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Deep well injection in south Florida - The vertical confinement experience

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Abstract

The successful operation of a Class I injection well system requires (1) the presence of a high transmissivity injection zone capable of accepting the design injection capacity of the well and (2) at least one effective vertical confinement interval between the injection zone and the base of the Underground Source of Drinking Water (USDW). The adequacy of injection zones is typically determined during the initial injection testing of the well. The effectiveness of confining zones cannot be fully determined in pre-design studies, but confinement has always been sufficient in South Florida to prevent injected fluid from migrating above the USDW. Data available from South Florida injection well sites where the top of the injectate invaded zone can be identified reveals that some upward migration of injected fluid inevitably occurs because the limestone and dolomite beds in the Floridan aquifer system are not totally impermeable. Injected low density fluids migrate upward until unfractured horizontally continuous beds with very low vertical hydraulic conductivities are encountered. Dolomite beds provide the primary vertical confinement in South Florida because they commonly have much lower vertical hydraulic conductivities (often < 10^{-8} cm/sec) than limestone beds (mostly > 10^{-6} cm/sec). The location of the effective confinement varies between wells and regions. Effective vertical confinement at the Broward County North Regional WWTP site, for example, lies above 2000 ft bls, whereas injected fluids have not been detected above 2400 ft bls at either the Collier North County Regional WTP site or Charlotte County East Port WWTP sites. Geological, geophysical, operational, and monitoring data from other regional injection well sites can provide critical information on the likely confining properties of strata at new injection well sites. Because of the potential for the upward migration of injected fluids, injection zones should be defined to include all the strata between the bottom of the injection interval and the highest potential effective confining beds below the base of the USDW.

Introduction

Federal Underground Injection Control (UIC) rules prohibit any injection activity that allows movement of fluid containing any contaminant into underground sources of drinking water that may result in endangerment of the water supply (40 CFR, Part 144.12). The successful design and operation of Class I injection wells requires the presence of effective vertical confinement between the injection zone and the base of the lowest underground source of drinking water (USDW). Where high density fluids, such as some concentrates from desalinization facilities, are injected into less saline waters, the density difference between the fluids prevents upward migration of injected fluids due to hydraulic confinement. In the more common case, where relatively low salinity and density fluids are injected into higher salinity waters, the vertical confinement is provided by intervals of rock with low vertical hydraulic conductivities. Critical tasks during the design and construction of Class I injection wells are therefore the identification of an injection zone(s), the base of the USDW and intervening confining units.

Whether or not an injection zone is present with a high enough transmissivity to accept the design capacity of an injection well can normally be determined during the initial injection testing of the well. The ultimate test of the effectiveness of vertical confining zones is whether or not they actually act as barriers to upward fluid flow. The exact effectiveness of vertical confining zones cannot therefore be determined with certainty until after years of operation. In practice, the results of core analyses, drill stem tests, and geophysical logging are used to provide assurance that effective vertical confinement is present during injection well permitting. The accuracy of the confinement analyses depends to a large degree on the ability of the hydrogeologist performing the analyses, as well as, the predictability and continuity of local hydrogeology. For example, determination that adequate vertical confinement is present may be a simple matter where a thick, regionally extensive shale formation is present between the injection zone and base of the USDW. Confinement analysis is a much more complicated matter where the injection zone, confining units, and base of the USDW all occur within an aquifer composed of shallow water carbonate deposits, such as is the case in Floridan Aquifer System in South Florida. A characteristic feature of shallow water limestone deposits is that individual beds tend to be discontinuous. Multiple generations of healed and open fractures are also locally present in the Floridan Aquifer System. The objective of this investigation was to examine the nature of vertical confinement in the Floridan Aquifer System of South Florida, which includes Broward, Charlotte, Collier, Dade, and Lee Counties..

Hydrogeology of the Floridan aquifer system

The regional hydrostratigraphy of South Florida is summarized in Figure 1. All Class I injection wells in south Florida discharge into the Floridan Aquifer System, which is one of the most productive aquifers in the United States and underlies all of Florida and parts of Alabama, Georgia, and South Carolina. In South Florida, the Floridan Aquifer System includes, in descending order, the lower part of the Arcadia Formation of the Hawthorn Group (Miocene-Late Oligocene), Suwannee Limestone (Oligocene), Ocala Limestone (Late Eocene), Avon Park Formation (Middle Eocene), Oldsmar Formation (Early Eocene; Miller 1986).

