Appendix 2c – Interpretation of borehole logs for 11 wells on the USGS Leetown Science Center, West Virginia

Jef-0589 (anticline well)

Borehole Jef-0589 (site 41 on fig. 1 and in table 1) was constructed as a 6-inch (in.) diameter open hole to a depth of 260 ft and cased to 38.5 ft below land surface (bls). It is located on the crest of a small anticline and completed entirely in the Ordovician Rockdale Run Formation of the Beekmantown Group. The geologist's well log indicates 25 ft of clay overlying bedrock and a total yield of 18 gal/min from water-bearing zones at 91-92 and 137-140 ft bls. Additional fracture zones were noted at 52-55, 57-60, 77-79, 91-92, and 137-140 ft bls. The static water level in the borehole at the time of geophysical logging was 13.65 ft bls.

The caliper log recorded major fractures at 52, 64, and 124 ft bls, plus numerous small fractures throughout the open-hole interval (app. 2a, fig. 1). Under ambient (non-pumping) conditions changes in fluid-resistivity are seen at 38.5 ft (the bottom of the casing), 50 and 194 ft bls. Subtle changes in slope can be seen in the fluid-temperature log between 190 and 200 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs (app. 2b, fig. 1) indicate no vertical flow of water in the borehole under ambient conditions.

A pump was placed in the well casing and the well pumped at 5.8 gal/min. The fluid-resistivity log recorded more resistive water entering the borehole at 65-70 ft bls. Slope changes in fluid-temperature are seen at 64 ft and between 70 and 75 ft bls. Under pumping conditions, the fluid-resistivity, fluid-temperature, and flow-meter data indicate that all water enters the borehole at the N. 24° E. strike and N. 43° W. dip trending fracture at 63 ft bls. The deflection of the EM flow log at 52 ft bls is associated with an increase in borehole diameter and flow circumventing the tool at that depth.

The ATV and OTV logs indicate the borehole is intersected by 102 fractures between 38.5 and 260 ft bls (app. 3, table 1). Eighty seven of the 102 fractures have apertures ranging from 0.2 to 8.0 in. The character and orientation of these data, plotted on a lower-hemisphere equal-area net as poles to planes, indicate one major fracture-population cluster with a strike orientation of 167 - 266° and dips of N. 28 - 67° W. (fig. 17). In Appendix 3 strike is reported in azimuthal degrees, east of true North in the "right hand rule" where the direction of dip is to the right of bedrock strike.

Jef-590 (ball field well)

Borehole Jef-0590 (site 48 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 160 ft and cased to 38.5 ft bls. The borehole was drilled into the Ordovician Rockdale Run Formation of the Beekmantown Group at the inferred intersection of a thrust fault and land surface. The geologist's log (observations made by a geologist at the time the well was drilled) indicate 10 ft of clay overlying bedrock and a total yield exceeding 100 gal/min from zones located at 40-50 and 131-140 ft bls and a large void at 85-100 ft bls. Additional voids and weathered zones were noted at 52-53, 60-70, 75-76, 78, 82-83, 100-113, and 129-131 ft bls. The static water level in the borehole at the time of geophysical logging was 18.54 ft bls.

The caliper log recorded major fractures at 39, 42, 78, and 80-90 ft bls, plus several small fractures throughout the open-hole interval (app. 2a, fig. 2). Under ambient conditions the fluid-resistivity log shows a slight increase in fluid resistivity with depth. A sharp change in slope can be seen on the fluid-temperature log between 68 and 72 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs (app. 2b, fig. 2) indicate that water enters the borehole at 70 and 85 ft bls and flows upward, exiting the borehole at fracture zones at 39 and 42 ft bls.

A pump was placed in the well casing and the well pumped at 10.8 gal/min. The fluid-resistivity log recorded fluctuations in fluid resistivity at 42, 50, 53, 80, and 85 ft bls. Slope changes in fluid-temperature are seen at 42 ft and between 68 and 72 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicate that under pumping conditions water enters the borehole at 70 and 85 ft bls and flows upward.

The ATV and OTV logs indicate the borehole is intersected by 15 fractures between 38.5 and 160 ft bls (app. 3, table 2). The fractures have apertures ranging from 0.8 - 40 in. A plot of these data on a lower-hemisphere equal-area net as poles to planes indicates that 11 of 15 fractures cluster about a strike orientation of 1 - 152° with dips ranging from 31 - 68° southeast and southwest (fig. 17).

