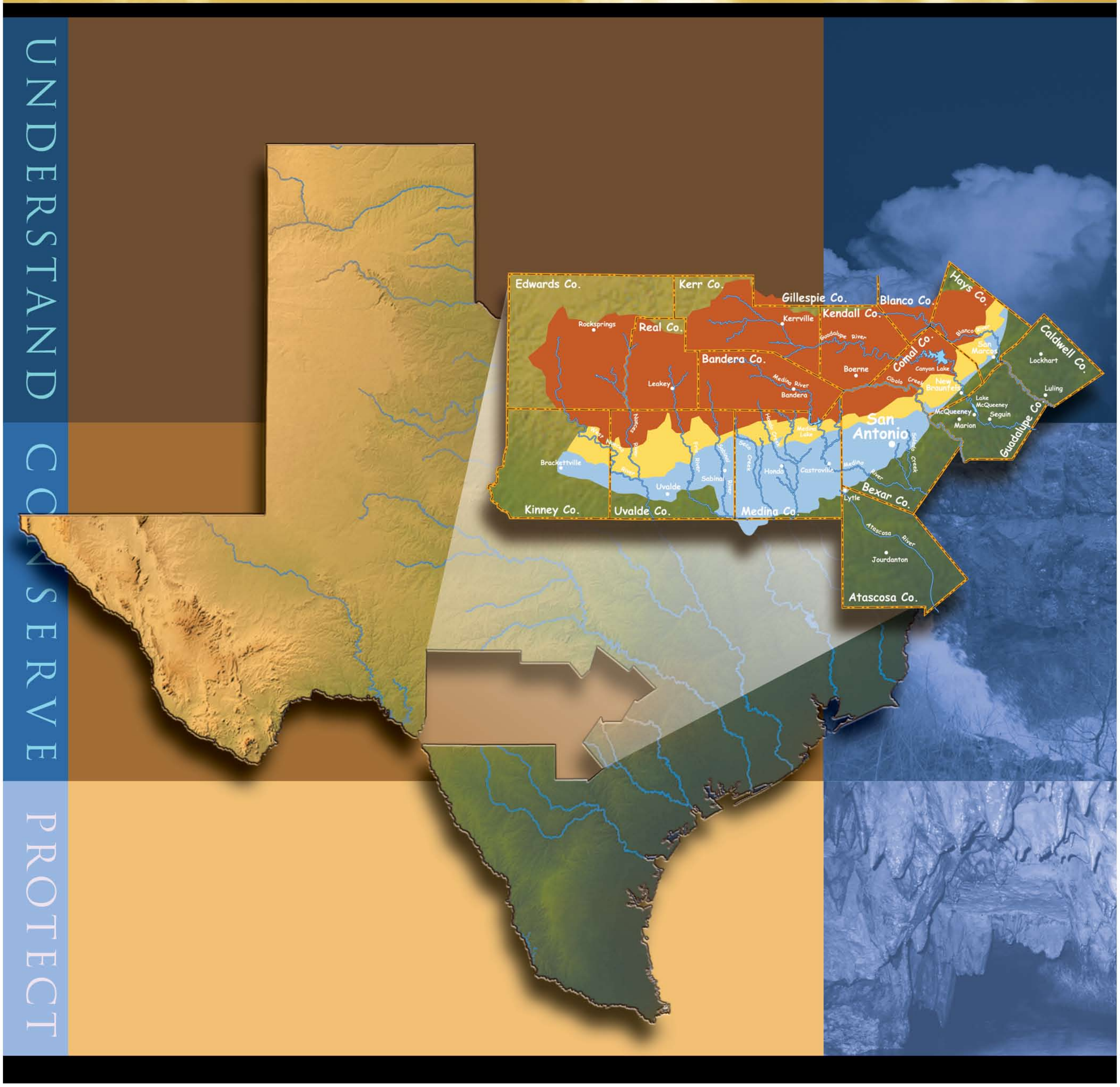
Edwards Aquifer Authority
Well Plugging and Abandonment Study



EDWARDS AQUIFER AUTHORITY

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EDWARDS AQUIFER WELL PLUGGING AND ABANDONMENT STUDY

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TABLE OF CONTENTS

List of Figures

List of Photographs

List of Tables

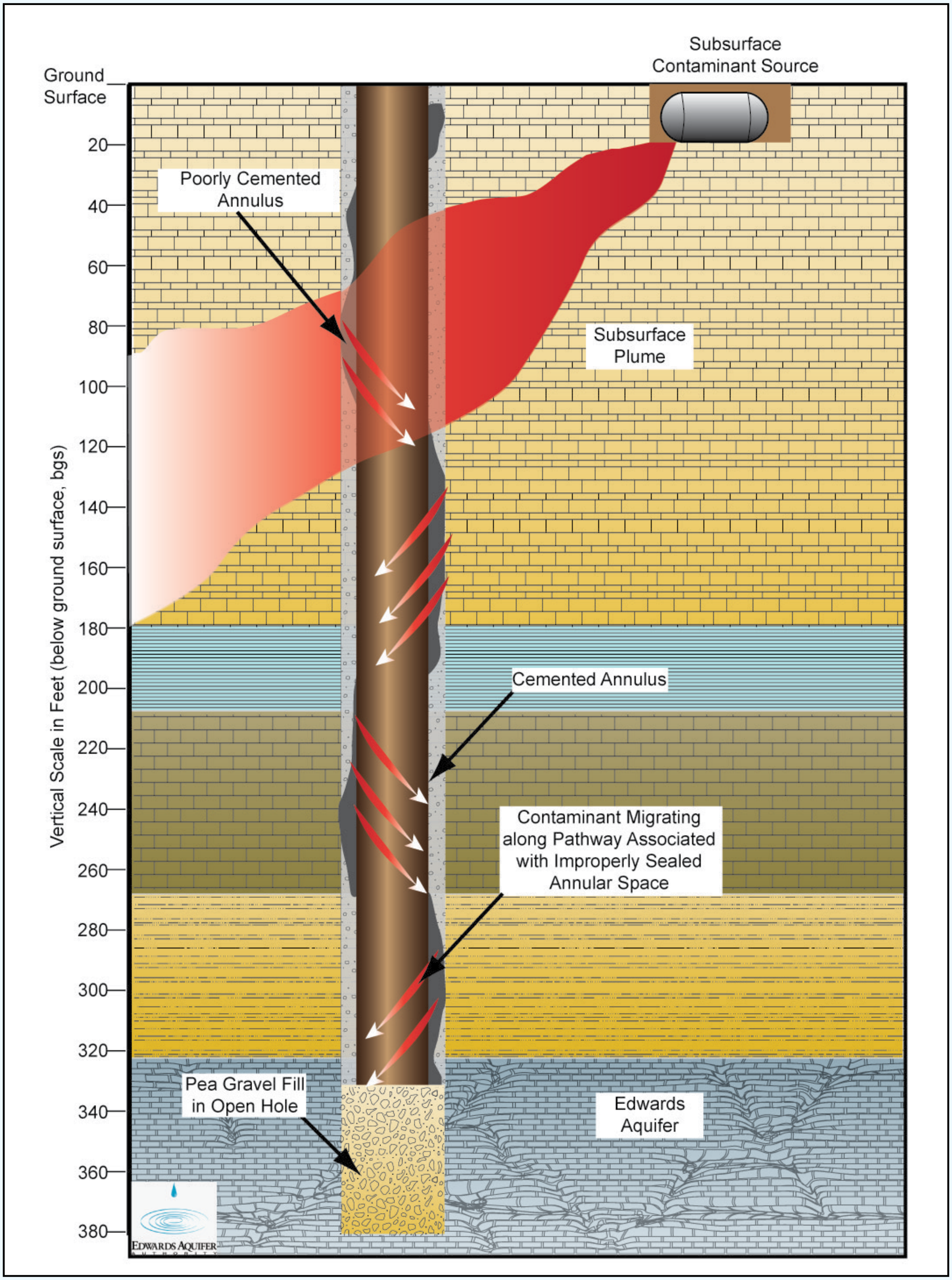
Appendices

INTRODUCTION

The Balcones Fault Zone Edwards Aquifer has been utilized as a water resource for municipal, industrial, and agricultural purposes for more than 100 years. Degraded or improperly maintained wells can act as conduits for undesirable water quality or materials to pass from the land surface into a groundwater resource. In addition, abandoned wells can be safety hazards for children, pets, and wildlife. Wells requiring sealing may occur because of changes in land use or maintenance practices, water quality or well material degradation, collapse of the aquifer formation, or an inability to remove well-pumping equipment, etc. However, wells in which only the well bore has been sealed create potential hazards to groundwater quality by allowing poor quality water to migrate between geologic zones within the annular space (the area between the formation wall and the outer well casing). This study evaluated the effectiveness of perforating a well casing to seal the annular space and prevent fluid migration.

The Edwards Aquifer Authority (EAA) conducts a variety of studies so that the characteristics of the Edwards Aquifer can be better understood, thus providing the technical basis for effective management and protection of the aquifer. EAA regulations require plugging of abandoned wells. These regulations include a requirement either to remove or perforate the well casing and sealing of the annular space. During well construction, the annular space on some wells may not have been sealed for any number of reasons, such as drilling practices at the time of construction, depth, cost, technical difficulties, etc. A properly sealed annular space prevents communication between formations, as well as seepage of contaminants from the surface, and is now required of all wells constructed in the Edwards Aquifer region. Figure 1 illustrates one scenario in which contamination can migrate from a source area into the aquifer through a well having an inadequate annular seal (many other scenarios exist for improperly abandoned wells). Contamination created by poorly abandoned wells is also difficult to detect, evaluate, or mitigate. This study focused on evaluation of the efficacy of perforating a well casing prior to plugging to ensure that an adequate annular seal is obtained when a well is sealed with cement grout.

Figure 1. Contamination Scenario Associated with an Improperly Plugged Well



OBJECTIVE

The need for this Well Plugging Study (WPS) was defined in the 2009 Aquifer Science Research Program Study Plan (ASRPP), (Edwards Aquifer Authority, 2009). The study was designed to evaluate the effectiveness of current well-plugging practices with regard to protection of water quality. Objectives of this study were to evaluate:

- A well plugging event to assess the methodology's effectiveness regarding protection of water quality;
- The quality of the annular seal in the well for the entire length of casing prior to perforation;
- The effect of perforating the casing prior to emplacement of grout; and
- The quality of the annular seal after perforation and grout emplacement.

