City of Flagstaff

Cinder Lake Landfill

Geophysical Survey and Drilling Program

Prepared for:

City of Flagstaff

211 West Aspen Avenue
Flagstaff, Arizona 86001

Prepared by:

HydroSystems, Inc.

9831 South 51st Street, Suite E-122
Phoenix, Arizona 85044
P: 480.517.9050 F: 480.517.9049
E-mail: info@hydrosystems-inc.com
Website: www.hydrosystems-inc.com

REGISTERED GEOLOGIST
CERTIFICATE NO.
41793
STEVEN J. SKOTNICKI
Date Signed 6/23/11
ARIZONA U.S.A.

Steve Skotnicki

Expires 12/31/2012

In Association with:

SDB Contracting Services

1500 East Cedar Avenue, Suite 86B
Flagstaff, AZ 86004

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1.0 INTRODUCTION

The June 2010 Schultz fire north of Flagstaff, Arizona, devastated most of the eastern side of the San Francisco Peaks, removing much of the forest and ground cover and greatly increased the flash flood hazard in the downstream communities to the east, in particular Doney Park. Subsequent heavy rains led to flooding which caused significant damage to some homes. It was quickly recognized that more robust flood-mitigation measures were necessary in order to prevent more damage in the future. Mitigation features such as the Copeland Avenue canal have been constructed to divert flood waters to the porous plains of Cinder Lake. However, the Lake's proximity to the Cinder Lake Landfill raised concerns about the possibility of perched water accumulating under the landfill, leaching toxic substances, and transporting them to downstream communities and/or to the regional aquifer.

More than 41,800 linear feet (8 miles) of CSAMT, TEM, and NANOTEM surface geophysical surveys were employed in conjunction with eleven boreholes to explore if a major perching layer exists in close proximity to the perimeter of the landfill. Information from the boreholes indicated the presence of one thin, 1 to 3 foot-thick clay layer mostly within 5 feet of the surface, and a mostly deeper fine sand layer, but most of the material above the bedrock is coarse basaltic sand and cinders. Data collected from the geophysical survey and borings was used to determine the thickness of the volcanic deposits beneath Cinder Lake to be about 200 to 300 feet. One borehole penetrated 340 feet but the others penetrated less than 60 feet. The geophysical survey penetrated up to about 3,000 feet. The speed of the survey—less than one month from start to finish—gave planners enough time to evaluate the effectiveness of diverting and recharging surface flows into the Cinder Lake area before the onset of the 2011 Arizona Monsoon season.

Cinder Lake is a rather unique area, geologically and physiographically. It is one of the few areas in the country where the land surface is blanketed by a more or less continuous sheet of loose clean volcanic cinders (basaltic scoria). Many volcanic deposits elsewhere also contain cinders, but they are not as young, not as well preserved, or are buried by soils, vegetation, or both. At Cinder Lake the surface deposits are thought to be associated with the eruption of Sunset Crater (Moore and Wolfe, 1976), a very young basaltic cinder cone less then two miles to the north, which last erupted in 1065 A.D (*Figure 1*). In Flagstaff's sub-arid climate weathering

and soil development have been very slow and, hence, only parts of the cinder field are covered with vegetation—mostly widely spaced sagebrush and Ponderosa Pine trees. Because large parts of the cinder plains are nearly devoid of vegetation and resemble a lunar landscape, it was the perfect place for NASA to train the Apollo astronauts that would land on the moon. In the late 1960's NASA used explosives to create crater fields similar to those that might be encountered on the moon. The loose, porous nature of the cinders on the surface makes this an attractive place to allow diverted flood waters to recharge quickly into the ground. For at least the last thousand years, and likely for much longer, the deposition of unconsolidated material in the area consists of cinders erupted from the cinder cone field to the east and alluvial sediment being shed eastward off of the San Francisco Peaks from the west. A major goal of this study is to evaluate the thickness and extent of any fine-grained alluvial layers that might act as perching layers beneath the cinders and to better identify the depth to hard bedrock and evaluate its affect on recharged surface water.

1.1 Project Team

The City of Flagstaff contracted SDB Contracting Services (SDB) to provide project oversight and act as the liaison between the City and various subcontractors to complete the work. SDB contracted HydroSystems, Inc. (HSI) as the project hydrogeologist to coordinate and oversee field activities, and prepare the completion report. SDB contracted Zonge Engineering & Research Organization, Inc. (Zonge) to perform the geophysical survey and Boart Longyear Environmental & Infrastructure Drilling Service (Boart) to perform the drilling.

1.2 Collaborative Effort

The urgency of this project allowed for several different organizations to come together and work concurrently towards its goals. Although this project and report were funded by the City of Flagstaff, the U.S. Geological Survey (USGS) and Coconino County (County) both supported the effort. The USGS, in fact, performed its own geophysical survey (CSAMT and TEM) north of the Landfill with the same goals in mind. Their survey was funded by Coconino County. Because the USGS has a strict quality-control and review process, their data will not be available soon enough to make decisions before the onset of the 2011 summer rainy season. Because of this, HSI was contracted to do a similar and concurrent study which would provide

the data in a much timelier manner. HSI worked closely with the USGS to make sure the efforts complimented one another while replicating efforts as little as possible. Where replication was necessary early results indicated that the two surveys agreed very closely with one another and gave confidence that the results were repeatable. To help verify the results of the geophysical survey, the USGS drilled four boreholes in the area of Cinder Lake. The City of Flagstaff drilled seven additional boreholes south of Cinder Lake itself, for a total of eleven (11) boreholes. Boart Longyear did the actual drilling, and drilled all of the confirmatory boreholes with the sonic drilling technique. One of the boreholes was drilled deeper, through the volcanic sequence and into the Paleozoic rocks, and in this hole an air rotary hammer bit was used. A representative from the County was onsite frequently throughout the drilling process and provided feedback about the project.

1.3 Acknowledgments

Don Walters, Vice President of SDB, was instrumental in assisting the City with the selection of the project team. He coordinated the different agencies involved and maintained a uniform flow of communication, keeping the project focused and within budget. We'd like to thank Jamie Macy with the U.S. Geological Survey for allowing the City to be present during their drilling program and for permission to analyze their borehole samples. Two individuals with the City of Flagstaff who contributed greatly to the success of this project include Matt Morales, who performed many behind-the-scenes coordination efforts with the City staff, and Ken Robinson, who provided daily guidance and was instrumental in the overall quality control of this project. We also want to thank Judy Adams with the Coconino National Forest for providing exceptionally timely assistance with the USFS permitting for various components of this project.

2.0 GEOLOGY

2.1 Regional Geology

Cinder Lake and its adjacent larger neighbor Flagstaff rest near the southern edge of the Colorado Plateau. In northern Arizona the Colorado Plateau is composed of Cambrian through Mesozoic sedimentary rocks overlain by Tertiary and Quaternary volcanic and sedimentary rocks. Unlike areas to the south and west in the Basin and Range Province, where Late Cretaceous through Tertiary tectonism have greatly modified the geology and the landscape, the Colorado Plateau has for the most part retained its layer-cake stratigraphy. The Paleozoic and Mesozoic formations on the Plateau are only slightly faulted and overall dip gently to the northeast. The regional groundwater table roughly follows the same trend, decreasing in elevation to the northeast (McGavock et al., 1986; and Bills, et al., 2000).

The Paleozoic and Mesozoic sedimentary rocks of the Plateau are overlain by at least two distinct sequences of volcanic rocks. An older sequence of mostly basalts erupted between about 9 to 4 million years ago (abbreviated Ma) and is exposed mostly south of Flagstaff overlapping the southern escarpment of the Colorado Plateau (Ulrich, 1984). The younger volcanic sequence includes the San Francisco volcanic field and includes flows of basalt, dacite, and rhyolite erupted from about 4 Ma up to only about 1,000 years ago (Ulrich, 1984). Remnants of red sandstones of the Triassic Moenkopi Formation underlying volcanic rocks in and around Flagstaff show that the area was still blanketed by a portion of the Moenkopi Formation when the volcanic rocks of the San Francisco volcanic field were erupted. At that time, just prior to eruption, where Flagstaff now resides was a relatively flat plain covered with fine-grained silty red sandstones.

Small graben (blocks of crust down-dropped and bordered by faults) are abundant on the Kaibab and Coconino Plateaus all around the San Francisco volcanic field. South of the volcanic field most of the graben strike northwest-southeast. Ulrich and others (1984) mapped several graben to the south within 5 miles of Doney Park. It is possible that other graben exist buried beneath Doney Park. Many graben have subsequently been filled with Quaternary alluvium and volcanic rocks. If grabens exist beneath the Cinder lake area, then future deep drilling may reveal offset in the Paleozoic rocks at depth. These graben are probably too old and too deep to

have any direct impact on the hydrogeology at the landfill.

2.2 Local Geology

A broad, flat surface slopes gently eastward off the east side of San Francisco Mountain and Elden Mountain. Most of this surface appears to be composed of fine-grained silty alluvium. In some areas, particularly west of the landfill in the area that was recently flooded, large subrounded cobbles are mixed with silty material, suggesting that they were transported as debris flows. There is some incision along some of the larger drainages, particularly close to the mountains, but the surface of the alluvium is characteristically relatively smooth and undissected, and is probably Holocene in age (less than 10,000 years old). The alluvium has mostly been shed eastward from San Francisco Mountain and Elden Mountain, two of the highest mountains in the area. Because of this, the larger sand and gravel fragments are composed dominantly of volcanic rocks of intermediate composition, such as dacite and andesite, which is in contrast to the darker basalt to the east. This alluvial material has likely been shedding eastward off the mountains for many tens of thousands of years. Some of this alluvial material is interbedded with cinders beneath Cinder Lake where it forms one or two silty and sandy layers north of the landfill and a sandy and gravelly exposed layer in a trench on the north side of the landfill. The trench (about 8 feet deep) is a particularly good exposure of the alluvial layer there because it contains rounded pebbles of dacite, some more than 10 cm across, whose only source is Elden Mountain.

The hills surrounding Cinder Lake are composed of basalt cinder cones (more specifically, alkali olivine basalt) which have been correlated with similar cones in the SP Crater quadrangle dated at 0.51 + 0.08 million years (Moore and Wolfe, 1976) (*Figure 2*). Cinder cones result from the eruption of gas from basaltic vents and the subsequent dispersal of the fluid spatter as cinders (also called scoria). The gas is the reason why cinders contain so many small holes known as ‘vesicles’. The sides of cinder cones are characteristically at or near the angle of repose and are composed of loose gravel-size cinders, locally held together by pedogenic (soil) carbonate cement and/or soil and plants. Harder, more competent basalt lava flows commonly erupt from the base of cinder cones. Remnants of basalt flows are exposed to the north, east, and south of Cinder Lake. Within Cinder Lake, and around the landfill, several small hills contain small rib-like exposures of hard basalt that stick up out of the ground. Their shape and extent

suggests that they are the remnants of solidified basalt lava that filled vents and conduits within cinder cones. The low elevation of the hills and the observation that most of the hills surrounding these rib-like exposures of lava are composed dominantly of cinders suggests that the hills themselves are the remnants of older cinder cones that have been mostly eroded away. It is also possible that the bedrock exposures represent the remains of eroded or collapsed basalt flows themselves. Moore and Wolfe (1976) mapped and interpreted all of the surface cinders in the area (above the fine-grained clay-rich layer) as all originating from the eruption of Sunset Crater to the north.

A deep drillers' log 1.5 to 2 miles south of the landfill in Doney Park (DPW-1; ADWR well registration number 55-214155) show cinders to a depth of 55 feet overlying hard basalt that extends to 205 feet below the surface (bls). Here, these younger volcanic deposits overlie about 55 feet of fine-grained red sandstone of the Triassic Moenkopi Formation, which extends from 205 feet to 260 feet bls. The Moenkopi Formation is exposed in road cuts in Flagstaff along Highway 89 and in well logs northwest of town, and in both areas it is overlain by younger basalt. In Doney Park the unit overlies about 300 feet of the Kaibab Formation (mostly dolomite with intrerbedded tan sandstone), which in turn overlies about 1,200 feet of Coconino Sandstone. According to well logs to the south in Doney Park, The water table of the deep, regional aquifer is within the lower part of the Coconino Sandstone, but most of the aquifer is within the Supai Formation (or Schnebley Hill Formation). It is logical to assume that a portion of the Moenkopi Formation is preserved and widespread underneath the volcanic rocks at and around Cinder Lake, though it may not be preserved everywhere.

Woodward-Clyde (1976) also reported encountering harder rock that caused refusal of the auger at variable depths, some as shallow as 28 to 35 feet bls. They interpreted these harder rocks as basalt flows and, since they occur at different depths across the study area, concluded that basalt flows in the area are not laterally extensive. Their interpretation may be correct. However, it is also possible that some of the hard rock that they encountered may be dikes or lava-filled conduits for cinder cones.

3.0 GEOPHYSICAL SURVEY

3.1 Layout of the Geophysical Survey

The USGS originally laid out their geophysical survey lines in north-south, east-west orientations. In their plan they located a convenient position for the CSAMT transmitter and then applied for and received a permit from the U.S. Forest Service (USFS). In doing so, the City's geophysical survey lines were constrained to be within about 10° of parallel with the transmitter. They are angled slightly from north-south and east-west to place the lines more or less parallel with the landfill boundaries.

The geophysical lines were positioned in a way to maximize the amount of information obtained from the survey. A total of 7 survey lines were laid out, for a total of 41,800 linear feet (8 miles) of survey (*Figure 3*). Lines 1 and 2 were intended to obtain information about the subsurface immediately north and south of the landfill, respectively. Line 4 was surveyed in an area that had undergone flooding recently (and probably in the past as well) where, in places, the surface is covered by up to a foot of tan silt and locally cobbles of felsic volcanic rocks. Lines 3 and 5 were intended to obtain information below the west and east sides of the landfill, respectively. Both Lines 6 and 7 were surveyed across Cinder Lake to obtain subsurface information there.

3.2 Methods

The surface geophysical survey methods were used as a screening tool to explore for the possible presence of conductive features at depth that might represent perching layers. The survey allowed much ground to be covered at a much lower cost, and with greater amounts of information, than an exploratory drilling program alone could accomplish. With the geophysical information in hand, exploratory boreholes could be strategically placed. Two geophysical methods were used for this survey—TEM and CSAMT. The TEM method (Time domain electromagnetics) uses a portable transmitter connected to a large loop of wire arranged in a square resting on the ground, each of its four sides approximately 400 feet long. Current flowing through the loop of wire induces current in the ground, which creates electric and magnetic fields in the ground that are measured by the same loop of wire. The transmitted signal is turned on and off many times a second so that the loop can both transmit and receive. Depending on the

resistivity of the materials beneath the surface, TEM is useful for measuring resistivities (measured in ohm-meters) to depths of about 500 feet or so. The TEM method is not very sensitive to features below a few hundred feet.

The NANOTEM method uses a setup that is nearly identical to the normal TEM method. It uses the same transmitter and loop of wire. It induces electric and magnetic fields in the ground, but to read the data it uses a much faster collection rate. The size of the loop of wire is also smaller. Typically, the smaller loop size and collection rate allow for better resolution at shallower depths. So NANOTEM is used for the shallow subsurface. The depths of TEM and NANOTEM can overlap, especially in very dry and resistive materials.

The CSAMT method (controlled source audio-frequency magnetotellurics) uses a grounded dipole (an antennae) that is connected to the ground. This grounded dipole (the transmitter—the controlled source) typically is up to half a mile in length. Because the transmitter is connected to the ground the current it generates is transmitted directly into the ground, unlike the TEM method which uses induction to transfer current. The transmitter for this project was constructed about 4.5 miles north of Cinder Lake, along an unimproved road just outside of Sunset Crater National Monument. A portable receiver connected to grounded electrodes connected by a linear length of wire several hundred feet long records the transmitted signal after it passes through the material in the ground. With CSAMT a wide variety of frequencies are used from 1 Hertz to over 8,000 Hertz. The higher frequencies provide information about shallow depths, while the lower frequencies provide information about the deeper depths. The data is combined to produce a profile that represents a model of the subsurface resistivity. The CSAMT method penetrates much deeper than either the TEM or NANOTEM methods, typically 2,000 to 3,000 feet. Although CSAMT is useful for exploring deeper levels, it is not good at resolving shallow features near the surface.

Resistivity of earth materials is a function of how well they conduct electric current. Hence, materials that contain water/moisture within their pore spaces are more conductive and less resistive—because water is a good conductor. Conversely, materials that contain less moisture are less conductive and more resistive. This signal is in addition to the normal resistivity differences between different types of rocks. Resistivity can also be a function of

water quality (where water exists). Water that contains more dissolved solids (typically salts) is more conductive and less resistive. The combination and interplay of these different factors often results in resistivity plots that that do not show obvious correlation with layered rock formations.

The resistivity information is color-coded as shown on the two-dimensional profiles described below. Warmer colors, such as orange and red, represent areas of low resistivity. Cooler colors, such as light blue and dark blue, represent areas of high resistivity. In general, notice how some colored bands form crudely horizontal bands, while others form crudely vertical bands. All resistivity values shown on the profiles have units of ohn-meters (ohm-m). As a very rough rule of thumb, the nearly horizontal rock formations in this area are controlling the appearance of the horizontally colored bands, whereas structural features such as fractures and/or faults are controlling the appearance of the vertically colored bands. Fractures and faults can act either as conduits or as barriers to water flow. Keep in mind that this is a very rough approximation and each site's particular characteristics must also be taken into account when interpreting the resistivity model.

To do the actual survey itself, HSI personnel surveyed each line in advance of the geophysical crew. HSI personnel placed stakes every 200 feet along the survey lines and recorded the coordinates of each stake with a hand-held GPS receiver. The survey began on May 16 and ended on May 28, 2011.

3.3 Interpretations

3.3.1 Line 1

Line 1 has a small offset immediately north of the 'north finger' of the landfill, between Stations 4800 and 5600. When the line was originally conceived, it was not realized that the line came closer than 200 feet of the landfill boundary fence. The fence is metal and will interfere with the TEM survey. This was only discovered when HSI personnel were surveying the line. It was decided at that time to move that section of the line slightly northward to avoid the interference.

Figure 4 shows the TEM cross-section across Line 1. The features that stand out the

most are the red low resistivity features toward the bottom of the profile. Based on the lithologic logs from two wells about 2 miles to the south in Doney Park, the water level in this area is near 1,600 feet bls. That places it at an elevation of about 5,100 feet. The top of the low resistivity features appear to be very close to this elevation, suggesting that they represent saturated groundwater conditions. The Doney Park well logs indicate that the water table is near the base of the Coconino Sandstone. A noticeable gap exists between Stations 3000 and 3400. It is unknown what caused the gap. West of the gap, the lower resistivity values are again prominent below about 5,100 bls. However, the feature here climbs to the west until it intersects the western edge of the profile at an elevation of about 6,200 feet. In this same area, the land surface slopes gently upward to the west and, thus, it is an area that receives runoff from the San Francisco Peaks. Therefore, it is quite likely that the sloping low-resistivity feature represents water running off the mountains and being recharged in this area.

The upper part of the profile shows rather uniform high-resistivity values. Because it was not possible to distinguish any geologic units with this information, a second TEM survey was conducted across this line that used a smaller transmitter loop and should have been able to show more detail closer to the surface. A smaller-loop TEM survey was conducted across a portion of Line 1 to try to resolve this even further (*Figure 5*). In this profile, there is a sharper distinction between the dark blue resistivity feature near the surface and the slightly lower resistivity values below. The depth of the 'contact' between them is near an elevation of 6,450 feet. The blue high-resistivity layer is thus about 150 to 200 feet thick, which is close to the thickness of the volcanic rocks (cinders and basalt) sampled in the Doney Park wells (about 200 feet thick). However, since the depth to the base of the volcanic sequence within CL5 is 315 feet, this suggests that either the resistivity values do not closely follow rock types, or the volcanic sequence varies in thickness laterally. Also, conglomerate was encountered in CL5 at depths between 90 and 165 feet bls. It is quite possible that the change to slightly lower resistivities in the profile represent the conglomerate.

3.3.2 Line 2

Line 2 parallels the southern boundary of the landfill and extends from the north side of the cinder cone southwest of the landfill, to the east side of one of the crater fields southeast of the landfill. The TEM profile across Line 2 (*Figure 6*) shows a more or less horizontal horizon

of relatively high resistivity within about 400 feet of the surface. The thickness of this horizon varies from a maximum of about 500 feet near Station 3000 to about 300 feet near Station 6000. As with the profile of Line 1, it is not possible to distinguish any individual geologic within this horizon. Several lower resistivity features are visible along the bottom of the profile. Their somewhat vertical character, their presence below the estimated water-table depth, and the fact that they appear to be separated from one another, all suggest that these features are controlled by fractures.

A second, smaller-loop NANOTEM survey was conducted across the line to attempt to reveal more detail within the uppermost 500 feet (*Figure 7*). The resistivity profile is very similar to that of the first TEM line. So another even smaller-loop survey was performed, on a portion of the line between Stations 3400 and 6800. The resulting profile contains some significant differences. The eastern side of the profile shows a relatively horizontal high-resistivity horizon within about 150 to 200 feet of the surface, consistent with the thickness of the volcanic sequence in the Doney Park well. It is also possible that the change to lower resistivities below about 150 bls may be a reflection of the 75-foot thick conglomerate layer that was encountered in CL5 at depths between 90 and 165 feet bls.

A dark blue high-resistivity 'finger' projects downward much deeper where, at Station 4800, it is about 400 feet bls. Then, immediately to the west the thickness is again about 200 feet. Further west, near Station 4000, the high-resistivity horizon is again much thicker. The pattern, and the abruptness with which the pattern changes, resembles a horst or graben (a block of crust that has moved with respect to the neighboring crust, up and down respectively). Alternatively, the deep high-resistivity 'fingers' may represent dikes or conduits of harder basalt. It is also possible that the changes in thickness of the low-resistivity horizons reflect, in part, the presence and discontinuous nature of the conglomerate, as encountered in CL5.

3.3.3 Line 3

Line 3 is a northwest-southeast survey line on the west side of the landfill, and extends from near the cinder cone southwest of the landfill northward to the southwest side of Cinder Lake. The most obvious feature in the TEM plot (*Figure 8*) is the orange and yellow low-resistivity feature in the northern half of the profile. This feature is centered about midway

between survey Lines 4 and 1 and appears to project upward all the way to the surface. It is interesting to note that the elevation near the top of the feature is very similar to the elevation near the top of the low-resistivity 'ramp' on the west side of Line 1. As with the feature on Line 1, this feature on Line 3 is interpreted to represent water recharged in this area. The feature may not reach the surface possibly because the profile cuts across a deeper part of the 'ramp', or possibly because that is how far water has infiltrated since the last major recharge event.

3.3.4 Line 4

The City wanted to place Line 4 immediately to the west of the landfill, across an area that was inundated during the last flood event. Observers said that the water was at least one foot deep across this very flat forested plain that slopes very gently to the southeast. This is the area that received up to one foot of fine tan-colored silt, visible in aerial photographs even with the forest cover. In some areas large cobbles up to about 20 cm across were deposited. So the City was interested in being able to better understand what the result of that large influx of water was in the subsurface.

The TEM profile (*Figure 9*) shows a blue high-resistivity horizon from the surface to a depth of about 800 feet or so. It is interesting that the profile does not show any low-resistivity zones in the shallow subsurface, which might indicate the presence of recharged water. The absence of such a feature may indicate either that none of the flood waters recharged into the ground in this area (which seems very unlikely considering the porous and permeable nature of the cinders on the surface) or it may indicate that the ground was so porous that all of the recharge water has since left the area. Without additional information, the later explanation seems the most logical. It is also possible that fine-grained sediment that settled out of the flood waters acted as an impermeable layer at the surface, thereby preventing water from percolating through the cinders.

The smaller-loop NANOTEM profile (*Figure 10*) shows this blue high-resistivity horizon even better and shows a fairly abrupt change in resistivity values at depths below about 100 to 150 feet bls. The high-resistivity horizon appears very homogeneous and regular, though slightly variable in thickness. The thickness of the feature is again consistent with the thickness of the volcanic sequence observed in the Doney Park well. The CSAMT profile (*Figure 11*)

shows what appears to be a discrete horizon from the surface down to a depth of between 100 and 150 feet. The change to lower resistivities below this depth may correspond to the conglomerate, which was encountered within CL5 at depths between 90 and 165 feet bls. The dashed red line about 100 feet below the surface was a preliminary estimate of the depth to the top of the basalt based upon an apparent discontinuity in the resistivity data at that depth.

3.3.5 Line 5

Line 5 is interesting because it very closely resembles Line 1. As with Line 1, the TEM profile for Line 5 (*Figure 12*) shows a prominent low-resistivity feature along its northern half. Also like Line 1, the top of the feature is at a depth of about 1,600 feet bls—the approximate elevation of the water table two miles to the south at Doney Park. It is possible that this low-resistivity feature represents saturated groundwater conditions. The eastern part of Line 1 and the northern part of Line 5 both lie beneath the barren ground of Cinder Lake. As you will see below, the TEM profile of Line 6, which is completely beneath Cinder Lake, also shows a low-resistivity feature at depth. Is there a correlation between the low-resistivity features at depth and the surface physiography? Although there is no known hydrothermal activity in the area, Sunset Crater erupted very recently and is less than 2 miles to the north. If there is a source of heat at depth it may be possible that it is also heating the groundwater beneath Cinder Lake. Warm water typically has greater solubility and, hence, often contains higher concentrations of dissolved minerals. If this is occurring beneath Cinder Lake it is unclear how this would affect the surface.

Unfortunately, the TEM data do not discriminate between formations above the deeper low-resistivity feature. Like the other profiles, Line 5 also shows a blue high-resistivity horizon near the surface.

