City of Sedona WWTP

CSAMT Survey

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1.0 INTRODUCTION

This survey follows on the recommendations provided to the City of Sedona in the *Groundwater Recharge Feasibility Evaluation* (Hydrosystems, 2009). The City has been examining options for managing treated wastewater for some time, and is currently exploring the possibility of using surface or well recharge as a means of managing treated effluent through recharge the local groundwater system. Recharge has the advantage of supporting a more long-term, sustainable water-supply plan, but it must be done in such a way as not to adversely affect water quality in the protected waters of Oak Creek, which flows a little more than two miles to the southeast of the Sedona Waste Water Treatment Plant (WWTP).

As listed in the recommendations of the previous report there appear to be several different recharge options: (1) Surface recharge at or near the WWTP property, (2) direct injection into the Supai Formation, (3) direct injection into the Redwall Limestone, and (4) Direct injection into or near the Sheephead fault zone. Surface recharge at or near the WWTP property has been shown to be nonviable, due to the very high water levels (perching) as indicated in the piezometer wells and the low infiltration rates of the near-surface materials. The other three direct injection options require a better understanding of the hydrologic properties of the subsurface formations. That is where this study comes in.

Water injected down a well and into a formation will develop a mound of water in the surrounding formation that is analogous to a mirror image of a cone of depression in a well pumping water to the surface. This is not an exact comparison because, as a rule of thumb, only about half as much water injected into a well will give a similar effect as the amount withdrawn over any given time. The height of the mound and its lateral extent depend on the hydrologic characteristics of the particular formation. In a formation that is fine-grained and has a small hydraulic conductivity the mound will grow higher and closer to the surface than in a formation that is coarser-grained and has a greater hydraulic conductivity. Sedimentary rocks of the Colorado Plateau sequence, which are beneath the site, are also typically fractured as a result of multiple episodes of uplift and subsidence over geologic time. Fractures are open pathways for groundwater flow and their identification in the subsurface can greatly enhance the ability of a formation to both produce and accept water. These fractures may or may not be in predictable patterns and directions, and some may have even ‘healed’ or filled with mineral deposits over time.

The surface geophysical technique Controlled Source Audio-frequency Magnetotellurics (CSAMT) is well suited to help detect fracture systems. As previously described, the technique involves measuring radio frequencies (in this case emitted from a transmitter) at a series of equally spaced electrodes along a line across the area of interest. The wide range of frequencies from 1 Hz to more than 8,000 Hz are measured at each station and integrated into a repeatable model of the resistivity of the formations from the surface to several thousand feet beneath the Earth’s surface. Since water is more electrically conductive than dry earth material, portions of a formation that contain groundwater within its pore spaces tend to possess a *lower* resistivity than the dry portions of the formation. Additionally, areas that contain abundant water-filled fractures are typically more conductive and show even lower resistivity values. Once the CSAMT survey is completed, the resulting data are plotted as color cross-sections that show the distribution of resistivity both horizontally and vertically to a depth of about 3,000 feet or more. It should be noted that the resulting plotted data are a *model* of the subsurface resistivity values, and not an actual image. Subsequent drilling may be necessary to better understand local conditions.

2.0 RESULTS OF THE CSAMT SURVEY

The following sections describe the CSAMT results with respect to each individual line. Six lines were originally planned for this survey, but because of land-use inconsistencies associated with obtaining access to State Trust Land, the two lines farthest to the southwest were temporarily removed from the survey (*Figure 1*). Lines 1 and 2 were positioned in order to obtain as much subsurface information as possible on the WWTP property. Line 1 extends across the property, through the existing production well, and extends almost one mile north of the property across the inferred existence of the Dry Creek faults (as mapped by Paul Lindberg in Burgess and Niple, 2008), and into surface exposures of the Supai Formation. Line 2 is parallel to Line 1 and was placed to compliment and verify any anomalies found on Line 1 as well as to collect more data on the WWTP property. Lines 3 and 4 were both placed across the inferred Page Springs fault (as mapped by DeWitt et al., 2008) with the intent to help verify the existence of this structure. All of these lines had the second purpose of exploring the hydrologic characteristics of the Supai Formation and Redwall Limestone.

The geology and the thickness of the geologic units below the surface were acquired from two sources: the driller's log of the potable water well for the wastewater plant and the geologic cross-section in Burgess and Niple (2008) (*Figure 2*). The driller's log of the potable water well on the northeast corner of the WWTP property penetrates alluvium, basalt, the Supai Formation, and part of the Redwall Limestone. This log appears to be reasonably accurate and gives the best estimate for the depth and thickness of these units below the WWTP. Paul Lindberg's cross-section in Burgess and Niple (2008) shows these same units as well as the underlying Martin Formation and Tapeats Sandstone, and shows the attitude of these layers and their relationships to possible faults in the area. Using these attitudes and thicknesses, the subsurface geology was drawn superimposed on the CSAMT cross-sections. The boundaries between formations are dashed to indicate that their positions are estimated. Careful logging of future boreholes should more accurately verify and/or refine their positions.

2.1 Line 1

Line 1 (*Figure 3*) shows two separate prominent low resistivity zones at and near the surface. The first is between Stations 0 and 3400 and the second between Stations 4500 and 5900. The first zone roughly corresponds to the locations of the present and past 'rapid infiltration basins' (RIB's) between about Stations 400 and 3000 (*Photos 1,2, and 3)*, and the wetlands between Stations 0 and 400. The low resistivity zone visible in *Figure 3* likely represents water that has infiltrated from these basins. It is interesting to note that although these basins have been used for several years the lowest resistivity values are mostly within about 200 feet of the surface (with two notable exceptions). This configuration further supports the conclusion explained in the *Groundwater Recharge Feasibility Evaluation* that the surface materials (alluvium and basalt) possess infiltration rates that are too low to support appreciable surface recharge. Because even some amount of infiltration is expected to have occurred since the RIB's entered service, the observation that there appears to be very little infiltration below about 200 feet suggests that water may instead flow predominantly laterally in the near-surface, probably towards the southwest parallel to the slope of the land surface. Another alternative is that possibly a large part of the infiltrated water is infiltrating into the subsurface preferentially below Station 2100. Here, there is a prominent vertical low resistivity anomaly that extends down to at least 1,000 feet below the surface (3,000 feet elevation) and probably at least another

400 feet deeper. This may be a fracture system. Based on the log of well 55-600125 (the potable water well at the northeast corner of the WWTP) this zone penetrates through at least the Redwall Limestone and into the Martin Formation. If this zone does represent a fracture zone this may be a favorable site to consider for recharge. This appears to be the lowest resistivity zone within the Redwall Limestone found on the WWTP site. Although it cannot be confirmed with the available data, possibly this area represents a solution cavity within the Redwall and the vertical low resistivity zone above may represent the fractured zone of an incipient collapse structure (sinkhole). The depth of the Redwall Limestone here is about 700 feet below the elevation of Oak Creek. If the mound height of injected water is sufficiently low there is a reduced probability of migration of injected water to Oak Creek.

Another deeper low resistivity anomaly occurs below Station 3100. This one is not as pronounced as the previous zone but it extends from the surface to a depth of at least 2,000 feet below the surface. The potable water well fortuitously penetrated part of this zone, which is likely one of the better areas from which to produce water. Because the potable water well is used only intermittently up to about 1,000 gallons per day (WWTP personal communication), however, there is no information about the performance of the well or of the underlying aquifer it penetrates. The moderately low resistivity values below the level of the well within the Martin Formation may also represent a fracture system and may be worth considering as a deeper target in the event that the shallow targets are for some reason not applicable.

The second near-surface prominent low resistivity zone is north of the WWTP between Stations 4500 and 5900. On the surface a tan-colored alluvial deposit is exposed between Stations 3600 to 5500 (*Photo 4*). It is mostly fine quartz sand and silt but also contains rounded cobbles of basalt and the Supai Formation, and it is not clear if this represents the basalt conglomerating portion of the Verde Formation or if it is a younger Quaternary alluvial deposit. Whatever its origin it is relatively thin, up to a few meters thick, as revealed in the highway road-cuts immediately to the east. These sedimentary deposits overlie basalt here and both occupy a fairly level area near the top of a small divide. It is possible that the deposits here act as a ‘sponge’ and preferentially collect precipitation and allow it to infiltrate more readily than the steeper areas to the north and south. It is also possible that the position of the low resistivity zone is more influenced by the position of the possible fault as inferred below Station 6000.