The study involved the following process: (1) application of various geophysical logging methods to an Edwards Aquifer well prior to abandonment so that areas with an inadequate annular seal behind the casing could be identified, (2) subsequent perforation of the well casing at selected depths using mechanical methods and findings of the geophysical logs, (3) sealing of the well bore and annular space, and (4) redrilling and relogging of the well to evaluate the efficacy of the seal prior to final plugging of the well.

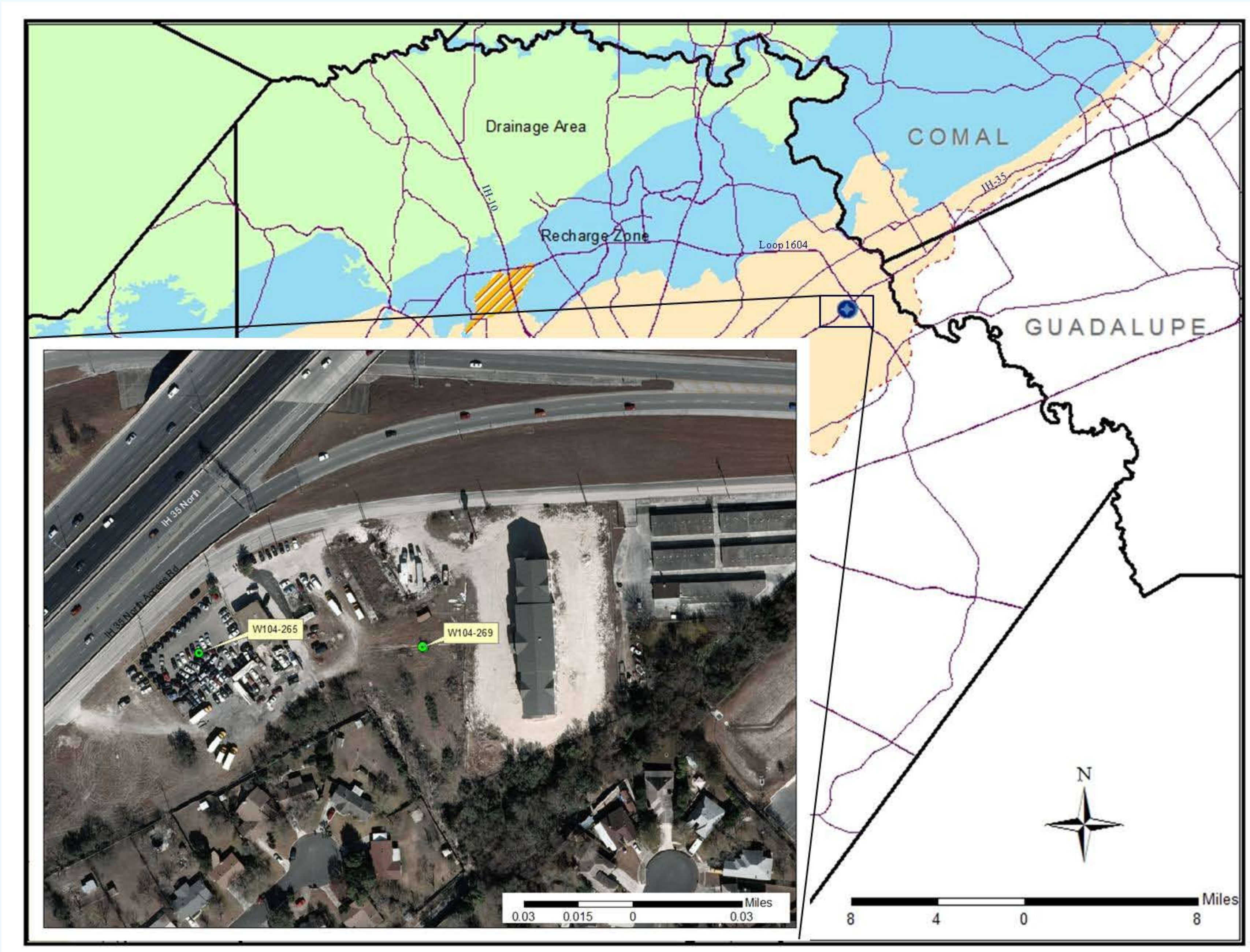
DATA ACQUISITION

Well selection

EAA staff searched extensively for wells that would meet the study criteria. Candidate wells were evaluated on their location (geology), well depth, amount (depth) and size (diameter) of casing, and willingness of the owner to participate in the study. Multiple wells, with various casing diameters and depths ranging from 200 to 800 ft, were evaluated as possible candidates for the study. Two wells on property owned by Uni-Vest Assets, L.P., in northeastern Bexar County, Texas, were selected as potential candidates (Figure 2).

Another criterion considered in the selection process was an opportunity for a cost-sharing agreement with the well owner. Evaluation of the two Bexar County wells indicated that each well required removal of pump and well debris by a drill rig prior to final determination of their true condition.

Figure 2. Location of Candidate Wells for Well Plugging Study



After removal of the pump and well debris, a physical inspection of the condition of each well was made using the EAA's downhole camera and geophysical logging tools. The wells were assessed for total depth, casing depth, casing diameter, and borehole diameter. In addition, an attempt was made to determine the presence and distribution of material in the annular space of the wells using the EAA's full wave sonic tool. In this process, geophysical logging tools were placed into a well to develop a record of the physical properties of a well. Probes that measure different properties were lowered into the borehole to collect continuous or point data that are displayed graphically on a geophysical log. Geophysical well logs are used in groundwater and environmental investigations to obtain information on well construction and rock properties such as permeability, porosity, and water quality. Much more can be learned by analysis of a suite of geophysical logs than by analysis of a single geophysical log. Geophysical tools used for the study are described in Table 1.

Table 1. Description of Geophysical Tools Used in This Study and Their Attributes.

Tool Name	Abbreviation	Description
Three-arm caliper		Continuously measures diameter of well casing and hole.
Natural gamma		Measures natural radioactivity of geologic materials, but does not reflect condition or nature of annular material. These logs are commonly used to identify borehole stratigraphy.
Downhole camera	DHC	Provides visual inspection of casing and open borehole.
Full wave sonic or cement bond log	FWS or CBL	Detects annular space or voids.
Compensated gamma–gamma density (or compensated density log)	CDL	Measures natural bulk density, porosity, and moisture content of geologic materials.
Neutron (source)		Detects hydrogen content and saturated porosity.

Tool description

The natural gamma and caliper tools were used to identify geologic units and determine casing and borehole depths (Appendices A and B). The natural gamma tool records natural gamma radiation emitting from a formation and is commonly used to identify specific rock units within a well. The caliper tool measures a borehole or casing diameter and can commonly be used to determine casing depth. It may also indicate damaged casing or large voids encountered by the borehole. The downhole camera (DHC) was used to visually inspect the well casing to identify possible corrosion or damage and/or condition of the open borehole, as well as to determine or confirm well and casing depth. Imaging of the geological formation in the open-hole section by the DHC enabled characterization of the physical appearance of the rock section.

The full wave sonic (FWS), also called the *cement bond log* (CBL), is a geophysical tool that can be used for annular void detection by recording the characteristics of sound waves as they travel through liquid-filled rock. The amplitude of the early arriving signal of the CBL log provides information on the presence of annular fill material (cement or grout) and the quality of the bond between the casing and the cement and between the cement and borehole wall. The velocity at which the signal is recorded, i.e., the formation acoustic velocity

(FAV), measured in μS/ft (microsec/ft—the inverse of velocity used to evaluate the acoustic property of the medium [Keys, 1989]). The FAV is the main component of the CBL (Keys, 1989). Good bonding of cement to casing is represented by a decrease in amplitude of the early signal, or fast FAV. The CBL was the initial log used to determine the presence and amount of material within the annular space of the well. However, this tool is ineffective above the water level in the well.

The compensated gamma–gamma density tool, which produces the compensated density log (CDL), consists of a radioactive gamma-ray (neutron) source that is lowered into a well bore to measure the bulk density of a formation. A radiation counter mounted above the gamma-ray source on the tool measures the intensity of the signal traveling through the material. Radiation passes through the rock and is recorded by the counter. Denser rock allows fewer gamma rays to reach the counter versus less dense rock, which allows more gamma rays. Rock density is generally a function of porosity.

The neutron source tool continuously measures induced radiation from an isotopic source as it travels through the formations penetrated by a borehole (Keys, 1989). The neutron tool is used primarily to evaluate formation porosity and is effectively a hydrogen (water) detector. It is used to correlate between open- and cased-hole logs, usually in conjunction with the natural gamma tool. In some areas where gamma-ray logs produced by the natural gamma tool show little variability, the log from the neutron tool is indispensable for correlation purposes (Keys, 1989). A neutron tool sends out high-speed neutrons into the formation, and neutrons interact with the formation, losing energy. Counts of these low-energy neutrons, or gamma rays that they produce, can be related to porosity. The terms *near* and *far* refer to the signal received by the near and far detectors that are placed at different distances from the neutron source (Figure 3). The nuclear source tool uses near and far detectors to estimate the size of the neutron cloud around the source by calculating the ratio of the count rates at these detectors.