3.3.6 Line 6

Line 6 was surveyed northeast, across most of Cinder Lake itself. The most prominent feature in the 400 by 400-foot loop TEM profile (*Figure 13*) is the orange and red low-resistivity feature along the bottom of the profile. The top of the feature resides near a depth of about 1,600 feet bls, which is consistent with the approximate depth of the water table to the south at Doney Park. The blue high-resistivity horizon above about 1,500 feet bls and the surface does not show

different formations. The smaller 164 by 164-foot loop NANOTEM profile (*Figure 14*) was surveyed from Station 2000 to Station 4200 along Line 6. In this profile the blue high-resistivity feature near the surface varies in thickness between about 100 feet on the western side to about 200 feet on the eastern side. The dashed red line about 100 feet below the surface was a preliminary estimate of the depth to the top of the basalt based upon an apparent discontinuity in the resistivity data at that depth. This depth is again roughly consistent with the thickness of the volcanic sequence observed in the Doney Park well to the south. The CSAMT data (*Figure 15*) also appears to show a layer near the surface that is about 100 to 150 feet thick. However, as mentioned in Line 1, since the depth to the base of the volcanic sequence within CL5 is 315 feet, this suggests that either the resistivity values do not closely follow rock types, or the volcanic sequence varies in thickness laterally. As with the other profiles mentioned above, it is possible that the change to lower resistivities below this depth corresponds to the conglomerate, as encountered in CL5 between depths of 90 and 165 feet bls. It is interesting that the depth of the lower resistivity zone becomes shallower to the west. This is the direction from which the sediments in the conglomerate were shed (based on the felsic to intermediate volcanic clasts within the unit). It is possible that the conglomerate thickens to the west while the basalt and cinder deposits thin in the same direction.

3.3.7 Line 7

Line 7 projects from the top of the 'north finger' of the landfill northward into Cinder Lake (*Figure 16*). Along this profile the uppermost 100 feet shows the lowest resistivity values. The top of the basalt as encountered in borehole CL2 is shown with a small horizontal red line. In this profile, it appears that the lowest resistivity values appear to correlate with the cinder deposits and the upper part of the basalt. If the thickness of the basalt here is the same as that encountered in the deep borehole CL5 (315 feet), then the base of the basalt is just below the bottom of the profile at an estimated elevation of about 6,310 feet. In this profile the lowest, darkest blue, resistivity values appear to correlate with the cinder deposits and with the upper weathered part of the basalt. The remainder of the profile below is slightly less resistive, suggesting that in this profile, at least, the cinders and basalt can be somewhat differentiated. As with the profiles mentioned above, this change in resistivity is also consistent with the presence of conglomerate, as encountered in CL5 between depths of 90 and 165 feet bls. The south end of

the profile (the left side) shows an abrupt change to high (dark blue) resistivity between Stations 300 and 400 (or Stations 75 and 175 meters as shown on the top of the profile). This is in an area that is near the top of a hill on the south side of Cinder Lake. There are exposures of basalt at the surface on hills not far to the west that resemble dikes. It is possible that the high-resistivity feature represents a subsurface dike of harder basalt lava.

3.4 General Observations

In general, the geophysical plots do not correlate well with the expected geology at depth. They all show a zone of high resistivity within a few hundred feet of the surface, which is consistent with the presence of relatively dry and resistive volcanic cinders and basalt. However, the contact between the cinders and the underlying basalt is not clearly shown by the geophysical data. The deep borehole data from CL5 show that at least in that area the volcanic sequence contains layers of conglomerate which have a fine-grained matrix. Elsewhere, conglomerates with a fine-grained matrix commonly exhibit a much lower resistivity signature than neighboring volcanic rocks, because the clays in the matrix tend to hold moisture. The normal TEM resistivity profiles do not show a distinction between these rocks. However, the NANOTEM profiles in Figures 5, 7, 10, 14, and 16 (Lines 1, 2, 4, 6, and 7, respectively) show a decrease in resistivity at depths below about 100 feet. The actual depth of this change varies between about 100 and 200 feet or more. This is the approximate depth that conglomerate was encountered in borehole CL5 (between 90 and 165 feet bls). If the lower resistivity zone below these depths does in fact correlate with the conglomerate, then it is possible that the conglomerate layer varies both in thickness and in depth. Because the conglomerate layer encountered within CL5 is 75 feet thick, and the lower resistivity zone is thicker than that, the lower resistivity values likely represent a combination of the conglomerate and interbedded basalts.

A few of the geophysical profiles show a low resistivity feature at deeper depths, below about 1,600 feet, which is consistent with the estimated depth to the water table. The low-resistivity 'ramp' on the west side of Line 1 in consistent with surface water flowing off the San Francisco Peaks being recharged in that area. Photos taken during the geophysical survey are in *Appendix B.*

4.0 BOREHOLE DRILLING

The purpose of the drilling program was two-fold: to better understand the nature of the subsurface materials, and to use the data points provided by the boreholes to calibrate the geophysical data and attempt to extend the stratigraphy between the boreholes. This approach provides a more robust model of the subsurface geology.

4.1 Drilling Methods

4.1.1 Sonic Drilling

Because one of the goals of the study was to understand the subsurface stratigraphy close to the surface, it was necessary to drill the boreholes in such a way that relatively clean samples could be returned, in their correct order, with little disturbance as possible. In addition, the material exposed at the surface of Cinder Lake is unconsolidated. As a result of these conditions, sonic drilling was chosen as the most optimal drilling method. Boart was selected to drill the boreholes for both the USGS and the City to save money, time, and for consistency.

Sonic drilling used an outer steel casing and an inner, smaller diameter steel drill pipe connected to a hollow pipe that fits inside the outer steel casing. A 7-inch diameter steel cutting shoe containing tungsten-carbide buttons on its end is attached to the bottom of the hollow inner casing. High frequency vibrations are transferred to the drill pipe, which vibrates the cutting shoe as it rotates. The result is similar to that obtained by ultrasonic cleaning tools used by dentists to clean teeth. It loosens and penetrates material much easier than by drilling alone. As the steel drill casing is advanced into the ground, it forms a sleeve around the material in the borehole, in effect creating a ‘core’ which is held within the pipe by friction. The pipe is then raised to the surface, a long clear plastic bag is pulled up over the open end of the pipe, the casing is vibrated, and the material loosens and falls into the bag. When the bag is full the vibrations are stopped, the bag is removed, and the process is repeated until the pipe is completely evacuated of material. Each bag typically holds about 2.5 feet of material. These bags are then laid out on a tarp for inspection. Because the bags are clear, it is relatively easy to examine the contents through the bag. Samples can then be obtained via the open end of the bag.

Another advantage of the sonic drilling method is it advances its own outer casing as it penetrates. This is particularly advantageous in loose material like Cinder Lake. Without the

casing to support the borehole wall, material would continually cave in on the drill bit. With the borehole wall supported and caving nearly eliminated, only the material at the bottom of the drill pipe is material that is sampled.

The drilling fluids used in these boreholes consisted of air and water. When possible, the holes were drilled using air only. Air works best in sediments or weakly consolidated material, but in strongly consolidated deposits and hard bedrock a large amount of friction is generated, which can result in the drill pipe locking and becoming stuck. To counter this, in each borehole when hard rock was encountered, a small amount of water was added. This was typically in the lowermost 10 to 15 feet of each borehole. According to the driller, the average amount of water used in drilling the bottom of each hole was between 400 and 500 gallons. Photos taken during the sonic drilling program are in *Appendix C*.

4.1.2 Air Hammer Drilling

The air hammer (or air rotary) method employed here used the same drilling rig and setup as the sonic. This method was only used in the deep borehole (CL5) because it is much quicker than the sonic technique in hard rock. When the sonic rig had penetrated to 36 feet in the basalt, the outer steel casing was left in place to stabilize the borehole, and the inner drill pipe was withdrawn. The sonic drill shoe was removed and a hammer bit was installed on the drill string. Like the sonic bit, the hammer bit also contains several tungsten-carbide buttons on its surface, but instead of creating a core, the hammer bit smashes downward as it rotates, pulverizing the rock into small bits. Compressed air from a 950 ft^3/min air compressor provided the power necessary to lift the cuttings out of the borehole. The air pressure was set at 300 psi. A special swivel and diverter were installed on the drill string and casing, respectively, in order to form a flow path for the compressed air. Even with the large amount of air pressure, some intervals within the basalt took all of the air and allowed no cuttings to be returned to the surface. To counteract that loss, water and foam were added to the air to help plug the cavities at depth and to increase the density of the drilling fluid. The driller estimated that about 2000 gallons of water were added during the drilling of the borehole. Very little of that water came back up to the surface as foam.

The cuttings rose up the casing, through the diverter, and into a horizontal plastic pipe,

where they launch out the end of the pipe with about 60 psi of pressure. To collect samples a bucket was held (carefully) in front of the opening. Foam and cuttings fill the bucket partially. These cuttings were then poured into a hand-held strainer and washed with water to clean them of foam and residue. Although the disadvantage of this collection technique is that it removes nearly all of the fines from the sample, it does produce representative samples from each interval. Occasionally, fragments from overlying formations were incorporated into the rising stream of air and foam. This is almost unavoidable. But by looking at the samples it is obvious of what the majority of the samples are composed. A small part of the sample from each ten-foot interval was placed in a plastic chip tray for easy reference. The remainder of the samples was put in a sealable plastic bag for later more detailed analysis. Photos taken during the air rotary drilling program are also in *Appendix C*.

4.2 USGS Boreholes

The USGS drilled four (4) sonic boreholes in the area of Cinder Lake, all north of the Landfill. Three of their boreholes lie along a north-south line very close to their north-south geophysical survey line in the same location. These boreholes are named, from south to north, CL2, CL1, and CL3. The fourth borehole was sited on the east side of Cinder Lake, and was named CL4 (*Table 1*). All four boreholes were completed as monitor wells and were installed with 10 feet of slotted PVC casing in the bottom of the wells, all within and slightly above basalt. A representative from HSI, on behalf of the City, was on site (with permission from the USGS) during the drilling and completion of the wells, from which samples were collected for detailed descriptions. A description of the stratigraphy in these wells is included with the City of Flagstaff borehole descriptions below. A geologic description of these boreholes is also shown in *Figures 17 through 20.*

4.3 City of Flagstaff Boreholes

The City boreholes were drilled immediately after completion of the USGS boreholes, beginning on June 6, 2011. A total of seven boreholes were drilled. Their positions were chosen with two goals in mind, (1) to maximize the amount of stratigraphic information obtained across the site, and (2) to complete some of these wells as monitor wells that would give information about future groundwater flow. Geologic description of these boreholes is also shown in *Figures*

21 through 27.

4.3.1 Abandoned Boreholes

The City boreholes that were not completed as monitor wells were abandoned. These included CL6 and CL8. In these boreholes, concrete (a mixture of cement and aggregate) was mixed with water at the surface, and poured directly down the hole. Cement grout is commonly used to abandon boreholes, but because of the very porous and permeable nature of the cinders cement that was added disappeared rapidly into the formation. The concrete was brought up to within about 1 foot of the ground surface, allowed to harden, and then the remaining hole was filled with surrounding surface cinders. The area was naturalized as much as possible, leaving little trace of the original borehole.

4.3.2 Monitor Wells

Boreholes CL5, CL7, CL9, CL10, and CL11 were completed as monitor wells. After boreholes CL7, CL9, CL10, and CL11 were drilled to the desired depth, the bottom of the well was backfilled with sand up to a level 5 feet below the top of the basalt. A ten-foot length of 4-inch diameter slotted PVC was installed in the bottom of the well. The lowermost 5 feet of the slotted interval was installed below the top of the basalt, and the upper 5 feet of the slotted interval was installed above the top of the basalt. Above this, 4-inch diameter blank PVC well casing was installed to the surface. Filter pack sand, consisting of 10/20 Colorado Silica Sand, was installed around the slotted casing. Above the filter pack a 20-foot thick bentonite seal (pellets) was installed. The remaining annulus between the PVC well casing and the borehole wall was filled with concrete up to the surface. A 12-inch diameter metal vault with cap surrounds and protects the PVC and is flush mounted to the surface. A 2x2-foot square cement pad was constructed around the vault at each monitor well. The deeper well, CL5, was also completed in the same manner, by filling most of the borehole with concrete, and then installing a PVC casing that extended 5 feet down into the basalt. Well construction diagrams for each monitor well are included in *Appendix A.*

The wells were constructed with a cap on the bottom of the PVC well casing. Above the cap is 8-inches of blank PVC pipe below the slotted PVC well casing. If water enters the well screen it will fill the lowermost 8 inches. Even when water levels are below the bottom of these

wells it may then seem that the water level is always at the same level, when in fact it is just the eight inches at the bottom of the PVC. This should be taken into account by whoever measures the water level in the monitor wells. It can be easily accounted for by lowering the water-level sounder another foot and realizing that it hits the bottom of the well.

4.3.3 Depth to Basalt

All of the boreholes encountered hard basalt at relatively shallow depths. The sonic drilling rig penetrated the overlying unconsolidated material very easily, but when it encountered hard unyielding basalt it penetrated much more slowly. Sonic drilling is not designed to drill through hard bedrock, but it can, very slowly, if it is not too deep, and creates a core of the rock at depth.

Hard basalt was encountered in all of the USGS and City of Flagstaff boreholes at depths between 24 and 37 feet bls (except for borehole CL8 south of the landfill, where it was encountered at 17 feet). This is consistent with Woodward-Clyde's (1997) study where they reported encountering harder rock that caused refusal of the auger mostly between 28 to 35 feet bls (see cross-sections in *Figures 31, 32, and 33*). Many of the sonic borehole samples indicate that much of the basalt encountered is fractured. This is expected. Fractures in basalt are very common and form immediately after eruption when the lava cools, shrinks, and cracks. Mineralogically all of the samples of basalt look identical. They all contain up to 1% fresh light orange to light green glassy crystals up to 2 mm that resemble olivine and/or pyroxene. The similar mineralogies and similar depths both suggest that all of the basalt encountered belongs to one flow unit. A future study may determine the origin and flow direction of this flow, but at the moment there is not enough information to make those determinations.

It is tempting to want to determine the direction that the basalt flow is sloping (which may correlate with the direction of the lava flow) by looking at the elevations of the top of the basalt. This is not recommended here for two reasons: Firstly, when a basalt flow first cools and solidifies, it cracks, founders, and lava tubes collapse. Hornitos and push-up structures may protrude 10 feet or more above the level of the flow. So the surface of a solidified lava flow typically has a very uneven surface that can vary in elevation by 20 feet or more. Secondly, the basalt flow may have been subjected to erosion. We don't know how much time the basalt was

exposed at the surface before it was buried by the younger cinder deposits. It may have been thousands or tens of thousands of years. Basalt is chemically unstable at the Earth's surface and undergoes chemical and mechanical weathering relatively rapidly compared to other rock types. It is possible that part of the basalt was stripped away by erosion in one area and not as extensively eroded in another area, giving an erroneous slope to the top surface. In fact, Woodward-Clyde (1997) observed this variation in elevation and concluded that the basalt flows in the area are not laterally or vertically extensive. In contrast, it should not be surprising that there are variations in the elevation of the basalt at depth as observed in the boreholes. The basalt encountered at depth is quite likely all part of the same flow.

4.3.4 Fracturing in Basalt

Several observations suggest that the basalt encountered in the boreholes in extensively fractured. These observations are in addition to the explanation given above about how it is normal for basalt flows to crack and fracture during cooling and solidification. Woodward-Clyde (1997) reported that the auger drilled into between 1 and 9 feet of 'extremely weathered basaltic rock' before refusal was reached. This is consistent with the cuttings that were recovered during the current effort with sonic drilling. The sonic rig penetrated the overlying cinders very quickly, and in most cases penetrated a dark brown to purple zone immediately overlying basalt composed of weathered fragments of vesicular basalt in some boreholes 10 or more feet thick. The drilling rate below this zone slowed noticeably.

During sonic drilling a large amount of friction was produced as the drill bit cut through the basalt. To cool the bit water was added. The drillers expected some of this water to be returned to the surface through the drill pipe, yet almost no water was returned. This is consistent with the water disappearing into the formation. Because unfractured basalt itself is very impervious, the logical conclusion is that the water was disappearing into fractures and cavities with the basalt.

In some of the holes the basalt was competent enough such that the sonic drill brought up short lengths of rock core. Many of these cores contained abundant vesicles (small holes created during cooling and outgassing of the lava) and cavities that extended all of the way through the core. These are obvious pathways for water. Fractures were common between segments of core.

In fact, because of the way that sonic drilling works, the drill rig tends to grind up fractured rock into small bits and powder, and there was a lot of basalt powder returned to the surface. Based on these observations, and the observations made by Woodward-Clyde (1997), the overall conclusion is that the basalt within 100 feet of the surface will likely not act as a perching layer for water. More competent basalt was encountered within the deep borehole (CL5) at depths below 160 feet bls, but this is very far below the level of the landfill. If water perches above basalt at that depth, within the overlying conglomerate, it seems unlikely that it will form a perching layer more than 120 feet thick. As mentioned below, however, the conglomerate layer may still act as a perching layer that may affect possible future lateral flow beneath the landfill.

4.3.5 Possible Perching Layers

Above the basalt only one layer has the potential to form a perching layer beneath the area—the clay-rich layer close to the surface. It is typically between 1 and 3 feet thick and the top of it varies between 1 and 3 feet beneath the land surface (see cross-sections in *Figures 31, 32, and 33*). The horizon was encountered in all wells except CL 9 on Line 4 where, instead, the underlying fine sand layer is thicker there. The fact that the clay-rich layer is so regular in thickness and depth, and is seen almost everywhere suggests that it is basin wide in extent and forms a continuous sheet just beneath the surface layer of cinders. A representative from the County was onsite sometime last year (personal communication) and observed storm runoff collect in a pond behind a berm immediately south of the landfill near borehole CL7. The berm was created by excavating and removing the surface cinders and exposing the clay-rich layer beneath it. He observed the standing body of water about 6 inches deep completely infiltrate into the ground, through the clay layer, over a time span of between 2 to 3 hours. This is equivalent to an infiltration rate of between 2 and 3 inches per hour.

Although City personnel have collected and submitted samples to obtain quantitative information about the perching rate of this unit, at present there is only the one observation mentioned above. Considering the regional extent of this unit, it would be advisable to get more information on the hydrologic properties of this unit before a recharge plan is formulated.

Interestingly, the depth of the clay-rich layer is so similar everywhere irrespective of the elevation of the surface. That means that it wraps up and down the topography of the surface—it

is not horizontal. This is unusual for a sedimentary layer deposited by alluvial processes. Streams tend to fill in the low-lying areas and leave the higher places unaffected. Since this layer wraps up and down across topography, it is possible that some of it may be pyroclastic in origin. It is possible that the clay portion may have originated as ash, but without further study this is just conjecture. The rounded pebbles of intermediate to felsic volcanic rocks exposed in the trench on the north side of the landfill wee almost certainly deposited by streams (location T1, *Figure 30*).

The deeper conglomerate, encountered within CL5 at depths between 90 and 165 feet, may also act as a perching layer. Although the air rotary drilling and collection process tends to clean the cuttings of most of the fines, the dark brown muddy material brought to the surface entrained in foam indicates that the matrix of the conglomerate contains appreciable amounts of fine material. If this is so then the 75-foot-thick conglomerate layer may be a significant barrier to downward infiltration of water. The NANOTEM profiles in Figures 5, 7, 10, 14, and 16 (Lines 1, 2, 4, 6, and 7, respectively) show a decrease in resistivity at depths below about 100 feet. The actual depth of this change varies between about 100 and 200 feet or more. If the lower resistivity zone below these depths does in fact correlate with the conglomerate, then it is possible that the conglomerate layer varies both in thickness and in depth. Because these depths are significantly deeper than the bottom of the landfill (at the shallowest, 70 feet below the bottom) it is possible that lateral flow above the conglomerate may remove water from beneath the landfill before the recharge mound rises to the landfill. However, without quantitative information about flow direction and infiltration rates at depth the conglomerate layer should still be viewed as a possible perching layer.

4.3.6 The Deep Borehole

The deep borehole was drilled immediately west of the northwest corner of the landfill. This site was selected because much of the water from the most recent flood converged here as it made its way south adjacent to the west side of the landfill. The TEM profile on Line 4 was also very consistent and suggested that the stratigraphy here was more representative of the site overall.

The uppermost 2 feet of the borehole was composed of the most recent dark sandy cinder

deposit (*Figure 21*). From 2 to 3.5 bls feet the clay-rich layer was encountered. Wet material collected from this layer could be easily rolled between the hands into long ropes over 10 cm in length, indicating it has abundant clay content. From 3.5 to 9.5 feet more dark cinders were encountered, some up to small pebbles, mixed with a small amount of brown clay and silt. From 9.5 to 13 feet is an interval of mixed dark cinders and larger cobble-size clasts of basalt. This interval has an overall dark brown color. A thin layer of hard, fractured basalt was encountered between 13 and 16 feet. It may be a large boulder or a dike, but it seems too thin to be another flow unit. Below this hard rock is an interval from 16 to 24.5 composed of dark brown and red cinders and cobble-size clasts of basalt, very similar to the rock that is exposed at the bottom of pit in the eastern side of the landfill.

Below these upper deposits, basalt was encountered at a depth of 24.5 feet bls. Part of the rock came to the surface as short lengths of core, while some came to the surface as powder. The short core lengths contained abundant vesicles (holes). The driller noted that the formation took most of the drilling water that was added, indicating that it was very porous. The section of material from the surface down to this depth (36 feet bls) was drilled with a sonic drill. Below here a rotary hammer drill was used. As mentioned above, this method is much quicker than the sonic method through harder materials. In fact, the drilling rate through the basalt increased from about 10 feet per hour using sonic to 10 feet in 10 minutes with the air hammer. Below about 50 feet the basalt was apparently so fractured and porous that no cuttings were returned to the surface. Air under high pressure was being used to lift the cuttings to the surface, but nearly all of the air was disappearing into the formation, and almost none was making it to the surface. To help raise the density of the drilling air and help seal off the cavities in the formation foam was added to the air. These conditions lasted to a depth of 90 feet, except for a small amount of cuttings being returned between 70 and 80 feet bls. These cuttings were mostly sand- to small gravel-size grains of dark and red basalt scoria. Then at a depth of 90 feet air and cuttings began returning to the surface.

The hammer bit had penetrated through the base of the basalt somewhere at a depth between 70 and 90 feet and had entered a dark brown conglomerate. The unit contains abundant subrounded sand and pebbles up to 4 cm composed mostly of intermediate to felsic volcanic rocks, and minor basalt. It turns out that the color of the foam was quite distinctive between

different formations. For this unit below 90 feet the foam was dark brown. A sample of the foam was collected and allowed to settle. It was composed of abundant dark silt and clay. This probably represents the matrix surrounding the sand and pebbles.

At a depth of 165 feet basalt was again encountered. Small chips up to 1 cm were being returned. The rock is mostly very fine-grained (aphanitic) and contains less than 1% glassy green crystals less than 1 mm across that resemble olivine or pyroxene. The drilling rate slowed down periodically to a rate of about 40 feet per hour. The driller said that the harder conditions likely indicated that the rock at these depths was harder and less fractured. Few of the cuttings show vesicles, which supports that conclusion. The color of the foam was light gray. Between 230 and 250 feet bls the interval encountered contains abundant large angular pebbles of basalt and smaller pebbles of felsic volcanic rocks. The most striking characteristic of this interval was the bright red color of the foam. A sample of the foam was collected and allowed to settle. It was composed of very fine red-colored quartz sand and silt. This interval appears to represent a thin sedimentary deposit. It is possible that this deposit accumulated when older basalts and Moenkopi Formation were exposed nearby and eroded. From 250 to 270 feet bls was a deposit of purple vesicular basalt clasts and cinders. The color of the foam was noticeably purple.

From 270 to 315 feet hard basalt was again encountered. The composition looks identical to that of the overlying basalts. The bottom of the basalt was reached at 315 feet. It took almost exactly one hour for the drill to penetrate the 45 feet of this unit. Below the basalt light gray chips of fine-grained limestone/dolomite were collected at the surface for the first 5 feet, and then the chips between 320 and 340 feet bls were darker pink. Both the light gray and pink chips fizz weakly in diluted hydrochloric acid, indicating that they are composed of limestone and/or dolomite. The original plan was to drill to 400 feet bls, but since the base of the Kaibab Formation was likely another few hundred feet below, it was not necessary to drill any further. It took about 3 hours and 20 minutes to drill from 36 feet to 340 feet bls (304 feet total) using the air rotary method. The upper most 30 feet of this borehole was completed as a monitor well.

The next closest well with the best well log is about 2 miles to the south in Doney Park, the Doney Park Well No. 1 (DPW-1). At Doney Park the upper most deposit is tan silt to a depth

of 20 feet. The cinder deposits in DPW-1 extend from 20 feet to a depth of 55 feet. In CL5 the cinder deposits are about 25 feet thick. Overall, the volcanic sequence in CL5 is 315 feet thick and directly overlies the Kaibab Formation. In DPW-1 the volcanic sequence is only 200 feet thick and overlies 55 feet of red sandstones of the Moenkopi Formation. The volcanic sequence in CL5 contains a 75-foot-thick interval of conglomerate towards the middle and a smaller interval towards the bottom. It is possible that both conglomerate layers connect laterally as the intervening basalt pinches out. The absence of these beds within DPW-1 indicates that they pinch out over a relatively short distance. It is possible that the conglomerate beds represent stream channel deposits or small alluvial fans that were restricted to low-lying areas between higher volcanic flows, just as they are today.

4.3.7 Basin Wide Stratigraphy

Several observations can be made using the new geophysical data and borehole information. Near the surface is an interval of small, unconsolidated dark cinders that forms a relatively thin layer mantling the surface between 17 and 55 feet thick. These cinders are almost completely unconsolidated and samples crumble easily, even from the bottom of the horizon. The lack of consolidation (cementation) suggests either that these deposits are very young or they transmit water quickly enough such that there has not yet been enough time for a cemented soil horizon to form. Because there exists one or more sedimentary layers within this horizon, the cinders must represent more than one episode of volcanic activity. Moore and Wolfe (1976) interpreted the uppermost 1 to 2-foot-thick layer of cinders as being deposited from the 1065 A.D. eruption of Sunset Crater less than two miles to the north. The cinders further down in the horizon may have come from other nearby cinder cones that erupted further in the past. The depth of cinders and other pyroclastic deposits is often determined directly by the direction of the prevailing wind, and may explain the variations seen in the thickness of these deposits.

The thin clay-rich layer just beneath the surface is basin wide. In most boreholes it contains abundant clay and silt, and also medium to coarse subrounded sand composed mostly of intermediate to felsic volcanic rocks. The currently exposed source of these grains is to the west at Elden Mountain and San Francisco Mountain. Therefore, this layer likely represents, at least in part, alluvial material that was shed off the San Francisco Peaks and transported eastward, where it was deposited at Cinder Lake. Before the 1065 A.D. eruption, the surface may have

looked much different. Instead of being covered by barren unconsolidated cinders it was fine-grained soil and was likely much more fertile. A few feet below this clay-rich layer is a layer composed almost entirely of subrounded quartz/lithic silt. The silt is light tan to brown and is very well sorted. No larger grains are visible. There is no source of quartz currently exposed anywhere in the Flagstaff region, so the grains must have traveled a great distance. The silt-size and far-traveled nature of this deposit suggests that it represents wind-blown material. When this layer was deposited the surface probably looked very arid and covered with small dunes. This layer is underlain by more than 10 feet of unconsolidated loose basaltic cinders that likely represent more than one pyroclastic eruption.

