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Continuous pressure monitoring for large volume CO_2 injections

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Abstract

Elevated formation fluid pressure resulting from large-volume injection of carbon dioxide (CO_2) for sequestration is a key factor affecting storage seal integrity (containment risk) and ultimate capacity. Current methods for predicting pressure evolution (e.g. natural gas storage, EOR, groundwater withdrawal/recharge) have unique considerations (temporal cyclicity, associated production) and have only recently been applied for the injected volumes, durations, and extents of sequestration projects. Monitoring pressure dynamics (buildup during injection and subsequent falloff upon cessation) is a fundamental and relatively inexpensive technique for monitoring storage performance. Our research employs multiple numerical techniques to predict the evolution of pressure within reservoirs and to evaluate the potential impact on confining systems (seals), thus constraining site-specific sequestration storage integrity and capacity. We focus on the use of pressure measurements for pragmatic integrative monitoring of reservoir, seal, and well performance. The results presented here focus on real-time pressure and temperature evolution in a dedicated observation well, combining observations from both the injection interval and a monitoring interval 120 m higher for early detection of unanticipated migration out of the injection zone via wellbores or confining system. Results indicate that for the Cranfield reservoir, increases (and by inference, decreases corresponding to pressure loss due to out of zone migration) in injection rates of 100's of tons per day are observable from less than a kilometer distance from the source.

Keywords: pressure; monitoring; Cranfield; CO_2; migration, seal, well integrity

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1. Introduction

The Southeast Regional Carbon Sequestration Partnership (SECARB) field projects conducted by the Gulf Coast Carbon Center at the Texas Bureau of Economic Geology with support from the National Energy Technology Laboratory (NETL) and the U.S. Department of Energy (DOE) and managed by the Southern States Energy Board (SSEB) at Cranfield Field in southwest Mississippi provide a unique opportunity to monitor large-scale (10^5-10^6 tons) CO_2 injection in both hydrocarbon-dominated (Phase II) and brine (Phase III) environments on the flank of an anticline at 3 km depth. The reservoir has been shut-in for decades and was at near hydrostatic initial pressures when injection began, making this an excellent analog for sequestration into brine formations. The evolving CO_2 distribution and pressure perturbation has been monitored since mid-July 2008 (beginning prior to injection) by a combination of continuous pressure and temperature monitoring in the injection zone and an overlying monitoring zone in a dedicated monitoring well. Time-lapse saturation logging accompanies this research, but repeat logging passes have not yet been made for comparing changes in fluid saturation. The results reported here are from two pressure gauges in a dedicated continuous monitoring well within the field.

2. Setting

The study area is approximately 20 km east of Natchez in Adams County, southwest Mississippi, USA. The site is an active enhanced oil recovery operation in Cranfield field. Carbon dioxide from the natural geologic accumulation at Jackson Dome (near Jackson, MS) is transported via pipeline to Cranfield and injected at depths of 10,300 feet (convert to meters), where it exists in supercritical phase.

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3. Geology

The injection interval constitutes the lowermost 18 m of the basal sandstone of the middle Cretaceous Lower Tuscaloosa Formation (Figure 1). The facies receiving the carbon dioxide are fluvial conglomerates and sandstones with porosities averaging 25% and permeabilities in the 10's to 100's md. Underlying the injection formation are marine mudstones of the Washita-Fredricksburg Formation. The erosional base of the basal gravels is regionally significant as it represents a dramatic change in depositional environments, and has been described in publications of the mid-Cretaceous unconformity throughout the Mississippi Interior Salt Basin province [1]. The amalgamated fluvial lower Tuscaloosa section transitions upwards from quartz and chert pebble conglomerates to more homogeneous medium to fine quartz sandstone. A variable thickness (5 to 15 m) of terrestrial mudstone directly overlies the injection interval providing the primary seal, isolating the injection interval from a series of fluvial sand bodies occurring in the overlying 30 m of section. Above these fluvial channels, facies transition to marine mudstone forming a continuous secondary confining system of approximately 75 m. A continuously mapped sand body (6 m in thickness) approximately 120 m above the injection zone with permeabilities estimated at 100 md (well test) was chosen as a monitoring interval.

