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Seismically Derived Aquifer Characteristics, Across Faulted Coastal Plain Sediments, Savannah River Site, South Carolina

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Summary
The integration of core, downhole geophysical, seismic and hydrologic data, made possible the detailed delineation of the stratigraphy and structure of the sedimentary sequence underlying the proposed site of a new sanitary landfill at the Savannah River Site, and the hydrologic response of the attendant hydrogeologic units. The proposed landfill site (Site R) was located near the updip limit of the Atlantic Coastal Plain sedimentary sequence and is underlain by a 275 m thick wedge of Cretaceous and Cenozoic sediments. Lateral and vertical facies changes are characteristic of the sequence, accounting for the observed complex variations in sediment lithology at the site.

The landfill siting study involved the hydrogeologic characteristics of the sediments in the upper 105 m thick Tertiary part of the section. This includes the Floridan aquifer system and its attendant aquifer and confining units and zones. The Floridan, in the updip coastal plain setting where the site is located, is composed mostly of clastic sediments and minor calcareous sediments and includes two aquifers, the Upper Three Runs aquifer and the underlying Gordon aquifer, separated by the Gordon confining unit.

Two faults (faults M and L) were delineated that significantly impacts the hydrologic characteristics of the aquifers beneath the site. Fault L, is a major northwest-southeast striking, northeast-dipping normal fault. Fault M is a down to the southwest normal fault that flanks fault L on the northeast and provides the northeastern limb of the down-dropped graben block located at the northwest end of the site. Fault L coalesces with fault M towards the center of the site, and Fault L continues to the southeast with reduced throw. All the aquifer and aquifer zones in the Tertiary portion of the section are breached along all or part of faults M and L. The result is hydraulic communication between the aquifers, eliminating the site for consideration as a landfill.

Introduction
Hydrologic, geologic and downhole geophysical data obtained from 16 borings and wells during the initial characterization phase of Site R (Figure 1), suggested that the site possibly had a "complex hydrogeology;" a SCDHEC regulatory term meaning multi-directional flow of the ground water. In addition, no upward hydraulic gradient was observed across the shallowest confining beds (a SCDHEC regulatory requirement), and possible faulting that offset and breached the shallowest confining beds was also suggested by the data. Based on these initial results, the drilling program was expanded to corroborate the findings. The expanded program included eleven new holes, six were core holes, four of which were converted to wells, and five holes were drilled only as wells. The core holes and wells were designed to augment core and potentiometric data in areas where core recovery was poor and/or potentiometric data were incomplete.

A high resolution seismic survey was conducted by the Earth Sciences and Resources Institute (ESRI), University of South Carolina, Columbia, SC. The purpose was to confirm the possible faulting suggested by the difference in elevation of the stratigraphic tops picked in well clusters LWR-5 and LWR-2, both of which were drilled during the initial characterization phase.

The seismic data were acquired using a 2401 Geometrics 24 channel seismograph and 100 Hz geophones. A 12-gauge downhole Betsey Seisgun was used as the source. The seismic data was processed using the Kansas Geological Survey software Evesdropper. The acquisition, recording and processing parameters are listed on the seismic line.

Stratigraphy
Site R is located near the updip limit of the Atlantic Coastal Plain sedimentary sequence and is underlain by a 275 m thick wedge of fluvial to marine Cretaceous and Cenozoic sediments, Figure 2 (Aadland and others, 1995). The sequence consists of about 170 m of Late Cretaceous quartz sand, pebbly sand, and kaolinitic clay, overlain by about 30 m of Paleocene clayey and silty quartz sand, glauconitic sand, and silt. The Paleocene beds are overlain by about 75 m of Eocene quartz sand, glauconitic quartz sand, clay and limestone grading into calcareous sand, silt and clay. The calcareous strata, though minor in amount, are common in the middle portion of the Eocene section. In places, especially at higher altitudes, deposits of pebbly, clayey sand, conglomerate, and clay of the Miocene/Oligocene age "upland unit" cap the sequence. Regional dip is to the southeast.