Jef-0752 (new Dodson farm well)

Borehole Jef-0752 (site 61 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 166 ft and cased to 38 ft bls. The borehole was completed in the Ordovician Stonehenge Limestone of the Beekmantown Group near a cross-strike fault. The geologist's well log recorded 8.5 ft of clay overlies bedrock and a total yield exceeding 200 gal/min from zones located at 116-118, 128, and 148-150 ft bls. Additional fractures were noted at 85-86, 111-116, 118-121, 122-124, 144-147, and 155-156 ft bls. The static water level in the borehole at the time of geophysical logging was 13.26 ft bls.

The caliper log recorded major fractures at 145, 147, and 152 ft bls plus several small fractures throughout the open-hole interval (app. 2a, fig. 3). The natural-gamma log recorded an increase in gamma readings between 145 and 152 ft bls that correlates to clay and water filled fractures noted in the drilling log. Under ambient (non-pumping) conditions a change in slope with depth can be seen in the fluid-temperature log at 60, 120-125, and 140-160 ft bls. Integrated analysis

of the fluid-temperatures and flow-meter logs (app. 2b, fig. 3) indicate that potential water-bearing fractures are present at depths of approximately 144, 146, and 152 ft bls.

During pumping, sharp changes on the fluid-temperature log are shown at 104, 144-148, and 153 ft bls. Integrated analysis of the fluid-temperature and flow-meter logs indicate that the majority of water enters the borehole at the major water-bearing fracture located at 144-148 ft bls.

The ATV and OTV logs indicate the borehole is intersected by 10 fractures between 38 and 166 ft bls (app. 3, table 3). The fractures have maximum apertures ranging from 0.9 - 15 in. The orientation of these fractures change abruptly and become
sub-horizontal at depths below 80 ft bls. Fracture data plotted on a lower-hemisphere equal-area net as poles to planes indicates that 7 fractures are sub-horizontal with orientations of 142 - 186° and a dip of 2 - 3° SW. (fig. 17).

Jef-0753 (new Kaiser farm well)

Borehole Jef-0753 (site 62 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 121 ft and cased to 39.5 ft bls. It was completed in the Ordovician Stonehenge Limestone of the Beekmantown Group along the eastern limb of an overturned anticline. The geologist's well log recorded 8.5 ft of clay overlying bedrock and a total yield exceeding 200 gal/min from fracture zones located at 89-90 and 96 ft bls. Additional fractures or weathered zones were noted at 66-68 and 87-88 ft bls. The static water level in the borehole at the time of geophysical logging was 6.51 ft bls.

The caliper log recorded major fractures at 66, 73, and 89 ft bls plus several small fractures throughout the open-hole interval (app. 2a, fig. 4). The fluid-temperature log recorded minor deflections in temperature at 47, 73, and 95 ft bls. Integrated analysis of the fluid-temperature and flow-meter logs (app. 2b, fig. 4) indicate potential water-bearing fractures at depths of 66, 73, and 89 ft bls.

During pumping, the fluid-temperature log recorded minor deflections in temperature at 47, 67, 73, and 91 ft bls. A slight increase in fluid resistivity is recorded with depth; subtle slope changes are noted at 43 and 85 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperature, and EM flow-meter data indicates that the majority of water enters the borehole at a dominant fracture at a depth of 89 ft bls.

The ATV and OTV logs indicate the borehole is intersected by 22 fractures between 39.5 and 121 ft bls (app. 3, table 4). The fractures have maximum apertures ranging from 0.3 - 6.9 in. The character and orientation of these data plotted on a lower-hemisphere equal-area net as poles to planes indicate two steeply dipping groups sub-parallel to strike of bedrock with orientations of 3 - 42° with dips of S. 44 - 83° E. and 185 - 218° with dips of N. 73 - 83° W. (fig. 17). A third group, consisting of two near horizontal fractures (1° dip), strike at 187° and 229°.