4. Field history

Hydrocarbon accumulation at Cranfield was originally discovered in 1943, in a low-relief 7,750 acre (3130 hectare) domal structure associated with deep underlying salt diapirism [2]. The original hydrocarbon accumulation can be described as a typical gas cap with an underlying oil ring. Oil production began in the oil ring in 1944 and the gas cap was produced at the end of the production history. Since abandonment in 1960, the field subsequently recovered to near original reservoir pressure (essentially hydrostatic for a nominal brine gradient) by 2008. Thus, the early injection and pre-production period taking place currently at Cranfield is a reasonable analog for initial pressure buildup associated with injection into brine reservoirs for sequestration.

5. Monitoring design

The intent of the monitoring design was to allow for reservoir conditions in the injection zone to be monitored for conformance, and to demonstrate capabilities for early detection of pressure or temperature perturbations in the above zone interval. This is the first field deployment at a large-volume CO_2 injection of the above zone monitoring technique described by Sally Benson at Stanford, which is considered important for monitoring both injection performance and long term containment. Pressure response in the injection zone from a known injection (pressure elevation) is predictable and can be compared to measured response. Reservoir modelling and flow simulation is being done to match observed reservoir performance. The response of the upper monitoring sand gauge was anticipated to be negligible provided anticipated integrity of the geologic seal. In addition, the monitoring zone is penetrated by 43 wells within an area of 4.76 sq. mi (12.3 sq. km) surrounding the monitoring well (Figure 2). Thus, the pressure signal in the monitoring sand integrates possible contributions from pressure communication between the two sands via these existing wellbore pathways. We are thus able to directly monitor the integrity of the monitoring well completion, as well indirectly monitor the integrity of the surrounding wells.

An existing plugged and abandoned well was selected for re-entry and instrumentation as a dedicated continuous monitoring well. This well was drilled and completed in 1945 and used for oil production until abandonment in 1960. Re-entry of the well began in the summer of 2008 and lasted for approximately 3 months at a cost of $982,000. Unforeseen costs included the existence of abandoned tubing in the lower portion of the well, and casing inspection and cement bond logs indicated four locations requiring remedial cement jobs at depths of 1007, 1054, 3060, and 3077 m. Instrumentation completion lasted approximately 1 month at a cost of approximately $1.5M. Final well completion design can be seen in Figure 3. Well completion focused on the isolation of both the injection zone as well as the monitoring zone 120 m above using three mechanical isolation and Schlumberger production packers (Figure 3). The monitoring zone was perforated over a 3 m interval. Original perforations over an 11 m interval were used to monitor the injection zone. A final mechanical integrity test qualified the well for service.

Both the monitoring and injection zone were instrumented with Panex model 6250 digital pressure and temperature gauges. Resolution for pressure is 0.01 psi and for temperature is 0.01 degrees F. Data is tubing-conveyed to surface via ¼" stainless steel encapsulated tubing. At the surface wellhead data is transmitted wirelessly to a local recording station and subsequently uploaded via satellite to a dedicated website for remote access and monitoring. Data sampling frequency is ten minutes. This design allowed for continuous real-time monitoring of temperature and pressure in the injection and monitoring sands.

6. Results

Injection initiated in two wells (1121 and 1940 meters from the monitoring well), with eight injectors contributing additional CO_2 within the following three weeks (Figure 2). Average injection rates have been 4 to 8 MMSCFD and to date approximately

100,000 tons (2000 MMCF) of CO_2 have been injected. The injection zone gauge showed pressure increase within days of the start of injection and pressure in this zone has increased steadily for 3 months, raising the ambient reservoir pressure approximately 760 psi above initial conditions (Figure 4). This is anticipated behavior, and indicates communication within the injection zone throughout the field. During this time, the pressure in the overlying monitoring zone has remained constant, indicating lack of pressure communication between the injection and monitoring zones (i.e. containment; Figure 4). The lack of increase of pressure in the monitoring zone indicates that communication between zones is unlikely both through the confining system geology and the existing wells. Specific responses identified in the pressure history are annotated, and include temporary field shut-in (injection cessation) most notably due to hurricane Gustav, as well as various data gaps resulting from signal communication issues.