Figure 3. Schematic Drawing of Neutron Tool; Source and Detectors Are Held Pressed against the Borehole Wall (from Keys, 1989)

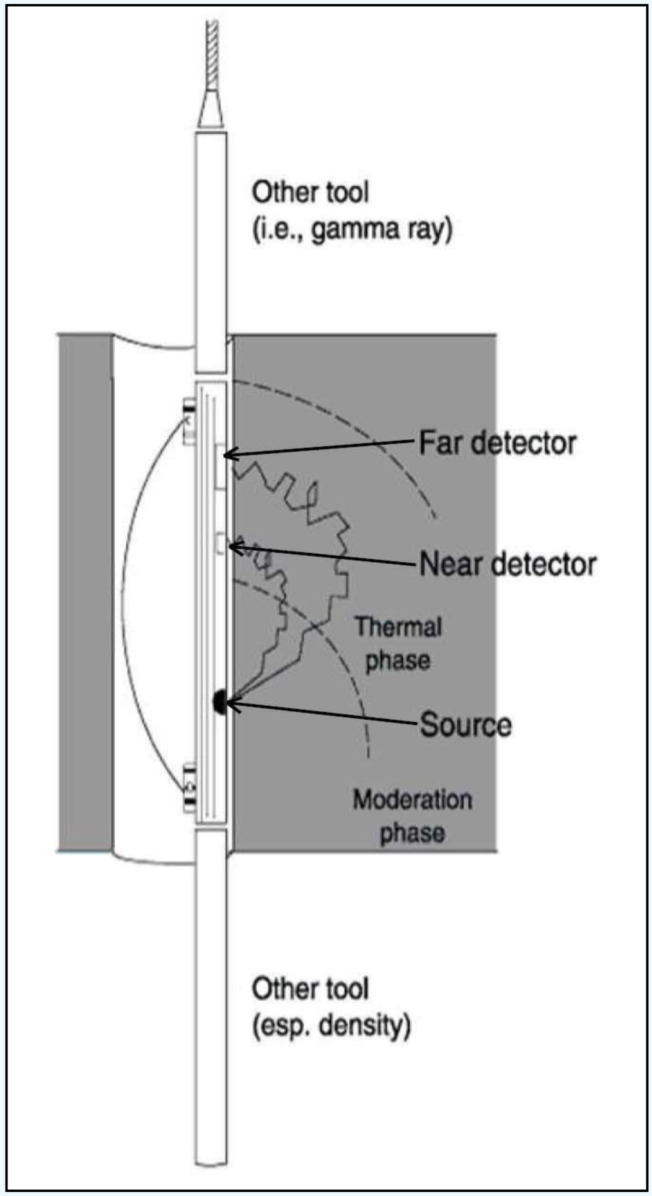


Table 2 describes the two wells extensively evaluated for this study, Table 3 lists the geologic units in each well identified from geophysical logs, and Table 4 displays a summary of the hydrogeologic subdivisions of the geologic section usually encountered above and below the Edwards Aquifer in northeastern Bexar County, as developed by Stein and Ozuna (1996).

Table 2. Well Descriptions.

EAGIS Well ID Number	Well Name	Well Depth (ft)	Casing Diameter (inches)	Casing Depth (ft)	Top of Edwards Aquifer (ft)
W104-265	Car Lot	373	6	333	322
W104-269	Empty Lot	316	5	257*	307

*Casing did not extend into the Edwards Aquifer and ended in the Del Rio Clay.

Table 3. Depths and Thicknesses, in Feet, of the Geologic Units Identified Using Natural Gamma Logs.

Geologic Formation	W104-265 Car Lot Well Depth and Total Thickness ( ) in Ft	W104-269 Empty Lot Well Depth and Total Thickness ( ) in Ft
Pecan Gap Chalk	0 to 67 (67)	0 to 65 (65)
Austin Chalk	67 to 180 (113)	65 to 173 (108)
Eagle Ford Group (shale)	180 to 210 (30)	173 to 203 (30)
Buda Limestone	210 to 268 (58)	203 to 257 (54)
Del Rio Clay	268 to 322 (54)	257 to 307 (50)
Edwards Group	322 to 373 (51)	307 to 316 (9)

After the DHC video and geophysical data were evaluated in detail, well W104-265 (Car Lot Well) was selected as the principal well for the study because it best met study criteria. Specifically, W104-265 was deeper, had a larger diameter steel casing, had a longer casing, was cased into the top of the Edwards Aquifer, and had more open section of the Edwards Aquifer available than did W104-269 (Empty Lot Well). Well W104-269 was permanently plugged without further evaluation.

Table 4. Summary of Lithologic and Hydrologic Properties of Geologic Subdivisions of Confining and Edwards Aquifer Units in Bexar County, Texas.

[Hydrogeologic subdivisions modified from Maclay and Small (1976); groups, formations, and members modified from Rose (1972); lithology modified from Dunham (1962); and porosity type modified from Choquette and Pray (1970). CU, confining unit; AQ, aquifer]

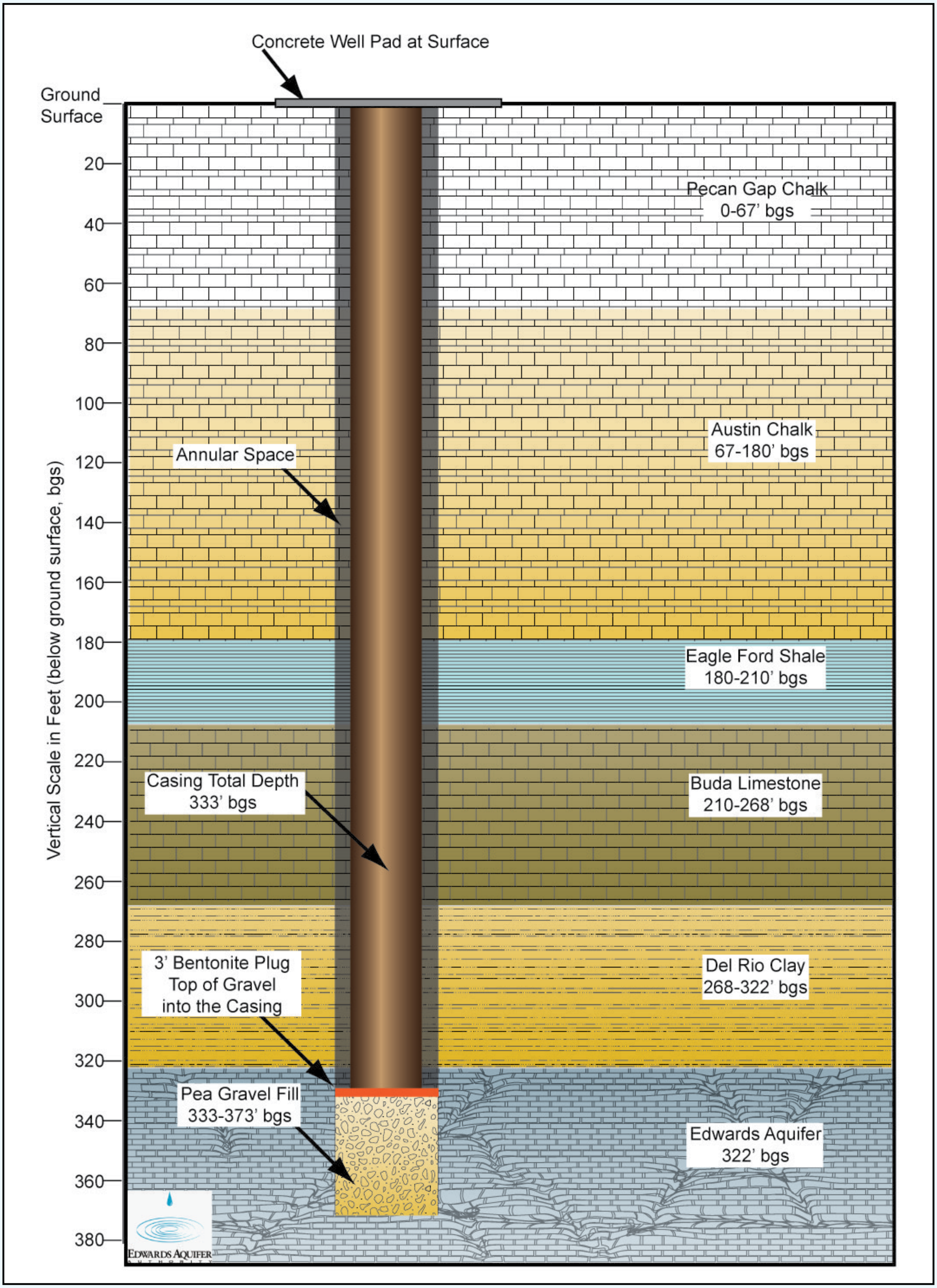
Hydrogeologic subdivision	Group, formation, or member	Hydrologic function	Thickness (feet)	Lithology	Field identification	Cavern development	Porosity/ permeability type
Upper Cretaceous; Upper confining units	Eagle Ford Group	CU	30 – 50	Brown, flaggy shale and argillaceous limestone	Thin flagstones; petroliferous	None	Primary porosity lost/ low permeability
Upper Cretaceous; Upper confining units	Buda Limestone	CU	40 – 50	Buff, light gray, dense mudstone	Porcelaneous limestone with calcite-filled veins	Minor surface karst	Low porosity/low permeability
Upper Cretaceous; Upper confining units	Del Rio Clay	CU	40 – 50	Blue-green to yellow-brown clay	Fossiliferous; *Ilymatogyra arietina*	None	None/primary upper confining unit
Lower Cretaceous; Edwards aquifer; I	Georgetown Formation	Karst AQ; not karst CU	2 – 20	Reddish-brown, gray to light tan marly limestone	Marker fossil; *Waconella wacoensis*	None	Low porosity/low permeability
Lower Cretaceous; Edwards aquifer; II	Edwards Group; Person Formation; Cyclic and marine members, undivided	AQ	80 – 90	Mudstone to packstone; *miliolid* grainstone; chert	Thin graded cycles; massive beds to relatively thin beds; crossbeds	Many subsurface; might be associated with earlier karst development	Laterally extensive; both fabric and not fabric/water-yielding
Lower Cretaceous; Edwards aquifer; III	Edwards Group; Person Formation; Leached and collapsed members, undivided	AQ	70 – 90	Crystalline limestone; mudstone to grainstone; chert; collapsed breccia	Bioturbated iron-stained beds separated by massive limestone beds; stromatolitic limestone	Extensive lateral development; large rooms	Majority not fabric/one of the most permeable
Lower Cretaceous; Edwards aquifer; IV	Edwards Group; Person Formation; Regional dense member	CU	20 – 24	Dense, argillaceous mudstone	Wispy iron-oxide stains	Very few; only vertical fracture enlargement	Not fabric/low permeability; vertical barrier
Lower Cretaceous; Edwards aquifer; V	Edwards Group; Kainer Formation; Grainstone member	AQ	50 – 60	*Miliolid* grainstone; mudstone to wackestone; chert	White crossbedded grainstone	Few	Not fabric/ recrystallization reduces permeability
Lower Cretaceous; Edwards aquifer; VI	Edwards Group; Kainer Formation; Kirschberg evaporite member	AQ	50 – 60	Highly altered crystalline limestone; chalky mudstone; chert	Boxwork voids, with neospar and travertine frame	Probably extensive cave development	Majority fabric/one of the most permeable
Lower Cretaceous; Edwards aquifer; VII	Edwards Group; Kainer Formation; Dolomitic member	AQ	110 – 130	Mudstone to grainstone; crystalline limestone; chert	Massively bedded light gray, *Toucasia* abundant	Caves related to structure or bedding planes	Mostly not fabric; some bedding plane-fabric/water-yielding
Lower Cretaceous; Edwards aquifer; VIII	Edwards Group; Kainer Formation; Basal nodular member	Karst AQ; not karst CU	50 – 60	Shaly, nodular limestone; mudstone and *miliolid* grainstone	Massive, nodular and mottled, *Exogyra texana*	Large lateral caves at surface; a few caves near Cibolo Creek	Fabric; stratigraphically controlled/large conduit flow at surface; no permeability in subsurface
Lower Cretaceous; Lower confining unit	Upper member of the Glen Rose Limestone	CU; evaporite beds AQ	350 – 500	Yellowish tan, thinly bedded limestone and marl	Stair-step topography; alternating limestone and marl	Some surface cave development	Some water production at evaporite beds/relatively impermeable

Source: Stein and Ozuna, 1996, U.S. Geological Survey WRIR 95-4030.