One of the reasons for extending Line 1 north of the WWTP was to verify the existence of the fault mapped by DeWitt and others (2008), also shown as the Dry Creek fault(s) in Burgess and Niple (2008). In the highway road-cut exposure on the west side of the highway in about the middle of the curve it certainly appears that reddish tan conglomerate on the north is faulted and down-dropped against basalt on the south (*Photo 5*). This exposure is isolated and there are no good exposures of the contact to the northwest. The exposures to the southeast do not reveal a fault, but instead show the contact between the basalt and the Supai Formation (*Photo 6)* as conformable and wrapping around the exposed hills. Therefore, it is possible that this fault possesses only a limited amount of offset (a few meters) which is only visible in the clean road-cut. Even so, this limited offset apparently is enough to change the groundwater characteristics on either side of the fault. Below Station 6000 in *Figure 3* there is a rather abrupt change in the resistivity values from southwest to the northeast. Values are lower to the southwest, and values are consistently higher to the northeast. The change occurs immediately northwest of the fault exposure in the road-cut. These data are mutually supportive and suggest that there is a real structure here below Station 6000. It is interesting to observe that the Supai and Redwall Formations both show high resistivity values north of the fault, especially considering that the drainage of Dry Creek is only about ½ mile to the east. This may indicate that the permeabilities of these formations in this area are sufficiently small to preclude major seepage into these rocks from Dry Creek, or it could indicate that groundwater flow is mostly to the south from Dry Creek and not to the southwest. The prominent low resistivity feature south of the fault centered below Station 5700 could also represent groundwater either ponding adjacent to or flowing laterally along the fault.

South of the fault, below Stations 5100 and 5200, moderately low resistivity values exist from the surface down to relatively deep depths of at least 1,500 feet below the surface (about 2,600 feet elevation). The lowest values at depth are centered on the approximate position of the Redwall Limestone. This may indicate a more permeable part of the Redwall here and may be worth exploring further as a possible injection site. The Redwall Limestone here is about 700 feet below the elevation of Dry Creek and 500 feet below the elevation of Oak Creek. If the mound height of injected water is sufficiently low there may be a very low probability of injected water migrating to Oak Creek.

2.2 Line 2

Line 2 is roughly parallel to Line 1 but is on the east side of State Route 89A (*Figures 1 and 4*). It starts about 200 feet south of the property and ends about 400 feet north of the northeast side of the property. It crosses the graded flat fields here which are supplied by a sprinkler system. *Figure 5* shows a low resistivity zone near the surface and roughly parallel to the surface to a depth of about 400 to 500 feet. A deeper low resistivity zone extends downward beneath about Stations 2700 and 3000 to depths of about 1,500 feet (2,600 feet elevation). The position of Station 2900 is only a few hundred yards immediately east of the potable water well location on Line 1 at Station 3000, which also shows a deeper low resistivity feature. The low resistivity projection below Station 1700 is also only a few hundred yards immediately east of the prominent deep low resistivity zone on Line 1 at Station 2100. These two observations support the conclusion that the deep low resistivity features on Lines 1 and 2 are real and that they probably represent a fracture system oriented northwest-southeast that intersects, in part, both cross-sections. It is quite possible that the deeper anomalies below Station 5100 on Line 1 also project in a northwest-southeast direction. It is also possible that the fracture system, and associated low resistivity anomaly, project both southeast of Line 2 and northwest of Line 1. The anomaly beneath Station 1700 on Line 2 is weak, however, and, based on the trend from Line 1, may not exist southeast of Line 2. The anomaly below Station 2900, however, still appears rather strong and may indicate a prominent through-going fracture system.

For the most part, below about 400 feet much of Line 2 exhibits relatively high resistivity values, suggesting rather dry conditions. As with Line 1, the observation that the low resistivity values are restricted to within about 400 feet of the surface, even after prolonged use of the RIB’s on the surface, suggests that the material within about 500 feet of the surface has very low infiltration rates. Notice that the basalt and younger alluvial sediments occupy only the top 200 feet or so. The remainder of the low resistivity zone is comprised of part of the Supai Formation. Since there does not appear to have been significant infiltration in the Supai Formation below about 500 feet it is possible that the Supai Formation here is relatively impermeable.

2.3 Line 3

Line 3 shows two dramatic low resistivity anomalies, the first between Stations 1500 and 2300 and the second between Stations 2900 and 4000 where the line ends (*Figures 6 and 7*).

These anomalies extend mostly to about 3,000 feet elevation, or about 800 to 1,000 feet beneath the surface, and become much weaker below this depth. On the surface, basalt is exposed between Stations 0 and about 2400 (*Photo 7*). A thick layer of tan-colored sand and silt is partly exposed between Stations 2400 and 3200, where it forms the smooth, easily erodable slope north of the road and appears to both underlain and overlain by basalt. North of Station 3200 to 4000 basalt is again exposed on the surface.

At the surface the two anomalies do not show any preferred correlation to rock type. It seems unusual that such low resistivity features are associated in part with basalts at the surface in these two areas but are not associated with similar basalts exposed at the surface along the southern portion of the line. It is common for basalts to be strongly fractured as a result of cooling and contraction from liquid lava to solid rock, and as a result of tectonic uplift. Where extensively fractured the rocks probably posses abundant pathways for water infiltrating downward from the surface after rain events. It is also common for fractures in basalts to become filled with later mineral deposits. It is possible that the non-predictable pattern of the low resistivity anomalies is in part controlled by the presence of open and closed fractures.

The low resistivity anomalies are separated by a more-or-less vertical high-resistivity feature centered near Station 2600. This is close to where DeWitt and others (2008) placed the Page Springs fault. There is also another vertical high resistivity zone between Stations 200 and 800. This zone shows even higher resistivity values than the zone centered on Station 2600. This feature may represent a fracture zone, but likely not a fault because no offset was seen in the basalt flows and interbedded sediments exposed in the cliffs less than 0.5 miles to the northwest in the center of Section 9.

It is possible that the zone near Station 2600 represents a fault, but this is difficult to verify. On the surface the trace of the inferred Page Springs fault occupies a series of small valleys. The position of remnants of the nearby Verde Formation shows that the Verde Formation was deposited within small ancient valleys carved into the basalt by ancient streams that flowed before the Verde Formation was deposited. It is possible that the modern streams partly reoccupied these ancient stream valleys as the Verde Formation was subsequently stripped away more recently. If this is the case, then the apparent alignment of the valleys may be a coincidence of erosion rather than a result of faulting. On the other hand, streams commonly do follow older fault and fracture zones because these areas commonly erode more easily that non-fractured rock. The apparent alignment of the high resistivity zone centered on Station 2600 with the high resistivity zone on Line 4 centered on Station 1100 supports the existence of a possible fault. If this does represent the alignment of the Page Springs fault it should be noted that this fault zone appears to be *less* porous and permeable than the surrounding rock and, hence, appears acts as a barrier to groundwater flow rather than a conduit. On the other hand, if the resistivity (and hence permeability) of the fault zone changes along strike then it is also possible that one (or both?) of the two deep low resistivity projections at Stations 2300 and 3000 on Line 3 represent the fault. On this cross-section the fault was drawn where the gradient in the resistivity values is the greatest, below Station 2400.

The positions of the subsurface formations were estimated using the cross-section created by Paul Lindberg in Burgess and Niple (2008). The low resistivity zones clearly show no correlation with any particular subsurface formation and extend from the surface all the way through the Supai, Redwall, and Martin Formations irrespective of the layers themselves. The reason for this is uncertain. Because of this uncertainty it is also difficult to interpret the very low resistivity of the Redwall Limestone in this area, and whether it really does reflect high permeabilities in this formation. Probably the best location to explore this possibility is at Station 3200, which would allow exploration of the deep feature near Station 3100 as well as the lower resistivity Redwall Limestone from Station 3200 northeastward.

2.4 Line 4

Line 4 (*Figure 8*) shows a low resistivity zone mostly within 800 to 1,000 feet of the surface, but with significant variations in depth. Most of the lowest resistivity values occur within about 200 to 400 feet of the surface and appear to correlate with the basalt and interbedded thin sedimentary deposits. Low to moderate values down to about 3,100 feet elevation are probably within the Supai Formation, but as with Line 3, the low resistivity zones below about 200 feet show no obvious correlation with rock type. However, looked at from a distance it appears that most of the low resistivity values are mostly within the nearly flat-lying sequence of Paleozoic sedimentary rocks, and most of the higher resistivity values are within the deeper Precambrian rocks.

The most obvious high resistivity zone is the vertical feature centered on Station 1100. As with Line 3, this high resistivity feature divides the low resistivity anomaly into two separate areas, and may represent the trace of the Page Springs fault. And also as in Line 3 the trace of the fault on Line 4 was placed below Station 1000, where the gradient in the resistivity data appears to be the greatest.

3.0 RECHARGE FEASIBILITY

As described above, the goals of this survey were to obtain subsurface resistivity data to better evaluate the different recharge options available: (1) Surface recharge at or near the WWTP property, (2) direct injection into the Supai Formation, (3) direct injection into the Redwall Limestone, and (4) Direct injection into or near the Sheephead fault zone.

3.1 Surface Recharge at or near the WWTP Property

As mentioned, the low infiltration rates of the fine-grained surface deposits and basalt beneath the WWTP have shown that surface recharge is not a feasible option. Consistently high water levels in piezometer wells near the infiltration basins, as observed by City personnel, also indicate that long-term infiltration rates are small. The observation from the CSAMT data that the lowest resistivity values are predominantly restricted to within 200 to 400 feet of the surface supports this conclusion.