Lateral and vertical facies changes are characteristic of the upper Coastal Plain sequence. Fluctuating depositional conditions account for the observed complex variations in sediment lithology. Because the lithology of the sediments largely determines hydraulic conductivity, the occurrence and flow of ground water at Site R is strongly influenced by the granularity, composition, and bedding characteristics of the sediments.

The hydrogeologic characterization was concerned with the Tertiary part of the section. Tertiary sediments are divided into three groups that are further subdivided into nine formations, all overlain by the Miocene/Oligocene "upland unit." (Fallaw and Price, 1995). These formations are: the Black Mingo Group, (Sawdust Landing and Lang Syne formations the Snapp Formation, and the Fourmile Formation); the Orangeburg Group consisting of the Congaree Formation, the Warley Hill Formation, and the Santee Formation. From base upward, the Orangeburg Group sequence varies from clean shoreline sand characteristic of the Congaree Formation to shallow shelf marl, clay, sand, and limestone typical of the overlying Warley Hill and Santee formations. The carbonate content constitutes up to 30 percent of the sediment in the Santee at Site R. The contact between the Santee Formation and the sediments of the overlying Barnwell Group represents a major regional erosional unconformity; and the upper Eocene sediments of the Barnwell Group lie unconformably on the Santee Formation and includes the Dry Branch Formation, and overlying Tobacco Road Formation. The Dry Branch and Tobacco Road formations average 24.4 m in thickness. The Dry Branch Formation averages about 18.2 m in thickness, and consists of 9.1 to 10.7 m of slightly clayey to clayey, fine to medium sand interbedded and interlaminated with clay and locally calcareous mud (Fallaw and others, 1990), overlain by a prominent 6.1 to 7.6 m thick sand bed. The clay beds, which are not continuous over long distances, but can be a meter or more thick in places, constitute the Twiggs Clay Member of the Dry Branch Formation. The Tobacco Road Formation averages about 6.2 m in thickness, and consists of moderately to poorly sorted, fine- to coarse-grained, clayey quartz sand (Fallaw and Price, 1995). The top of the Tobacco Road Formation is defined where comparatively well sorted sand is overlain by more poorly sorted silty, clayey sand, pebbly sand, conglomerate and clay of the "upland unit."

Geologic Structure
The wells and bore holes drilled and completed prior to the drilling of well LWR-5 indicated an eastward dip in the section overlying the Santee unconformity, and a northerly to northwesterly dip in the section beneath the unconformity. In contrast the regional dip is to the southeast, and varies from about 6.6 m/km at the basement-Cretaceous contact to 2.3 m/km at the Santee unconformity (Aadland and others, 1995). The eastward dip orientation of the post-Santee sediments raised some concern that structure due to local faulting or folding was the cause for the anomalous dip orientation at the site, although none was demonstrated with the available well data.

LWR-5 was to be the last well drilled in the Initial Site Hydrogeologic Characterization (ISHC) of Site R. Located 70.1 m west-southwest of cluster LWR-2 (Figure 2), LWR-5 proved to be the critical well for the determination of the existence of faulting at the site. The Tobacco Road-Dry Branch contact horizon in LWR-5 was penetrated 5.5 m low to the contact in LWR-2. As a result, a down towards well LWR-5 fault (Fault M) was mapped between LWR-5 and LWR-2. West of LWR-5, at wells LWR-1 and LWR-6, the Dry Branch-Tobacco Road contact was penetrated at 66.1 m and 64.9 m (msl) respectively. Here a monoclinal dip was mapped assuming a downward rotation of the fault block on the southwest flank of Fault M. Well LWR-9 was drilled half way between wells LWR-6 and LWR-5 to confirm this interpretation. The Tobacco

Road-Dry Branch contact was predicted at 61.3 m above msl at the LWR-9 location, however, the contact was actually penetrated at 63.1 m above msl. This suggested a down towards well LWR-5 normal fault (Fault L) located between wells LWR-9 and LWR-5 with approximately 5.5 m of offset at the Tobacco Road-Dry Branch contact horizon. Consequently a graben was mapped (a flexured sag was also considered), with down towards well LWR-5 faults flanking the well both to the southwest and northeast.