It should be noted that there are some excellent exposures of these uppermost cinder and sediment deposits within the landfill itself. A few of these were examined and are marked on the location map (*Figure 3*) as points T1 through T6. Three of these locations are included as figures in this report. Location T1 (Figure 28) is within a deep trench dug on the north side of the landfill. Location T4 (*Figure 29*) is a good exposure in the eastern pit of the landfill where the bottom exposes large red cinders. Location T5 (*Figure 30*) is a backhoe trench dug near the northwest corner of the landfill.

Basalt bedrock underlies the cinder deposits which has an upper surface at a consistent depth of between 24 and 37 feet bls. The data from the deep borehole (CL5) indicates that the volcanic sequence is about 300 feet thick, and contains at least three separate basalt flow units. All of the basalt units are mostly fine-grained (aphanitic) and contain less than 1% glassy green phenocrysts up to 2 mm across that resemble olivine or pyroxene. They are all likely alkali-olivine basalts, which is consistent with descriptions of surface basalts by Moore and Wolfe (1976). The geophysical data and the deep borehole data both suggest that the depth of the volcanic rocks in the Cinder Lake area is about 300 feet thick. The TEM data suggest there are variations in thickness, which is common in volcanic fields. Lava flows pinch out or stop abruptly against cinder cones or other topographic features.

The basalts directly overlie the Kaibab Formation. No red sandstones of the Moenkopi Formation were encountered in the deep borehole (CL5). Thin remnants of Moenkopi Formation are exposed to the southwest in Flagstaff and to the north in Wupatki National Monument, where

they are preserved beneath basalt flows. It was expected that the Moenkopi Formation would be encountered in CL5 as well. However, there is a long-lived unconformity on top of the Moenkopi, representing a period of erosion that lasted since the end of the Cretaceous (65 million years ago) to the late Tertiary (less than 1 million years ago—the age of the basalts in this area). During that time, the Moenkopi beneath CL5 must have been removed by erosion.

5.0 IMPICATIONS FOR FLOOD WATER RECHARGE

If one had to pick a type of material that would be best for transmitting water from the surface into the subsurface, the loose, unconsolidated cinders in the Cinder Lake area would make a very good candidate. The cinders themselves, however, do not appear to be the controlling factor that will determine the rate of recharge. The shallow, thin clay-rich layer is the only layer in the near–surface that may act as a perching layer. The geophysical data do not show perching conditions near the surface. In fact the geophysical data do not show perching conditions anywhere within 1,600 feet of the surface. This does not mean that the clay-rich layer will not act as a perching layer, however. The amount of precipitation that has fallen on Cinder Lake over a given time period has not been investigated. The amount of water that was diverted to Cinder Lake during the last flood event is also not known. This information should be investigated and combined in conjunction with infiltration rate tests of the clay layer to model the hydrologic behavior of the clay-rich layer. As mentioned above, the clay-rich layer does not form a horizontal sheet, but appears to wrap up and down a pre-existing landscape (see cross-sections in *Figures 31, 32, and 33*). Therefore, the clay layer may enhance lateral flow of water only within the uppermost 1 to 2 feet of material, and only in the local downhill direction. That is to say, since it follows topography, the layer on the north-facing slope north of the landfill should enhance lateral flow northward into the topographic low formed by Cinder Lake.

The sonic borehole samples indicate that much of the basalt is fractured. Therefore, although the basalt is relatively close to the surface it may transmit water at a sufficient rate to inhibit perching. The TEM data support this interpretation because the very high resistivities revealed in all of the profiles are consistent with the absence of significant moisture within the basalt. Since the overlying cinders must act as a sponge to torrential monsoon rains that almost certainly have fallen here in the recent past, there must have been some periods of time when significant amounts of water flowed downward through the basalt. Since we don't see the signature of that water we can conclude that it must have percolated through the cinders and basalt at a rate quick enough to remove all of it since the last large recharge event (2010?). Alternatively, the water may have traveled out of the area laterally across the top of the basalt. This doesn't seem likely, however, given the fractured nature of most basalt flows. Basalt flows are almost nowhere like flat tables. There is also no compelling evidence for lateral flow in any

of the geophysical profiles. However, it may be argued that even with torrential rains, this area has not seen the kind of recharge it is likely to receive now that the Copeland Avenue diversion has been created. Even so, the uneven upper surface of the basalt does not seem conducive to lateral flow.

Another possibility for lateral flow is at the surface itself. Diverted flood waters will likely bring with it abundant silt, which will be deposited on top of the cinders. Over time the silt will likely begin to plug the underlying cinders and lower the infiltration rate. As this happens, water may begin to flow laterally at a rate faster than it can recharge. This may cause to expand the initial boundaries of the recharge basin (and may even create a temporary shallow lake). Since the subsurface stratigraphy appears to be very consistent across the whole area this may not pose a problem with respect to interaction with the landfill—it may just increase the area of recharge. However, this will likely increase the silt cover across more and more of Cinder Lake. This may not be acceptable from an aesthetic point of view. Cinder Lake is a unique area. There are very few areas like it. Also, the NASA crater fields may be covered with silt over time. This is a cultural resource that may become more valuable in the future. Spreading silt may also impact the area's use as a recreational vehicle area. It may also increase the amount of fine sediment exposed at the surface and create an expanding source of dust. All of these possible impacts should be considered when designing Cinder Lake as a recharge location. Overall, though, there does not appear to be a great potential for lateral flow either across the shallow clay layer or across the top of the basalt that will directly impact the landfill.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions were based on surface geophysics drilling, and sampling program recently completed during the May-June 2011 field activities. The conclusions are as follows:

1. Hydrologically, there do not appear to be any major impediments to recharging water at Cinder Lake with the exception of a clay-rich horizon 1 to 3 feet thick near the surface and possibly also the deeper conglomerate layer between 90 and 165 feet bls. This clay-rich horizon may act as a perching layer. The loose, unconsolidated cinders at Cinder Lake beneath the clay-rich horizon appear to be an ideal material for recharging surface runoff.

2. The horizon of cinders is between about 25 and 55 feet thick and likely represents pyroclastic deposits erupted from one or more nearby cinder cones.

3. A clay-rich horizon 1 to 3 feet thick exists just below the surface mostly between 1 and 5 feet bls. It was encountered in all but one borehole drilled, indicating that this feature exists throughout the Cinder Lake area. This shallow clay layer may act as a temporary perching layer, but since this clay layer appears to drape over preexisting topography it does not form a flat, horizontal layer. Because of this, the layer does not preferentially channel surface water towards the landfill from the preexisting Cinder Lake recharge area.

4. The deeper conglomerate layer between 90 and 165 feet bls (as encountered in borehole CL5) likely contains a significant amount of fine material and may act as a deeper perching layer.

5. The basalt was encountered at relatively shallow depths. In most of the boreholes it was encountered between 24 and 37 feet bls. The consistently high-resistivity TEM data indicate that the basalt does not form a perching layer beneath the cinders.

6. Borehole data are consistent with the geophysical data, and indicate that the basalt is

highly fractured and has an uneven upper surface. These observations suggest that the basalt will not act as a perching layer and will not support lateral flow in any particular direction.

7. Five out of the seven boreholes drilled by the City were completed as monitor wells with 4-inch diameter PVC well casing and will serve as observation points in the future. These observation points will help to better understand the migration of the runoff water through the cinder bed and the basalt.

6.2 Recommendations

The following recommendations are in support of the above conclusions and they are as follows:

1. Continue to recharge diverted flood waters from Copeland wash to Cinder Lake based on the contingency that the clay-rich layer is removed or scarified from within the recharge area in order to avoid possible perching of the water on the clay-rich layer. There do not appear to be any major impediments to recharging water below the clay-rich layer.

2. Develop a program to monitor the water level in all of the new monitor wells during significant storm or diversion events. Consider technologies that allow for the installation of data logging equipment that can continuously record water levels during specific times of the year. This would reduce the manpower requirement to be available during potentially sudden events.

3. Develop a program to significantly reduce the silt content before the water reaches Cinder Lake (such as the construction of upstream settling basins, trenches, and/or terraces). Be aware that the cinders within Cinder Lake may become plugged over time by silt transported with the diverted recharge water. This will quite likely decrease the infiltration rate over time and extend the surface flows.

4. Develop a program to periodically scarify the silty material from flood-water deposition to temporarily increase the infiltration rate. However, a periodic scarification program may tend to mix the finer silt from the flood waters with the cinders, and over time it may

make it more difficult to remove the silt altogether.

5. Monitor the water level at the end of the Copeland Avenue diversion at Cinder Lake to determine how long it takes for the water to completely infiltrate. This information may become valuable over time to track changes in the infiltration rate. This information may help in determining the frequency of sediment removal and to quantitatively support future operation and maintenance activities.

6. Develop a program to quantify the amount of water entering the system at the end of the drainage canals along with a data collected from the flow measurement devices to better understand the dynamics of the recharge system at Cinder Lake. These data will be very helpful in better understanding the runoff/recharge relationships for the modeling future events.

7. Continue to explore ways to minimize the sediment flows from up gradient to avoid having to deal with the sediment at the cinder beds. This could include terracing the runoff area, developing cinder pits to capture the sediment while allowing the water to continue to flow down gradient and into the drainage canal.

8. Consider installing one or more monitor wells that penetrate into the conglomerate layer that exists between 90 and 165 feet bls, as encountered in borehole CL5. Monitor the groundwater level in these wells to determine how much if any perching occurs on this deeper layer.

9. Continue to evaluate the geophysical data and correlate it with the drill cutting to enhance our understanding of the hydrogeology and recharge capability of the area.

10. Evaluate the results of the first runoff event and use this information to plan for future runoff events.

7.0 REFERENCES

Bills, D.J., Truini, Margot, Flynn, M.E., Pierce, H.A., Catchings, R.D., and Rymer, M.J., 2000, Hydrogeology of the regional aquifer near Flagstaff, Arizona, 1994-97: U.S. Geological Survey Water-Resources Investigations Report 00-4122.

HydroSystems, Inc, 2009, City of Sedona WWTP CSAMT Survey, prepared for the City of Sedona, 21 p., 7 photos, 8 figures.

McGavock, E.H., Anderson, T.W., Moosburner, Otto, and Mann, L.J., 1986, Water resources of southern Coconino County, Arizona: Arizona Department of Water Resources Bulletin 4.

Moore, R.B., and Wolfe, E.W., 1976, Geologic map of the eastern San Francisco volcanic field, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-953, scale 1:50,000.

Ulrich, G.E., Billingsley, R.H., Wolfe, E.W., Nealey, L.D., and Sutton, R.L., 1984, Map showing geology, structure, and uranium deposits of the Flagstaff 1x2 degree quadrangle, Arizona: U.S. Geological Survey Miscellaneous Investigation Series Map I-1446, scale 1:250,000.

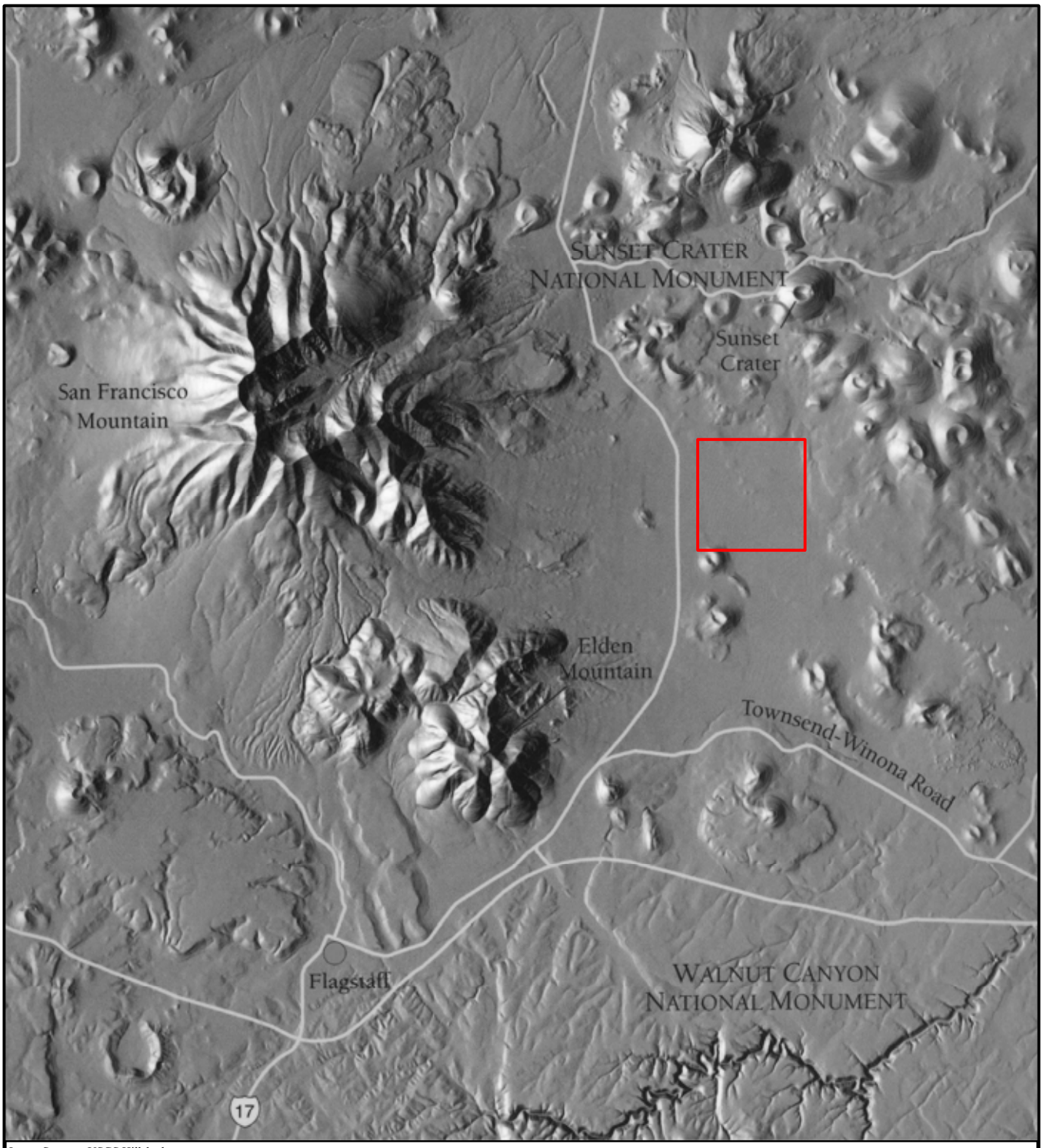

Image Sources: USGS Hillshade

Legend

Study Area

0 1.5 3 6 Miles

N

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Cinder Lake Landfill
Study Area Location Map
Flagstaff, AZ

Figure 1

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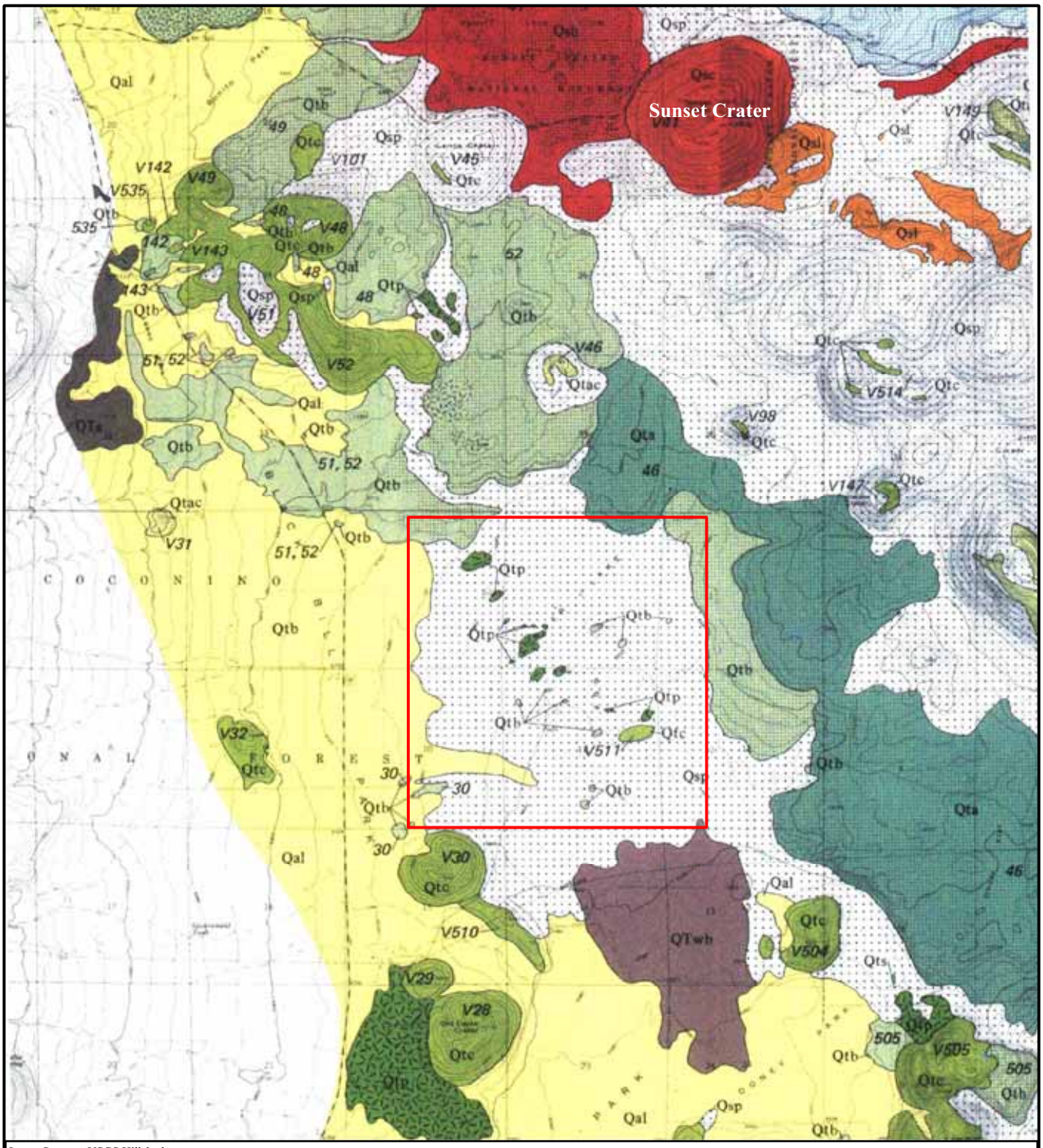

Image Sources: USGS Hillshade

Geology from Moore and Wolfe (1976)

Legend

- Study Area
- **Qal** Alluvium
- **Qsp** Basalt Cinders (from eruption of Sunset Crater at 1064 A.D.)

0 0.5 1 2 Miles

N

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Cinder Lake Landfill
Geologic Map
Flagstaff, AZ

Figure 2

R:\11-623\GIS\Maps\Geologic_Map.mxd 06/14/2011

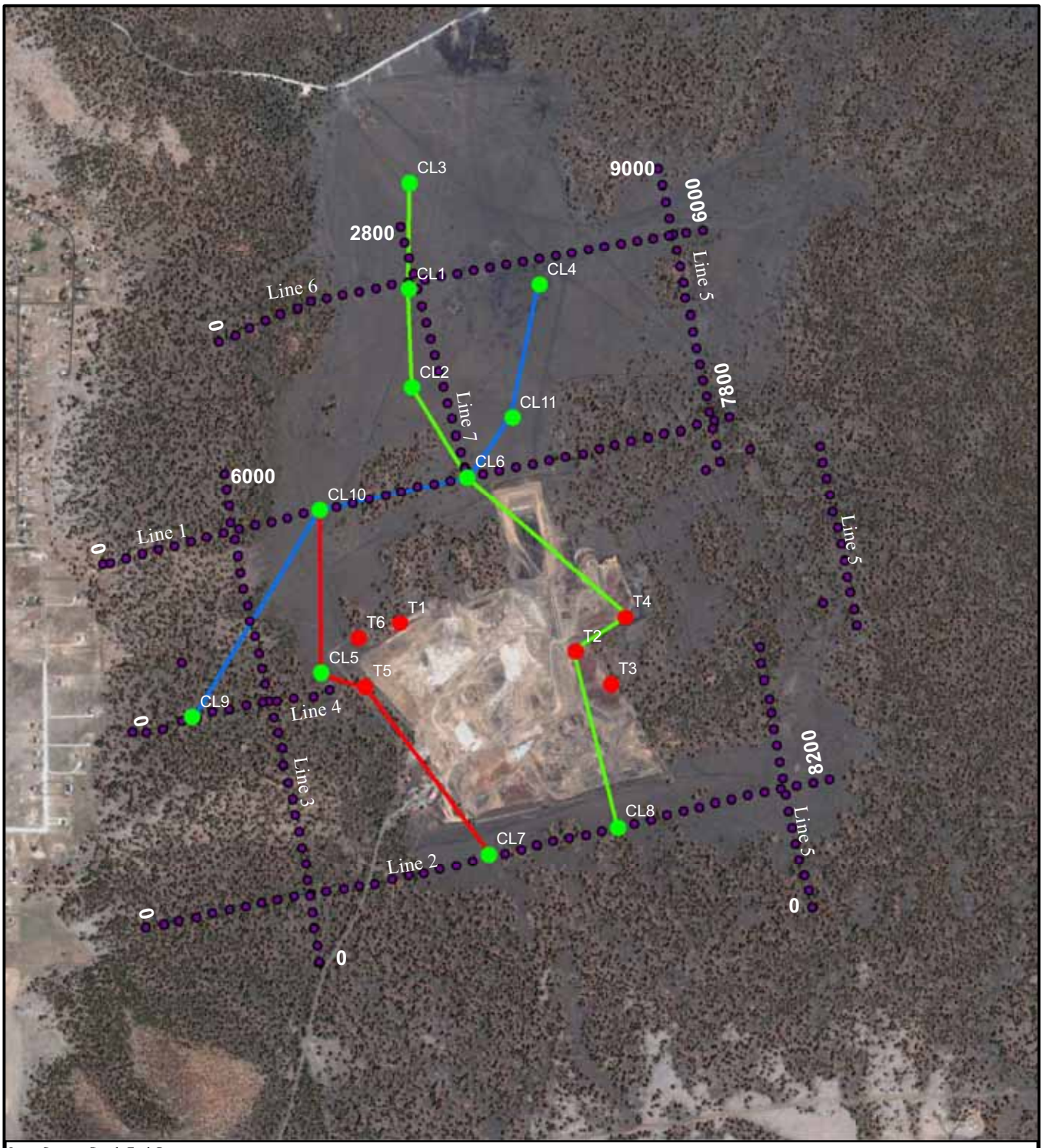

Image Sources: Google Earth Pro

Legend

- Exposures
- Boreholes
- TEM Points
- Cross Section 1
- Cross Section 2
- Cross Section 3

0 0.25 0.5 1 Miles

N

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Cinder Lake Landfill
Geophysical Lines, Boreholes, and Surface Exposures Location Map

Figure 3

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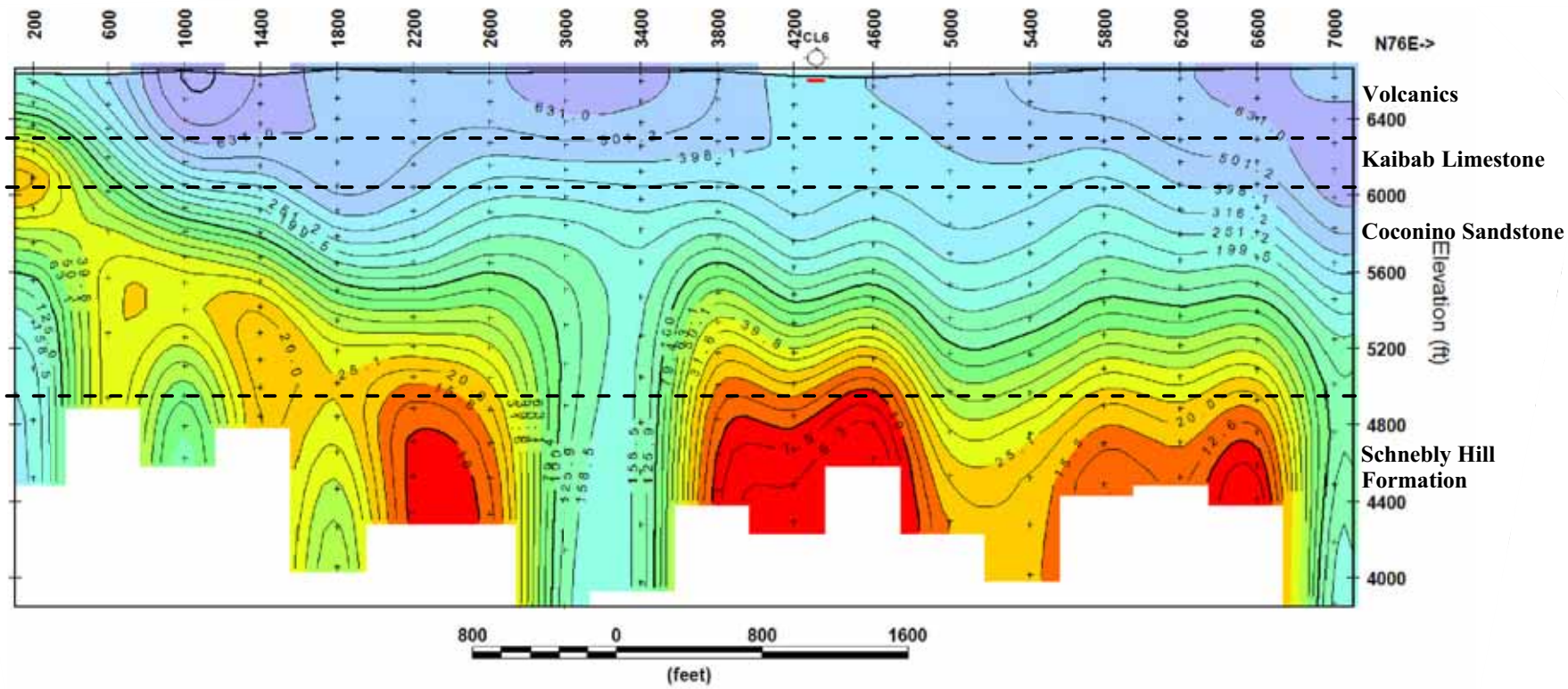