The derivative of the pressure curve (rate of pressure change; Figure 5) reveals finer detail of pressure response to various events identified in Figure 4, and is particularly powerful for understanding pressure evolution. In particular, changes in the rate of pressure increase are clearly observable for events such as filed shut-in (most dramatically for hurricane Gustav, which resulted in negative rates and pressure decline), field-wide increase in injection rates, and initiation of additional injection wells, especially the closest injector to the observation well. While we have not observed any pressure signals suggesting unwanted migration out of the injection zone, the data support the capability of the design for early detection of non-conformance within the injection zone. From these results, it can be inferred that the initiation of unintentional migration of CO_2 out of the injection zone would be clearly identifiable at time scales that would allow for dynamic modification of injection and possible mitigation (e.g. well remediation, decreased injection, abandonment). For example, the initiation of injection at the injection well closest to the monitoring well 2900 ft (882 m) away is clearly identifiable in the rate of pressure change in the injection zone (Figure 5). The injection rate at this well was initially 8.4 MMSCFD (437 tons per day), or approximately 18.8% of total contemporaneous field-wide CO_2 injection rates. This suggests that were a similar rate of migration out of zone to occur at similar timescales, it could be identified quickly as a similar magnitude but opposite sense (decrease) signal in the rate of pressure change. This is clearly identified for larger changes in injection rates such as field shut-in for hurricane Gustav (Figures 4 & 5). Given the sensitivity of the rate of pressure change, it is likely that a significantly smaller percentage increase or decrease could be detected, perhaps as little as half the amount associated with the initiation of injection at the injector closest to the observation well. A key observation is that high resolution changes in the rate of pressure increase can be correlated with field activities to infer conformance.

7. Discussion

One drawback of the cost-limited deployment of this technique at the study site (i.e. single well deployment) is that it could be initially challenging to identify the cause or location of unwanted migration. However, above zone monitoring can be employed to distinguish between relatively instantaneous communications between zones via wellbores versus more attenuated (temporal and magnitude) signal that would be expected from migration through geologic confining systems. Employing a suite of similar deployments (i.e. multiple wells) would be extremely useful for eliminating possible migration scenarios. That is, distinguishing between localized well leakage and more pervasive failure in confining systems should be possible. In addition, comparisons of response from various spatially-distributed gauges in the same overlying monitoring zone (or alternatively different monitoring zones) would aid in this interpretation. Finally, temperature data from the injection and monitoring zone can also be used to corroborate injection conformance. That is, rapid communication between the injection zone and the overlying monitoring zone would almost certainly be accompanied by attendant temperature fluctuations (albeit minor) associated with either CO_2 or brine migration. We have not observed any temperature anomalies suggestive of any such rapid communication in the observation well, again indicative of conformance of the injection within the injection zone and integrity of the monitoring well completion.

8. Conclusion

Continuous pressure measurement is an extremely useful tool for monitoring CO_2 injections. The data presented indicate that increases in injection rates of 8.4 MMSCFD (~440 metric tons per day) can be observed from distances of less than 1 km. By inference, a similar decrease (or loss of CO_2) at similar rates is also expected to be detectable. While the detailed distribution of CO_2 may not be inferred with any fine spatial resolution and the specifics of multi-phase flow processes are not discernable, the broad conformance of an injection is possible. The temporal frequency of measurements in a deployment such as that used at Cranfield is extremely cost effective. Because pressure is a broadly integrative tool, it allows monitoring of extensive areas at relatively low cost for long periods of time. Similar frequency of other observations (i.e. fluid sampling, well logging, etc.) is cost prohibitive in most situations. Any non-conformance identified in pressure and/or temperature data could be followed up with other techniques such as logging or seismic imaging to further investigate inter-well CO_2 distribution. Pressure monitoring is a primary dataset for demonstrating conformance and for identifying areas needing further investigation.