METHODOLOGY

The following methods were employed for the well abandonment study. Wells were first logged to total depth (TD) in the Edwards Aquifer by Geo Cam before any material had been placed (Appendices A and B). Washed pea gravel, one-quarter to one-half inch in diameter, was placed into the well bore from the bottom of the well to just below the bottom of the casing (373 to 333 ft below ground surface [ft bgs]). A plug composed of bentonite was then placed on top of the gravel until it extended into the steel casing (333 to 330 ft bgs). The gravel and bentonite plug were placed in the well bore to provide support for the emplacement of cement grout in the well casing. The fill material was also added so that the nuclear source tool could not be lost in the formation during assessment. The DHC, the three-arm caliper, and natural gamma logs were then reapplied to the well to ensure location and quality of the gravel and bentonite plug (Figure 4).

Figure 4. Schematic Drawing of Well W104-265 and Surrounding Geologic Units



Plugging activities then proceeded as follows:

1. Potable water was added to the well casing, and the FWS tool was used to evaluate the extent of cement in the annular space by analysis of the CBL (Appendix C).
2. On the basis of these additional data and subsequent interpretation, W104-265 was then logged using the compensated gamma–gamma density and neutron tools to further identify and characterize the annular seal in the well (Appendices D and E).
3. Data (logs) from the compensated gamma–gamma density and neutron tool were used to identify the most appropriate locations for perforation of the well casing to test the efficiency of sealing of the annular space with grout. This activity was compared with perforation of the well “whenever practicable to assure placement of an effective seal” (Edwards Aquifer Authority Final Rules, 2009, § 713.320 Standards for Plugging Wells), i.e., EAA well plugging permits, issued for wells within the area of the well plugging study, generally require 50-foot casing perforation intervals beginning at the base of the Austin Chalk.
4. The steel well casing was then perforated using either two or three directional perforation charges at specific depths (Figure 5). The three-shot directional charge string was used in the water-filled section of the borehole to compensate for water resistance to the blast. The two-shot directional charge string was used in the air-filled section of the borehole.
5. Perforation of the casing was followed by DHC and caliper tools to ensure that the casing was perforated. Observations indicate that perforations affected mostly one side of the casing. This asymmetry was most likely the result of the shot string not being centralized in the borehole. Photographs 1 through 7 are pictures of perforated casing at different depths.
6. After perforation and logging, the steel casing was filled with cement grout using the tremmie method and allowed to cure for 24 hours. The grout was drilled and reamed, ensuring that the casing would not be damaged.
7. The DHC, FWS, CDL, and neutron source tools were rerun in the well to compare and assess the quality of plugging and cement bonding behind the steel casing.
8. After final well logging, the well was plugged by placing cement in the borehole, as required by the EAA’s plugging regulations.

Figure 5. Explosives Used to Perforate Casing; Charges are Approximately Two and Three-Quarters to Three Inches apart Vertically

DATA ANALYSIS

Century Wireline Services of Tulsa, Oklahoma, performed nuclear-source (compensated gamma–gamma density and neutron source) logging, whereas RAS, Integrated Subsurface Evaluation, Inc., of Golden, Colorado (RAS, Inc.), provided interpretations of the full wave sonic (FWS) and nuclear source (CDL and neutron) logs. Additional borehole logging was also performed by EAA staff using the EAA's nonnuclear logging equipment. With the exception of the FWS tool, the EAA's downhole geophysical tools are incapable of evaluating a well's annular space. However, the EAA's suite of tools can be used to determine casing diameter, casing depth, formation characteristics, water quality, vertical and horizontal water movement, etc., which were important in the design of this study. Table 5 describes the characteristics of the geophysical tools used to determine annular seal; FWS tools can provide some indication of the annular seal in a well. FWS logging by the EAA indicated the presence of voids or partly voided space behind the well casing in some locations within the test well. Preparation for the FWS log included filling of the well casing with water, although the well could be filled only to approximately 85 ft. The upper 85 ft of casing would not retain water owing to an apparent casing leak, which rendered the FWS unusable in this section of the casing. FWS must be submerged in water to provide reliable data. The inability of the casing to fill to the surface could be an indication of possible rotted casing, combined with no or poor annular seal. FWS logging was performed before CDL or neutron logging. An evaluation of the FWS log indicates the presence of voids from 85 to 125 and 165 to 270 ft bgs.

A comparison of the FWS with nuclear logs did not provide good agreement. Nuclear tools are the industry standard for evaluating annular space and geologic formations because of their nuclear source. They are considered a much more accurate and reliable tool, and, FWS tools were therefore considered insufficiently reliable for this study. A number of variables might create a suspect FWS log, including a malfunctioning tool, incorrect calibration, cement film on the inside of the casing, poor contact between the casing and the concrete, etc. Because of these limitations, nuclear source logging with compensated gamma–gamma density (CDL) and neutron (source) tool were selected to confirm the location and extent of the annular seal.

On the basis of nuclear logging, significant variations in the integrity of the annular seal were discovered. A nuclear log response for an interval with poor annular seal (i.e., 50–100% voids) was identified from 28 to 42 ft bgs. Over this interval, the CDL and near and far neutron logs were anomalously low compared with logs of the intervals immediately above and below this zone. The low-density response is caused by the absence of an adequate annular fill (air-filled void) because the density of air is effectively 0 gram per cubic centimeter (g/cc), (RAS, Inc., personal communication, unpublished report). The near and far neutron logs and CDL response indicate a decrease in relative hydrogen content (air has effectively no hydrogen content). Similar responses were also observed at the interval from 192.5 to 215 ft bgs (Appendix F—RAS Montage).

By comparison, the nuclear source log responses for the interval from 42 to 192 ft bgs depict good to marginal annular conditions (solid with no to few voids). The cement-filled annular intervals possess higher relative hydrogen content (as indicated by maximum values from near and far neutron logs) and lower detector counts due to clay minerals of the concrete (from the CDL), as well as associated interstitial water. Near and far neutron logs and CDL are at maximum values over this interval and reasonably constant (RAS, Inc., personal communication, unpublished report).

RAS, Inc. (personal communication, unpublished report), reported that marginal annular conditions in the unsaturated interval, i.e., above the measured water level of 215.85 ft bgs, described as being 10 to 50% void, are most likely native back-fill material. Figure 6 summarizes parts of the well montage in Appendix F, indicating the quality of the annular seal that is based on interpretation of log data. RAS's detailed assessment of these logs suggests that approximately 102 ft (35%) of the well had poor annular seal, 45.5 ft (15.6%) had marginal annular seal, and 142.5 ft (49%) had good annular seal, for a total casing length of 290 ft (Appendix F).

Figure 6. Analysis of Annular Seal in Well104-625 Derived from Density Compensated and Neutron Logs