3.2 Direct Injection into the Supai Formation

There are at least three criteria that need to be considered when evaluating recharge into the Supai Formation: (1) the average overall hydraulic conductivity of the formation, (2) the location and connectivity of fracture systems, and (3) the existence of faults and their effect, if any, on the direction of flow of the recharged water. The CSAMT lines give us very planar views of the subsurface only along the lines themselves, but some conclusions can be made with the available data.

The only surface exposures of the Supai Formation occur northeast of the WWTP. Interestingly, this area shows the highest resistivity values both within the Supai Formation and within all other rock types as well. The reason for this is not entirely clear. The presence of a possible fault at its southern boundary may prevent groundwater south of here from crossing northward. However, since the regional groundwater flow direction is towards the southwest, and Dry Creek is not far to the northeast, it makes more sense that the permeability of the Supai Formation here is inherently fairly low, otherwise one might expect to see ponding of water on the north side if the possible fault.

Other areas show much lower resistivity values and are probably dominated by fracture systems. The best locations include Line 1 at Stations 2100, 3100, and 5700, Line 2 at Station 2900, Line 3 at Stations 2100 and 3200, and Line 4 at Stations 1700, 2600, and 3500. The position of the deeper low resistivity anomalies on Line 1 and 2 suggest that the fracture systems are oriented in a northwest-southeast direction. If so, then the deeper low resistivity zone on Line 1 between Stations 5100 and 5900 may also continue in a northwest-southeast direction. The elevation of Oak Creek southeast of Lines 1 and 2 is at an elevation of about 3,600 feet. Much of the low resistivity anomalies, therefore, are well below this elevation, suggesting that mounded recharged water, even if it flows laterally, may not intersect Oak Creek. Since the orientation of the inferred fracture systems are just about parallel to the groundwater contours in the area recharged water could flow northwestward in addition to, or instead of, southeastward. Northwestward-flowing recharged water would be advantageous because it would further reduce the possibility of intersecting Oak Creek.

A possible way to help validate the orientation and continuation of the fracture systems would be to place one or two new CSAMT lines oriented northwest-southeast through Stations 2000 and 3000 of Line 1. The advantage of these positions is their accessibility. The line through Station 2000 can follow the dirt road all the way across the property. The line through Station 3000 intersects the well and can extend north of the main building without intersecting any other structures. In conjunction with these lines an aquifer test can be performed on the potable water well to provide hydrologic data on the aquifer beneath the site. This data can then be directly compared to the CSAMT data to help estimate aquifer characteristics elsewhere. This also allows some hydrologic data to be collected before drilling another well.

3.3 Direct Injection into the Redwall Limestone

One of the major goals of this study was to use CSAMT to help locate possible caverns within the Redwall Limestone and to estimate hydrologic parameters. One of the advantages of this area is the interpretation (from Burgess and Niple, 2008) that the depth to the top of the

Redwall Limestone is only about 900 feet below the WWTP and becomes shallower southward to within about 500 feet of the surface. In most other areas up on the Colorado Plateau the Redwall Limestone is in excess of 3,000 feet deep. So here, near the WWTP, it is much shallower and much less expensive to reach. It should also be noted that the Martin Formation, directly underlying the redwal Limestone, is also a carbonate (mostly dolomite) that may also contain some amount of dissolution cavities. However, very little hydrologic information exists for the Martin Formation.

On Line 1 there are three separate low resistivity zones that are located at least partially within the Redwall Limestone—below Stations 2100, 3100, and about 5100. These zones are not centered on the Redwall, however, but project into rocks both above and below. Because of this it is unclear if these areas represent solution caverns within the Redwall Limestone or if they are parts of larger fracture systems (or collapse system?) that cut across all of the formations. Whichever the case, these areas probably possess higher hydraulic conductivities than neighboring areas and it is possible that the Redwall Limestone is collecting water from surface recharge and funneling it laterally out of the plane of the cross-section. Station 2100 on Line 1 is probably the most favorable location for an exploration test well. This is a little more than 100 feet southwest of the well named PZA1 (RW-1).

Portions of Lines 3 and 4 show very prominent low resistivity zones across the estimated depth of the Redwall Limestone. As mentioned above, these zones are more difficult to interpret because the low resistivity zones are connected to the surface. Because of this, the zones likely reflect some property that is shared by the overlying Supai Formation and basalt, such as fracture systems, rather than just caverns. In any case, it may be advantageous to consider Station 3200 on Line 3 as the location for a possible exploration test well.

As stated in the June 2009 Sedona Wastewater Treatment Plant Groundwater Recharge Feasibility Evaluation (HydroSystems, 2009) Burgess and Niple's (2008) conclusion that Page Springs discharges from the Redwall Limestone is possible but difficult to verify. Figure 6 (their cross-section) does indeed show that the Redwall Limestone is entirely below the surface. Although not specifically stated, the report may have surmised that the water from the subsurface Redwall may have flowed up the fault some distance to the surface at Page Springs possibly as a result of artesian pressure. Again, this is difficult to verify.

3.4 Direct Injection into the Sheephead fault zone

Because of the length of time necessary for the application process to obtain permission to perform the survey on State land, the survey was performed on Lines 1 though 4 and the data analyzed before the Line 5 survey across the inferred Sheephead fault was performed. Based on the CSAMT data received from Lines 1 though 4, it was decided that a reasonable course of action would be to temporarily suspending Line 5 while considering using the intended funds to obtain additional information near promising sites at the WWTP itself (see the recommendations section below).

3.5 Does the Page Springs fault exist?

As described in sections 2.3 and 2.4, the CSAMT data in Lines 3 and 4 show relatively deep, linear features near stations 2400 and 1000, respectively. The observation that these features both also form a discontinuity in the resistivity data near the surface and at depth suggests that there is a real structure here. The CSAMT data, therefore, support the existence of the Page Springs fault. What is not clear is how much, if any, displacement there is across the fault. The amount of displacement may be irrelevant, however, to the hydrologic properties.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Because of the heterogeneous nature of open fractures and pore space within hard rock formations at depth, finding suitably productive well sites is not an easy matter. Using traditional methods such as fracture-trace-analysis has had limited success in large part because fractures are not always well exposed at the surface and they are rarely perfectly vertical. The CSAMT survey has allowed a broad area to be studied—a total of 18,000 line feet (3.4 miles)—to depths between 3,000 and 4,000 feet, resulting in at least four promising recharge sites. The relative cost of the survey has provided a significant cost savings when compared to drilling wells randomly. The conclusions and recommendations offered in the subsequent paragraphs are based predominantly on the CSAMT results supplemented by available hydrogeologic information specific to this area.

The rock formations on the southern part of the Colorado Plateau are fairly well understood, especially considering that they are well exposed to visitors from all over the world along the Mogollon Rim and further to the north in the Grand Canyon. South of the Rim, and within the study area, these Paleozoic sedimentary rock formations are likely between about 1,400 and 1,700 feet thick, and are nearly horizontal, dipping very gently to the northeast. The CSAMT data, however, do not reflect this predictable stratigraphy. The data show irregularly shaped zones of low resistivity that probably reflect differences in the location and amount of fracturing as well as the amount of fluid-filled porosity. Fractured bedrock aquifers are important sources of water on the Colorado Plateau. The CSAMT data show a few deep zones of moderate to low resistivity that may be the signature of permeable fracture zones within the hard rock formations.

4.1 Conclusions

The CSAMT data on Lines 1 and 2 clearly show that most of the water that has been added to the Rapid Infiltration Basins has not infiltrated below about 400 feet beneath the surface, even though these basins have been used for some time. This supports HSI’s former conclusion that surface recharge is not a viable long-term option at the WWTP. The overall moderate to high resistivity values for the Supai and Redwall Formations in the vicinity of the WWTP suggest that most of these formations probably possess rather low permeabilities and may not, in general, be suitable as recharge areas. However, several areas of low resistivity in both formations suggest the presence of permeable fracture zones that extend from near the surface to depths below the Redwall Limestone. With the limited information available it is also possible that some of these zones may represent collapse structures, particularly on Line 1 below Station 2100. The resistivity features on Lines 3 and 4 are a little more difficult to interpret, but some of the deeper features may also be associated with fracture systems. Lines 1, 3, and 4 all show sharp, near-vertical discontinuities in the CSAMT data that closely correspond to the inferred positions of the Dry Creek fault immediately to the north of the WWTP and the Page Springs fault, a few miles to the south. Hence, the CSAMT data support the existence of these two structures.

Site A is located at Station 2200 on Line 1. This is the strongest low resistivity feature on Line 1 and appears to decrease in strength near the inferred depth of the Redwall Limestone. The anomaly’s width and depth suggest it could be an incipient collapse feature or a fracture system. This site also has good accessibility, being within the WWTP property and located on or very near a dirt road.