The Floridan Aquifer System is composed predominantly of limestones and dolomites that were deposited in shallow subtidal to supratidal environments in a depositional setting similar to that of the present day Florida Bay and the Bahamas Platform. With reference to the limestone classification scheme of Dunham (1962), the bulk of the limestones are categorized as mudstones and fossil peloid wackestones to grainstones. The dolomites formed by the diagenetic replacement of limestone precursors.

With a few exceptions, Class I injection wells in South Florida discharge into the so-called Boulder Zone of the Lower Floridan aquifer. The Boulder Zone is a hydrogeologic and diagenetic facies that consists of intervals of very high transmissivity dolomite that are characterized by greatly enlarged borehole diameters, long sonic transit times, and borehole collapse during drilling. The Boulder Zone was originally defined as an interval of cavernous dolomite and limestone in which the drilling action of the bit was similar to that of drilling through boulders (Kohout, 1965; 1967). Subsequent studies have demonstrated that the Boulder Zone consists of highly fractured dolomites in which the bulk of the cavities and caverns form after drill bit penetration (e.g., Safko and Hickey, 1992; Duerr, 1995). The geological and geophysical characteristics of the Boulder Zone facies have been described by Haberfeld (1991), Safko and Hickey (1992), Duerr (1995), Winston (1996), Maliva and Walker (1998), and Maliva et al. (2000). The Boulder Zone is present throughout most of South Florida and no injection well has had to be abandoned because of the absence of an adequeate injection zone

The vertical confinement between the Boulder Zone and the base of the USDW is provided by laterally continuous, unfractured, limestone and dolomite beds with relatively low vertical hydraulic conductivity. Although there is considerable overlap in values, dolomite beds in the Floridan Aquifer System tend to have significantly lower vertical hydraulic conductivities than limestone beds (Maliva and Walker 1998). It is not uncommon for dolomite core samples from the Floiridan aquifer system to have vertical hydraulic conductivities of less than 1×10^{-8} cm/s (< 0.01 millidarcies; Maliva and Walker, 1998).

Criteria for identification of potential confining strata

Vertical confinement of buoyant injected effluent is provided by strata with low vertical hydraulic conductivities. The vertical confinement of a interval of horizontally bedded rocks (K_z) is expressed by the following equation (Freeze and Cherry, 1979):

$$K_z = d / (\sum d_i/K_i)$$

where d = the total thickness of the interval of rock and d_i and K_i are the thickness and vertical hydraulic conductivities of the individual beds. The above equation indicates that the vertical hydraulic conductivity of an interval of horizontally bed rock is largely a function of the vertical hydraulic conductivity of the least conductive beds. Thin beds with low vertical hydraulic conductivities can provide greater vertical confinement than much greater thickness beds with higher vertical hydraulic conductivity, provided that the beds are laterally continuous and are not fractured or penetrated by other potential flow channels. Confinement analysis thus involves identification of horizontally extensive beds of low vertical hydraulic conductivity dolomite and limestone.

Beds or intervals of rock in the Floridan aquifer system that are likely to offer good vertical confinement can be identified using the following criteria:

- Low sonic transit times and derived sonic porosities.
- Variable density log (VDL) pattern consisting of either straight parallel vertical bands, where lithology is relatively uniform, or a "chevron" pattern of continuous parallel bands, where the formation consists of interbedded rock with differing densities and/or degrees of consolidation.
- Low vertical hydraulic conductivities measured on core samples.
- Low hydraulic conductivities calculated using packer and flow test data.
- Low macroporosity (i.e., visible pore spaces) and a high degree of cementation (hardness) as observed in microscopic examination of cuttings and core samples.
- Bore hole diameters on caliper logs close to the bit size. Fractured dolomite and

limestone is commonly manifested by an enlarged bore hole.

- Relatively high resistivities, which in the middle and lower parts of the Floridan Aquifer System is often indicative of tight dolomite beds.

- Absence of evidence of fractures on the television survey video, and borehole televiewer and fracture identification logs.