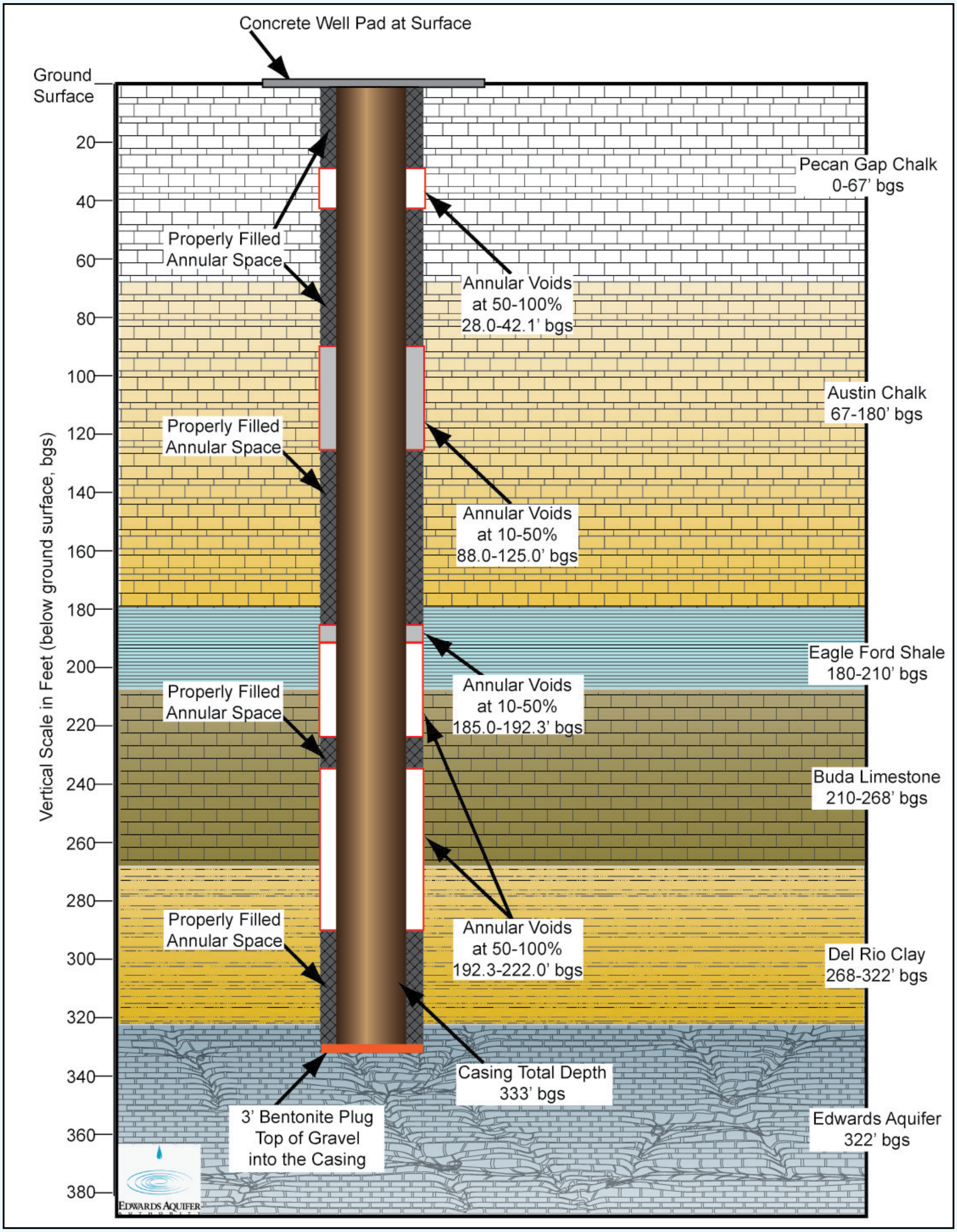


Table 5. Characteristics of Logging Tools and Their Effectiveness Determining Annular Fill.

	Relevant Well Condition	
Log Type	**Above Water**	**Below Water**
Full wave sonic (FWS)	Ineffective	Slower transit time (many microseconds per foot) may indicate a good seal between casing, annular fill, and formation because the wave travels through annular material before it is refracted back to detector. When there is a poor seal, the wave travels along steel casing before being refracted back to detector—resulting wave arrives at detector much sooner. Note that transmitter and receiver spacing may therefore impact effectiveness of given sonic tool for detecting annular voids and degree of cement bond.
Compensated gamma–gamma density (compensated density log [CDL])	Low count rate will correlate to low density because results are proportional to electron density of surrounding materials. Consequently, low density will indicate void within annular space.	Low count in water correlates to low density because results are proportional to electron density of surrounding materials. Low density will indicate void within annular space because cement is much denser than water.
Neutron (source)	Neutron log related to hydrogen content of surrounding material because hydrogen readily absorbs neutrons. Consequently, this log will show higher count rate when void is behind casing owing to air having much lower concentration of hydrogen than cement.	Log will show lower count rate owing to hydrogen atoms in water molecule in casing. However, an even lower count occurs when fluid-filled porosity occurs behind casing.

Source: RAS, Inc. (personal communication, unpublished report)

RAS, Inc. (personal communication, unpublished report) reported small-amplitude spikes in the neutron density log at approximately 20-foot intervals for the length of the casing. These anomalies are apparently due to casing couplings or joints. The overlapping of the casing couplings, or increased density associated with a joint weld, is apparent in the signal of the near neutron tool sensor log at depths of 27, 50.6, 70.5, 87, 110.5, 130, 150.5 and 169 ft bgs. These depths were confirmed with the DHC, although why the depths between joints are not exactly 20 ft apart is unknown, indicating that the near detector density log is also effective for evaluating tool response at about one to three inches away from the source, whereas the far neutron tool sensor looks deeper into the formation, approximately ten to 14 inches away from the source (depending on density of formation). The lack of a coupling response at depths greater than 170 ft bgs suggests that the casing may have deteriorated, in comparison to the upper casing (0–170 ft). This interval may also correspond to higher historical water levels and wet/dry cycling of the casing associated with pumping activities (RAS, Inc., personal communication, unpublished report).

As previously discussed, the upper 85 ft of casing could not be filled with water when the well was prepared for FWS logging because of possible rotted casing, combined with no or marginal annular fill (water leaked from casing at this level). As such, the upper 85-ft interval did not provide adequate data for an FWS void analysis. The uppermost annular void section, detected using nuclear logs at 27 to 42 ft, was above the water level at the time of logging and was therefore unsuitable for evaluation using the FWS tool. A comparison of the FWS with nuclear source logs indicates that the FWS log did not conclusively identify filled or annular void locations. However, water reaching only to a depth of 85 ft bgs is a direct indication of failed casing and annular space. This depth did correspond to data from the neutron and CDL logs, indicating marginal to poor annular seal and confirmed the reliability of nuclear source logs for this study.

Comparisons of two specific intervals in which the FWS and nuclear source tools obtained measurements reveal a noticeable lack of correlation. These intervals are at 150 to 185 and 193 to 280 ft bgs. In the interval from 150 to 185 ft bgs, the FWS log showed a marked increase in FAV, which is related to change in pressure and density of the geologic formation as a pulse per unit of length. FAV increases from 200 to approximately 400 µS/ft from 153 to 160 ft bgs only. This increase in acoustic speed is considered anomalous (in contrast to baseline values) and corresponds to good annular seals. However, nuclear source logs indicate that a good annular seal extends from 125 to 185 ft bgs. The nuclear density log, therefore, does not support sonic log interpretation (RAS, Inc., personal communication, unpublished report). Interpretation of the second interval, from 193 to 280 ft bgs, suggests that the annular seal is poor, with only the interval from 222 to 232.5 ft bgs indicating a good annular seal when using the nuclear logs are being used. The FWS log over the same interval is reasonably constant, with FAV from 100 to 170 µS/ft. The lowest part of the sonic log, from 271 to 290 ft bgs, does show a variation from this baseline and appears to correspond to the poor annular seal suggested by CDL (RAS, Inc., personal communication, unpublished report). Appendix F shows a comparison of results of nuclear density and FWS logs and indicates areas of suspected poor annular seal. Data from the nuclear source logs were used to select perforation points on the basis of distinctive qualities of the annular material (Table 6).

Table 6. Depths and Quality of Annular Material Based on Source-Log Interpretation.

Depth Range (ft)	Annular Material Quality from Interpretation of Source Log
0–28.0	Mostly solid to very solid annular material with minimal voids from original cementing
28.0–42.1	50 to 100% voids in annular space
42.1–88.0	Mostly solid to very solid annular material with minimal voids from original cementing
88.0–125.0	10 to 50% voids in annular material or native backfill
125.0–185.0	Mostly solid to very solid annular material with minimal voids from original cementing
185.0–192.3	10 to 50% voids in annular material or native backfill
192.3–222.0	50 to 100% voids in annular space
222.0–232.7	Mostly solid to very solid annular material with minimal voids from original cementing
232.7–289.0	50 to 100% voids in annular space

Source: RAS, Inc., personal communication, unpublished report

Selection of Perforation Locations

A total of five perforation locations were selected using information derived from the geophysical logs. Three of the perforation depths were selected either near the top of or within the interval in which voids were indicated in the annular space. The other two perforation locations were selected in solid annular material to act as a control on reliability of the source logging. The strategy of placing perforations near the top of identified voids was to allow grout to enter the void and then flow by gravity to fill the annular space. Perforations were created by lowering directional explosive charges into the well casing to the desired depth. Perforation charges were detonated at 31, 53, 135, 193 and 271 ft bgs. Table 7 indicates the depth of perforations, number of directional explosives used, whether the perforations were made above or below water level, and whether they will be placed in an annular fill or void.

Table 7. Results and Characteristics of Perforations.

Targeted Perforation Depth (ft) and Annular Fill Material	Number of Shots per String	Targeted Geologic Unit	Depth of Perforation Confirmed with DHC (ft)	Perforation Description
31 Void	2	Pecan Gap Chalk	31.31	Uniformly round shot holes and spilt casing (no annular fill)
53* Annular Fill	2	Pecan Gap Chalk	53.65, 53.82	Uniformly round shot holes (annular fill)
135* Annular Fill	2	Austin Chalk	135.3, 135.53	Uniformly round shot holes (annular fill)
193 Void	3	Eagle Ford Group	193.35, 193.53	Round shot hole and split casing (no annular fill)
271 Void	3	Del Rio Clay	271.54 (water too turbid for full confirmation)	Possible split casing (no annular fill)

* CDL and neutron logs indicate interval with good annular seal.

Response of the casing after perforating indicated the absence or presence of an annular seal, as presented in results of the video log. In areas where the annular space was filled, directional explosive charges punched round holes in the casing. In areas where annular fill was absent, charges cracked the casing. Under both conditions, explosive charges were effective in penetrating the casing, as indicated in photographs 1 through 7.

Photograph 1. Perforation at 31 ft bgs in Area Where Nuclear Source Log Indicated Presence of a Void

Photograph 2. Split Casing at 31 ft bgs, at Opposite Side of Shot above, in Area Where Nuclear Source Log Indicated Presence of a Void

Photograph 3. Perforations at 53 ft bgs in Area Where Nuclear Source Log Indicated Solid Annular Fill

Photograph 4. Perforation at 135 ft bgs in Area Where Nuclear Source Log Indicated Solid Annular Fill

Photograph 5. Perforation at 135 ft bgs in Area Where Nuclear Source Log Indicated Solid Annular Fill

Photograph 6. Split Casing at 193 ft bgs in Area Where Nuclear Source Log Indicated Presence of a Void; Casing is Cracked

Photograph 7. Perforations at 193.5 ft bgs in Area Where Nuclear Source Log Indicated Presence of a Void; Photograph Indicates Cracked and Perforated Casing with Space behind Casing

Upon completion of casing perforation, the casing was filled with cement grout from the bottom of the casing to the surface using a tremmie pipe and a low-pressure grout pump. Backfilling the well bore from bottom to top ensures that the casing is filled completely with grout and that no spaces have been created by bridging of the fill material. Perforation of a well casing is also intended to allow grout to flow behind the well casing by gravity and completely seal the annular space.

The grout was allowed to cure for 24 hours, and then grout was removed by drilling using a six-and-one-half-inch-diameter drill bit and air rotary methods to a depth of 280 ft. The well casing was relogged with a three-arm caliper, natural gamma tool, and DHC. This relogging confirmed that the well was clean and free of obstructions. Nuclear source tools were subsequently placed in the well bore, and the well was logged again so that the degree of grout penetration through the perforations and into the annular space behind the casing could be evaluated.