Site B is located at Station 3100 on Line 1. This is the deepest low resistivity anomaly on Line 1. It appears to line up with a similar anomaly below Station 2900 on Line 2, suggesting both may be part of a northwest-southeast-oriented fracture system. The depth of the feature below Station 3100 is appealing because any water recharged here will likely remain well below the level of Oak Creek. The potable well for the WWTP was also drilled very close by at Station 3000, so it is possible to use this existing well to perform a limited aquifer test and obtain some hydrologic data before a recharge well is drilled.

Site C is located at Station 5100 on Line 1. This site shows a low resistivity zone centered on the Redwall Limestone and may represent a fracture system intersecting the formation. Its relative proximity to the WWTP (just over 2,000 feet distant) is convenient for conveyance, and its depth is appealing because any water recharged here will likely remain well below the level of Oak Creek.

Site D is located at Station 3000 on Line 3. This site shows a very strong low resistivity feature from the surface down to a depth of about 1,000 feet below the surface, and a deeper slightly less resistive feature that projected at least another 800 feet below that. This site intersects the Redwall Limestone at about 600 feet and may represent a more extensive fracture system that appears to penetrate at least several hundred feet into the deeper Precambrian rocks.

Possible effects to the potable water well and to Oak Creek:

The specific effects to the potable water well caused by injection at either of Sites A, B, or C are unknown, and difficult to estimate without additional hydrogeologic testing and characterization. The most likely effect of any of the sites will be the creation of a groundwater mound. The rate of mound dispersion is directly related to well construction and the hydraulic properties of the aquifer materials. Fractured rock will also affect the mound. The following paragraphs offer some possible mound dispersion scenarios for each site. It must be remembered, however, that these are only estimated effects that need to be verified by additional hydrogeologic testing an analysis.

The mound height at Site A may be the lowest of the three sites if the lower resistivity values there correspond to higher permeabilities. That would mean that water would disperse into the formation quicker than at Sites B and C. Also, since Site A is 900 feet down-gradient from the potable water well, the mound may be displaced downslope away from the potable water well, further decreasing its influence. It is quite possible that the shape of the mound will be affected by the system of fractures near the injection well, in which case injected water may follow the low resistivity feature below Station 1900 and flow deeper into the subsurface, it may rise in part preferentially upward below Station 2100, or it could flow laterally either eastward or in or out of the plane of the cross-section. With respect to the last point, further CSAMT data perpendicular to Line 1 may help to address this.

The mound of injected water at Site B has the highest potential to impact the existing potable water well. The amount of impact also depends on the height of the mound. As with Site A, the mound height will depend on the permeability of the formations there and upon how readily the injected water will tend to disperse laterally, either to the southwest or in or out of the plane of the cross-section.

Site C appears to have the least ability to impact the potable water well. Although it is up-gradient, Site C is 2,100 feet distant and is separated from the well by an area of dominantly medium to high resistivity. The resistivity data suggests that mounded water will flow very slowly down-gradient towards the potable water well, and may preferentially find quicker flow paths either deeper into the subsurface or laterally in or out of the cross-section.

Although additional CSAMT lines perpendicular to Line 1 will not resolve the uncertainties conclusively, they will likely help to determine the extent of flow paths in the third dimension northwest and southeast of Line 1. They will have the additional benefit of adding to our understanding of possible hydrogeologic features that could constrain fluid movement towards Oak Creek. The additional CSAMT data may also reveal a more optimum injection site that is further away from the existing potable water well to minimize potential water quality issues.

Another possibility to consider is re-locating the potable water well, possibly to Site C about 2,000 feet up-gradient to the northeast. This will significantly reduce the possibility of adverse effects caused by mounding from the recharge well. Should an injection well be constructed at Site A (only 1,000 feet from the potable water well) it is also quite likely that the existing potable water well will have to undergo some type of water quality monitoring. Drilling a new potable water well at Site C also allows for the possibility that the existing potable water well could be retrofitted as an injection well. Land ownership around Site C will need to be investigated. Consideration should also be given to performing an aquifer test on the existing potable water well

4.2 Recommendations

Based on the available information, the following two options are offered:

Option 1:

1. Due to the extended permitting time required by the State Land Department to provide access to Line 5 of the CSAMT survey (to the south across the inferred Sheephead fault) use the existing funds to survey three additional lines centered on and perpendicular to Line 1 trending northeast across the WWTP site. Doing so will have the following benefits: (1) the additional CSAMT data will add to our understanding of potential subsurface flow paths for injected water around the plant site as well as water traveling toward Oak Creek, (2) the additional CSAMT data may

2. Site A is recommend for drilling and testing of an exploration/test well on Line 1. The depth of the boring should be 1,800 feet deep. New CSAMT data could refine the recommended drilling location.
3. Establish a water level and water quality monitoring program on the potable water well to detect any impact caused by injection recharge on the plant site.
4. Perform an aquifer test on the potable water well to help better understand the hydrologic characteristics of the Supai Formation and how they correlate to the CSAMT data.

Option 2:

1. Same as Step 1 of Option 1.
2. Based on the results of the additional on-site CSAMT survey, consider drilling a new potable water well up gradient at Site C. This will significantly reduce the possibility of mounding effects from plant site injection on the new well and reduce the need for water quality monitoring of the potable water well.
3. Evaluate the possibility of retrofitting the existing potable water well as an injection well if its construction characteristics allow for it. If it cannot be used as an injection well, the existing potable water well should be retrofitted as a monitor well and an injection well be drilled at Site A.
4. Perform an aquifer test on the potable water well to help better understand the hydrologic characteristics of the Supai Formation and how they correlate to the CSAMT data.

4.3 Cost estimates

The following are cost estimates for budget purposes only. The costs are based on estimates obtained from previous projects and do not represent costs based on technical specifications.

1. Perform three additional CSAMT survey lines (6,000 line-feet total) perpendicular to Line 1 at Sites A, B, and C (existing budget)	$24,000
2. Drilling, developing, and testing of an exploration/test hole drilled to a depth of approximately 1,800 feet deep (Site A)	$225,000
3. Retrofit the existing potable water well to an injection well	$160,000
4. Retrofit the existing potable water well to a monitor well	$25,000
5. Use the existing pump in the potable water well to perform an aquifer test within the potable water well	$10,000
6. Remove the existing pump from the potable water well and use a test pump to perform the aquifer testing to increase the flow rate	$28,000
7. Drilling a new potable water well to a depth of 1,000 feet and construct a 2,000 foot small diameter pipeline to the WWTP (Site C)	$180,000

5.0 REFERENCES

Burgess and Niple, Inc., Tempe, Arizona, May 2008, Report for a point discharge study with a directed revision to a water reuse study: Prepared for the City of Sedona, Arizona.

DeWitt, E., Langenheim, V., Force, E., Vance, R.K., Lindberg, P.A., and Driscoll, R.L., 2008, Geologic map of the Prescott National Forest and the headwaters of the Verde River, Yavapai and Coconino Counties, Arizona: U.S. Geological Survey Scientific Investigations Map 2996, scale 1:100,000, report 100 pages.

HydroSystems, 2009, Sedona Waste Water Treatment Plant Groundwater Recharge Feasibility Evaluation, prepared for the City of Sedona.