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Cinder Lake Landfill
Zonge Geophysical Analysis
Line 1 TEM 400X400

Figure 4

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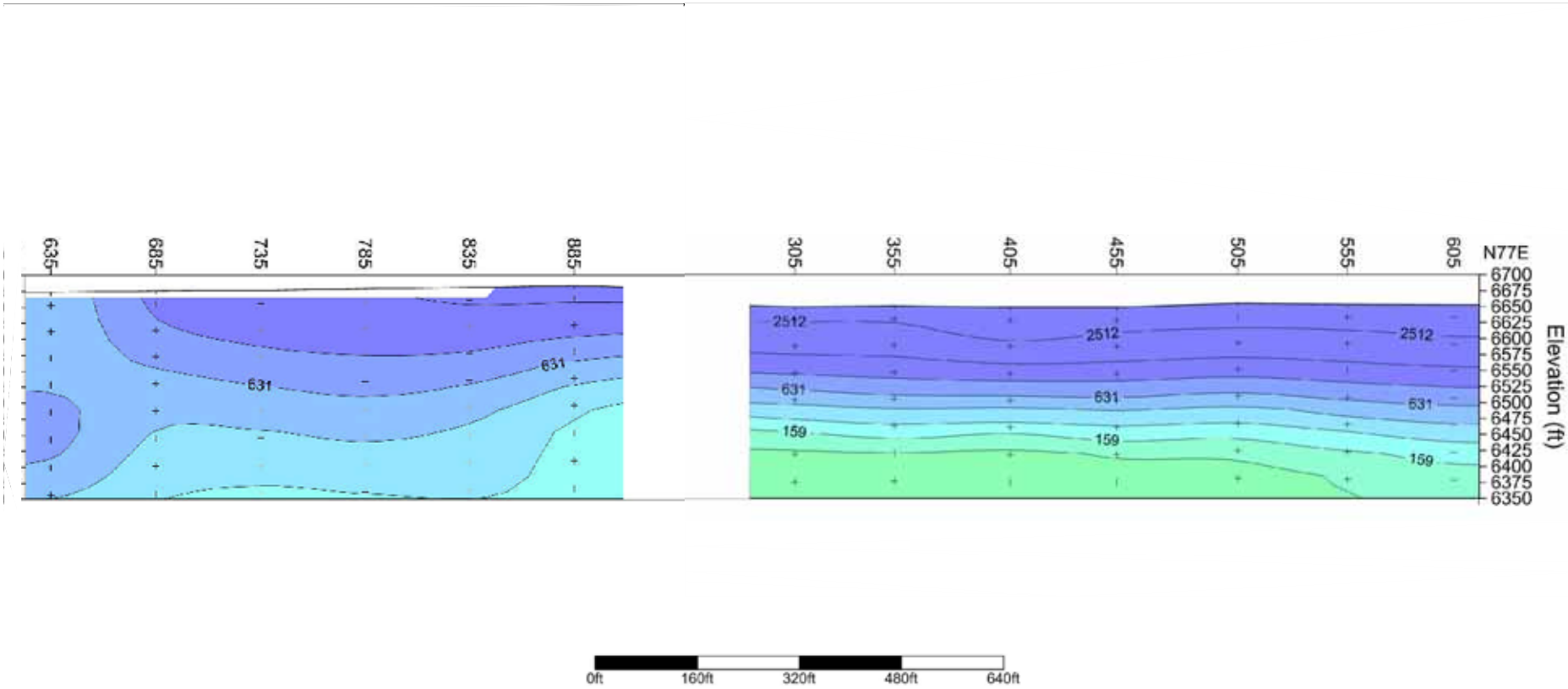

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Cinder Lake Landfill
Zonge Geophysical Analysis
Line 1 nanoTEM 164X164

Figure 5

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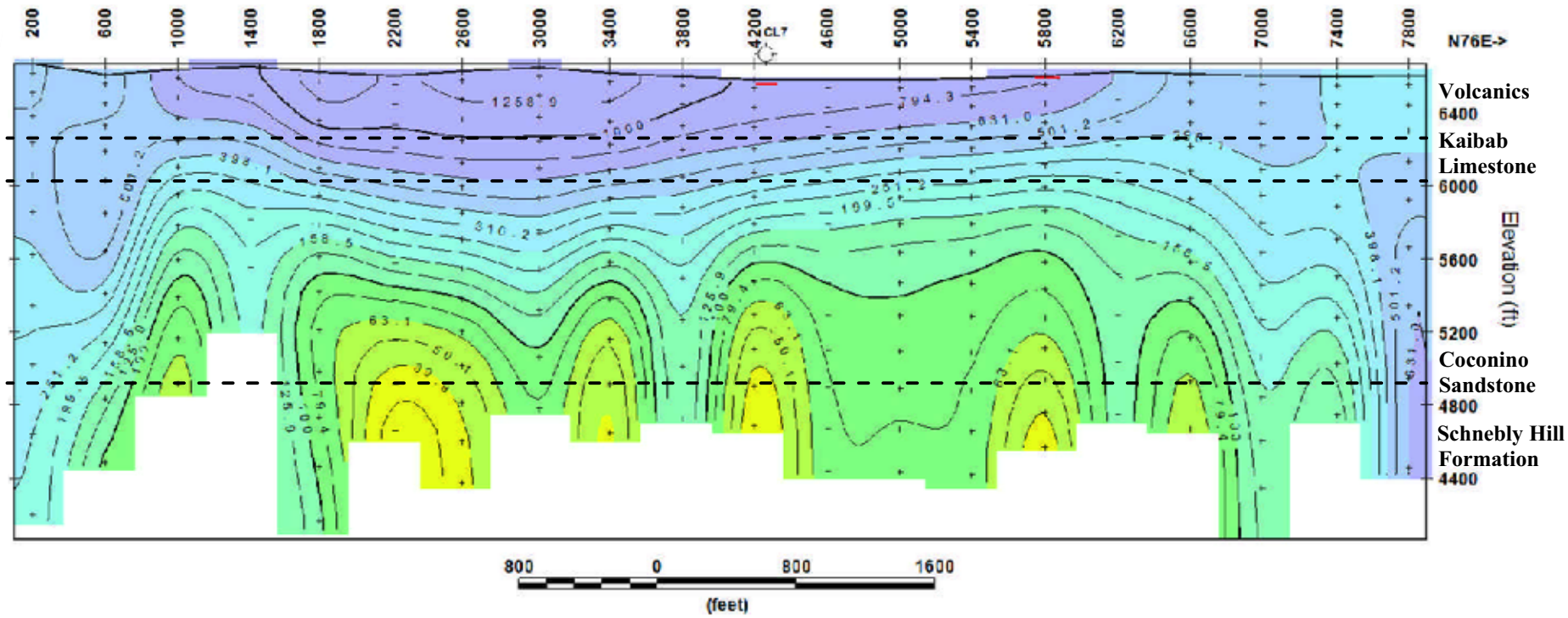

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Cinder Lake Landfill
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Line 2 TEM 400X400

Figure 6

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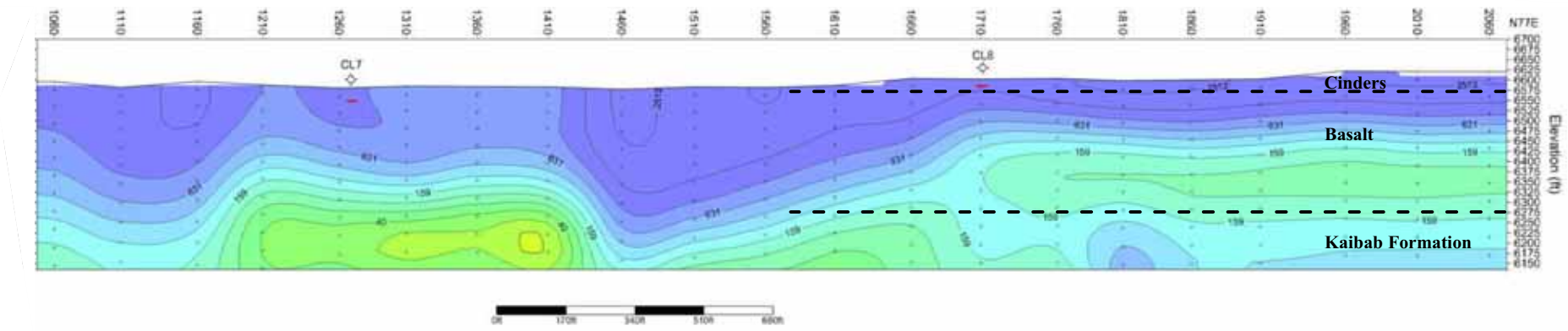

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Cinder Lake Landfill
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Line 2 nanoTEM 164X164

Figure 7

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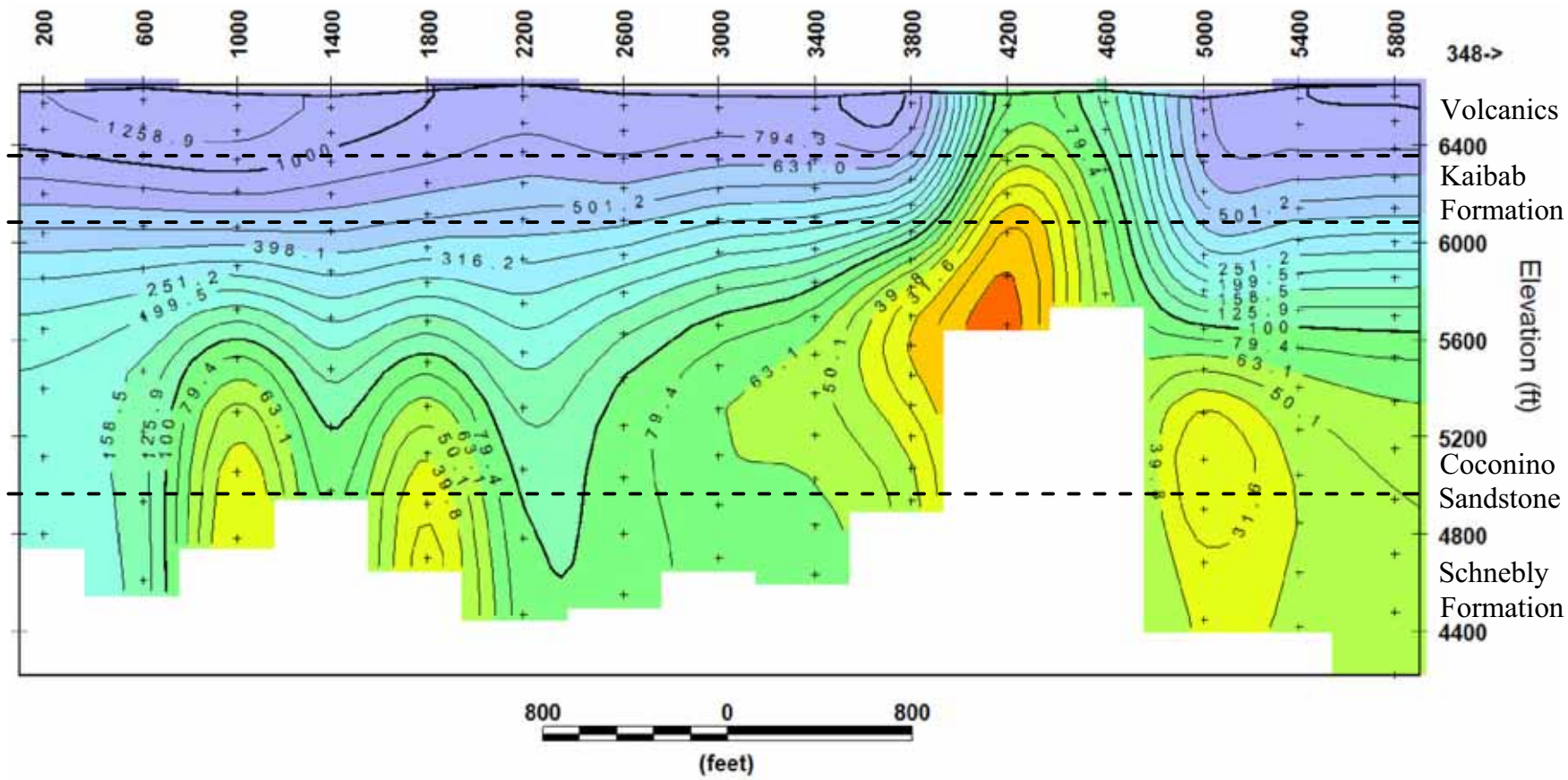

HydroSystems Inc.

Cinder Lake Landfill
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Line 3 TEM 400X400

Figure 8

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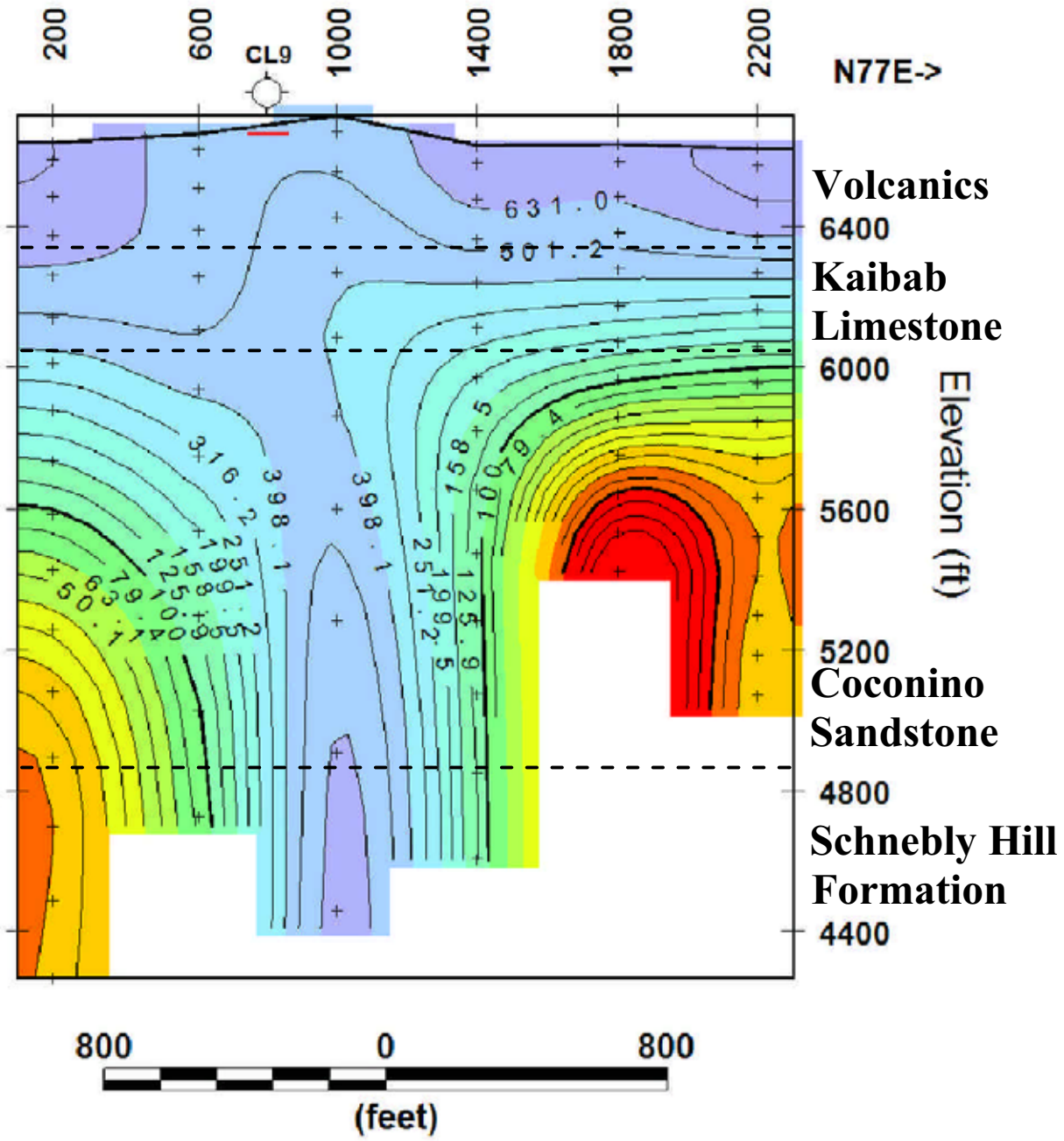

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Cinder Lake Landfill
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Line 4 TEM 400x400

Figure 9

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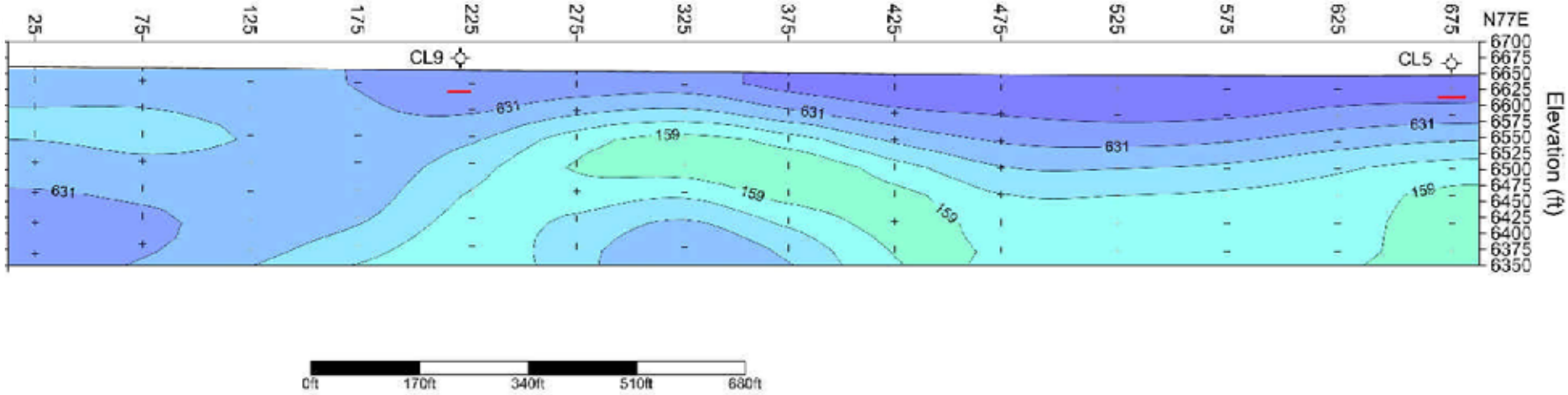

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Cinder Lake Landfill
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Figure 10

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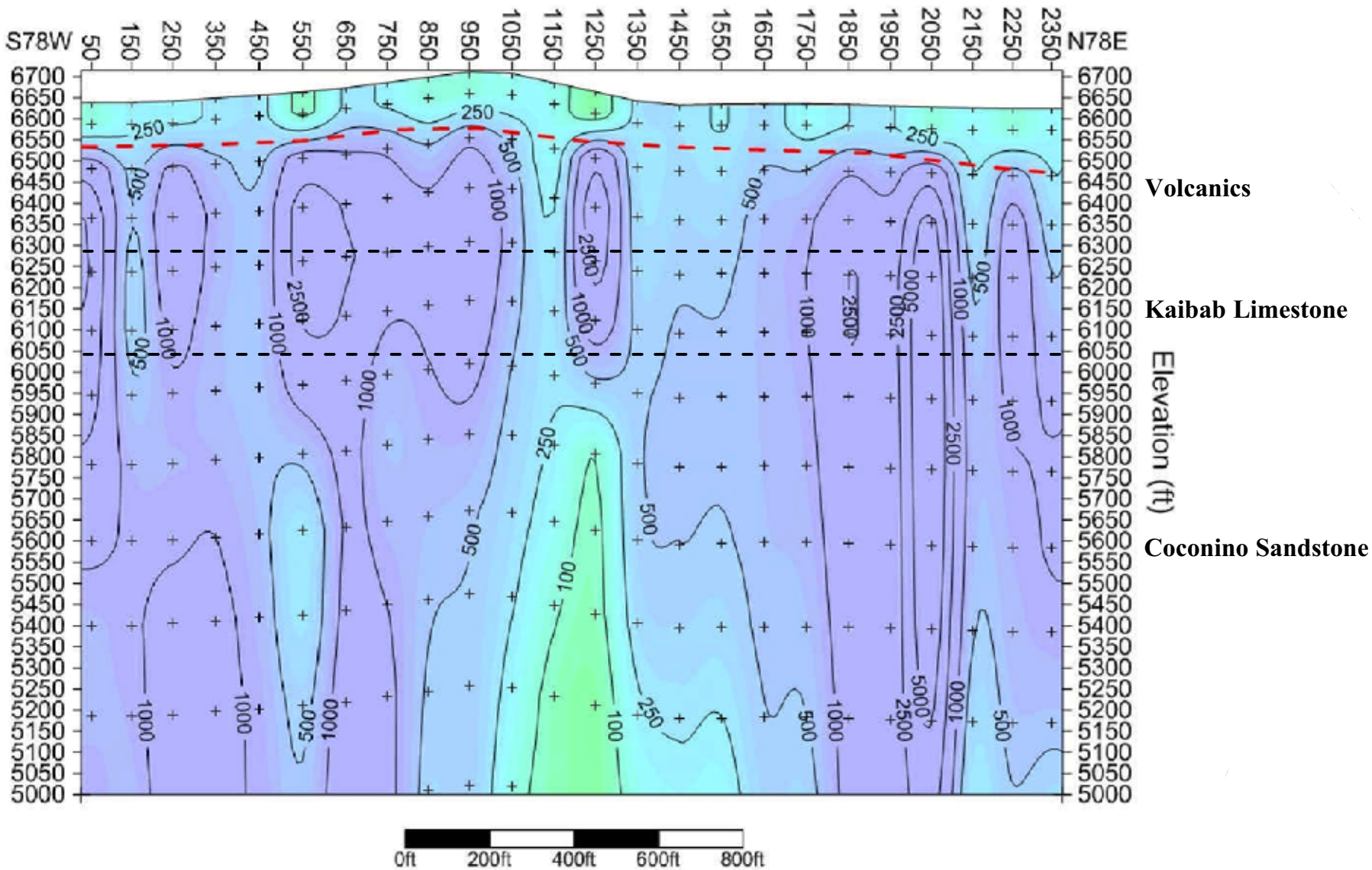

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Figure 11

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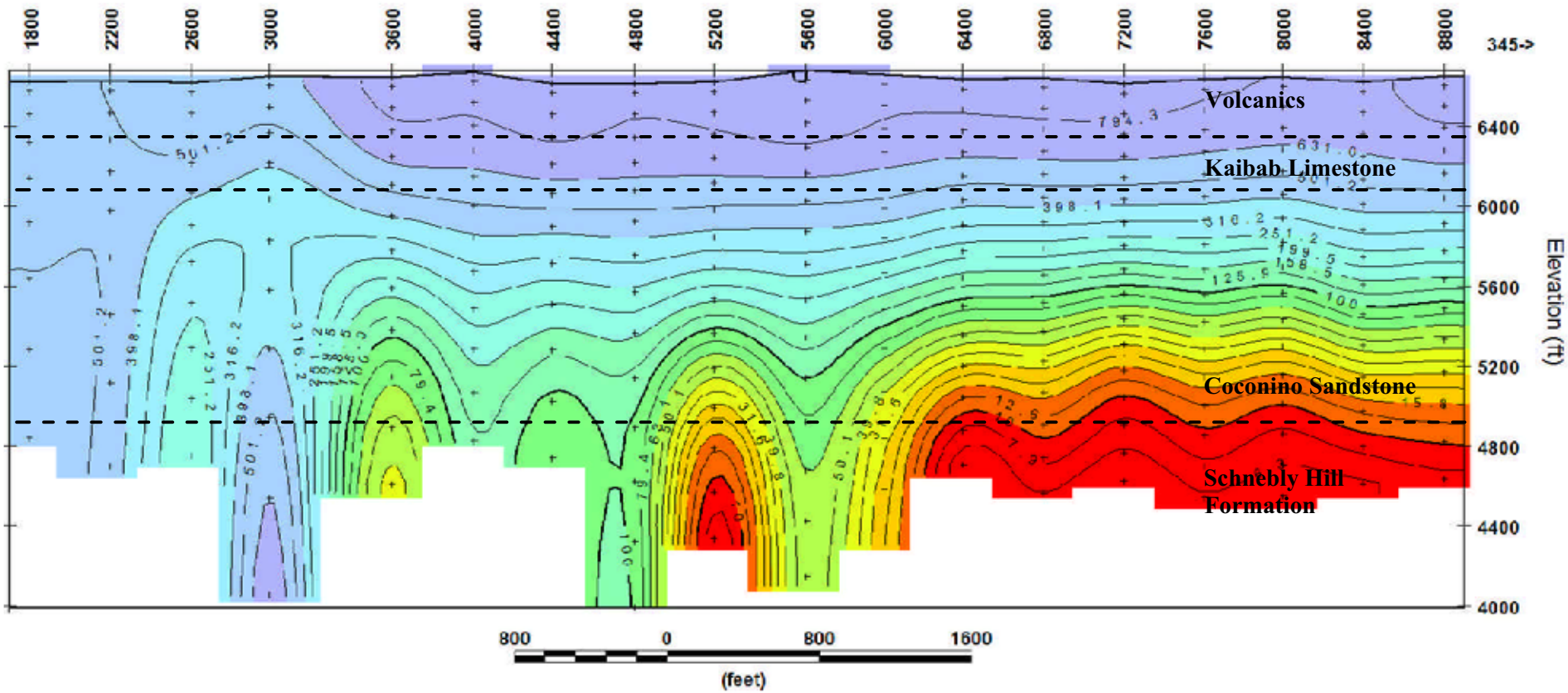

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Cinder Lake Landfill
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Figure 12