Limitation of the above analyses is that they provide information on the petrophysical properties of the rock in the immediate borehole vicinity. The geophysical logs and packer tests do not provide information on the lateral continuity of potential confining beds. Strata having properties characteristic of good vertical confinement may offer no effective vertical confinement if they are of limited horizontal extent or are penetrated by fractures that are not evident in bore holes.

Field and operational evidence on the location of effective confinement

Unequivocal evidence on the location of effective confining zones can be obtained from water quality data obtained during the drilling of an additional well at an operational injection well system site and from long term monitoring data. Injection of low density liquids into saline aquifers creates an injectate "bubble" that rises until it encounters confining strata or becomes diluted. Water quality data collected during the drilling of an additional well at operational injection well site can be used to locate the top of the injectate bubble. Long term water quality data from monitoring wells at injection well system sites also provide evidence whether or not leachate bubble has migrated upward to the monitor zones. Three case studies from south Florida are discussed below where subsequent injection or monitor well drilling at an active injection well site provided information on the extent of vertical fluid migration.

Collier North County Regional Water Treatment Plant

An injection well (IW-1) and dual-zone monitor well were constructed at the Collier North County Regional Water Treatment (NCRWTP) in 1992-1993. The NCRWTP is located in Golden Gate area of northern Collier County. A second well (IW-2) was constructed in 1995-1996. Membrane softening reject water with total-dissolved solids concentrations of ~5000 mg/l is injected into the Boulder Zone whose water has a total dissolved solids concentration of ~35,000 mg/l. Concentrate from a reverse-osmosis desalination train has also been injected since late 1999.

The base of the USDW was located during the drilling of well IW-1 at approximately 1,200 ft below land surface (bls). The injection casing of well IW-1 was set at 2,492 ft bls and the confining zone was interpreted to be located between 1,460 ft bls and 2,300 ft bls (ViroGroup, 1993). The top of the injectate bubble was located during the drilling of well IW-2 primarily from water quality data collected during packer tests and analyses of the discharge water from the reverse-air drilling system (Missimer International, 1996; Figure 2). Because discharge water is recirculated back down the well during reverse-air drilling, the composition of the discharge water is not entirely representative of that of the formation water. Nevertheless, changes in the salinity of formation waters can usually be detected by a corresponding trend of salinity change in the discharge water.

A water sample collected during a single packer test run between 2236 and 2259 ft bls had a salinity close to that of seawater (Chloride concentration = 19,000 mg/l). The injected water was detected in the next lower packer test (2434 - 2455 ft bls), which had a chloride concentration of only 5,420 mg/l. The packer test data thus bracket the top of injectate bubble as being located between 2259 and 2434 ft bls. The top of the injectate bubble was more precisely located at the top of a small cavernous zone at 2,406 ft bls using reverse-air discharge water, geological, and geophysical data (Missimer International, 1996; Figure 2).

The data collected during the drilling of IW-2 indicate that the injected fluids had migrated upward only 86 feet from the bottom of the injection casing. The injected fluids had not even entered the confining zone, as originally proposed by ViroGroup, Inc. (1993). Unfractured, low vertical hydraulic conductivity dolomite beds located immediately above the small cavernous zone at 2,406 ft bls are providing effective vertical confinement of the injected fluids at the NCRWTP site.

Charlotte County East Port Wastewater Treatment Plant

An exploratory well was drilled at the Charlotte County East Port Wastewater Treatment Plant (EPWWTP) in 1987-1988. The well was subsequently converted to an injection well (IW-1) that is cased to 2977 ft bls and discharges into the Boulder Zone. The base of the USDW in well IW-1was placed at 1427 ft bls (CH_2M Hill, 1988). A second injection well (IW-2) was drilled at the EPWWTP in 1995-1996. The base of the USDW was interpreted to be located at approximately 1580 ft bls during the drilling of well IW-2 (ViroGroup, 1996). Treated effluent from the wastewater treatment plant has been injected down both wells.