9. Acknowledgments

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10. References

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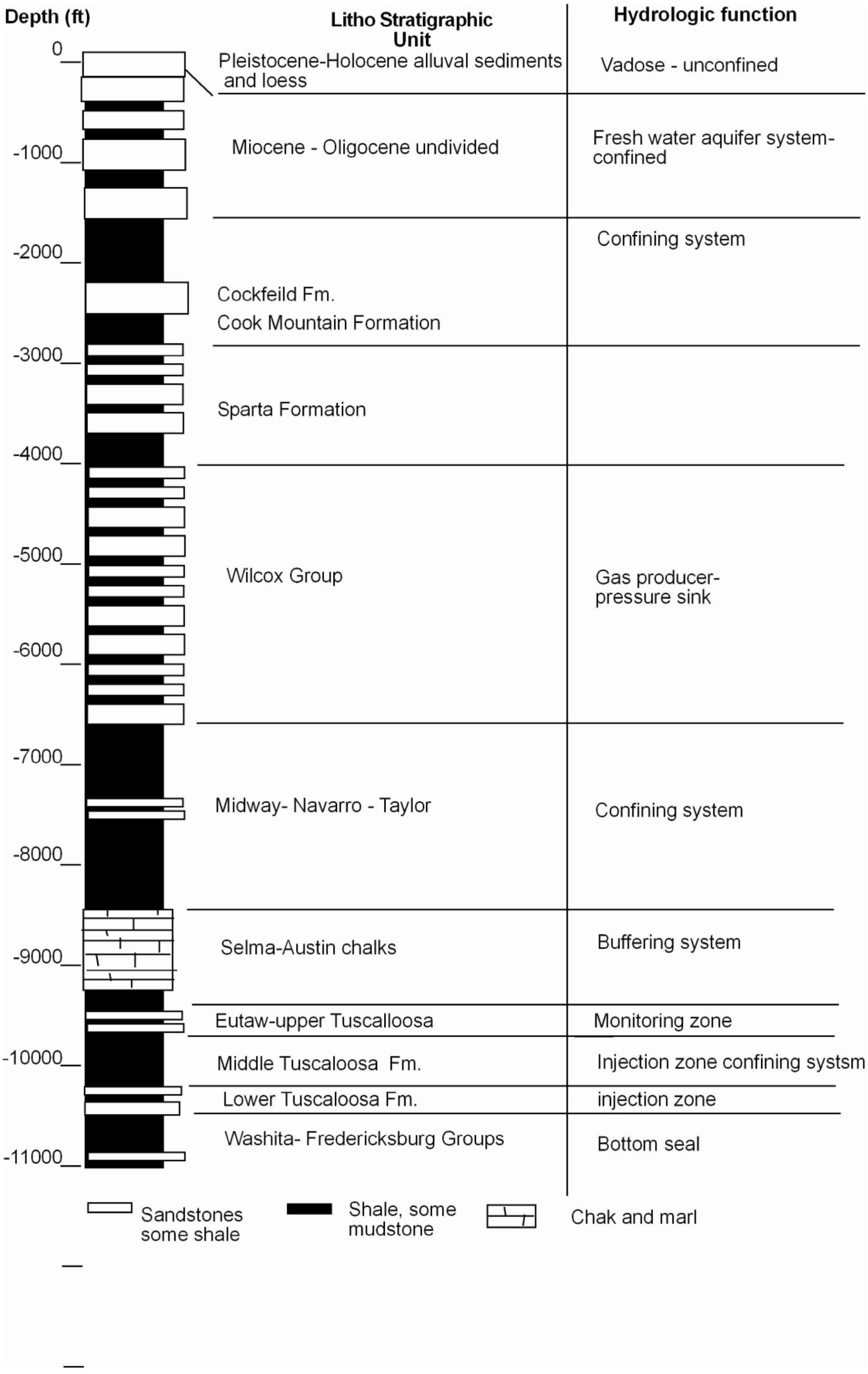

Figure 1. Stratigraphy at Cranfield Field indicating bottom seal, injection zone, confining system, and monitoring zone.

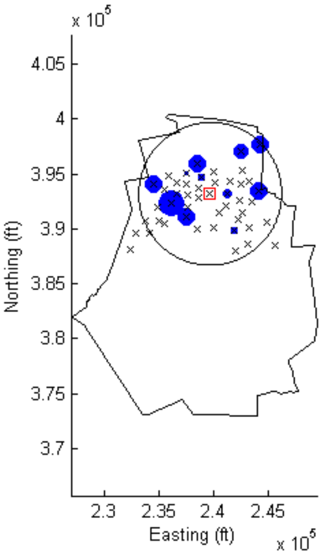

Figure 2. Map showing outline of Cranfield Field and well locations (x) only for the northern portion of the field. Square indicates location of dedicated monitoring well. Solid circles are scaled to total CO_2 injection volume to date. Large circle centered on monitoring well has radius of 1.23 miles (distance to farthest injector) and area of 4.76 sq. mi.