Nuclear logs from initial borehole evaluation (preperforating and grouting) and from postperforating and grouting are presented in Figures 7 and 8. A comparison of logs is particularly instructive in evaluating the extent of emplaced cement. Figure 7 presents pre- and postplugging CDL. Intervals with the greatest difference between these logs indicate that cement filled the annular voids at 31, 193, and, to a more limited degree, at 271 ft bgs (RAS, Inc., personal communication and unpublished report). No significant difference was found between the logs at 53 and 135 ft bgs because these perforations were performed in areas where logs indicated adequate annular fill. Figure 8 emphasizes the diagnostic differences between the density logs and illustrates a density difference log by taking the original (preplugging) CDL, subtracting the postplugging or abandonment CDL, and plotting the differences. Density differences greater than -0.2 are shaded in red to highlight intervals in which previous voids were backfilled with cement grout. Intervals from 29 to 42, 190 to 220, and 230 to 250 ft bgs clearly indicate intervals of the annular space that were originally voids but subsequently filled with cement. So that the presence of new cement in areas of initially poor annular seal might be highlighted, the new cement is presented in red in column eight (8) of postabandonment conditions in the Data Montage (Appendix F).

Volume calculations indicate that the annular space was filled with approximately 19.86 ft^3 of cement. Volume calculations for the interior of the casing and total volume of grout used were determined as follows:

Volume of casing (Vc) = $\pi r^2 h$,

where π = 3.1416,
r = radius of casing in ft,
h = height of casing in ft,
casing diameter = 6 inches (0.5 ft), and
radius of casing = 0.25 ft.

$$Vc = 3.1416 \times (0.25)^2 \times (290) = 56.94 \text{ ft}^3$$

Total volume of concrete used (Vt) = grout volume factor × number of bags used

Grout Volume Calculation	
Grout Matrix	Volume (ft^3)
Benseal (50 lb sack)	**4.75**
Quikrete (80 lb sack)	**0.60**
Portland Neat (94 lb sack)	**1.20**
Bentonite (94 lb sack)	**3.60**

Source: Edwards Aquifer Authority Well Construction Program Volume Calculator

128-80# bags of Quikrete were used to fill casing and voids

$$Vt = 128 \times 0.6 = 76.8 \text{ ft}^3$$

Volume of voids/annular space (Vv) = total volume of concrete used – volume of casing filled

$$Vt = 76.8 - 56.94 = 19.86 \text{ ft}^3$$

Figure 7. Compensated Density Logs (CDL) of Pre- and Postplugging Procedures; Intervals Showing Greatest Separation between Pre- and Postabandonment Logs Indicate that Voids in these Particular Depths Have Been Filled with Cement (RAS Inc., personal communication and unpublished report); Complete Diagram Showing Perforation Depths and Condition of Annular Space Shown in RAS, Inc., Data Montage (Appendix F)

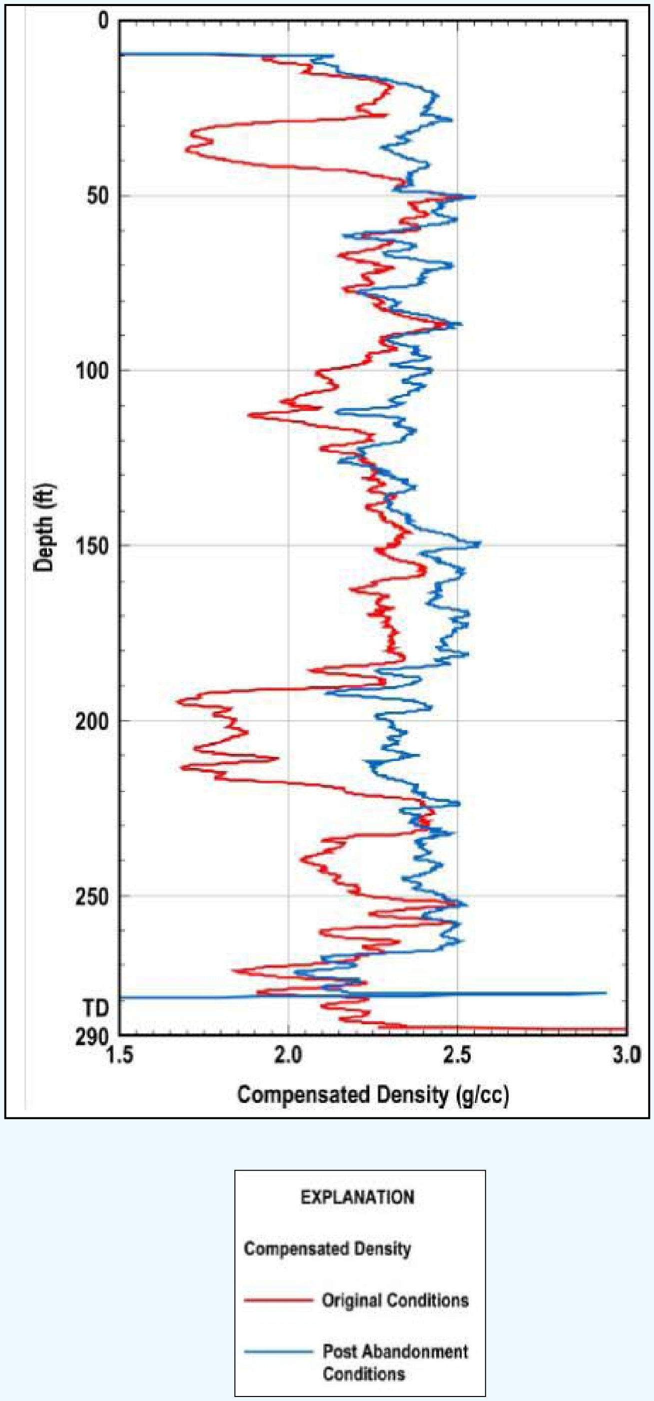
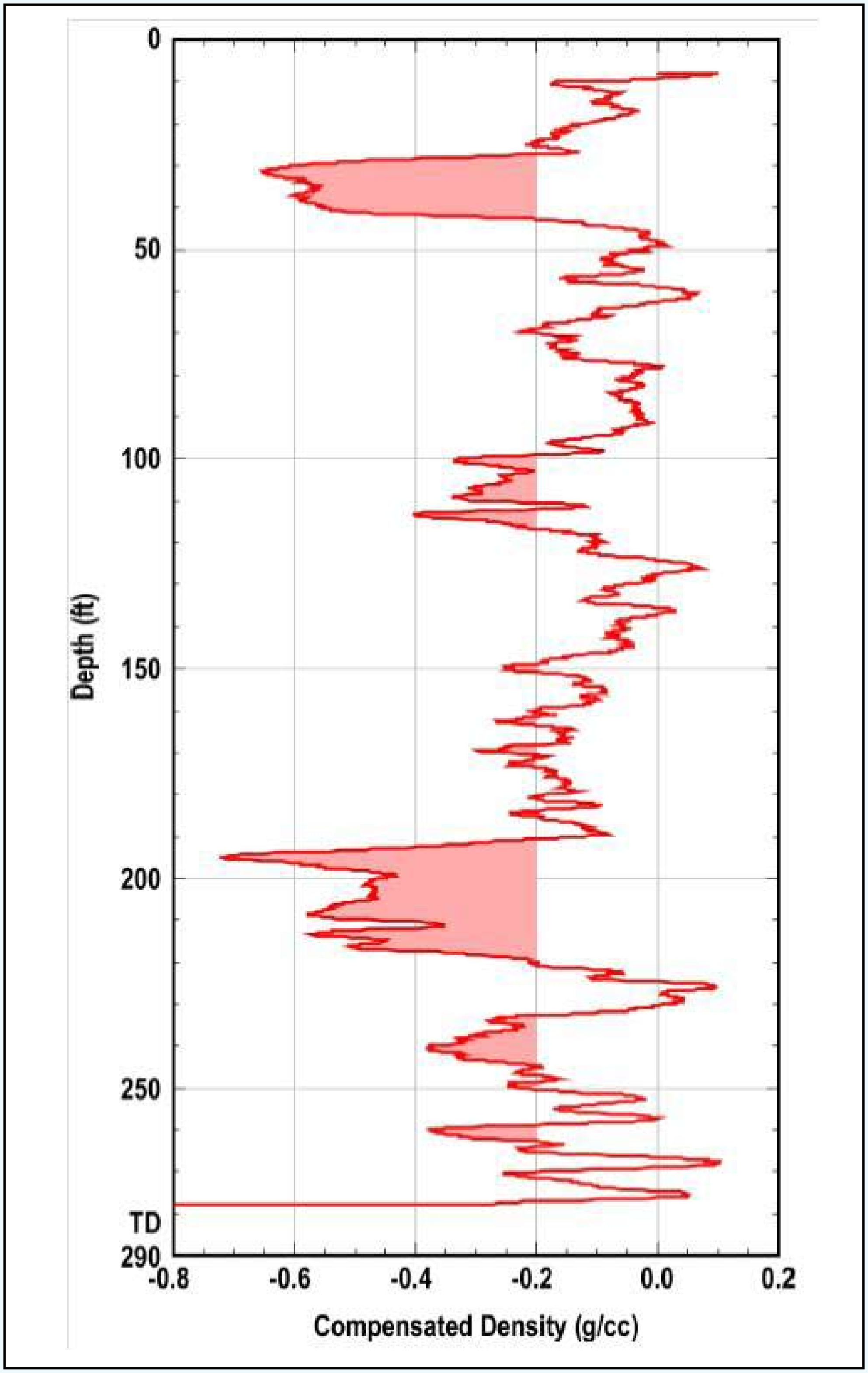


Figure 8. Density Difference Log; Shaded Red Areas Highlight Intervals where Previous Voids Have Been Filled with Cement Grout (RAS Inc., personal communication, unpublished report); Complete Diagram Showing Perforation Depths and Condition of Annular Space Shown in RAS Data Montage (Appendix F)



Intervals 42 to 88 and 125 to 185 ft bgs are where a good annular seal was indicated by the initial CDL signal. When these zones were perforated for comparison at selected perforation depths of 53 and 135 ft bgs, change was slight to nonexistent in annular-seal CDL data in these zones. This result is consistent with existing adequate annular fill, as indicated in the nuclear logs. No notable difference in improvement in sealing of the annular space between two or three perforations is evident. For example, the 31-ft-bgs interval contained two perforations and appears to have performed just as well as the 193-ft-bgs interval, which contained three perforations (RAS Well A Data Montage, Appendix F).