Effluent has not been detected in the lower monitor zone (2249-2330 ft bls) at the EPWWTP site. A water sample collected during a packer test at 2743-2815 ft bls in IW-2 consisted mostly of effluent as evidenced by a chloride concentration of only 960 mg/l (ViroGroup, 1996). A downhole decrease in the chloride concentration of the reverse air discharge water was first detected during the drilling of well IW-2 between the samples collected at 2735 and 2765 ft bls (Figure 3). The ammonia and total Kjeldahl nitrogen (TKN) concentrations of the discharge water increased from 0.21 and 0.22 mg/l, respectively at 2735 ft bls to 0.89 and 0.95 mg/l respectively, at 2795 ft bls (ViroGroup, 1996). The top of effluent invaded zone was thus located between 2735 and 2765 ft bls at the EPWWTP site.

Effluent at the EPWWTP site has thus migrated upward approximately 212 to 242 from the bottom of the IW-1 injection casing. The top of the effluent invaded zone is still over 1,100 feet from the base of the USDW. A sequence of dolomite beds is present between 2730 and 2765 ft bls in IW-1 and IW-2, which corresponds with the top of the effluent invaded zone (Figure 3). The dolomite beds appear to be providing effective vertical confinement for the injected effluent.

Broward North Regional Wastewater Treatment Plant

Injection wells are used for the disposal of treated wastewater effluent at the Broward County North Regional Wastewater Treatment Plant (NRWWTP), located in Pompano Beach. The first two of six injection wells currently at the facility were constructed in 1989-1990 and cased to 2990 ft bls (Geraghty & Miller, 1990). All six wells inject into the Boulder Zone. The base of the USDW is present between 1630 and 1660 ft bls at the NRWWTP. Two (2) dual zone monitor wells were installed for injection wells IW 1 through IW-4. The original lower monitor zones of the dual-zone wells were from 2000-2079 ft bls (MW-1) and 2000-2081 ft bls (MW-2). In response to the detection of effluent in the lower monitor zones, as evidence by a decrease in salinity and increase in the concentration of nitrogen compounds, the dual-zone monitor wells were partially cemented and the casing perforated. The lower monitor zones were moved upwards to between 1590 and 1630 ft bls.

The source of the effluent in the lower monitor zone has not been determined with any certainty.
The detected effluent may be fluid that has actually migrated upward from the injection zone, or alternatively, the effluent may have been introduced into transmissive zones located above the injection zone during well drilling of later injection wells.

Effluent was not detected in the deepest packer test (1886 - 1896 ft bls) conducted during the drilling of a new monitor well (MW-4) at the NRWWTP site in 1996-1997 (Hazen and Sawyer, 1997). The water sample from the 1886-1896 ft bls was compositionally similar to seawater. The top of effluent invaded zone had therefore not reached 1896 ft bls, suggesting the presence of vertical confinement between about 1900 and 2000 ft bls..

The confinement appears to be provided by unfractured dolomite beds located between approximately 1930 and 2000 ft bls at the BNRWWTP site (Figure 4).

Discussion

The top of the injectate invaded zone or bubble marks the top of strata that did not provide vertical confinement. An resolved question is whether the top of the invaded zone marks the actual bottom of the confining zone or just represents the location of the top of a continuosly migrating zone or bubble at one point in time. If the strata immediately above the injectate invaded zone exhibits petrophysical properties characteristic of good vertical confinement, as compared to underlying strata, then it is reasonable to conclude that the base of the confining zone has been identified.

Identification of confining zones within an aquifer composed of shallow water carbonate deposits, such as the Floridan Aquifer System, is not a straightforward matter because of the inherent depositional and diagenetic heterogeneity. Limestone and dolomite beds having characteristics during injection well drilling as offering confinement based on their petrophysical properties may prove in practice to not provide effective confinement. The limestone and dolomite beds that appear tight at the borehole may be either discontinuous or are penetrated by fractures or solution features. The vertical conductance of potential confining units within aquifers composed of shallow- water carbonate deposits may not be identifiable with total confidence using geophysical and hydraulic data obtained during well drilling alone. However, at this relatively mature stage in the injection well history of the South Florida, considerable regional data are available on the location of effective confining zones. The experience at nearby injection wells sites is an invaluable source of information for confinement analyses at new injection well sites, significantly augmenting site specific data.

Effective vertical confinement is consistently present in South Florida between the Boulder Zone and the base of the USDW. At both the Collier County NCRWTP and the Charlotte County EPWWTP the effective confinement occurs over 1000 ft below the base of the USDW. Even if the effluent detected in monitor zones at the Broward County NRWWTP was actually fluid that had migrated upward from the injection zone, adequate vertical confinement is still present between the top of effluent invaded zone and the base of the USDW. Low vertical hydraulic conductivity dolomite beds at all three sites appear to provide the primary vertical confinement.