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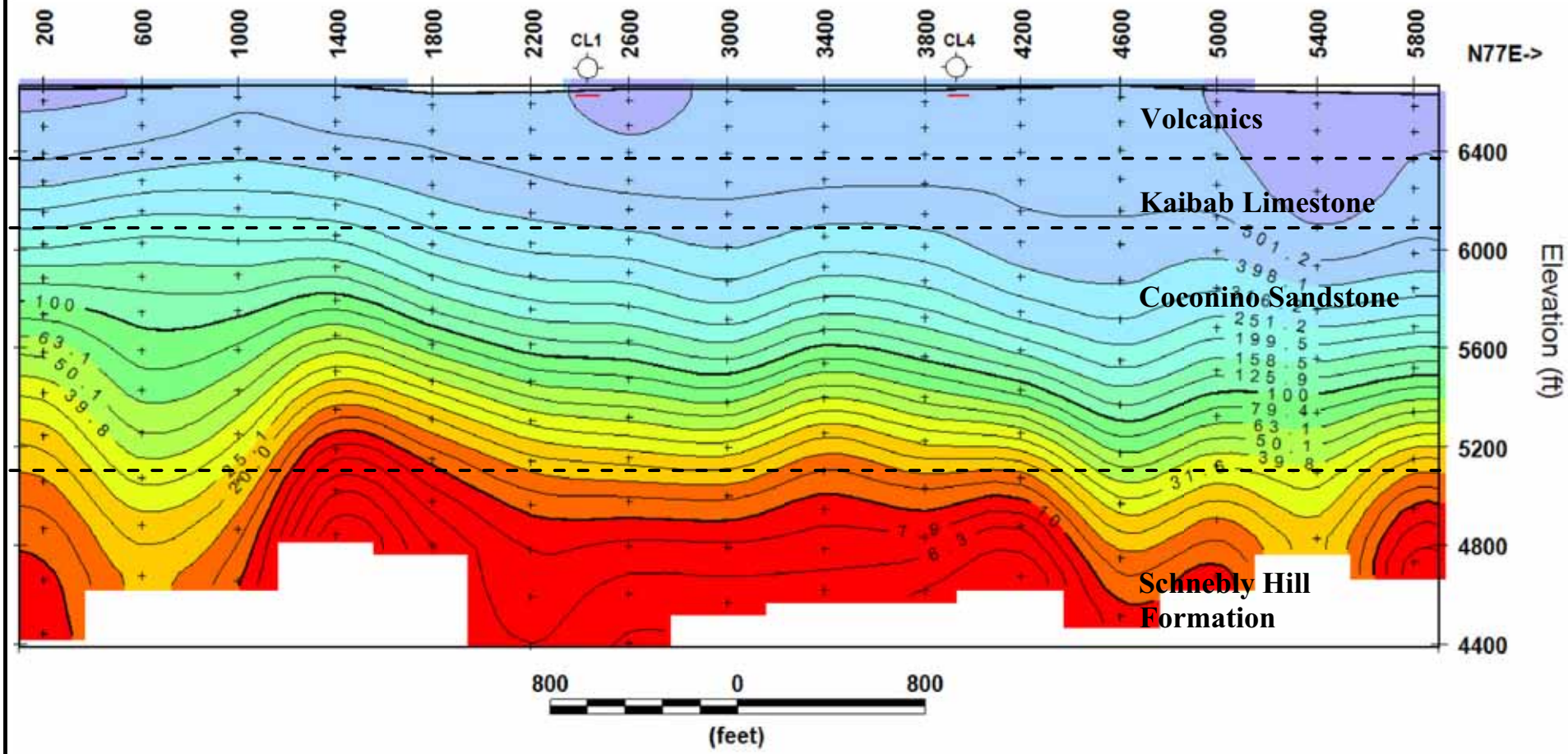

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Line 6 TEM 400X400

Figure 13

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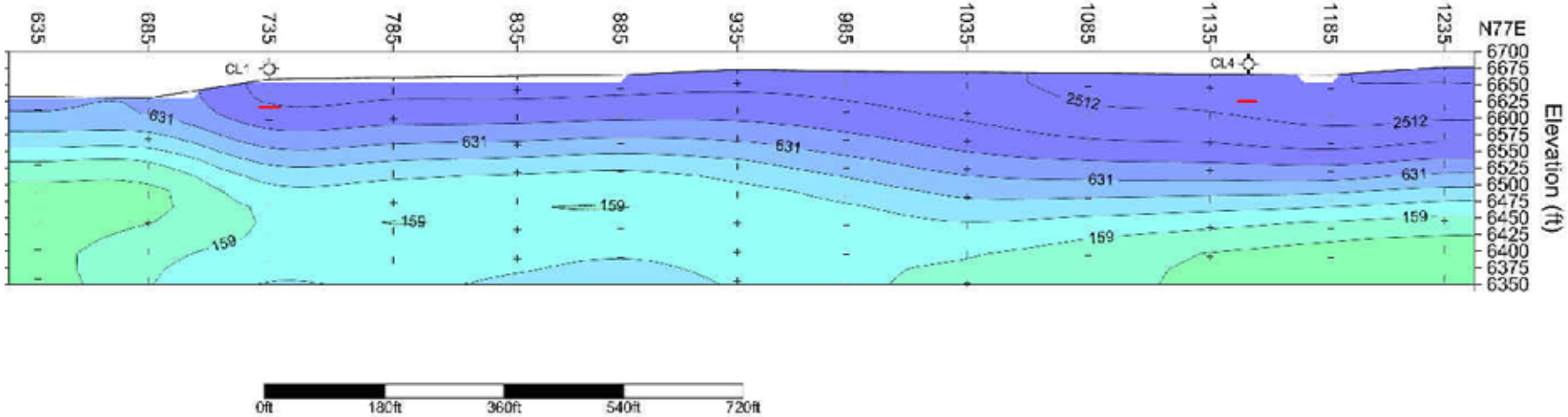

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Cinder Lake Landfill
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Figure 14

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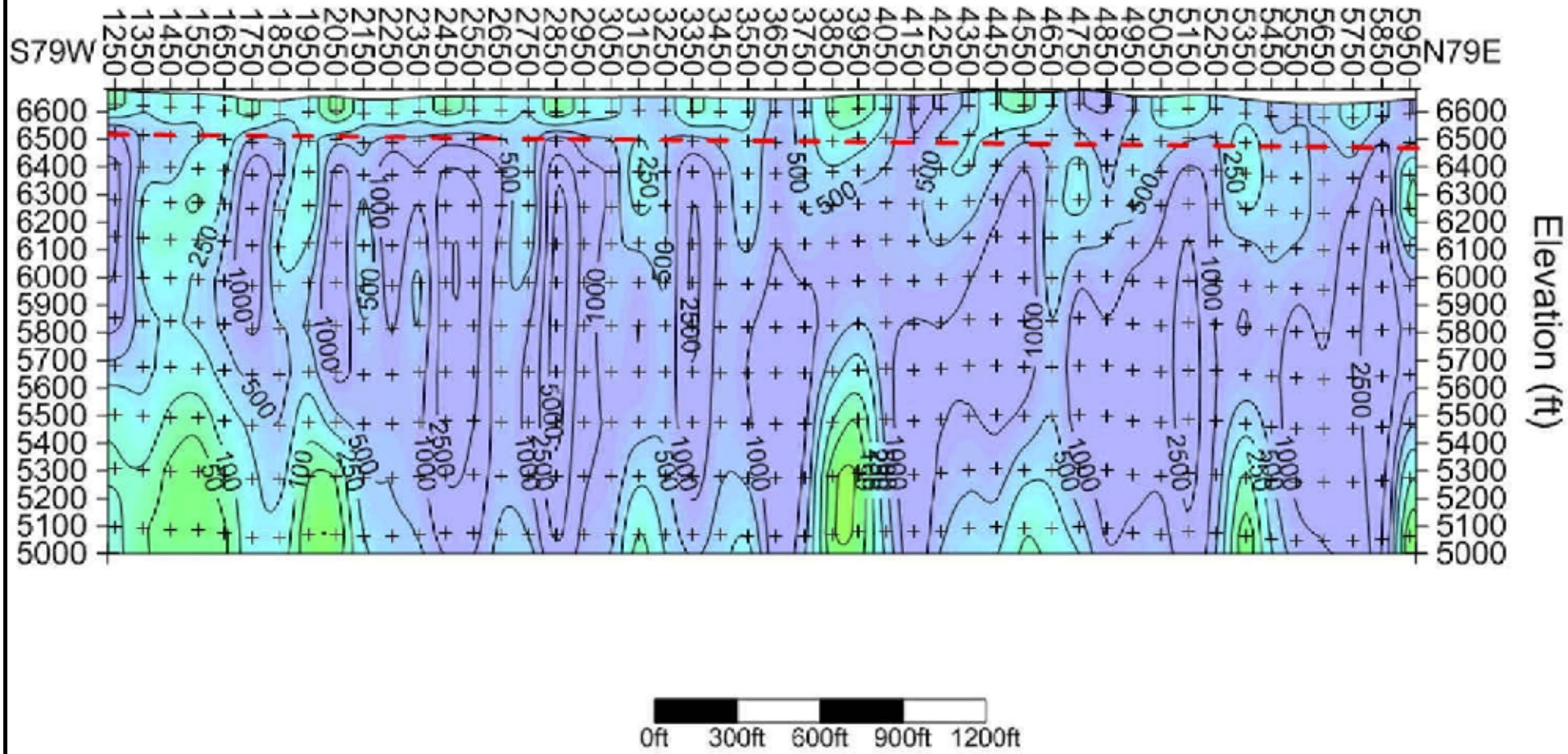

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Figure 15

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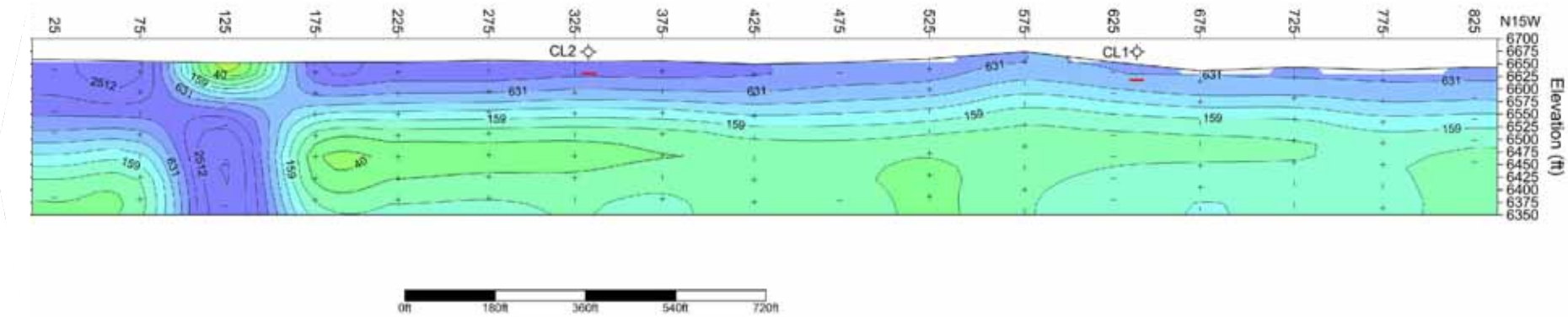

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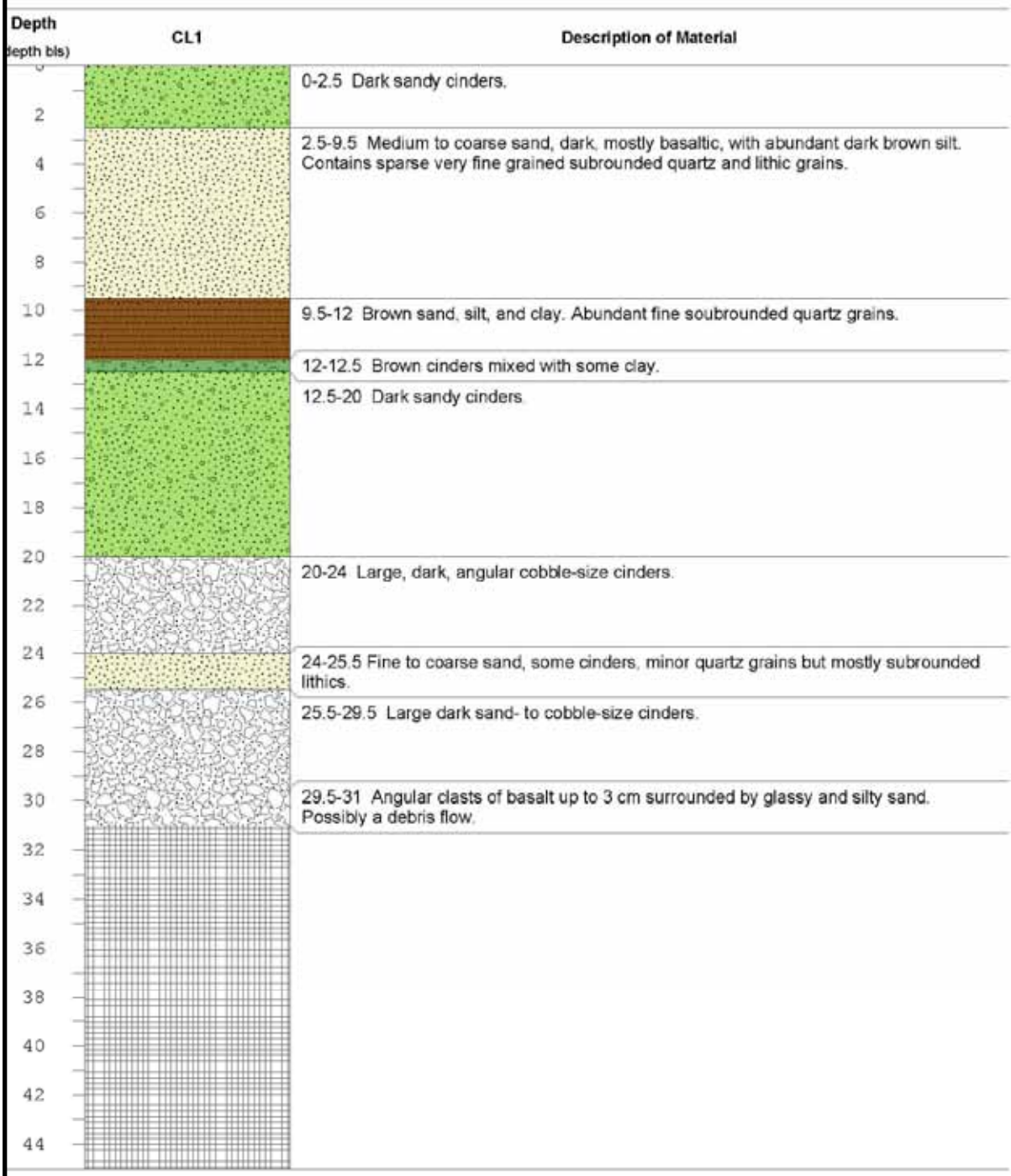

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Cinder Lake Landfill
Borehole CL-1

Figure 17

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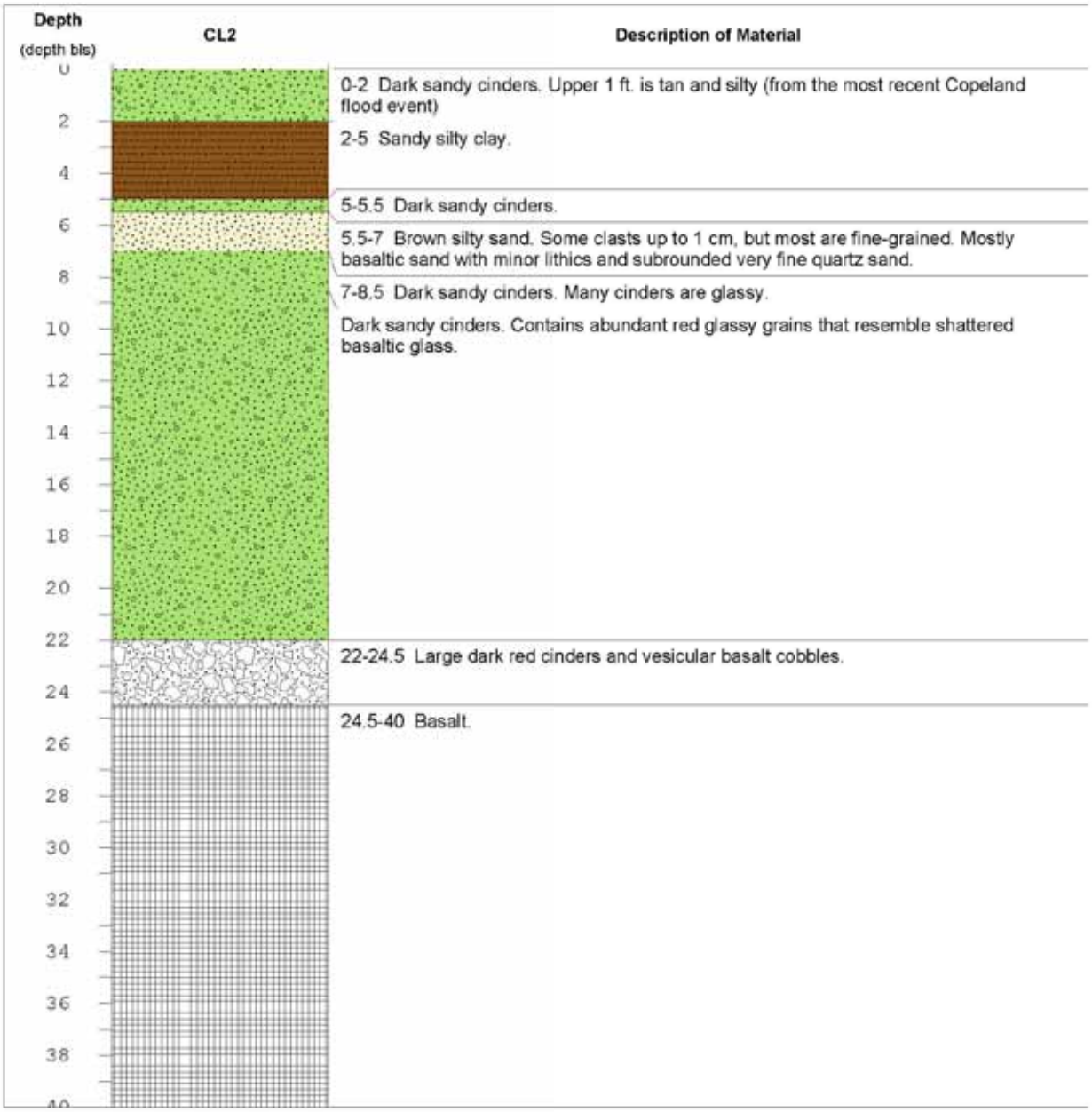

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Cinder Lake Landfill
Borehole CL-2

Figure 18

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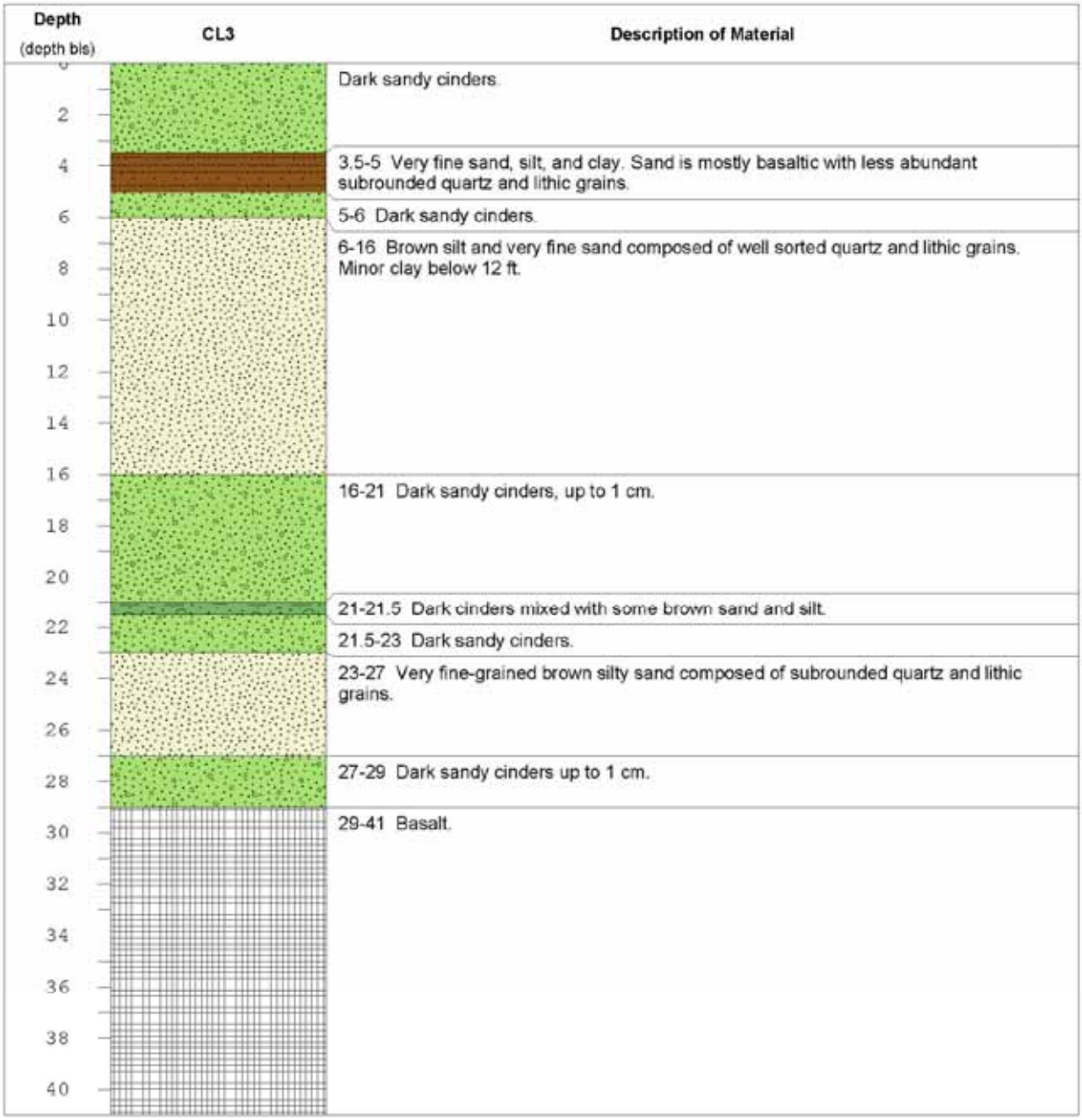

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-3

Figure 19

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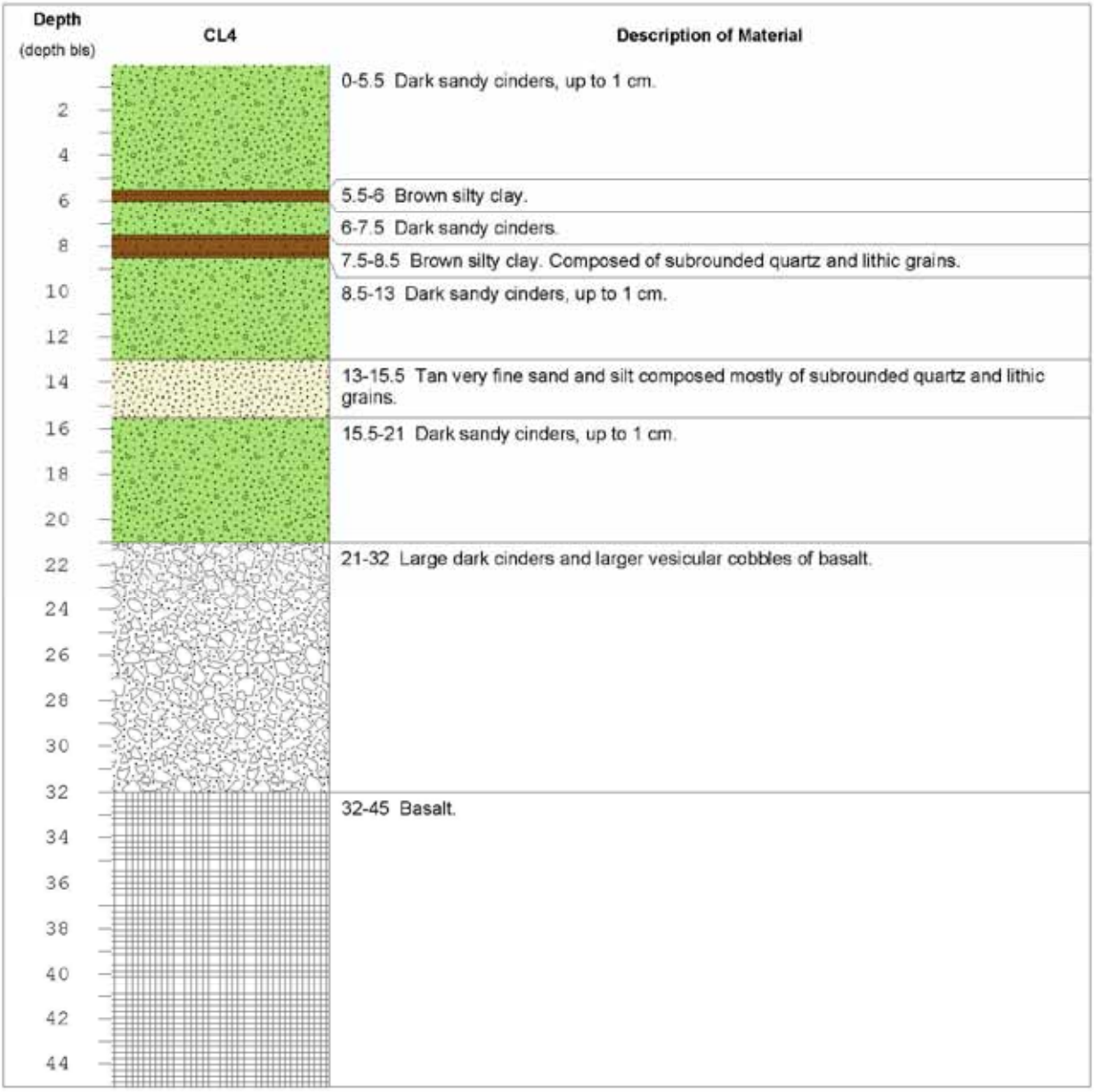