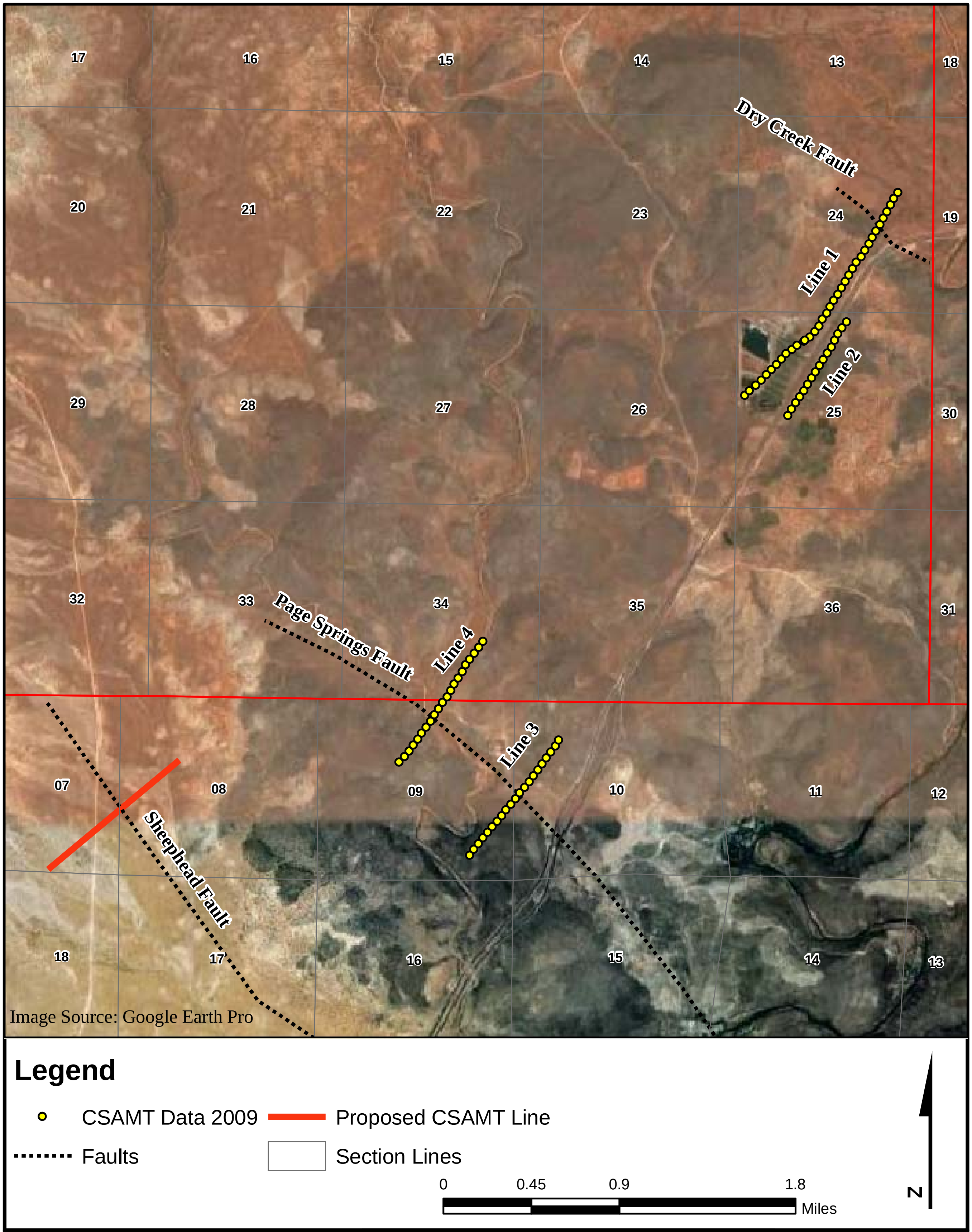

Image Source: Google Earth Pro

HydroSystems, Inc.

**Map Showing the Location
of the CSAMT Lines
City of Sedona Recharge Project**

Figure 1

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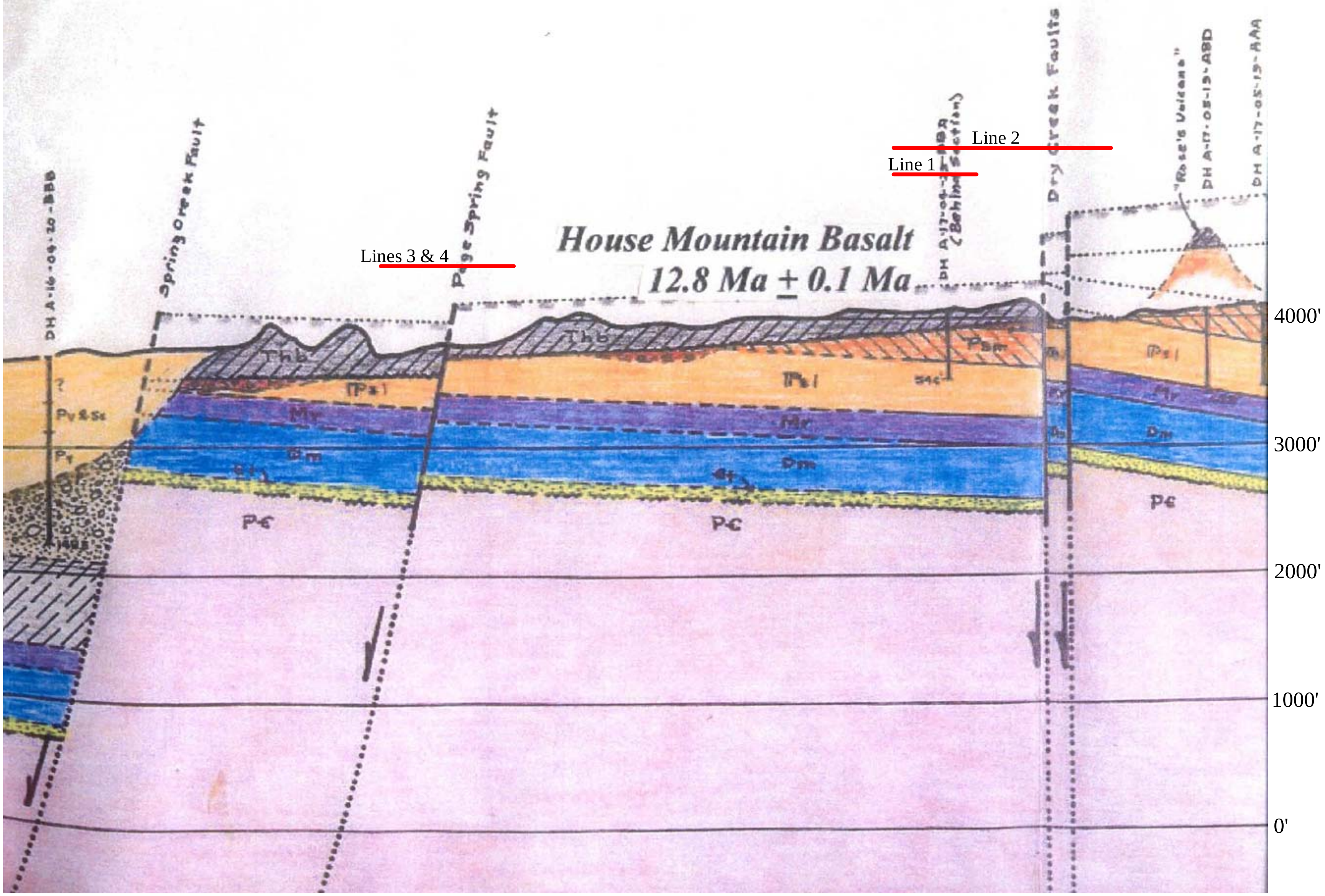


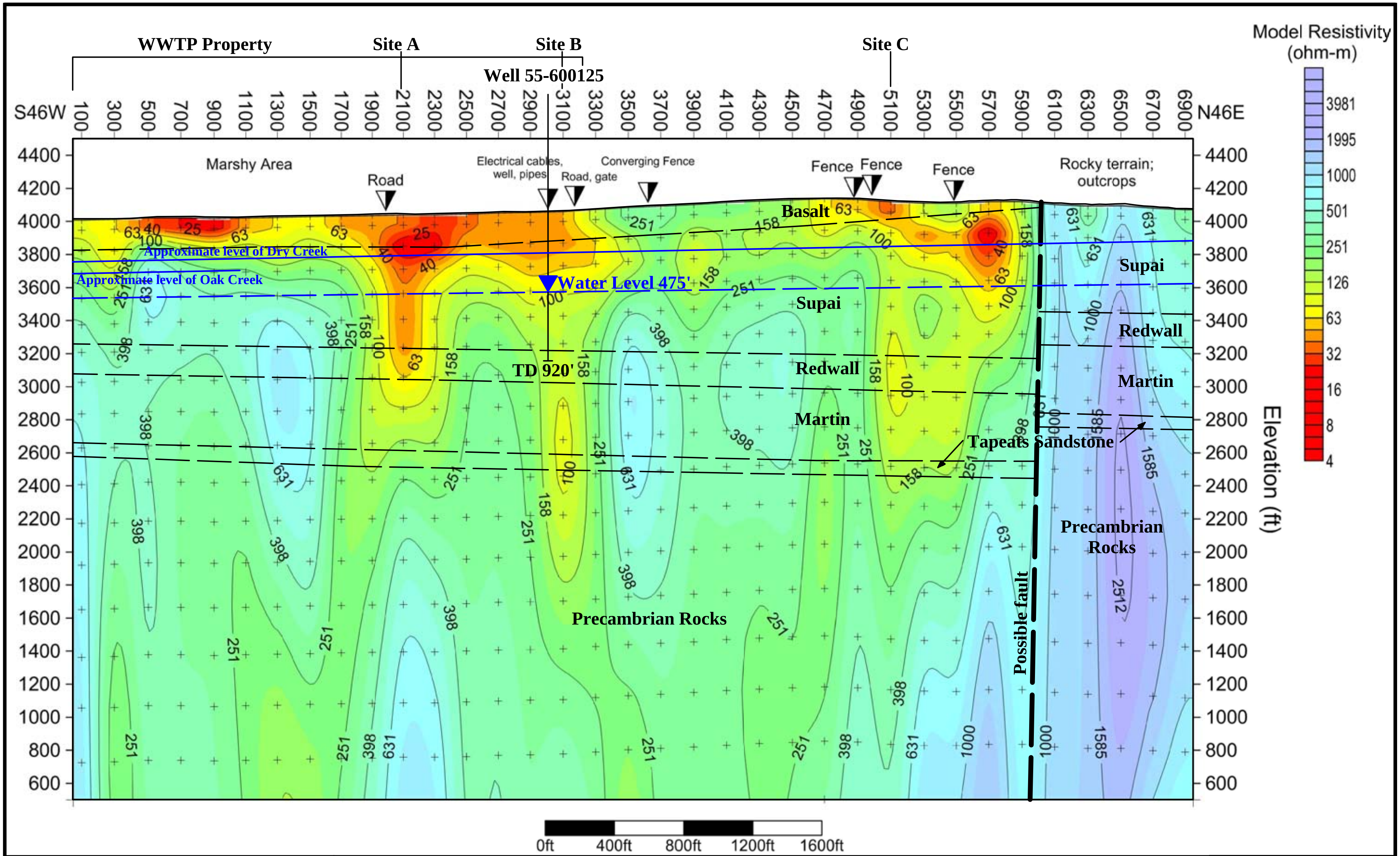
HydroSystems Inc.