Seismic lines #R-1 (Figure 3) and #R-2 (not shown) were acquired along the line that connects wells LWR-6, -9, -5, and -2, and parallels Cross-Section A-A'. The overall length of Line #R-1 is 335.1 m, however only the section of the line located from LRW-9 to LRW-2 is displayed. Examination of Line #R-1, indicates a major northwest-striking, northeast-dipping fault (Fault L) is present beneath site R. The fault extends into the Cretaceous to a depth of about 185 m below ground surface (the maximum penetration depth of this seismic survey). One of these, Fault M, provides the southeastern limb of the down-dropped graben block at well LWR-5.

Hydrostratigraphy

The hydrostratigraphic section beneath Site R consists of the upper Cretaceous to Holocene unconsolidated clastics and limestone of the Southeastern Coastal Plain hydrogeologic province (Aadland and others, 1995). The province is subdivided into three aquifer systems, in descending order, the Floridan aquifer system, the Dublin aquifer system and the Midville aquifer system, separated by the Meyers Branch confining system and the Allendale confining system respectively (Figure 4).

The landfill siting study was concerned with the hydrogeologic characteristics of the Floridan aquifer system and its attendant aquifer and confining units and zones. The Floridan, in the updip coastal plain setting where the Site R is located, is composed mostly of clastic sediments and minor calcareous sediments and includes two aquifers, the Upper Three Runs aquifer and the underlying Gordon aquifer, separated by the Gordon confining unit.

The Upper Three Runs aquifer is subdivided into two aquifer zones, the upper C Area aquifer zone (the unconfined water table aquifer) and the lower C Area aquifer zone separated by the Tan Clay confining zone. The lower C Area aquifer zone includes fine-grained lithologies that locally divide the zone into upper and lower aquifer sands.

The vadose zone at Site R includes the poorly sorted clayey sands and pebbly sands of the ''upland unit,'' the moderately to poorly sorted, fine- to coarse-grained, clayey quartz sand (Fallaw and Price, 1995) of the Tobacco Road Formation and the prominent 6.1 to 7.6 m thick sand bed that caps the Dry Branch Formation. The thickness of the zone varies from 24.1 m at well LWR-4 to 11.5 m at well LWR-5.

The upper C aquifer zone consists of medium to coarse sand to clayey sand of the Dry Branch Formation, above the clay, silty sandy clay, micritic clayey sand and calcareous mud of the Twiggs Clay Member of the Dry Branch. Twiggs Clay lithologies constitute the Tan Clay confining zone. The Tan Clay lithologies are not continuous over long distances, and range in thickness from 1.8 m at well locations LWR-5, -6 and -8, to 5.8 m at well location LWR-9.

Summary and Conclusions

The integration of core, downhole geophysical, seismic and hydrologic data, made possible the detailed delineation of the stratigraphy and structure of the sedimentary sequence underlying the site, and the hydrologic response to the continuity and geometry of the attendant hydrogeologic units.

In summary:

- All the aquifers above the Crouch Branch confining unit discharge, in varying degrees, to the northwest towards Fourmile Branch and its tributaries.
- The Tan Clay confining zone which separates the upper and lower C Area aquifer zones supports hydraulic heads of more than 1.5 m (at LWR-1) to 3 m (at cluster LWR-3) suggesting hydraulic separation between the two aquifer zones. However, piezometric heads measured in LWR-2 in the upper C Area aquifer zone and LWR-5 in the upper part of the

lower C Area aquifer zone were the same. Both wells straddle Fault M, suggesting hydraulic communication between the two zones at the northern end of Site R. Here, the 5.5 m of vertical displacement along faults L and M proved sufficient to breach the Tan Clay and groundwater from the unconfined upper C Area aquifer zone in part flows downward into the lower C Area aquifer zone along the breach.