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-4

Figure 20

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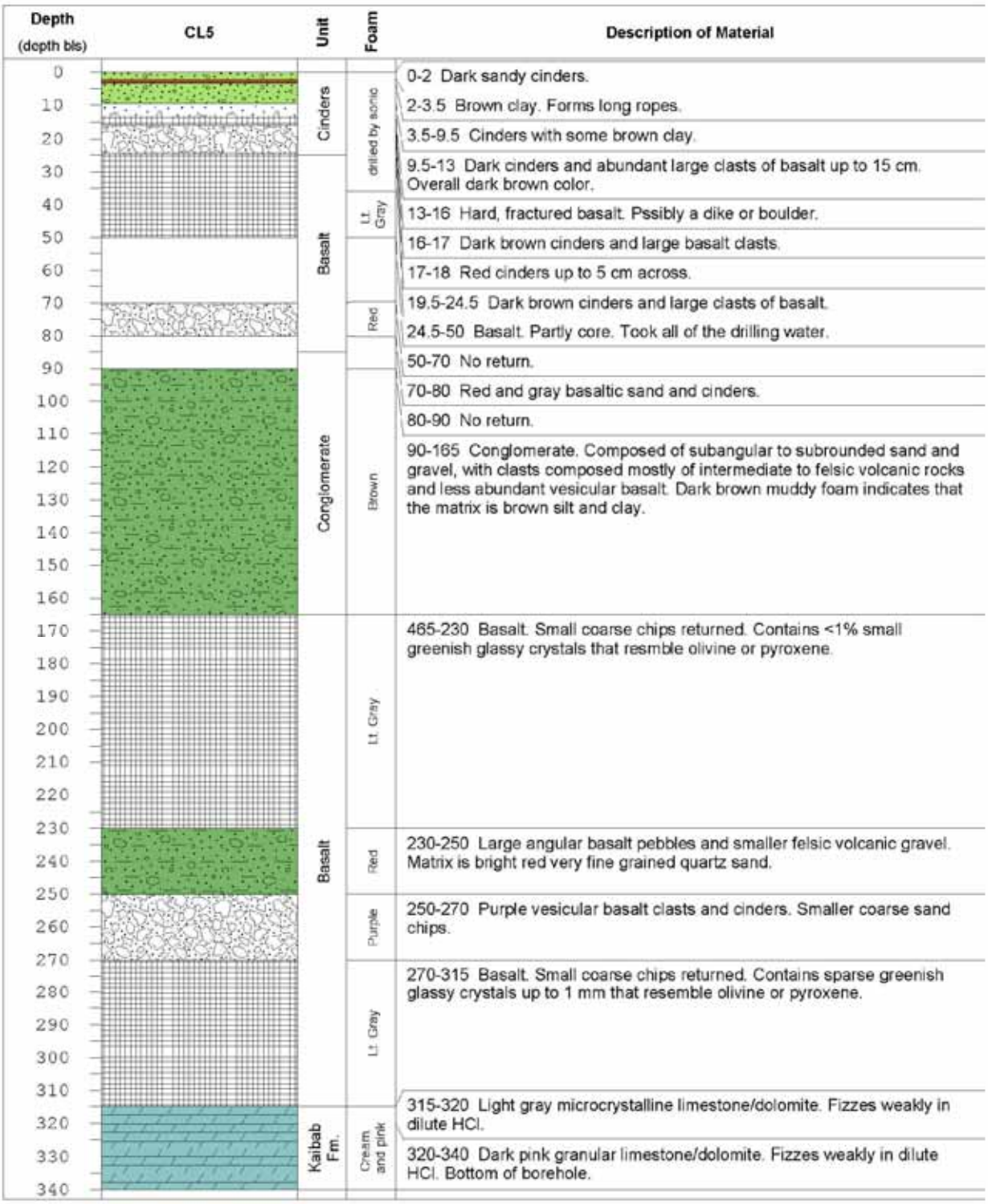

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-5

Figure 21

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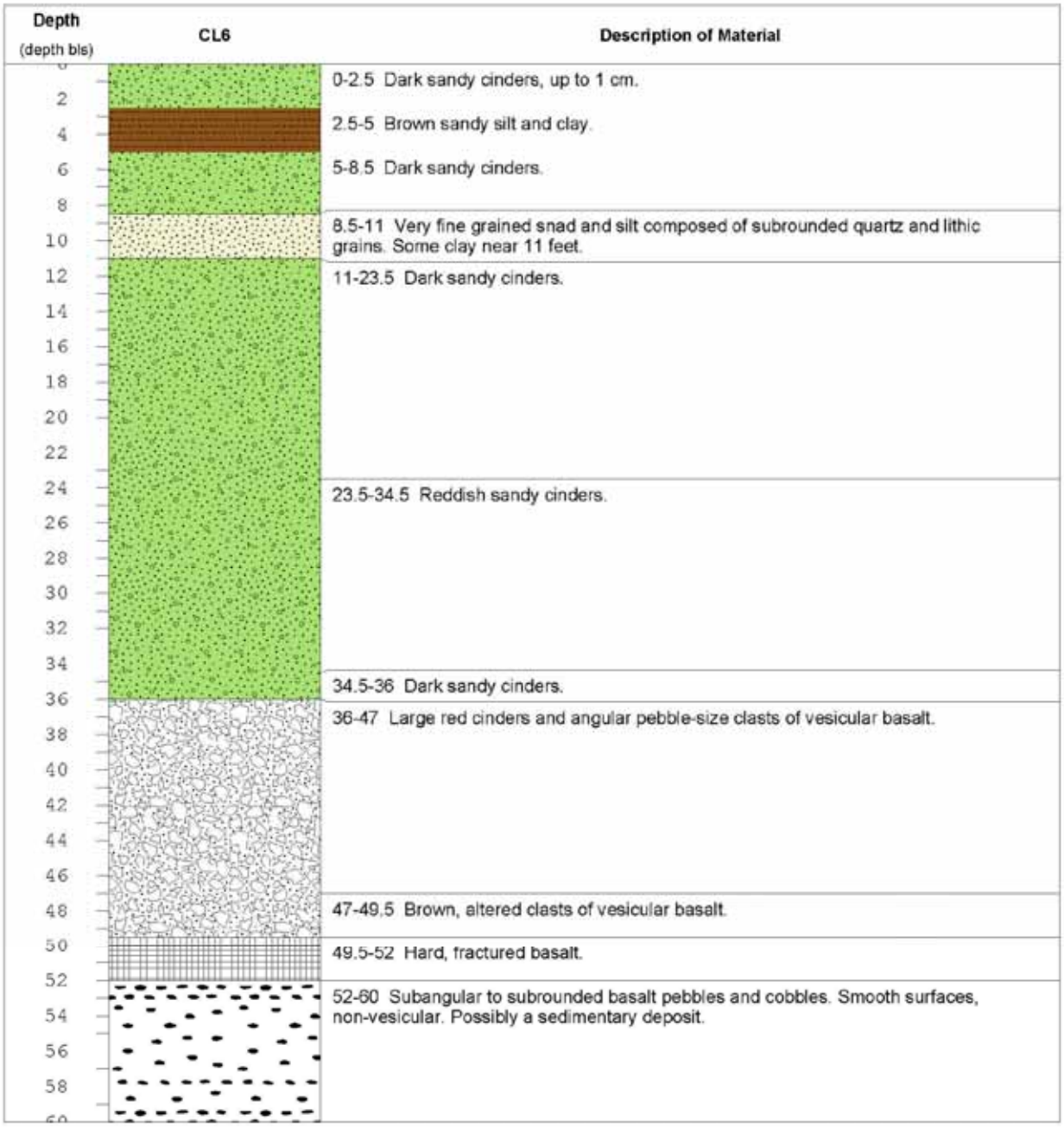

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-6

Figure 22

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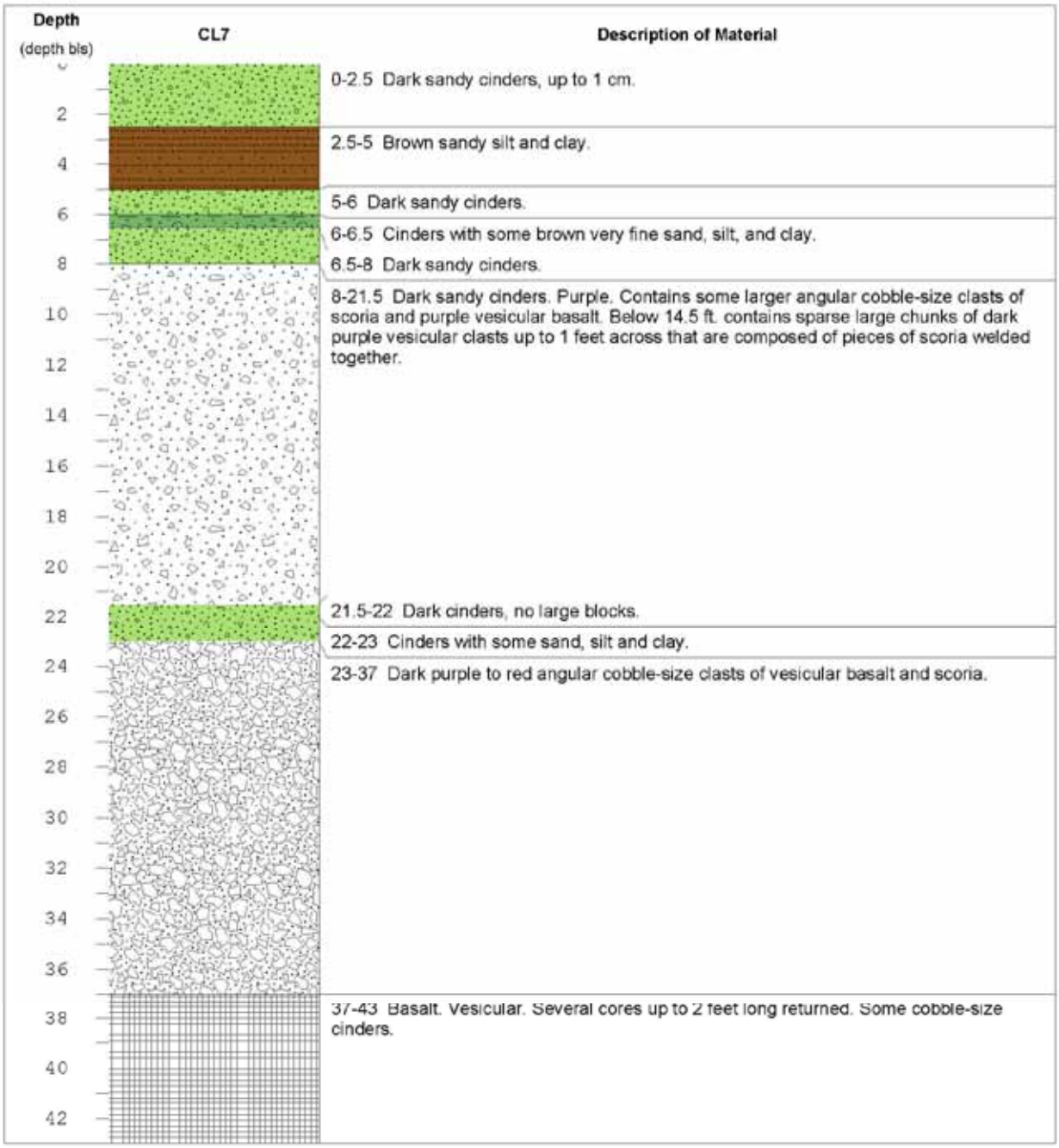

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-7

Figure 23

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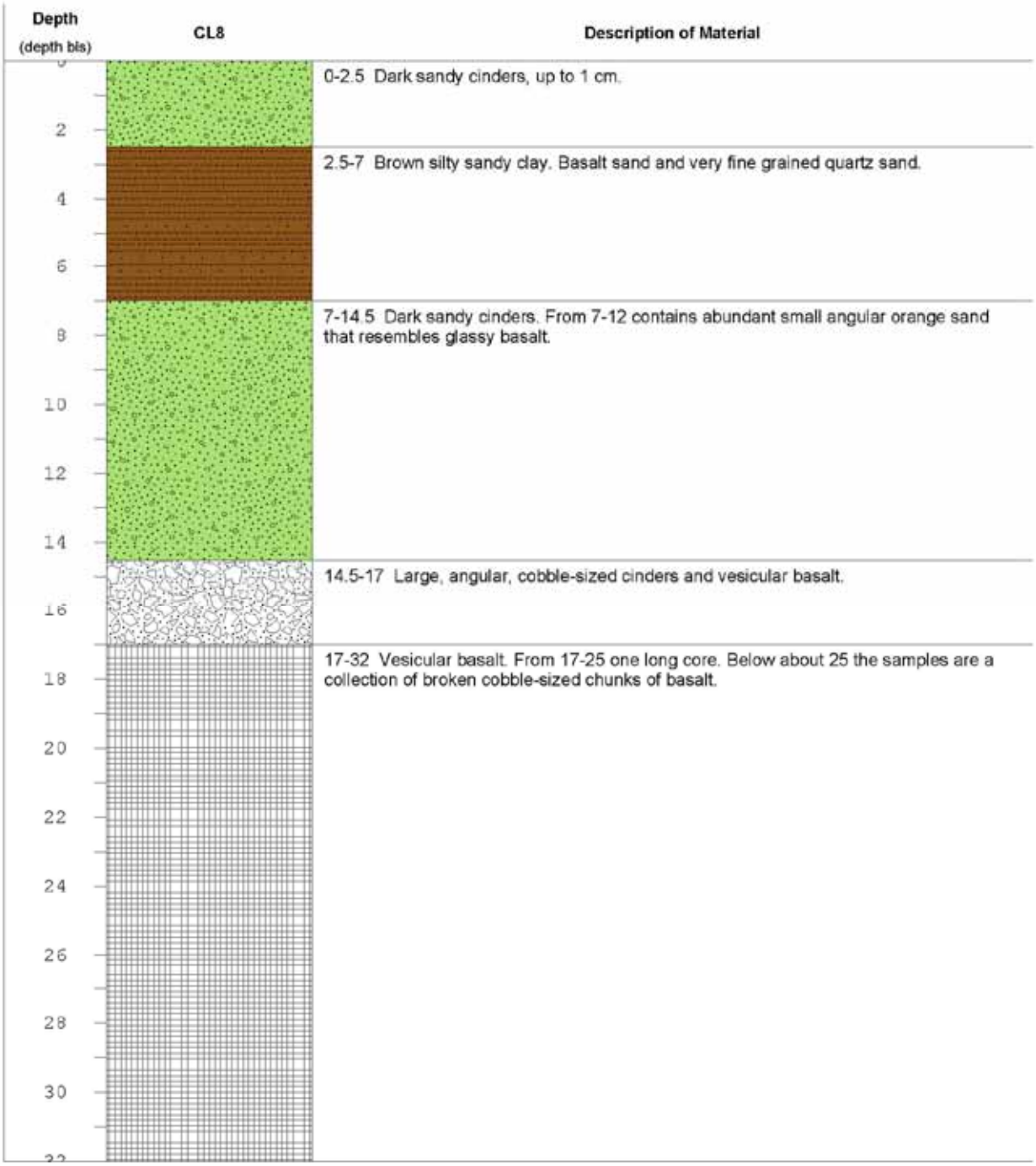

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-8

Figure 24

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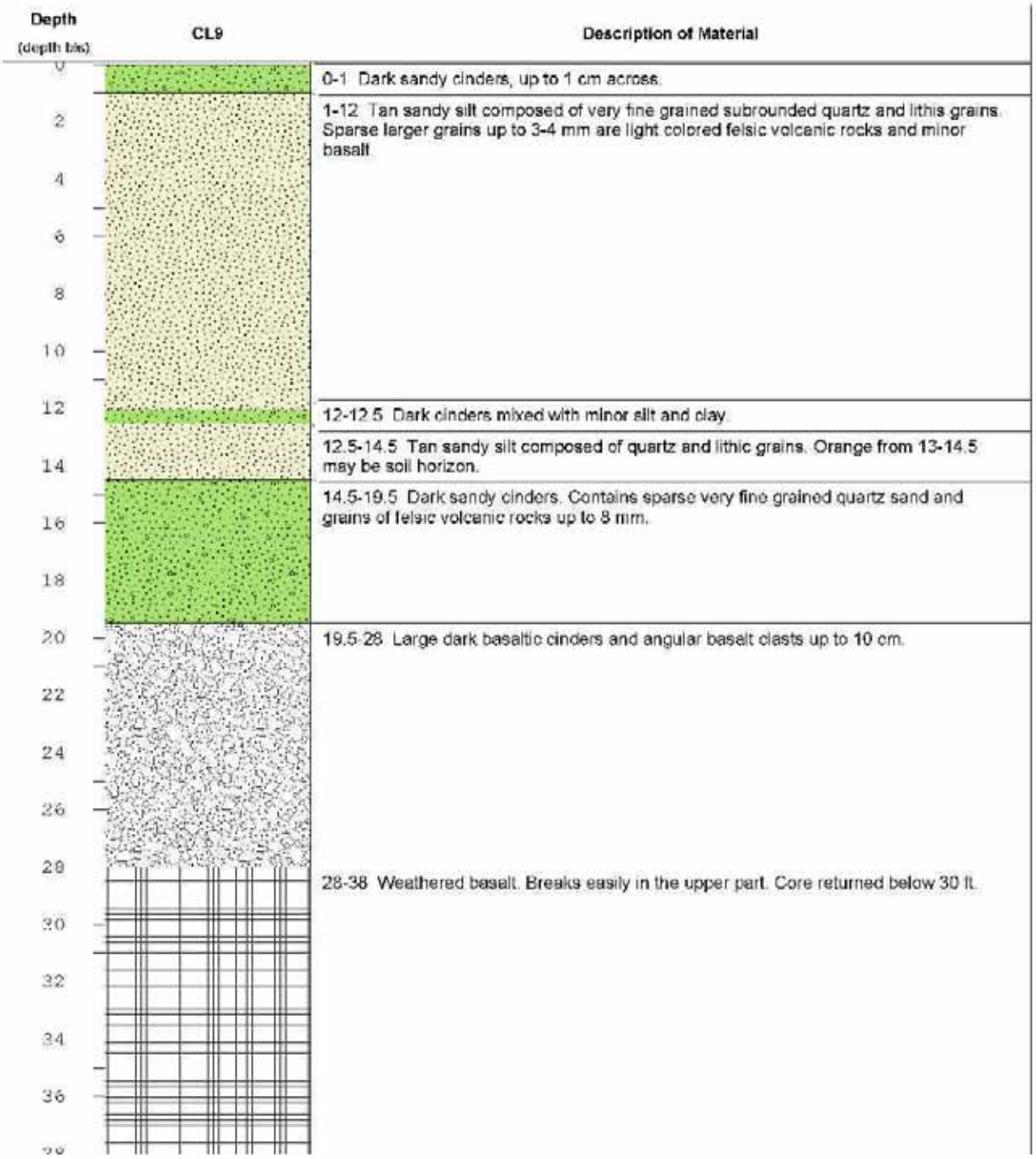

HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-9

Figure 25

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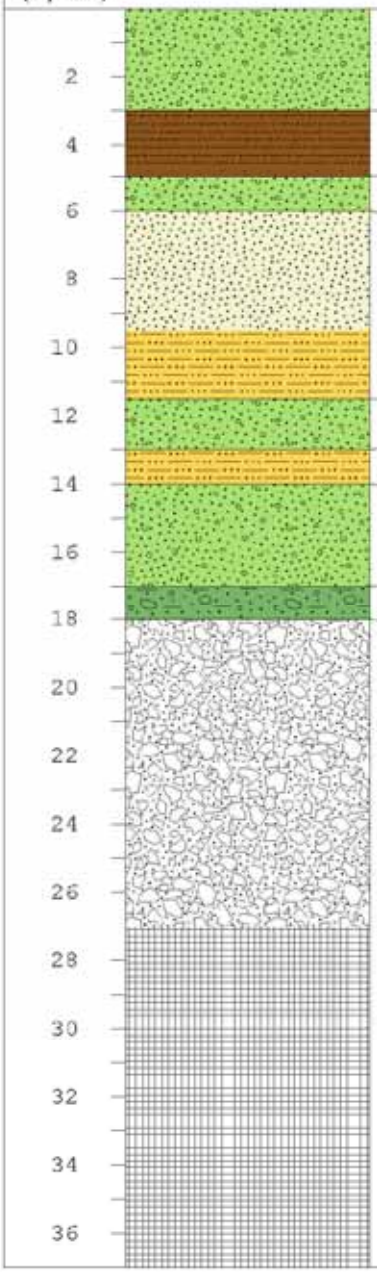

Description of Material

0-3 Dark sandy cinders. The uppermost 1/2 foot contains some tan silt.

3-5 Brown pasty clay, with sand and silt.

5-6 Dark sandy cinders, up to 1 cm.

6-9.5 Tan silt and very fine grained sand composed of subrounded quartz and lithic grains. Some coarse sand below 7 feet.

9.5-11.5 Brown sand, silt, and clay.

11.5-13 Dark sandy cinders.

13-14 Coarse brown sand with silt and clay.

14-17 Dark sandy cinders.

17-18 Cinders mixed with brown sand and silt.

18-27 Large dark red cinders up to 7 cm across from 18 to 23.5 ft. Below this the cinders are more purple in color and are up to 10 cm across.

27-37 Basalt.

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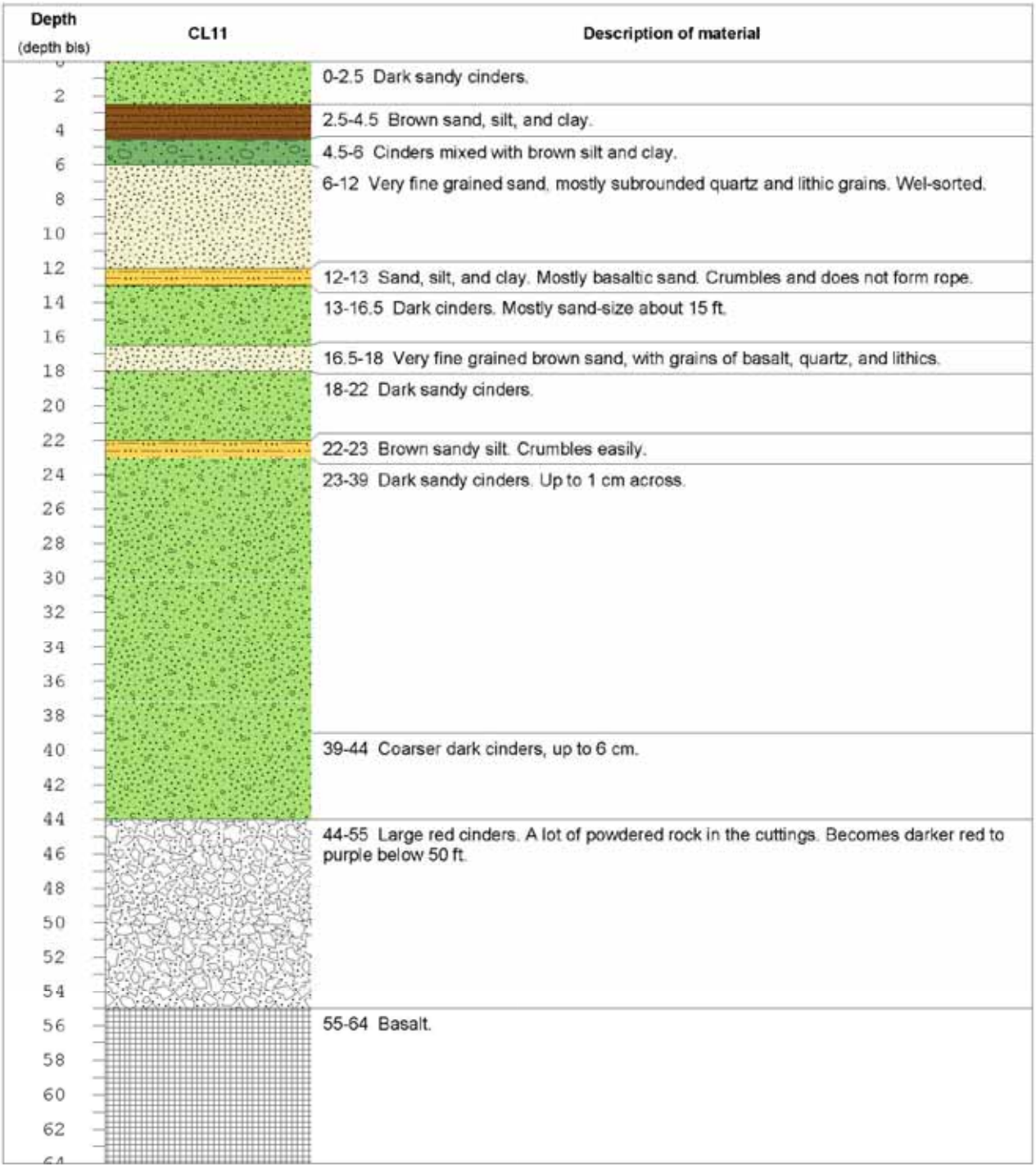
Cinder Lake Landfill
Borehole CL-10

Figure 26

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 26 Borehole CL-10.dwg, 6/15/2011 10:17:23 AM

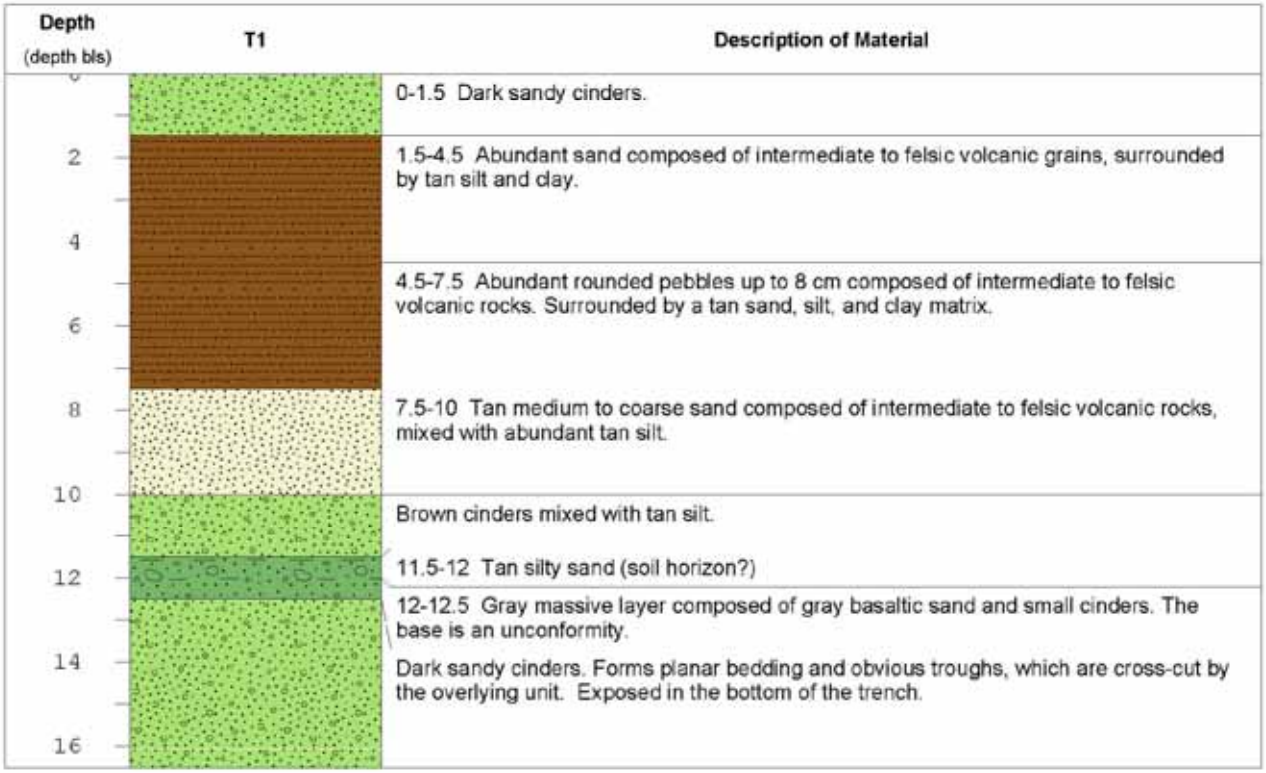


HydroSystems Inc.