SW-NE Geologic Cross-Section
City of Sedona Recharge Project

(from Paul Lindberg in Burgess and Niple, 2008)

Figure 2

S:\08-563 Carollo-Sedona Recharge\Final Report\Phase 2\Figure Workspace\Figure 2 Geologic X-Sxn.dwg, 12/9/2009 6:17:55 AM

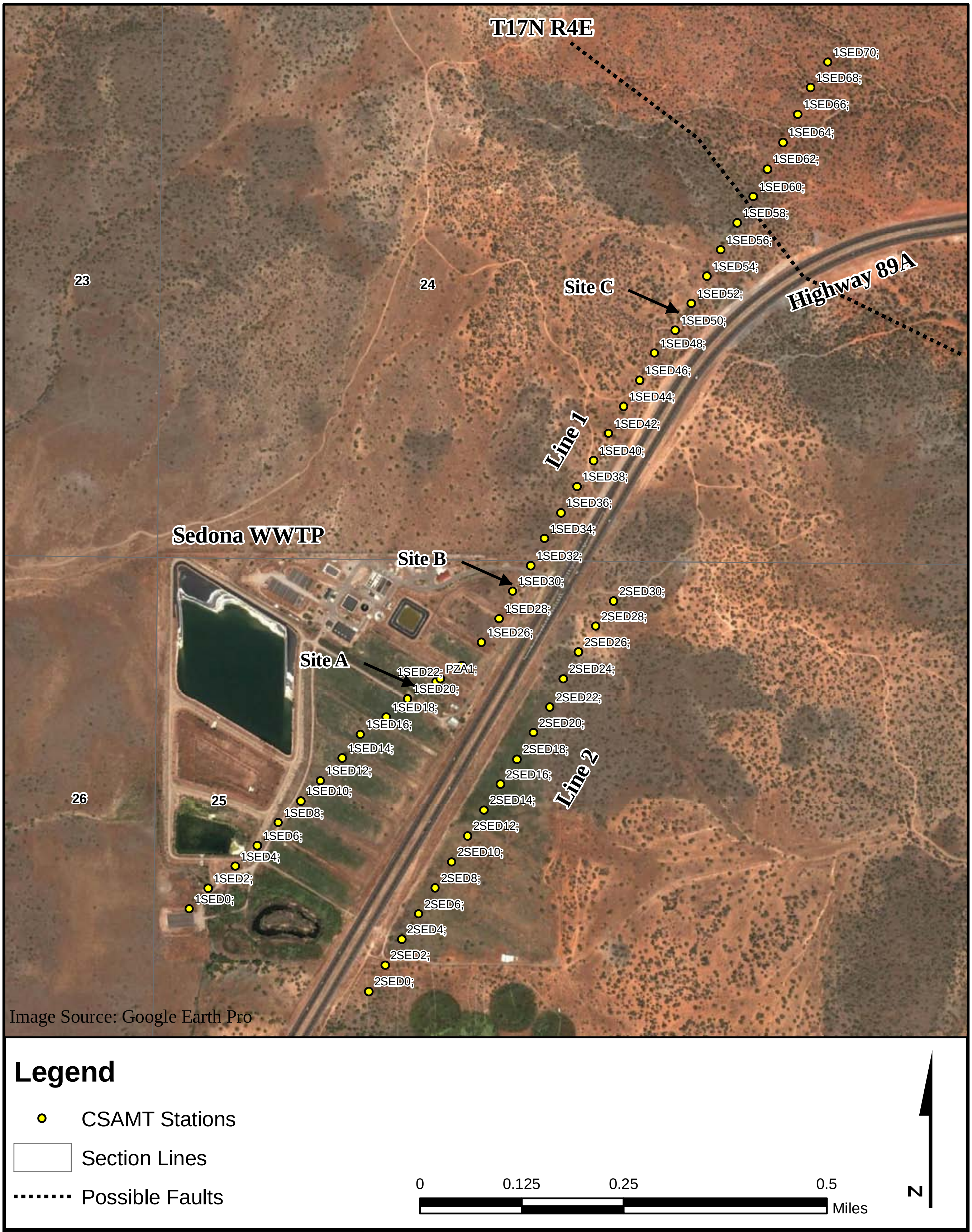


HydroSystems, Inc.

Line 1 CSAMT Cross-Section
City of Sedona Recharge Project

Figure 3

S:\08-563 Carollo-Sedona Recharge\Final Report\Phase 2\Figure Workspace\Figure 3 Line 1 with geology.dwg, 1/22/2010 11:29:47 AM

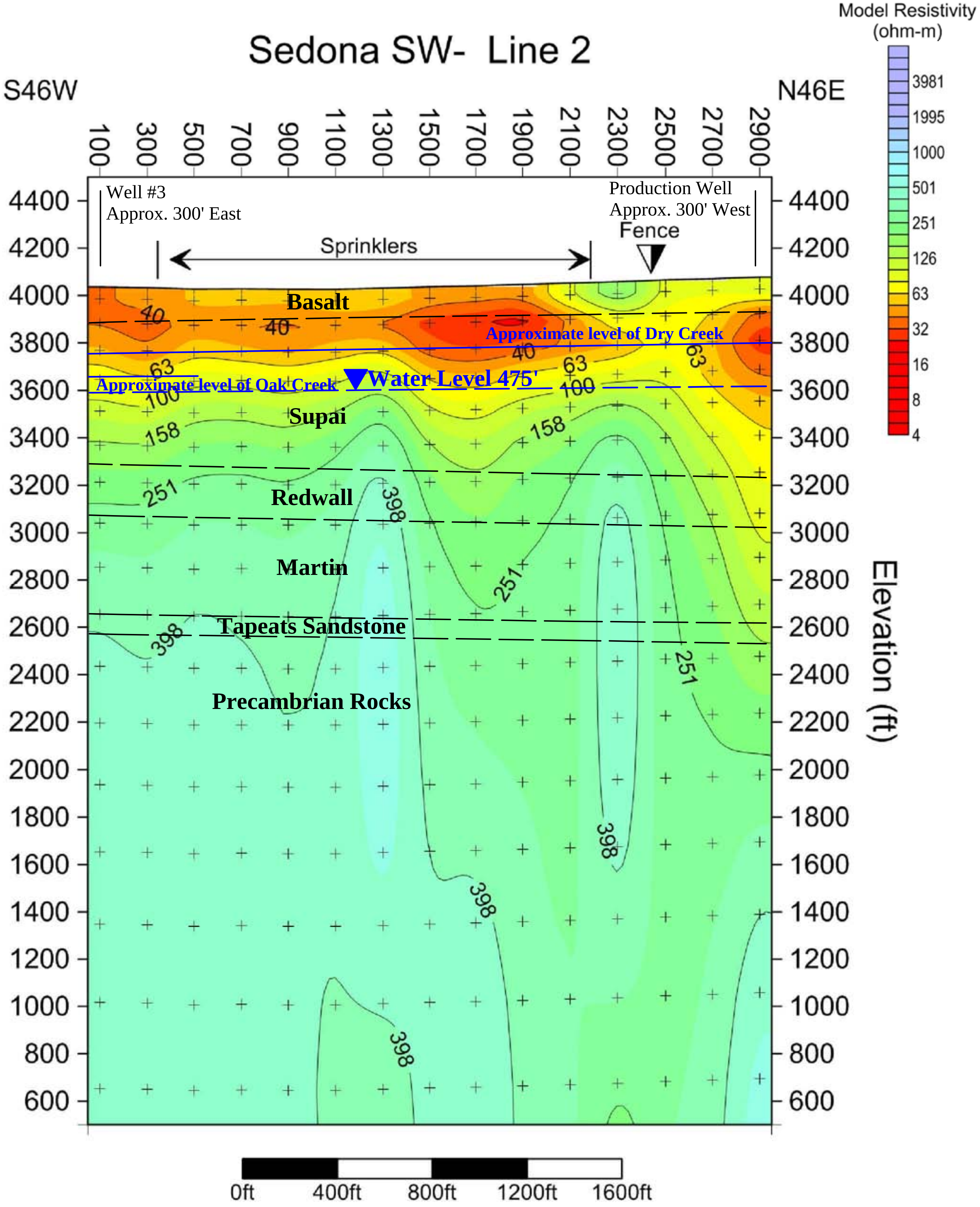


HydroSystems, Inc.