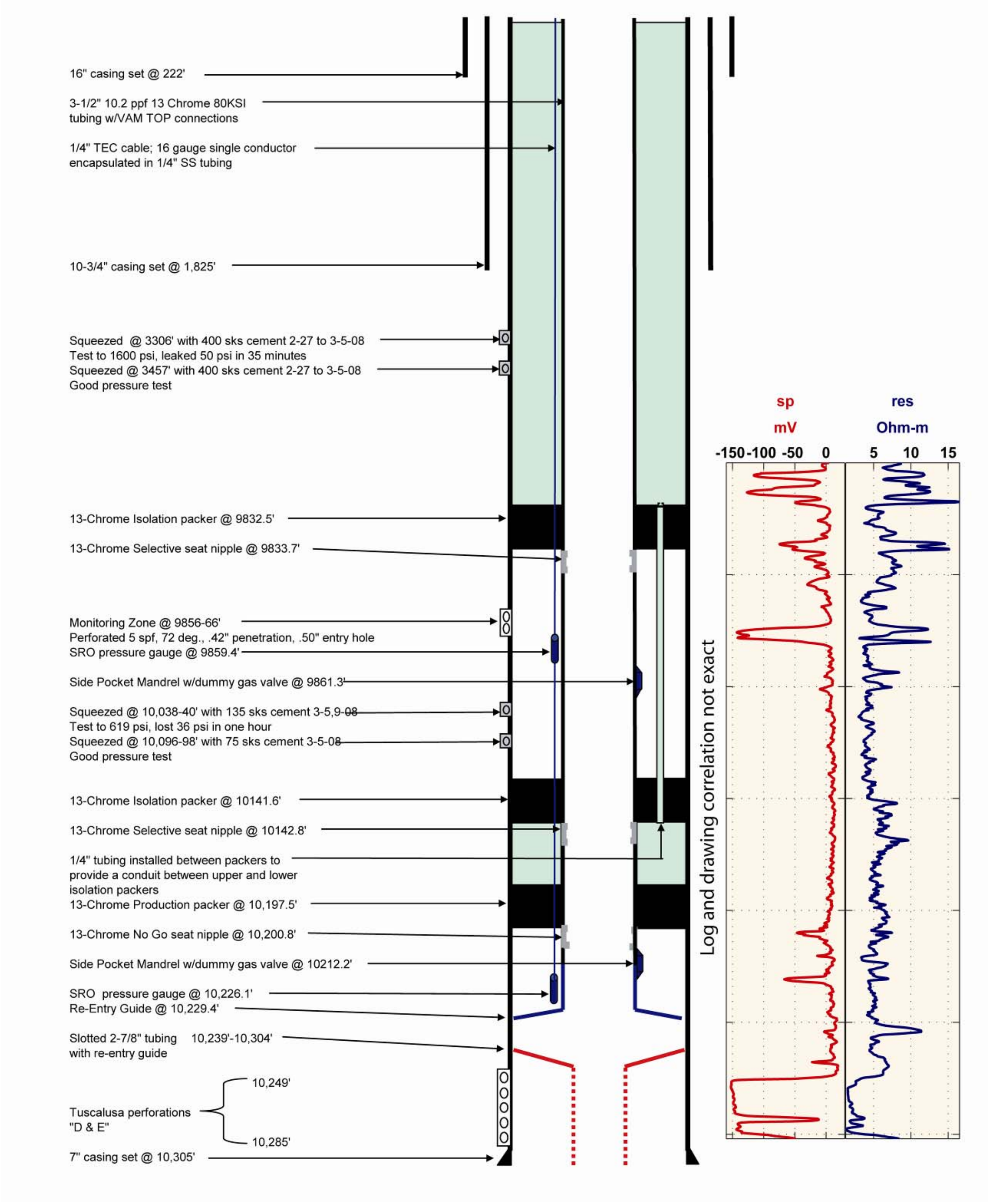

Figure 3. Observation well completion diagram indicating pressure and temperature gauge locations. Log image to right shows correlated approximately to well design.