Effluent has been detected in the lower monitor zones at some southeastern Florida injection well sites. UIC rules require that the lower monitor zone be placed in the first transmissive unit below the USDW. However, the lower monitor zone of early injection wells were intentionally placed at greater depths to provide additional early warning of upward fluid migration. At several sites it was subsequently found that the lower monitor zone was placed within the injection zone, below the primary effective confining unit. Effluent was not detected when the lower monitor zones were moved upward above the confining unit into the first transmissive unit below the USDW.

Conclusions

Upward migration of fluids from the bottom of injection well casings will invariably occur unless a casing was fortuitously set in a laterally continuous impervious bed. It has been the experience in South Florida that effective vertical confinement is consistently present between the main injection interval, the Boulder Zone, and the base of the USDW. The vertical confinement is provided primarily by intervals of laterally continuous dolomite beds with low vertical hydraulic conductivities. The inevitable upward migration of low density injected fluids should be considered when defining injection zones and confining zones. The top of the actual injection zone in practice corresponds to the base of the lowest effective confining strata, rather than the top of uppermost high transmisssivity zone.

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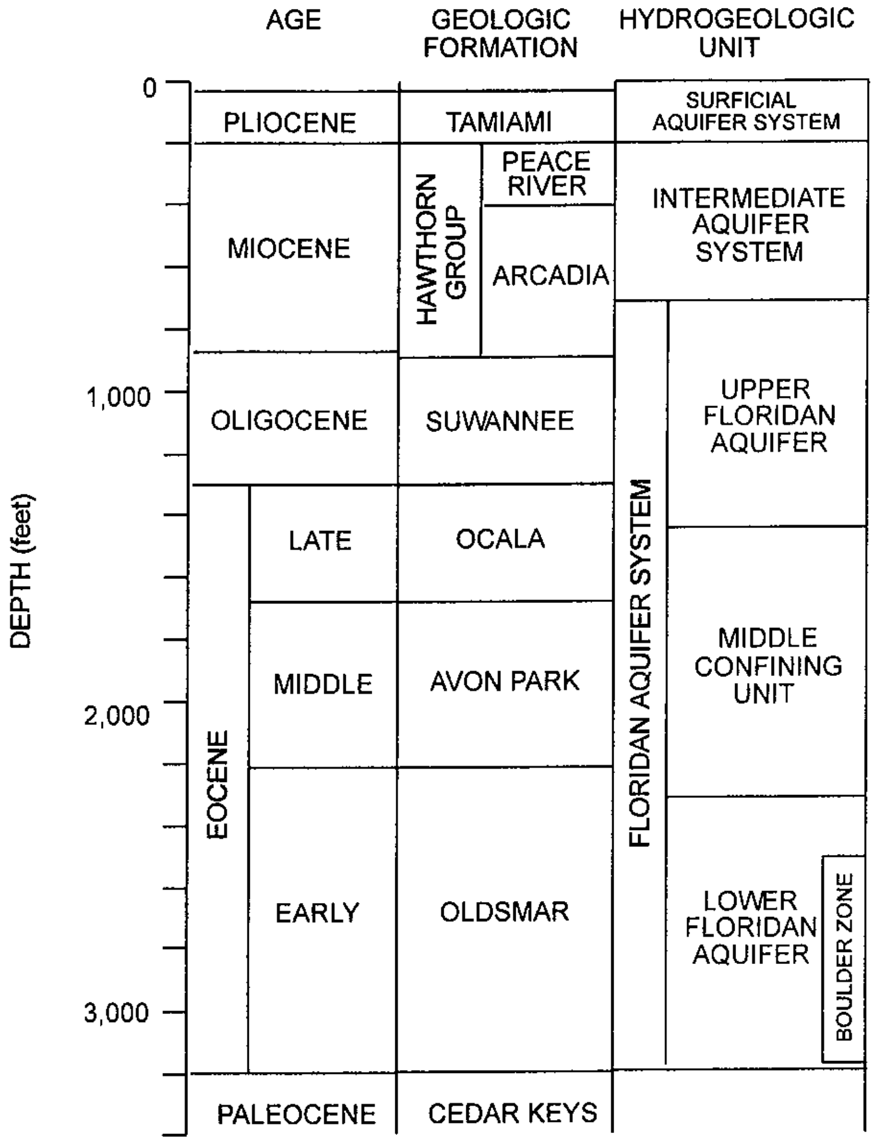