- The downward flow of ground water into the upper part of the lower C Area aquifer zone results in the elevated piezometric surface observed in the unit over the trace of Fault M. The ridging is pronounced where both Fault M and L are present to the north.
- To the south at wells LWR-8 and LWR-7 which straddle Fault L, the Tan Clay confining zone supports head differences of 2.3 m and 2.7 m respectively. Where faults M and L coalesce, the offset on the continuation of Fault L is insufficient to breach the confining zone and downward flow of groundwater into the lower C Area aquifer zone is minimal and the piezometric ''ridge'' noted to the north is much less pronounced.
- The potentiometric map of the lower sand of the lower C Area aquifer zone generally defines a northwesterly flow of water through the unit. The depression in the piezometric surface near well cluster LWR-4 suggests a downward component of flow in the vicinity of Fault L where the underlying Gordon confining unit is breached.
- Because of the reduced offset on Fault L to the south, recharge to the lower sand unit of the lower C Area aquifer zone from the overlying upper sand unit is minimized and is insufficient to compensated for the downward component of flow into the underlying Gordon aquifer. The result is the pronounced depression in the piezometric surface of the lower sand unit of the lower C Area aquifer zone to the south.

In conclusion, faults M and L first postulated from core and downhole geophysical correlations, and corroborated with the seismic data, have a profound influence on the flow paths and direction of ground water discharge through the various aquifer units and zones and on hydraulic communication between the aquifer units and zones. Indeed, all aquifers and confining units and zones in the Floridan aquifer system down to the Crouch Branch confining unit have been breached along all or part of the fault trace. The result is hydraulic communication between the aquifers, eliminating Site R for consideration as a site for a new sanitary landfill.

References

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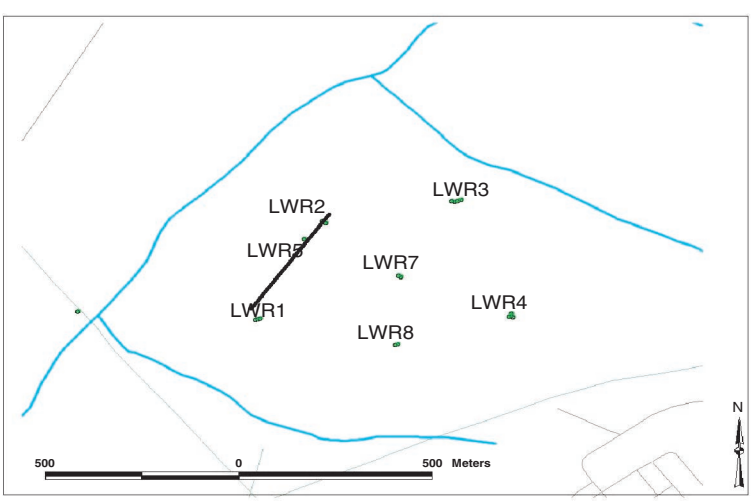

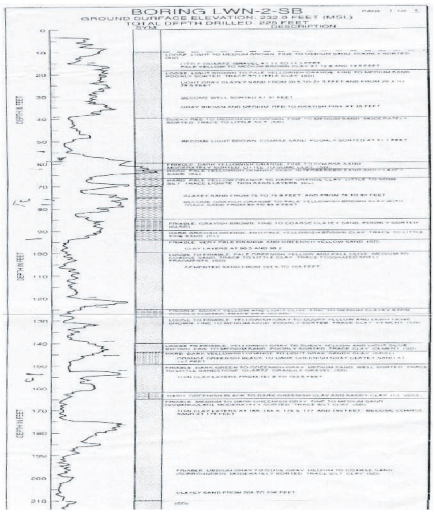

Figure 1 (site map) and Figure 2 (reference geophysical log). Figure 1 shows wells and the location of seismic line R-1 (dark line). Figure 2 shows a reference gamma ray curve.