Comparison of Nuclear Logging with EAA Perforating Standards

Prior to this study, EAA staff, under Chapter 713, Subchapter D. Well Closures, § 713.320-Standards for Plugging Wells, issued a well plugging permit to the well owner and allowed the EAA to perform research on well plugging methods on this well. EAA well plugging permits, issued for wells within the area of the well plugging study, generally require 50-foot casing perforation intervals beginning at the base of the Austin Chalk. Below the Austin Chalk, two perforation intervals are typically required in the Buda Limestone plus other perforations within the Del Rio Clay as needed. However, a 50-ft interval would have missed the annular space void indicated by the CDL and neutron logs at 185 to 192.3 ft bgs in the upper Eagle Ford Group. Decreasing the interval of explosive charges from 50 to 25 ft would have provided a higher probability of intersecting the section with a poor annular seal. Decreasing the explosive charge spacing to 25 ft would also have ensured that at least one perforation would occur within both the Eagle Ford Shale and Del Rio Clay above the Edwards Limestone. Each of these units is more than 25 ft thick but may not be more than 50 ft thick in some locations.

SUMMARY AND CONCLUSIONS

EAA regulations require plugging of abandoned wells, including either removal of existing casing or perforation of the well casing and subsequent sealing of the annular space. Prior to implementation of EAA regulations, wells were commonly abandoned by filling of the well bore and casing with cement or grout and ignoring the annular space. Poor sealing of the annular space of wells, either during drilling or plugging, has the potential to contribute to groundwater contamination.

This study was developed to evaluate the effectiveness of current well-plugging methodology required in the EAA's rules when applied to Edwards Aquifer wells. The study involved

- Applying a suite of geophysical logging tools to an Edwards Aquifer well before plugging to identify depths at which little or no annular seal was present.
- Subsequent perforation of well casing at selected depths with perforation intervals on the basis of results of geophysical logging.
- Sealing of well bore and annular space, redrilling of well bore, relogging of well to ascertain quality of cement seal, and final abandonment of the well.

Geophysical tools, including a three-arm caliper, natural gamma, DHC, FWS, and nuclear (compensated gamma–gamma density and neutron) tools, were used to evaluate the effectiveness of current well-plugging practices for the protection of water quality. The caliper, the DHC, and the natural gamma tools provided an assessment of the inside condition of the casing, but they were unable to evaluate the condition of the annular space between the outside of the casing and geologic formations. The FWS tool may provide some insight into the annular seal of a well; however, it does not appear to have the resolution or reliability of the nuclear tools. The compensated gamma–gamma density and neutron source tools provided a means of evaluating the condition of the annular seal, as well as a delineation of voids in the annular space. Additionally, the CDL seemed to be more useful in void detection in the annular space, requiring both compensated gamma–gamma density and neutron source tools to get the job done. These tools can be used within or above the water table without impact to log quality or diagnostic capabilities.

W104-265 (Car Lot Well) was selected for this study because it offered a larger diameter casing (six inches) and a longer casing than other wells that have been examined. Perforation points were chosen on the basis of distinctive qualities of the annular seal, as determined from nuclear logs. Two of the perforation locations were selected at intervals in which the annular seal was evaluated as good, and three perforation locations were selected at intervals in which the annular seal was evaluated as poor to nonexistent. The intervals 42 to 88 and 125 to 185 ft are locations at which a good annular seal was suggested. Intervals from 28 to 42, 192 to 222, and 232 to 289 ft were evaluated and estimated to contain 50 to 100% void space. So that the effect of perforations on casing with good annular seal versus casing with 50% or greater void space in the annulus could be compared, perforations were made in both areas. Perforation depths of 53 and 135 ft bgs were selected for “good” annular seal tests, whereas perforations at 30, 193, and 271 ft bgs were selected to test areas with 50% or greater annular void space. Clean, round holes were formed by shaped explosive charges where solid annular material occurred between the casing and the borehole wall. Casing cracked or split in intervals where little or no material occurred in the annular space. Analysis of nuclear logs indicates that plugging of the annular void area through the perforations was highly successful. Postperforation and cementing source logging indicated that a good seal was achieved in areas previously indicating 50% or greater void space, and no significant change was noted for the two areas that indicated a good annular seal.

This study showed that grouting of the well using gravity-fed tremmie methods from the bottom to the top provided pressure sufficient to force cement through the perforations in the well casing, creating an adequate annular seal. Decreasing the explosive-charge interval from 50 to 25 ft would increase the likelihood of intersecting an annular void.

ACKNOWLEDGMENTS

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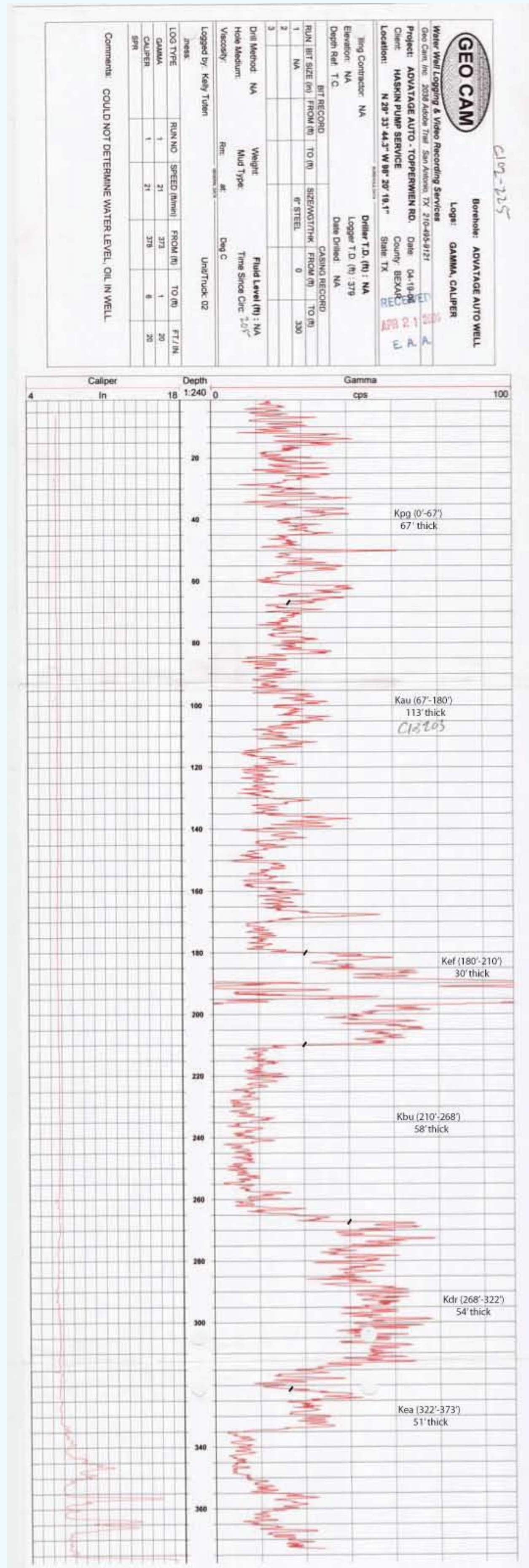
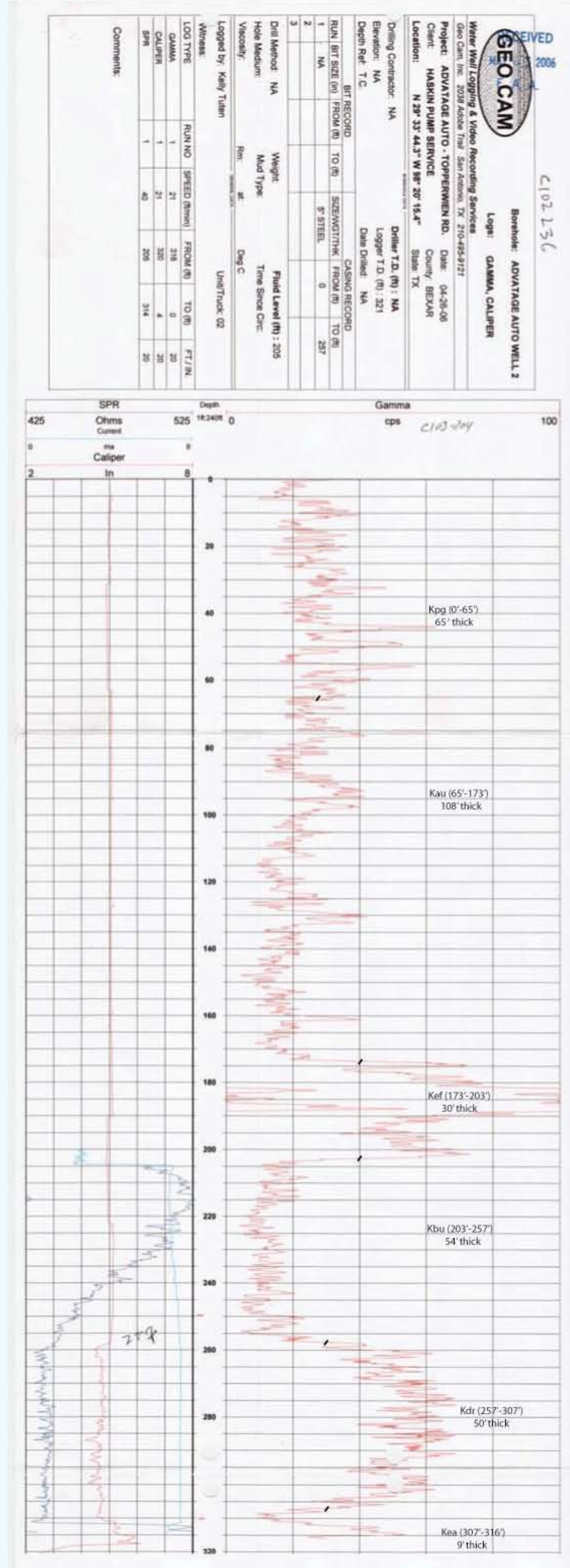
APPENDIX A