Figure 1. Hydrostratigraphy of South Florida. Data are from the Collier County NCRWTP

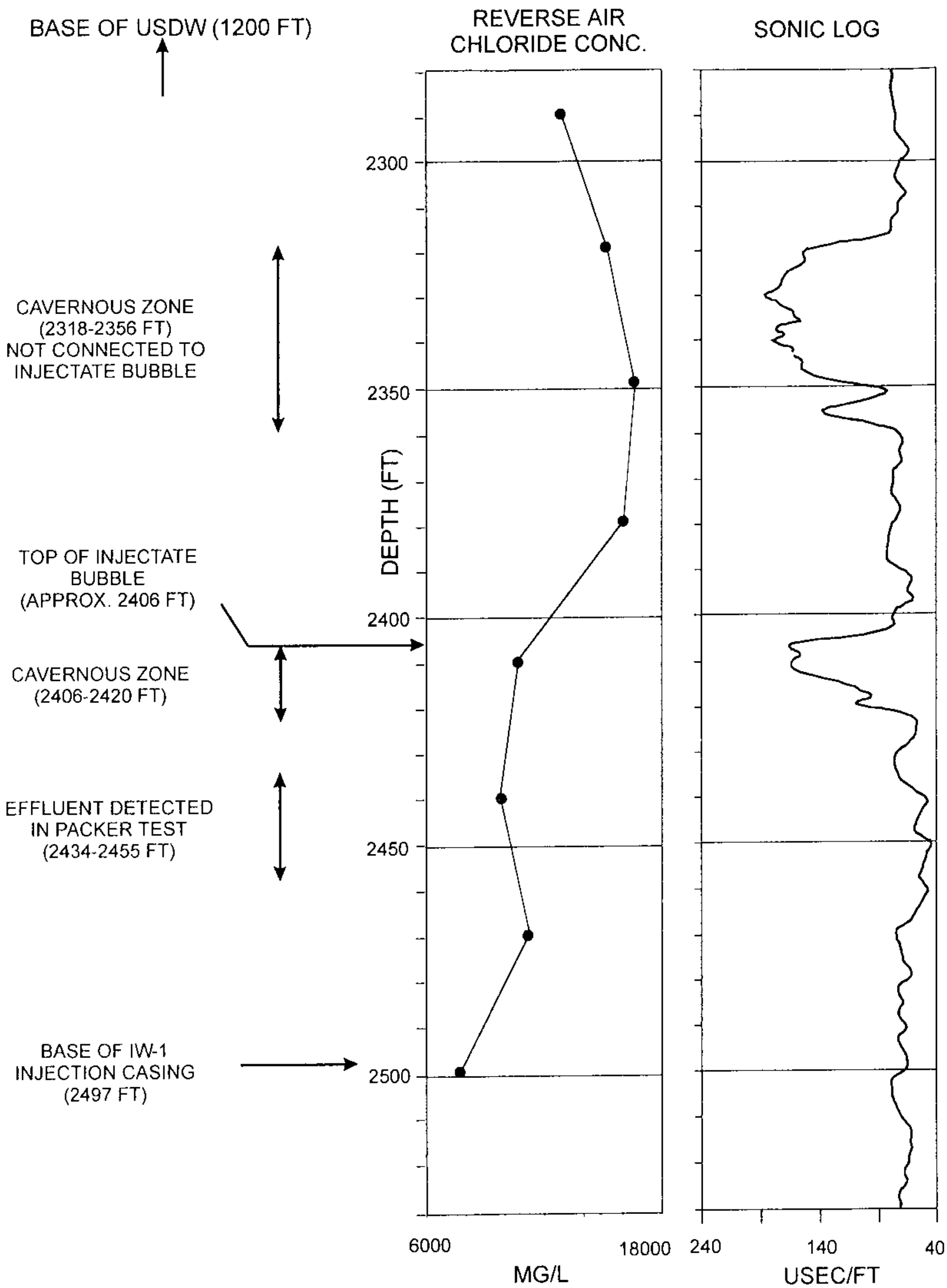

Figure 2: Confinement summary of the Collier North County Regional Water Treatment Plant site (IW-2 data). The 2280-2530 ft interval consists mostly of dolomite.