Cinder Lake Landfill
Borehole CL-11

Figure 27

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 27 Borehole CL-11.dwg, 6/15/2011 10:16:57 AM

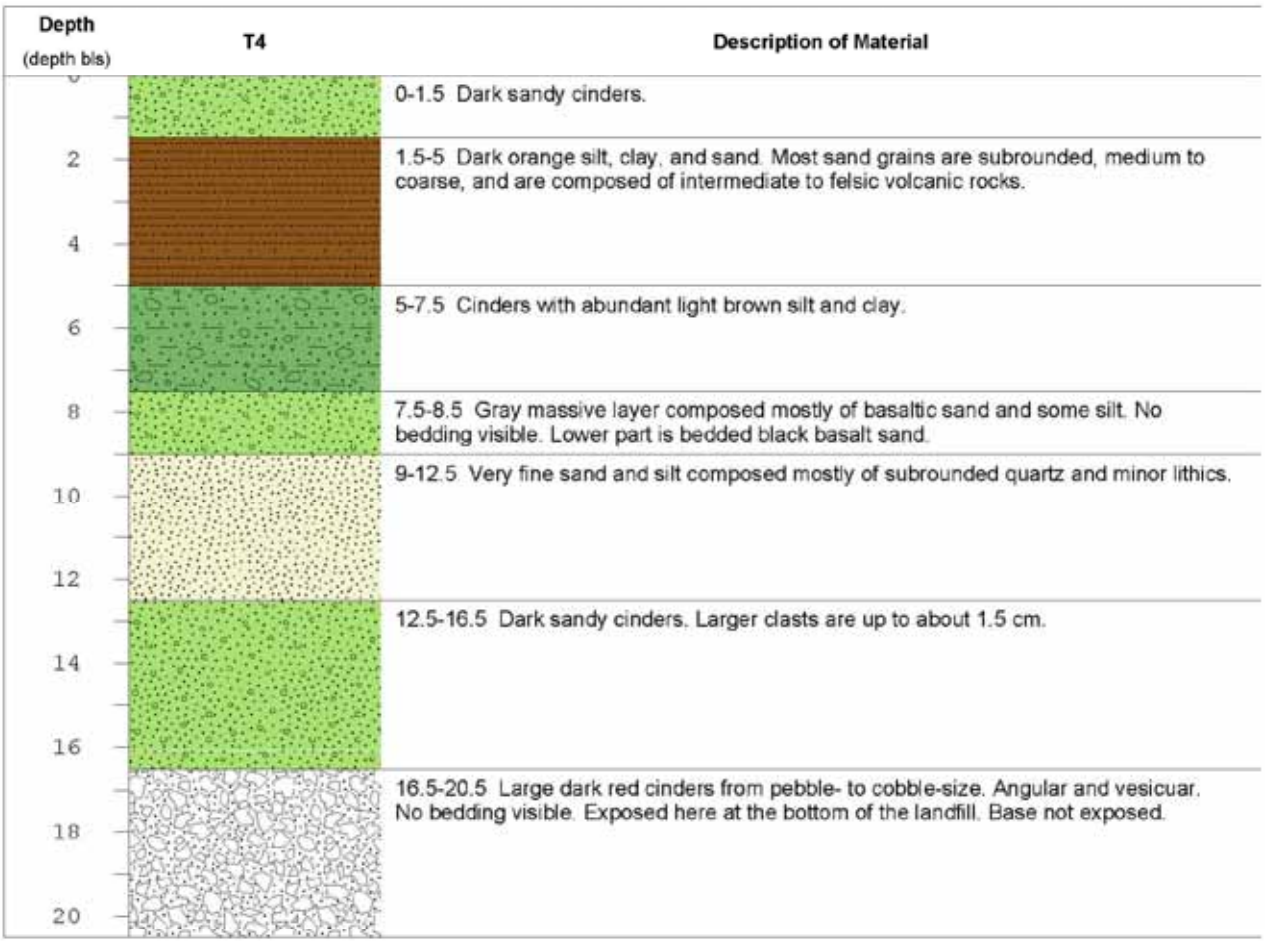


HydroSystems Inc.

Cinder Lake Landfill
Trench Exposure T1

Figure 28

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 28 Trench T-1.dwg, 6/15/2011 10:16:32 AM



HydroSystems Inc.

Cinder Lake Landfill
Pit Exposure T4

Figure 29

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 29 Trench T-4.dwg, 6/20/2011 6:35:28 AM

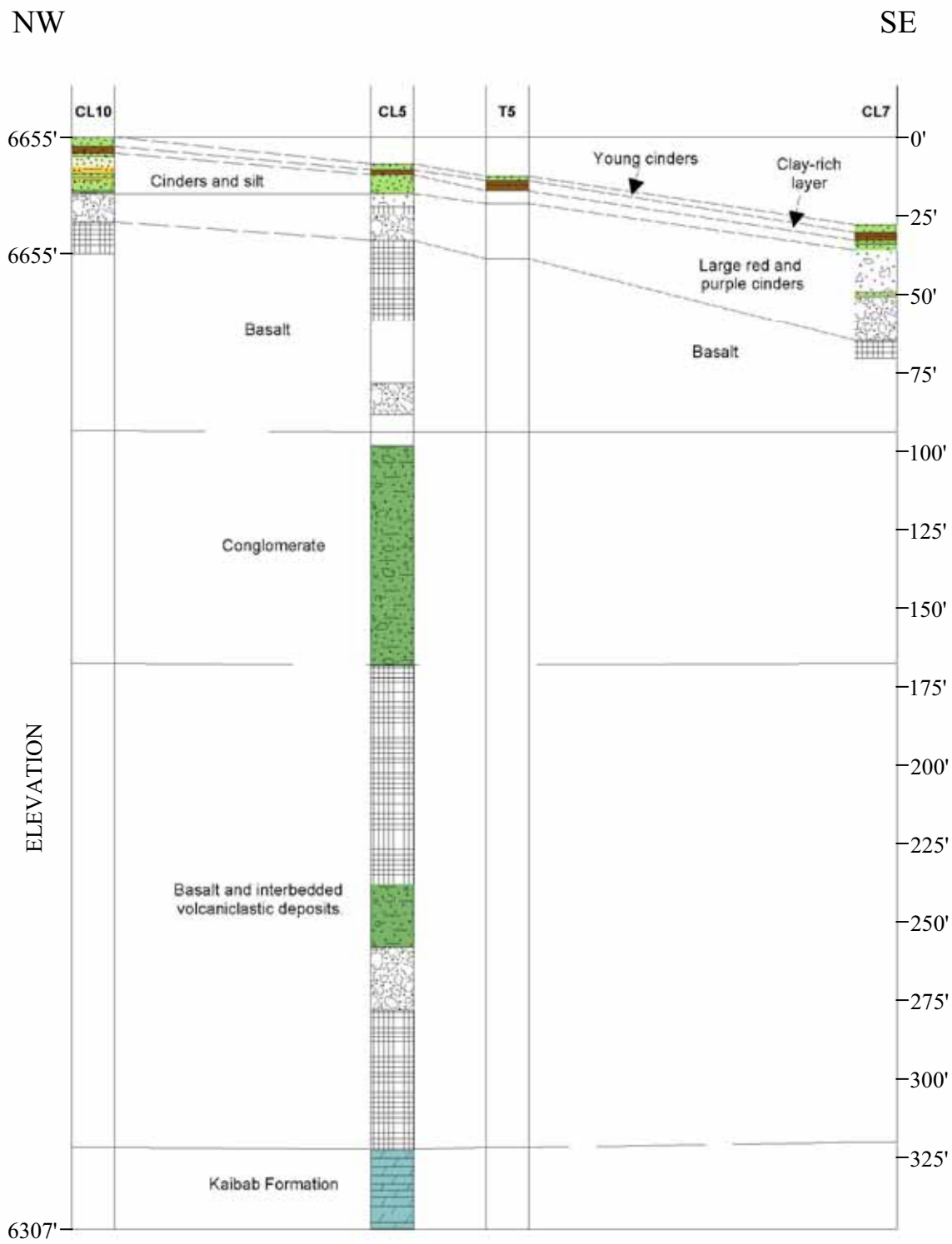
Depth (depth bls)	T5	Description of material
1		0-1.5 Dark sandy cinders. Shows horizontal bedding.
2 3 4		1.5-4.5 Tan sandy silt and clay. Exposed to the bottom of the backhoe trench.

HydroSystems Inc.

Cinder Lake Landfill
Backhoe Exposure T5

Figure 30

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 30 Backhoe T-5.dwg, 6/20/2011 6:34:53 AM

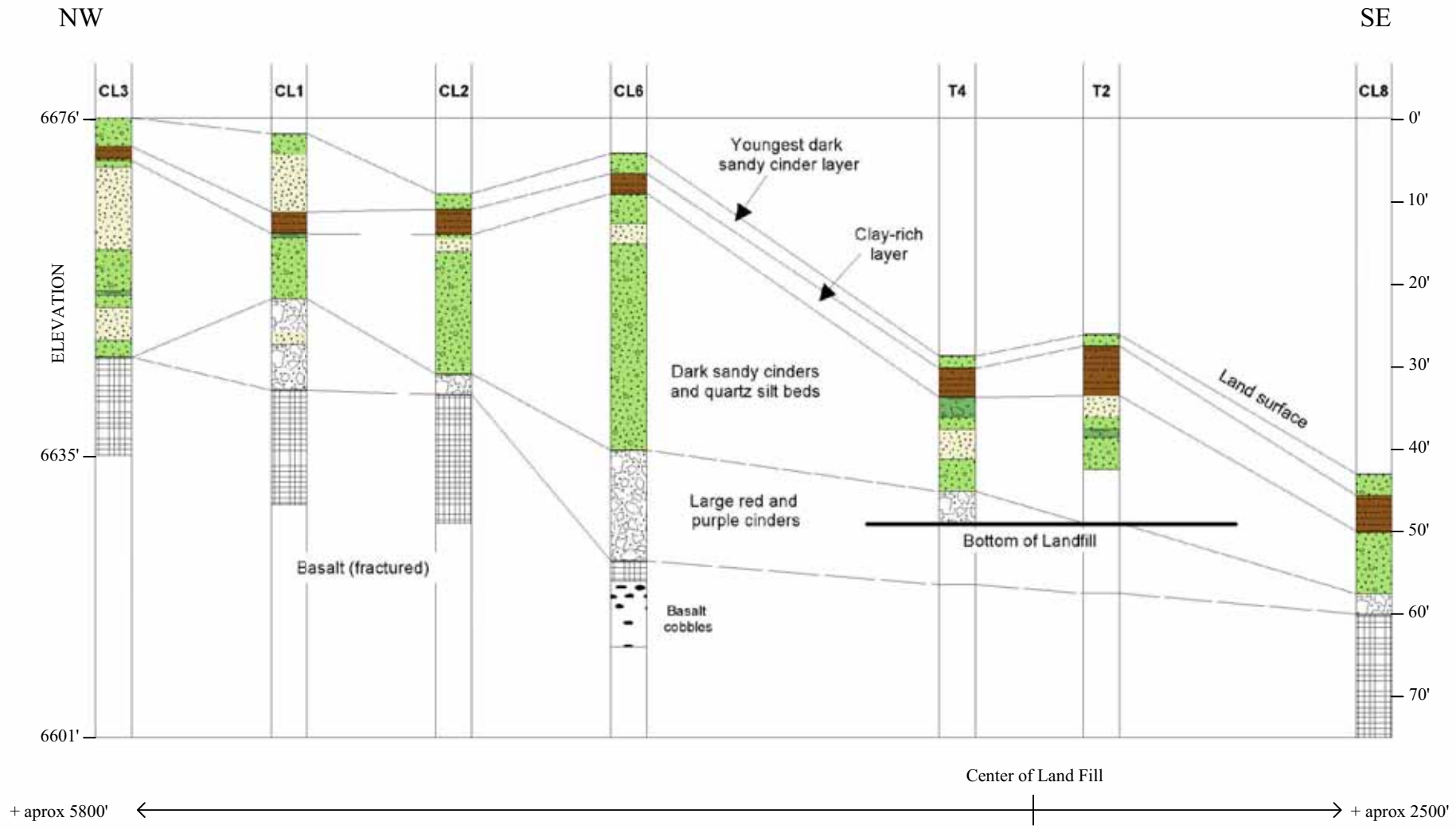


HydroSystems Inc.

Cinder Lake Landfill
Soil Boring Cross-section 1
Flagstaff, AZ

Figure 31

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 31 X-sxn1.dwg, 6/15/2011 10:15:17 AM

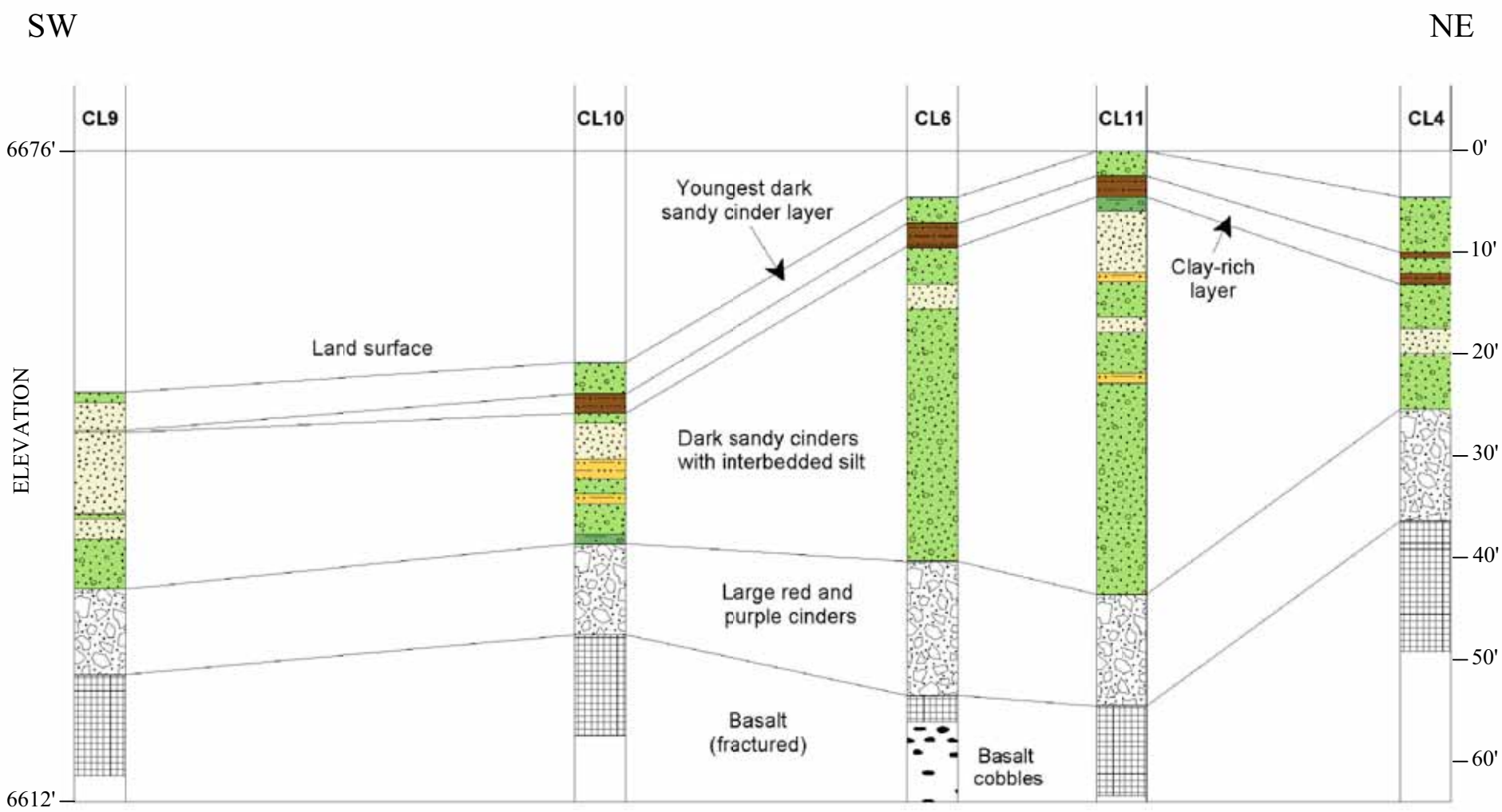


HydroSystems Inc.

Cinder Lake Landfill
Soil Boring Cross-section 2
Flagstaff, AZ

Figure 32

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 32 X-sxn2.dwg, 6/15/2011 10:14:47 AM



HydroSystems Inc.

Cinder Lake Landfill
Soil Boring Cross-section 3
Flagstaff, AZ

Figure 33

R:\11-623 SDB Cinder Lake Landfill\Design Concept Report\Figures Workspace\Fig 33 X-sxn3.dwg, 6/15/2011 10:14:07 AM

Table 1. Borehole Information at Cinder Lake

Name	Cadastral Location	Latitude NAD 83, Zone 12N			Longitude NAD 83, Zone 12N			UTMs NAD83, Zone 12N		Land Surface Elevation (ft)	Depth of Basalt (ft)
		D	M	S	D	M	S	UTM East	UTM North		
CL1	A-8-22-02BCD	35	19	19.0	111	31	16.2	452639	3908870	6671.1	31.0
CL2	A-8-22-02CBA	35	19	7.3	111	31	15.7	452640	3908512	6667.2	24.5
CL3	A-8-22-02BBD	35	19	31.6	111	31	16.2	452631	3909258	6676.0	29.0
CL4	A-8-22-03ACB	35	19	19.6	111	30	57.3	453107	3908888	6672.4	32.0
CL5	A-8-22-11BBC	35	18	33.3	111	31	28.6	452309	3907465	6647.6	24.5
CL6	A-8-22-02CDB	35	18	56.7	111	31	7.6	452844	3908183	6672.3	49.5
CL7	A-8-22-11CAD	35	18	11.9	111	31	4.2	452921	3906804	6627.6	37.0
CL8	A-8-22-11DBA	35	18	15.2	111	30	45.5	453395	3906902	6632.9	17.0
CL9	A-8-22-10ADB	35	18	27.9	111	31	46.6	451855	3907300	2028.2	28.0
CL10	A-8-22-02CCC	35	18	52.7	111	31	28.9	452304	3908062	2029.1	27.0
CL11	A-8-22-02CAD	35	19	3.8	111	31	1.1	453008	3908400	2035.5	55.0

BOART LONGYEAR
Well Construction Report

Job Name FLAGSTAFF USGS
Job Number 3416-
Location FLAGSTAFF, AZ Cinder Lake

Well Name CL-1
Driller TRAVIS Osterberg
Helper LEWIS Fisher
Date Installed 6-4-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground 2.0 ft.

B. Diameter of Well Casing 4 in.

C. Surface Seal Bottom 20 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top 20 ft.

F. Fine Sand Top NA ft.

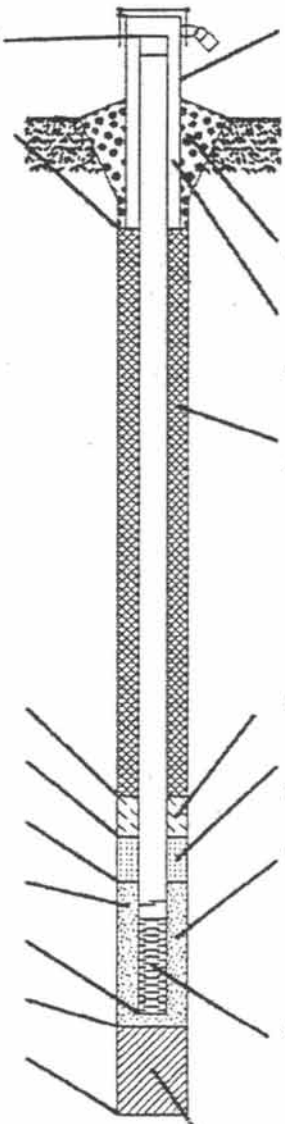
G. Filter Pack Top 28 ft.

H. Screen Joint Top 30 ft.

I. Well Bottom 40 ft.

J. Filter Pack Bottom 46 ft.

K. Borehole Bottom 46 ft.



1. Locking Cap? X Yes ___ No

2. Protective Cover:
- a. Inside diam. 12" in.
- b. Length 12" ft.
- c. Material
  - X Steel
  - ___ Other ___
- d. Bumper Post ___ qty ___ 3" ___ 4"

3. Surface Seal:
- ___ Bentonite
- X Concrete
- ___ Other ___

4. Material between Casing and Protop:
- ___ Bentonite
- X Other concrete

5. Annular Space Seal:
- ___ Granular Bentonite
- ___ Bentonite Slurry
- ___ Cement-Bentonite Grout
- X Other Concrete

How Installed:
- X Gravity
- ___ Tremie Pumped

6. Bentonite Seal:
- ___ Granules
- X Pellets Chips 3/8

7. Type of Fine Sand: NA

8. Type of Filter Pack: 10/20 SAND

9. Screen Material: Prepack
- Type: X Factory Cut ___ Continuous Slot
- Slot Size: .020 in. 4"x6"
- Length: 10 ft.

10. Backfill Material: (Below filter pack)
- X None
- ___ Other ___

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

Screen is Prepack
4" inner
6" outer

BOART LONGYEAR
Well Construction Report

Job Name: USGS
Job Number: 3416-
Location: Flagstaff, AZ Cinder Lake

Well Name: CL-2
Driller: Travis Osterberg
Helper: Lewis Fisher
Date Installed: 6-5-11

Type of Well:
- [x] Water Table Observation
- [ ] Piezometer
- [ ] Other _____

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4 in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- [x] Schedule 40
- [ ] Schedule 80
- [ ] Other _____

E. Bentonite Seal Top: 20 ft.

F. Fine Sand Top: NA ft.

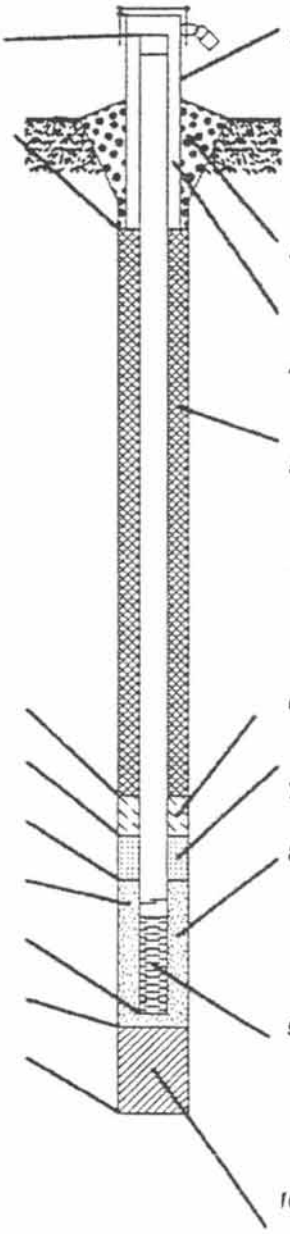
G. Filter Pack Top: 22 ft.

H. Screen Joint Top: 24 ft.

I. Well Bottom: 34 ft.

J. Filter Pack Bottom: 40 ft.

K. Borehole Bottom: 40 ft.



1. Locking Cap? [x] Yes [ ] No
2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - [x] Steel
      - [ ] Other _____
   d. Bumper Post ____ qty
      ___ 3" ___ 4"
3. Surface Seal:
   - [ ] Bentonite
   - [x] Concrete
   - [ ] Other _____
4. Material between Casing and Protop:
   - [ ] Bentonite
   - [x] Other Concrete
5. Annular Space Seal:
   - [ ] Granular Bentonite
   - [ ] Bentonite Slurry
   - [ ] Cement-Bentonite Grout
   - [x] Other Concrete

   How Installed:
   - [x] Gravity
   - [ ] Tremie Pumped
6. Bentonite Seal:
   - [ ] Granules
   - [x] Pellets / Chips
7. Type of Fine Sand: NA
8. Type of Filter Pack: 10/20 Sand
9. Screen Material:
   Type:
   - [x] Factory Cut Prepack
   - [ ] Continuous Slot 4" x 6"

   Slot Size: .020 in.
   Length: 10 ft.
10. Backfill Material: (Below filter pack)
   - [x] None
   - [ ] Other _____

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name USGS
Job Number 3416-
Location Flagstaff, AZ Cinder Lake

Well Name CL-3
Driller ~~Dan~~ TRAVIS OSTENBERG
Helper Lewis Fisher
Date Installed 6-5-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground -.6 ft.