Map Showing Station Numbers for Lines 1 & 2 City of Sedona Recharge Project

Figure 4

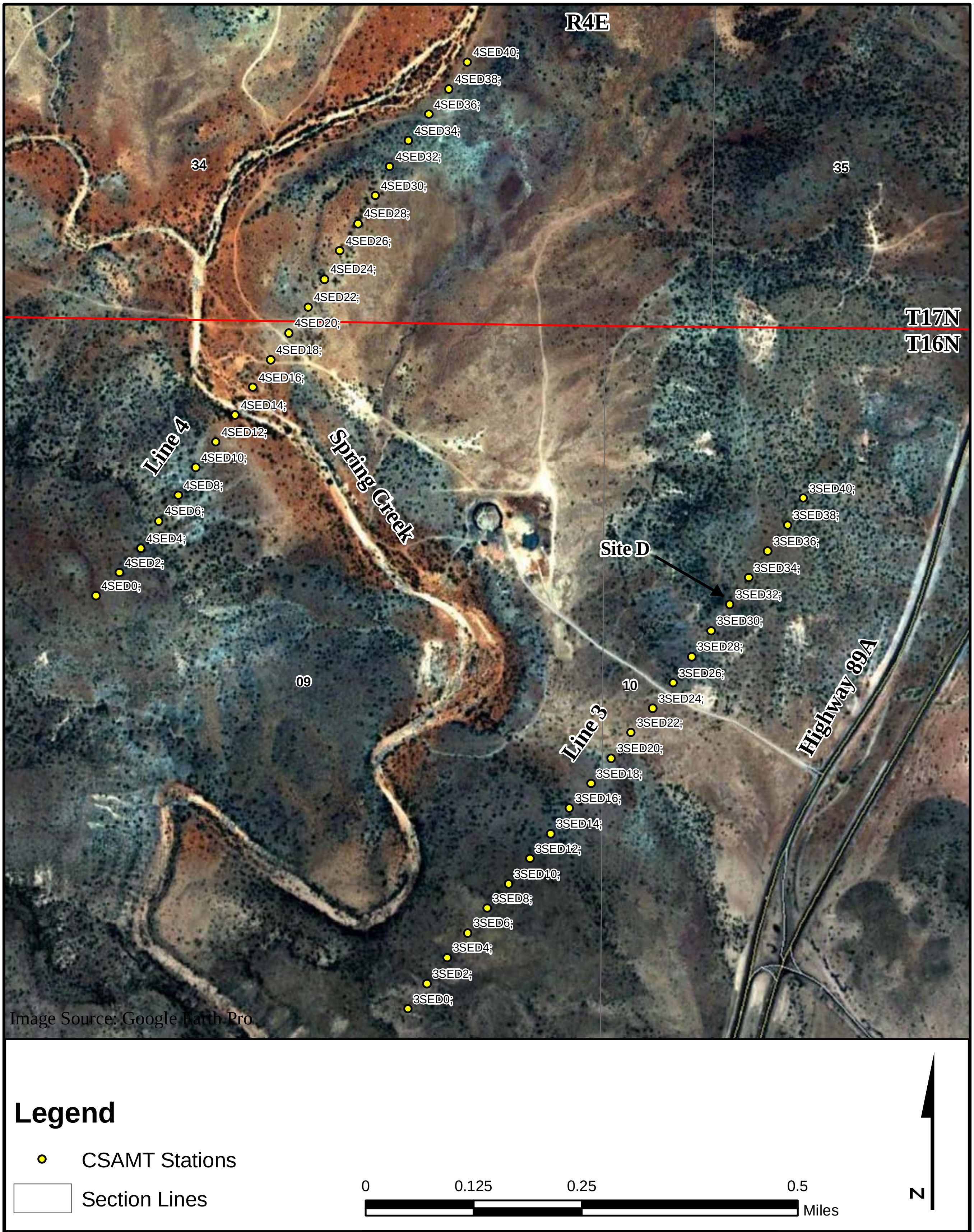
S:\08-563 Carollo-Sedona Recharge\Final Report/Phase 2/Figure Workspace/Figure 4 CSAMT Lines 1&2.mxd 12/08/2009



HydroSystems, Inc.

Line 2 CSAMT Cross-Section
City of Sedona Recharge Project

Figure 5

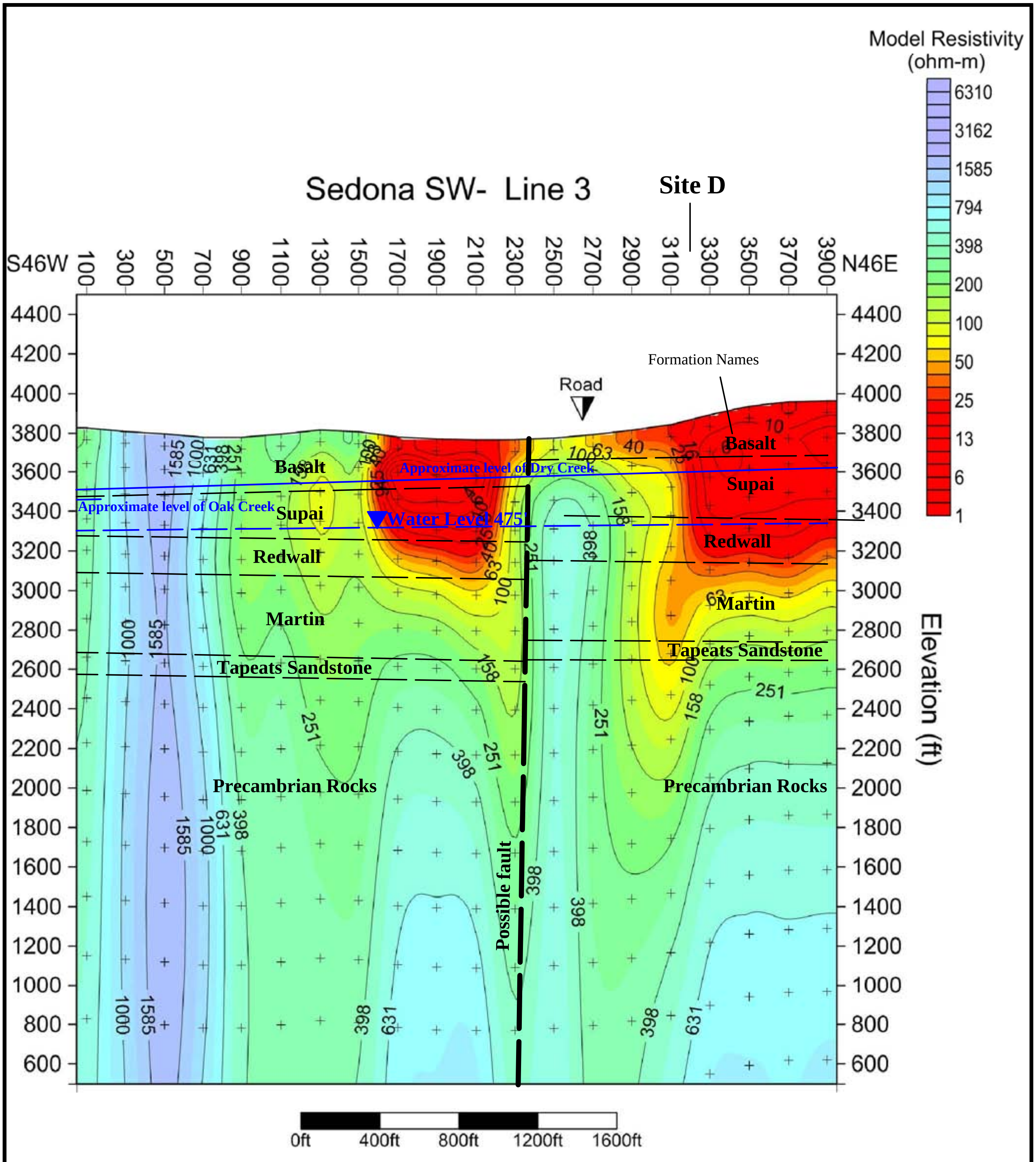


HSI HydroSystems Inc.

Map Showing Station Numbers
for Lines 3 & 4
City of Sedona Recharge Project

Figure 6

S:\08-563 Carollo-Sedona Recharge\Final Report/Phase 2/Figure Workspace/Figure 6 CSAMT Lines 3&4.mxd 12/08/2009



HydroSystems Inc.