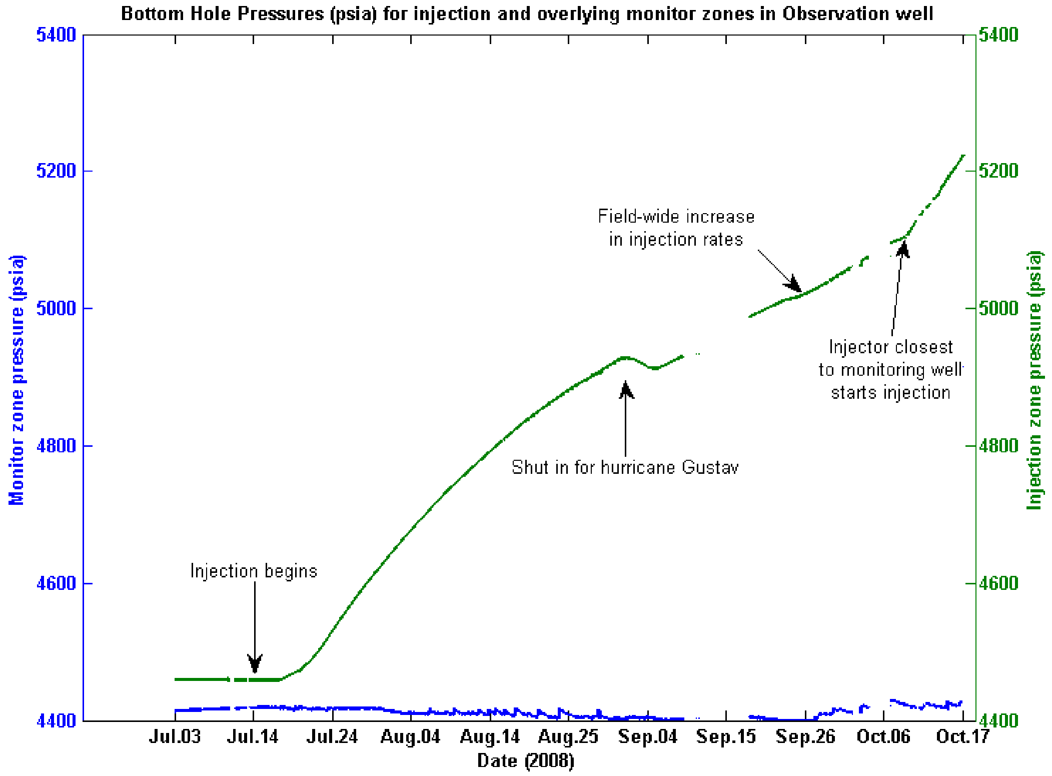

Figure 4. Plot showing evolution of pressure within injection zone and overlying monitoring zone. Injection pressure has increased >760 psia since injection, while monitoring zone pressure has stayed constant, indicating no communication between the two zones. Annotations are for various events during field injection. Data gaps are a result of data communication issues between downhole gauges and surface recording devices.

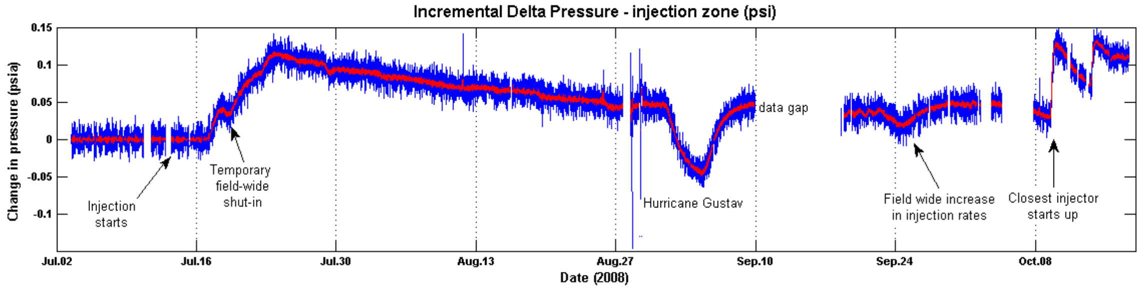

Figure 5. Rate of pressure change for data in Figure 5. Both the measurement-on-measurement difference (10 minute interval) and the hourly average are shown. Specific events that are discussed in the text are field shut in for hurricanes Gustav, field wide increase in injection rates, and the initiation of injection in the injector closest to the dedicated monitoring well (2900 ft; 882 m).