Natural Gamma and Caliper Log of Well W104-265



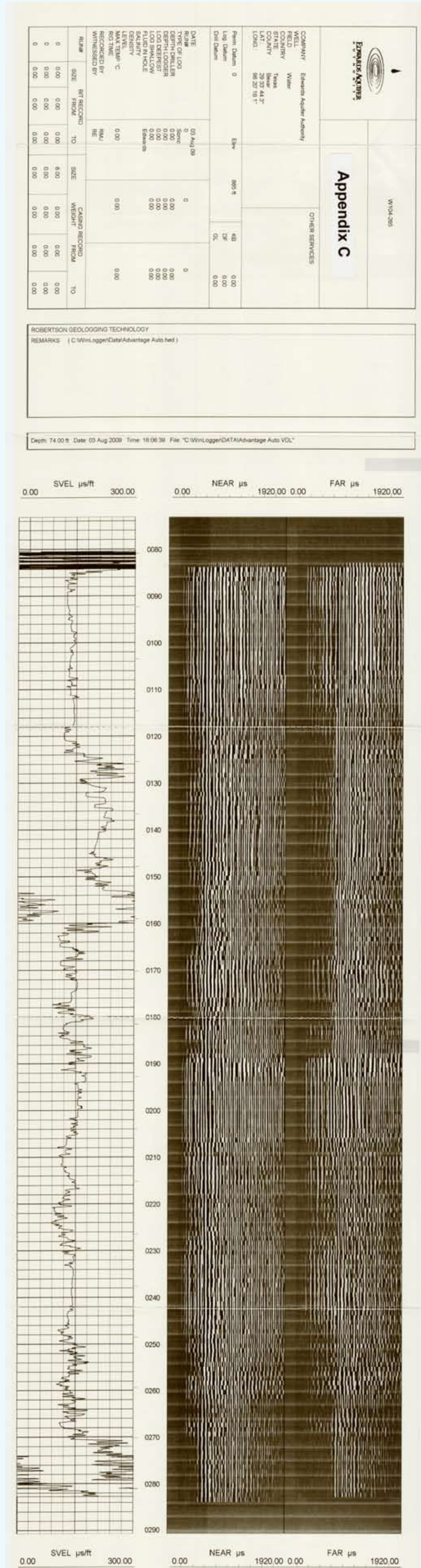
APPENDIX B

Natural Gamma and Caliper Log of Well W104-269



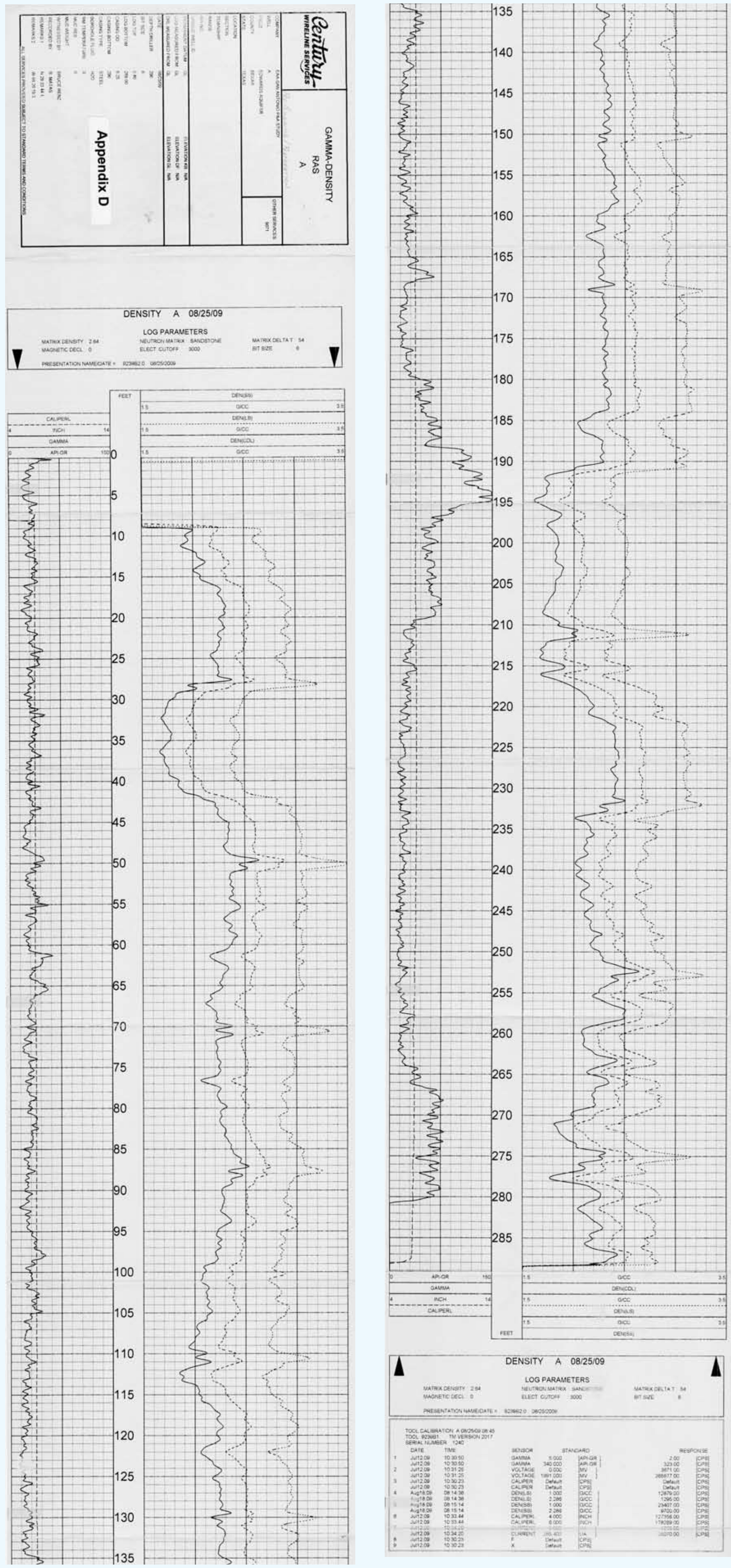
APPENDIX C

Full Wave Sonic Log of Well W104-265



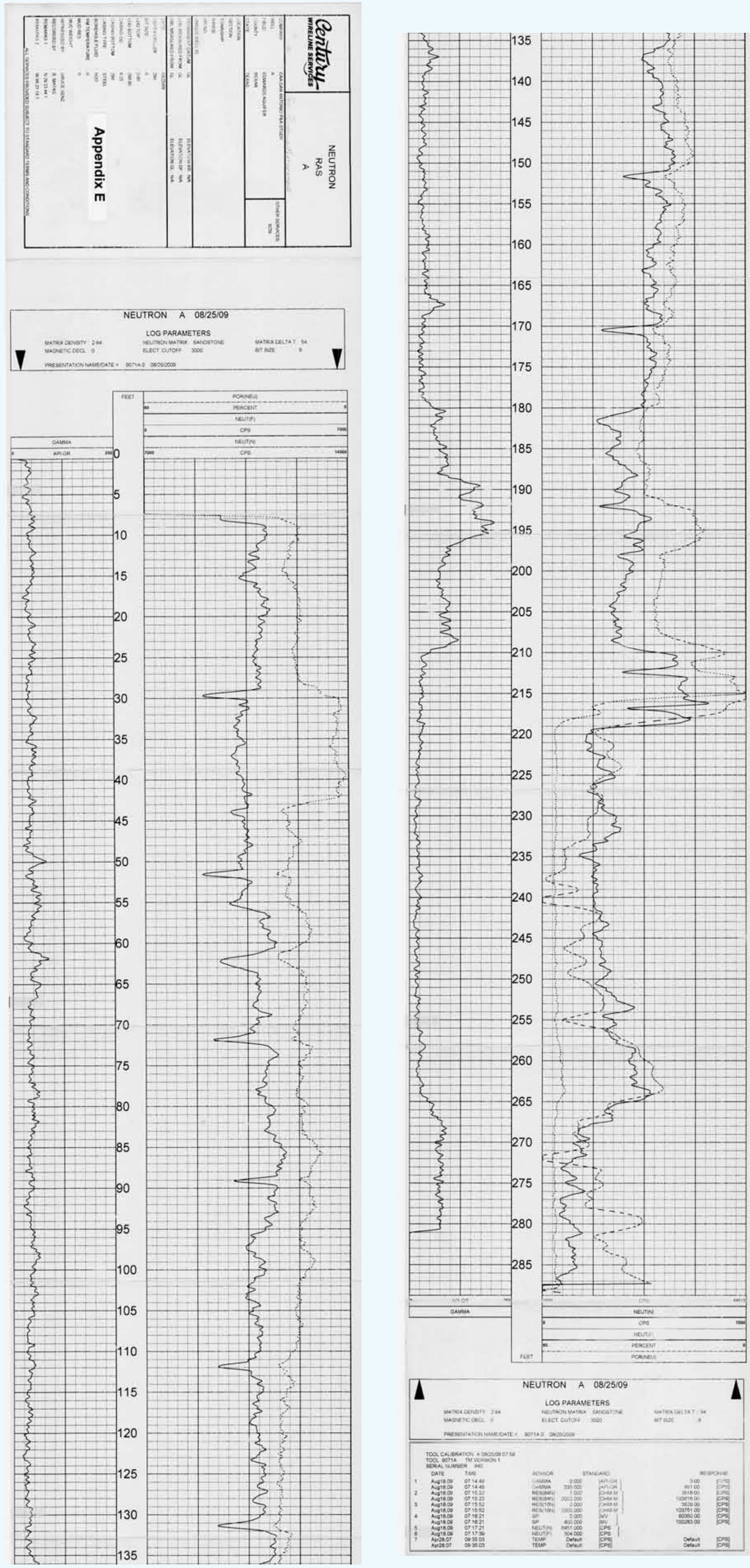
APPENDIX D

Gamma-Gamma Density Log of Well W104-265



APPENDIX E

Neutron Log of Well W104-265



APPENDIX F

RAS, Inc., Montage (personal communication, unpublished report)