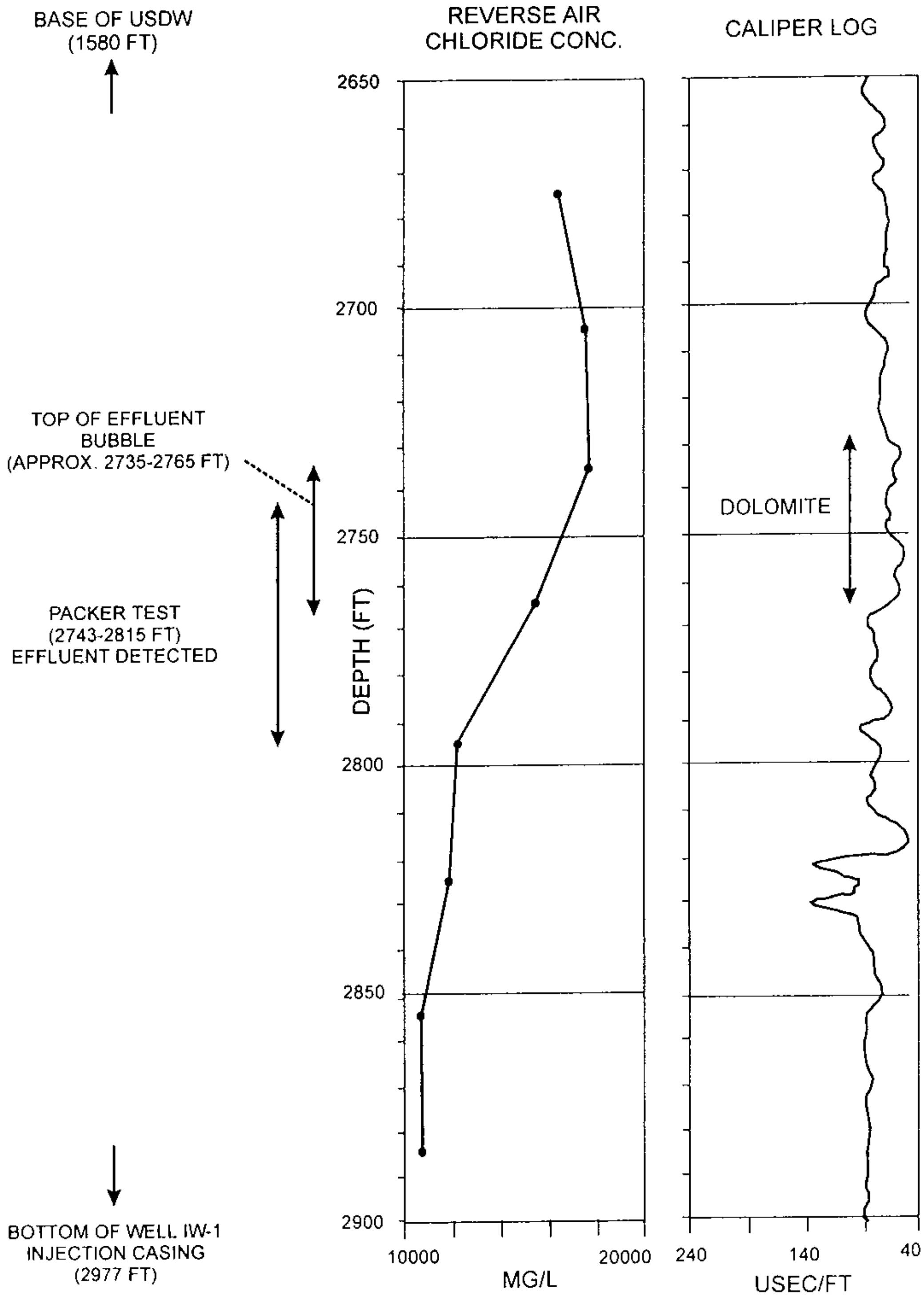

Figure 3: Confinement summary of the Charlotte County East Port Wastewater Treatment Plant site (IW-2 data).