B. Diameter of Well Casing 4 in.

C. Surface Seal Bottom 20' ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top 20 ft.

F. Fine Sand Top NA ft.

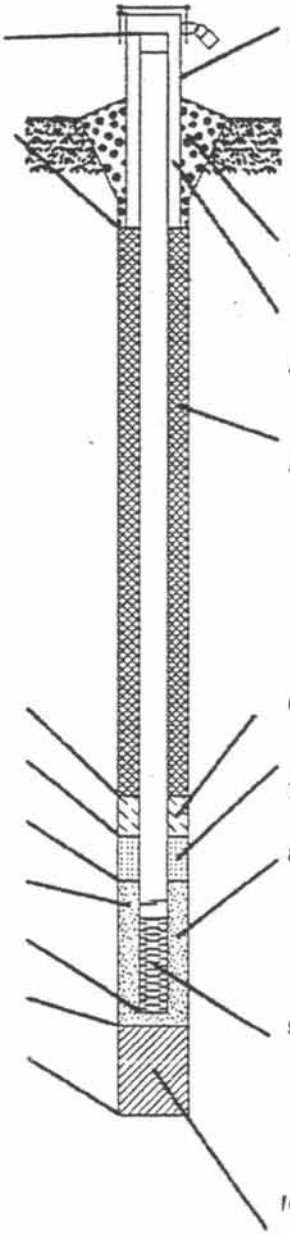
G. Filter Pack Top 25 ft.

H. Screen Joint Top 27 ft.

I. Well Bottom 37 ft.

J. Filter Pack Bottom 41 ft.

K. Borehole Bottom 41 ft.



1. Locking Cap? X Yes ___ No
2. Protective Cover: a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
   - X Steel
   - ___ Other ___
   d. Bumper Post ___ qty ___ 3" ___ 4"
3. Surface Seal: ___ Bentonite
   - X Concrete
   - ___ Other ___
4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other Concrete
5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped
6. Bentonite Seal:
   - ___ Granules
   - X Pellets / chips
7. Type of Fine Sand: NA
8. Type of Filter Pack: 10/20 Sand
9. Screen Material:
   Type: X Factory Cut
   - ___ Continuous Slot

   Slot Size: .020 in. Prepack
   Length: 10 ft. 4" x 6"
10. Backfill Material: (Below filter pack)
   - X None
   - ___ Other ___

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name: CL-4 USGS /
Job Number: 102053 3416-
Location: Flagstaff, AZ Cinder Lake

Well Name: CL-4
Driller: Travis Osterberg
Helper: Lewis Fisher
Date Installed: 6-6-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4" in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top: 20 ft.

F. Fine Sand Top: NA ft.

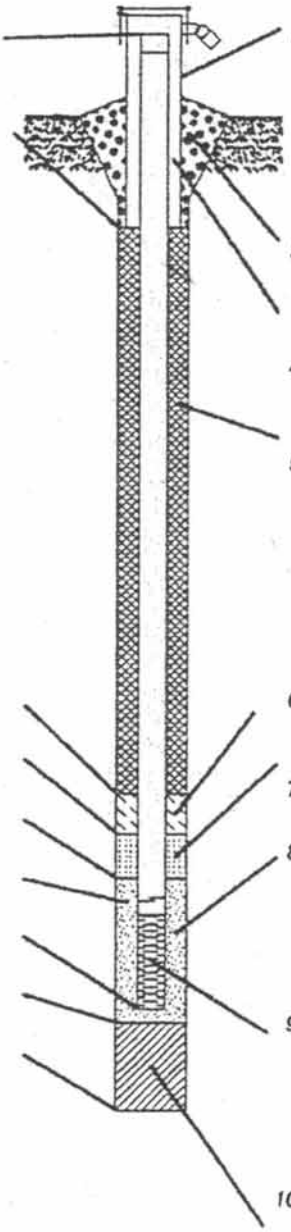
G. Filter Pack Top: 28 ft.

H. Screen Joint Top: 30 ft.

I. Well Bottom: 40 ft.

J. Filter Pack Bottom: 45 ft.

K. Borehole Bottom: 45 ft.



1. Locking Cap? X Yes ___ No

2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - X Steel
      - ___ Other ___
   d. Bumper Post ___ qty
      ___ 3" ___ 4"

3. Surface Seal:
   - ___ Bentonite
   - X Concrete
   - ___ Other ___

4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other Concrete

5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped

6. Bentonite Seal:
   - ___ Granules
   - X Pellets / chips

7. Type of Fine Sand: NA

8. Type of Filter Pack: 10/20 Sand

9. Screen Material:
   Type: X Factory Cut
   ___ Continuous Slot
   Slot Size: .020 in.
   Length: 10 ft

10. Backfill Material: (Below filter pack)
   - X None
   - ___ Other ___

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name: City of Flag
Job Number: 102053 ~~3416~~
Location: Flagstaff, AZ

Well Name: CL-5
Driller: Travis Ostenberg
Helper: Lewis Fisher
Date Installed: 6-13-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4" in.

C. Surface Seal Bottom: 17 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top: 17 ft.

F. Fine Sand Top: NA ft.

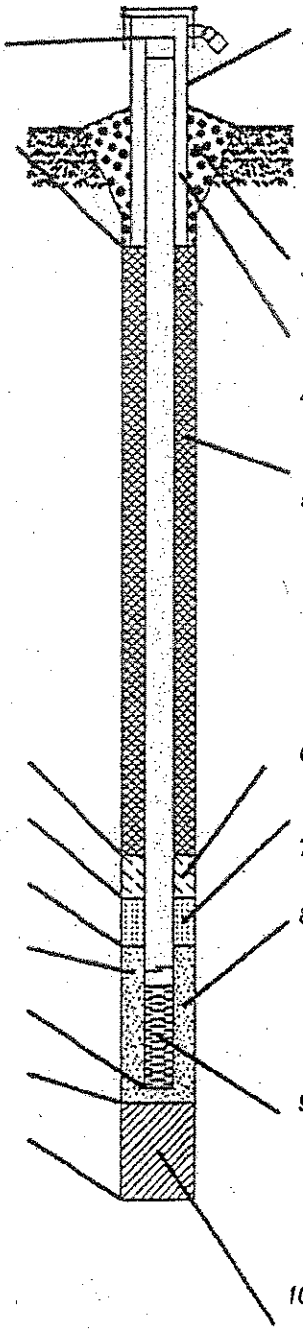
G. Filter Pack Top: 19 ft.

H. Screen Joint Top: 20 ft.

I. Well Bottom: 30 ft.

J. Filter Pack Bottom: 31 ft.

K. Borehole Bottom: 340 ft.



1. Locking Cap? X Yes ___ No
2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - X Steel
      - ___ Other ___
   d. Bumper Post ___ qty ___ 3" ___ 4"
3. Surface Seal:
   - ___ Bentonite
   - X Concrete
   - ___ Other ___
4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other concrete
5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped
6. Bentonite Seal:
   - ___ Granules
   - X Pellets/Chips
7. Type of Fine Sand: NA
8. Type of Filter Pack: 10/20 SAND
9. Screen Material:
   - Type: X Factory Cut; ___ Continuous Slot
   - Slot Size: .020 in.
   - Length: 10 ft.
10. Backfill Material: (Below filter pack)
    - ___ None
    - X Other Grout Portlan/Bent

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

"DAILY DRILL REPORT"

BOART LONGYEAR
Environmental Drilling

EQUIPMENT ON SITE (CCD #1)

Drill Sonic / 1507 / 1508
TYPE DRILL NO. TRUCK NO.

Pick-Up Trucks 2362

Water/Service Trucks 1986

Other Equipment

Contract: City of Flagstaff # 102053 Date: 6 - 13 - 20 11
MONTH DAY

Location: Flagstaff, AZ Supervisor Signature

				Footage Summary			Casing Summary	
Shift	Hole No.	Angle	Bit Size	Drilling From	Drilling To	Total Footage	Casing From	Casing To
A								
B								
C								

HOURLY DISTRIBUTION	A HOURS	A EVENT	B HOURS	B EVENT	C HOURS	C EVENT
Drilling						
Well Construction	4.5					
Vaults	1	1				
Hydro Punches						
Split Spoon						
Development						
Cementing						
Moving - Hole to Hole						
Rigging up - Rigging down						
Re-entry						
Hole Abandonment						
Decontamination						
Mobilization/Demobilization	3					
Delays - Client Acct.						
Stand By						
Pre-shift Safety Mtg.						
Crane Inspection	.25					
Pre-Shift Inspection	.25					
Travel	1					
Other (Explain)						
Take Air Compressor Back	1					
TOTAL HOURS/EVENTS	11					
Initials	T.O.					

SUPPLIES CONSUMED DESCRIPTION	SIZE	WEIGHT	QUANTITY A	QUANTITY B	QUANTITY C
PVC Riser	4"	Sch40	20'		
PVC Screen .020	4"	Sch40	10'		
Bottom Cap	4"	Sch40	1		
Compression Cap	4"	Sch40	1		
Sand	10/20	50lbs	9		
Hole Plug	3/8	50lbs	20		
Cement		94lbs	49		
Vaults	12"		1		
Sacrete		60lbs	20		
Barrels					
Volclay Grout					
~~Granular~~ Bentonite Gel		50lbs	8		
Core Boxes					
Other					

For Diem

Shift	Driller	Hours	Drilling Assistant	Hours	Drilling Assistant	Hours
A	Travis Osterberg	11	Lewis Fisher	11	Dave Lund	
B					Roger Rodriguez	
C						

Remarks: (Note any problems from pre-shift inspections here.) Abandoned hole from 340' to 30' & set the well @ 30' build vault, clean site (all the cuttings) load up take air compressor back to CAT Hen Demobe to Phoenix

Client Signature: Date:

BOART LONGYEAR
Well Construction Report

Job Name: City of Flag / USGS
Job Number: 102053 ~~9410~~
Location: Flagstaff AZ

Well Name: CL-7
Driller: Travis Ostenberg
Helper: Lewis Fisher / Dave Iund
Date Installed: 6-8-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4 in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top: 20 ft.

F. Fine Sand Top: NA ft.

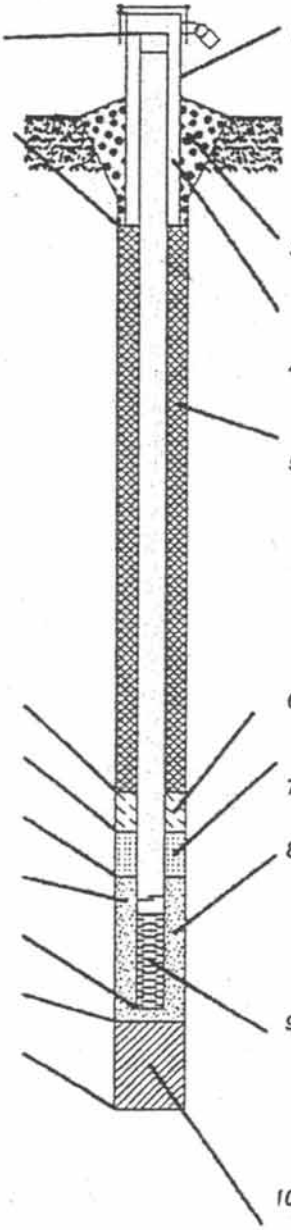
G. Filter Pack Top: 30 ft.

H. Screen Joint Top: 32 ft.

I. Well Bottom: 42 ft.

J. Filter Pack Bottom: 45.5 ft.

K. Borehole Bottom: 45.5 ft.



1. Locking Cap? X Yes ___ No
2. Protective Cover: a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
   - ___ Steel
   - ___ Other ___
   d. Bumper Post ___ qty ___ 3" ___ 4"
3. Surface Seal:
   - ___ Bentonite
   - X Concrete
   - ___ Other ___
4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other Concrete
5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped
6. Bentonite Seal:
   - ___ Granules
   - X Pellets / Chips
7. Type of Fine Sand: NA
8. Type of Filter Pack: 10/20 SAND
9. Screen Material:
   Type: X Factory Cut 4"x6" Prepack
   ___ Continuous Slot
   Slot Size: .020 in.
   Length: 10 ft.
10. Backfill Material: (Below filter pack)
   - ___ None
   - X Other SAND

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name: City of Flag
Job Number: 102053 3416-
Location: Flagstaff AZ

Well Name: CL-9
Driller: Travis Osterberg
Helper: Lewis Fisher / Dave Lund
Date Installed: 6-9-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4 in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top: 20 ft.

F. Fine Sand Top: NA ft.

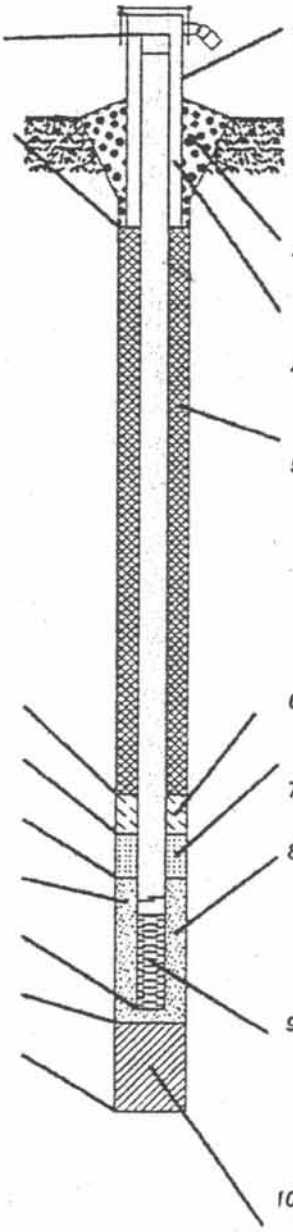
G. Filter Pack Top: 22 ft.

H. Screen Joint Top: 23 ft.

I. Well Bottom: 33 ft.

J. Filter Pack Bottom: 38 ft.

K. Borehole Bottom: 38 ft.



1. Locking Cap? X Yes ___ No
2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - X Steel
      - ___ Other ___
   d. Bumper Post ___ qty ___ 3" ___ 4"
3. Surface Seal:
   - ___ Bentonite
   - X Concrete
   - ___ Other ___
4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other Concrete
5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped
6. Bentonite Seal:
   - ___ Granules
   - X Pellets / Chips
7. Type of Fine Sand: NA
8. Type of Filter Pack: 10/20 Sand
9. Screen Material:
   - Type: X Factory Cut ___ Continuous Slot
   - Slot Size: .020 in.
   - Length: 10 ft.
10. Backfill Material: (Below filter pack)
   - ___ None
   - X Other Sand

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name: City of Flag
Job Number: 102053 3416-
Location: Flagstaff, AZ

Well Name: CL-10
Driller: Travis Osterberg
Helper: Lewis Fisher / Dave Lund
Date Installed: 6-9-11

Type of Well:
- [x] Water Table Observation
- [ ] Piezometer
- [ ] Other

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4 in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- [x] Schedule 40
- [ ] Schedule 80
- [ ] Other

E. Bentonite Seal Top: 20 ft.

F. Fine Sand Top: NA ft.

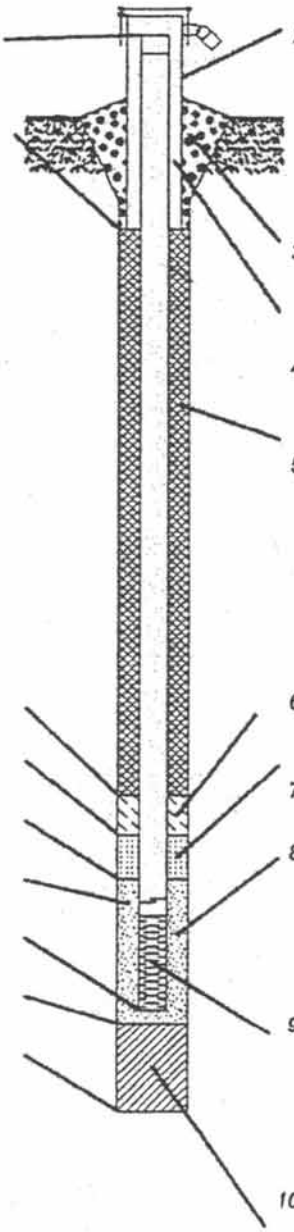
G. Filter Pack Top: 21 ft.

H. Screen Joint Top: 22 ft.

I. Well Bottom: 32 ft.

J. Filter Pack Bottom: 37 ft.

K. Borehole Bottom: 37 ft.



1. Locking Cap? [x] Yes [ ] No

2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - [ ] Steel
      - [ ] Other
   d. Bumper Post ___ qty
      - [ ] 3" [ ] 4"

3. Surface Seal:
   - [ ] Bentonite
   - [x] Concrete
   - [ ] Other

4. Material between Casing and Protop:
   - [ ] Bentonite
   - [x] Other concrete

5. Annular Space Seal:
   - [ ] Granular Bentonite
   - [ ] Bentonite Slurry
   - [ ] Cement-Bentonite Grout
   - [x] Other Concrete

   How Installed:
   - [x] Gravity
   - [ ] Tremie Pumped

6. Bentonite Seal:
   - [ ] Granules
   - [x] Pellets/CHIPS

7. Type of Fine Sand: NA

8. Type of Filter Pack: 10/20 SAND

9. Screen Material:
   Type:
   - [x] Factory Cut
   - [ ] Continuous Slot

   Slot Size: .020 in.
   Length: 10 ft.

10. Backfill Material: (Below filter pack)
   - [ ] None
   - [x] Other SAND

Boart Longyear
7773 West Seldon Lane
Peoria, AZ 85345
Phone (623) 935-0124
Fax (623) 935-9302

BOART LONGYEAR
Well Construction Report

Job Name City of Flag
Job Number 102053 ~~3416~~
Location Flagstaff, AZ

Well Name CL-11
Driller Travis Osenbaugh
Helper Lewis Fisher
Date Installed 6-10-11

Type of Well:
- X Water Table Observation
- ___ Piezometer
- ___ Other ___

A. Height of Well Casing above ground: -.6 ft.

B. Diameter of Well Casing: 4 in.

C. Surface Seal Bottom: 20 ft.

D. Well Casing: Flush Threaded PVC
- X Schedule 40
- ___ Schedule 80
- ___ Other ___

E. Bentonite Seal Top 20 ft.

F. Fine Sand Top N/A ft.

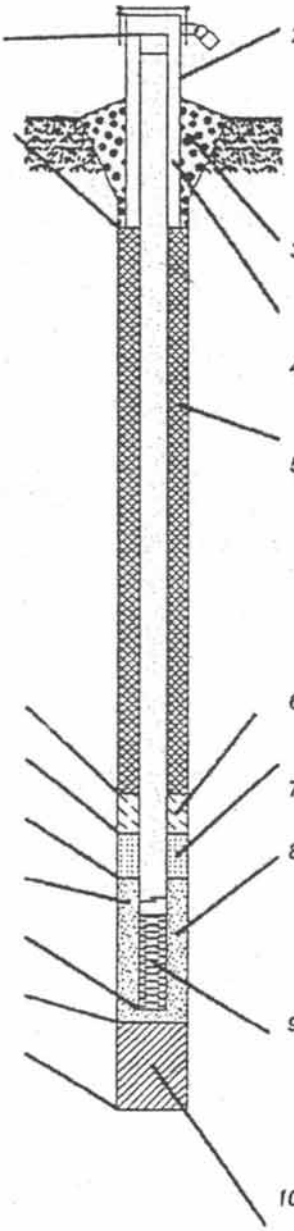
G. Filter Pack Top 49 ft.

H. Screen Joint Top 51 ft.

I. Well Bottom 61 ft.

J. Filter Pack Bottom 60.5 ft.

K. Borehole Bottom 65 ft.



1. Locking Cap? X Yes ___ No
2. Protective Cover:
   a. Inside diam. 12 in.
   b. Length 1 ft.
   c. Material
      - X Steel
      - ___ Other ___
   d. Bumper Post ___ qty ___ 3" ___ 4"
3. Surface Seal:
   - ___ Bentonite
   - X Concrete
   - ___ Other ___
4. Material between Casing and Protop:
   - ___ Bentonite
   - X Other Concrete
5. Annular Space Seal:
   - ___ Granular Bentonite
   - ___ Bentonite Slurry
   - ___ Cement-Bentonite Grout
   - X Other Concrete

   How Installed:
   - X Gravity
   - ___ Tremie Pumped
6. Bentonite Seal:
   - ___ Granules
   - X Pellets Chips
7. Type of Fine Sand: N/A
8. Type of Filter Pack: 10/20 Sand
9. Screen Material:
   - Type: X Factory Cut ___ Continuous Slot 4"x6" Prepack
   - Slot Size: .020 in.
   - Length: 10 ft.
10. Backfill Material: (Below filter pack)
    - ___ None
    - X Other Sand

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Peoria, AZ 85345
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Fax (623) 935-9302

Appendix B. Photos of the Geophysical Survey

Photo 1. 200 feet was measured between geophysical stations with a tape measure.

Photo 2. Stakes were place at intervals of 200 feet along each line, and marked with flagging.

Photo 3. A close-up of the surface shows the loose, unconsolidated nature of the surface cinders.

Photo 4. Showing station stakes on the western part of Line 6, looking west.

Photo 5. Portable generator for TEM survey.

Photo 6. Portable receiver for TEM survey.

Appendix B. Photos of the Geophysical Survey

Photo 7. Geophysical equipment set up to read TEM data on Line 1.

Photo 8. The antennae used to transmit and collect TEM data.

Photo 9. Close-up of the antennae.

Photo 10. Reading the TEM data with the portable receiver.

Photo 11. View across Cinder lake to the west toward the San Francisco Peaks.

Photo 12. Portable GPS receiver used to record the locations of the geophysical stations.

Appendix B. Photos of the Geophysical Survey

Photo 13. This crater southeast of the landfill was created by NASA to train astronauts. Note tape measure laid while surveying Line 2.

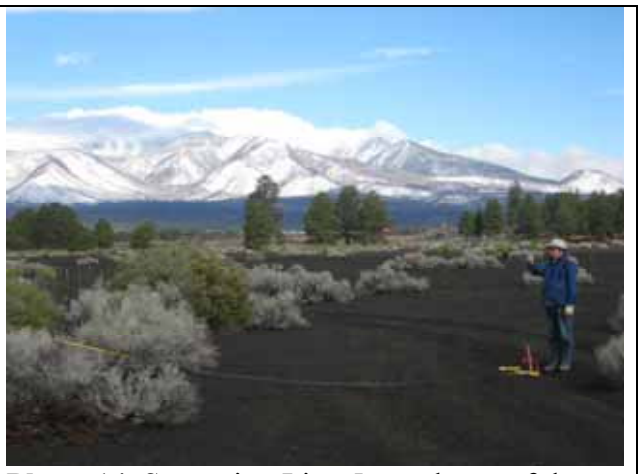

Photo 14. Surveying Line 5, southeast of the landfill, looking west toward the snow-covered San Francisco Peaks.

Photo 15. View of the north side of Cinder Lake, near the north side of Line 5, looking north toward Sunset Crater.

Photo 16. Surveying Line 6. View is to the east from the center of Cinder Lake.

Appendix C. Photos of the Drilling Operations

Photo 1. Set-up of Boart's sonic drilling rig at borehole CL1 on Cinder lake.

Photo 2. Another view of the sonic drilling operations at Cinder Lake.

Photo 3. Close-up of the head of the sonic drilling rig.

Photo 4. The samples empty from the drill pipe into long, clear plastic bags for analysis.

Photo 5. Differences in materials can be seen through the bag. A more detailed analysis will be performed later.

Photo 6. Several bags show differences in material type. The numbers on the bags indicates the bottom depth in feet.

Appendix C. Photos of the Drilling Operations

Photo 7. Samples are placed into chip trays for easy reference.

Photo 8. The working deck of the sonic drilling rig.

Photo 9. The sonic rig set-up on CL11.

Photo 10. Samples are laid out for analysis.

Photo 11. Basalt was often brought up as core.

Photo 12. Note the abundant cavities in basalt.

Appendix C. Photos of the Drilling Operations

Photo 13. Cracks in basalt core from CL9 pass all the way through the sample.

Photo 14. The inner drill pipe (left) and outer drill casing (right) of the sonic drilling rig.

Photo 15. The 7-inch diameter sonic cutting shoe (or bit). Note the buttons.

Photo 16. Boart, the USGS, HSI, and the County at CL1 on Cinder Lake.

Photo 17. Appearance of the drainage basin south of the landfill adjacent to CL7.

Photo 18. CL7 was drilled about 50 feet north of the drainage basin. View is N-NE.

Appendix C. Photos of the Drilling Operations

Photo 19. Typical surface completion for the monitor wells; 2x2 concrete pad (CL10 here).

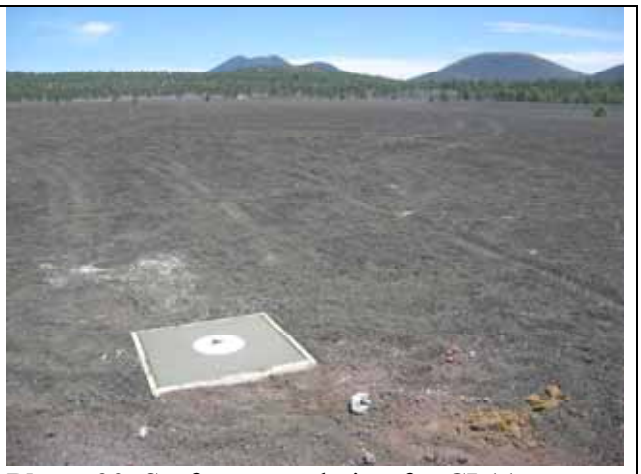

Photo 20. Surface completion for CL11, looking north.

Photo 21. Close up of concrete pad for CL11.

Photo 22. Hammer bit (for air rotary) shows tungsten-carbide buttons on its cutting surface.

Photo 23. The red swivel allows compressed air to enter the drill pipe.

Photo 24. The diverter allows air and cuttings to exit the casing and be expelled to the surface.

Appendix C. Photos of the Drilling Operations

Photo 25. Air compressor used to supply air the air-rotary method.

Photo 26. Another view of the air compressor and air lines.

Photo 27. Rig set-up for air rotary on the deep borehole CL5.

Photo 28. The cuttings with minor foam exit the plastic diverter pipe at about 60 psi.

Photo 29. Carefully collecting a sample of cuttings in a plastic bucket.

Photo 30. The cuttings are poured into a strainer and cleaned of foam and fines.

Appendix C. Photos of the Drilling Operations

Photo 31. Close-up of clean basalt cuttings.

Photo 32. Cuttings are placed in chip trays for easy reference.

Photo 33. View of the discharge pipe onto the surface. The colors visible are mostly foam.

Photo 34. Another view of the foam discharged from the pipe.

Photo 35. Fresh foam is a good analogy for hot lava. Note the relatively smooth surface.

Photo 36. Dried foam is a good analogy for cooled lava. Noted the irregular surface.