Jef-0587 (low road well)

Borehole Jef-0587 (site 36 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 410 ft and cased to 38 ft bls. It is located on a small topographic rise in an area characterized as a diffuse flow type setting and is absent of any nearby karst features. The borehole was drilled near the contact of the Conococheague Limestone and the Stoufferstown Member of the Stonehenge Limestone. The geologist's well log recorded 26 ft of clay overlying bedrock and a total yield of 18 gal/min from zones at 119, 192, 276-279, and 369-370 ft bls. No additional fracture zones were noted. The static water level in the borehole at the time of geophysical logging was 42.33 ft bls.

The caliper log recorded numerous small fractures throughout the open-hole interval (app. 2a, fig. 5). Under ambient conditions the fluid-resistivity log shows changes between 160 - 180 ft bls. The fluid-temperature log recorded a gradual increase in temperature that is due to the geothermal gradient. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter logs (app. 2b, fig. 5) indicate that the fracture zone at 181 ft bls is contributing flow across the borehole. The geologist's well log also notes appreciable flow of water from fractures near the bottom of the borehole at 369 - 399 ft bls during drilling.

A pump was placed in the well casing and the well pumped at a rate of 4.4 gal/min. The fluid-resistivity log recorded more resistive water entering the borehole at the 181 ft bls fracture zone. A slight cooling of water at that zone is also seen in the fluid-temperature log. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicates that under pumping conditions water enters the borehole at the fractures at 181, 280, 375, and 400 ft bls. The major fracture at 181 ft bls has a strike of 14° and dips S. 42° E.

The ATV and OTV logs indicate that the borehole is intersected by 53 fractures between 38 and 410 ft bls (app. 3, table 5). The fractures have apertures ranging from 0.16 to 7.7 in. The character and orientation of the data plotted on a lower-hemisphere
equal-area net as poles to planes indicates one major fracture-population cluster with a orientation of 4 - 41° with dip angles from S. 39 - 74° E., that are approximately sub-parallel to local bedrock strike of 20 - 30° (fig. 17).

Jef-0602 (old Dodson farm well)

Borehole Jef-0602 (site 55 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 61 ft and cased to 20 ft bls. It is located near an inferred cross-strike fault and is completed in the Ordovician Stonehenge Limestone of the Beekmantown Group. Construction of

Jef-0602 preceded the period of study, thus geologist's or driller well logs for the well were unavailable. The static water level in the borehole at the time of geophysical logging was 6.09 ft bls.

The caliper log recorded one large fracture in the borehole at 36-37 ft bls with aperture width of 8.4 in (app. 2a, fig. 6). Under ambient conditions changes in fluid resistivity correlate with this fracture. The flow-meter log indicates no ambient flow in the borehole but integrated analysis of the fluid-resistivity and fluid-temperature logs indicate that some ambient flow may occur in the well, mostly in the interval from 37 - 61 ft bls (app. 2b, fig. 6).

A pump was placed in the well casing and the well pumped at a rate of 10.5 gal/min. The fluid-resistivity log recorded a slope change in the borehole at the 36-37 ft bls fracture zone. Cooler water at that zone is also seen in the fluid-temperature log. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter logs indicate that all water under pumping conditions enters the borehole at the fracture zone 36-37 ft bls. This fracture has a strike of 22° and dips N. 41° W.

The ATV and OTV logs indicate that the borehole is intersected by 13 fractures from 20 - 61 ft bls (app. 3, table 6). These fractures have apertures range from 0.2 - 8.4 in. The character and orientation of the data plotted on a lower-hemisphere equal-area net as poles to planes indicate a scatter of planes predominantly dipping N. 19 to 77° W. (fig. 17).

Jef-0601 (stable A well)

Borehole Jef-0601 (site 37 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 312 ft and cased to 37 ft bls. It is located in an area characterized by a diffuse flow type setting and does not contain any karst features. The well is entirely completed in the Ordovician Stonehenge Limestone of the Beekmantown Group. Construction of Jef-0601 preceded the period of study, thus driller's or geologist's well logs for the well are unavailable. The static water level in the borehole at the time of geophysical logging was 31.75 ft bls.

The caliper log recorded numerous small fractures throughout the open-hole interval (app. 2a, fig. 7). Under ambient (non-pumping) conditions changes in fluid resistivity are seen between 210 and 230 ft bls. A spike in fluid-temperature log is recorded from 218 - 220 ft bls, although a gradual increase in fluid-temperature is due to the geothermal gradient. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs indicates there is no ambient flow in the borehole (app. 2b, fig.7).