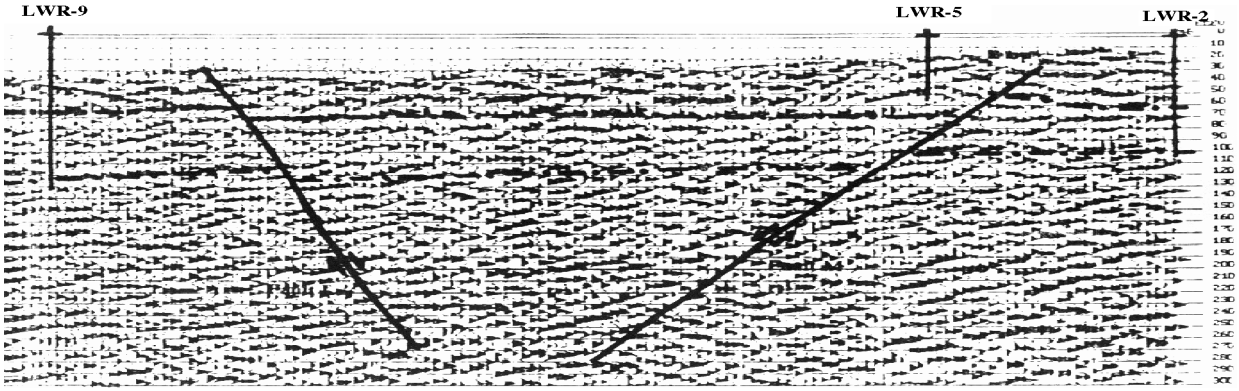

Figure 3. Seismic line R-1 (refer to Figure 1). Faults M (right) and L (left) are shown defining a graben in shallow sediments.

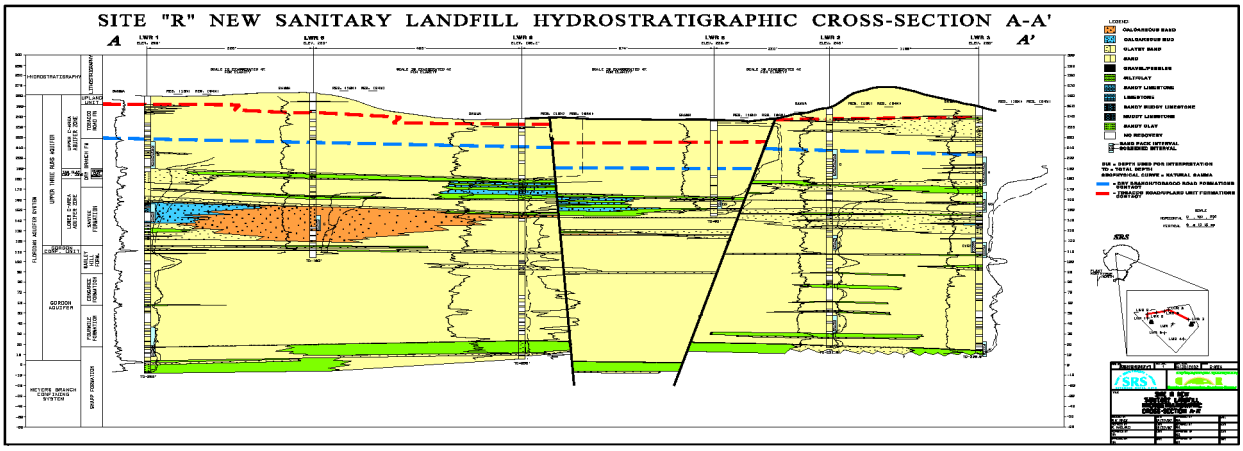

Figure 4. Interpreted cross-section A-A' following seismic line R-1. The graben and subsequently measured water table levels are shown (dashed lines).