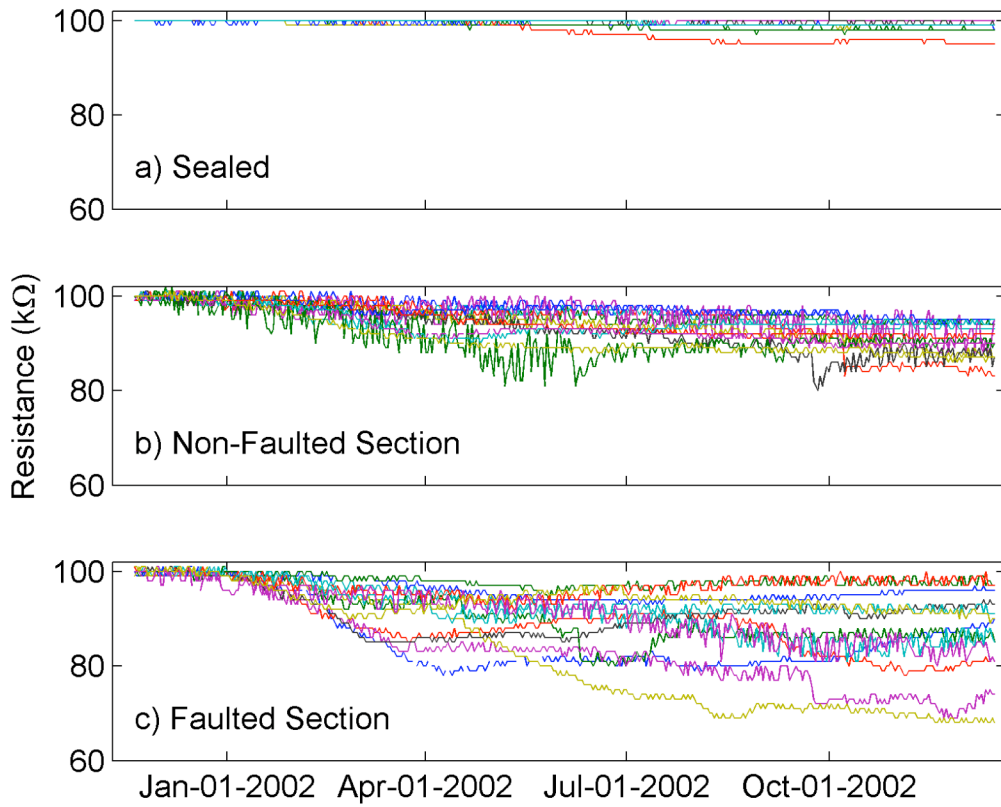


Figure 5.