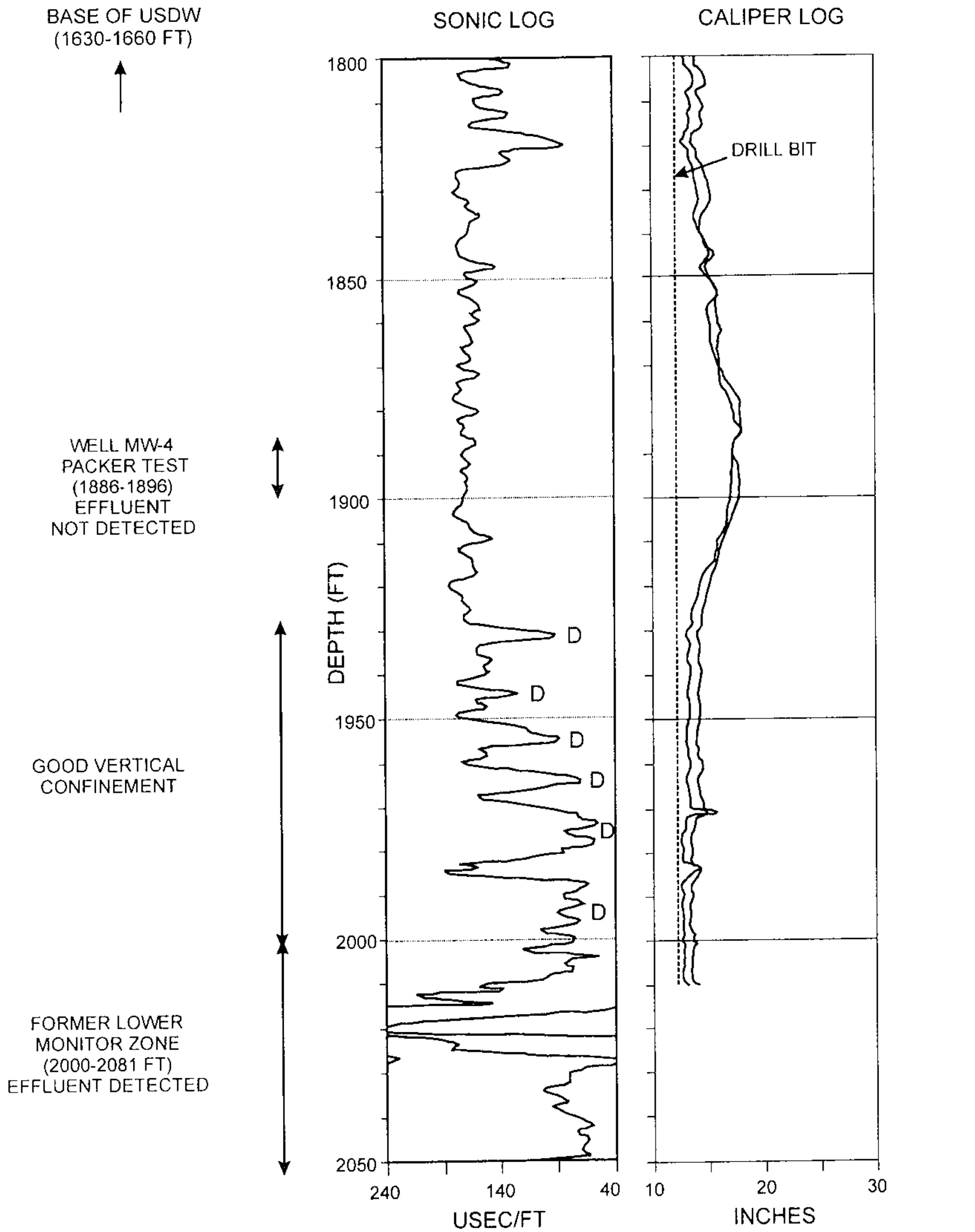

Figure 4: Confinement summary of the Broward North Regional Wastewater Treatment Plant site. Dolomite beds (D), characterized by short sonic travel times, provide effective vertical confinement.