Line 3 CSAMT Cross-Section
City of Sedona Recharge Project

Figure 7

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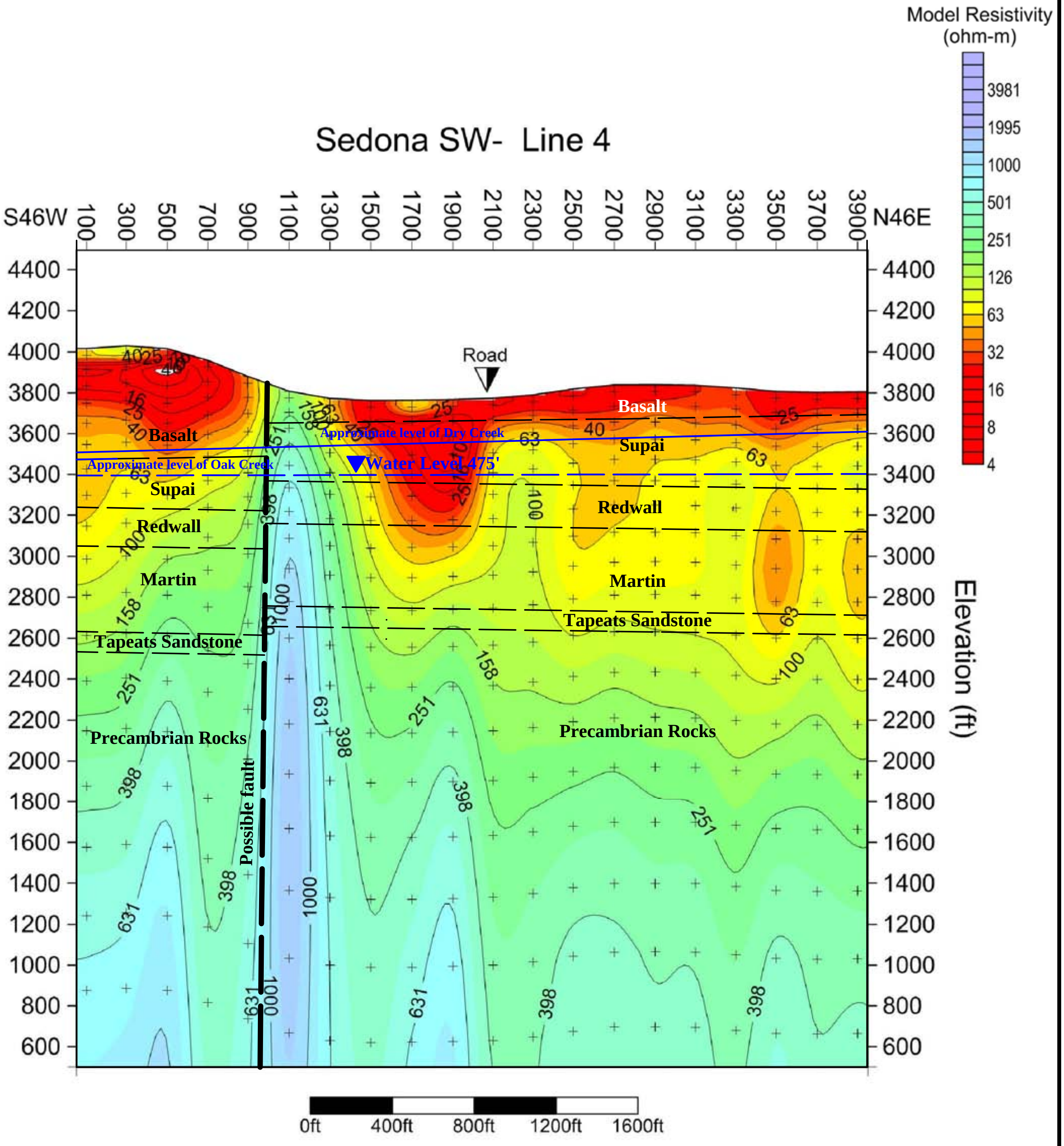

HydroSystems, Inc.

Line 4 CSAMT Cross-Section
City of Sedona Recharge Project

Figure 8

S:\08-563 Carollo-Sedona Recharge\Final Report\Phase 2\Figure Workspace\Figure 8 Line 4 with geology.dwg, 1/22/2010 11:30:11 AM

Photo 1. Character of the water-filled marshes separating the rapid infiltration basins on the WWTP.

Photo 2. The rapid infiltration basins on the WWTP property are covered with waist-high grass. Looking southeast towards House Mountain.

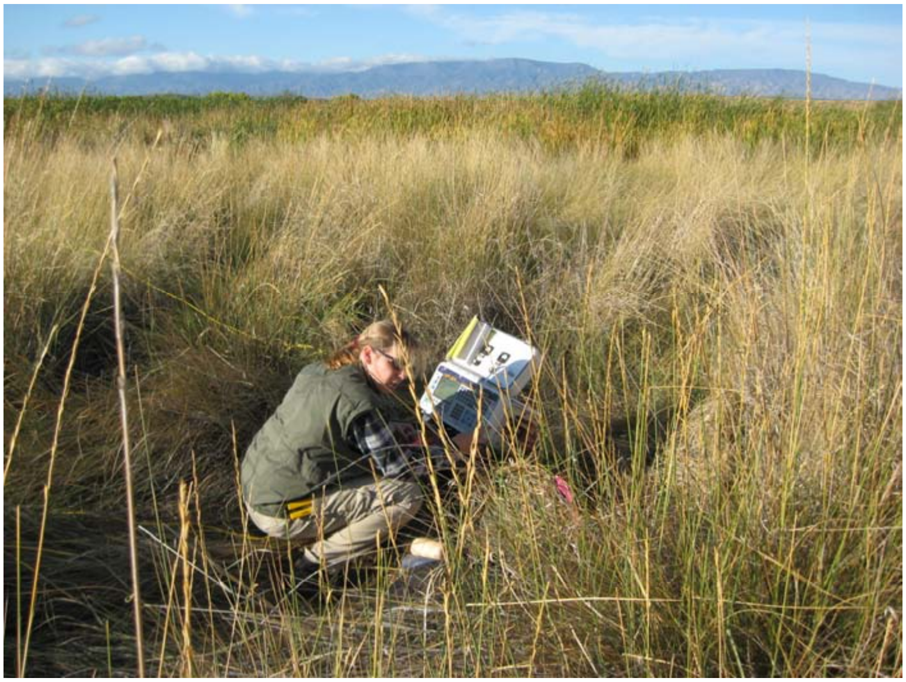

Photo 3. Receiver set-up in the rapid infiltration basins. Wires continue along line of sight through marshes in the distance.

Photo 4. A good view of the portable receiver set up to record data a few hundred feet north of the potable water well. Note electrode in the ground.

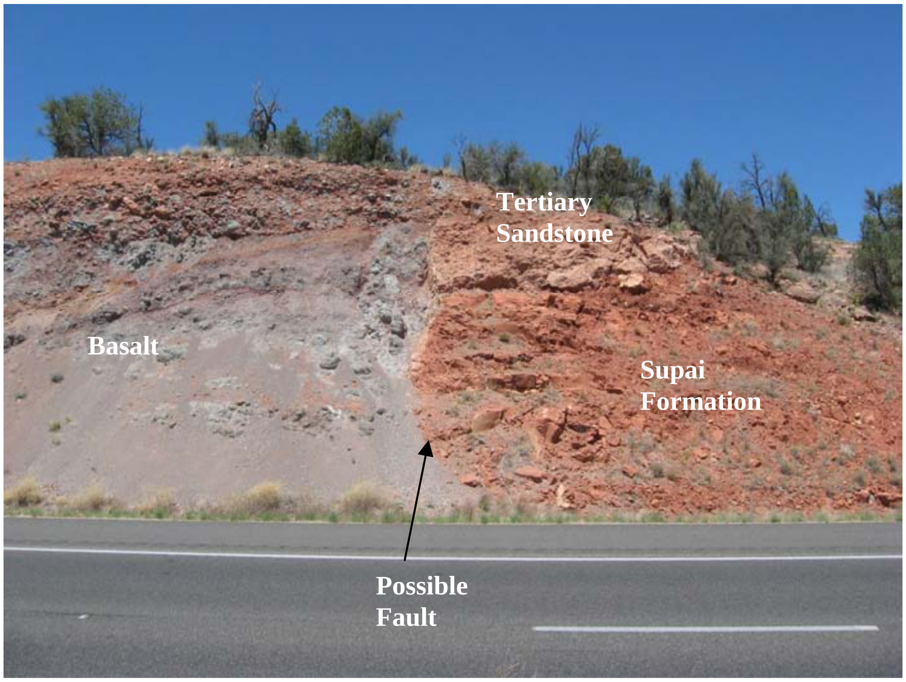

Photo 5. Road-cut exposure, looking west, immediately north of the WWTP showing a possible fault cutting basalt and Supai Formation.

Photo 6. Exposure of fine-grained sandstone and siltstone in the middle part of the Supai Formation along Highway 89A north of the WWTP.

Photo 7. A view of the landscape taken from near the south end of Line 3 looking northwest towards Line 4. The southern end of Line 4 is up on top of the tall hill to the left.