A pump was placed in the well casing and the well pumped at a rate of 1.6 gal/min. Under pumping conditions, the fluid-resistivity log recorded more resistive water entering the borehole between 210 - 230 ft bls with a decrease in fluid-temperature from 170 - 211 ft bls indicating a water-bearing zone. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter logs indicates that under pumping conditions, water enters the borehole through two zones at 111 and 218 ft bls.

The ATV and OTV logs indicate that the borehole is intersected by 112 fractures between 37 and 312 ft bls (app. 3, table 7). The fractures have apertures ranging from 0.2 - 6.9 in. A plot of these data on a lower-hemisphere equal-area net as poles to planes indicates a major fracture-population clusters with strike orientations of 2 - 52° and dips of S. 23 to 82° E., approximately sub-parallel to local bedrock strike of 20 to 30° (fig. 17).

Jef-0585 (stable B well)

Borehole Jef-0585 (site 38 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 326 ft and cased to 39 ft bls. It is located in an area characterized as a diffuse flow type setting absent of any nearby karst features. The well is entirely completed in the Ordovician Stonehenge Limestone of the Beekmantown Group. The geologist's well log recorded 13 ft of clay overlying bedrock and a total yield of 6 gal/min from zones at approximately 106, 115, 231, and 313 ft bls. No additional fracture zones were noted. The static water level in the borehole at the time of geophysical logging was 30.95 ft bls.

The caliper log recorded numerous small fractures throughout the open-hole interval (app. 2a, fig. 8). Under ambient conditions, the fluid resistivity log chows changes near the bottom of the borehole at 320 ft bls that may indicate a water-bearing fracture at that interval. The fluid-temperature log shows a gradual increase in temperature that is due to the geothermal gradient. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs indicates there is no ambient flow in the borehole (app. 2b, fig. 8).

A pump was placed in the well casing and the well pumped at a rate of 1.5 gal/min. The fluid-resistivity log recorded changes at about 310 ft bls indicating a water-bearing zone. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicates that under pumping conditions, water enters the borehole at fracture zones near 53 and 310 ft bls.

The ATV and OTV logs indicate the borehole is intersected by 120 fractures between 39 and 326 ft bls (app. 3, table 8). The fractures have apertures ranging from 0.11 - 5.1 in. A plot of these data on a lower-hemisphere equal-area net as poles to planes indicates a major fracture-population cluster with a strike orientation of 1 - 69° with dips of S. 15 - 57° E.,

that are approximately sub-parallel to the local bedrock strike of 20 - 30° (fig. 17).

Jef-0592 (stable C well)

Borehole Jef-0592 was constructed as a 6-in. diameter open hole to a depth of 321 ft and cased to 38 ft bls (site 39 on fig. 1 and in table 1). It is located in an area characterized as a diffuse flow type setting absent of any nearby karst features. The well is completed entirely in the Ordovician Stonehenge Limestone of the Beekmantown Group. The geologist's well log recorded 18 ft of clay overlying bedrock and a total yield of 37 gal/min from fracture zones at 61, 71, 133, 141-145, 151, 247, and 270 ft bls. Additional fractures and weathered zones were noted at 135 and 175 ft bls. The static water level in the borehole at the time of geophysical logging was 27.70 ft bls.

The caliper log recorded a large fracture just below the casing at 40 ft bls and numerous small fractures throughout the open-hole interval (app. 2a, fig. 9). Under ambient conditions, the fluid-resistivity log shows changes between 130 and 160 ft bls and near the bottom of the borehole at 310 ft bls. The fluid-temperature log shows a gradual increase in temperature due to the geothermal gradient. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs indicates that under ambient conditions, water enters the borehole at a fracture at 40 ft bls and exits the borehole at 138 ft bls (app. 2b, fig. 9).

A pump was placed in the well casing and the well pumped at a rate of 6.5 gal/min. The fluid-resistivity log recorded fluctuations between 130 and 160 ft bls that correlates to fractures on the caliper and ATV logs. Under pumping conditions the fluid-temperature log represents the geothermal gradient. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicates that under pumping conditions, water enters the borehole through the fracture at 138 ft bls.

The ATV and OTV logs indicate that the borehole is intersected by 98 fractures between 38 and 321 ft bls (app. 3, table 9). The fractures have apertures ranging from 0.16 - 12.4 in. A plot of these data on a lower-hemisphere equal-area net as poles to planes indicate a major fracture-population cluster with strike orientations of 1 - 57° with dips from S. 23 - 81° E., that are approximately sub-parallel to local bedrock strike of 20 - 30° (fig. 17).

Jef-0603 (USDA sulfur well)

Borehole Jef-0603 (site 34 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 475 ft and cased to 56 ft bls. The well was completed at a fault contact between the overlying Chambersburg Limestone and underlying Martinsburg Formation. Construction of Jef-0603 preceded the period of study, so geologist's or driller well logs for the well were unavailable. The static water level in the borehole at the time of geophysical logging was 35.90 ft bls.

The caliper log recorded major fractures at 99, 150, 340, and 473 ft bls and numerous small fractures throughout the open-hole interval (app. 2a, fig. 10). The natural gamma log shows higher gamma readings at 101, 312, 336, and 394 ft bls likely indicating shaly layers within the Chambersburg Limestone. Under ambient conditions subtle changes in fluid resistivity are recorded between 140 and 198 ft bls. The fluid-temperature log recorded a gradual increase in temperature that represents the geothermal gradients. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs indicates there is no ambient flow in the borehole (app. 2b, fig. 10).

Significant deviation in fluid-resistivity values measured under ambient and pumping conditions reflects the unique chemistry of ground water in borehole Jef-0603. A pump was placed in the well casing and the well pumped at a rate of <10 gal/min. Under pumping conditions, the fluid-temperature log represents the geothermal gradient below 200 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicates that under pumping conditions all water enters the borehole from the fracture zone at the fault contact near the bottom of the borehole at 473 ft bls.

The ATV and OTV logs indicate that the borehole is intersected by 89 fractures between 56 and 475 ft bls (app. 3, table 10). A plot of these data on a lower-hemisphere equal-area net as poles to planes indicates one major fracture-population cluster with strike orientations of 1 - 75° with dips of S. 22 - 78° E. (fig. 17).

Jef-0586 (USDA fault well)

Borehole Jef-0586 (site 60 on fig. 1 and in table 1) was constructed as a 6-in. diameter open hole to a depth of 201 ft and cased to 98 ft bls. The well was constructed along a fault zone and is completed in the Ordovician Rockdale Run Formation of the Beekmantown Group. At the time of drilling, rock cuttings of fault breccia were collected. The geologist's well log recorded 4 ft of clay overlying bedrock and a total yield of 300 gal/min from zones at 104-115, 124-131, and 151 ft bls. Numerous additional fractures and weathered zones were noted during drilling. The static water level in the borehole at the time of geophysical logging was 16.49 ft bls.

The caliper log recorded major fractures at 103, 124-132, 142, and 146-151 ft bls with numerous small fractures throughout the open-hole interval (app. 2a, fig. 11). Under ambient conditions an increase in fluid resistivity is seen

above 155 ft bls. The fluid-temperature log recorded slight deviations at 115, 158, and 187 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperatures, and flow-meter logs indicate that under ambient conditions, water enters the borehole at the fracture zone at 152 ft bls and exits at 104 and 142 ft bls (app. 2b, fig. 11).

A pump was placed in the well casing and the well pumped at a rate of <10 gal/min. The fluid-resistivity log recorded changes at 105 and 155 ft bls, and the fluid-temperature log recorded slight deviations at 108 and 140 ft bls. Integrated analysis of the fluid-resistivity, fluid-temperature, and flow-meter data indicates that under pumping conditions, water enters the borehole from the fracture zones at 110 and 158 ft bls.

The ATV and OTV logs indicate the borehole is intersected by 50 fractures between 98 and 201 ft bls (app. 3, table 11). A plot of these data on a lower-hemisphere equal-area net as poles to planes indicates two major fracture-population clusters. The first cluster, with strike orientations of 7 - 59^{o} and dips of S. 35 - 84^{o} E. are approximately sub-parallel to local bedrock strike of 20 - 30^{o} (fig. 17). The second cluster of fractures has strike orientations of 200^{o} - 238^{o} with dips of N49^{o} to 87^{o} W.